

# **Gen IV Coolants Quality Control**

## **Dr. Christian Latge, CEA, France**

### **Berta Oates**

Doing today's introduction is Dr. Patricia Paviet. It's a privilege for me to work with Patricia and do this introduction for her every time we do these webinar presentations. Patricia is the technical group manager of the Radiological Materials Group in the Nuclear Sciences Division at the Pacific Northwest National Laboratory. She is also the chair of the Gen-IV International Forum Education and Training Task Force. She is the most recent recipient of the Significant Contribution Award presented by the American Nuclear Society Fuel Cycle and Waste Management Division in recognition of her many accomplishments as a researcher, educator, manager, and leader in the field of radiochemistry associated with nuclear fuel cycle. It's my honor and privilege to turn the time now over to Patricia.

### **Patricia Paviet**

Thank you so much Berta. It's so nice of you. Well, I was not prepared. Okay. So, everyone, good morning. Otherwise, it's early on the West Coast.

It's an honor to have Dr. Christian Latge from CEA with us. He graduated in Chemical Engineering and earned his Ph.D. from the Institute National Polytechnique of Toulouse in France. His Ph.D. at the CEA Cadarache was dedicated to sodium chemistry and purification systems. He participated in the startup and then operation of Superphenix and operational feedback analysis at Phenix, Superphenix and foreign reactors in the field of chemistry, radiochemistry, and technology.

He was involved in design activities of European Fast Reactor and Small Modular Fast Reactor. He has been involved in multiple activities from ITER to waste conditioning to waste transmutation. He now teaches at CEA-INSTN and at several French universities. He is involved in several international collaborations related to the development of fast neutron reactors and of course he is serving on the GIF Education and Training Task Force. It's an honor to have you, Christian. Thank you again for volunteering to give this webinar and I give you the floor.

### **Christian Latge**

Hello. Good morning to everybody. First, it's a great pleasure for me to give this presentation and I hope it would be beneficial for all the people who listen to this lecture.

I will start to address the coolant functions for the primary circuit of XFR, X being the coolant. It can be SFR, it can be LFR, it can be also that bismuth eutectic and we have the rest, primarily, the metallic coolants.

The coolants must complete the following key tasks. First, of course, extract the heat from the core. It depends on the specific heat, high specific heat, and, of course, a very high thermal conductivity which ensure a good extraction. It helps to transfer the heat to an energy conversion system directly or through an intermediate circuit. It depends on the coolant. Generally, the energy conversion system is based on a steam generator in case of Rankine cycle or it can be also, for example, sodium gas heat exchanger based on Brayton cycle. Or also, we can have a direct production of heat in order to support some potential applications like heavy oil extraction, thermochemical production of hydrogen, and for the residual heat at low power, the desalination of sea water. And another point, ensure the safety by providing the system with a high degree of thermal inertia.

In a fast neutron reactor, of course, the coolant must not significantly slow the neutrons, is a key point; activate the flux producing compounds which create unacceptable dosimetry; change the behavior of structural materials; induce unacceptable safety conditions; induce insurmountable operating problems; and lead also to waste which cannot be processed during operation or dismantling.

### **Berta Oates**

Christian, bear with me. There's just a bit of lag time here. I apologize. Hang on please.

### **Christian Latge**

Okay, next.

Yes. Just a review of the coolants used in nuclear applications. Of course for fission, we have sodium which is probably the most well-known coolant due to the last operational feedback in the past used for SFRs. Sodium-potassium also was used for the DFR reactor in Scotland. Lead for fast neutron reactors. Even up to now, there was no application of this coolant for some innovative reactors. Lead-bismuth eutectic, which is currently foreseen for subcritical reactors, particularly what we call ADS, Accelerated Driven Systems, including the spallation targets. But also it benefits from the operational feedback also from the Russian submarines in the past.

Molten salt for molten salt reactors. Gas like helium, helium-nitrogen, also supercritical carbon dioxide for the innovative energy conversion systems. The water-steam also can be used for the pressurized water reactors which is not often addressed here but also for supercritical water reactors. Also, for fusion, they use lead-lithium eutectics for blankets but the main objective is to produce tritium. And lithium can be used also particularly as a coolant. It was investigated for space applications due to

its very low density. It can be used also to produce particles for the IFMIF project, to irradiate some materials.

Some peculiarities from the sodium. The sodium is also called the natrium, natri [ph], depends on the countries. It came from the natron. It was already known from Egyptians. In fact, it was sodium carbonate and as *neter* from the ancient Egyptian language. It's a word which means that this product was extracted from dried lake located in the desert of Nitrie, *Wadi El Natrun*, which is close to Cairo in Egypt. Sodium also was prepared in 1807 by Sir Humphrey Davy by electrolysis of the caustic soda. Characteristic, it has no specific toxicity like lead but induce irritation and corrosivity. It's essential on the biological point of view and we have a consumption. Everybody has eaten sodium at noon [ph].

The sodium is in the alkali metal family. Its name comes from Arabic, *al kaja*, meaning ashes coming from the sea.

The sodium is on the left column and it has the peculiarity to have an electron on the external layer.

Here, you can see on the right side the main applications of the sodium. Every year, about 200,000 tons are produced per year and you can see that one-third is only produced for the indigo production, which is the blue color, for example, for the clothes. But there are many other applications like in chemistry, to reuse and also to purify some metallic elements like titanium and tantalum, and can be used for some specific applications like dynamo effect studies to understand the magnetic field of the earth and due to the movement of the magma.

About the lead. The lead has a relatively low cost also like sodium, but it has two main production routes: primary production from mined lead ore, but more and more a secondary production where it is recovered from recycled products, mainly, batteries. It is used because of its malleability and resistance to corrosion. We have seen also in Egypt some figurines made of lead. And, later, it was used by the Romans for water pipes. Here you can see on the bottom here a pipe which was found in the City of Arles in the South of France.

Lead properties are the following ones. First, the most characteristic properties are the following ones, melting point which has a high 327 degrees Celsius boiling point, very high, it's an interesting property with regards to boiling. And here, we have the density which, of course, well known has to be very high, 11.36 grams per cubic centimeter.

Here are some differences with sodium and, of course, we can see the main differences are on the density and also on the similar thermal conductivity, and the weight, of course. This coolant is investigated for

alternative options for fast breeder reactors, current projects and bottom projects are BREST-300 studied by NIKIET in Russia and also by IPP. ALFRED in Europe studied by the *Ansaldo Nucleare* in Italy, and the CLEAR project, for example, in China.

The lead-bismuth eutectic, it's of interest because the main reason is also because it has a low melting point compared to lead, 125 degrees Celsius. It is, in fact, a byproduct of the lead ore. It can be oxidized and, particularly the lead is oxidized which can be significant. We can have significant precipitation of lead oxide particles. We have no chemical reaction with water but water may violently vaporize depending on local conditions. Effectively, it depends on the difference of temperature between the two phases, between the metallic phase and the water phase. It depends also on the dispersion.

We can have significant corrosion so it means that a protective coating is required. There are some coatings or some specific steels which have been developed particularly including aluminum and silicon. Another complimentary option is to control the oxygen to maintain a protective oxide film at the surface. It means that we need a minimum oxygen content. Significant efficient control can be obtained thanks to the introduction of steam and hydrogen. And if we want to increase the oxygen content also, it can be done by equilibration method, for example, using lead oxide pellets.

There is a very large operational feedback available on this coolant, of course, coming from our Russian colleagues due to their research activities to support submarines but also from more recent ADS studies done within the frame of several projects, MYRRHA, CLEAR, MEGAPIE project which was a spallation target, and some European Union project and, of course, many other studies in other organizations.

The LBE has been investigated as an alternative coolant also for intermediate circuits of SFR but it was not mostly studied because in case of LBE ingress in the primary vessel of course we can have an interaction with primary sodium which produces bismuth sodium free with some exothermy. And of course if you introduce bismuth you can produce polonium in the primary circuit.

Here, on this diagram you can see a minimum value of the oxygen content in order to keep a sodium oxide layer in order to prevent deep corrosion and dissolution on the structure material but you have also a par value of the oxygen content. If you are above this line, you can produce lead oxide particles. So there is some range here which is very important to follow in order to avoid these two deleterious effects.

Here, you can see the position of lead and bismuth in the [Unclear] of table.

The main impurities. In the primary circuit, generally we have initial impurities from the nuclear grade coolant prior to reactor operation which can induce deleterious effects. Of course, we have to take into account these impurities because the consequences can be important. For example, if you have traces of lithium, you can produce tritium; if you have potassium in the sodium, you can have production of argon-41; chlorine and fluoride can produce corrosion; clogging also because calcium oxide is very stable; carbon can induce mechanical effects; and of course you can produce also some nuclear reactions if you have uranium and boron.

The main impurities introduced during operations, during operation now are, of course, oxygen and moisture from fresh metallic surface during handling operations. And when you introduce metallic surface, you have some metallic oxide which can be dissolved in the coolant. Activated corrosion products can be produced and they can be dissolved or under the form of particles. You can have also some fuel particles and fission products in case of pin rupture and the tritium can be produced from plutonium ternary fissions from the boron carbide.

In the intermediate circuits, which is only characteristic of sodium fast reactor, of course the sodium-water products can be introduced and particularly in the case of hydrogen, sodium hydroxide which is converted into oxygen and hydrogen thanks to dissolution in the sodium. The hydrogen is also produced by this reaction. It means that you can have detection of sodium-water reaction thanks to this hydrogen. Hydrogen can be also produced by aqueous corrosion on steam generator side and due to that you have a constant source of hydrogen in the intermediate circuit of a sodium fast reactor. This flux is driven by the Richardson law.

In terms of energy conversion systems, of course, the tritium coming from the primary circuit goes through the intermediate circuit if this is sodium, all directly to energy conversion system. It's a characteristic of all nuclear systems. And for all circuits, we have to take into account the potential oil ingress, for example, from the pump due to lubrication and the metallic filling due to some maintenance operation.

Why is it necessary to control the quality and to purify the coolant? For the primary coolant, it's important because the oxygen is a key parameter of corrosion. For sodium fast reactor, for example, corrosion produces contamination due to the transfer from the core to the intermediate heat exchanger, for example, of the pumps, induce dosimetry. And there is the necessity to decontaminate in case of handling or repair or even in service inspection operations. For that, generally, we consider that it is

important to keep the oxygen content below 3 parts per million. For heavy liquid metal fast reactor or ADS, there is necessity also to master the dosimetry and to eliminate some corrosion particles, so it means the necessity of filtering.

Oxygen well mastered can help to maintain oxide layer stable as we have seen previously. Also, this oxide layer allows enhancement of tribology for the rotating components. Oxygen can induce precipitation of coolant oxide. It is the case for lead oxide. It is not the case for sodium because the sodium oxide, oxygen is dissolved and there is generally no homogeneous precipitation of sodium oxide in the sodium bulk.

For intermediate circuits of SFR, of course, hydrogen has to be maintained as low as achievable in order to detect as possible a water ingress in sodium. Generally, the hydrogen content has to be below 0.1 parts per million. The operational feedback shows that we are often around 0.07 and it can be detected thanks to hydrogen meters.

In steady state operation, aqueous corrosion in steam generator units can produce magnetite and hydrogen which goes through the intermediate sodium. And thanks to purification in the intermediate loop in order to minimize the hydrogen content and to detect very quickly the sodium-water reaction. Thanks to this sodium purification, we trap also the tritium.

All the circuits, we have to control the plugging hazards in narrow gaps, tubing, openings, and seizing of rotating parts. Sometimes, we can have a reduction of heat transfer coefficient in the IHX or some other components.

To limit the plugging hazard, it is necessary to maintain an oxygen or hydrogen content below solubility at the coldest point of the circuits. Generally, we suggest to have a saturation temperature below the coldest point temperature of the circuit and generally we recommend a difference of 30 degrees.

Various processes to purify the liquid metal. The cold trap based on the crystallization process is the most well-known process but also hot trap, we call that also sometimes getter where we are about to trap oxygen or hydrogen. Oxygen thanks to, for example, zirconium titanium alloys. Hydrogen like yttrium can be used also, but generally it is only considered for small amounts of coolant. The RVC trap, called also sometimes as a carbon trap means reticulated vitreous carbon trap is used to trap the cesium. Mechanical filters are used also, generally a sintered filter or mesh for particles. Skimmer can be used also for floating oxide layer. It has been developed, for example, for sodium fast reactor particularly when we operate a vessel at a low temperature. For example, external

vessel storage tank which is operated at 180 and sometimes we can have a floating oxide layer. And at the end, a chemical reduction of metallic oxide can be also used for the purification.

About the sodium now. So, here, we have a simplified description of a sodium fast reactor. Here, we have described what we call a pool concept. It means a concept where we have the core and the main components of the primary circuit inside the main vessel. You have the main vessel. In fact, you have also a safety vessel in case of leak on the primary vessel in order to contain the sodium. Above that, we have argon which has been selected, of course, because I would say it has a good property. And particularly to cover the sodium and to limit the convection, it has a poor specific heat. Below the slab, it limits the transfer of heat between the sodium bulk and the slab itself. Here, you have the control plug which is above which the main function is to control the temperature of the outlet of each fuel assembly in order to control, to have an overall monitoring of the reactivity of the core. Here, you have the intermediate circuits – intermediate detection which transfer the hot sodium which cools the sodium from the hot planum, drive the sodium to the cold planum, and the mechanical pump push the sodium through a link called also reposo [ph] and push the sodium in the diagrid [ph] which distribute the sodium in the core.

You have here the intermediate loop which transfers the heat from the primary circuit to the energy conversion system. It can be a steam generator or heat exchanger like it was in ASTRID.

Here, you can see ASTRID scheme but it's also possible to show also other fast reactor which I would say have a similar function inside the main primary vessel.

Here is just a slide to show the mechanism of transfer of the pollution from the argon to the sodium. In the case of sodium, we have a transfer ingress of oxygen. There can be traces in the argon but it can be introduced during the handling operations. Here, you have the natural convection. You have a transfer by diffusion across the boundary layer. We consider then that we have transference through an oxide film. This oxide film is present only at, I would say, low temperature. And you have a transfer by diffusion across boundary layer and then you have a transfer, of course, by convection in the liquid sodium. And of course the purification system allows to maintain the oxygen content at the low value.

Here, you have the solubility laws which are key properties which give you the maximum amount of hydrogen or oxygen you can dissolve in the sodium at a given temperature. Generally in France but also in some other countries, we use these laws. And you can notice that there are

two values here on the scheme which value is very low near the melting point, the melting point being 98 degrees Celsius.

So here for sodium, there is not a necessity to keep a minimum value to protect structures because the interaction between sodium and the structure is very limited even if we have to take care about corrosion of structural material in the core and transfer and distribution in the primary system. We can produce some ternary oxides but the stability depends on the temperature and the oxygen content except the sodium chromite which is stable in several conditions.

Here, you can see the cold trap principle. Here, you have the solubility law and we have also the so-called sursolubility curve. It means that when you cool the sodium, you could assume that you could obtain nucleation of crystals when you go through the solubility curve. In fact, you need to have a lower temperature and to reach the so-called sursolubility curve which depends several parameters and particularly the cooling rate and the presence of some impurities. And here you can create nuclei, small crystals, that can grow. In all these area called also metastable area; you can have growth. You don't have nucleation but you have growth.

Here, just below, you have a cold trap, it's a system where when you introduce the sodium it is cooled and then you have also, for example, a mesh which is able to create the good conditions to have heterogeneous nucleation. You can see here a steel wire on which you have some crystals and then you can have growth. Here, you can see some pictures where you have crystal growth of sodium oxide, here and here.

Here, you have the kinetics. We have obtained here kinetics for oxygen for the production of sodium oxide and also for hydrogen and production of sodium hydride. Here you have a law where you can see a constant and activation energy which indicates the effect of temperature, the impact of temperature on the kinetic rate. The order of the kinetic, it's some kind of [Unclear] law and, here, you have the sursaturation, it means the difference between the concentration and the solubility at the temperature of the sodium.

We have established the kinetics and the main parameters of these kinetics. And for the nucleation here you have the values. You can observe that the energy of activation for sodium hydride is much higher than for sodium oxide. And the order for the nucleation is about two times – the order for sodium hydride is two times the order for the sodium oxide. It means that the influence of temperature is very important. That means that the consequence is that it is possible to create the good conditions to have the crystallization of sodium hydride on the cold wall. And for the growth, we have about the same activation

energies for the sodium oxide and the sodium hydride but there is a difference. The order is 2 for the hydride and 1 for the oxide.

Here you can see to come back on this point. In fact, we have two steps for the growth. You have diffusion through the boundary layer. We consider that there is a boundary layer here. You have the concentration in the sodium bulk. And here, you have the concentration at the interface. So you have first diffusion through the boundary layer and then integration in the crystal lattice, two steps.

When you have a step, an order of the kinetic of growth of 1, it means that this step one is a limiting step. If you have an order of 2, as we have seen for the sodium hydride, it means that this is the integration of hydrogen in the crystal lattice, which is the limiting step. That means that the diffusion of hydrogen through the boundary layer, it's not the limiting step for the hydrogen which is equivalent with the size of the atoms.

So the consequences are the following. We have developed in France a cold trap which separates the impurities. In the upper part, we have created the conditions to crystallize the sodium hydride on the cold wall. Here, you have the modular cooler with three different successive coolers which can be the  $\Delta T$  on this area can be adapted. And when you reach the cold point after that, we have an area, a zone where we have a mesh which is able to trap the sodium oxide. In fact, we need to stay a certain time at the cold point temperature in order to give enough time for the crystallization and particularly the growth of sodium oxide. This trap has been built, manufactured, and implemented on Superphenix.

About the crystal growth, here we have just a scheme where we indicate that it's important when you model these phenomena. Of course, to model the nucleation, the growth, and of course, these kinetics are linked also to the cooling. We have heat transfer. And so it means that the modeling of the cold trap has to take into account mass transfer, heat transfer, and also influence of the deposits on the pressure drop inside. So it means that during the operation of a cold trap, progressively, we have a modification of the flow inside the cold trap.

We have developed a simulation tool in order to take into account the results we have obtained, results from the basic studies particularly on the kinetics, but also to take into account the operational feedback from some cold traps implemented on sodium facilities or reactors. We have developed two modeling approaches for the cold walls for sodium hydride or the mesh for the sodium oxide. For both approaches, we have described the porous media with a porosity which describes the evolution of the void fraction of the liquid phase and particularly the biphasic phase, solid liquid. The porosity is initially equal to 1 with deposits on the walls,

and it's equal to the void fraction of the mesh packing if the deposits occur on the wire mesh. So it's the initial value. And then we have an evolution. For example here we are showing you the deposits of sodium hydride on the cold wall which is on the right side. And progressively, we have a progression. Here, you have nucleation. We have a porous media. And you have diffusion of hydrogen through the first crystals, and this hydrogen is used for the growth of existing sodium hydride crystals. So you have a progression of this interface and the model is able to describe this evolution.

And of course then you have some consequences on the flows here in this part of the vessel where you have circulation of sodium. And step by step you have the modification of the, let's say, geometrical limits of this area. The main equations are here. I don't describe these equations but we have a system which describes accurately the evolution of this interface.

Here, you can see on this picture the presence on the cold wall of sodium hydride and we have used this data to validate our model. This model is developed inside a Comsol Multiphysics software and validated with regards to previous experiments in the last 10 years.

Here, about the sodium oxide crystallization modeling. Here, you have the oxide so we have studied the oxide trapping on the packing and here you have seen a very simple cold trap which was used in the past for some experimental studies. Here you have the description and the color describes the mass of deposits which is distributed in the part where you have a supersaturation. You can see here a supersaturation which is between, let's say, we have about 15 degrees of supersaturation here and you can observe some deposits here.

Here you can see step by step the evolution with time of the mass of impurities which is deposited in the mesh. This model has been also implemented in the Comsol Multiphysics model. So, it means that the tool which has been developed is able to take into account various options in terms of geometry, in terms of deposit zones in order to satisfy the requirements in terms of impurities to be trapped.

Purification system design methodology. First, we have to identify, of course, the impurities to be removed from the sodium, mainly oxygen and moisture and potentially sodium hydroxide in case of very large sodium-water reaction. We have to assess their sources and their production rates, can be continuous or discontinuous sources, and it is possible to estimate the amount of water reacted and, consequently, the amount of products to be trapped after sodium-water reaction.

Assessment of the potential sinks, a key point is also oxygen can be trapped by the cold trap but it can be also used by corrosion. So it means

that this data induce some specifications on the removal rate in the cold trap.

Evaluation of the amount of impurities to be removed from the sodium circuits vessels is important because you have to define the data, the loading capacity of the cold trap. It depends of course on the strategy you intend to use, we will see that later, small cold trap or bigger colder trap for the whole life of the reactor.

After that, you have to select several trapping zones. Here, there is effectively some engineering data and some information that you have to use in order to decide, I would say, the general geometry of the cold trap. Of course, a cooling zone, for example, and isothermal zone as I show you for an example of cold trap.

We have to mention that many concepts have been developed in various countries particularly those who are operating reactors. And, of course, this concept can be different depending, of course, on the requirements you want to have. But I don't describe these other concepts of interest.

Performance criteria for the cold trap. First is efficiency. This is a ratio between the variation of concentration between the inlet and the outlet of the cold trap and the maximum difference of concentration between the concentration and the inlet and the solubility corresponding to the cold point temperature.

The purification rate, here, which depends on the efficiency, of course, and the flow rate and the concentration at the cold point temperature. So you can see the main parameters to control, to monitor the cold trap, the temperature and the flow rate.

The capacity which is generally considered a product between the filling rate and the deposited element concerned. So it can be a surface volume or surface and so on. So this data had been obtained thanks to some experimental experiences carried out in some sodium facilities.

And the compactness, of course, which is the ratio, it is the maximum volume of the impurities over the volume of the cold trap in which the deposit zones are located. Of course, the capacity has to be, if possible, close to 1 in order to avoid to have a huge cold trap to trap a very limited amount of impurities.

Here are some basic choices. The capacity can be low or high. You can have for a service life, a short service life or a long service life. If you have a long service life, of course you can avoid to remove your cold traps but at the same time you accumulate a lot of radio-contamination and in this case the decommissioning operations can be more complex.

In France, we have had two choices, a long service life for Phenix, for example, for the primary circuit of Phenix, but also a short service life thanks to the so-called primary integrated purification system.

The secondary cold trap can be also regenerable. It means that we have developed some technologies and some processes in order to reuse the cold trap with or without removal of the cold trap and the process can be a chemical process or a physical process dissolution of impurities in order to reuse this cold trap and to avoid to install a new cold trap.

Here, you can see a picture on the very interesting cold trap which is a primary integrated purification system. Here, you can see the system. In fact, you integrate, you have electromagnetic pump in the lower part. We have sodium at 550 degrees Celsius in the hot plenum. Here, you have an exchanger economizer where we reuse the temperature and we introduce the sodium in the area where you have the cooling system. Here, you can see the coils, the pink coils in which we have circulation of nitrogen.

The inside, here, you have a cartridge with two main parts, the cartridge itself with the mesh and the biological shielding in the upper part, just at the same level of the slab. In fact, when the cartridge is full of impurities, it is possible, thanks to a cask, to extract this cartridge and to replace it and to introduce a new one without impurities.

Here, you can see the picture of this cold trap. It is about 12 meters high and the diameter 1.2 meters. This system has been operated successfully in Superphenix even in some conditions which I have not anticipated before, it means during the main ingress [ph] we had in 1990. The nominal flow rate of each unit is 10 cubic meter per hour. This system is also foreseen for some new reactors like BN-1200 in Russia and also FBR-1 and -2 in India.

About the Superphenix secondary purification system, it's just a choice. But just to explain the implementation, you have a cold trap here, a heat exchange with the possibility to bypass it in order to be able to do some variations of the cold point temperature.

Here you have the cold trap itself. You can see the coil which is oil [ph] cooled. And in order to ensure heat transfer, you have here sodium potassium between the coil and the inner vessel. In yellow, you can see the area where you have the mesh. Here, you have an exchanger economizer which you have a first cooling of the sodium thanks to the cold sodium which comes from the cooled area. And thanks to this exchange, you have generally a variation of temperature of 25 degrees. In case of ingress of pollution in the main circuit, you can avoid plugging of the inner tube in the inlet and to avoid potential plugging of these pipes.

Purification rule. Of course, we measure the plugging temperature. It's the same principle. You promote the crystallization in a plugging meter in a system where you cool the sodium. And this information allows you to monitor the cold trap. We will see that we can follow the plugging temperature and also the unplugging temperature which is obtained with the same device, the plugging meter we'll see later.

Here, you have the evolution of the saturation temperature which is considered to be close to the unplugging temperature and here you have the plugging temperature. And you fix the saturation temperature below the plugging temperature. Generally, we consider a delta-T of 20 degrees Celsius.

Here you have the operating rules of this system. And, of course thanks to the cold trap the oxygen or hydrogen content is reduced in the main vessel. And when the saturation temperature is lowered by 10 degrees, the cold point temperature is also again lowered by 10 degrees Celsius. You proceed like that up to the 110 which is generally to consider as the minimum cold point temperature of the cold trap in order to avoid freezing of the sodium in the cold trap.

Just to summarize some evolution of the cold traps. We have developed different cold traps from Phenix to Superphenix, first version and second version for the secondary cold trap. And, even for EFR project, we have developed this system which is called Pyramid where we promote the crystallization on some plates filled with mesh. We have free coolers also. And this concept has been also selected recently for the ASTRID project.

Qualification strategy of the cold trap. In the '80s, of course, a lot of experimental work with definition of the main requirements, design of the scale-one cold trap for the reactor, identification of similitude rules for the heat transfer, residence time, mesh density, loading capacity, and then you downscale the mockup in order to have a small cold trap. You manufacture the mockup, loading of the ancillary cold trap used as a polluting device where you dissolve some sodium oxide or sodium hydride in order to give a constant oxygen content or hydrogen content at the inlet of the mockup. And then you operate the cold trap during several weeks in order to assess the allocated performance.

It's a complex process, very expensive, and so it means that at the very beginning you need to have a good idea of what should be the design of the cold trap.

Today, we can use the new CEA code I have introduced to you briefly previously. And it is important to note that this tool is very important to check, to support the design and also, why not, to support also the

operation of some existing cold traps in some reactors in order to estimate their loading capacity and the evolution of their loading and maybe prediction of some premature rate plugging.

About chemical instrumentation. We have generally the plugging meter. Here, you have a view on the plugging meter of the Superphenix. It's an integrated plugging meter. Here, you cool the sodium and you send the sodium through a small hole, some several holes, grooves corresponding to the coldest point of the device. And when you reach, I would say, the solubility curve like in the cold trap, you create the good conditions to have nucleation and growth. And of course if you measure the flow rate at the same time, you can notice a decrease of the flow rate, so you measure the plugging temperature.

After that, when you dissolve by increasing the temperature, you can measure the unplugging temperature and this unplugging temperature, when it is obtained, it is close to the solubility curve, it means the saturation temperature. So this information allows you to monitor to control the cold trap and particularly to set up the cold point temperature of the cold trap but also it helps you to estimate the pollution of the sodium in some specific situations.

Oxygen meter also has been developed extensively in the past and now there is a new attempt to develop new oxygen meters. It is the case in CEA particularly. In the past we used several electrochemical cells. There are several producers in the '80s. But unfortunately, this, I would say, commercial production has been stopped. So this apparatus is very interesting to monitor the oxygen content.

Hydrogen meters, you can have a well-known hydrogen meter, diffusion plus mass spectrometer, in French called [Foreign Language] or EVA [ph] in Russia. But also you have development of electrochemical hydrogen meter as it was redeveloped in some organizations like IPP or in India also.

Carbon meter has been developed and can be used to follow the carbon evolution but it has not been extensively used on the reactors because the carbon concentration has a low and slow evolution.

You can have also sometimes some periodical measurements using a crucible. This technique has been used and followed by an analysis in laboratory but this is generally considered for radioactive species, activated corrosion products, and tritium.

Specific point of chemistry. As you know, we developed in several countries a system, a potential energy conversion system using supercritical CO<sub>2</sub>. Why? Because you can anticipate, you can foresee thermodynamical efficiency of the energy conversion system, let's say,

more than maybe 44%-45% compared to 42% in case of a Rankine cycle with steam. Nevertheless, it was necessary to study their interactions.

There were several studies in several countries and the studies have shown that at the load below 500 degrees Celsius, this interaction produced some complex intermediates like oxalate, carbonate, sodium oxide carbon, but also you have carbon monoxide formation. And this you can have a reaction. You have an induction period and this induction depends on the difference of temperature, the delta-T between the temperature and 500 degrees Celsius. About the high temperature, let's say above 500 degrees Celsius, you have a reaction which is more global and you produce carbonated carbon. The carbonate has a very low solubility in the liquid sodium.

Here, you can see a scheme of the injection of carbon dioxide in the sodium. And of course due to the fact it's an exothermal reaction the temperature here depends on the position of your thermal couples. Nevertheless, we didn't observe any so-called wastage phenomena. It was a result of a Korean study which was developed and shown that the consequences are less than for sodium-water interaction.

Here, you have a view on the system we used in CEA to study the interaction between the sodium and the carbon dioxide. This is a system which is generally used for chemical studies in the safety developed by the DIERS, Design Institute for Emergency Relief Systems. Nevertheless, we have to deal with the particles and so it means that if we think to purification, we need to foresee some filtration because, as I told you, the dissolution of sodium carbonate will have a very low kinetic.

About the sodium decontamination, cesium trapping, it's important particularly before the decommissioning, for example, as it is foreseen for Phenix. And the system is the following one. You have a solid carbon foam. And when you have cesium dissolved in the sodium, you can have adsorption and then absorption thanks to a variation of temperature. This system is very efficient. In the past, we had some studies in CEA in order to study more accurately the kinetics of this process. It was used in several reactors like EBR2, BOR60, RAPSODIE, CABRI. And in the near future for Phenix we want to decontaminate the sodium prior to its treatment and conversion into sodium hydroxide. So this system, as you can see here, is a very simple technology and this product is very efficient.

About activated corrosion products trapping, there we are some developments in several countries, in Germany, in France, and in EBR2 also. Generally, the nickel is able to trap by adsorption the manganese-54, zinc, and some other impurities. So it is efficient and we know that, if necessary, it could be set up on reactors. For example, in EBR2 it has been mounted in a fuel assembly, dedicated so-called assembly, not fuel

assembly. And up to now we consider it is not mandatory for SFRs to be investigated for longer operation. It's not mandatory. But the question is what about 60 years of operation. It should be investigated in order to see if it should be required or not.

Some words about heavy liquid metal systems, lead and lead bismuth. Here, you can see, for example, sorry, I have to select two European projects, very representative of these technologies. The MYRRHA project which is a well advanced project in Belgium in the SCK-MOL where the characteristic is to have of course a spallation target where we have a proton flux impacting directly the LBE of the primary circuit. It's not a closed system like it was in the project MEGAPIE which was a project performed by international community and tested in Switzerland in PSI

Here, you have the ALFRED project and, here, you have the fuel assemblies. And of course we need to have an extension of the fuel assemblies in order to fix these fuel assemblies on the slab because of the difference of density between the fuel and the pure lead.

Then the hot lead is sent thanks to, I would say, a double component where you have the primary pump and the steam generator in the same area. We push here the pure lead inside the fuel assemblies. So here you have a pure lead and here lead-bismuth. So it means that here we are able to work at the relative low temperature due to the melting point of the lead-bismuth which is 125. Here we have lead, so it means that we need to operate the reactor at the minimum temperature, let's say, around 380 degrees Celsius.

I don't come back on this slide because, here you have the well-known diagram where you can see three zones. Here, you have an area where you can have material oxidation; here, you can have lead oxide precipitation; and, here, you have the working area where you have to take into account these two curves in order to demonstrate that you are able to work in this range of concentration in order to avoid these two deleterious effects.

Here, you have a system where you have also here you can see it's a scheme where you can see the potential effects of the presence of oxide particles and to corrosion in the core. Of course, the effect is exaggerated but nevertheless it's described two main phenomena.

Here you can see a picture where you can see the oxidation phenomena. You can see on the surface of the material; you have magnetite and exchange between the magnetite and the initial material.

This diagram shows the results of a very interesting study which has been finished quite recently by a Ph.D. study, Kristof Gladinez, in SCK-MOL in

collaboration with the University of Gent and this study, the defense was last week. So here you can see again the same diagram and they have established the solubility curve. So it means that knowing this diagram, you know that potentially by cooling the coolant, you can promote the nucleation and the growth of impurities. So it's very similar to a scheme I have shown to you particularly for the operation of plugging meter in sodium, but it means that we have a very similar behavior. The main result is that they have established the metastable field and the possibility to nucleate then to favor the crystal growth.

The nucleation, what is seen is that the most important nucleation phenomena is the so-called homogeneous nucleation in the lead-bismuth bulk but also it was observed that it's possible to have on a metallic cooled surface, you can have nucleation of lead oxide. So it means that potentially you can have development of a system where you could favor the deposition of lead oxide. But when you have presence of particles, it means that it's different from the sodium because you have not sodium oxide particles but in sodium we need to develop some metallic surface in order to promote heterogeneous nucleation on the metallic structure of the cold trap and on the mesh. We have different properties, so it means that there are some consequences. It is possible for the lead-bismuth and probably for the lead to foresee the use of a cold trap which includes cooling to increase the supersaturation, it's clear, and they promote homogeneous nucleation and, of course after that you have to provide a filtering area with the packing. And the packing has to be selected in order to retain the particles and also to be able maybe to favor the growth of the crystals which are trapped in order to have a good capacity for this cold trap. But maybe there could be some possibilities to favor heterogeneous nucleation on cold walls. It has to be investigated deeply.

For the sodium, the cold trap, as we have seen, the cooling increased the supersaturation but it's not dedicated to promote the nucleation of sodium oxide because it's not possible. And then the packing is implemented to provide heterogeneous sites for nucleation. So it's quite a different process.

Here, you can see the crystals of lead oxide which has been obtained in a facility in Mol in the MEXICO loop.

Some previous R&D, but I will not insist, is for the lead. We have developed a filtering in the past and we have compared in Cadarache in the facility but also in Italy in Brasimone or within the frame of some European projects. We have tested some different techniques like metallic mesh, Dynalloy filter which is, in fact, stuff where some holes in order to fix the particles, to retain the particles. And also the so-called Pall cartridge. So this filtration depends on various parameters, of course, of the technique but the liquid metal properties, the viscosity which can

be maybe modified by the presence of particles, the density, the particles, the nature, the form, the size, the temperature, the flow velocity, of course, the flow medium characteristics, and the location in the system. Because if you have particles, of course, we have to set up the filter in a well identified area where you can trap the particles. The best results were obtained with the Dynalloy filter and there was some characterization of these deposits. It means that with regard to filtration, you can have some specific processes efficient to trap these particles, not only particles of lead oxide but also corrosion products.

In conclusion, I would say that the quality control of the coolant is a key point to operate safely a fast neutron reactor, most particularly cooled by a liquid metal with regard to corrosion, production of particles, dosimetry, and consequence on maintenance and decommissioning. This sentence could be also said to gas and gas cooled reactors even if I have not addressed in detail these reactors. Here, we focused on liquid metals and even if the requirements are slightly different for sodium or lead or lead-bismuth eutectic, nevertheless, thanks to the large operational feedback from SFRs, some possibilities of material change between the two communities are possible in order to develop efficient purification systems as we have seen, which is a very important point in order to ensure a safe operation of the reactors.

I would like to thank you for your kind attention.

### **Berta Oates**

Thank you, Christian, for your presentation. If you have questions, please go ahead and type those into the chat pod now. And while those questions are coming in, we'll take a quick peek at the upcoming webinar presentations.

There's just a little bit of delay. There it goes. In October, a presentation from Dr. Farmer on passive decay heat removal system; in November, a presentation on the Czech experimental program on MSR technology development by Dr. Uhlr; and in December, a presentation by Dr. Feltus on TRISO fuels.

The first question. Does the remarkable complexity of sodium cooling make the molten salt reactor more attractive in the future?

### **Christian Latge**

Sorry, can you repeat it please?

### **Berta Oates**

Does the remarkable complexity of sodium cooling make the molten salt reactor more attractive in the future?

### **Christian Latge**

You mean the comparison between sodium and molten salt? My personal feeling is that, but maybe it is not felt by the other people. But I think that the sodium, which is even if it has a higher reactivity, we have seen. This reactivity also gives also some advantages because we can clean up the components with steam and so on. And the chemistry, as you have seen, is rather simple. We don't have a very complex strategy to maintain a high quality of the sodium. The feedbacks from the operation of fast reactors have shown that otherwise it was possible to get again a high quality of the sodium in order to restart the reactor without any difficulty.

About the molten salt, I think that the chemistry is probably more complex. I am not sure that today it has been extensively studied but the more important point is to fix effectively and to decide what are the requirements for the purity. And generally, these products are rather complex. So they are rather complex so it means that – I am not sure that the quality control of the molten salt will be easier.

### **Berta Oates**

Thank you. The next question goes with tritium. How problematic is tritium permeation through heat exchanger walls and are there techniques proposed to limit it?

### **Christian Latge**

The tritium, as you know, is produced in all the nuclear systems by ternary fission. Boron carbide also produce the tritium, so it means that it is necessary. Even if the production is rather limited, it's enough to give necessity to control the tritium release in the environment. For example, just for information, for Superphenix the production for this very large reactor was about 2 grams per year so it's really not a lot but enough if all the tritium is released. So it means that it's necessary to control the tritium. I would say in a sodium fast reactor, thanks to the necessity to purify the intermediate loop and particularly to trap the hydrogen which is produced continuously by the aqueous corrosion in the stimulator, we need to trap the hydrogen. And we trap of course simultaneously the hydrogen and the tritium. So it's necessary to control this tritium and particularly to respect the regulations. But up to now it has been demonstrated it is easy. Currently, we have a new study because in the case of Brayton cycle, when we have energy conversion system based on the sodium gas heat exchanger, we don't have corrosion so it could be an advantage. But with regard to tritium, we have to find another solution because we don't have natural introduction of hydrogen in the secondary loop. Currently, we have tested this in CEA-Cadarache to inject a well-controlled and limited amount of hydrogen in order to trap simultaneously the hydrogen and the tritium. I am not sure that the tritium issue has

been fully analyzed for the innovative reactors like those I have mentioned in my presentation or even in the gas-cooled reactors.

So I think that this is important. And particularly, for example, if you will see to use the reactor to produce hydrogen and when you have a high temperature exchange between the primary gas and the secondary system, typically very temperature reactors, the tritium is probably an important point to address and also for other systems.

### **Berta Oates**

Thank you. What kind of coolant is better for FRS, L or B?

### **Christian Latge**

Sorry. It's a very provocative question. I would say that my personal feeling is that it is difficult. When you have worked during a lot of years in sodium, it is difficult. But my personal feeling, and it is based also on the analysis on the operational feedback, sodium is very attractive. I think we know how to master sodium-water reaction. Sodium fire also thanks to efficient leak detection systems, so it means that the mitigation systems for these deleterious events are well known. There was recently a lot of progress also and I would say that the operational feedback from previous reactors – I would like to mention BN-600, for example, which is operated since almost 40 years, is a demonstration that it is possible to operate these fast reactors. Of course, we have faced with some technological difficulties but I think that this technology can be easily referenced.

About lead, I think that there are a lot of similarities, in fact, between lead and sodium. Of course, we have not the same coolant but nevertheless we have probably an approach which is similar. The key point also is the necessity to operate at high temperature. But lead-bismuth is interesting but there is a more important issue with regard the radio-contamination. But these systems are, of course, of interest. It's important to have several tracks for the development of fast reactors in the world and particularly in Europe. But there are efforts to be done particularly how to master the chemistry, the interaction with materials, development of materials which deals with corrosion, and so on.

Today, I don't want to lie. For me, it's sodium but I think it's important to have different options to be developed in the future and I think there some important progress in this field.

### **Berta Oates**

Thank you. That's all the questions that I've seen. Are there additional questions for Christian? While those are coming in, I do want to thank you one more time. I know how much time it takes to put these presentations together and I appreciate all of you support and practice

and putting up with the technical difficulties, the delay that we have, the lag time between the slide advancements. But I think we worked through those okay.

**Patricia Paviet**

Yeah. It was a great presentation, Christian. Thank you so much.

**Christian Latge**

Thank you. Thank you very much. If some participants want to ask additional questions, of course they can send me an e-mail and I will be pleased to answer.

**Berta Oates**

Absolutely. Thank you.

**Patricia Paviet**

Thank you, Christian.

**Christian Latge**

Thank you.

**Patricia Paviet**

Thank you, everybody.

**Berta Oates**

Okay. Now, bye.

**Patricia Paviet**

Bye bye, everybody. Bye. Bye, Christian.

**Christian Latge**

Bye bye.

**END**

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