SFR Safety Design Criteria (SDC) and Safety Design Guidelines (SDGs)

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Berta Oates
Doing today's introduction is Dr. Patricia Paviet. Dr. Paviet is the group leader of the radiological materials group of the Nuclear Sciences Division at Pacific Northwest National Laboratory. She is also the chair of the Gen-IV International Forum Education and Training taskforce. Patricia.

Patricia Paviet
Thank you, Berta and thank you Kubo-san for volunteering to give this webinar. He is the Deputy Director of the Reactor Systems Design Department in the Sector of Fast Reactor and Advanced Reactor Research and Development of the JAEA and he has been engaging in sodium-cooled fast reactor development since 1989 when the Heisei-era in Japan began. His specialty are SFR system design, safety design, and related R&Ds. Currently, he is involved in the development of Safety Design Criteria for SFR as a chair of the GIF Safety Design Criteria taskforce. He has been involved with this taskforce since its beginning in 2011.

He previously participated in the feasibility study on commercialized fast reactor cycle system and the Fast Reactor Cycle Technology Development project and he served as the design task leader and severe accident task leader in the France-Japan ASTRID collaboration. One of his most impressive accomplishments is the work performed on the EAGLE project (SFR severe accident experiments using IGR and out-of-pile experimental facility in Kazakhstan.) He earned a Master of Science in Nuclear Engineering in 1989 from Nagoya University in Japan. So, thank you so much again, Shigenobu for volunteering to give this webinar and without any delay, I give you the floor. Thank you again.

Shigenobu Kubo
Thank you very much, Patricia and thank you very much for everyone participating in this webinar. My name is Shigenobu Kubo. This presentation I am making from Japan. Japan is now in the morning, around 10 a.m. Today, my today's topic is about development of GIF, SFR Safety Design Criteria and Safety Design Guidelines. Perhaps you see the page of contents. My presentation is about – the main part is about the development of SDC and SDGs.

As background information, I present at first some elements to be considered for the development. That includes GIF's Safety Goals and Basis for Safety Approach and characteristics of sodium-cooled fast reactor and lesson from Fukushima Daiichi nuclear power plant accidents. And as part of the development of SDC and SDGs, I will develop three documents. So, I briefly introduce these three documents. Please go to next page.

Okay, background. Concerning the safety standard of the nuclear power plant, IAEA has systematically developed international safety standard but that has the hierarchical structure, the documents in the upper-level standard applied for any type of reactors. So those are technology neutral. But lower-level standards are mainly for existing light water reactors. So, our GIF project are dealing with advanced reactor, so we don't have internal standards for them including sodium-cooled fast reactor. So, there is growing demand to set global standards for generation IV reactors.

So, our effort starting from 2011 to make specific taskforce named SDC taskforce. This taskforce dealing with sodium-cooled fast reactor at first because sodium-cooled fast reactor has high technical maturity at that time. And this effort will expand another type of reactors.

So, concerning the elements to be considered, at first I am talking about GIF's safety goals and basis for safety approach. Here it shows summary of the GIF's goal regarding safety and reliability. There are three such kind of goals. First one SR-1: Excel in operational safety and reliability. Second, very low likelihood and degree of reactor core damage. And third, eliminate the need for offsite emergency response.

In order to achieve these three goals, we set basic safety approach as shown here. Defense-in-depth, combination of deterministic and risk-informed safety approach and safety to be built-in to the design, not added-on. And emphasize utilization of inherent and passive safety features.

Here shows the explanation/definition of DiD and plant states. Basically, we referred IAEA terminology and some of their definitions. Concerning DiD, basically we adopt their definition. So, the DiD levels consist these five levels. First one is for the normal operation. And second, so this means prevention of the abnormal conditions. And level 2, for anticipated operational occurrence. This means to prevent to expand abnormal condition to the design basis accident.

Level 3, to prevent core damage and manage the consequence of design basis accident. And level 4, this is for additional measures for the design extension conditions which include design measures without significant fuel degradation and with core melting. So, we think about these five levels for the reactor plant design. In addition, there is fixed level of DiD. That is mainly for the off-site emergency response. This is basically out of the design but some consideration in the connection with this level may be required.

Next is characteristics of SFR (sodium-cooled fast reactor). Here shows the schematic image to express the characteristics of sodium as a coolant for the SFR. The upper part shows the advantage. This is a comparison with water, and lower part is disadvantage. First important point is about neutronics point of view. So, in order to realize fast spectrum neutron reactor, fast reactor, we need proper material such as lower moderation capability. We don't need to moderate neutron. This is because fast spectrum reactor. So, sodium has good capability regarding this point.

On the other hand, water is suitable for the thermal reactor. So, the thermal reactor needs moderation of neutron. So, water has good moderation capability, but it is not suitable for the fast reactor.

Next is about heat transport capability, thermal conductivity and so on. So, sodium is used as coolant as liquid metal. So in the reactor vessel, sodium keeps the liquid state without pressurization. So the sodium boiling temperature is around 900 degrees C. So, we just keep little sodium inside the vessel. That is like ordinary cooking pot, but in case of the water reactor, for the case of pressurized water reactor, water mainly is used as liquid state.

So in order to keep the liquid state, PWR needs pressurization. So, this reactor vessel is like pressure cooker. So this means when we think about leakage from the boundary. In case of sodium, leaked sodium can be maintained without backup structure like we say guard vessel. But in light water reactor case, such leakage causes loss of coolant inside the reactor vessel due to de-pressurization.

And here shows the kind of demonstration for the comparison of heat transfer capability between water and sodium. Here are glass tubes. One side contains water, the other side contains liquid sodium. So here is the thermography to show the heat transfer from the heat source. So, this shows an example to show good heat transportation capability of sodium. So, sodium has good material for the heat removal from the core and the coolant system can be made without pressurization.

And for the disadvantages, sodium reacts with water and air, so we need special care about this point. Here it shows some picture of the experiment of sodium combustion in the air and water. About this sodium combustion, I will be talking a little bit more about it in the next slide. And another point is the possibility of freezing because the melting point is around 98 degrees C, so we need preheating of the system to prevent freezing inside the coolant system. But in the normal operation temperature range is more than 400 degrees C. And even in the shutdown state, the temperature keeps higher than 200 degrees C to prevent coolant melting.

Here shows characteristic of sodium combustion. Here shows some example, the property of the sodium as burning material. Here shows the comparison of sodium and gasoline. This graph shows the heat generation. Gray shows the sodium, orange shows gasoline. So, the produced heat is about a quarter of that of gasoline in case of sodium and here it shows the comparison of the evaporation heat. Sodium needs more than 10 times heat than gasoline to evaporate. The vapor pressure is lower in case of sodium. So here we think about fire – sodium fire and gasoline fire. The flame length is very small for the sodium fire because sodium vapor generates only around the surface of the liquid. But in case of gasoline, the flame length is very high so the influence of the fire has large area. But in case of sodium such fire influence is limited to the surface of the liquid sodium. But in case of droplet dispersion in this case and interface with sodium of the air is getting larger. So in case fire may be violent. And also, we need to take care of sodium aerosols generated as sodium burning. So, we need to take care of such a point, but by careful design we can manage such chemical potential of sodium.

So, for example, we provide nitrogen atmosphere to prevent combustion and double-wall piping to prevent leak and early detection of leak is one of the important points. And so again, the SFR has low pressure system. So the sodium leak may occur but violent leak is not likely.

Here shows summary of the comparison of light water reactor and sodium-cooled fast reactor. LWR is thermal neutron system and lower fissile density and lower fuel burnup. SFRs are aiming at higher core performance including higher burnup and higher breeding ratio. So SFR utilizes fast neutron.

And the coolant system, light water reactor has high pressure system like this and SFR has high thermal conductivity and higher boiling point, so the reactor system keeps nearly atmospheric pressure. Operation temperature of SFR is higher. This is good point for power generation efficiency. But we need to take care about influence of such higher temperature in the reactor materials.

Here shows the comparison of the reactor cooling system between light water reactor and SFR. Left hand side is an image of PWR. So here is the reactor core and reactor coolant boundary and reactor containment boundary. And in case of PWR there is a steam generator connected to the turbine. And for the water leakage, so cold or loss of coolant accident, in order to cope with this there is this kind of barrier system to water injection.

And in case of SFR, core is here and reactor coolant boundary is like this and reactor containment boundary is like this. And as a conventional system, SFR uses steam generator for the power conversion. So, in order to prevent the influence to the core, we introduce closed secondary system. So, this system has intermediate heat exchanger between the primary system and the secondary system. Primary system and secondary system is sodium coolant system.

And for the heat removal, in case of SFR leaked sodium can keep this dotted line system. This indicates guard vessel or guard pipe to keep the leaked sodium with this vessel-like structure. And for the heat removal here is so called ‘decay heat removal system.’ This decay heat removal can be achieved by the heat transfer from the core to this heat exchanger and there is secondary sodium circuit and heat transfer through this secondary system to the atmospheric air. So, here is the air exchanger here.

In the normal operation primary coolant of course keeps inside the reactor coolant boundary. This is both of PWR and SFR. But in case of primary coolant leak, the leaked coolant dispersed inside the containment vessel in case of PWR, but such leaked sodium can be maintained backup structure like guard vessel and guard pipe. So, the core can keep inside the leaked sodium. So, keep covering of the leaked sodium. This is an important point.

Here again a schematic view. This is just for the SFR system. As I explained, there is a decay heat removal system like this and core and reactor boundary and containment boundary like this. And for the chemical reaction here may be steam generator tube failure might happen. In such case, the water vapor injected inside the secondary sodium circuit. So, in order to mitigate such situation, we provide countermeasure like detection and blow pressure release, reaction products treatment, etcetera.

So, in order to mitigate sodium water reaction, we make such special care. Thanks to these design measures, we can prevent influence on the core of such accident.

So here is the summary of the safety characteristics of sodium-cooled fast reactor. Here shows some safety advantages. Low pressure coolant system. In order to keep core submerged under liquid sodium, we provide guard vessel and guard pipes. And we don’t need high-pressure injection system because no risk of loss of coolant accident due to the depressurization.

So, the core has inherent safety features with net negative reactivity feedback. And there is large margin to coolant boiling. And as I explained, we provide dedicated system for the decay heat removal to ultimate heat sink, so this can be made by utilizing liquid metal coolant good point, excellent thermal conductivity, and natural circulation characteristics. So this system can be operated without electric power. This can be operated on passive manner with natural circulation.

So, containment system itself, it isn't necessary to keep the higher pressure tolerance. But we need to care about sodium fire. And another point is about retention capability of fission materials in case of core damage situation. Sodium has good capability for the retention of the non-volatile or some volatile fission products. And we don't need to care about de-pressurization. The operation itself is not so complicated, so we can make simple operation and we can keep long a grace period by utilizing sufficient margin to coolant boiling.

Here it shows the challenges for SFR. This system has high temperature and high core power density. So we need to care about this point, so we have developed a good material to cope with creep damage in such higher temperature and higher power density and also higher neutron fluence.

And concerning about chemical reaction, we need adequate prevention and mitigation measures for all such effect of the chemical reactions. And in the core, this is fast neutron system so the core is not – it's most reactive configuration in the normal operation state. So if we think about core voiding, positive void effect may arise. But we can take carefully about such situation even in the design extension condition to mitigate core damage. And sodium is liquid metal, so sodium has no transparency. So we have special development for the inspection and maintenance.

Lesson from the Fukushima Daiichi nuclear power plant accident. So, this tragic accident happened about 9 years ago here in Japan. There was severe earthquake and tsunami hit around northwest side of Japan. And Fukushima Daiichi nuclear power plant got severely damaged. So, we never get such severe accident again. So, we take care to cope with severe accidental event which may cause long-term station blackout and loss of cooling function. So for that purpose we have designed measure for such severe accidental event cases.

Also enhance the design measures against such kinds of severe accident. So, in case of the Fukushima accident, the loss of heat sink happened as a result of tsunami. This is because ultimate heat sink of the plant, major ultimate heat sink is seawater. But most part of such auxiliary system lost its function due to the tsunami. In case of sodium-cooled reactor, as I explained, decay heat removal can be made through the decay heat removal system. That system mainly used atmospheric air, not sea water as the ultimate heat sink. So, this is a good for the SFR. So, we need to utilize such capability of SFR to cope with such kind of severe plant conditions.

Okay, so next is about outline of the SDC and SDG for generation IV sodium-cooled fast reactor. Our SDC taskforce developed three kinds of document for SDC and SDGs. This is aiming at providing the common design safety approach and possible application to the design. So, the member of SDC taskforce come from China, EU, France, Japan, Korea, Russia, United States and we have an observer from IAEA. These countries have their own project for the SFR development, so they have their own experience and design concept and R&Ds. So, we are gathering such information in this taskforce and try to make common understanding of the safety aspect for the SFR.

So, we already completed these three kinds of documents. And now SDC taskforce is reflecting feedback in the document from external authorities such as national regulatory bodies of the countries, IAEA and OECD/NEA WGSAR. WGSAR is working group for the safety of the advanced reactor.

And our taskforce participates in GIF-IAEA joint liquid metal fast reactor workshop on safety and we will develop SDC for the other reactor systems though the activities of RSWG (Risk Safety Working Group) of GIF.

So here is the hierarchy of the safety in our GIF. So SDC is located here and SDG is located here.

Here it shows the SFR design options in GIF. We have several design concepts. One is a large size loop-type design. This has been developed in Japan. And intermediate-to-large size pool-type reactor. Loop type has oxide fuel and pool type has oxide fuel and metal fuel. Pool type has another concept of small size modular type design like this.

Here shows the process or relation between the SDC and SDGs. SDC is here. This is corresponding to the IAEA SSR 2/1. This IAEA document is for the design mainly for the existing light water reactors. So, we referred this document and we made generation SFR version of such kind of criteria. So, this criteria including about 80 criteria, about 200 statements. This including safety approach and on SFR characteristics and lesson learned from Fukushima Daiichi accident.

And for the application guide, we provide two kinds of safety guides. First one is for the SDG on safety approach and design conditions. This including both of general part and some specific part. General part including about the definition of plant conditions such as AOO (Anticipated Operational Occurrences) and DBA (Design Basis Accident) and design extension conditions (DEC). And also for the practical elimination of accident situations. As for the specific point, we cover reactivity issue and decay heat removal issue with this document.

In the next SDG document, this SDG document is for the key structure systems and component of SFR. This document covers the reactor core and reactor coolant system and containment system. In order to develop these three kinds of documents, we are gathering the information from the member from the taskforce about design options and design conditions. This means the actual design and related development activity of this from the member countries of the taskforce. And also, we referred some of the IAEA document. Here is IAEA SSR 2/1. This is generic design requirement. And also IAEA NS-G series. This document covers design guidelines for the specific system of the nuclear power plant including reactor core, reactor coolant system, and containment system but this covered for the existing light water reactor.

Okay, so I will show the outline of the three SDC SDG documents. First one is SDC. This document is available on the GIF website here. So, if you are interested in this, you can see the document at this site.

Here shows the table of content. As I said, the first part covers the generic safety approach that can be applicable for most of sodium-cooled fast reactor. Sorry, this is SDG, so this document covers the important element as I explained in the first part of this presentation here. And from chapter 3, this document describes each of the criteria including the 80 criteria about 200 statement. Criteria number 1 to number 42 is rather generic part. And in chapter 6 covers design of specific plant systems including specific plant system of the SFR reactor core system, the reactor coolant system, containment system, and so on.

So next is guideline. Here shows the first SDG document, SDG on safety approach. This document is also available on the website. This document provides recommendation or guidance how to comply with SDC.

So here are the contents of the document. Chapter 3 covers general approach and chapter 4 rather specific one for the SFR, reactivity issues and decay heat removal issues. And chapter 5 there is a specific chapter to deal with SFR characteristics with reactivity control.

Here shows some of the general design approach from the SDG on the safety approach. Basically, safety concept, safety design is to use the multiple redundant engineered safety features to lower the probability of the accidents and to limit the consequence for the AOO and DBA. These features include independent and diverse systems in GEM [ph] safety features. In addition to this, passive and inherent features for cooling, shutdown and power reduction also play a significant role to cope with the design extension condition. That has diversity to the active in GEM [ph] safety feature.

So here shows the part of the engineering feature [Unclear]. And for the design approach or design extension conditions, we provide some additional measure. For this, our concept is to introduce passive inherent feature to prevent core damage and to mitigate core damage. These two design measures are corresponding to the level 4 of the DiD [ph] and deal with design extension conditions.

Here shows some examples of the typical AOO and DBA for SFRs. Such events may be results of imbalance of core power and cooling. So, there are some mechanisms about such imbalance that include core power increase of primary coolant flow decrease and abnormality in heat sink. So here it shows typical events that causes such mechanisms and challenges. And for the design extension conditions for the prevention of core damage, passive and inherent safety feature will be introduced to control reactivity and to remove decay heat. So, inherent reactivity feedback and passive mechanisms will be used to control the reactivity even in the anticipated transient without scram.

And for the decay heat removal, natural circulation capability should be introduced and various configuration. I will explain later on, we call it various configuration such as DRACS, PRACS, and RVACS.

For the mitigation of core damage, our strategy is in-vessel retention. So, even in the core damage situation, damaged core material should be kept inside the reactor vessel. For that purpose, we think about mitigation to release mechanical energy due to their criticality and keep the degree to core material as a coolable inside the reactor core. For that purpose, we provided core catcher inside the reactor vessel. And also, we provide permanent heat removal path. For this purpose, core should be submerged under liquid sodium even in such core damage situation.

Here shows about practical elimination. This concept is a little bit complicated. Here shows the IAEA’s terminology on practical elimination. This term was used in requirements for the design of nuclear power plants to convey the notion that the possibility of the potential occurrence of certain hypothetical event sequence in serious scenarios could be considered to be excluded. To say such situation to be excluded, we need to demonstrate such situation is physically impossible by design or with residual risk with high degree of confidence.

Situations which may lead to early or large radioactive release and which cannot be mitigated under acceptable conditions, this means when we provide design measures for the mitigation, that needs a very expensive design measure. That cannot be acceptable. So in such case, it should be identified and practically eliminated by implementation of design provisions. So, we need to provide design provision to say such situation is practically eliminated. That is important. So, the practical elimination can be considered as part of general approach and as an enhancement of the DiD principle. But such situation should be very limited list of situation.

Here shows some example of such situations. One example is power excursions due to their large gas bubble passage, large scale core compaction, something like that. Situations leading to the failure of the containment risk. We should practically eliminate complete loss of decay heat removal and core uncovering situation and core damage during maintenance and spent fuel melting in the storage.

Finally, I am talking about SDG on the structures, systems, and components. Here shows the table of contents. These guidelines cover reactor core and coolant system and containment system. Unfortunately, this document is not available on the website, but this may be available in the near future. This document has a variety of appendix and annexes to help the read and to understand the contents of these guidelines. This includes about example of design concept of active reactor shutdown system and passive reactor mechanism and so on.

So, this document mainly covered design feature of SFR which summarizes 14 points. These 14 points are included in this document. This orange part is for the reactor core system that covers core fuel integrity and reactivity control. And for the containment system, also integrity of the component and primary system and measures against chemical reaction and decay heat removal. And containment system, we discussed about SFR specific load conditions for the containment design.

So, I am talking about some of the examples for the design for the decay heat removal system. As I said, we can choose – this selection can be made by the designer. We can make various configurations of decay heat removal system shown in this figure. So DRACS has heat exchanger inside the reactor vessel. PRACS has primary circuit, and IRACS has secondary circuit and RVACS cooling can be made outside the reactor vessel like this.

Here shows the example for the design for the decay heat removal system. This is an example for JSFR. JSFR is loop-type design. So, this design has DRACS like this and PRACS. PRACS has heat exchanger inside this primary pump and intermediate exchanger vessel. In addition to this system, there is alternative cooling system. This system is independent from the main cooling system.

Here shows the example of the ASTRID design. This ASTRID is pool-type design. So, two diversified in-vessel decay heat removal system is here. One is passive decay heat removal system and the second is active decay heat removal system. And these two systems have diversity in the configuration. And in addition to this, heat removal from the outside of the safety vessel is introduced like this.

This is an example of the PGSFR by Korea. Here are two diversified decay heat removal systems inside the reactor vessel like this. And also, cooling system from outside the safety vessel. Here shows the cooling path, air inlet and outlet to the reactor vessel cooling.

That's all of my presentation. Here are the concluding remarks. As part of development of GIF reactor systems, GIF is developing SDC and SDGs based on the consideration about basic safety goal and basic approaches of generation IV and safety characteristics of SFR and lesson learned from Fukushima Daiichi Nuclear Power Plant accident,. And also, we are gathering the information from the various designs of the member countries to develop these SDC and SDGs. As a result, we have developed three kinds of documents SDC and 2 SDGs. And GIF is making effort in reflecting feedback in the document from external bodies and participating in the activities such as GIF-IAEA joint workshop. And these efforts now are going to develop as a type of reactor. So, that's all. Thank you.

Berta Oates
Thank you, Kubo-san. If you have questions, go ahead and take those into the Q&A pod. While those questions are coming in, we're going to just take a quick look at the upcoming webinar presentations scheduled in March. MicroReactors: A Technology Option for Accelerated Innovation. In April, the GIF VHTR Hydrogen Production Project Management Board. And in May, Performance assessments for fuels and materials for advanced nuclear reactors. There are few questions, the first of which reads how are AOOs and DBAs in the design extension scenarios determined?

Shigenobu Kubo
Let me answer by oral.

Berta Oates
You bet, absolutely.

Shigenobu Kubo
Sorry, I cannot write down so quickly. Concerning AOOs and DBAs, one aspect is occurrence [Unclear]. So the lower band of AOOs is about 10 to minus 2 per reactor year. For the DBAs, it's about 10 to minus 4 per reactor year or something like that. But our consensus is just only for the AOO, so such lower limit value is indicated in the SDC or SDG document. Another point is coming from the experience of each countries. Each country has experience of development of SFR. Some country has the experience of licensing application. And such experience can be the basis

to select AOOs and DBAs. And in the past, we don't have any design extension conditions, but we have some experience to evaluate beyond design basis accident. So, such accident can be basis to select the design extension conditions.

Berta Oates
Thank you. The next question is what keeps the core melt stay in the core? Maybe I read that incorrectly.

Shigenobu Kubo
Yes. We think about kind of core damage due to the failure of the reactor shutdown. In this case, core damage may happen due to overheating. So, in such case core melt situation may appear even if liquid sodium remains inside the reactor vessel. So, we can keep the damaged core inside the reactor vessel, but we take care about leak criticality when we think about molten core materials remain inside the reactor core region.

So, we think about molten fuel discharge from the core area outside the core area. But such molten fuel still keeps inside reactor vessel, and still keep on the liquid sodium. And in order to make sure to hold such degraded core material inside the reactor vessel, some design installed in-vessel core catcher in the bottom of the reactor vessel.

Berta Oates
Thank you. The next question is are there any SFRs under construction?

Shigenobu Kubo
Next question. In the world we already have a lot of experience of the construction of SFR. The oldest one is in the United States in 1950. That was the experimental reactor EBR-I. From that time in the world we developed SFT technology. From starting point, we developed experimental reactors, smaller one, but liquid cool fast reactor. Such experimental reactor was built worldwide and now China constructed such experimental SFR. And also the prototype reactors and even demonstration type reactor is constructed and operated. Especially in Russia, now they are operating BN-600 and BN-800. Those reactors are in the stage of commercial operation.

Berta Oates
Excellent, thank you. The next question asks, has GIF considered making SDC and SDG documents available to designers or vendors?

Shigenobu Kubo
Sure. First objective of our development is to provide such document for mainly the designers and vendors. We try to collect good practice from the member states to provide such information to the designers and vendors. But we need communication with regulators, so we get

feedback from the regulators. Such activity is important. Now we have connection with IAEA and OECD/NEA WGSAR.

Berta Oates
Excellent, thank you. That is all the questions I see in the question pane. Are there other questions that anybody has as an afterthought? We can hold on for just a minute. If people have questions and want to type those in.

While we are waiting, I do want to take this opportunity again to thank you Kubo-san for your efforts and your putting this presentation together and sharing your expertise with us this evening or this morning depending on where you are at internationally. It's been a pleasure working with you and I appreciate your effort very much.

Shigenobu Kubo
Thank you very much for the time.

Patricia Paviet
Thank you again Kubo-san. It was very good.

Shigenobu Kubo
Is it okay to go back to my work?

Berta Oates
Yeah, I don't see any more questions coming in. So, I think we'll go ahead and close the presentation for today. Thanks again. Have a great day.

Shigenobu Kubo
Thank you very much everyone.

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