Instrumented fuel plate
for IRIS irradiation program in the OSIRIS reactor

Patricia BOULCOURT, Pablo SACRISTAN, Matthieu MARTIN, Sylvie NAURY,
Danielle GALLO-LEPAGE, Jean-Marc CHAUSSY, Stéphane LOUBIERE,
André CHABRE, Patrick LEMOINE

Commissariat à l'Energie Atomique (CEA) – Centre de Saclay –
91191 Gif-sur-Yvette Cedex - FRANCE

ABSTRACT

CEA has been engaged for many years in the qualification of experimental fuels for research reactors. These programs consist in irradiating full-sized fuel plates in the IRIS device located in the core of OSIRIS reactor. They integrate plate thickness measurements after each cycle of the reactor.

The maximum heat flux on the IRIS plates is, at the present time, limited to 231 W/cm^2, except particular cases. In order to increase this value and get authorization from the Nuclear Safety Authority to irradiate fuel plates in the IRIS device at higher heat flux (300 W/cm^2 in any experimental location of the core), a specific campaign named "IRIS instrumented plate" has been performed in 2004. The aim of this experiment was to check the thermal-hydraulic modelling of the device done with the FLICA III code.

A dedicated IRIS device has been designed for the experiment and manufactured by CERCA. It contains four U_3Si_2 plates and four crimped Al plates. One of the U_3Si_2 plate is instrumented with 5 thermocouples distributed along the plate height and one of the Al plate is instrumented with 3 thermocouples. These thermocouples are inserted into small grooves worked out in the cladding layer of the plate and are covered with a strip of aluminum and then, welded.

During these tests the measured temperatures were compared to those calculated by the thermal hydraulic models for different operating conditions of the reactor: during increase of the reactor power up to 63 MW and during the shutdown transients of the reactor primary pumps.

A good agreement was observed between the calculated and measured temperature values.

1. Introduction

Important efforts have been made by United States, France, Argentina and Russia to develop, qualify and licence UMo dispersion fuels. Within this context, the French program was initially mainly built to determine, experimentally, the effect of heat flux on the irradiation behaviour of full-sized plates []. Thus, in 1999, CEA performed the IRIS 1 experiment in OSIRIS at 140 W/cm^2 and in 2003, the IRIS 2 experiment at 240 W/cm^2.

Actually, the heat flux authorized by the French Safety Authority in the fuel plates of an IRIS device is limited to 231 W/cm^2. Just for the IRIS 2 experiment, it was allowed to reach 250 W/cm^2 during 60 days. As this last experiment led to an important swelling of the plates, the tests of remedies for UMo behaviour have to be done at least at the same heat flux. That's

why CEA asked the French Safety Authority to be allowed to increase power in the IRIS plates up to 300 W/cm^2. One of the conditions imposed by the French regulator to obtain this authorisation was that CEA demonstrates that the cooling of the plates is sufficient and that the thermal-hydraulic computer codes used for the IRIS safety studies are qualified for steady states and transient phases. Therefore, CEA undertook to make a suitable experiment with an instrumented fuel plate inserted in an IRIS device. CERCA manufactured this specific instrumented IRIS device which has been irradiated twice in OSIRIS, in April 2004.

This paper first gives a description of a standard IRIS device and its associated equipments. Then it focuses on the instrumented IRIS device, the preliminary calculations of the experiment and the procedure of the test which has been chosen to answer, as best as possible, to the French regulator request. Finally, it gives the results of the experiment and the comparison between calculated and measured temperatures in the instrumented fuel plate.

2. Description of an IRIS device

An IRIS device allows the simultaneous irradiation of four full-sized fuel plates. Its external dimensions are the same as a standard fuel element in OSIRIS and it can be placed in different locations of the core according to the power required in the fuel.

This device, made of AG3NET, has two parts. In the lower part, four fuel plates can be inserted in order to be irradiated. During intercycles of the reactor, these plates are removed from their device to be dealt with thickness measurements. Between fuel plates, there are also 4 aluminum plates crimped in their grooves. The upper part is a stopper which prevents plates from being ejected during irradiation. Let's remind that in OSIRIS, the flow is going upwards.

Dimensional characteristics of the device are the following:
- thickness of the hydraulic gaps : 3.6 mm,
- fuel plate dimensions : 641.9 x 73.3 x 1.27 mm,
- maximum dimensions of fuel zone : 609.5 x 65.4 x 0.7 mm.

Fig. 1: IRIS device

3. Description of the thickness measurement device

After each irradiation cycle, fuel plates are removed from the IRIS device and put in a measurement bench, one by one, in order to measure the thickness increase. This measurement device, under water, is made up of a support and two sensors which are located face to face on both sides of the plate. Results are given in micrometers with an uncertainty of 15.9 μm [].

Usually, measurements are made along five longitudinal traces and one transversal trace chosen once for all at the beginning of an irradiation program. A longitudinal trace gives 248 thickness measurements every 2.5 mm and a transversal trace gives 114 measurement points every 0.5 mm. If during a measurement campaign a swelling is suspected, it is possible to make additional transversal measurements anywhere on the plate.

An example of the variation of thickness plate obtained on a longitudinal trace after each irradiation cycle is shown below.
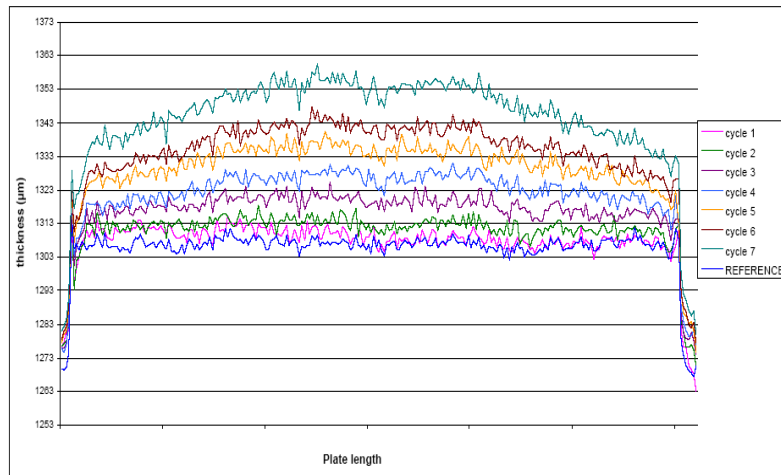
Fig. 2: Longitudinal measurements of the thickness of a plate after several irradiation cycles

4. Gamma spectrometry

IRIS programs usually include gamma spectrometry on one of the plates. This spectrometry has three main goals:
- to obtain spatial distributions of counting rate of the principal fission products,
- to quantify the average fission product activities in the maximum power area of the plate in order to compare the calculated activities with the measured ones,
- to evaluate the fission density reached in the plate.

More details on measurements by gamma spectrometry can be found in reference [].

5. Description of the instrumented IRIS device

The main characteristics of the instrumented IRIS device are the same as the device mentioned in § 2. It principally differs by the following elements:
- every fuel plate is crimped in the grooves,
- one fuel plate is instrumented with five thermocouples distributed along the plate height and one aluminum plate is instrumented with three thermocouples. These thermocouples are located on both sides of the same cooling channel.
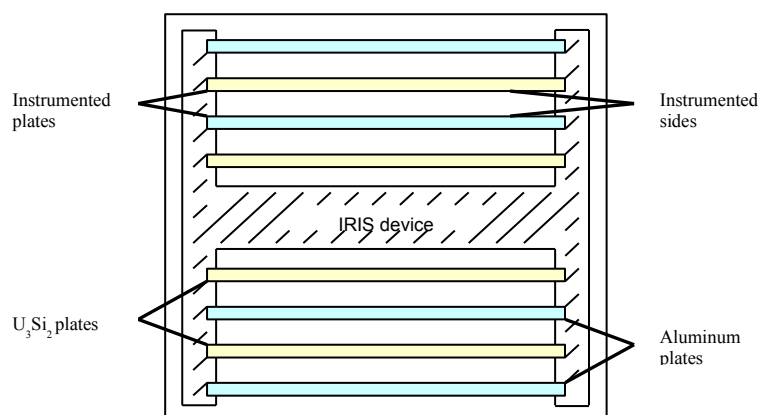
Fig. 3: Instrumented IRIS device

Thermocouples are K-type. The location of the hot weldings is presented in figure 4. The cables of the thermocouples have a cylindrical shape and are hammered to different diameters according to their route in the plate.
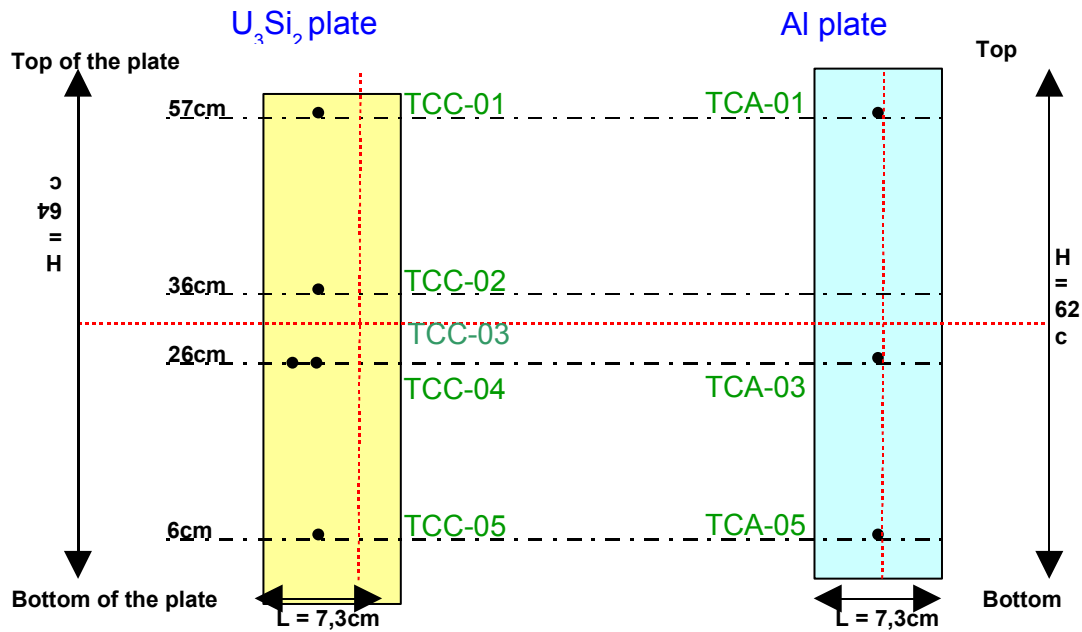
Fig. 4 : Location of the thermocouples in the plates

On the surface of the plates, thermocouples have a diameter of 0.2 mm. They are inserted into small grooves worked out in the cladding layer of the plate and are covered with a strip of aluminum, welded.

On the side of the plate, thermocouples have a diameter of 0.34 mm.

Above the IRIS device, the diameter of thermocouples is more important (1 mm). Then, thermocouples are linked to the data acquisition system.
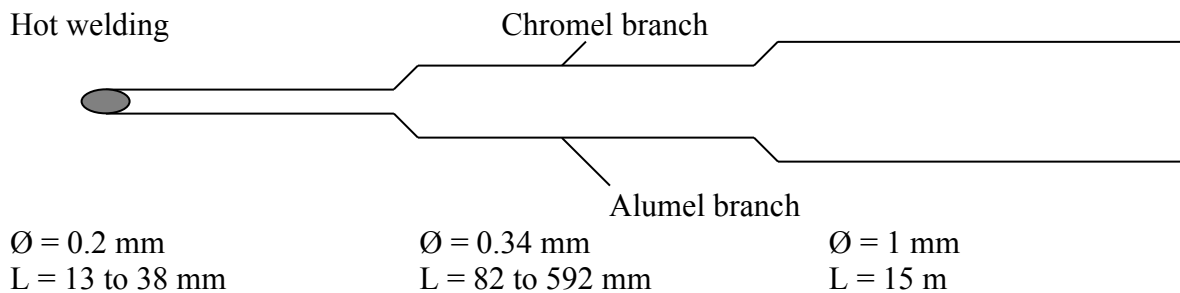

Fig. 5 : Various diameters of the thermocouples according to their location in the plate

6. Safety authority request

The French regulator requested that CEA demonstrates during steady states and transients (such as voluntary stop of the three primary pumps to simulate a power blackout) that the fuel plates are correctly cooled in the IRIS devices and that thermal hydraulic computer codes are qualified. Further to CEA's commitment to perform a suitable experiment with an instrumented plate located in an IRIS device, the safety authority specified that the experiment had to be done at a maximum reactor power defined as the minimum between:

-   the reactor power which corresponds to 231 W/cm^2 in the IRIS plates (maximum local value),

- the reactor power for which the temperature in the cladding at the hottest point of a standard element during the transient phase does not exceed the temperature of the cladding at the same point at the nominal power of the reactor (70 MW). This power had to be determined with conservative calculations.

The first criteria led to 68 MW and the second one to 63 MW. Therefore, the maximum power reached by the reactor during the steady states operating conditions was 63 MW.

Moreover, before realizing the transient phase by stopping voluntarily the 3 primary pumps, the French regulator asked CEA to check that during the steady states, the calculated temperatures in the cladding were close to the measured ones; otherwise the experiment could not be done. Consequently, CEA decided to check this good concordance between calculated and measured temperatures at least on one of the hottest thermocouple (TC 2 or TC3). To take into account that a thermocouple might be out of service during the experiment, CEA decided, as well, to check the good concordance on one more thermocouple among TC1, TC4 and TC 5.

7. Procedure of the experiment

In order to answer the safety authority request, CEA chose to irradiate the instrumented IRIS device in two locations of the core: one day in a central position of the OSIRIS reactor (location 52) and one day in a peripheral location of the core (location 17). For each location, the following stages have been performed. First, the reactor power has been increased by steps of 10 MW, up to 63 MW. At 40 and 63 MW, a thermal balance has been carried out and the good concordance between calculated and measured temperatures of the cladding, checked. Then, the three primary pumps have been voluntarily stopped. This led, by decrease of the pressure in the core, to the rod drop and 54 s later, to the opening of the natural convection valves. All along the experiment, thermal-hydraulic parameters have been recorded (flow, temperature, pressure) every second during the steady states and every 0.1 second during the transient.

8. Preliminary neutronic calculations

Preliminary neutronic calculations have been done on one hand to determine the maximum power of the reactor core before the transient phase, on the other hand to know the heat flux at the thermocouple locations in the instrumented plate in order to calculate, with the thermal hydraulic FLICA III computer code, the expected cladding temperatures.

2D Neutronic calculations leading to the heat flux in the plate are made with a transport code (APOLLO) and a diffusion code (DAIXY), followed by post-treatment. The transport calculations give neutronic constants in the fuel and in the structures (macroscopic cross sections, diffusion coefficient) and the core calculation (with four neutron energy groups), gives the power developed in the plate (kW) and the map of the fission sources by mesh. After a post treatment, the average heat flux can be obtained on every point of the width of the plate. The use of the form factor measured beforehand in ISIS reactor (neutronic mock-up) allows to determine the axial heat flux in every point of the plate. This form factor was equal to 1.23 in location 52 of the core and 1.22 in the location 17.

For instance, these calculations led to the following surface power at the location of the thermocouple number 2:

Reactor power	Location 52 in OSIRIS (near the center of the core)	Location 17 in OSIRIS (in the corner of the core)

| 40 MW | 121 W/cm^2 | 68 W/cm^2 |
| 63 MW | 191 W/cm^2 | 107 W/cm^2 |

Table 1 : Surface power at the location of the thermocouple TC2

9. Preliminary thermal-hydraulic calculations

Many thermal-hydraulic calculations have been carried out before the experiment to foresee the cladding temperatures because the real conditions of the reactor could not all be precisely anticipated. Consequently, calculations of the cladding temperatures were done for several positions of the control rods, several reactor powers, several inlet temperatures in the core and several variations of the pressure in the core.

10. Comparison between calculated and measured temperatures during the steady states

The criteria of good concordance of temperatures during steady states consisted in checking that the calculated cladding temperatures, including uncertainties, were higher or equal to the measured cladding temperatures, including uncertainties.

The calculated cladding temperature including uncertainties, has been defined as the cladding temperature taking into account a heat flux increased of 10 % and a cooling flow in the channel reduced of 8 %. Concerning the measurement uncertainties, they include the uncertainty of the thermocouples, the measuring channel and the analog/digital converter. A conservative value of ±1.2°C has been evaluated.

The results of the comparisons are given in graphs below.

Thermocouple n°, Reactor power (MW)	
$T_{measured}+\Delta T$	$T_{calculated}$ (P+10 %, Q-8%)
$T_{measured}$	$T_{calculated}$ (FLICA best.estimate.)

Results in the 52nd location of the core :

TC2, 40 MW		TC2, 63 MW		TC1, 40 MW		TC1, 63 MW	
63.1	64.2	83.6	86.8	53.5	56.3	69.6	75.2
61.9	59.7	82.4	80.1	52.3	52.7	68.4	69.9

Results in the 17th location of the core :

| TC2, 40 MW		TC2, 63 MW		TC1, 40 MW		TC1, 63 MW	
46.4	47.7	60.4	62.6	42	43.6	53.8	56.3
45.2	45.4	59.2	59	40.8	41.8	52.6	53.6

A very good concordance was observed between measured temperatures and "best estimate" calculated temperatures since the maximum difference was 2.3°C. Besides, the criteria defined by the safety authority to be aloud to carry on the experiment, was fulfilled.

11. Results during the transient phase

The measured kinetics of transient phase is the subject of figure 6 (thick curves). Just after the shut down of the three primary pumps, the drop of pressure in the reactor core led in less than a second to an emergency shutdown. After a quick decrease of temperatures in the plates, this event has been followed by a stabilization of temperatures on a low plateau. This is due to the drop of power and to the flywheel of the pumps which go on to maintain a forced convection. Fifty four seconds later, the opening of the natural convection valves, which are situated on

the inlet primary coolant pipe, causes a decrease of the cooling flow in the reactor core, the main flow getting towards the pool threw the valves instead of going towards the core. Consequently, temperatures increase in the plates during 66 seconds until the natural convection operating condition sets up. Then, a slow decrease of temperature in the plates can begin.
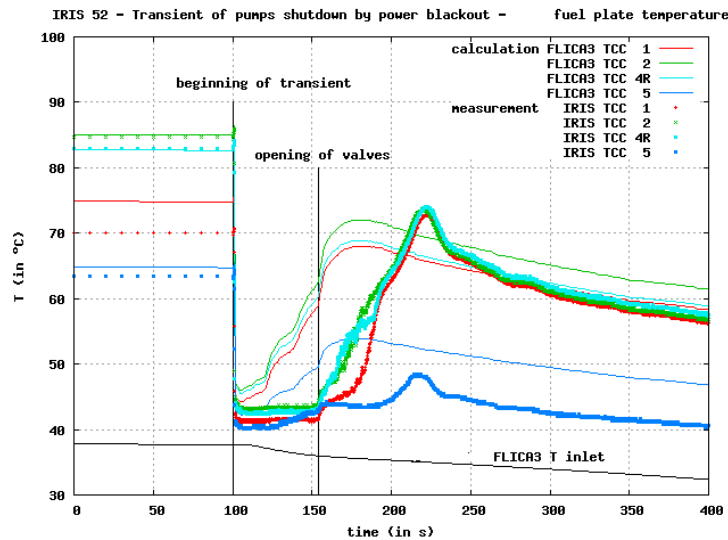
Fig 6: Measured (thick curves) and first calculated temperatures (thin curves) in the instrumented plate

12. Thermal-hydraulic computer codes used for calculations

Thermal-hydraulic calculations are performed thanks to two different computer codes : SIRENE-4 devoted to the system calculation (core, lower and upper plena, pipes, heat exchangers, pumps…) and FLICA-3M devoted to the core calculations (IRIS device). Both codes are linked, SIRENE-4 providing boundary conditions for FLICA-3M [].

To calculate the cladding temperatures in the instrumented plate, the IRIS device has been divided in 26 parts: 2 rows of 9 meshes for the instrumented cooling channel, one mesh per channel for the others cooling channel, and one mesh for the peripheral volume of the IRIS device.

13. First calculation results of the transient operating conditions

After the experiment, the real thermal-hydraulic parameters have been taken into account (inlet temperatures of 37°C, ΔP in the core of 1360 mbar) as well as the position of the control rods. A SIRENE-FLICA simulation of the instrumented IRIS experiment has been carried out. The results correspond to the thin curves in figure 6. One can observe that:
- after the primary pumps shut down and the drop of temperatures, the increase of temperatures occurs slightly too soon,
- temperature peaks obtained by calculations in the instrumented plate, though underestimated, are close to the measured ones (difference of 3°C).

The reason of the forward increase of temperature has been identified. After the shut down of the pumps, measured flows on the primary side of the exchangers cannot be considered anymore as representative of the flow in the core. Therefore, a more realistic decreasing flow law has been evaluated thanks to the measurement of the differential pressure in the core, until the opening of the natural convection valves and thanks to the measured temperatures in the plate for the rest of the transient. With this modified flow law, a new SIRENE-FLICA

calculation of the experiment has been performed, which led to satisfactory results with better kinetics and conservative temperatures (figure 7).
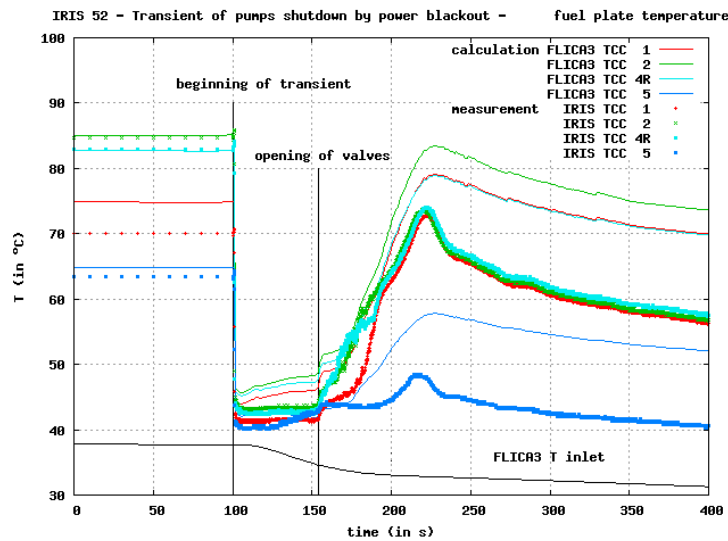
Fig 7: Measured (thick curves) and calculated temperatures (thin curves) in the instrumented plate after the flow adaptation

In order to validate again that this flow law was appropriate, it has been applied to the IRIS experiment performed in the location 17 of OSIRIS. Calculated temperatures fit very well to the measured temperatures, especially for the hottest thermocouples.

14. Conclusion

The aim of the instrumented IRIS experiment was to demonstrate the appropriate cooling of the fuel plates in an IRIS device during steady states and transients, and to complete the qualification of the thermal-hydraulic computer code used for the IRIS safety studies. The objective has been fulfilled and a specific authorization for an IRIS experiment at 314 W/cm^2 has been recently delivered by the Safety Authority.

More generally, this experiment validates also the neutronic calculations which are made in amount since their results are inlet data of the thermal-hydraulic computer code FLICA-3M. Finally, this experiment, added to the gamma spectrometry REX on previous IRIS experiments, shows that, whatever the location of an IRIS device in OSIRIS, there is a very good knowledge of the irradiation conditions (power in the plates, temperature and burn-up).

15. References

1. Patrick Lemoine, James L. Snelgrove, Nikolay Arkhangelsky, Luis Alvarez : "UMo dispersion fuel – Results and Status of qualification programs" – RRFM2004

2. P. Sacristan, P. Boulcourt, S. Naury, L. Marchand, H. Carcreff, J. Noirot, D. Gallo-Lepage : "MTR fuel plate qualification in OSIRIS reactor"