Advanced Lead Fast Reactor European Demonstrator, ALFRED Project
Dr. Alessandro Alemberti,Ansaldo Nucleare, Italy

Berta Oates
Gen 4 International Forum webinar presentation. Today's presentation is on the ‘Advanced Lead Fast Reactor European Demonstrator,’ otherwise known as ‘ALFRED project.’ Today's presenter joins us from Italy. Doing today's introduction is a person not unknown to the GIF webinars, Dr. John Kelly. John is the Chairman Emeritus of the Generation IV International Forum. He will do today’s introductions. John?

John Kelly
Thank you, Berta. Good morning to everyone good. Good afternoon, good evening, wherever you are in the world. Today we have Dr. Alessandro Alemberti who is the Nuclear Science Development Manager of Ansaldo Nucleare. In this position, he takes care of the Research & Development activities for the company. He coordinated the ELSY and LEADER projects in the framework of 6th and 7th Framework Program of the European Community, projects devoted to Lead cooled Fast Reactors development and participated as well to the main EU projects related to Lead and Lead Bismuth Eutectic coolant technologies in recent years.

From 2012, he serves as the chairman of the Gen IV Lead Fast Reactor Provisional System Steering Committee representing Euratom. After receiving the degree of Physics at the University of Genoa in 1979 and joining Ansaldo in 1981, he dedicated his efforts to thermal-hydraulic simulations for Light Water Reactors safety and licensing and participated in the research projects like OECD-LOFT as well as AP600 and SBWR activities. He is the author of a number of papers and patents devoted to the development of passive safety. In 2017, he was awarded the title of ‘Maestro del Lavoro’ by the President of the Italian Republic. Alessandro, the floor is yours.

Dr. Alessandro Alemberti
Thank you so much, John, for your kind presentation. Thank you to Berta and Patricia for organizing this webinar series including also ALFRED project in this webinar. Welcome to all the audience. I see now 37 participants to this online webinar.

I’d like to start my presentation with the outline of the presentation itself. First of all, I will talk a little bit, just one slide, on the history of lead coolant development in Europe. Then, I would like to trace a picture of the European context and the FALCON consortium which is in support of the ALFRED project. Then we go back to 2010, at the beginning of the LEADER project, was the project used to define the main design of

ALFRED reactors. The present ALFRED status. Finally, to conclude the presentation, we will take a look on the last technology development, especially in terms of material with respect to lead coolant contact, and the awareness of the status of this technology we have reached. Then just some word on the ALFRED strategy in the near future for the development of ALFRED.

Let's go to this bit of history. In Europe, you see on the top of this slide three different names of projects. The first one is a preliminary design study for experimental accelerator-driven system, PDS-XADS. It was a project of the 5th framework program from 2002 to 2004. Then you see the IP-Eurotrans and the CDT project in the successive years that brought all those projects, all those three projects brought to the development of a nearer [ph] accelerator-driven system, already presented in the previous webinar by Professor Hamid.

In parallel to this accelerator-driven system technology which uses as a basis the heavy liquid metal coolant technology, in 2006 we started a project called ELSY, the European Lead System which was the design of an industrial site, the lead fast reactor up to 600-megawatt electric, to give us confidence on the feasibility of such industrial size reactor. Then, from 2010 to 2013, we started a LEADER project which modified the design and we called this new design of the industrial site machine ELFR, European Lead Fast Reactor. And then we cited a scaled demonstrator of the ELFR at the size of around 100 megawatts electric and we called it ALFRED, Advance Lead European Fast Reactor Demonstrator.

If we go to see a little bit the European context in which we move in terms of fast reactor, we have one main initiative which is the sustainable nuclear energy technology platform, SNETP, which is based on three main pillars. The first pillar is NUGENIA which is a pillar dealing with research and safety characteristics of Generation 2, 3 and 3+ reactors, and is mainly dedicated to further the development of such reactors. Then we have another pillar called NC2I which means nuclear cogeneration industrial initiative which is dedicated to the development of nuclear energy to have also in parallel not only electricity production but also heat production, high-temperature heat production for industrial applications.

Then, the last one is the ESNII. ESNII is the European sustainable nuclear industrial initiative. This pillar is really dealing with the word ‘sustainability’ because it's based on fast reactors. Fast reactor can make use of the so-called closed fuel cycle which can increase the use of natural resources of uranium and plutonium up over a factor of 50 with respect to the present light water reactor technology.

ESNII is based on four main initiatives. The ASTRID, which is the sodium fast reactor prototype. MYRRHA, as an irradiation facility and demonstrator for the accelerator-driven system technology. ALLEGRO which is a gas fast reactor. And then ALFRED, the lead fast reactor demonstrator. We have those four initiatives pertaining to ESNII. Two of them, ALFRED and MYRRHA are based on the same technology which is the heavy liquid metal technology. In this technology, the European community invested more than €200 million in the last 10 years. This is to give you an idea of the efforts that are being spent on this new technology by the European community.

Talking about ALFRED support. We are two sites, the formation of a FALCON consortium which is a consortium of three different entities, organization, ANSALDO Nucleare; ENEA, which is the research lab in Italy; and RATEN ICN PITESTI, which is the research lab for nuclear matters in Romania.

FALCON consortium was established first in 2013 to bring LFR technology to industrial maturity. We evolved this consortium recently to better cope with the European context. The main objectives of this consortium are a firm commitment to ALFRED as a major project in Romania; the finalization of ALFRED feasibility study; and the construction of supporting in the first phase R&D facilities for ALFRED. We are presently inviting many industrial and research lab European partners to take part in this evolution to bring and acknowledge and support to this initiative.

In terms – we wanted to involve the whole heavy liquid metal community of Europe at first in the initiative to perform the development of this new reactor technology.

About Romania, I remember I talked the first time at the LEADER kickoff meeting about Romania representatives. We had from Romania the availability in 2011 to host the ALFRED reactor on the Mioveni site that you see here in the map. Then, in this slide, I present many different initiatives and the steps that have been made in Romania in such – maybe years, from 2011 till today. One of the main initiatives was to the inclusion of ALFRED in the Smart Specialization Strategy of the South Muntenia region. Then, in 2015, ALFRED was included also as a priority in the National Energy Strategy of Romania.

In 2017, we had at the Nuclear Congress in PITESTI [ph], the commitment to support a share of 20% of the total cost of ALFRED by the Romanian government. Then, in February this year, there was an issue of a Romanian position paper on ALFRED. In March 2018, ESNII, the European Sustainable Nuclear Industrial Initiative included ALFRED in the demonstrator fast track for the European community. Now, ALFRED is in the front position in terms of the evolution of demonstrators.

If we go back now to 2010 year when we started the LEADER project that was originating the first design of ALFRED, I have to thank all those organizations, I will not cite them but you see all the symbols here in this slide, that participated to this really successful project.

When we started with this project, we really realized that we were using completely new technology and we need to develop a new concept. We made some main decision for the development of this technology. We decided to go from a small realization to a bigger sized realization, so following the evolution of a project which goes from a demonstrator, ALFRED, to a medium-sized prototype called the PROLFR, prototype LFR, and then to the full sized first-of-a-kind a reactor called ELFR. In those technical evolutions, we tried to identify the main advantages, and also the issues related to the use of such a technology. Then, also in terms of facilities, we started from small facilities to go to larger sized facilities. Then we know that we need an irradiation test in the coolant environment specific of this new technology. When making the design of ALFRED, the first design, we tried to exploit the full potential of the coolant, including from the beginning, not adding it but including from the beginning safety in the design.

Also, one of our objects was to show the sustainability of the fuel cycle in terms of final industrial application, and then define and evolve a reference conceptual design of the first-of-a-kind reactor to use it as a reference for scaling down the demonstrator. This was the main concept that we tried to use when we started our development of the LEADER project. And so I would like also to add to this slide some very early sketch of the configuration that I developed for the presentation, for the first presentation at the kickoff meeting of LEADER. You see how rough it is, the sketch, but try to identify the main characteristics of a reactor that at that time we wanted to develop.

What are the main design characteristics that are very useful and can be used as a basis for the development of this new design? First of all, the fact that the lead does not react with water or air. The idea is that we can install a steam generator using water, normally high-pressure water, and they can be installed directly inside the reactor vessel.

Also there is a very high boiling point, 1745 degree Celsius of lead which exclude practically any boiling possibility of the coolant inside the core with the void feedbacks on the core reactivities. But also, very low vapor pressure of the lead at the reference temperature of 400 degree Celsius, which means that we have no practically vapor of lead inside the cover [ph] gas, and we have practically no lead deposition on cold surfaces.

Also, another very important characteristic that we have to take into account is the high density of lead. One of the main advantages we identified is that, in case of breached fuel dispersion, a dispersion mechanism instead of a combustion mechanism is favored. Lead is also a low moderating medium and has low absorption cross-section in terms of neutral absorption. In a lead fast reactor, you don't need to use a fuel rod design; you can use a very large p/d parameter T/H of a diameter parameter. And this is not imposed, like in other design, by the neutronic design of a core but can be defined by thermal-hydraulic characteristics of a core. It can be defined by the thermal-hydraulic design of the reactor itself.

Our request to the design was to obtain very low-pressure losses in the whole primary system. We assigned approximately 1 bar for the core and 1.5 bar for the steam generator. In total, 1.5 bar for the primary loop. This allows us to obtain a very high primary natural circulation capability and also we can implement natural circulation decay heat removal system, so including also passive safety from the beginning in the design of the reactor. This is why always we say, lead coolant imply also in some way and favor the use of passive safety inside the reactor.

Obviously, we have not only advantages in terms of coolant, we have also some issues to be faced. The first one, for example, is the high lead melting point which is 330 degree Celsius around. So we have to keep the lead temperature above 340-350 degree Celsius in all operation states, and also in refueling state for example. We will probably need and we understood this from the beginning that we need a knitting system and also take particular care in the development of design and operating procedures.

Also for the same reason, we need to face [ph] of that cooling transient in order to prevent any possible freezing of lead which may enter the coolant circulation inside the reactor. We have a very strict requirement in terms of feed water and decay heat removal requirements.

One of the main problems, issues of the use of, in general, heavy liquid metal coolant is the corrosion/erosion of the structural materials, and also the possible sludge accumulated inside the primary coolant depending on the operating condition. I will have a slide at the end of the presentation, taking care of this problem directly. In any case, we started from the beginning development of coatings, oxygen control strategies, limitation of flow velocity to limit the erosion of the effect of the coolant.

We also have developed the strategy which uses a low oxygen content in the sense that we would like to have an extremely clean coolant but without affecting the integrity, obviously, of the structural material. The density of lead is not only an advantage, it is also a problem due to the seismic risk. You have a strong wait to face. We decided that our reactor will be mounted on a seismic isolator. This gives us many advantages in terms of a standard division of design and reduction of seismic consequences on the reactor itself. Then we have to develop specific in-service inspection of core support structures.

Procedure and machines for fuel loading/unloading, and you will see how we face also this development. We would like also to take care of the steam generator tube rupture because we will use high-pressure water [Unclear] the primary side, and we do not want to impair the primary side which is at atmospheric pressure by the ingress of water which comes into the lead due to the steam generator tube rupture. Then, again, in relation with this larger collision [ph], we have to face flow blockage and the mitigation of consequences of partial or total flow blockage on the core of the reactor.

We developed some design guidelines at the beginning of the LEADER project. We wanted our machine, ALFRED, to be connected to the grid, to show that it is able to produce power, and dispatch to the electrical network. We also said that ALFRED should be based on the available technology as much as possible. You will see at the end how we will try now to develop a strategy to implement this point.

ALFRED shall also use structural materials compatible with the corrosive lead used as coolant and we selected some candidate materials, the 316, and 15-15 titanium. Also, we limit the coolant flow velocity to a value compatible with the erosive lead used as a coolant. We said from the beginning that we will limit this velocity up to 2-meter per second inside the primary side. Design solution of ALFRED shall allow also components to be removed. In fact, in our design, practically, all components can be removed from the pot of the reactor. Safety and decay heat removal solution should be characterized by robust reliable choices to smooth as much as possible the licensing process. We decided from the beginning, again, to use the passive technology as a basis of this development.

And this was how ALFRED looks like at end of the LEADER project. The main idea is to have – here the core. You can see here, with the fuel element in this region, the flow comes from the bottom called the 'lead flow,' to the core, and then enter this region, goes to such curved tubes which may feed the pump which elevate the flow of the lead up to 1-1/2 meter in respect to this which is the total pressure drop of the system. Then, by the tubes, I used as a steam generator, and the lead goes back cold to the reactor.

You can see a top view here of this reactor in which you see the pump, the small circle, 8 pumps, with this C shape of the bayonet tube bundle of the steam generator. The main characteristic of the reactor are [Unclear] the heat, 300-megawatt thermal, which means, with our expected cycle efficiency, about 42% efficiency, 125 megawatts electric. The primary cycle is atmospheric with the temperature difference from cold to hot regions from 400 degree Celsius to 480 degree Celsius. Secondary cycle is a well-known cycle, superheated steam cycle at 180 bars from 335, which is a temperature slightly above lead melting temperature, to 450 degree Celsius for the high efficiency of the turbine. You see in this slide, in this table the main characteristic of a different part of the reactor. You can note, we have two vessels. As usual in these types of reactors, we have the main vessel and a safety vessel. Here is the steam generator. The main coolant pump. The vessel is hanged to the top of this support structure by a 'Y' junction that will be described in the following. You can also note a particular solution that we used to simplify fuel handling. We extended the fuel assemblies up to the cover gas region so that all fuel assembly can be directly visible from the top of the reactor itself. This will imply that we will have no fuel handling machine inside the lead. The fuel handling machine will operate only on the cover gas region.

Going ahead, we have some small particular description of a reactor. We have to start from the reactor core because the reactor core is the basic part that we designed first in order then to size all other components around the core. We have 171 hexagonal wrapped fuel assemblies that you see here, with the number of pins inside, with all dimensions. Here is the pin representation. And here is the fuel assembly from the foot, from the bottom to the top. Here is the active region. Then, here from some holes in this point, the flow, the coolant flow is directed to the pump.

We have two different regions in terms of plutonium enrichment described here in this table, and two different systems for control of reactivity, the control rod system, 12 control rods, here in these points, blue fuel assemblies. And four safety rods to shut down and scram the reactor itself. Here you see different sections in different points of the fuel assemblies.

How such control and safety rod work? Such a design was developed together with the CDT project, with the concurrent project, and the same control rods are used also practically in MYRRAH. In fact, such control rods developed for MYRRAH originally in the CDT project, and then adopted to the ALFRED reactor. Control rod, here represented, you see the absorber location. They are withdrawn from below the core and are inserted pushing the control rod up, which means that the control rod is moved by a motor, but in case of an accident they can be passively inserted, simply relieving them, and they are inserted by buoyancy because they float inside the lead. Also, instead the safety rod, which is represented here, are inserted instead from top to the bottom, and they are withdrawn from bottom to top.

They are forced and passively inserted by a pneumatic mechanism, but also there is a backup mechanism which is tungsten ballast which forces by gravity the safety rod inside the core. We have two different control systems for reactivity to control the power and to scram down the reactor, shut down the reactor. Both systems are inserted during refueling, maneuvering, and so on. And both systems are designed against most reactive rod stack. If one of the rods is released, still the total reactivity is negative.

Going to the vessel, some specific characteristic of a vessel, it is cylindrical with a torospherical bottom. head anchored to reactor pit from top, here. Here is the so-called 'Y' junction which is used to just separate the load due to temperature on this cylindrical structure from the load due to weight which is carried by this 'Y' junction. Also, you can note this cone frustum in the bottom which holds what we call the 'inner vessel' which is the support of the core and prevent any horizontal movement of the core in case of the seismic event. Here in this table, you have the main characteristic of the reactor vessel itself.

This is what we called 'inner vessel.' It is constituted by a double wall, an external wall, and a thin internal wall which follows the geometry of the fuel assemblies, providing lateral support to the fuel assemblies. This part of the inner vessel is inserted in the cone frustum that we just saw before in the previous slide to prevent any movement in the horizontal direction. Eight bend pipes that bring the coolant flow to the pumps. Connection here is to the reactor cover and upper core plate. And here is what we call 'barrel.' Then you see some particular of a lower core plate where the foot of the fuel assemblies are inserted, and the upper core plate which holds on the top, also this cover which is provided by spring to force down the fuel assembly when the reactor is in operation. One characteristic is that the inner vessel is radially restrained at the bottom but it is actually free to expand downwards due to thermal expansion. There are no loads coming from expansion because it is free. Here again, the main – in the table, some dimension of the inner vessel for ALFRED.

Here, we worked a lot on this assembly of the steam generator and pump for ALFRED. Here is the typical pump which is inserted into the C-cube [ph] bundle which is made by bayonet tubes. What is the concept of the bayonet tubes? First, we have to say that this is steam generator is a one-through steam generator, so the feedwater enters subcooled. You see here the main cycle. And the subcooled here goes here [Unclear] to saturation and takes the saturation for around 2-meter, 2.5-meter. Then, we have superheating up to 450 for the exit. And here is the behavior of the lead on the other side, on the primary side.

So, how this is realized? This is realized using double-wall tubes on the left side. You see here, feed water is coming in the central tube. There is some insulation to prevent any regeneration effect between the feed water and the steam leaving in this region. Feedwater comes down.

Boils, transform into steam and goes up to this region and then to the turbine. We have however here another tube wall which is filled by the gap between the two walls, it is filled by high conductivity particles to increase the heat exchange. And this provides the possibility to continuous monitoring of a status of the tube bundle of a steam generator.

Here, you see on the left-hand side how the pump is coupled with the steam generator. Tubes are arranged in a triangular lattice with the p/d parameter of 1.42, a typical design condition to prevent any vibration problem on tubes.

Here you see the ALFRED secondary system. We also performed some studies on how to design the balance of plant of ALFRED. This is a typical arrangement with the steam line going to the high-pressure turbine, low-pressure turbine, with some extraction going to feedwater heaters. The generator, condenser, pump from the condenser to the feedwater pumps which goes back to the reactor. The cycle is a superheated cycle. We said 180 bars at [Unclear] turbine with a dual turbine configuration and some extraction on HP and LP with the main characteristic of a cycle represented in this table.

Then, also some studies about the buildings because it is important to understand how this building looks like. You see here a total height of about 33 meters from zero. The whole building is mounted on seismic isolation and this was developed in a European project that followed the LEADER project. It is called SILER project if you want to take any notes to consult this project on the web. We obtained by this seismic isolation, a strong reduction of ground acceleration. This helps a lot in the design standardization of a plant itself because in reality try to make the design independent from the site where you are going to put your reactor.

Safety. As we said, safety was just one of the first things that we want really to implement a high level in our reactor. We decided in this reactor to make use of a technology that was developed previously for the simplified boiling water reactor. Also, here is a typical picture of this machine which is constituted by two headers, one lower header, upper header, and tube bundle, and it is called an 'isolation condenser.' The isolation condenser is here represented and is immersed into a pool and isolated by an isolation valve that connects the lower radar to the feedwater line.

When we have any accident condition in our reactor, the main idea is that the first thing we do is to have an isolation of the containment. We close the two valves that isolated that feed water line and the main streamline of the steam generator. Then if we want and need to have a decay heat removal system after SCRAM has been actuated by the control system, by the protection system, we need to open simply this valve.

And how this system works? The machine in a normal condition is filled by water because it is connected to the main streamline without valves. So, opening these valves, the isolation valves, injects the water inside the tube bundle to the steam generator feedwater line which feed the steam generator and produces steam going out from the outlet of the steam generator. This steam is then condensed by the tube bundle inside the pool.

This provides something that is similar to a natural circulation inside this system and provide passive cooling simply by gravity and condensation mechanism of removing the decay heat from the reactor itself. How this works for the lead fast reactor? You can see here a plot where you see the lead temperature from the beginning of initiation of operation of this insulation condenser, it takes about 250 minutes, so 4 hours to bring the lead coolant to the freezing condition. We said during the LEADER project that this was enough for the operator to make some isolation of such DHR [ph] system and take some action to prevent any freezing of the system. However, we wanted also to improve the behavior of this system and extend the grace time, what we called the 'grace time to freezing.'

We patented a new system and we simply had a very simple tank of non-condensable gas which is shown here in this picture. Here is the condenser. You have this tank which is a pressurized tank. It is known from the previous experience that we made in the BWR campaign that the presence of non-condensable gas inside the tube bundle will decrease strongly the heat exchange in the tube bundle and will prevent the heat exchange. The idea is then when the system pressure on the secondary side of this system, on the waterside of this system, is going to decrease, the non-condensable gas is fed to the tube bundle, preventing further the increase of heat exchange. This is the behavior that we just saw in the previous slide. In 4 hours, we are going to lead phasing. This is the behavior of the same system equipped with this non-condensable tank. You see that the timing to freezing is now of the order of weeks. We increased a lot the grace time, let's say, able to prevent and delay as much as possible the freezing phenomena in the reactor in a way that operators can act on the reactor to recover the normal condition within this time.

Last point about safety is just something we just do with the main characteristic of the lead fast reactor. In the previous slide, when we talked about decay heat removal, decay heat removal systems are normally used when SCRAM is actuated, so when the reactor is shut down. However, in such transient that I am going to present is we suppose that we do not have any SCRAM of a reactor. The reactor is kept, let's say, at full power and what we will see in terms of the response of the reactor is the real characteristic of the lead fast reactor itself. Here you see the evolution of temperature in the primary side of the reactor for an unprotected – we called this transience ‘unprotected,’ ‘unprotected loss of flow,’ which means that we lose all the primary pumps. So, the reactor goes from forced circulation condition to natural circulation condition. You have an increase of temperature, but then the feedback of the neutronics into the core will decrease the power of the reactor, let's say, by a passive inherent feedback. In this way, the reactive power is decreased and the coolant temperature is decreased up to a new stable condition which is not able to have produced any major degradation of the core.

The idea is that also if we do not have SCRAM but we have an accident of loss of flow, we will have some maximum temperature provided by the natural circulation inside the primary side, and the reactor can be managed also in such a really challenging condition. This is true not only for this transient but for all transient, unprotected, that we simulated inside the project. And it is the basic feature really of the lead fast reactor-based technology.

To go to the present ALFRED status, I can say that, now, presently, the FALCON consortium is doing the design review. And we have this design review ongoing, we have confirmed the main option, so the location of the pumps, for example, solutions for steam generators, and so on. But we also introduced some diversification of decay heat removal system. We are working presently on an aspect that was not directly – because of the reason of time, and funding by the LEADER project originally developing the ALFRED design.

Also, in the years from the end of the LEADER project till now, several facilities have been constructed and experiments have been done. We have to talk about technology developments, chemistry and materials possibility. Some new ideas about the operational strategy that we can use for ALFRED startup. And the experimental facility support ongoing.

Here you see, for example, thanks to ENEA lab the so-called ‘CIRCE facility,’ CIRCulation Eutectic. We had an integral experiment of 1 megawatt. You see here the riser of this facility. Then the down coming of the lead called to the power channel here which is represented here with grids and so on. Just to give you an idea of the dimension of this facility, the diameter is about 1.2-meter and the height about 10 meters.

It was used for an oxygen control systems texting in a large pool. Component qualification and steam generator tube rupture experiments were also done, and as also steam generator and pump unit test.

Other facilities are, for example, NACIE, Natural Circulation Experiment that you see in this picture here with the instrumented tube bundle here.

Up to 250-kilowatt electric is also used for oxygen control system testing in loop component qualification and the instrumentation test as well.

Then, for example, LECOR loop was one of the first built to test corrosion characteristics of the heavy liquid metal. And the HELENA loop that was mainly used for pump testing, here you see the pump impeller for HELENA.

Some important point that I addressed before at the beginning of this webinar was the chemistry of heavy liquid metal, both lead and LBE. I try to give you an explanation as simple as possible. We have a possibility to add oxygen inside the liquid lead coolant. But we have two different kuvs depending on temperature. You see here the temperature. And this is the concentration of oxygen inside the coolant. The blue kuv [ph] is the maximum kuv you have to respect. The red kuv is the minimum concentration of oxygen you have to respect. If you stay with your coolant inside this region, you obtain a condition that we call 'steel passivation.' The oxide is formed on the surface of the structures and this protects the structure from corrosion of the coolant itself.

What happens if we have too much oxygen? If we have too much oxygen inside the coolant, we are going to produce oxides, lead oxides. And the result is shown here. High oxygen implies a slug deposit in your system, which means that you have a dirty coolant and the slug deposit can really plug your system and block the coolant circulation in your system. If you wanted to have a clean coolant instead, you can go to low oxygen. But if you go below this red line, you have still corrosion. The main mode of attack of a material structure when you have low oxygen is the dissolution of the main components of the material, nickel and others and chromium etcetera into the coolant itself. However, in this condition at low oxygen you will have really a clean coolant which is not able to produce a lot of oxides and producing flow blockage of other negative phenomenon.

This is in detail what is the corrosion which attacks the piece of 15-15 titanium in the static lead at 550 degree Celsius, and you see visible, the different corroded layer of material. The main idea was from the beginning to develop coating protection to this material in order to prevent this corrosion. It is known that alumina is not attacked at all by lead and this is a result of the same material that has been quoted by alumina, so aluminum oxide. This coating was developed by the Italian Institute of Technology in Italy, in Milan.

This is the result of the experiments when we put this coated material inside the lead in the same condition previously shown. So, for 4000-hour at 550 degree Celsius with a low oxygen concentration. This was made by pure pulsed laser deposition and in this case, we have no evidence of lead corrosion, neither at the macroscopic scale nor at the microscopic scale. This was one of the main, let's say, improvement in terms of materials and ideas to be implemented to prevent corrosion of lead inside our reactor.

If we want to have now a small summary about what is the present status and what is our present understanding of the status not only of the ALFRED project but in general of the technology of lead. We can say that we have made many relevant activities that have been performed at the national and European level. We have relevant evidence that it is possible to extend significantly our technological base and we had identified also some solutions to the main issues for such technologies.

If we look to what we have in our hand which is represented by this figure, now we are aware of much higher technology readiness of what we previously thought. So, we can target for the development and the implementation of such a technology, a timeframe that goes from 2035 to 2040 for the industrial expectation of this technology itself. This would be the proper time window to exploit this market segment, and also this shortened perspective is able to raise much more the industrial interest.

At the end, we tried also following the design guidelines that we followed in the LEADER project to try to use from the beginning in the development of ALFRED, and the commissioning of ALFRED, and the operation, the materials that are already available. So, our strategy to operate ALFRED reactor is to follow different phases. In phase 1, we are going to use a lower temperature compatible with the material we have available now and define only hot channels inside the reactor where we can test the operation at the highest temperature for the next phase. The ALFRED demonstrator will be used really as a way to achieve technology maturity in the sense that it will be able, this experimental reactor, to provide evidence that one phase is able to qualify the operation at the following phase, and so we can go step-by-step up in temperature up to the temperature we want to reach.

The main idea of that is that when we started the LEADER project, we had the idea to develop from demonstrator to a prototype LFR, and then to ELFR. Now this is possible, however, leveraging on lead fast reactor feature which are a very intrinsic and passive safety features, high level of safety that we have been able to reach, we have also the exclusion of domino effect between the reactors because of too high safety level, here, depicted. Optimum for multi-unit site. We can foresee also a shorter deployment of ALFRED with this time window target in this timeframe using something that we now call a ‘small modular fast reactor.’

This is the present strategy of the FALCON consortium. I thank you so much for your attention.

Berta Oates
Thank you very much, Alex. It was a very informative presentation. If you have questions, I see several questions in the Q&A pod, but if you have additional questions please go ahead and type those in now. Before we take those, we'll take a brief look at what we anticipate coming in the near future for GIF webinars. In October, a presentation on the 'Safety of the Gen IV Reactors' by Dr. Ammirabile. In November, 'The Allegro Experimental Gas-Cooled Fast Reactor Project' by Dr. Belovsky. And, in December, a presentation on the 'Russia BN 600 and BN 800' by Dr. Ashurko.

John Kelly
I would just like to tell Alessandro that I very much enjoyed his talk. It was very informative. So, thank you.

Dr. Alessandro Alemberti
Thank you.

Berta Oates
Before we start running through these questions, I do want to point out that the PowerPoint, the PDF of today's presentation are available for download in the download PowerPoint pod on your computer screen. If you click that filename, it will download directly to your laptop or PC. There is also a link to a survey. We always appreciate your feedback and we take your comments seriously for opportunities for continuing improvement and that is in that very bottom link. And I didn't address those, I apologize, prior to the start of our webinar today.

Without any further ado, let's start addressing some questions. How about that?

Dr. Alessandro Alemberti
We start with the first one, 'Do you have some layout for DHR safety system proposed for ALFRED?' For sure, yes. I did not present here the detailed layout. Also, this layout depends strongly from the number of steam generators that we are going to revise inside the design. However, this layout, has been also implemented in some experimental facilities that have been built here in Italy to test the system, this system. We are building now a facility in [Unclear], and the main dimension of the relative rate of the system and so on are available in these facilities.

Berta Oates
And do you see the one right below it?

Dr. Alessandro Alemberti
Yeah. 'What are the heat load of feed water comparing with a normal preheating heat load?' Maybe we can answer this question by the

evaluation that we made for the heat losses of ALFRED. Heat losses of ALFRED, if I understood well the question, are around some hundred kilowatt. This is the order of magnitude that we need to provide to the reactor to keep the heat in temperature when the decay heat is going down to very low values.

Many questions. ‘What is the height of IC comparing with SG height?’ The steam generator height of the tube bundle, heat exchanger height is around 6-meter. Then, you have 1 meter which cross the cover gas region around. Then you have to cross the roof of the reactor, so it would be around 8-meter the height of the steam generator. You have at least 10 meters from the roof of the reactor to the center of the IC, isolation condenser tube bundle, just to provide the necessary height for gravity injection into the steam generator.

‘How you remove non-condensable gas after one operation of IC?’ You have to isolate the system, the tube bundle and the non-condensable. And you have to remove the non-condensable from this by extracting them by a pump simply. Then you fill the steam and extract everything from the system. This is a matter of cooperation after an accident. It needs to be done carefully to bring again in the initial conditions the passive system. It has to be tested very, very carefully, this operation.

‘In the event of a fuel defect, how is the lead coolant purified?’ Thank you for this question because it gives me the opportunity to give some more information about lead properties. Lead has a very, very good performance in terms of retention of fission products inside the lead coolant itself. If we have fuel defects, we will detect it from careful cover gas analysis inside the reactor, and then the purification system for the lead coolant is provided continuously into the reactor itself.

‘In the diagram, there was a reference to 90 atom percent B10 which seems a bit extreme. Please discuss this and why natural boron is not used?’

I am not an expert of this field. I can ask to the person that designed the core and provide you an answer by email I think. We skip this question. In the event of a primary to secondary leak…

You have to remember that secondary would be at a very high pressure. In the case of LEADER, we have a double tube steam generator which that prevents any contact between the water and lead. We suppose that we will break [ph] one tube because both tubes are able to sustain the total pressure of the water inside the tube. In any case, we will probably never have the leakage from primary to secondary; but instead, we will have a secondary to primary leakage. To prevent pressurization of the primary side, we also added some ruptured disc on the rooftop with appropriate piping which provides the steam dumping to push through [Unclear].

'How is the generation of gas like xenon, krypton, helium in the reactor coolant removed? That is, does the coolant system have degasification capabilities?' No. Those noble gases go directly to the cover gas and are not, let's say, retained by lead obviously. If the cover gas purification system which takes care of this, in case of helium and tritium, also in this case the double-wall steam generator helps a lot in having some possibility to trap such gases in the gap between the two tubes. 'When compared MOX fuel with nitride fuel, which is better? It depends strongly from the technology development needed. I can say that in Europe for all fast reactor designed in Europe, and all demonstrators like ASTRID, ALLEGRO, MYRRHA and ALFRED, we choose MOX fuel as a reference mainly because this fuel was already developed and the technological problem is solved for this fuel in the past with the development of fuel for Phenix and Superphenix in France. However, for example, a completely different solution, the nitride fuel is developed in Russia for the BREST reactor. It is the reference solution for the lead fast reactor in Russia. There are some advantages for nitrides. For example, one is the very high conductivity of the fuel which decreases a lot the temperature and the heat stored into the [Unclear]. But this implies a very strong technological development which is carried out now in Russia. We were not in Europe able to you afford such a strong technology development.

'For the control rod, is the control rod in the inserted state during refueling? Intuitively, the control rod should be taken out before refueling?' No. The two systems, as I said in my slide, you can refer to it, are both inserted during refueling, just because you want to be sure, nothing happens to the core during such a condition.

'Could you please comment on any research done on source term during an accident involving fuel failure?' Yes. We did some calculations in the LEADER project and we supposed that the whole cladding of the core was broken and so all fission products were released to the coolant. We had very good results because the coefficient of retention of the fission product inside lead are very high. In terms of release to the environment, this type of accident is not considered for this type of reactor a problem.

'Hello. I have a question about heat exchanger temperature profiles in slide 18?' I should know the question. However, but okay, you can write me the question afterward.

Berta Oates
I think it might be the one down below, I'll post it and see since it's from the same person. I am wondering if the question has to do with the profile. He says...

Dr. Alessandro Alemberti

Okay. Okay, cross each other? No, it's not possible, maybe because the temperature scale for the lead is different from the scale for the secondary side flow water. 'Feedwater temperature control preheater…

Yes. We need to put particular attention to the feedwater temperature control because we do not want the feedwater to reach the steam generator in conditions such that it may cause lead freezing inside the steam generator. We can use some device. One idea at the beginning of the project I tried to introduce was the presence of a big tank before entering the steam generator in a way that if you lose a feedwater heater of the last chain which provide the increase of feed water temperature up to 335 degree Celsius, you have some damping through the capacity of this tank.

There are different ways of protecting heater with using available technology now, digital technologies, temperature measurements, or devices like tanks which possibly in prevent any sudden change of temperature in the inlet of the steam generator.

You mention that the lead reactor advantageous for multi-unit sites. What thermal output would these be designed at and at what efficiency?' Okay. In terms of efficiency, at the beginning of ELSY and LEADER project, we tried to introduce also the possibility to have a supercritical secondary site. However, when we made calculations about the net cycle efficiency of such cycles, we discovered that the change in terms of cycle efficiency from supercritical to superheated steam cycle is only 1%. So, the gain is only 43 against 42, 41 total percent. However, the introduction of a supercritical steam cycle was introducing an undue increase in the heat exchanger in the primary side, increasing the main dimension of the [Unclear].

We decided to go superheated in terms of the secondary cycle. There are some designs now that propose also the level of Generation IV for LFR. The use of supercritical CO2 cycle yet to be technologically developed at the sides needed to feed this lead fast reactor. The advantage would be only when you go really higher in temperature, which is not our case. We will stay on superheated now. And the reactor is advantageous for multi-unit sites because of an intrinsic characteristic of the reactor in response to any accident. We have an extremely low probability that an accident on one reactor is going to develop a problem on a side reactor.

Okay, I just answered already this one. 'Thanks for your answers.' Thank you to all the audience for attending this seminar. If you have more questions to ask, please send me a question by email and we'll try to give you an answer. Thank you so much.

Berta Oates
Alex, do you see the additional – if you scroll through your scroll bar, do you have time to take the last few questions that are here.

Dr. Alessandro Alemberti
There are two more questions. I see the last one from Iulian Nita which is 'Thanks for your answer.'

Berta Oates
And then there is a scrollbar to your right. The next question is regarding the temperature result of decay heat removal system on page 22, from the simulation or testing. How to control the desired temperature, adjust NC gas tank pressure?

Dr. Alessandro Alemberti
Sorry – can you repeat it.

Berta Oates
'On page 22, is the temperature result of decay heat…

Dr. Alessandro Alemberti
Let me go to page 22. Okay.

Berta Oates
Is the temperature result of the decay heat removal system from simulation or testing? How to control the desired temperature, adjust NC gas tank pressure?'

Dr. Alessandro Alemberti
No, there is no control at all of the temperature. We design the system of a non-condensable gas tank and rather this tank just to prevent lead freezing. But once you opened the valves of this system, both valves which are located in – I don't know if people are showing – okay. But once you put the system in operation, the system is completely passive, so we do not have any control on the pressure of the system. The system is responding passively to all the thermal-hydraulic conditions that take place inside the reactor.

Berta Oates
Then, 'Can you please comment on research done on source term?' 'Can you please comment on research done on source term during an accident involving fuel failure?'

Dr. Alessandro Alemberti
On source term when you have a cladding failure…

John Kelly
Yes, that's correct.

Dr. Alessandro Alemberti
Okay, thank you. During my speech, answering to those questions, I just said that we made simulations, and supposing the whole cladding of ALFRED reactor will break up and release the whole content of fission gases into the lead coolant. And we have no major consequences in terms of cover gas changes in terms of radioactive impact because the lead has a very, very high rotation of all fission gases and prevent those gases to leave the lead box. So those gases remain inside the lead coolant without going outside the liquid lead level. This is one of the very interesting properties of a lead fast reactor.

Berta Oates
It looks like there are just two more. ‘Do you have a plan of irradiation experiments of fuel pins with alumina coating cladding?’

Dr. Alessandro Alemberti
We had some irradiation already of some specimen for material inside the Russian facilities, for 60 namely. We are planning to add something also in the better reactor inside some experimental program related to projects funded by the European community. Of course, we will need to perform some irradiation for some pins and for some fuel assemblies in prototypical conditions because before being able to start up the ALFRED construction licensing and so on.

Berta Oates
And then the last question is, ‘Can you say something about fuel route: Storage and reprocessing time?’

Dr. Alessandro Alemberti
This is a very interesting question. It is one of the main problems that we are going to face inside the European community. Development and for factoring of MOX fuel, and reprocessing is presently not available in Europe. So, we had a strategy in terms of LFR development of a strong collaboration for fuel manufacturing and reprocessing together with the sodium fast reactor project.

This was the main option. Those two technologies in some way different but both using liquid metals. Both need the development of MOX. There are presently some European projects working on MOX fuel, but strong development is needed before we will be able to implement the reprocessing for MOX fuel in Europe.

This is one of the main problems that we have to face for the development of ALFRED and most fast reactor, I would say, in Europe, not only for ALFRED. I would be really happy, if you have any more questions, to answer to you by email.

Berta Oates
Thank you very much. What a great round of questions and presentation today. Have a great day.

Dr. Alessandro Alemberti
Thank you to all for attending this webinar. Bye.

END