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Regulatory Perspectives on Safety Aspects Related to Advanced Sodium Fast Reactors

Part 4. Fuel Qualification for Sodium Fast Reactors

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NUCLEAR ENERGY AGENCY
COMMITTEE ON NUCLEAR REGULATORY ACTIVITIES

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Part 4. Fuel Qualification for Sodium Fast Reactors

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COMMITTEE ON NUCLEAR REGULATORY ACTIVITIES (CNRA)

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The Committee promotes transparency of nuclear safety work and open public communication and oversees work to promote the development of effective and efficient regulation.

The Committee focuses on safety issues and corresponding regulatory aspects for existing and new power reactors and other nuclear installations, and the regulatory implications of new designs and new technologies of power reactors and other types of nuclear installations consistent with the interests of the members. Furthermore it examines any other matters referred to it by the Steering Committee for Nuclear Energy. The work of the Committee is collaborative with and supportive of, as appropriate, that of other international organisations for co-operation among regulators and consider, upon request, issues raised by these organisations. The Committee organises its own activities. It may sponsor specialist meetings, senior-level task groups and working groups to further its objectives.

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List of abbreviations and acronyms

AGR	Advanced gas-cooled reactor
AOO	Anticipated operational occurrences
CANDU	Canada deuterium uranium reactor
CFR	Code of federal regulations (United States)
CNRA	Committee on Nuclear Regulatory Activities (NEA)
CNSC	Canadian Nuclear Safety Commission
CSNI	Committee on the Safety of Nuclear Installations (NEA)
DBA	Design-basis accidents
DEC	Design extension conditions
EBR	Experimental Breeder Reactor (United States)
FA	Fuel assembly
FCCI	Fuel-cladding chemical interactions
FCMI	Fuel-cladding mechanical interactions
FFTF	Fast Flux Test Facility (United States)
GDC	General design criterion
GIF	Generation IV International Forum
GSAR	Ad Hoc Group on the Safety of Advanced Reactors (NEA)
IAEA	International Atomic Energy Agency
IRSN	Institut de Radioprotection et de Sûreté Nucléaire (France)
KAERI	Korean Atomic Energy Research Institute
KTA	Nuclear Safety Standards Commission (Germany)
LAR	License amendment request
LTA	Lead test assembly
LWR	Light water reactor
MOX	Mixed oxide fuel
NEA	Nuclear Energy Agency
NRC	Nuclear Regulatory Commission (United States)
OECD	Organisation for Economic Co-operation and Development
PCMI	Pellet-cladding mechanical interactions
PGSFR	Prototype Gen-IV sodium-cooled fast reactor
PWR	Pressurised water reactor
QA	Quality assurance
RIA	Reactivity-initiated accident
SAFDL	Specified acceptable fuel design limit
SAR	Safety analysis report
SARDL	Specified acceptable radionuclide release design limit
SFR	Sodium fast reactor
SMR	Small modular reactor
USNRC	United States Nuclear Regulatory Commission
VVER	Water-water energetic reactor
WGSAR	Working Group on the Safety of Advanced Reactors (NEA)

Table of contents

Executive summary

This technical report describes the regulatory perspectives on safety aspects related to the fuel qualification for advanced sodium fast reactors (SFRs) and identifies topics that should be investigated in the frame of SFR safety regulation, potentially involving additional research and development needs.

Fuel qualification has been identified in recent years as a subject of increasing importance in relation to regulatory and research activities in the area of advanced reactors and associated nuclear installations. Work thus far has focused on the following technical topics: general issues; regulatory requirements and guidance for sodium fast reactor (SFR) fuel qualification; fuel assembly design and qualification; fuel operational experience; and reporting requirements.

In 2017, a questionnaire was distributed to members of the Nuclear Energy Agency (NEA) Working Group on the Safety of Advanced Reactors (WGSAR) to gather information on fuel qualification, and responses were provided by seven countries (Canada, France, Germany, Italy, Korea, Russia and the United States). These responses have contributed to the development of the present report, which ultimately benefits from countries' experiences in licensing and in ongoing work on future SFR projects.

Based on a comparison of the information provided by the WGSAR participating countries in response to the survey, seven common positions have been identified in this report. These common positions are presented in Chapter 2 and represent common approaches to high-level safety goals and objectives, as well as safety functions to be applied to Generation IV SFRs. The essence of these common positions can be summarised as follows:

- The term "fuel qualification" is defined as the process for verifying that fuel is acceptable for use.
- Failure mechanisms have been well established for specific existing SFR fuel designs. For new innovative SFR fuel designs, failure mechanisms will need to be established. Fuel bowing and distortion are examples that should be evaluated for SFR fuel.
- The demonstration of fuel integrity at normal operation, transients and anticipated operating conditions should be supported by both experiments and analyses.
- As part of a fuel qualification programme, an irradiation testing programme needs to be implemented, covering at least the burn-up limits and fuel performance at normal operation, as well as the range of anticipated operating conditions.
- As part of the fuel qualification programme, testing data should be available to assess fuel performance for limiting design-basis events.
- Safety analysis of the SFR fuel assemblies should address the safety function of maintaining core compactness and ensuring core mechanical stability.
- Fuel testing and manufacturing should be conducted under a quality assurance programme, with associated record keeping and reporting of operational events.

The report also describes areas in which there was general agreement among participants, and areas in which there were significant variations in opinion.

1. Introduction

Sodium fast reactors (SFRs) are under consideration as a future means of power production in several countries around the world. While the operating experience and policies for licensing light water reactors is well advanced, sodium fast reactors represent a challenge to regulators who must ensure public safety. Fuel failure mechanisms for standard light water reactor fuel assembly designs are fairly well understood, but significantly different fuel designs or reactor designs may introduce new failure mechanisms. A robust fuel qualification programme is therefore important for any fuel design, but becomes even more important for radically new fuel designs that do not have a great deal of related operational experience.

This technical report was written by the NEA Working Group on the Safety of Advanced Reactors (WGSAR) as part of the activity "Regulatory Perspectives on Safety Aspects Related to Advanced Sodium Fast Reactors". The aim of this activity is to develop technical reports increasing regulators' knowledge of selected safety aspects related to advanced sodium fast reactors (SFRs) as well as to identify additional research and development needs to support the regulators' safety review. It was agreed to develop reports based on regulatory experiences in the following technical areas: 1) severe accident prevention and mitigation measures; 2) neutronics and criticality safety; 3) analytical codes; and 4) fuel qualifications.

This technical report describes the regulatory perspectives of safety aspects related to fuel qualification for advanced sodium fast reactors meant to identify the fuel qualification requirements of participating countries, fuel design analysis requirements, their experience with SFR fuel and fuel qualification reporting requirements under quality assurance programmes.

The present report is based on answers to a questionnaire received from Canada, France, Germany, Italy, Korea, Russia and the United States.

This report documents the responses of each participant, along with the common positions established by the participating WGSAR members. The complete survey responses from member countries are in Annex A of the report.

The United Kingdom became an active member of the WGSAR at a time when the report was being finalised and therefore did not participate in the development of the common positions.

2. Common positions

This chapter presents the common positions that were established by member countries participating in the NEA Working Group on the Safety of Advanced Reactors (WGSAR) based on the questionnaire answers detailed in Chapter 3.

Seven common positions were identified:

- The term "fuel qualification" is defined as the process for verifying that fuel is acceptable for use.
- Failure mechanisms have been well established for specific existing SFR fuel designs. For new innovative SFR fuel designs, failure mechanisms will need to be established. Fuel bowing and distortion are examples that should be evaluated for SFR fuel.
- The demonstration of fuel integrity at normal operation, transients and anticipated operating conditions should be supported by both experiments and analyses.
- As part of a fuel qualification programme, an irradiation testing programme needs to be implemented, covering at least the burn-up limits and fuel performance at normal operation, as well as the range of anticipated operating conditions.
- As part of the fuel qualification programme, testing data should be available to assess fuel performance for limiting design-basis events.
- Safety analysis of the SFR fuel assemblies should address the safety function of maintaining core compactness and ensuring core mechanical stability.
- Fuel testing and manufacturing should be conducted under a quality assurance programme, with associated record keeping and reporting of operational events.

In addition to these seven common positions, WGSAR members are in agreement that guidance should be developed in the area of fuel qualification to address regulatory requirements associated with fuel neutronic behaviour and thermal-mechanical performance.

3. Survey results

The survey consisted of five thematic areas regarding the regulatory approach to fuel qualification for sodium fast reactors (SFRs), namely:

1. general definition and status of SFR fuel qualification;
2. regulatory requirements and guidance for SFR fuel qualification;
3. fuel assembly design and qualification;
4. fuel operational experience;
5. fuel qualification reporting requirements.

3.1. General definition and status of SFR fuel qualification

Participating countries were first asked how fuel qualification is defined in their national regulatory frameworks. The countries provided a similar interpretation of fuel qualification, namely that it is a process for verifying that fuel is acceptable for use. For some countries, the requirement for fuel qualification came through fuel design limit regulations, and for others it is necessitated by their quality assurance programme requirements.

The majority of respondents stated that there are no current licensing processes in their country specific to SFR fuel. However, Russia responded that they do have an active SFR licensing process and the United States indicated that they are in a "pre-submittal" phase with an applicant and will be addressing SFR fuel licensing issues as part of the process. It can be expected that more specific SFR licensing processes will be developed as interest in SFR designs becomes more prevalent, but until then, it can be expected that the intent of current rules and regulations would be used.

The third general question focused on licensed SFR fuel and requested the participants to describe the fuel and its expected operating environment. Canada, Germany, Italy and the United States responded that there are no currently licensed SFR fuel designs in operation. Although France has no SFR fuel in operation, it provided a description of the relevant fuel dimensions for the fuel used in Phénix and Superphénix as well as some of the operating parameters. Similarly, Germany provided information for the fuel made for SNR-300; Korea provided information from PGSFR; and Russia provided information from fuel designed for the BN-1200 reactor. It is worth noting that there are significant differences in fuel assembly design and operation conditions, which could result in different concerns in terms of fuel qualification.

3.2. Regulatory requirements and guidance for SFR fuel qualification

The participating countries were asked if they had specific requirements and guidance for qualification of SFR fuel and, if applicable, whether they were significantly different from those for conventional light water reactor fuel. As can be expected, the countries with more experience in SFR reactor designs have more regulatory requirements and guidance available for SFR fuel. From the responses, none of the participating countries have fuel qualification requirements or guidance that are specific solely to SFR fuel types. However, most have regulatory requirements and guidance that would be applicable to SFR fuel qualification in addition to other fuel designs. For example, Russia has a regulatory document covering U-Pu (MOX) fuel, which would be applicable to both SFR and VVER reactor types. France explained that there is an ongoing effort to develop guidance, and it provided some of the elements from draft guidance that can apply to a new SFR fuel.

Similarly, the responses do not identify any SFR-specific requirements regarding fuel damage, but they do identify general fuel damage requirements that would be applicable to various fuel types. The guidance provided through the various responses generally addresses issues such as fuel damage, fuel rod failure and core coolability. The specific failure mechanisms discussed in the guidance may or may not be applicable to a specific SFR design, but the guidance can still be useful in evaluating a new SFR fuel design. For example, in Canada, fuel rod failure criteria must be provided for all known fuel rod failure mechanisms. This and other examples should be generically applicable to any fuel designs that use cladding.

There is also variation in requirements for fuel element qualification in either irradiation facilities or test reactors before use in an SFR. For the countries that specifically require fuel qualification of SFR fuel, all of them would allow fuel qualification in either a test facility or test reactor. However, some of them (e.g. Canada, France, Germany, Korea, and Russia) have specific requirements regarding what type of fuel qualification would be necessary. The United States does not have specific requirements as to the type of testing, but does allow irradiation in test facilities or operating reactors as would be necessary per the particular design.

3.3. Fuel assembly design and qualification

The participating countries were requested to identify what analyses and testing requirements they had for fuel assemblies. From the responses, it appears that the testing and analyses are typically implicit rather than explicitly required. There is general agreement that vendors carry the responsibility of demonstrating that their fuel is suitable for the expected normal and off-normal operating conditions. Some of the responses go into greater detail and state that ageing, operating conditions, uncertainties, etc., would need to be addressed. While this is not explicitly stated in each response, it is assumed that all of the participating countries are in general agreement on the type of analyses and testing needed, based on all of the responses as a whole. The variation in response appears to be tied to whether these are explicit requirements or implicit.

Based on the responses from the participating countries, bowing was the most commonly mentioned failure mechanism. It is also clear from the responses to questionnaire as a whole that it is up to the applicant to identify the failure mechanisms.

3.4. Fuel operational experience

The participating countries were asked for a description of any fuel damage that occurred, if they had experience of operating SFRs.

Canada, Germany, Italy, Korea and Russia responded that they did not have experience with failed SFR fuel. France responded that Phénix experienced 42 pin failures during the life of the reactor and that 27 were caused by prevention of coolant ingress into the pin. The only other respondent with examples of SFR fuel failures was the United States who responded that the Experimental Breeder Reactor I (EBR-I) reactor did experience a partial meltdown driven by an unexpected thermal expansion.

The respondents were also asked if their existing regulations were determined to be adequate after any SFR fuel damage. France responded that the operational experience led to improvements of operational procedures. In the United States, the lessons learnt from EBR-I led to design improvements being incorporated into the EBR-II programme.

3.5. Fuel qualification reporting requirements

The participating countries were first requested to identify what analysis reports on fuel safety and fuel qualification are required in their respective country. The responses varied according to each country's specific requirements, but generally the responses demonstrate that each country has a method by which a fuel vendor may develop and license new fuel designs.

The respondents were also asked about any quality assurance (QA) reporting requirements for fuel manufacturing. In general, there is a common position that fuel manufacturing requires a quality assurance programme; however, there is variation among the respondents regarding reporting requirements. Both Germany and Korea require QA reporting, but the other respondents did not identify specific QA reporting requirements. The USNRC stated that the QA programme associated with fuel manufacturing facilities typically includes reporting requirements for quality issues, but that there is no requirement to periodically report otherwise. Records may however be inspected at any time.

4. Conclusions

The analyses undertaken by the NEA Working Group on the Safety of Advanced Reactors (WGSAR) were based on a comparison of the information provided in response to the first stage of the survey and have led to the following observations in addition to the identified common positions:

1. There does not appear to be a robust regulatory framework specific to SFR fuel in any of the countries that responded. However, the countries with more operational sodium fast reactor (SFR) experience (e.g. France and Russia) appear to have developed, or be developing, more SFR-specific regulations and guidance than the other respondents.
2. For all countries, current regulations could be used to ensure that SFR fuel is designed to a standard necessary to ensure public safety; however, without greater detail in the regulations, the burden is placed on the fuel vendor to identify and address the likely failure mechanisms.
3. There is also variation in the testing requirements necessary to introduce new fuel. Some countries have specific requirements, but most of them have generic high-level requirements that would presumably necessitate testing in order to be met. In the end, it appears that testing of new fuel would be needed for each country, but regulations vary.
4. All of the participating countries require analyses to demonstrate fuel integrity. From the responses, it appears that some regulators are more prescriptive in identifying the failure mechanisms that require analysis while others state that it is up to the applicant to identify the failure mechanisms, and the regulator must review these conclusions.
5. The responses indicated that there is limited operational experience with SFR fuel damage. The failure mechanisms mentioned in the responses vary and no clear conclusions can be drawn based on the limited data.
6. Quality assurance reporting requirements also vary among the respondents; however, there generally is a requirement for maintaining records that can be reviewed or inspected. Some countries additionally require periodic reporting.

5. Country responses to survey for fuel qualification for sodium fast reactors

5.1. General questions

5.1.1. The term "fuel qualification" can have several meanings depending on the role of the regulator, fuel designer, fabricator or the utility. Please clarify your interpretation of "fuel qualification" and your role(s) for this questionnaire.

Canada

In this survey the Canadian regulatory point of view is expressed. In Canada, fuel qualification is part of the reactor design regulatory requirements. As such, fuel qualification is the process of verifying that fuel is fit for service.

The CNSC REGDOC 2.5.2, *Design of Reactor Facilities: Nuclear Power Plants* (CNSC, 2014a) states the programmatic requirements with respect to fuel qualification:

"Fuel design and design limits shall reflect a verified and auditable knowledge base. *The fuel shall be qualified for operation, either through experience with the same type of fuel in other reactors, or through a programme of experimental testing and analysis, to ensure that fuel assembly requirements are met*."

France

The fuel qualification process enables to guaranty the required performances of all the components of a fuel assembly (pellets, clad, assembly structures, neutron shielding, etc.) during normal operation and abnormal transients. Qualification covers in core operation, handling phases and storage. The utility and the fuel manufacturer are responsible for the fuel qualification. For a new reactor, the IRSN assesses the process and the results of the fuel qualification in the frame of the preliminary safety report. For a new generation of fuel to be loaded in an existing plant, qualification is assessed along the different steps of the fuel standardisation: irradiation of experimental assemblies, introduction of some new assemblies in the core, modification of the core loading management.

Qualification of French SFR fuel was a long process following development phases and optimisation that spreads from the beginning of Rapsodie (1967) to the shutdown of Phénix (2009). It is important to note that, since the French SFR programme was suspended after a short time of operation of Superphénix, we do not consider that the fuel has reached a level of qualification corresponding to a commercial product.

In France, there is no regulation dealing with SFR fuel. By now, the designer of ASTRID project is building a fuel qualification programme that would be assessed at the stage of the preliminary safety report scheduled after 2019. So only safety requirements (see answer to question 2.4) have been proposed for ASTRID fuel and safety criteria are not yet defined. In this frame, answers to the present questionnaire are mainly based on the IRSN's experience with the safety assessment of the fuel assemblies that have been irradiated in Phénix and Superphénix reactors: this is the case in particular for questions 1.3, 2.2, 2.3, 3.1, 3.2, and 4.1.

Moreover, the Safety Authorities and the IRSN are preparing guidance dealing with PWR fuel and associated numerical tools qualification. Many of the principles and recommendations set up in these draft documents might be applicable to SFR fuel (see questionnaire on analytical codes).

Germany

In general fuel qualification is understood as process demonstrating that regulatory requirements (e.g. Safety Requirements for Nuclear Power Plants, KTA Standard 3101.3 [KTA, 2015]) are met such as requirements related to the exclusion of systematic fuel failures or quality assurance requirements.

Italy

The process of qualification of a fuel is to be interpreted as the sum of all the experimental campaigns aimed at verifying: a) the general safety requirements represented by the fuel itself, its first envelope (the cladding), and its structurals (spacer grids, plena, springs, debris filters, etc.), and b) the performance indicators as specified by the vendor, like achievable burn-up, etc.

The experimental campaigns must be conducted, after approval by the regulatory body, for several years in an operating power plant or, where a specific power plant does not already exist, in a dedicated test facility that is capable of reproducing the real physical environment in which the new fuel is supposed to work, in terms of neutron flux, neutron fluence, neutron spectrum, thermo-hydraulic conditions, coolant types, etc. Post-irradiation examinations are then to be conducted to assess all the characteristics of fuel, cladding, and structurals, including fission products distribution inside the first envelope, thermo-mechanical properties after irradiation, etc.

Korea

It is understood that the fuel should be designed and manufactured under a quality assurance (QA) programme, with 18 criteria. This is also required in the Atomic Law. The designer, manufacturer, utility should get evaluated annually, or bi-annually for their QA programme.

Russia

Fuel qualification by the regulator is carried out in the process of licensing the power unit based on the safety analysis report (SAR).

Fuel qualification by the designer is performed on the basis of the requirements of federal norms and regulations in the field of nuclear energy use and also technical tasks for the development of fuel rods and fuel assemblies (FAs) designed in accordance with the technical assignments, including the conditions of normal operation, design-basis accidents, handling of spent nuclear fuel, its storage, transportation and reprocessing.

Qualification of fuel by the fabricator is carried out on the basis of the design and technological documentation submitted by the designer, certificates of conformity confirming the quality of materials, semi-finished products and components.

Fuel qualification by the utility is carried out on the basis of the accompanying documentation, including the passport on FA, specifications, dimensional drawings and the operation manual.

United States

The US Nuclear Regulatory Commission (NRC) does not have a specific published definition for “fuel qualification”, but it is generally interpreted to refer to the process of testing large quantities of fuel rods (or other geometry) to statistically demonstrate performance and to validate fuel performance models. In this sense, fuel qualification is used by the NRC to review the safety significance of a particular fuel design given expected operational parameters and to ensure that general design criteria related to fuel design (e.g. ten CFR Part 50 Appendix A [USNRC, 2017a], General Design Criterion [GDC] ten regarding specified acceptable fuel design limits [SAFDLs]) will be met.

5.1.2. Is there an ongoing licensing process in your country for SFR fuel, and do you have licensing and fuel qualification requirements specific to SFR fuel? If there is a process for the qualification of an innovative fuel product in its developmental stage, please describe.

Canada

There is no ongoing licensing process in Canada for SFR fuel. In Canada, there are no licensing and fuel qualification requirements specific to SFR fuel. All fuel qualification requirements are generic and qualitative. REGDOC 2.5.2 (CNSC, 2014a), Section 8.1.1, *Fuel Elements, assemblies and design*, provides generic fuel design and qualification requirements. The spirit of these requirements is to design fuel rods so that they do not fail for all plant operational states; fuel rod failure could happen during DBA and DEC events and must be accounted for in safety analysis. Fuel qualification requires establishing programmes of testing and inspection of new fuel, as well as online fuel monitoring and post-irradiation surveillance of irradiated fuels.

France

At the present stage of ASTRID development the licensing process has not yet started. It is to be noted that the fuel qualification for the purpose of commercial SFRs will be completed in ASTRID.

Germany

No, there is currently no licensing process in Germany for SFR fuel.

Italy

No.

Korea

There is no ongoing licensing process at the moment. But KAERI is going to submit topical reports for fuel and safety analysis at the end of this year. Discussion is under way for scope, schedule, and perhaps also the fee.

Russia

Improvement of fuel for SFRs and, accordingly, its licensing has been ongoing since the start-up of the first BN-350 prototype reactor in 1973.

There is the regulatory document NP-080-07 “Basic requirements for fuel rods and fuel assemblies with uranium-plutonium (MOX) fuel for nuclear power plants” (Rostechnadzor, 2007a), which sets out basic safety requirements for design and manufacture of fuel rods and FAs with oxide pellet uranium-plutonium fuel for nuclear power plants with SFR type reactors.

At present, work is underway to justify innovative nitride uranium-plutonium fuel for the BN-1200 sodium fast reactor project. Experimental fuel assemblies with nitride fuel are now irradiated in the BN-600 reactor. The regulator has issued licences to irradiate these fuel assemblies and is controlling the testing.

United States

Currently there are no SFR fuel designs submitted for NRC review; however, one applicant (Oklo Inc.) has begun pre-submittal interactions and has indicated an interest in submitting a design for NRC review and approval. While the NRC does not have specific fuel qualification programme requirements, the NRC staff will review the applicant's qualification programme to ensure that it covers the full range of expected operating parameters and that the SAFDLs or specified acceptable radionuclide release design limits SARDLs) will have sufficient basis to support the staff making a regulatory finding.

5.1.3. If used or licensed within your country, please describe the SFR fuel and its expected operating environment; rod or plate dimensions, fuel and cladding composition, enrichment level, expected power level, operating temperature, limiting burn-up, etc. (Please be careful not to disclose Proprietary information.)

Canada

There is no SFR fuel design activity in Canada at this time.

France

Fissile fuel used in French SFRs Phénix and Superphénix was made of a mixture of plutonium and uranium oxide obtained by the co-milling process (MOX fuel).

Different fuel compositions have been tested, mainly in the Phénix reactor. The compositions of the standardised fuels are given in the table below.

At the beginning of the French SFR programme, reference material for the cladding was a hardened 316 type stainless steel. This alloy has been further optimised to obtain finally the 15-15 Ti cladding (stainless steel containing around 15% of chromium and 15% of nickel with titanium addition), which is now foreseen for the ASTRID project.

	Pellet diam. (mm)	Clad ext. diam/thick (mm)	Pu content[1] (%mass)	Max. Clad temp.(°c)- nominal[2]	Max. burn-up (GWj/t)	Linear power W/cm (max)
Phénix Internal	5.42	6.55 / 0.45	18%	<650°C	90	<450
External	5.42	6.55 / 0.45	23%	<650°C	115	<450
Superphénix Internal	7.14	8.50 / 0.56	11%	<620°C	73	<480
External	7.14	8.50 / 0.56	14%	<620°C	70	<480

1) Equivalent Pu-239
2) Maximum temperature of the hottest pin calculated in the mid-thickness of the clad. In practice, nominal temperatures are expected to be statistically lower in operation because this criterion integrates some uncertainties.

It is worth noting that, for Phénix, the pin linear power was limited by the centreline temperature, which has to remain sufficiently below the fuel melting point. In the Superphénix case with annular pellets, the linear power was limited by the temperature reached at the time of activation of the protection system during an inadvertent control rod withdrawal.

Germany

The SNR-300 used a mixture of Uranium-and Plutonium-oxide with an enrichment of 24% to 34%. 205 fuel elements with each 166 fuel rods were used in a hexagonal grid. The breeding material (Uranium-dioxide with less than 0.7 % enrichment) was partly above and below the fissile material and also in mere breeding fuel elements. The core power level was expected to be 300 MW/m³ with a coolant temperature of 546 C and a cladding temperature of 556 C. Cladding material was steel.

Italy

Never used, nor licensed.

Korea

- PGSFR design features (Draft, from the KAERI presentation at IAEA 46th TWG-FR meeting, 2013 (H.-K. Joo, 2013));
- Core I/O temperature: 390/545 °C.

Core		U	LTRU	MTRU
EFPD / # of Batches [day / #]		290 / 5	290 / 5	290 / 5
# of Fuel Assembly (IC/OC)		33/90	33/90	33/66
Fuel Pin Diameter [cm]		0.74	0.74	0.70
P/D Ratio		1.125	1.125	1.189
Active Core Height [cm]		100.0	100.0	100.0
Lower Shield Height		90.0	90.0	90.0
Fission Gas Plenum Height [cm]		150.0	150.0	150.0
Enrichment (IC/OC) [w/o]		14.0 / 19.5	14.9 / 21.8	20.2 / 29.6
Fuel Loading Amount [Ton/GWE]		107.9	107.8	76.4
Charged Amount [kg]	Heavy Metal	2205	2204	1576
	TRU	0	438	415
	MA	0	40	51
	Fissile	397	237	195
Reactivity Swing [pcm]		1184	695	1493
Burn-up [MWD/kg]	Average	50.2	50.4	70.5
	Peak	78.7	81.8	110.1
Fast N. Flux [x10^{15} n/cm^2·sec]	Average	0.98	1.18	1.41
	Peak	1.54	1.87	2.22
Peek Fast N. Fluence [x10^{23} n/cm^2]		1.95 / 1.93	2.37 / 2.36	2.83 / 2.71
Linear Power Density [W/cm]	Average	104.7	105.1	129.7
	Peak	180.0	178.6	219.7
Pressure Drop [MPa]		0.255	0.255	0.204
Cladding Midwall Tep. [°C]		645	645	645

Russia

At present, rod-type fuel elements with nitride fuel designed for the BN-1200 reactor are being tested in the BN-600 reactor:

- fuel composition–(UPu)N;
- the pellet density is 12.2 g/cm3;
- cladding material–austenitic steel EK164;
- the size of cladding is 9.3χ0.6 mm;
- level of enrichment of 13-14% fissile isotopes of plutonium;
- the maximum linear power of the fuel rod is 47 kW/m;
- the maximum cladding temperature is 560ºC;
- maximum local burn-up–11% of heavy metal;
- average burn-up–7.1% of heavy metal.

United States

There are currently no plants utilising SFR fuel designs in operation within the United States.

5.2. Regulatory requirements and guidance for SFR fuel qualification

5.2.1. Do you have specific requirements and guidance for qualification of SFR fuel, and if so are they significantly different from those for conventional light water reactor fuel?

Canada

As stated before, requirements and guidance for fuel qualification are generic in Canada.

France

Up to now, there was no specific regulation or guidance related to SFR fuel in France. However, the safety authority together with the IRSN are developing guidance to precise the recommended content of the application file for the authorisation of putting a new fuel or a modified fuel in a French PWR. Nevertheless, the requirements as written in the last draft version of the guidance, may be applicable to SFR fuel. Thus, the application file for a new SFR fuel could exhibit the following elements:

- description of the physical and chemical properties of the fuel assembly materials before and after irradiation;
- presentation of the thermo-mechanical design of the fuel pin including the physical phenomena to be taken into account, the modelling tools and their qualification, and evaluation of the fuel pin behaviour in normal operation and anticipated operational occurrences;
- presentation of the mechanical and thermo-hydraulic design of the assembly and its behaviour in normal operation and anticipated operational occurrences;
- neutronics of the fuel assembly;
- evaluation of the behaviour of the fuel under accidental conditions and DECs;
- presentation of uncertainties associated with the fuel assembly fabrication;

- presentation of the operational feedback (test irradiations);
- demonstration of the compatibility of the fuel assembly with its environment (other assemblies, absorber rods, handling devices, measuring instruments, core internals, storage, etc.);
- demonstration of the safety when handled outside the core;
- description of the monitoring and examination programme (step by step approach in term of irradiation dose);
- description of the fuel management;
- impact of the fuel assembly on effluents and waste management (for example mass and categories of wastes, cleaning effluents, etc.).

Germany

SFR fuel differs in many aspects from light water fuel. Therefore, safety requirements for SFR fuel must be specific. Nevertheless, there will be overlapping in the requirements with light water fuel like cladding strain limit, cladding stress limit, internal gas pressure limit, maximum fuel centreline temperature, etc.

Italy

No.

Korea

No specific requirements, yet. But the design and manufacture of nuclear fuel should be done under a strict QA programme, which is required in atomic law.

Russia

As stated in point 1.1, we have the regulatory document NP-080-07 "The main requirements for fuel rods and fuel assemblies with uranium-plutonium (MOX) fuel for nuclear power plants" (Rostechnadzor, 2007a), which applies not only to reactors of the SFR type, but also to light water reactors of the VVER type. More specific requirements for fuel qualification are established in the reactor design project.

United States

The NRC does not have specific requirements regarding qualification of any fuel types. That being said, GDC ten states that "The reactor core and associated coolant, control, and protection systems shall be designed with appropriate margin to assure that specified acceptable fuel design limits are not exceeded during any condition of normal operation, including the effects of anticipated operational occurrences." In part, for an applicant to demonstrate compliance with GDC ten, sufficient tests would be necessary to demonstrate that fuel damage would not occur for the plant conditions associated with normal operations and anticipated operational occurrences (AOOs).

5.2.2. Are there requirements or expectations regarding fuel damage (stress, strain, rupture), or fuel coolability (maximum centreline temperature, power or heat flux limitations, etc.)?

Canada

Short answer is "yes" and they are given in REGDOC 2.5.2, Section 8.1.1, *Fuel Elements, assemblies and design* (CNSC, 2014a). The fuel design robustness requirements are developed relative to all plant operational states expressed as AOO, DBA and DEC events. The fuel must not fail in AOOs but it is accepted that damage could happen during DBA and DEC events. Acceptance criteria should be established for fuel damage, fuel rod failure and fuel coolability. These criteria should be derived from experiments that identify the limitations of the material properties of the fuel and fuel assembly, and related analyses.

Fuel damage

Fuel damage criteria should be established for all known damage mechanisms in operational states (normal operation and AOOs). The damage criteria should assure that fuel dimensions remain within operational tolerances, and that functional capabilities are not reduced below those assumed in the safety analysis. When applicable, the fuel damage criteria should consider high burn-up effects based on irradiated material properties data. The criteria should include stress, strain or loading limits, the cumulative number of strain fatigue cycles, fretting wear, oxidation, hydriding (deuteriding in CANDU reactors), build-up of corrosion products, dimensional changes, rod internal gas pressures, worst-case hydraulic loads, and LWR control rod insertability.

Fuel rod failure

Fuel rod failure applies to operational states, DBAs and DECs. Fuel rod failure criteria should be provided for all known fuel rod failure mechanisms. The design should ensure that fuel does not fail as a result of specific causes during operational states. Fuel rod failures could occur during DBAs and DECs, and are accounted for in the safety analysis.

Assessment methods should be stated for, fuel failure mechanisms, reactor loading and power manoeuvring limitations, and fuel duty, which lead to an acceptably low probability of failure. When applicable, the fuel rod failure criteria should consider high burn-up effects, based on data of irradiated material properties. The criteria should include: hydriding, cladding collapse, cladding overheating, fuel pellet overheating, excessive fuel enthalpy, pellet-clad interaction, stress-corrosion cracking, cladding bursting and mechanical fracturing.

Fuel coolability

Fuel coolability applies to DBAs and, to the extent practicable, DECs. Fuel coolability criteria should be provided for all damage mechanisms in DBAs and DECs. The fuel should be designed to ensure that fuel rod damage will not interfere with effective emergency core cooling. The cladding temperatures should not reach a temperature high enough to allow a significant metal-water reaction to occur, thereby minimising the potential for fission product release. The criteria should include cladding embrittlement, fuel rod ballooning, structural deformation and, in CANDU, beryllium braze penetration.

France

The operating limits and criteria applicable to SFR fuel have been mainly determined by the experiments conducted in Rapsodie and Phénix. They stem from the analysis of the post-irradiation examinations that were used to validate the numerical models describing the fuel behaviour in normal operation. Some of them remain quite empirical as it is the case for the maximum nominal clad temperature.

In operation, there are three limiting criteria have to be fulfilled (fissile subassemblies):

- the maximum linear power during the first ten days of irradiation of a new subassembly;
- the maximum temperature of the clad (mid-thickness) at hot point with uncertainties (700°C);
- the maximum linear power.

Fulfilment of the above criteria is ensured by the procedures of plant operation and the thresholds associated with the protection system.

In addition, designed rules are defined to ensure the resistance of the cladding during irradiation and handling. Respect of the design rules are verified once for standard subassemblies, given that a constant quality standard is applied during fuel design and fabrication.

Germany

Maximum enthalpy rise in fuel is critical for SFR fuel because sodium boiling scenario will lead to reactivity increase. Fuel coolability (critical heat flux) is of less importance because sodium provides very efficient heat transfer from fuel to coolant.

Italy

Not in Italy. But in principle there must be requirements of this type.

Korea

The designer has their requirements, but no regulatory requirements yet.

The inner clad temperature should be limited to a certain value to avoid the eutectic formation. The value will be established evaluating the clad melting temperature, hopefully during topical report review.

Russia

The regulative document NP-082-07 “Nuclear safety rules for nuclear plant reactor units” (Rostechnadzor, 2007b) sets the following limits for fuel rod damage for SFR reactors:

Operational limits:

- defects such as gas leakage – not more than 0.05% of the number of fuel rods in the core;
- direct fuel contact with the coolant – no more than 0.005% of the number of fuel rods in the core.

Safe operation limits:

- defects such as gas leakage – no more than 0.1% of the number of fuel rods in the core;
- direct fuel contact with the coolant – no more than 0.01% of the number of fuel rods in the core.

Based on these requirements, the limits of fuel and cladding temperature, linear power or heat flux, fuel burn-up, dose damage on cladding, volume swelling of claddings, etc., are established and justified in the SAR.

United States

NUREG-0800, "Standard review plan for the review of safety analysis reports for nuclear power plants: LWR edition," Section 4.2, "Fuel system design" (USNRC, 2007) provides review guidance regarding acceptance criteria for fuel system damage, fuel rod failure and fuel coolability. The fuel damage criteria (e.g. stress, strain, fatigue, oxidation, etc.) are established for the purposes of meeting GDC ten (see response to 2.1). The coolability criteria (cladding embrittlement, clad melt, etc.) are established for the purposes of meeting GDC 27, GDC 35 and 10 CFR 50.46 (USNRC, 2017b) requirements. It should be noted that NUREG-0800 was created for, and applies to, large light water reactors. The guidance provided in NUREG-0800 may or may not be applicable to different fuel designs. The staff has been involved with efforts to update guidance and regulations for various new and advanced reactor designs, but it is up to the applicant to identify all potential failure mechanisms and to support proposed fuel design limits with fuel qualification test results based on their specific reactor/fuel design.

5.2.3. What fuel damage mechanisms are considered possible during normal operation and may limit fuel lifetime or warrant regulation?

Canada

In Canada, different requirements exist for fuel and fuel rods failure during normal operation. The regulations require that during normal operation and AOOs:

- Fuel damage criteria should be established for all known damage mechanisms in operational states (see 2.2 above).
- Fuel rod failure criteria should be provided for all known fuel rod failure mechanisms (see 2.2 above). The design should ensure that fuel does not fail as a result of specific causes during operational states.

Therefore, the burden is on the vendor to identify all damage mechanisms to fuel during normal operation but preclude, by design, the fuel rod failure.

France

Damage mechanisms in normal operation impair the structure of the subassembly, the clad and the fuel pellets. The main identified damages are listed below.

Fuel:

- swelling;
- plutonium migration (modification of the radial profile of power);
- cracking.

Clad:

- irradiation induced swelling;
- creeping;
- corrosion (internal and external);
- cracking;
- irradiation embrittlement.

Structure of fuel assembly:

- irradiation induced swelling (possible axial bending);
- embrittlement.

When the criteria specified in §2.2 are fulfilled, fuel life time limitation came from irradiation induced swelling of the cladding, which causes the reduction of the section of coolant channels and induces high stresses at contact points between the pins. High swelling of the clad may also unwrap the wire spacer.

It is noticeable that fuel swelling and corrosion would not be the limiting factor of the fuel life time in core for Phénix and Superphénix. Nevertheless, if cladding with very low swelling rate is used for a future reactor, then fuel/cladding mechanical interaction or internal corrosion could become limiting phenomena.

Germany

Abrasion resistance appears to be significant for assessing the dwell time of SFR fuel.

Italy

Especially for high burn-up fuel, which might be a goal for SFRs, PCMI may limit fuel lifetime and lead to first envelope damage.

Korea

No response.

Russia

Main processes of fuel damage:

- fuel swelling and fuel and fuel-cladding mechanical interactions (FCMI);
- gas release;
- fuel constituent redistribution;
- fuel-cladding chemical interactions (FCCI);
- rod to greed fretting;
- changes in mechanical properties of steel (creep rate, fracture toughness, yield strength);
- fuel-coolant interaction taking into account impurities.

United States

The NRC does not have specific guidance for SFR fuel designs and therefore cannot respond to this question.

5.2.4. What analyses are required to ensure integrity of a fuel element over its intended lifetime?

Canada

In Canada, fuel and fuel rods design requirements are linked to the core physics and thermal-hydraulic design. The thermal-hydraulic design should be such that sufficient margin exists with regard to maintaining adequate heat transfer from the fuel to the reactor coolant system, to prevent fuel sheath overheating. The design requirements can be demonstrated by meeting a set of derived acceptance criteria, as required by REGDOC-2.4.1, *Deterministic Safety Analysis* (CNSC, 2014b). The demonstration of thermal margin should account for all possible reactor operational states and conditions, as determined from operating maps including all AOOs. The demonstration should also include long-term effects of plant ageing and other expected changes to core configuration over the operating life of the plant.

The demonstration of thermal margin should thoroughly address uncertainties of various parameters affecting the thermal margin. The design should identify all sources of significant uncertainties that contribute to the uncertainty of thermal margin. The uncertainty for each of the sources should be quantified with supportable evidence.

In addition to the demonstration of thermal margin, the core thermal-hydraulic design should also address possible core power and flow oscillations and thermal-hydraulic instabilities. The design should be such that power and flow oscillations that result in conditions exceeding specified acceptable fuel design limits are not possible or can be reliably and readily detected and suppressed.

Finally, programmes for testing and inspection of new fuel, as well as for online fuel monitoring and post-irradiation surveillance of irradiated fuel should be established.

France

Damage mechanisms in normal operation impair the structure of the subassembly, the clad and the fuel pellets. The main identified damages are listed below.

Fuel:

- swelling;
- plutonium migration (modification of the radial profile of power);
- cracking.

Clad:

- irradiation induced swelling;
- creeping;
- corrosion (internal and external);
- cracking;
- irradiation embrittlement;

Structure of fuel assembly:

- irradiation induced swelling (possible axial bending);
- embrittlement.

When the criteria specified in §2.2 are fulfilled, fuel life time limitation came from irradiation induced swelling of the cladding, which causes the reduction of the section of coolant channels and induces high stresses at contact points between the pins. High swelling of the clad may also unwrap the wire spacer.

It is noticeable that fuel swelling and corrosion would not be the limiting factor of the fuel life time in core for Phénix and Superphénix. Nevertheless, if cladding with very low swelling rate is used for a future reactor, then fuel/cladding mechanical interaction or internal corrosion could become limiting phenomena.

Germany

Spring force evaluation for spacer grids appears to be relevant because of the high neutron flux irradiation, which results in early spring force relaxation. The same applies to the downhold spring in the top of the fuel element.

Italy

Again at high burn-up, fast power transients (like those induced by reactivity-initiated accidents [RIAs]) may lead to clad rupture. Flow blockage may also be very dangerous, as well as differential thermal dilatations. Careful analyses are to be conducted in these areas, maybe using also multi-scale approaches, together with the development, validation and qualification of analytical tools and codes. This however can be achieved only through experiments, both of non-destructive and destructive types.

Korea

Fuel performance analyses are required.

Russia

Strength and thermo-mechanical calculations for normal operation and in case of violations of normal operation, taking into account:

- design modes of operation of the reactor, their quantity and design flow;
- mechanical, thermal and radiation effects;
- limiting deviations of design and technological characteristics, process parameters;
- shock and vibration effects, thermocycling loading, radiation and temperature creep, as well as ageing of materials;
- influence of fission products and impurities in the coolant and fuel on the integrity and corrosion resistance of the fuel rods;
- other factors that impair the mechanical characteristics of the materials.

The modes of normal operation include reactor start-up, power operation with two and three heat removal loops, engagement of the third loop, reactor shutdown.

Regimes with a violation of normal operation include the unauthorised withdrawal of the control rod with the activation of scram by the power level, the disabling of the main pump of the primary circuit, the disconnection of the heat removal loop of with the activation of the scram by technological parameters.

As criteria for the strength and operability of fuel elements, the numerical characteristics of the following limit states are used:

The threshold value of the first principal stress in the cladding of the fuel rod, the non-exceeding of which excludes the unstable growth of the postulated initial crack, the size of which is established by the fuel element designer;

a) the maximum value of damage to the metal of the fuel cladding due to cyclically repeated loads;

b) the limiting value of damage to the metal of the fuel cladding due to thermal radiation creep;

c) the limiting value of the total flexural stresses (or flexural deformations) in the fuel rod shells under seismic or other dynamic influences;

d) the limiting value of the intensity of plastic deformation of the fuel cladding;

e) the limiting value of the change in the diameter of the cladding of the fuel element;

f) the limiting value of the elongation of the fuel rod;

g) the melting point of the fuel (for the fuel elements defined by the project, the chemical composition, burn-up and manufacturing technology);

h) the limiting value of the pressure of gases under the fuel cladding.

The numerical values of the above criteria should be determined and justified by the designers of the fuel element projects on the basis of experiments and (or) calculations and presented in the SAR of the nuclear power plant unit.

United States

The NRC does not have specific guidance for SFR fuel designs and therefore cannot respond to this question.

5.2.5. Does the fuel qualification process in your country require testing of a fuel element in an irradiation facility or test reactor before use in the SFR? If so, please describe those testing requirements.

Canada

Fuel qualification process in Canada requires irradiations of fuel in a test facility prior to loading into a reactor. The irradiation requirements are spelled out in the context of core design, including the fuel elements, reactivity control mechanisms, reflectors, fuel channel and structural parts. Specifically, the anticipated upper limit of possible deformation or other changes due to irradiation conditions shall be evaluated. These evaluations shall be supported by data from experiments, and from experience with irradiation. The design shall provide protection against those deformations, or any other changes to reactor structures that have the potential to adversely affect the behaviour of the core or associated systems.

France

Qualification process of the ASTRID subassemblies would comprise roughly three steps:

1) qualification of fabrication process;
2) semi-integral irradiation testing (pin scale);
3) integral testing of a fuel subassembly in representative conditions:
    a) mock-up testing for hydraulic characteristics (scale one);
    b) irradiation testing in normal operational conditions (core performances);
    c) testing in accidental conditions.

Finally, when a new or optimised fuel is loaded in the reactor a specific monitoring programme has to be set up by the applicant. Target burn-up would be reached step by step with intermediate examinations of test pins.

Germany

The introduction of new fuel requires three steps: first out-of-pile tests, second in-pile tests and third precursor fuel elements to be introduces in small number in a core.

Italy

No, because no qualification process is available in Italy for SFR fuels. But, if available, it should require testing.

Korea

In-pile test data under irradiation environment are required for rod and assembly

Russia

According to Russian requirements, the process of fuel qualification includes irradiation of fuel rod samples in experimental reactors and/or irradiation of experimental assemblies with a new type of fuel in operating reactors. For these purposes, the BOR-60 research SFR reactor and the BN-600 prototype SFR reactor are used. The main requirements of these tests are the achievement of design or close to them fuel burn-up and damaging dose on fuel rod claddings, the proximity of the irradiation conditions of the experimental power level and operating temperature to the operating conditions in the designed reactor.

United States

The NRC allows for testing of potential new fuel designs via the use of Lead Test Assemblies (LTAs).

5.3. Fuel assembly design and qualification

5.3.1. What analyses and testing requirements do you have for fuel assemblies?

Canada

The vendor analyses and testing are implicit in the generic regulatory design requirements for fuel assemblies.

Fuel assemblies and the associated components shall be designed to withstand the anticipated irradiation and environmental conditions in the reactor core, and all processes of deterioration that can occur in operational states. The fuel shall remain suitable for continued use after AOOs. At the design stage, consideration shall be given to long-term storage of irradiated fuel assemblies after discharge from the reactor.

Fuel design limits shall be established to include, as a minimum, limits on fuel power or temperature, limits on fuel burn-up, and limits on the leakage of fission products in the reactor cooling system. The design limits shall reflect the importance of preserving the fuel matrix and cladding, as these are first and second barriers to fission product release, respectively.

The design shall account for all known degradation mechanisms, with allowance being made for uncertainties in data, calculations and fuel fabrication.

Fuel assemblies shall be designed to permit adequate inspection of their structures and components prior to and following irradiation.

In DBAs, the fuel assembly and its component parts shall remain in position with no distortion that would prevent effective post-accident core cooling or interfere with the actions of reactivity control devices or mechanisms. The design shall specify the acceptance criteria necessary to meet these requirements in DBAs.

The requirements for reactor and fuel assembly design shall apply in the event of changes in fuel management strategy, or in operating conditions, over the lifetime of the plant.

France

The applicant issues a test programme before loading the assemblies in the core. This test programme shall be reviewed by the IRSN. The objective of the tests is to demonstrate the conformity of the assembly to the technical specifications established by the utility from the qualification process. In particular there are:

- visual examination (including endoscopic examination);
- dimensional check (diameter, bowing, etc.);
- establishment of the pressure losses characteristic.

A fuel monitoring programme is also developed. The objectives are to verify the correct behaviour of the fuel and assembly under irradiation and to gain feedback.

As an example, one can consider the custom programme developed for Superphénix assemblies, which comprised:

- geometrical controls (control of dimensional tolerances);
- preliminary irradiations in Rapsodie and Phénix (validation of the performance of the materials for structures and cladding);
- hydraulic tests (development of flow control device, control of induced vibrations, evaluation of lifting forces, pressure losses characteristic at high and low coolant flow, etc.);
- mechanical tests (bending stiffness, friction coefficient at the contact pads, insertion and extraction forces, test of the play between assemblies);
- tests for the qualification of the HARMONIE code (mechanical interactions in core between assemblies);
- test of thermal transients and thermal shocks;
- long-term test in sodium loop between 550°C and 580°C.

However, test programme is not yet available for ASTRID.

Germany

Mechanical stability against flow forces needs to be proven.

Italy

At present, nothing.

Korea

Normally required tests are the hydraulic ones like pressure drop test, control rod drop test, vibration test, etc.

Russia

According to NP-080-07, FA design should be such that:

- to withstand loads from thermal, mechanical and radiation effects in all design modes;
- the change in fuel elements and structural elements of fuel assemblies during operation should not lead to a violation of the conditions for their fixation in the spacing sieves;

- deformation of fuel rods and other fuel assemblies that is possible during normal operation and in case of normal operation violations, including design based accidents, does not cause overlap of the fuel rod cross-section, resulting in damage to fuel elements in excess of the corresponding limits, and does not interfere with normal operation of the control rods.

In accordance with these requirements, strength calculations of fuel assemblies are performed, including calculation:

- on static strength;
- on cyclic strength;
- on a long-term cyclic strength;
- on sustainability;
- resistance to brittle fracture;
- for a long static strength;
- on vibration resistance;
- external dynamic effects;
- on progressive form change;
- on corrosion-static strength.

The experimental justification of the strength and performance of fuel assemblies is carried out on experimental test stands under conditions that are as close as possible to the operating conditions of fuel assemblies in reactors.

Hydraulic testing

1) Tests of full-scale models of fuel assemblies and their components (input and output heads, support plates, anti-vibration) throughout the range of reactor operating parameters, including starting, nominal and emergency modes, to determine the dependence of pressure drops and the coefficients of hydraulic resistance from the flow rate of the coolant (Reynolds number).

2) Tests of full-scale FA models to confirm the absence of unacceptable amplitudes of hydrodynamically excited vibrations in the entire range of operating parameters of the reactor or to determine the rates at which such vibrations may occur.

3) Resource hydraulic tests of full-scale fuel assembly models for fretting wear of fuel rod claddings and vibration resistance of gratings.

Thermal testing

Experiments on fuel assembly model to determine the heat transfer coefficients for verification and improvement of methods for calculating the temperature of fuel rod claddings in such modes.

United States

Again, the NRC does not have specific required testing, however to meet more general fuel performance requirements, applicants for standard light water reactor (LWR) fuel design approvals typically include a combination of references to previous applicable tests and additional testing to cover any unique aspects of the new fuel assembly. The failure mechanisms listed in NUREG-0800 Section 4.2 (USNRC, 2007) typically have a test programme associated with it (either generic or fuel assembly design specific).

It should again be noted that the failure mechanisms listed in NUREG-0800 Section 4.2 (USNRC, 2007) are associated with more traditional large LWR reactor designs and that the failure mechanisms for other reactor designs might vary. It is likely that light water

Small Modular Reactor (SMR) fuel assembly design failure mechanisms might be largely similar, but the non-LWR fuel designs (including those for SFRs) can be drastically different and would require different fuel qualification testing to meet the general design requirements.

5.3.2. What physical mechanisms of major concern in fuel assemblies (i.e. flow induced vibrations, rod to grid fretting, bowing and distortion)?

Canada

All relevant phenomena must be identified as per Canadian regulations. The three suggested above are explicitly included in high-level requirements to be considered.

France

From the regulator point of view, physical mechanisms of major concern are those which challenge the confinement function ensured by the first barrier and the cooling function. For SFR assemblies only few phenomena could have an indirect impact on confinement function. They have been characterised by mean of irradiation test programmes and during the operation of the experimental reactors. The identified mechanisms are the following:

- axial expansion caused by irradiation;
- swelling of the hexagonal shroud.

Axial expansion is non-homogeneous and can lead to the disconnection of the outer contact pads, which are stamped in the lateral faces of the hexagonal shroud and maintain the compactness of the core (the contact pads of neighbouring assemblies are no more facing each other, creating a gap between the assemblies). The created gaps are potentially detrimental to the cladding integrity in case of earthquake because of the shocks between assemblies.

Swelling of the hexagonal shroud can lead to coolant flow reduction.

All these phenomena together with the structure embrittlement have been mastered by the development of suitable structural materials with low irradiation induced swelling and customised handling procedures.

Germany

Bowing is of major concern because it affects the power distribution in fuel pins.

Italy

The physical mechanisms are much dependent on the specific design, for instance, presence or absence of a FA subassembly box, design of spacer grids, etc., but general ones are listed under points 2.3 and 2.4 above.

Korea

The bowing and distortion will become a major concern because we believe it affects the reactivity feedback, which is not well quantified yet.

Russia

Main physical mechanisms are swelling of structural materials, bowing and distortion caused by non-uniform irradiation and flow induced vibrations.

United States

Any mechanism that would lead to a fuel rod failure is of concern. The failure mechanisms are highly design-dependent so a failure mechanism that is of great concern for one vendor's design might not be a concern for another. A common concern for pressurised water reactor (PWR) fuel designs is debris-induced fretting wear, but advances in debris filters has drastically reduced this failure mechanism. Other drastically different fuel designs (e.g. Triso fuel for High Temperature Gas-Cooled Reactor designs) might preclude the possibility of debris-induced fretting wear.

5.4. Fuel operational experience

5.4.1. If you have operated SFRs, have you experienced fuel damage and if so, can you provide a description of the damage that occurred? As a result of the experience, were existing regulations found to be adequate?

Canada

There is no SFR operational experience in Canada.

France

The operator of Phénix experienced 42 pin failures during the whole life of the reactor. Among these, 27 were limited to flaws with no sodium ingress into the pin and 15 failures have finally activated the delay neutron detection system (emission of delayed neutrons in the sodium).

These failures concerned various types of pins (standard and experimental) and they led to progressive cladding material and operational procedures improvement.

Germany

Not applicable.

Italy

No, SFRs were never operated in Italy.

Korea

No operational experience, but we have a keen interest in the AURN phenomenon and also the experience with metallic fuel in the Fast Flux Test Facility (FFTF) and Experimental Breeder Reactor II (EBR-II).

Russia

Since 1997 to the present, the number of damaged fuel rods at the BN-600 reactor has not exceeds the operational limits set by the regulator (0.05% fuel rods with gas leakage and 0.005% fuel rods with direct fuel contact with the coolant). No damaged fuel rods in experimental fuel assemblies with nitride fuel irradiated on BN-600 have been registered. Testing is in process.

United States

The United States does not currently have any SFRs in operation; however, Argonne National Laboratory and Idaho National Laboratory did design and operate research SFRs for a few decades. The specific reactors involved in this programme were EBR-I and EBR-

II. A third generation reactor design of this programme was in development, but funding was cancelled before completion.

EBR-I did experience a partial meltdown, but this was driven by unexpected thermal expansion that occurred during coolant flow tests. The design flaw that led to this partial meltdown was corrected before the EBR-II design.

The EBR programme was not licensed through the NRC so the regulations were not addressed in the process.

5.5. Fuel qualification reporting requirements

5.5.1. What analysis reports on fuel safety and fuel qualification are required in your country?

Canada

With respect to "qualification" we allude to the requirements in REGDOC 2.5.2 (CNSC, 2014a). The outputs of the fuel qualification process (i.e. "*a programme of experimental testing and analysis, to ensure that fuel assembly requirements are met"*) are normally documented in the fuel design manual.

France

See answer to question 2.1.

Germany

Reports are expected for fabrication process, test results, operational behaviour.

Italy

At present, none.

Korea

Safety analysis report or topical report.

Russia

Information on justification of fuel safety and its qualifications is included in the SAR of the nuclear power plant unit. The relevant requirements are contained in regulatory documents NP-080-07 (Rostechnadzor, 2007a) and NP-018-05 "Requirements for the contents of the safety analysis report of nuclear power plants with fast breeder reactors" (Rostechnadzor, 2005).

United States

There are a few methods by which a licensee may introduce a new fuel design into their reload. The most common way is for a fuel vendor to obtain NRC approval for a standalone topical report covering the new fuel design. This topical report is then referenced by the licensee in a license amendment request (LAR), or in the application for approval or licensing of a new reactor design, and the NRC's approval then forms part of the licensing basis for the plant.

The amount of analysis necessary for the topical report depends on the amount of design change between the new fuel design and the older previously approved fuel designs. As a whole, a new fuel design analysis must demonstrate compliance with GDCs 10, 27, and 35, as well as 10 CFR 50.46 (USNRC, 2017b). If the fuel design change is related to a new intermediate flow mixing vane grid, then the topical will most likely reference previous topical reports that cover non-thermal hydraulic aspects of the grid design (e.g. hydrogen pickup, corrosion, rod internal pressure gap reopening).

For a new design with more fundamental changes, the fuel design topical report will need to address all of the failure mechanisms and if necessary, an associated testing/qualification programme will be necessary to support the analyses. For example, if a new cladding material is developed, then a qualification programme would be necessary to reach a regulatory finding for mechanisms such as hydrogen pickup. This would be necessary because the testing associated with previous cladding materials would not be applicable.

For a fuel design which does not resemble past experience, the topical report would also need to spend considerable amount of time analysing potential new failure mechanisms that were not applicable to previously approved fuel designs. The qualification programme for such a radical change would probably be quite extensive. In the end though, the intent of the approval process is to provide reasonable assurance that the proposed fuel design meets all applicable regulatory requirements.

5.5.2. Do you have reporting requirements on quality assurance for the fuel manufacturing and fuel assembly production?

Canada

There is no requirement to report or provide the actual QA documentation (i.e. the fabrication history dockets). There is requirement to report any changes in fuel design, manufacturing process and manufacturing QA requirements.

France

For Phénix, the operator was asked to issue a quality handbook that contained the description of the common design rules and quality insurance tests applicable to all types of assemblies loaded in the core. This requirement was specific to the Phénix core, because of the various type of assemblies loaded at the same time to develop the SFR fuel concept (experimental assemblies, devices for sample irradiation, etc.). By now, there is no equivalent document available for the future assemblies of ASTRID (comparable to the RCC-C (AFCEN, 2017) rules applicable to LWR assemblies).

Germany

Yes.

Italy

At present, no.

Korea

Yes. Periodic evaluation of QA programmes focusing on the 18 criteria is done as is required by the Atomic Law.

Russia

Within the State corporation Rosatom there is a quality management system for all stages of design, manufacturing, operation and reprocessing of fuel assemblies.

United States

The quality assurance programme associated with fuel manufacturing facilities typically includes a reporting requirement for quality issues but otherwise only requires record keeping, which is available via audits. Additionally, some fuel design topical reports contain conditions/limitations for additional post-irradiation fuel testing, which includes reporting requirements.

References

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