Safety aspects and licensing requirements for new fuel qualification tests and use in research reactors

H. Abou Yehia, G. Bars and P. Tran Daï

Safety Evaluation Department
Institut de Radioprotection et de Sûreté Nucléaire (IRSN)
B.P. 17 - 92262 Fontenay-aux-Roses cedex - France

Abstract: After giving a brief reminder of the procedure applied in France for the licensing of the qualification tests and use of a new fuel type or design in a research reactor, the main safety aspects associated with these issues will be presented. As an example, we outline the safety assessment relating to the IRIS irradiation device used in Osiris reactor mainly for the qualification of silicied and UMo fuel plates.

1. INTRODUCTION

The type and the enrichment of fuel used in research reactors may be modified. Such a modification was carried out two times for Osiris and Isis reactors.

Prior to the use of a new fuel type (i.e. silicide fuel, oxide, metal alloy fuel, ...) or the use of a new fuel design, either in a new reactor or for the conversion of an existing reactor, the behavior of the fuel has to be verified by means of qualification tests including irradiation tests covering the operating conditions.

The licensing process and safety requirements associated with the new fuel qualification tests and use in the reactor core are presented below.

2. LICENSING PROCESS

For new fuel irradiation tests and use in research reactors, the reactor operators are generally asked by the safety authority (Direction Générale de la Sûreté Nucléaire et de la Radioprotection - DGSNR) to submit detailed safety files for review and approval. The technical prescriptions sent by the safety authority to the operators of research reactors describe the licensing procedure applicable to the modifications of the installations and to the experiments. According to this procedure, the reactor operator has to submit for the approval of the DGSNR a licence application along with the corresponding documents describing the fuel characteristics, the qualification program, the commissioning program in case of core conversion or a new reactor, and the safety analysis. These documents are then examined by the IRSN (Institut de Radioprotection et de Sûreté Nucléaire), for the benefit of the safety authority. The assessment work involves extensive discussions with the applicant, particularly as regards the safety arrangements. It terminates with an IRSN document equivalent to an expert opinion, followed by the DGSNR decision.

This procedure was applied when the Osiris and Isis cores were being converted from high enriched U-Al to low enriched Caramel fuel (in 1980 and 1979) and from this fuel to silicide fuel (in 1995 - 1996 and 1998).

For fuel design and manufacturing parameters related to safety, general requirements and guidelines were specified by the safety autority in a document issued in 1978 (letter SIN n° 2323/78, November 13th, 1978). These requirements deal with thermal, mechanical, neutronic and thermal-hydraulic behavior of the fuel assembly and associated strutures. They are primarily devoted toward ensuring that fuel design limits and safety criteria are not exceeded during normal operation and transient conditions.

3. SAFETY ASPECTS

The main safety issues relating to the irradiation tests and use of new fuel in research reactors should be dealt with in detailed safety analysis to be performed by the reactor operators. The safety documents submitted by the applicant, for approval by the safety authority, should contain mainly:

- the characteristics of the new fuel and specifications for its manufacture, the quality assurance system and details of fuel qualification and irradiation conditions,
- neutronic and thermal-hydraulic studies performed in order to determine the maximum power allowable for the experimental fuel,
- program of surveillance and tests planned before the first qualification irradiation of a new fuel,
- on-site and post-irradiation measurements,
- an analysis of the mutual interaction between the reactor core and the irradiation device containing the experimental fuel,
- studies of the radiological risks associated with the use of the irradiation device,
- in the case of the conversion of an existing reactor:
    - detailed analysis of the effect of the proposed modifications including those related to reactor systems, and to neutronic and thermal-hydraulic parameters of the core as well as the studies of the radiological consequences of the accidents identified in the safety analysis report,
    - the test program, including pre-operational tests and initial criticality, low-power and power build-up tests which are needed to check the neutronic and thermal-hydraulic calculations and to assure that adequate safety margins are maintained,

- the safety studies and the test program demonstrating that the use of the new fuel is in compliance with the specified neutronic and thermal-hydraulic safety criteria. They should also show that the radiological consequences of the design basis accidents do not call into question the conclusions of the analyses presented in the safety report.

The requirements issued by the safety authority define conditions concerning:

- the fuel damage (e.g, stress, strain, swelling, ...),
- fuel failure mechanisms (e.g, overheating, blistering, ...),
- fuel coolability conditions (e.g, limits on structural deformations resulting from excessive fuel swelling and/or fuel deformation).

The introduction of lead assemblies in the reactor core was proposed by reactor operators in some cases and approved by the safety authoritiy on a case-by-case basis. The irradiated lead assemblies are the subject of an examination program to check their good behavior and to validate the technical choices concerning the new fuel.

Finally, to check the proper application of the design sudies, the safety criteria and the quality assurance rules, the DGSNR performs inpections in the facility and fuel manufactures before giving the authorization.

Nuclear design of the fuel assembly

The nuclear design of the fuel assembly should ensure that it will be able to meet the core design specified performances and fuel management objectives. The neutronic compatibility of the lead assemblies with the other assemblies of the core must be demonstrated before their loading.

The nuclear design, via the reactivity effect, may influence the analysis of the accidents and transients concerning the reactor core, and modify the shutdown margin as well as the requirements relating to the shutdown system. It may also have an influence on the decay heat and the radioactive inventory in the core, and on fuel storage conditions.

The mechanical properties of the reactor structures and irradiation conditions of experimental devices could be modified due to possible changes of the neutron and gamma spectra relating to the use of the new fuel.

Thermal-mechanical design of the fuel assembly

The purpose of the fuel assembly thermal-mechanical design is to ensure the integrity of this assembly throughout the projected lifetime of the fuel. This is mainly ensured by designing the fuel assembly to satisfy a variety of conservative design criteria during normal operation and accident conditions. The design criteria include criteria relating to fuel cladding stress, strain and fatigue, cladding temperatures, and fuel blistering.

In addition, it should be checked that no abnormal vibrations are induced by the primary coolant circulation.

Thermal-Hydraulic design of the fuel assembly

The overall objective of the thermal-hydraulic design of the fuel assembly is to ensure that the heat generated in the core can be adequately removed by the reactor coolant systems in normal and anticipated transient conditions and that the temperatures acceptable for the fuel and the cladding are not exceeded. Thermal-hydraulic characteristics of new fuel assemblies should be compatible with those of the other fuel assemblies of the core. It is important to apply to new fuel assemblies the same requirements as those relating to the core fuel.

The safety analysis should demonstrate that the thermal-hydraulic safety criteria relating to the core are met with adequate margins. The main safety criteria are the followings:

- no nucleate boiling under nominal power and flow conditions, with the worst-case uncertainties cumulated at the hot spot,
- flow redistribution or critical heat flux should not be reached in operation at the maximum power and minimum flow safety thresholds, with the worst-case uncertainties cumulated at the hot spot; this criterion must also be satisfied in the anticipated transient conditions.

Radiological risks

Possible radiological risks in connection with the irradiation tests for new fuel qualification are:

- risk of irradiation during the handling of the irradiation box and the experimental fuel plates,
- risk of irradiation and/or of contamination if there is a loss of integrity of the cladding of a fuel plate or melting of the fuel.

The arrangements proposed by the operator to limit these risks should be assessed.

4. FUEL QUALIFICATION PROCESS

The qualification process for a new plate-type fuel were classically conducted first on miniplates in order to obtain a preliminary information on its behavior under irradiation and to minimize the reactor contamination in case of a fuel failure. This first step was followed by full-sized plate irradiations and in some cases by the introduction of lead assemblies in the core. These steps were followed for the conversion of the Osiris reactor from U-Al fuel to

UO_2 fuel and then from UO_2 fuel to silicied fuel. The qualification process allows finally the determination of the fuel utilisation limits, particularly in terms of maximum content of uranium and fuel burn-up.

The nuclear power generated in the new fuel and coolant conditions in the irradiation device may appreciably be different from those relating to the fuel assemblies of the reactor core. In this context, the use, when it is possible, of a fuel element instrumented with thermocouples allows experimental validation of the thermal-hydraulic calculations (this practice was applied in France for some pool-type research reactors). In addition, the use of SPND (Self Powered Neutron Detectors) in the irradiation device allows an important reduction of the uncertainties related to the calculations. The final objective is to demonstrate that the neutronic and thermal-hydraulic safety criteria corresponding to the new fuel are fulfilled with adequate safety margins.

Due to the uncertainties concerning the behavior of the new fuel, examinations have to be performed after each irradiation cycle to ensure that the width of the cooling channels, which depends on the swelling phenomena under irradiation, remains within acceptable limits. These examinations, which are performed according to a specified surveillance program, also include visual inspection. Fuel plate thickness measurements make it possible to verify the correlation between the fuel plate swelling and the burn-up.

Hydraulic tests should be carried out in order to check the characteristics of the irradiation device containing the experimental fuel and to ensure that there is no abnormal vibrations which could damage these structures during their irradiation in the reactor.

5. SAFETY ASSESSMENTS OF IRIS IRRADIATION TESTS

5.1. Presentation of the IRIS device

The IRIS device is intended to qualify various types of fuel plates for research reactors. It includes an in pile part consisting of a fuel plate irradiation box made of aluminium alloy and a part consisting of a plate thickness measurement bench and associated control and acquisition rack.

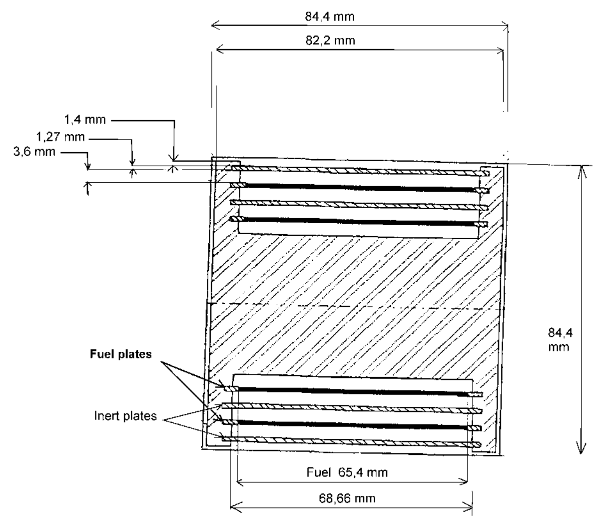
A first device was used in the Siloe reactor (35 MW) to qualify various types of silicide fuel and fuel based on uranium and aluminium alloy. The maximum surface power density authorized for the experimental fuel plates in Siloe was initially 150 W/cm^2, and has been increased to 175 W/cm^2. After the definitive shutdown of the Siloe reactor at the end of 1997, a new device was built for the Osiris reactor (70 MW). This device enables qualification tests to be carried out on the fuel at a higher power level. It also allowed the realisation of further qualification tests to those carried out at Siloe for the new German FRM-II reactor silicide fuel, and it is currently used for the qualification of UMo fuel plates planned for the future RJH reactor.

The conditions of use of the IRIS device were defined with allowance for the qualification programs planned for the following types of fuel:

- homogeneous silicide fuel with a density of 3 gU_{tot}/cm^3 and enriched to 93% in ^{235}U,
- mixed silicide fuel (with a zone at 1.5 gU_{tot}/cm^3 and another zone at 3 gU_{tot}/cm^3) based on uranium enriched to 93% in ^{235}U for the FRM-II reactor,
- UMo fuel with a low enriched uranium (19.725% ^{235}U) and having a variable Mo content,
- nitride type fuel.

The length of the experimental plates is 641.9 mm, the width and the thickness are respectively 73.3 mm and 1.27 mm. The maximum weight of U_{tot} per plate is 500 g and that of ^{235}U is 100 g. The maximum surface power density planned by the operator for the experimental fuel plates is 277 W/cm^2.

The irradiation box comprises a massive unit prolonged by two grooved side plates. Fuel plates to be irradiated and inert plates are placed in these grooves, alternating (see the figure below).



IRIS irradiation box

The width of the cooling channel between the plates is 3.6 mm. The device occupies, on the perimeter of the core, a location equivalent to that of a standard fuel element. The fuel plates to be tested are removable and the inert plates are crimped in the device. The mid-height plane of the plates corresponds to the mid-height plane of the core.

The IRIS device is cooled by the water of the reactor core cooling system. Because of the ascending direction of the flow in the Osiris reactor, special attention was paid to the locking of the irradiation device and of the experimental fuel plates, to avoid the risk of their taking off because of the hydrodynamic thrust.

There is no alarm and no automatic shutdown of the reactor directly associated with the IRIS irradiation device, which is not instrumented. In the course of the irradiations, the experimental fuel plates placed in the irradiation box receive the same surveillance as the fuel elements of the reactor core, particularly for cladding failure detection. Any failure of the cladding of an experimental fuel plate during the irradiation would be detected by the core fuel integrity surveillance system, based on the detection of delayed neutrons, and would lead to an automatic reactor shutdown if the maximum counting threshold were exceeded.

After each irradiation cycle, dimensional measurements (thickness, cooling width, blister, ...) and visual inspection are performed on the tested fuel plates according to the defined surveillance program in order to ensure the follow-up of their swelling versus the irradiation.

5.2. Safety documents submitted by the reactor operator

The safety documents sent to the DGSNR by the operator of the Osiris reactor presented, in particular:

- thermal-hydraulic studies intended to determine the maximum power allowable for the experimental fuel plates,
- the mechanical design of the IRIS device, in particular the arrangements made to avoid the fuel plates taking off because of the hydrodynamic thrust,
- program of surveillance and tests planned before the first qualification irradiation of fuel,
- studies of the radiological risks associated with the use of the IRIS device.

The objective of the thermal-hydraulic studies is to determine the maximum power allowable for the experimental fuel in normal and transient conditions. In particular, it was required by the safety authority that the experimental fuel plates irradiated in the IRIS device comply with the thermohydraulic safety criteria applied to the core which are presented in paragraph 3.

The criterion relating to flow redistribution and critical heat flux must be satisfied in the following situations:

- loss of flow due to the failure of the primary pumps with blockage of one of the pumps and with allowance for the inertia of both other pumps,
- guillotine break of the primary circuit downstream of the primary pumps and upstream of the heat exchangers.

It is recalled that these situations lead to an automatic shutdown of the reactor and to a changeover to the natural convection cooling configuration.

Check of satisfaction of the thermal-hydraulic safety criteria

The thermal-hydraulic calculations were done using the FLICA and SIRENE codes developed by the CEA, which were already used in 1995 when the Osiris reactor was converted to the silicide fuel.

The results of these calculations, performed with allowance for the uncertainties and operating margins, have shown that:

- the maximum heat flux that must not be exceeded to avoid the onset of nucleate boiling is 280 W/cm^2,
- the heat flux not to be exceeded in normal operation to avoid flow redistribution at the limits of the safety thresholds is 459 W/cm^2,
- the heat flux not to be exceeded in normal operation to avoid any risk of critical heat flux at the limits of the safety thresholds is 277 W/cm^2.

The operator has accordingly chosen 277 W/cm^2 as the peak surface power density value not to be exceeded in the mid-height of the hot channel of the experimental fuel plates.

5.3. Main results of the safety evaluation performed by the IRSN

Following the safety evaluation performed by the IRSN, the operator was asked to limit the surface power density at the level of the experimental fuel plates to the value authorized for the fuel elements of the reactor, namely 231 W/cm^2, instead of the 277 W/cm^2 proposed in the operator's documentation.

This limitation was motivated by the uncertainties associated with the calculation codes used, which did not correctly reflect the core fuel plate cladding temperature measurements made in 1997 using an instrumented fuel element. These measurements also showed a significant disagreement between the calculated and measured temperature evolutions during the shutdown transient of the pumps on their inertia. Furthermore, the measured heating of the water in the intrumented cooling channel was 37°C, whereas the calculated heating was 17°C. This difference was ascribed by the operator to an inadequate representation of the primary circuit by the SIRENE code, in particular as regards the operation of the natural convection valves.

In conclusion, the DGSNR authorized the Osiris reactor operator to perform the experimental irradiations in the IRIS device while limiting the surface power density to 231 W/cm^2, pending further information concerning the validation of the calculation codes used. To date, the operator has not yet submitted this additional information.

6. CONCLUSION

The French methodology for the licensing of the qualification tests and use of new fuel in research reactors, which is based on well defined criteria and intensive interaction with the applicant, was applied without any difficulty to the case of the IRIS irradiation device.

The safety documentation concerning irradiation devices for the qualification of new fuel in research reactors must include clear information on the examination program and on the validation of the calculation codes used, in particular as regards thermal-hydraulics. Fuel plates instrumented with thermocouples could be an efficient way to confirm the adequate cooling of the experimental fuel.