ESFR SMART a European Sodium Fast Reactor concept including the European feedback experience and the new safety commitments following Fukushima accident
Mr. Joel Guidez, CEA, France

Berta Oates
Welcome, everyone to the next Gen IV International Forum webinar presentation. This morning's presentation on ESFR SMART, A European Sodium Fast Reactor Concept including the European Feedback Experience and the New Safety Commitments following the Fukushima Accident will be presented by Mr. Joel Guidez.

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 the National Technical Director of the Molten Salt Reactor Program on behalf of the US Department of Energy, Office of Nuclear Energy. She is currently the Chair of the Gen IV International Forum Education and Training Working Group. I give the floor to you. Patricia?

Patricia Paviet
Thank you so much, Berta. Good morning and good evening, everyone. It's a pleasure to have Mr. Joel Guidez with us today. He graduated in 1973 from Ecole Centrale de Paris and his career focused on the field of nuclear reactors in France and in Europe. After working for Superphénix and then for Phénix as Head of Tests, he led the Thermohydraulic Laboratory in the CEA Center of Cadarache.

In 1993, he became Head of the Osiris reactor at Saclay, near Paris, and 5 years later in '97, he was seconded to the European Commission in Petten, the Netherlands, where he took responsibility for the European Commission reactor, the High Flux Reactor. From 2002 to the end of 2007, he was director of the Phénix nuclear power plant in the CEA Center of Marcoule. He continued until 2009 as Director of Industrial Nuclear Support at Saclay. His first European experience was followed by a second one in 2010, where he became nuclear representant at the French Embassy in Berlin.

In 2011, he returned to Saclay as the Director of the CEA Nuclear Energy division as an international expert. He wrote two books that have been published and translated and published in English. The first one on the experience feedback from the 35 years of operation of the reactor of Phénix and the second one on the technical and scientific achievement of Superphénix.

He served on several committees. He retired in March 2020, while remaining a Scientific Adviser to the CEA, working on the ESFR SMART European project, and writing a new book entitled "Fast Reactors: A Solution to Avoid Global Warming."

Without any further ado, I am really honored, and very happy to give you the floor, Joel. Again, thank you for volunteering to present this webinar, which is recorded and will be archived on the GIF website. Thank you, Joel.

Joel Guidez
Thank you, Patricia.

This slide is only to show the two books were made on the learning experience, one is Phénix and Superphénix reactor and the basis of ESFR SMART based on this experience and as I said in the title, ESFR SMART is a view of the final learning experience on sodium fast reactors.

Next slide, please.

The summary of the presentation of today.

We have first some words on the ESFR SMART history to explain the design of ESFR SMART is based on the feedback expressions of European sodium fast reactor.

The second point is methodology we use to increase the safety. The aim of the project was to increase the safety and to reach the new ask in safety after Fukushima.

The third point is core design.

The fourth point is containment and primary circuit design.

The fifth point is point on the decay heat removal that is special for ESFR SMART.

The sixth point are the secondary loops.

The seventh point is the final layout of the plan.

In the point eight, we make together the status of all the simplifications and the improvements of the design.

In the point nine, we have status of all the passive systems that are included in the design of ESFR SMART.

In point 10, the necessary research and development to reach the benefits of ESFR SMART design.

The point 11 are the conclusion.

Next slide, please.

We have to remain together the ESFR SMART history.

In '88, while the European Superphénix reactor was in operation, a new European Sodium Fast Reactor EFR project, with a slightly higher power of 1500 electrical megawatt, was launched in collaboration between France, Italy, Germany, and the UK. This project was stopped by the shutdown of Superphénix and was closed by a final file, very interesting to read, that summarized all the options selected.

On this basis, a project called CP ESFR, Collaborative Project on ESFR, was initiated a few years later to groom the EFR options and to integrate the new technical developments. It is on this new basis that a project called ESFR-SMART started at the end of 2017 mainly with the objective to integrate all the new safety rules resulting primarily from the Fukushima accident. This project tries to include all the long European experience on sodium fast reactor, not only from Phénix to Superphénix but also from project studies such as European Fast Reactor or ASTRID.

Next slide, please.

Though this type of project is a working horse or a concept car, I don't know, the two terms are used. In the Anglo-Saxon world, sometimes, we call a "working horse". Its role is to introduce, outside of any constructive planning, new ideas for the future, which can be valuable guides for the research and development. Though we are not in an industrial project, and we have no construction schedule, still we can easily introduce innovative ideas, even if their lower technological-readiness level would require research and development in the future.

Nevertheless, for these new ideas, research and first calculations have been performed to check their general feasibility and to see the absence of major impossibilities. In conclusion, we will see the status of the necessary research and development to provide to use these new ideas.

Next slide, please.

What methodology we use to reach the new safety requirements post-Fukushima?

First, we try to avoid dedicated systems for incidents because simple is safe. I have been the Director of three reactors, and I know that we need to have simple operational plan to be safe. We use all the advantages of sodium, especially for natural convection. Sodium is a very good feed to assure natural convection. We use the feedback experience of reactors and of projects as EFR, ASTRID.

We use the practical elimination methodology, to try as far as possible, to suppress by the design a lot of known possible incidents. All the incidents as we know the feedback experience of reactor, we have eliminated this incident going on by practical elimination in the design. Then, we have a final verification of accordance of the final design to the new safety rules post Fukushima has been and provided by a dedicated task.

Next slide, please.

On the feedback experience of reactors, it was to remind that the European Fast Reactor project was initiated during the end of Superphénix 1 operation. Superphénix has the biggest sodium fast reactor ever built and operated in the world. There was a lot of experience, industrial experience of Superphénix and we see that in the European Fast Reactor design, several new options are proposed, and these options are very interesting because the propositions were made on the basis of the huge and unique experience.

We will see mainly in the ESFR SMART design the proposition of massive metallic roof, as well as proposition of people that have worked on Superphénix. The primary pumps belted non-oscillating primary pumps and we see the proposition of modular steam generators. On Superphénix, it was compact steam generators and massive steam generators and there was a lot of problem with the type of massive steam generators and the people proposed this modular steam and we see the advantage of the modular steam generators.

Next slide, please.

We come back to the formulation, simple is safe. We tried to propose a design of reactor very simple because simple is safe.

Rather than adding devices to improve safety, we simplified the reactor design to promote passive and intrinsic safety, with a great grace period for the operator. We will resume in the conclusions, how we simplified the design – suppression of the dome, of the safety vessel, of the DHRS systems inside the primary vessel, etcetera – and how we increased the passive systems with either passive controls rods or passive decay heat removal, passive circulation of thermal pumps and those reactors are very simple to operate.

Next slide, please.

We arrive at the following point, point 3 of the core design.

The void effect. We know that we have in the sodium fast reactor the problem of void effect and the core design of ESFR SMART is mainly issued of the ASTRID project, the French project ASTRID works to minimize the void effect. A lot of various dispositions were taken as increased diameter of pins, to have a plenum above the core, mix of fertile and fissile inside the core, etcetera, that allow to obtain a global almost zero void effect. That is very important in terms of safety and in terms of severe accident. We see also that energy release is very low.

Then, we have had in the core, passive control rods. We have two gains of values perceived, two gains of active control rods. Then, we have a short gain of 12 control rods that stopped the reactor if a physical parameter is reached. For example, if the temperature of sodium is more than 600 degrees, they fall without operation or any control command order. It's totally passive control, or they can stop the reactor if there is a problem.

Then, we have several tubes for corium discharge. We have made a lot of work to increase the mitigation of incident and for the corium, in case of severe accident of corium formation, we have several tubes in the core that arrive above the core catcher. In case of severe accident with the core melting, they should conduct the corium to this core catcher. We shall see that in the next slide, please.

This slide shows the artistic view of the preferential ways for the melted core. You see we have in the core lot of tubes that we melt. These tubes are filled with sodium and once they melt, the corium will arrive through these tubes above the core catcher. We will come back later on the geometry of the core catcher. But we see that the position that was taken at the beginning, there was a mitigation of severe accident.

Thanks, please.

Always on the core design, we have in this core, 24 active control rods responding to the usual safety criteria, especially for diversification, with two different types of control rod. As for the other Sodium Fast Reactor, the pads on the fuel assembly are in contact when the power of the reactor begins to increase. A compaction of the core is not possible when the reactor is in operation. To verify that there is no modification of the global core geometry during the operating cycle, some ultra-sonic measurements can be provided to calculate the geometry of the core.

Thanks. Next slide, please.

That is the view of the ESFR SMART core. We see the inner zone, as well you will see the control assembly, the corium discharge path, the corium discharge path you see here with the red point, that is the corium discharge path. We have the shielding of the subassembly. We have the internal spent fuel storage in the external path. We have the fossil fuel mixed with the fertile blanket, and we have the fission gas plenum that is above, and we have the sodium plenum, and we have the shielding absorber. We see the conception of the core is used mainly as the conception of the ASTRID core.

Thanks. Next slide, please.

Now, after the core of the reactor, we arrive to the containment and to the primary circuit.

The design of the primary circuit is mainly characterized by following improvements. We suppress the safety vessel. We suppress the possibilities of primary sodium leaks that allows the suppression of the dome or the polar table. The dome was on Superphénix reactor, and the polar table was on the ASTRID project. Though in ESFR SMART, we quite suppressed this very expensive fact [ph]. After we have suppressed the dedicated circuit for decay heat removal inside the primary circuit, other circuits for the decay heat removal outside of the primary circuits. Then, you have a new core catcher for better mitigation of severe accident.

Those are the four main points that characterize the ESFR SMART primary circuit.

The first point is the safety vessel. As you know that safety vessel functions also exist in sodium fast reactors, built or operated, have a safety vessel around the main reactor vessel. The function of the safety vessel is to contain the primary sodium in case of the main vessel leakage, to avoid lowering the primary sodium-free level below the exchanger inlet window which would have the effect of interrupting the cooling of the core by natural convection.

Two, if you have a leak in the safety vessel and we have an accidental situation, the reactor will never start again, and the unloading of the core is necessary. But this unloading will take at least one year because it is necessary to wait until the decrease of assemblies' residual power. The other function of the safety vessel during the accidental situation is to maintain the sodium without leakage in the pit during more than one year. Remember, we need to make the demonstration as possible. We have this functional.

This is an arial overview of the safety vessel of Superphénix. You see that it's a big component, 21-meter diameter, and in the pit inside, you will see the cooling system around the safety vessel on the pit.

Next slide, please.

Why to suppress the safety vessel?

A number of measures have been taken to prevent leakage of the safety vessel. We have a slight overpressure between the two vessels to detect a possible initial leak during the reactor operation and we have choice of different materials between safety vessel and main vessel to avoid a common failure mode on corrosion. But the scenarios of main vessel leakage are diverse. There can be corrosion leakage. There can be corrosion to leakage after a severe accident with a big mechanical energy release and the uncertainties in the temperatures and leakage rates make it difficult to demonstrate the safety vessel mechanical strength against the corresponding thermal shocks.

For example, if we have a big leak in one part of the main vessel, we can have different thermal shocks, strong thermal shocks on the safety vessel and we can lose the safety vessel. The demonstration is difficult to do because we don't know the scenario of the incident.

The evolution of the safety standards leads us to look at other options where its functions could be directly taken over by the pit of the reactor. If the pit can assure the withstanding of sodium leak and assures a long-term mitigation, if we can do that, in this case, all the functions of the safety vessel can be taken by the pit of the reactor and in this case, we can suppress the safety vessel.

Next slide, please.

What are the advantages to suppress the safety vessel?

If we arrive to have a pit design to take the safety vessel function, we can, in this case, suppress the safety vessel and so we can maintain the function to have a volume between safety main vessel, that is the same as volume between the pit and the main vessel.

This design presents several advantages. The heat screen from the safety vessel is suppressed and the power removal through the reactor pit is facilitated. We see that it is interesting to increase the decay heat removal possibilities by the pit circuit. We have response to the question from the safety authority relating to a double leak of the two vessels. The main vessel in-service inspection remains still possible as before, and the final structure is better adapted to the mitigation functions, because this pit design is now able to support any sodium leaks at the beginning of the accident and after the accident with more data.

Thanks. Next, slide.

We have made a pit design proposition. A mixed concrete/metal structure with a water-cooling system inside the concrete supports the thick metal slab to which the reactor vessel is attached. Together with the reactor roof, it provides a sealed containment which must keep its integrity in all the cases of normal and accidental operations. Above the bottom of the concrete/metal structure, blocks of insulating materials, non-reactive with sodium, are installed in the lower part. Alumina is selected as a reference material for these insulation blocks.

A metallic liner is placed on the surface of these insulation blocks. The gap between the reactor vessel and the liner is small enough to avoid decrease of the primary sodium free level in case of leakage. An oil cooling system is installed on the liner in front of the main vessel. This oil system is compatible with sodium. There is no hydrogen in case of reaction to sodium and this only can operate at very high temperatures. Finally, a special concrete with alumina, aluminous concrete, which could withstand, without significant chemical reaction with sodium, we can withstand a leakage of the liner could be used between the liner and the external structures.

Next slide, please.

In the following slide, we have a view of the pit. You see the area in red, you can see the external part in concrete with the possibility to have the concrete under 70 degrees all the time and we have the slab. The slab is with ideal techniques. Here, we have the main vessel and in front of the main vessel, we have the liner, liner that is here, so aluminous concrete behind the liner, some insulation between liner and aluminous concrete. We have in the lower part, alumina blocks to support the liner and anti-seismic devices on the primary vessel that we can see there. You see the diameter. We have a diameter that is in Superphénix. It was more than 21 meters, and we arrive to 20 meters.

Next slide, please.

Here we have two independent active cooling systems. The oil cooling system is close to the liner. The oil is under forced convection and can remove the heat transferred by radiation from the reactor vessel. We use for this oil system an example of commercial oil. Whereas Therminol SP can be used in normal operation, and can operate at 315 degrees, at very high temperature, and in case of accident and sodium with this oil will not produce hydrogen.

After we have a second cooling system, the water-cooling system inside the concrete in the external part and this system can maintain the concrete temperature under 70 degrees in all the possible situations, even if the oil system is lost. Both systems are working during normal operation and maintain the concrete temperature at low temperature and in case of the reactor vessel leak and the loss of the oil system, the water system is able to alone to remove the decay heat generated by the core and to maintain alone the concrete below 70 degrees.

Next slide, please.

That is the view of the oil system inside that is on the liner. There are several independent oil circuits on the liner able to take the residual power.

Next slide, please.

We have made preliminary thermal calculations of the system. These calculations were provided by JRC for the following three main scenarios:

First scenario is normal operation. The main vessel is at about 400 degrees, and we see that the operation of the oil cooling system is sufficient to maintain the correct thermal conditions in the pit.

Scenario 2 is operation in exceptional decay heat removal regime. We are already in accidental case in exceptional situation of categories 3 and 4. The reactor vessel in this accidental case can reach temperature of 650 degrees and you will see that the two cooling systems can maintain the concrete temperature below 70 degrees without problem.

Scenario 3 is operation in accident situation of sodium leakage. In this situation, we even don't try to demonstrate that the oil system can operate. We say that we lose the oil system, and we demonstrate that the operation of the water-cooling system alone is sufficient to maintain the concrete temperature below 70 degrees.

Next slide, please.

This slide is a view of the modelization that has been provided for the calculation. These calculations have been presented in ICAPP 2019. The paper is available on the subject.

Next slide, please.

The calculation results show that at nominal power, about 3 megawatts are extracted by the oil circuit to maintain the oil at 200 degrees and the situation is, even if the water circuit is not operating, the temperature of the concrete is under 70 degrees.

Scenario 2, in exceptional regime of decay heat removal with the main vessel at 650 degrees during a short time, we can expect a power of about 15 megawatts. The liner remains at about 200 degrees, and the concrete remains easily under 70 degrees.

In scenario 3, in case of sodium leakage after a big accident, we don't even try to demonstrate that the oil circuit was always in operation but only with the water circuit it's easy to maintain the concrete at a good temperature.

You see, in all the cases, we can maintain the temperature of the concrete under 70 degrees.

Next slide, please.

Interest of the question of the safety vessel is also that the decay heat removal capabilities of the oil cooling system is bigger than before because the heat screen of the safety vessel has been suppressed and though we have the exact [ph] calculation that showed the possibility to extract 3 megawatts of nominal power and 15-megawatt acceptance threshold without problem with this is system, that is more efficient.

Next slide, please.

The conclusion on the safety vessel suppression.

We arrived to have an innovative design of the pit that allows to suppress the safety vessel. The safety vessel is a very expensive component and at an industrial level, it has a very difficult component. There is also a big advantage in terms of industrial realization. We have two active forced-convection cooling systems, an oil cooling system close to the metallic liner and a water system inside the concrete structure. The preliminary thermal calculations showed the system is very efficient in all the scenarios to maintain the concrete below 70 degrees.

The proposed reactor pit design has several advantages: Elimination of the safety vessel, better efficiency of the decay heat removal by the reactor pit cooling systems, and safer configuration in case of accidental or mitigation situations.

Thanks.

If you want to know on this pit organization and calculation, the results have been presented in the ICAPP 2019 Symposium. You can read this paper that explained, in detail, the calculation and the geometric disposition. They are also presented in the NERS paper, the publication that will be made this year. You have two papers that explain more in detail this pit organization as well as calculation.

Thanks.

The term-bound [ph] innovation with the primary sodium confinement was a massive metallic roof.

Superphénix experience feedback leads to recommend hot slabs at their bottom part to minimize the aerosol deposits and with no water cooling inside because in Superphénix, there was water cooling inside the roof. This last point is also part of the demonstration of practical elimination of sodium/water reactions on the primary side.

For the European Fast Reactor, the people that were already considering the concept of Superphénix, proposed a thick slab that presents many advantages. Simplicity of operations, the thick slab, you have nothing to do for the operator. There is no circulation of air or water inside to operate. It gives a good neutron protection. It aids in mechanical oversizing in the event of a severe accident because it's very used with massive metallic roof. Then, we have a limitation of thermal flow because the thermal flows are controlled by conduction.

The conduction is artificial and so we have the limitation of the thermal flow that caused current by the convection. The thickness will be defined by the industrial manufacturing contingencies but should be about 80 centimeters. In the upper part, we can add eventually a heat insulator to limit the heat flow to be evacuated during nominal conditions, but its flow should be evacuated by natural convection.

Thanks, please.

We took a lot of other dispositions in the design of the plant to avoid any primary sodium leaks during severe accidents. The disposition is as following:

All the components introduced [ph] and involved are firmly bolted and welded, welded in the upper part to avoid any risk of leak. You have the rotating plugs that have eutectic seals that are solidified during the operation, so no leakage is possible. You have no circulation of sodium outside the vessel. The cold traps are integrated in primary circuit, and we have low argon pressure to avoid any sodium fountain effect.

All these measures do enable to prevent any primary sodium leakage outside the roof, and so any overpressure possibility due to primary sodium fires after a severe accident.

I forget one of the dispositions, we will see later, that there are six systems to consider. There are no tacit [ph] systems inside the primary vessel and there is no possibility of sodium leaks at the several labs also. As there is no possibility of primary sodium leaks, even in case of severe accident, we can suppress the expensive and complex system as a dome that was in Superphénix and the polar table that was on ASTRID project. The systems are complex. They generate higher cost and later there are difficulties for the operation of the plant and those are good for the safety.

Thanks. Next slide, please.

That is the view of the Superphénix dome that has 22-meter diameter. It's a big procedure. As you can see, it's very complicated and after and during operation of the plant, when you have to make handling, you have to make a lot of work that is not in the terms of the safety but in terms of simplicity.

Thanks. Next, again.

This is another point of disposition. We have suppression of decay heat removal systems inside the primary vessel. The decay heat removal is assured by systems in the secondary loops. Superphénix was independent systems, DHX, located in the primary circuit and it was also in the CP ESFR. We have suppressed the systems inside the primary circuit, so we have no slab penetrations required. It gives a gain on the main vessel diameter.

In terms of a leak, we have a cold column that is maintained in the intermediate heat exchanger, which is the guarantee of a good natural convection in the primary circuit. It was not the case with DHX because with DHX, there were very complicated transient situations before to cool the core of the reactor.

This circuit uses the already existing purification circuit of the corresponding secondary loop. We minimize the number of sodium circuits. We have no new sodium circuit managed by the operator. The DHX of Superphénix was a sodium circuit to manage with purification system and draining system and all that had the capacity for the operator. We have less risk of sodium leak out of the primary vessel, we have more penetration inside the primary vessel, and all systems that are out of the primary vessel are more resilient in case of energy release in the core during a severe accident.

Thanks.

Last but not the least, we have the in vessel core catcher that was installed inside the reactor.

The mitigation of a severe accident with the core meltdown is achieved by means of a core catcher, located at the bottom of the vessel, under the core support plate that we call also a strongback. The guide tubes, coming from the core, you have already seen the design before, emerge above this core catcher so as to channel the molten corium on the core catcher. The tubes arrive above conical hats which disperse the corium and protect the core catcher. We used molybdenum as material that can prevent the melting of the core catcher structures and facilitate the heat removal by conduction, very good conduction. The use of hafnium-type poisons in the core catcher structures enables to avoid any re-criticality of the corium. The core catcher volume has been dimensioned for the whole fissile core meltdown and for this cooling by natural convection of sodium.

Next slide, please.

The choice of core catcher material by Russian fast breeder reactor BN 800, we chose molybdenum because it has good resistance to corium ablation. It has good chemical compatibility with sodium. It has a very high melting point above 2000 degrees. The material is available, weldable, and affordable. It has a very good conduction coefficient that is important for the natural convection and indicates model by natural convection. It has an excellent mechanical resistance against thermal shock.

Thanks. Please.

That is the view of the core catcher. You see the conical hats above the chimney and the tubes are right above the conical hats, while the core is in molybdenum and natural convection is possible inside to it but for the evacuation of the residual power by the sodium around this core catcher. We can say a thorough test has been made in the kit in Germany and thermally under natural convection around this core catcher.

Thanks, please.

Here, we see the core catcher. This is in green. But even though the core is there, here we can see the tubes, the rising, the melting core inside the core catcher. You see that we have a system that is well dimensioned for the severe accident.

Thanks. Please.

That is a drawing of the core catcher. We have to say that all the drawing of the ESFR SMART project has been made and perceived during the project and all the drawings are available for further work on the subject. In the drawing, we see again the chimney. We see the possibility of natural convection around the core catcher and inside, there are chimneys.

Thanks. Please.

We have seen the four main improvements of the primary vessel and we arrive at this final view of the primary vessel. You see the containment that is very strong containment of concrete that is always at low temperature. We have the slab, metallic slab with a high thickness and we can support any severe accident with this containment. There is normal dome [Unclear] above this containment.

There is no possibility of sodium leaks and also decay heat removal is met at external level by this heat exchanger that allows to have a good natural circulation inside the reactor and a good cooling of the core in natural convection in all the situations. The component that will lead under the pump will avoid any leakage. If we were to take out components for maintenance, we can cut the weld and you can extract the component without difficulties. The purification is also inside the primary vessel. There is no primary sodium going out of the primary vessel.

Thanks.

We will arrive now go to the next chapter of the decay heat removal systems. The reactor has three decay heat removal systems, DHRS, and we have no more DHX systems inside the primary circuit. In the three DHRS systems, there are six secondary loops able to evacuate in active and passive way by air cooling the DHRS 2. We have two active circuits in oil and water in the pit. We have already spoken on the circuit, and you have six passive systems DHRS 1 able to remove power even if the secondary loop is drained in natural convection by air cooling.

Next slide, please.

Here, we begin passive DHRS 2. They are the secondary circuits. They are the normal power removal circuits and their use for decay heat removal is very useful since they are allocating in the intermediate heat exchanger, a cold column that is essential for the establishment of a good natural convection in the primary circuit with the core of the reactor.

The design of the secondary loops has been optimized to enable a good power removal by air in natural convection. In difficult situation, like the Fukushima situation, when both release the cooling water and the electrical power supply, the secondary loops are able to make bilateral convection power removal and one thermal pump is installed to increase natural convection circulation flow rate.

We will come back later on the thermal pumps. They are passive pumps with no need of any electricity supply.

The CP ESFR option or the ESFR option for the steam generators was modular, with six modules per loop. Though the six module loops were warranted, large exchange surface, and we have opportunities to cool these modules by natural convection with air. We open hatch in the casings, as on the Phénix reactor, and the air circulation around the modules are allowed to cool by natural convection of the reactor.

Next slide, please.

We have six loops. All calculations are made with the principle that one loop is out of order. Here we have made the calculation, but in the calculation, I have shown that in normal operation, one loop is sufficient to assure the decay heat removal. If we lose water in the steam generators, the circulation of secondary sodium with the open casings is okay to assure the decay heat removal by natural convection.

If we lose also the electricity supply, Fukushima situation, low sodium circulation, low speed is able to assure alone the decay heat removal and if we stop totally the secondary pumps, natural convection in the loops is able with DHRS 3 to assure all decay heat removal without the help of DHRS 1. After several hours, DHRS 2 is able alone, without DHRS 3, to assure alone the decay heat removal. Though we see that the same is very efficient in natural convection.

Next slide, please.

This is a view of the secondary loop as DHRS 2. We see the heat exchanger is there. Actually, there is DHRS 1 that we will speak after this DHRS 1. DHRS 2, we see that the sodium is going in the six modules and comes back here and so if you open the cups, this part, the upper part, there is natural convection of the air [Unclear], and as on the Phénix reactor, the cooling is in the reactor by natural convection.

Next slide, please.

DHRS 3, we have already spoken of these two cooling active circuits located in the reactor pit. It is capable to maintain the entire pit at temperatures below 70 degrees. We have suppressing safety vessels that make these devices much more efficient than before. These circuits are redundant, three or more, and can assure when the primary vessel is at 650 degrees, a power extraction of about

15 megawatts. There are active circuits, not passive circuits. After three days, these circuits can assure alone the decay heat removal of the plant without the secondary loops.

Thanks. Please.

We arrive at the last system, DHRS 1. They are cooling circuits, with sodium/air heat exchangers connected to the intermediate heat exchangers and out of the primary vessel. They operate in natural convection in air in natural convection and sodium. There is thermal pump for the circuit to increase its capabilities and to help for the starting of the operation. The circuit remains active even if the loop is drained. In case of accident, the circuits are out of primary vessel and mechanically protected and without problems of mechanical worries.

What are the advantages?

There are several advantages compared to the independent systems, DHX, that were located in the primary circuit in Superphénix or CP ESFR. We have no slab penetrations though we have a gain on the main vessel diameter. We have a cold column that is maintained in the intermediate heat exchanger, which is a guarantee that the natural convection with the core is operating very well, very quickly. This circuit uses the already existing purification circuit of the secondary loop. We don't add new loops of sodium. We use the loop of secondary loops, and we have less risk of sodium leak out of the primary vessel because we are not in the primary vessel, and we are more resilient in case of energy release in the core.

Thanks.

Here, we have a huge system. This is very simple. We have the air [ph]. It is shown here where you can see with the red breadth [ph], and we have the liaison, and we have the heat exchanger. We insert Owings [ph] which are smart. We took the heat exchanger of Superphénix 1. It was exactly what we needed. Though we have all the calculation, all the tests of the heat exchanger that exist, and we have a big chimney, this chimney is only to increase the natural convection of the air that allowed cool air and comeback [ph] air, and with the chimney, we have a good natural convection operation.

The sodium is cooled in comeback air and the difference in density between the hot sodium and the cold sodium allowed the system to operate without any mechanical problems. We will see that we add the thermal pumps on the circuit to increase the flow rate, but the circuit is operating totally passively. When we need the circuit, we had only to open the arch of the chimney, the cooling begins to operate, and the system is operating by natural convection.

Thanks. Next, please.

We have made a lot of calculations of the DHRS capabilities to validate the proposition and so we have the illustration [ph] that shows the secondary loops, and the pit oil circuits can assure as decay heat removal after three days can assure alone the decay heat removal. The secondary loops can assure in natural convection more than 20 megawatts. It is able together with DHRS 3 to assure the decay heat removal.

With a low speed of secondary pumps, the DHRS 2 is able to assure alone the decay heat removal, and even if these circuits are lost, if all the circuits are lost, the DHRS 1 is able to assure alone the function without need of water or without need of electricity. The DHRS 1 are six independent systems, totally passive, using air that is always available. They are able together to assure 100% of the decay heat removal. Inside the calculation we have made, we have five developed systems and one that was out of order.

Thanks. Next slide, please.

We have a global safety acceptance, the new goals set up after Fukushima is that the probability of prolonged loss of residual power systems in ESFR must be less than 10-7. For this, it's admitted in a simplified way, that the system of evacuation of residual power must comprise two lines of strong defenses, reliable and capable to assure alone the evacuation of residual power and one line of weak defense. In our case, the first calculations made it possible to demonstrate that DHRS 1 and 2 could constitute the strong lines of defense and DHRS 3 the weak line of defense.

The final design is in a containment with the new rules of safety after Fukushima and the design showed that in the disposition with flexible pipes, that it's not the final disposition of the layout of the reactor but the system showed the six casings of the secondary loops that are able by natural convection, if you open the case by natural convection, it can assure DHR. We have the six chimneys of the DHRS 1 systems that's on the top of the heat exchanger and the DHRS 3 inside the primary vessel, around the main vessel and with the three systems, we are able in other case to have a very efficient evacuation of decay heat removal.

Thanks. Next slide, please.

If you want to know more because a lot of calculations were made, particularly it was EDF that made a lot of calculations with the catalysis [ph], with the [Unclear] which occurred, calculations were made by EDF on the subject to make the calculation and virtual corrections here [ph]. We have information with ICAPP 2018, ICAPP 2019, ICAPP 2021, and we have a paper and there are some special issues of this year that explain all the calculation of all the vessels on the subject.

Thanks. Next, please.

We arrive now to the secondary loops. We have seen the primary circuit. We have seen the DHRS system. Now, we arrive to the improvement of the secondary loops. Though the secondary loops are designed to assure the decay heat removal, but the big proposition of the secondary loops was to suppress the flexible pipes and to use straight pipes with bellows.

Another proposition was to use thermal pumps. The secondary loop design increased the safety against water/sodium reactions because with the modules, the reactions are easier to detect and easier to manage with the modular steam generator. The sodium fires in case of leakage are also easier to detect in the new disposition and to manage with the straight pipes option and we will see that later.

Next slide, please.

Why we go to the straight pipes is due to the difficulties with the flexible pipes. The feedback from operating experience on Phénix and Superphénix shows a number of difficulties with the flexible pipes. Thus, the expansion of the pipes is important and difficult to manage because we need to manage a free expansion and that is not easy. With new safety rules on seismic conditions, the pipes fixations are not compatible with this expansion. If they are firmly bottled on the pipes, you cannot have a free expansion and a free expansion is not possible if firmly bottled for the seismic conditions.

The length of the pipes is increased because with a flexible, and with a big length of the pipe, is that it increased the number of welds and also the risk of sodium leaks. If the pipes are moving, we cannot separate insulation from the pipes because they have difference in expansion and that complicates the leak detection with a lot of false alarms. In case of sodium leak, corrosion effects can occur between sodium/insulation and pipes. We have seen this type of corrosion on Phénix.

What are the advantages to have straight pipes?

There are a lot of potential advantages.

First, we reduce the length of piping which goes from 200 meters to 120 meters, and we reduce the sodium volume of secondary loop from 116 to 57. You see that's a huge reduction. We reduce the number of welds and reduce the number of risks of sodium leaks. We have easier operation of the plant and possibility of credible anti-seismic systems. This is regarding kind of the anti-seismic systems that are very firmly bottled.

We can reduce the distance between the fixed points and get significant savings on secondary buildings. We can separate the insulation from the piping, and that is simpler and safer and it's a very big advantage for the operator of the plant for the sodium leak detection. We have reduced risk of pipes corrosion because the insulation of thermal contact is tight. We have better possibilities of leak detection with an offset thermal insulation.

Thanks. Next, slide.

There we see we have the straight pipes. It is always possible to have insulation with a gap between the insulation and the straight pipes. There is no false alarm when the reactor begins to operate because you get assured of the straight pipes. There is a gap with insulation. There is no contact. It's also easier to detect a sodium leak because if you have a sodium leak, the system will fail as a normal part of insulation where it's possible to detect.

Next slide, please.

Here we come back to the same view as before with a view of a secondary loop with straight pipes and you see now the bellows. You need to have bellows here, here, here, and here. This bellow takes remaining dilatation on the pipes. The dilatation is very reduced because you can use the materials with a low dilatation effect and you can also have lengths for the part that has very little length, so 1 or 2 meters, and those bellows have not a lot of dilatations to take into account.

Thanks. Next slide, please.

The bellows, so with the straight pipes, it's possible to bring near the components and the fixed points. We reduce the pipes length, and we reduce a lot of dilatations. Some materials can be used with lower dilatation coefficient than most of the secondary systems [ph]. The remaining dilatation will be taken by the bellows.

Some research and development are necessary for these bellows of diameter 850 millimeters in terms of dilatation capacity and time life. However, the use of bellows in sodium is not new. These bellows exist on many sodium valves, especially in Phénix and Superphénix and inside also the Phénix heat exchangers.

A bellow of large diameter, approximately 800 millimeters, was installed in Superphénix on the internal part of the hot collector of the intermediate exchangers and even on the steam generator module of ESFR SMART, we need a bellow of large diameter to allow relative dilatation between the external wall of the steam generator and its internal bundle. If there is reduction, what to do [ph]? If there is some reduction, then what to do? But we know that this type of things exists and can be used.

Another point we had are the thermal pumps on the secondary loops. It's passive electromagnetic pumps, which uses thermoelectricity generated by the difference of temperature between the hot sodium and the atmospheric air. This is air we can see on the view. We have the Chromel and Alumel air.

Though there is a difference of temperature between them, there is this electrical circuit that will exist here and though we create some millivolt between the Chromel and Alumel, the millivolt of the field [ph] but the resistivity of sodium is very low and you have a big electric column that will circulate the air and here we have a magnetic field that is trapped by permanent magnet and also passive pump will give about 20 millivolts of pressure with a good order [ph], with a good electricity. We have nothing with do. It's totally passive.

Thanks. Next slide, please.

Here, we have made some calculation. Those pumps provide a passive flowrate. Here, we see the calculation of the electric circulation and so they can give a pressure of about 20 millimeters of case [ph] that is useful to have a better natural convection and to have a better circulation of the sodium inside the DHRS 1 and even in DHRS 2. If these pumps give you resistance development, it's that indeed this pump, we could replace by electromagnetic pumps with emergency electric current, but the cost will be ideal and it's not passive.

Thanks. Next slide, please.

Here, we have another view of the thermal pump. You see also the two permanent magnets that are here that give the magnetic field and here you have Alumel and Chromel in this case where the product [ph] can be used. That will give the electricity, the amount of electricity inside and so this type of pump can operate on the tube and give some pressure and some circulation of sodium without anything to do for the operator. It's a simple system, not expensive at all in comparison of electromagnetic pumps with all of the components behind.

Thanks. Next slide, please.

Now, we arrive to the final ESFR SMART layout.

The secondary loops have straight pipes. You have seen the advantage of the straight pipes. Another advantage is that the straight pipes allow circular disposition of the loops around the primary vessel. This disposition allows a reduction of the length of the pipes by a factor of two which we used again. The reduction of the secondary sodium volume by a factor two. Reduction of all related auxiliary systems, all the systems, sodium storage are also reduced.

We have significant savings on the size of the secondary buildings, about 50% or so because their area is proportional to the square of the distance between reactor vessel and steam generator casing. With this disposition, the DHRS 1 and casing are very near, and it is possible to have the save chimney for the two components. Not save, but the same chimney for the two components.

Note: We can also note that in order to reduce the costs, the layout of the buildings is made so that the handling building can serve two reactors.

Next slide, please.

Here, we see the circular disposition of the six loops, one that finalized services [ph] that is very compact, and we see that the lengths of the pipes are very low, low to have very few dilatations and the bellows are easy to manage. Here, we see the secondary loops and you see that DHRS 1 is very near from the casing and though it's possible to have the same, a new one chimney for the DHRS 1 and for the DHRS 2 in comparison of the slide with the flexible type pipes, we have in this slide, there were 12 chimneys and with only 6 chimneys, we are able to have natural air convection inside the casing of the steam generator or inside the DHRS 1. You see that we have a very compact disposition.

Thanks. Next slide, please.

Here, we have comparison. On this slide, we have the comparison between the working [ph] of straight and flexible pipes. If you have flexible pipes, you need to have a length of the pipes, so you need to have 12 chimneys and you are not compact at all. We have only 6 chimneys and we are very impact in comparison of the flexible pipes.

Thanks. Next slide, please.

We have a comparison of the secondary building between the two options. We have the original design. With flexible pipes, we have a big secondary building that is necessary and with the new design with the straight pipes, we have very compact here, and we have the handling building. You have seen in the slide before there that was some place for the handling building, and here, we have the turbine building coming from this part. You see that we have lot of gain on the secondary building.

Next slide, please.

We need to say that the disposition of straight pipes and circular disposition is not very new, even if we took that disposition to ESFR SMART. It's also the disposition purpose of the Russian ESFR project BN 1200 project. They also tried straight pipes and circular disposition around the primary vessel. We are not allowing this new disposition.

Next slide, please.

We arrive at this interesting slide with a final layout of the plant. We have a secondary building that is very compact around the primary vessel. We see three chimneys, three of them are under the part, and we have the handling building, which is chimney 4 on the building and we have the turbine and if we want to add another reactor, then another reactor can be added here with the same handling building like this reactor because one of the buildings should be shown for two reactors in fact.

You see, we have a compact area that is useful. Furthermore, you have these two papers, a paper for the meeting this year, FR 22 and ESFR SMART Secondary Loops Optimization and we have also the papers of the ASME NERS special issue done of this year. The secondary loop optimization of the ESFR as part of the ESFR SMART project. This paper will explain in detail on the disposition with a straight pipe and also vessels.

We arrive to the conclusions.

Now, we have a status of the simplifications and improvements of ESFR SMART. We have suppression of the safety vessel. The functions were taken over by the reactor pit. The suppression of dome or the polar table due to primary sodium containment improvement with a massive metallic roof and other dispositions were seen together. We have a good natural convection in the secondary side. We have optimized and simplified the DHRS circuits. There is no DHX system in the primary vessel and there are no supplementary sodium circuits to manage.

We have a gain of about 50% on the secondary loops with straight pipes, and we have a general layout gain with circular disposition of the secondary loops for all the primary circuits. We can note that no cost exercise was provided during the ESFR SMART project, but all these simplifications give improvements for the safety, gives also improvement in terms of cost and the cost of the reactor.

Next slide, please.

This slide defines the status of all the passive systems we have seen together during the presentation and also intrinsic safety of the reactor. We have the passive control rods to stop the plant on physical parameters, only on physical parameters, and without any of the control command. We have a low void effect in the core that helps to cope with the severe transients. A lot of calculations were made on the severe transients, as you know, by other groups and showed that they have a very good response of the core.

We have passive decay heat removal by the DHRS 2 and DHRS 1, 12 independent loops that operate in natural convection using only air always available. You have seen the thermal pumps totally passive to increase the flow rate in natural convection and the result of that is you have always long delay before necessity of operator action, even in case of simultaneous loss of water and of electricity supply, as in Fukushima. With an accident as Fukushima, on ESFR SMART, there is almost nothing to do. We have all the needs to open the pipes to start the natural convection.

Now, we have status of the mitigation situation.

Due to the core design with a void effect very low, the probability of severe accident is reduced and in case of severe accident, the energy released is lower. Nevertheless, we have made a very robust design proposed towards severe accident mitigation. We have the core catcher that is designed for the whole core meltdown. We have the mitigation devices inside the core, the corium discharge tubes, to channel the molten fuel to the core catcher. We have the impossibility of re-criticality of the core we have inside the core catcher. We have the coolability of the core catcher by natural convection in sodium that was tested by testings in Kyritz [ph], Germany.

We have the reactor pit that should accept sodium leakage, and, with its massive metallic roof, that should form a solid containment system. There is no primary sodium ejection, even in case of a severe accident. The corium long-term cooling should be managed by the diversified cooling measures, and we have no problem for long-term cooling of the corium.

The use of DHRS-1 circuits can be used as a supplement to continue the reactor block cooling, even if we lose also the systems. Those systems are protected in case of accident, severe accident because they are out of primary vessel. The temperature of the pit concrete remains easily under 70 degrees in all the cases and even if the oil circuit is lost. Then, we have a very good safety for mitigation situation.

What research and development we need to demonstrate all these improvements? But it's relatively low. It's relatively low research and development. We need industrial confirmation of the proposed organization for the reactor pit, and we proposed some things that are already being made for the concerned reactor but during this, we all should propose the organization of the building of the reactor pit.

We need also an industrial validation of the manufacturing method of the EFR-type thick slab. The slab should be with a weld of 8 centimeters, and industry has to propose some way to make the fabrication of the slab.

We have to qualify low-expansion materials and large-diameter bellows for the secondary circuit but that is not a big problem because it has already been made in the past and if we want to add the thermal pump, that is not necessary. We can work without the pump. But it's better with the thermal pump. If we can use it, we need to make a test of the thermal pump because the calculations have shown that the activity was correct, but we need to make some test to demonstrate and to validate the material. We have very low research and development to do to validate all the options of the reactor.

Following slide, please.

The point important is general application to SMR.

In ESFR SMART, we have a big power of 1500 electrical megawatts, totally big reactor. Nobody will directly build a Sodium Fast Reactor today with this type of very big power. Though the first step with little sodium reactor will be necessary and we have verified that all the ESFR SMART improvements can also be used for more reactor with a little power and if we go with reactor with, for example, 200 or 300 electrical megawatts, we can bring some further simplifications, so the DHRS system becomes more and more efficient in this case and at the end, it requires one of the DHRS systems. It is possible to apply all the conclusions of ESFR SMART to the little sodium fast reactor project.

Thanks. Next slide, please.

We have all the conclusions.

As I have already said, all the drawings have been made of the plant and are available on CAD and we can make all the designs and all the calculations today available. We have made special publication in NERS Papers of all the first calculations that were provided for the first assessment and all these calculations are available in the NERS Papers and also in a lot of publications. They, also, show the European final report.

On this basis, a startup was created for further design of sodium fast reactor using these improvements. This startup is based in Switzerland.

The last point.

A detailed presentation of the project ESFR SMART results will be available in the forthcoming Elsevier Book, I am writing today. The title of the book is Fast Reactors: A Solution to Avoid Global Warming and chapter five of this book is explaining 50 pages also improvement of ESFR SMART design.

In conclusion, thank you very much for listening for one hour and thank you very much.

Berta Oates
Thank you, Joel. We have some questions that have come in but if you have questions, please do type them into the question pane now and while those last questions are coming in, we'll take a quick look at the upcoming webinar presentations that we have scheduled.

In February, AI in Support of the NE Sector.

In March, Scale Effects and Thermal-Hydraulics: The Application to the French SFR.

In April, we have a special webinar event. It's a panel discussion with members of the GIF/IAEA, a Joint Webinar presentation on the Role of Nuclear Energy in Reducing CO2 Emissions.

Give me just one second, please. Okay, Patricia and Joel, I have validated both of you, so you should be able to read the questions as well. Sometimes, it's easier to see them. There are several. The first, if I just start at the top. In light of ASTRID work stoppage, France abandoned the SFR technology.

Joel Guidez
I don't see the questions.

Berta Oates
There should be a…

Joel Guidez
I see the questions. What is inside the gap between pit and vessel? Okay? That is the first question I see. There is a gap between the liner and the vessel, and in the gap, there is the oil system to cool the liner and between the liner and the external concrete, there is insulation and also this alumina concrete, silicon concrete [ph] that doesn't react with the sodium.

Berta Oates
Thank you.

Joel Guidez
What is the cooling point for the magnets? It's a good question but I don't have in mind the response. The magnets are permanent magnets, and as the temperature of operation of the concrete [ph], there is no problem to find this type of magnets that can work at 400 degrees.

Berta Oates

There should be a scrollbar too that would allow you to go to the top.

Joel Guidez
I see another question. Please add several words about coefficients of reactivity. What type of fuel is planned to be used? The fuel planned to be used is the classical fuel sodium fast reactor. It means about 20% of plutonium and 80% of depleted uranium, and I don't have in mind the coefficient of reactivity of the plant but the design of the core was mainly using the design of ASTRID core and so I cannot give a more precise response of the reactivity by use of the core. I should read the paper. I should send you the paper that indicated, in the ASME NERS publication, verified a paper that explained all that and dedicated to the core of the reactor.

I have no other questions already. Do you know if there is…? This mainly says, in core operation, some of the results around the…? Yes, I know that I could not explain ESFR SMART used in several projects. They are used in projects of NSA [ph] in France, and I know that in the US also, some dispositions are studied in the project about already totally. We have seen that in BN 1200, there are a lot of dispositions that are the same than ESFR SMART. I think we are not alone with this improvement, and I don't see questions.

Berta Oates
Let me help you just a minute, please. If you click in your control panel, there is an X, it will close out the whole dialog and to the left of it is like unlock your pane from the control panel, and that will pop it out into a separate screen and then you should have access. You can drag the sides and make it larger and use the scroll bar. Otherwise, the pane is so small that you can't see the questions.

Joel Guidez
I see another question on hafnium. The same is proposed on the total progress [ph] of hafnium. Yes, there is in hafnium some disposition that is the same as ESFR SMART. But I think that it would be interesting for that kind of project to analyze a better way, to analyze ESFR SMART disposition because a lot of things are applicable for the project. I think that this should improve the project by using some of the disposition purpose.

Berta Oates
Thank you.

Joel Guidez

Okay. I don't see other question but perhaps it's very little – I think it's all for the questions.

Berta Oates
Up to the top, there are several about the core catcher. How is the corium in the core catcher cooled?

Joel Guidez
The corium arrives in the core catcher, and we have seen that we have to act to disperse the corium inside the core catcher to avoid that second maintenance [ph] in place, and after there is cooling by natural convection, the sodium can arrive through the chimneys and it can assure the cooling of the corium and to demonstrate that, a test was made in Germany, in Kyritz [ph]. The test was made on the thermal leak of the natural convection around the core catcher.

If we have an accident, the corium inside the core catcher as operator has nothing to do. The circulation of sodium inside the reactor allows to maintain the corium and to maintain the integrity of the core catcher. You remember the core catcher is molybdenum and the melting point of molybdenum is above 2000 degrees and the compatibility of molybdenum with corium is good. There is no ablation by corium and though the corium can remain inside this molybdenum structure during a long time and with cooling by natural convection, the operator needs to assure the evacuation is decay heat removal. That is easy with a system that are in natural convection and out of the main vessel.

Berta Oates
Thank you. Can you take a minute to describe the freeze protection in the system ESFR SMART, if it has one?

Joel Guidez
Sorry, take a minute for what?

Berta Oates
The freeze protection system, if ESFR SMART has one.

Joel Guidez
Protection system for what?

Berta Oates
For freeze. I suppose they mean freezing temperatures.

Joel Guidez
It is for the control rods. You mean for control rods, yes, there are two possibilities for the passive control rods. One is to freeze with

the temperature. For example, we take at 600 with the control rod with freeze [ph] without any order.

There is on the flow rate. We have on the sodium reactor, bayoneting [ph] grid. There are control rods that freeze automatically when the flow rates decrease because it is the flow rate that maintains the control rods in a good position and when the flow rates decreased, they fall, and the reactor is stopped. There are two possibilities for the passive control rods. The third has not been really made for ESFR SMART. The two possibilities are operating, one is operating on [Unclear] and the solution with the high temperature is the solution tested by Japan and France together for ASTRID.

Berta Oates
Thank you. In DHRS 1, will there be a chance of sodium solidification in the tubes to the air heat exchangers?

Joel Guidez
In the tube of heat exchanger, the risk of – I don't understand well the question.

Berta Oates
It reads, in DHRS 1, will there be a chance of sodium solidification in the tubes to the air heat exchangers?

Joel Guidez
For sodium solidification, yes, it's the main problem of the natural convection inside the DHRS 1 is to avoid the solidification of sodium and for that, it's every easy. There is measurement of temperature at the outlet of the sodium heat exchanger, sodium air exchanger. At outlet, we resume temperature and if the temperature is lower than 140 or 150 degrees, in this case, the traps will set down directly. There is automatically shut down of the traps and so there is normal circulation of air and so there is normal risk of solidification.

It's essentially something we have to survey when we start. But there is a permanent flow rate in the system due to the 20 millibar of pressure drop inside the heat exchanger and due to this specific drop, there is a permanent circulation of sodium inside the DHRS 1 during the operation of the plant and those are done to avoid any solidification of the sodium in the system and see in circulation and today, we will have to use it probably never, we have never to use it, but if one day you have to use it, you have only however to open the traps and the natural convection will begin and you have to set the verification that the temperature of the inside of the heat exchanger is above 540 degrees so that you have no risk of solidification.

Berta Oates
Thank you. Mr. Guidez, thanks for the interesting presentation. How much the mass flow chart of natural convection of DHRS can be increased using a thermal pump rather than a standard configuration without any pump, 10 to 20% or even more?

Joel Guidez
The thermal pumps, we have no time and money to make the test on the thermal pumps. We made only calculations, and we arrived at a pressure of 20 millibar. This pressure is not the same pressure as the pressure obtained by natural convection. Though it increased by a factor of 2, the pressured dropped, and though it increased the flow rate, it's not totally necessary. Without thermal pumps, it also separates, that is the problem, but with thermal pumps, a little better. It's not a very expensive concept, and it's a little better thermal pump which is about 20 millibars more on the circuits.

Berta Oates
Thank you. What are the materials of the discharge tubes?

Joel Guidez
The discharge tubes, that is something new that was proposed in DHRS [ph] project in fact, and the discharge tubes are filled with sodium. You can have inside also if you want hafnium and so, if one day, the corium arrives in these tubes, it will fall in the tubes, it will take the hafnium within, and it will arrive inside above the core catcher and the core catcher should be in the operation of the plant without defect. There are tubes filled in sodium and without activity, I would say.

Berta Oates
Thank you.

Joel Guidez
There are 12 tubes that are inside the core and it's a different place.

Berta Oates
Thank you. I am going to skip down to the one that says what are the highest pressures inside the core vessel and what pressures are the salts operating at?

Joel Guidez

The pressure inside the core of the reactor? Yes, I don't have in mind the kind of value because I have another value, but I don't have the exact value in mind. But all the papers I explained are in the presentation. If you want to know more, you have to read the paper with all the calculations I explained with the final results and I think it's better to read in this case this paper to have the good values in them.

Berta Oates
Thank you. Are the cold traps accessible for maintenance?

Joel Guidez
Are the cold… sorry?

Berta Oates
Cold traps, are they accessible for maintenance?

Joel Guidez
Yes, the cold traps, in Superphénix, the cold traps were inside the primary vessel and so we took the same disposition. We have the cold traps inside the primary vessel because with this disposition, we avoid to have a primary sodium circulating out of the primary vessel. You know that in terms of safety, we have to demonstrate that even in case of severe accident, we don't have any other active release on the plant and those radioactive releases can arrive only with the primary sodium and with the cold traps inside the primary vessel, we avoid any leakage, any risk of leakage of primary sodium and the operation of the cold traps was very good.

Berta Oates
Thank you. Is the core catcher designed to recover the fuel and return it to operation?

Joel Guidez
The core catcher design has been validated for natural convection moving in [ph]. The other place which shows for the core catcher, it is not interestingly in terms of geometry because there is a place under the core and under the strongback [ph], the place was available and so it's not expensive because it's inside the place that was available in the reactor. It is rather conceived that if the core catcher was out of the vessel, then it's better efficiency also because on sodium, it is easy to manage the decay heat removal.

Berta Oates
Thank you. Are there any safety concerns regarding the third loop, water sodium content?

Joel Guidez
The third loop other than sodium contact.

Berta Oates
It just reads, if there are any safety concerns regarding the third loop, water sodium content?

Joel Guidez
What do you mean by third loop?

Berta Oates
Tobias, if you would like to add to your question, that would be helpful. In the meantime, what is the startup that you talked about? Can you add more to the discussion on the startup?

Joel Guidez
I don't understand the question.

Berta Oates
It's down here. It's one of the very last questions to have come in by Pascal Terrassen [ph]. What is the startup you talked about?

Joel Guidez
There was a question, what is the material of discharge tube. The material of the discharge tube is metallic. It's 316 steel.

What is the life of the reactor and discharger? Is it the same time life as the water reactor? It's exactly the same time.

In the core catcher at this time, what happened to the operation? Over-reactivity at this time will increase the load from weighing the one…. I don't understand the question in this case. What is the startup you talk about? I don't understand the question. What is the startup, you talk of the startup of the plant? I don't understand the question of the startup. What is the startup you talk about? No, I don't understand the question. I don't remember that there is work of the startup of the plant. Sorry, I don't…

Berta Oates
That's okay. Thank you. Why is hafnium selected as the absorber to avoid re-criticality in the core catcher? How much hafnium would need to be used? You talked about that.

Joel Guidez
Sorry. What is the startup that was created for the design? Okay. I understand. In Switzerland, the responsible of the ESFR SMART project has created a startup to be able to respond to the design of

sodium fast reactor in values. I don't know more on this startup because it's just beginning to operate.

How responsive is the reactor to demonstrate [ph] from the grid? Can I follow the visible reaction times? That is the reaction times of reactor, or sodium fast reactor is relatively not too quick because you need to manage the difference of temperature between the vessel that flow quickly the temperature of sodium and the part of the reactors that follow the temperature with a long time of delay.

Though you have a mechanical constraint, it's the junction between the vessel and sodium and the vessel welded on the roof. There is mechanical constraint in this place if you change the temperature of sodium too quickly, you will need to manage to maintain, you cannot change too quickly the temperature of the primary sodium and so we need one or several hours before to change basically the power. After, it depends if you want or need to manage the variation of power, for example, dilatation [ph]. In this case, you can manage that with the secondary loops and without moving the [Unclear] of the tube.

Berta Oates
Thank you. I think in regard to people's time and respect of their time, we should take maybe one more question.

Joel Guidez
After, I think there are lot of screenshots where people have to read the next publication that will be arriving this year. We'll have to read the publication that were made. They will find a lot of explanations and lot of values that I can give in the short time.

Berta Oates
Thank you.

Joel Guidez
How much hafnium should be used to validate it? I will say only enough. We don't make the calculation. But you see that it is easy to have a lot of hafnium in the lower part of it but the lower parts are not inside the core and so they don't interact with the core heat of the reactor and if one day there is corium that arrived in tubes, they will find this hafnium without difficulty. Another thing also that you can find in industry is molybdenum with hafnium. Molybdenum with hafnium is sold and you can buy molybdenum and hafnium exist also. That is the sort of work to be done when you have the project.

Berta Oates

Thank you. How responsive is the reactor to demand from a grid? Can it load follow and what reaction times would it have?

Joel Guidez
The reaction times is not so quick. If we have to change only some percent of the grid, you can manage until 10% or 20%, you can manage with the secondary loop in terms of speed of secondary loop and you maintain the same temperature inside the primary vessel. After which we have to change the temperature in the primary vessel, you need to have more time. I will say one day if you, for example, go from 0 to 100%. In this case, you have two or three days before coming from 0 to 100%. But if you have to follow the grid directly with only 10 or 20% of fluctuations, you can do it with the secondary loops directly.

Berta Oates
Thank you again, Joel, for sharing with us your expertise and thanks everyone who stayed on. We have managed to cover almost two hours. We did not get to all of the questions. We'll see if can perhaps…

[Multiple Speakers]

Joel Guidez
I see a question on the reaction with water sodium. People are afraid of the reaction with water and ask if electricity is made with water. Yes, the electricity is made with classical turbine with water and there is no problem with sodium because the modular or steam generator allowed quick detection of water sodium reaction and quick detection is easy to manage and easy to repair. For example, it was achieved for Phénix reactor, and I have seen five sodium water reactions and it was without any problems and any difficulty. It's very easy to manage with modular steam generator. The response is, yes, it's classical water turbine.

Berta Oates
Thank you. Patricia, do you have any final words?

Patricia Paviet
Yes, thank you. I am almost ready to bring my daughter from school. I wanted to thank you, Joel, *merci*, *merci beaucoup*. It was a very, very nice presentation and as always, a very good interaction with the audience. Thank you, Joel. I hope to see you sometime in a conference once the pandemic is over. Thank you, everyone. Thank you, Berta, again. Thank you. Bye-bye, everyone.

Berta Oates
Bye-bye.

Joel Guidez
Bye-bye. Thank you very much. See you soon.

Patricia Paviet
Oui. Merci. Bye-bye.

Joel Guidez
Bye-bye.

END