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EXPERIMENTS WITH CARAMEL FUEL IN OSIRIS REACTOR DESCRIBED ([illegible])

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[Text] After a presentation of the Caramel fuel to be used in the Osiris reactor, the authors describe the first experimental phases of the use of this fuel in the reactor. They then analyze the behavior of the fuel and its consequences for operational purposes.

Starting in the 1960s and until the present time, the many research reactors all over the world have used highly enriched fuel. The choice of this type of fuel, which offers some technical advantages, was made possible because the United States made the necessary fuel available. The technical advantages of this fuel are quite obvious: the very low amount of highly enriched uranium required can be placed in a low density matrix. In the present case, a uranium and aluminum alloy is used to produce fuel elements consisting of thin plates. These fuel elements are perfectly suited for producing the high specific powers associated with the high neutron flows needed for these reactors.

This dissemination of large amounts of highly enriched uranium led to a growing awareness of the associated dangers of proliferation, and during the 1970s, a movement developed, tending to restrict the supply of highly enriched uranium. Then there arose the problem of converting the highly enriched fuel used in research reactors into a slightly enriched fuel, with the upper limit for enrichment set at 20 percent U 235.

While research and development programs for the production and qualification of fuels that could be used for slightly enriched fuels were being set up in a number of countries, such as the United States, Germany, and France (CERCA [Company for the Study and Manufacture of Atomic Fuel]), in 1977 the CEA [Atomic Energy Commission] decided to conduct an experiment using slightly enriched fuel with the Osiris reactor at Saclay. The technology for such an experiment, developed at the CEA, was already available. This fuel, known by its generic name of Caramel, consists of uranium oxide strips, whose thickness can vary, encased in zircaloy and assembled to form plates. By using this fuel, the problem of increasing the density of the uranium matrix necessary for the reduction of enrichment was resolved: 9 g U/cm^3, compared with 1.6 g U/cm^3 in the U-Al alloy.

The Osiris reactor has been using this new fuel for nearly 2 years now (it began in January 1980). This experiment has provided a very complete and strict test; its duration has now been long enough to produce meaningful results in the following areas: operating conditions, consequences for testing, behavior and monitoring of the fuel.

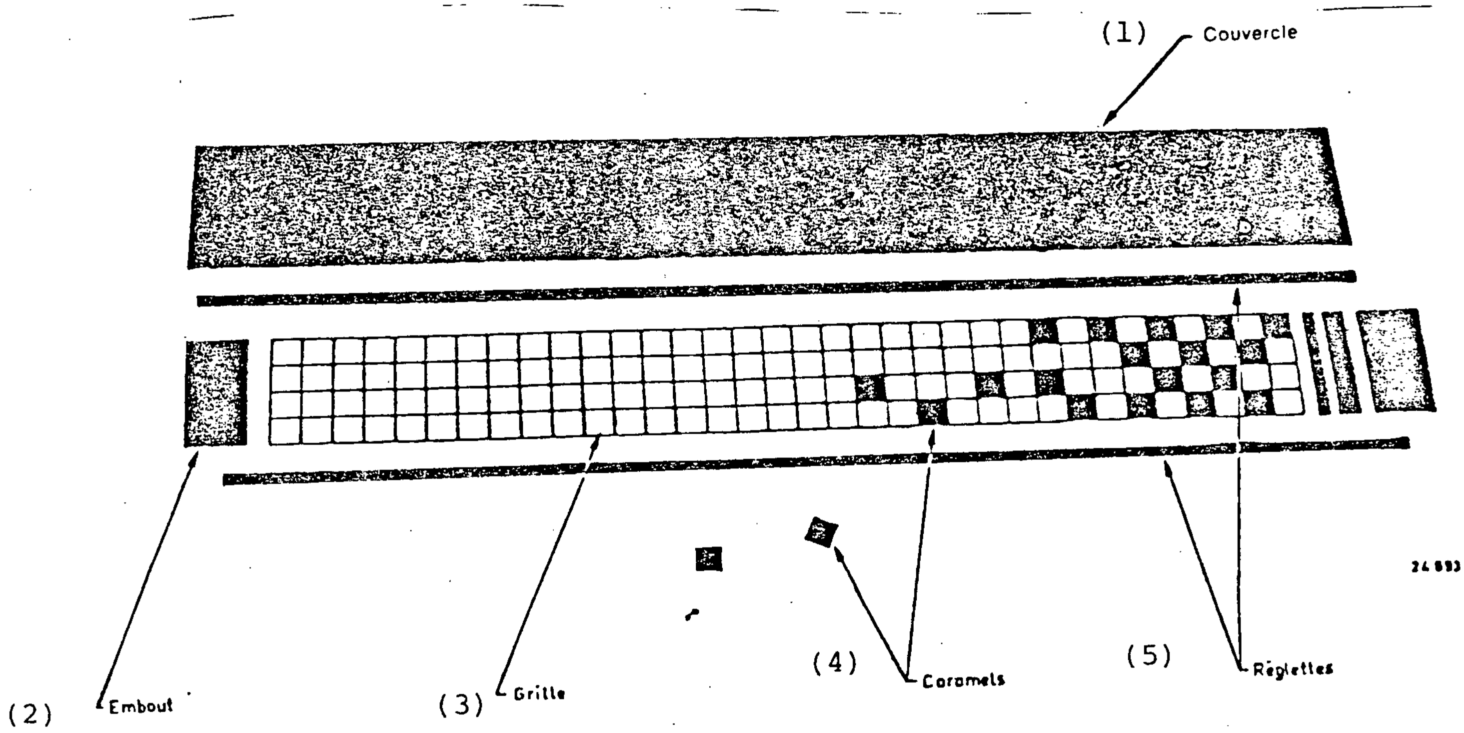


Figure 1: Elements of a Caramel plate.

Key for Figure 1:

1. Lid
2. Tip
3. Grid
4. Caramels
5. Side strips

I The Caramel Fuel

1.1. Presentation

One result of the various programs conducted in France for the design, manufacture, and development of nuclear fuels has been the CEA's development of a uranium oxide fuel (called the Caramel fuel) whose characteristics and performance are essentially quite different from those of the conventional rod or pencil type of fuel. The Caramel fuel is distinguished from the conventional type of nuclear fuel by the following features:

a. Its plane geometry;

b. The lack of any free volume;

c. Good contact between the oxide and the protective shield (absence of any clearance);

d. The splitting of the fuel into a large number of compartments, all tightly sealed in relation to each other.

The basic element of the Caramel fuel is in the shape of a plate, formed by two zircaloy sheets which act as lids. Between these sheets are the strips of UO_2, which are themselves arranged in the cavities of a grid. The plane geometry is an effective way to convert the disadvantage of the poor conductivity of uranium oxide into an advantage, by combining a high specific power with a low fuel temperature.

Because of their use in water-cooled reactors, the components of the Caramel fuel--the UO_2 and the zircaloy--are very well known in terms of their physical properties, their behavior under irradiation, their manufacture, etc.

The special features of the Caramel fuel do require particular operating conditions. Because of the lack of free volume (except for the open porosity of the fuel), the temperature at which fission gases begin to be released must never be exceeded. For this reason, it is essential to have excellent contact between the oxide and its covering from the very start; this contact should last for the entire life of the fuel element. The manufacturing methods described later can ensure the good quality of this contact.

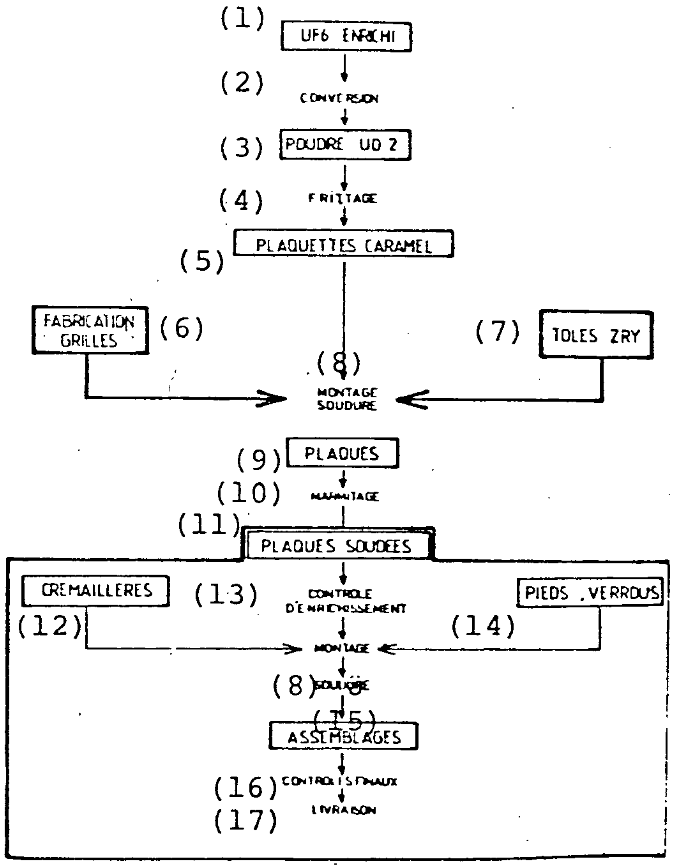


Figure 2: Manufacturing schematic for the Caramel fuel.

Key:

1. Enriched UF_6
2. Conversion

3. UO_2 powder
4. Pressing
5. Caramel strips
6. Manufacture of grids
7. Zircaloy sheets
8. Assembly/soldering
9. Plates
10. "Shelling" [form of soldering]
11. Soldered plates
12. Racks
13. Enrichment control
14. Feet, bolts
15. Assemblies
16. Final controls
17. Delivery

The splitting of the fuel into a large number of tight compartments is a major safety factor. Because of its dispersion, any possible loss of seal only puts a small amount of fissile material in contact with the coolant, which limits any possible contamination of the primary circuit.

The operating temperature, well below the temperature at which fission gases begin to be released, is another safety factor.

The first studies done at the CEA were oriented toward such applications as electricity or heat-generating reactors and naval propulsion reactors, and these used very thick Caramel (4 mm), because the specific powers required were limited. The thin Caramel, which was developed later, has been used in the Osiris research reactor, for which very high specific powers are needed (the average value is approximately 1,640 W/cm^3, and the maximum value is 4,300 W/cm^3).

Table 1 lists the main features of the reactors which are operational or planned (such as the Thermos reactor) with Caramel plate fuels.

1.2. Description of the Osiris Fuel

The basic module of the Osiris fuel element of the Caramel type is a plate 700 mm long, 80 mm wide, and 2.25 mm thick. Figure 1 lists its various components. The UO_2 fuel is pressed into a parallelopiped with a square section of 17.1 x 17.1 mm and 1.45 mm thick. These strips are arranged in the cavities of a grid and encased between two sheets of zircaloy. This unit, fitted with side and end pieces made of zircaloy, undergoes a series of soldering procedures in order to ensure the perfect seal of each UO_2 strip in relation to the outside and in relation to its nearby strips. These manufacturing procedures are described later.

Réacteur (1)	Puissance (2) (MW)	Epaisseur CARAMEL (mm) (3)	(4) Température gaine (°C)	Pression réfrigérant (5) (bars)	(6) Puissance spécifique moyenne (W/cm^3)	(7) Puissance spécifique maximale (W/cm^3)
Pile piscine (OSIRIS) (8)	70	1,45	140	3	1 640	4 300
Calogène (THERMOS) (9)	100	2,25	160	11	275	1 070
ISIS	0,7	1,45	95	1,5	16	43

Table 1: Principal Features of Operational or Planned Reactors Using Caramel Fuel

Key:

1. Reactor
2. Power (MW)
3. Caramel thickness (in mm)
4. Temperature of casing (°C)
5. Coolant pressure (bars)
6. Average specific power (W/cm^3)
7. Maximum specific power (W/cm^3)
8. Swimming pool reactor (Osiris)
9. Heat-generating reactor (Thermos)

Clusters are formed of 14 or 17 parallel plates, which are kept joined by slotted side pieces. They are fitted with a base or foot to provide a water supply, and a head for handling.

Table 2 lists the main features of an Osiris fuel element. These features are shown in comparison with those of a highly enriched uranium fuel element, whose structures are made of aluminum.

The essential differences consist of:

a. The metallurgical nature of the fuel: UO_2 instead of U-Al alloy;

b. The nature of the enclosure and structures: zircaloy instead of aluminum;

c. The thickness of the plates: 2.25 mm instead of 1.27 mm;

d. The total amount of uranium, which is considerably increased.

Type d'élément combustible (1)	(2) Nombre de plaques	Epaisseur d'une plaque (3) (mm)	Epaisseur du canal d'eau (4) (mm)	Charge en uranium (5) (kg)	Charge en U 235 (6) (kg)
Elément à uranium très enrichi U-Al (7)					
Elément standard (8)	24	1,27	2,1	0,420	0,390
Elément de commande (9)	20	1,27	2,1	0,282	0,262
Elément CARAMEL (10)					(7 %)
Elément standard	17	2,25	2,6	8,6	0,602
Elément de commande	14	2,25	2,8	5,3	0,371

Table 2: Comparison of Highly Enriched Uranium Fuel Element and Caramel Fuel Element for the Osiris Reactor

Key:

1. Type of fuel element
2. Number of plates
3. Thickness of plate (mm)
4. Thickness of water supply ducts (mm)
5. Amount of uranium (kg)
6. Amount of U 235 (kg)
7. Highly enriched uranium U-Al element
8. Standard element
9. Control element
10. Caramel element

The amount of fissile uranium (U 235) also had to be increased in order to compensate for absorptions caused by the U 238.

1.3. Manufacturing and Quality Control

1.3.1. Manufacture of Strips

The manufacturing of the Caramel fuel is done in facilities belonging to the CEA or to its subsidiaries. Some components, such as the zircaloy sheets, and cast or machined parts, are provided by industry. The manufacturing schematic is given in Figure 2.

The following manufacturing phases can be distinguished.

Production of oxide strips (Caramel). The oxide strips are made by pressing UO_2 powder, using moisture. The process used is called the DCN (Double Normal Cycle). The pressing is done under hydrogen, at a temperature close to 1,600°C. The density of the pressed Caramel is equal to 94 percent of the theoretical density.

We should mention that the production of Caramel fuels benefits from the experience acquired in this field with PWR [Pressurized Water Reactors] fuels.

Deposit of Antidiffusion Barrier

Each Caramel is covered with a layer of chrome, deposited by cathode pulverization. This chrome acts as a barrier, preventing the diffusion of oxygen in the zircaloy, which could take place during the process of soldering by diffusion, which is also called "shelling," and is described later.

1.3.2. Manufacture of Plates

The following elements are combined to form a plate (Figure 1):

a. oxide strips;

b. zircaloy grid, made by soldering zircaloy wires;

c. a nickel tip, which has an effect on the neutrons;

d. side pieces made of zircaloy;

e. end pieces, also made of zircaloy; and

f. zircaloy sheets used as enclosures.

The Caramel are placed in the grid cavities. The entire unit--the grid with its Caramel fuel, the side pieces, the end pieces, and the tip--is placed between two sheets of zircaloy, and soldered to form a tight seal. The plate closing procedures are done in the following order:

a. After resistance soldering of the various parts, the sides are soldered to the roller, using a resistance solderer;

b. The end pieces are then soldered by electron bombardment, which also places the unit in a vacuum;

c. After the plate is closed in this way, it is transferred to a diffusion soldering enclosure, where it undergoes a high temperature (∼800°C) and high pressure (≃1,000 bars) treatment for 4 hours; this procedure is also called "shelling." This process ensures that all the zircaloy components, especially the grids and sheets, are properly soldered, separating each strip of UO_2 and ensuring a good contact between the oxide and the enclosure sheet.

d. This shelling process is then followed by a control procedure, done in a vacuum at 700°C.

1.3.3. Quality Control

All the materials and components must meet the stringent specifications: specific control procedures have been established, and a quality control organization has been set up.

These controls are done at all phases of production, and cover in particular:

a. Measurement of components and assembly (measurement of ducts);

b. Enrichment of each fuel strip;

c. The quality of soldering between metal parts;

d. The quality of the contact between the oxide and the enclosure.

These controls are done during the manufacturing process in the following manner.

1.3.3.1. Controls during the Production of Basic Elements

UO_2 strips: measurement (length, width, thickness, density, appearance, control of chrome deposit).

The tolerable surface density defects have been defined on the basis of correlations between the dimensions of the defect and the residual thickness of the sheet after diffusion soldering.

Zircaloy parts: measurement. Surface condition after abrasion.

1.3.3.2. Controls of finished plates

a. appearance;

b. measurement;

c. control of absence of entrapped gases, by thermal treatment at 700°C in a vacuum, with the plates free;

d. control of quality of soldering by micrography and corrosion testing;

e. enrichment controls.

The enrichment control of the Caramel plates consists of determining the surface content of U 235 by neutron measurement. This control offers a number of advantages:

a. overall control of the various manufacturing tolerances of the Caramel elements;

   1. enrichment;

   2. uranium titer in the UO_2;

   3. density of the pressed UO_2;

   4. thickness of the Caramel;

b. possibility of a systematic control of all the strips which combine to make up a fuel element;

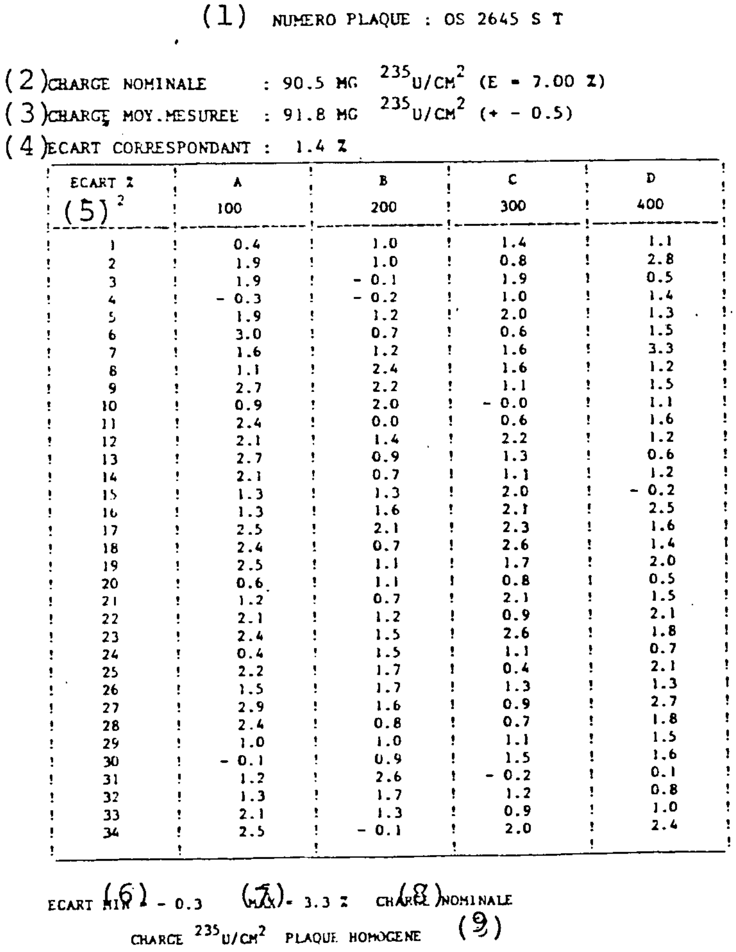
c. speed of control in relation to conventional methods;

d. exact measurement of the combined manufacturing variances;

e. control of a characteristic (surface content of U 235) that can be used directly to calculate the reactor's performances; and

f. control of the quality of the oxide-enclosure contact.

The quality of the oxide-enclosure contact appears to be an important parameter in the design of the Caramel fuel. A method of thermal analysis by infrared thermovision has been developed.



(1) NUMERO PLAQUE : OS 2645 S T

(2) CHARGE NOMINALE : 90.5 MG ^{235}U/CM^2 (E = 7.00 %)
(3) CHARGE MOY.MESUREE : 91.8 MG ^{235}U/CM^2 (+ - 0.5)
(4) ECART CORRESPONDANT : 1.4 %

ECART % (5) 2	A 100	B 200	C 300	D 400
1	0.4	1.0	1.4	1.1
2	1.9	1.0	0.8	2.8
3	1.9	- 0.1	1.9	0.5
4	- 0.3	- 0.2	1.0	1.4
5	1.9	1.2	2.0	1.3
6	3.0	0.7	0.6	1.5
7	1.6	1.2	1.6	3.3
8	1.1	2.4	1.6	1.2
9	2.7	2.2	1.1	1.5
10	0.9	2.0	- 0.0	1.1
11	2.4	0.0	0.6	1.6
12	2.1	1.4	2.2	1.2
13	2.7	0.9	1.3	0.6
14	2.1	0.7	1.1	1.2
15	1.3	1.3	2.0	- 0.2
16	1.3	1.6	2.1	2.5
17	2.5	2.1	2.3	1.6
18	2.4	0.7	2.6	1.4
19	2.5	1.1	1.7	2.0
20	0.6	1.1	0.8	0.5
21	1.2	0.7	2.1	1.5
22	2.1	1.2	0.9	2.1
23	2.4	1.5	2.6	1.8
24	0.4	1.5	1.1	0.7
25	2.2	1.7	0.4	2.1
26	1.5	1.7	1.3	1.3
27	2.9	1.6	0.9	2.7
28	2.4	0.8	0.7	1.8
29	1.0	1.0	1.1	1.5
30	- 0.1	0.9	1.5	1.6
31	1.2	2.6	- 0.2	0.1
32	1.3	1.7	1.2	0.8
33	2.1	1.3	0.9	1.0
34	2.5	- 0.1	2.0	2.4

ECART MIN (6) - 0.3 (7) MAX = 3.3 % CHARGE (8) NOMINALE
CHARGE ^{235}U/CM^2 PLAQUE HOMOGENE (9)

Figure 3: Caramel plates: Example of control of content of U 235/cm^2.

Key:

1. Plate number: OS 2645 S T
2. Nominal content
3. Average content measured
4. Corresponding variation
5. Percentage of variation
6. Minimum variation
7. Maximum variation
8. Nominal content
9. 235 U/cm^2 content; homogenous plate

However, this method is not being used now, for the test done at 700°C in a vacuum can be used to test the plates under conditions which are more stringent than the conditions of operation in a pool reactor. Until the present, this test has been found to be highly satisfactory.

1.3.3.3. Control during the final assembly

a. overall measurement of the assembly (by placement in a standard measurement gauge);

b. measurement of all ducts;

c. control of superficial pollution.

The controls and final acceptance are handled by an organization independent of the fuel manufacturer. Moreover, a system of quality assurance has been set up and works with studies, development, and testing.

A descriptive file is drawn up for each fuel assembly. These records contain all the data for the assembly:

a. data concerning the various componenets: source, method of production, mechanical characteristics, measurements and weight, chemical analyses;

b. measurement results for each plate;

c. observations after a visual examination of each plate;

d. results of the enrichment control, done for each strip;

e. results of the measurement of all water ducts (a recording is made for each row of strips).

Figure 3 gives some examples of the data compiled for each fuel assembly, and contained in this descriptive file.

1.3.4. Manufacturing Experience

The experience acquired during manufacturing is based on the development of a large number of assemblies, in addition to the production of units for experimental irradiations. Table 3 gives a summary of this experience.

(1) Réacteur	(2) Nombre d'assemblages	(3) Nombre de plaques	(4) Nombre de plaquettes UO_2	(5) Poids UO_2 (kg)
(6) PAT (*)	16	576	101 952	1 497
(7) CAP (**)	4	44	13 728	192
OSIRIS	> 200	3 400	462 400	2 019

Table 3: Assemblies produced

1. Reactor
2. Number of assemblies
3. Number of plates
4. Number of UO_2 strips
5. UO_2 weight (kg)
6. Ground Prototype: PWR type reactor used as a prototype for naval propulsion, located at Cadarache.
7. Advanced Boiler Prototype: PWR type reactor with a power of 100 thermal MW, also located at Cadarache.

At present, the production capacity is 200 assemblies of the Osiris type a year.

1.4. Qualification of the Caramel Fuel

1.4.1. Various Qualification Programs for the Caramel Fuel

A broad testing and qualification program for the Caramel fuel has been undertaken and executed within a broad range of specific powers and combustion ratios. Its purpose was to determine first of all the technological limits, then the safe and reliable areas of operation of this type of fuel. This program includes both parametric tests in irradiation test circuits in test models with a limited number of Caramel elements, and irradiations of experimental assemblies done in the Osiris reactor and in the CAP and CAT prototype reactors.

Following are the major outlines of this program, as well as the principal results that have been obtained.

1.4.1.1. The EL 3 Program

A first exploratory program designed to determine the technological limits of the fuel was begun at Saclay in the EL 3 reactor between 1965 and 1970. It worked with 17 irradiation test units (including five or nine Caramel each) which were irradiated with variable combustion ratios and specific powers.

The range of specific power explored extends from 1,000 to 3,000 W/cm^3. The enclosure temperature: 280°C to 340°C. The results of these tests showed that:

a. It is possible to achieve combustion ratios of 30,000 MWj/t with specific powers as high as 3,000 W/cm^3 without damaging the fuel. Beyond 30,000 MWj/t, if this specific power is maintained, there is a danger of causing the strips to swell, thus releasing gases. This would not necessarily cause the enclosures to break.

b. On the other hand, if the specific power is decreased at this stage of irradiation, it is possible to reach combustion ratios up to 50,000 MWj/t without any notable change in the structure of the UO_2 strips.

1.4.1.2. Siloe Program

Two irradiations without external pressure were conducted in the swimming pool reactor, Siloe, at Grenoble, using two small units with a few test models each.

The irradiation conditions were as follows:

Specific power	1,060 W/cm^3		1,500 W/cm^3
Duration	245 days	and	202 days
Combustion ratio	18,300 MWj/t		25,100 MWj/t
Temperature	100°C		100°C

The results obtained show a very good behavior of the assemblies in the reactor and a very good appearance after irradiation.

1.4.1.3. Program of Experimental Irradiations in the Osiris Reactor

These are still experimental irradiations of test units, each with several Caramel, and should not be confused with the irradiations of Osiris elements done in actual size. The irradiations were done in an NaK container at a temperature of 300°C with external pressurization of 140 bars.

Historically, two series of irradiations were done:

a. In 1973-1974, with Caramel thicknesses of 3 and 4 mm;

b. In 1975-1978, with just a thickness of 4 mm; the objective was to determine the technological operating limits.

The test units in the first series exceeded 40,000 MWj/t with a thickness of 3 mm and 37,500 MWj/t with a thickness of 4 mm. The examinations conducted revealed the absence of any release of gases and the very good behavior of the separators.

The results cover in particular:

a. The thermal conductance of the uranium oxide as a function of the combustion ratio;

b. The determination of the extreme limit for the normal operational temperature ;

c. The extreme temperature of the separators;

d. The operating limits for the two thicknesses of 3 and 4 mm during operation.

Figure 4 gives an example of the operational limit for a Caramel 4 mm thick up to a mass combustion of 50,000 MWj/t U. If we know the extreme temperature for the fuel operation, it is possible to transpose these results to other Caramel configurations. So, in the case of the Osiris reactor, the extreme specific powers would be above 5,000 W/cm^3.

Other test irradiations were done in a loop on the Osiris reactor. Two irradiations were done as part of the Irene program, using a pressurized water loop which reproduced the real coolant conditions. One of them caused a leak detection signal due to the instrumentation (passage of thermocouples). This was used for safety studies (Ir-06). The second concerned the study of deposits of corrosion products. Moreover, power cycling tests were done, still using the 4 mm-thick Caramel, before the shutdown of the Osiris reactor in July 1978, on test models which reached a combustion ratio of 30,000 MWj/t. These cyclings were done under the following conditions:

a.	high level	1,250 W/cm^3
b.	low level	375 W/cm^3
c.	speed of rise and descent	400 $W.cm^{-3}/mn^{-1}$
d.	number of cycles	3,634

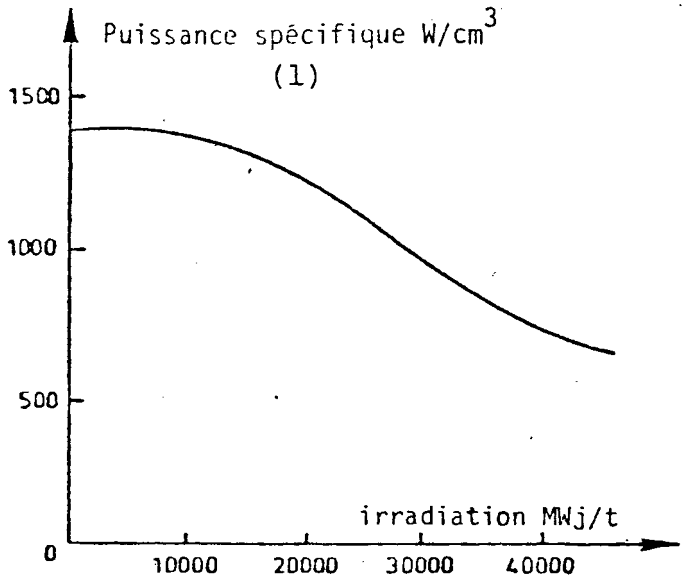


Figure 4: Operational limit for a Caramel 4 mm thick

Key:
1. Specific power W/cm^3

1.4.2. Carine Experiment: Study of Fuel Shield Rupture in Osiris

In order to evaluate the safety in operation of such a fuel in relation to the risks of a release of fission products or fissile matter in the primary circuit of the slightly pressurized reactor, a test of a shield rupture was done under conditions representative of the Osiris operation. This test was conducted in the independent test loop of the EL 3 reactor. This loop, located in the heavy water tank, is a heavy water cooling circuit distinct from the reactor's circuit. Thus, any possible pollution of heavy water is limited to this circuit.

1.4.2.1. Test Conditions

The fuel element, which was produced according to the same process as the standard fuel element, contained 32 strips of UO_2 enriched to 7 percent. The shield defect was a circular hole with a surface of approximately 1 mm^2. The specific power during irradiation was raised to 3,050 W/cm^3. Cooling was provided by the circulation of heavy water at a flow rate of 10 m/s. These conditions are quite similar to those in Osiris.

The fuel plate was placed in an aluminum case channeling the water to both sides of the fuel plate in order to provide adequate cooling.

The power released in the fuel was obtained by thermal records. The rise in the cooling water temperature was measured by a triple probe placed at the intake of the assembly in the reactor and by three triple thermocouples placed at the outlet. The flow rate was measured by a meter placed on the circuit.

Detection of the shield rupture was done by two parallel systems. One used a BF 3 counter which was normally in use on the loop, while the other was equipped with a ^{3}He counter similar to the one installed in Osiris.

1.4.2.2. Test Results

Changes in the DND (Delayed Neutron Detection) signal as a function of time are shown in Figure 5. We notice the presence of three pseudo-plateaus corresponding to increasing levels of activity. Their duration is about 5 hours for the first, 30 hours for the second, and 3 hours for the third. During the duration of the first two pseudo-plateaus, there were bursts of activity reaching peaks whose amplitude was close to the average signal.

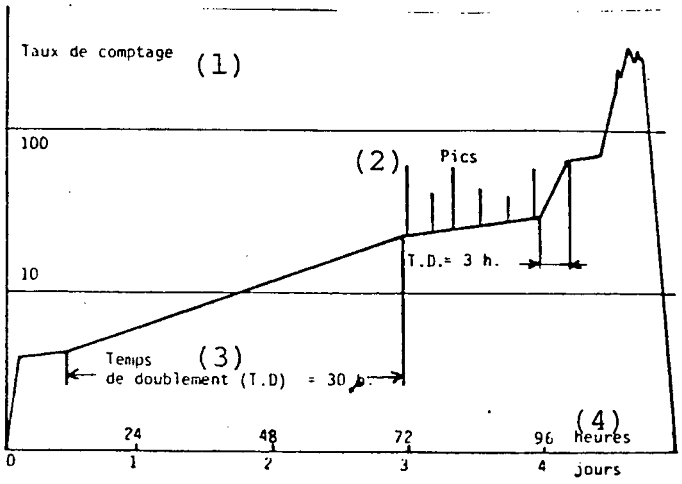


Figure 5: Changes in the Counting Rate of Neutrons Delayed during Irradiation

Key for Figure 5:

1. Counting rate
2. Peaks
3. Doubling time
4. Hours/days

Then there was an abrupt signal acceleration following an exponential curve.

The time required for the signal to double--30 hours during the first phase--was only 3 hours during the second phase.

After the third pseudo-plateau, there were recorded peaks of activity, with the average signal first changing rapidly and then stabilizing for 1 hour 40 minutes.

The delayed neutron detection equipment used was representative of the device installed in the Osiris reactor, which permits a determination of the time necessary for reaching the detection threshold of a shield rupture. The results indicate that the detection threshold is exceeded after the third pseudo-plateau.

Despite the continuation of irradiation in these conditions for about 2 hours, we found a very low level of radionucleid activity indicating a fuel leak. Moreover, the examinations made of the test fuel element after irradiation showed an absence of any significant change in the opening initially made and in the underlying fuel.

This test therefore showed the excellent behavior of the Caramel fuel in the event of a shield rupture, and also the possibility of detecting such a rupture in Osiris before any significant contamination of the reactor circuits could occur.

1.4.3. Irradiation of Three Complete Fuel Elements in Osiris

Before the start of service of the Osiris core, three precursor elements were irradiated in the old core. These irradiations were done during the first 6 months of 1978.

The first element put in the reactor was removed during the shutdown of the reactor for maintenance in July 1978, at an average irradiation level of about 18,000 MWj/t U. A destructive examination of this element was made at the Irradiated Fuels Research Laboratory at Saclay before the fueling of Osiris.

The other two elements were put in the reactor during the core fueling with Caramel fuel, for durations of one and two cycles, respectively, in order to actually have precursors, up to an average irradiation level of 18,000 to 20,000 MWj/t U.

II Changing the Fuel in Osiris

2.1. Refueling Schedule

The decision to conduct an operational experiment using slightly enriched fuel in Osiris was made in early 1977. The fuel chosen was the only one that would be available in the near future, the Caramel fuel. For the requirements of this operation, the thickness of the strips was reduced to 1.45 mm, as we said earlier.

The operation itself, with its main features: studies, work on the reactor, fuel testing, experimental studies, safety studies and reports, fueling and tests, took place following this schedule:

a. General studies, development of the fuel: 1977;

b. Testing of fuel elements in Osiris: early 1978;

c. Work on the Osiris reactor for the Caramel transformation: from autumn 1978 to the summer of 1979;

d. Isis safety report: January 1978;

e. Fueling of Isis and start of experimental studies on the core: October 1978;

f. Thermal studies on the loop in Grenoble: second half of 1978 to early 1979;

g. Osiris safety report: November 1978;

h, Fueling of the Osiris core: September 1979;

i. Tests of power increase: December 1979 to February 1980.

Note: The reactor was stopped at the end of July 1978 for the usual summer shutdown and for some major work, involving repairs of linings of the reactor (ducts, deactivation tanks), combined with work required for the change of fuel.

2.2. Adaptation of the Facility

The Osiris reactor was chosen for this experiment, involving the use of a slightly enriched fuel, because of its high performances. The fuel is thus placed in severe operating conditions which exceed the needs of all research reactors.

It is these conditions, combined with the fact that the Osiris reactor had no margin of U-Al fuel, beyond the margins required for safety, which explain to a great extent the need for certain modifications in the core's primary circuit. We should recall that the reactor had been originally designed for operation at 50 MW; the power of 70 MW was not reached until 1968, after a slight modification of the pumps.

The reduction in the number of plates per element (17 instead of 24) therefore had to be compensated for by an increase in the primary flow and thus by a change in the pumps and their motors.

As the primary circuit had four groups of exchangers and pumps operating in parallel in the U-Al core, each pump was associated with an exchanger. Three of these units were used simultaneously.

Because of the impossibility of increasing the flow in each of the exchangers simultaneously with the change in the pumps, a modification in the principal circuit allowed the four exchangers to be supplied in parallel from each of the four pumps. A main collecter now connects the outlet of the pumps to the intake of the exchangers. Only three of the pumps are used at the same time; the fourth remains on standby. However, the flow goes into the four exchangers.

The other adaptations made for operation with the Caramel fuel were very minor and were limited to a few reinforcements of the dry fuel storage facility.

The modification of the DRG [Shield Rupture Detection System] had already been considered for the U-Al fuel. In the former situation, the DRG only gave an alarm signal and only used a detection system for delayed neutrons. The modification made consisted of introducing the DRG in the sequence of protective actions for the signal caused by delayed neutrons (action at 2/3) and adding a measurement of the gamma signal.

2.3. Experimental Studies

In addition to the irradiations and tests of the fuel, a major experimental program was used to support the core transformation:

a. A study of the core with the Isis reactor, starting in October 1978, a year before the fueling of Osiris;

b. A study of the hydraulic behavior, loss of load and vibrations, and of the fuel element in a test loop at Saclay;

c. A study of the thermal behavior of the duct at Grenoble.

2.3.1. Experimental Study of the Core

This study, done on the Isis, was designed to verify the data for the core, which are highly important for safety, and to determine the neutron flows and gamma heating in the places reserved for the experiments. This was essentially a complete qualification of the method of calculation used.

In the first phase, the program consisted of:

a. Making a subcritical approach by gradual fueling of the core, and determining the minimal critical size, then the available reactivity of the core which was to be operational in Osiris;

b. Measuring the efficiency of each of the six control rods;

c. Determining the distribution of power inside each of the fuel elements of the core in order to know, in every situation, the maximum power to be removed by a water duct.

To do this, the Isis core was identical to the first Osiris core. The flow measurements in the experimental sites which were not essential for the safety study of the core and for the compilation of the corresponding records were done in a later phase.

These measurements enabled us to verify some major parameters for irradiations: the fast and thermal neutron flows, and gamma heating.

Flux thermique maximum (1) 10^{14} n/cm²/s	(2) Cœur U-Al cycle D 62	(3) Cœur oxyde Premier (4) cycle	Deuxième (5) cycle
		Δ %	Δ %
Moyenne des 6 (resp. 4) emplacements centraux (6)	2,24	1,46 — 35 %	1.33 — 41 %
Moyenne des emplacements (9) face Nord (7)	2,42	1,86 — 23 %	1,81 — 25 %
Moyenne des emplacements (10) face Ouest (8)	1,73	1,64 — 5 %	1,53 — 12 %
Moyenne des emplacements (10) face Est (9)	1,36	1,55 + 14 %	1.55 + 14 %

Table 4: Results of Experimental Core Study

Key:

1. Maximum thermal flow
2. U-Al core: cycle D 62
3. Oxide core
4. First cycle
5. Second cycle
6. Average of six central locations
7. Average of locations on north side
8. Average of locations on western side
9. Average of locations on eastern side

These measurements confirmed the calculations, and gave us a precise estimate of the changes to be expected under test conditions. These data have also been confirmed by the experience acquired during the operation of Osiris.

A summary of the results is given in Table 4 (above).

Rapid Neutron Flow (E > 1 MVe)

The calculations had shown that the rapid flow was affected in an inverse ratio to the size of the core. This result was verified with Isis and with Osiris. In fact, we found that the average loss in rapid flow was a factor strictly and inversely proportional to the increase in the core size, when the number of elements was raised from 39 to 44, for hydraulic reasons peculiar to Osiris.

Thermal Neutron Flow

The very significant absorption of the new Caramel fuel, caused by its high uranium content, is expressed, for the same power, by a significant decline in thermal flow in the system (~40 percent for these experiments). However, the spectrum quality is better (approximately 40 percent gain in the rapid flow/ thermal flow ratio).

The decline in thermal flow in the core has no unfavorable consequences for the experimental program, as the system is used solely for its rapid flow characteristics.

The thermal flow on the periphery is reduced on the average by 8 percent, but here we must also bear in mind the increase in the core size and the number of sites that can be used on the external grids.

γ Heating

γ heating decreases in the system, and this is an advantage for the experiments:

a. U-Al core	10 to 15 W/g
b. Caramel core	4 to 8 W/g

2.3.2. Thermo-Hydraulic Study

The measurements were designed to:

a. Determine the loss of load of the fuel element, bearing in mind the surface irregularities of the plate, caused by the special Caramel technology. This study was handled by the Reactor Service at Saclay, using the existing hydraulic loop for the tests of Osiris elements and irradiations;

b. And to ascertain the absence of vibrations in the standard fuel element and in the control element.

These measurements were made along with the determination of the loss of load in order to verify the lifting force of the elements and of the control rods (resulting from the upward circulation of the primary fluid in the reactor core).

A second series of tests conducted at Grenoble by the Department of Energy Transfer and Conversion concentrated on a thermal study of the duct. The results were analyzed jointly by the Department of Energy Transfer and Conversion and by the Reactor Study and Applied Mathematics Service.

All the results have shown that the Caramel element behaved much like the old U-Al element. The loss of load caused by friction is increased by about 5 percent but, considering this increase in the friction coefficient, the thermal behavior of the duct is slightly modified by the Caramel structure. The test results were analyzed under the code name of FLICA.

2.3.3. Safety Records

Because of the importance of the modifications, a detailed examination of their implications in terms of safety was conducted. In the very first phase, before the work, a complement to the Safety Report was issued and, after the fueling, a complete reedition of the Safety Report was released which covered, in addition to this safety study and the modifications made, the results of the start of service tests.

This reexamination of safety covered all the documents. However, the major studies and the most important modifications concerned the following areas:

a. Core physics: loading of the fuel, configuration, efficiency of the rods, power distribution, replacement of the fuel;

b. Primary cooling circuit of the core: new configuration of the circuit, pumps, exchangers, flows, loss of load, vibrations;

c. Thermohydraulics of the core at its permanent operational status, in transitional phases, and in natural convection;

d. monitoring of the first barrier: new DRG system; filtration circuit; automatic insulation of purification system;

e. Study of accidents and their radiological consequences on the environment.

III Behavior of the Fuel: Consequences for Operation

3.1. Record of Operation

The Osiris reactor was loaded with Caramel fuel in October 1979. The power increase test cycle took place in January/February 1980. Since then, and until July 1981, in addition to this test cycle, there have been 12 cycles of about 4 weeks each, operating at 70 MW, for a total of 21,600 MWj (see Table 5).

Cycles	Charge en uranium 235 en début de cycle (1) (g)	Energie fournie (2) (MWj)	Durée du cycle (3) en JEPP 70 MW	Irradiation moyenne des éléments sortis (4) (MWj/t U)
E 0	20 733	1 542	22	4 970
E 1	20 938	1 546	22,1	9 460
E 2	21 586	1 813	25,9	16 460
E 3	21 397	1 864	26,6	18 670
E 4	21 164	1 670	23,9	20 090
E 5	21 555	1 622	23,2	22 230
E 6	21 817	1 650	23,6	24 370
E 7	21 875	1 666	23,8	23 850
F 1	21 482	1 732	24,7	24 300
F 2	21 027	1 774	25,3	24 860
F 3	21 408	1 938	27,7	24 960
F 4	20 908	1 860	26,6	28 360
F 5	20 480	994	13,7	27 455

Table 5: Osiris Reactor: Cycle Characteristics.

Key:
1. Content of uranium 235 at start of cycle (g)
2. Energy supplied (MWj)
3. Duration of cycle in JEPP 70 MW
4. Average irradiation of elements removed (MWj/t U)

For each of these cycles, Table 5 gives the uranium 235 content at the start of the cycle, the energy supplied, the duration of the cycle, and the average irradiation of the elements removed. For the first core, the average enrichment had intentionally been reduced to about 6 percent, with fuels enriched to 4.75 percent, 5.62 percent, and 7 percent. The fuel now used is enriched to 7 percent. Towards the end of 1982, this enrichment will be increased to 7.5 percent.

Each element remains in the core for five to six cycles. During each cycle, there is a partial replacement of the fuel and a rearrangement of the remaining elements.

3.2. Conditions of Operation of the Fuel and Statistical Record

The conditions for the use of the fuel are quite stringent. In particular, the average and maximum specific powers are well beyond the values found for pressurized water reactors or for those possible for almost all the research reactors existing anywhere in the world:

a. Average specific power: 1,640 W/cm^3 of UO_2

b. Maximum specific power: 4,300 W/cm^3 of UO_2

In order to be certain of the good behavior of the fuel in the reactor, a program of systematic nondestructive examinations was undertaken. This entails monitoring the water ducts; this is done by a stress gauge and a comparison with the measurements made after manufacture. It covers all the assemblies unloaded after the first six cycles of operation and half of the assemblies removed after the next six cycles; this amounts to about 90 assemblies.

This program, which is now underway, will be completed by destructive examinations of one of the most heavily irradiated elements, having reached a mass combustion of 30,000 MWj/t U.

All the measurements done will help us to make an overall evaluation, statistically representative of the evolution of the characteristics and of the behavior of the Caramel Osiris fuel element under irradiation.

Since the start of service in Osiris, the average irradiation authorized has risen from 20,000 MWj/t U, the value designated as the first objective, to 25,000 MWj/t U in November 1980, and to 30,000 MWj/t U in February 1981. These authorizations are based on the good behavior of the fuel, the systematic nondestructive examinations made of the irradiated elements removed from the reactor, and destructive examinations of some elements. For the moment, the average irradiation level of 30,000 MWj/t U has not been reached in all of the elements removed. This level will be reached when the replacement elements are enriched to a level of 7.5 percent.

At present, 63 elements have exceeded 20,000 MWj/t U; of these, 26 are over 25,000 MWj/t U, and eight have reached an average irradiation level between 28,000 and 30,000 MWj/t U.

We should add that, for a fuel element whose average irradiation is close to 30,000 MWj/t U, the maximum irradiation is between 40,000 to 43,000 MWj/t U.

3.3. Behavior of the Fuel

The behavior of the fuel has been good and no major incident has caused any serious problems with contamination of the circuits. The only noteworthy incidents seem caused by problems arising from the manufacturing process used for the Caramel in this configuration and for the reactor's conditions of use.

During the power increase test cycle, three elements had to be removed even before the nominal power level was reached, because of abnormal rates in the DRG. Later, this sort of incident did not recur. An examination of one of the elements in hot cells at the Irradiated Fuels Research Laboratory at Saclay showed that this was caused by an initial manufacturing defect. After the first series of approximately 100 elements, the plate controls were improved and the satisfactory behavior of the fuel made it possible to increase the irradiation levels, as we indicated earlier.

Some bursts of γ-activity in the DRG at the end of 1980 and in early 1981, which did not release iodes or disrupt the delayed neutron signal, were probably a sign of micro-leaks in some of the Caramel elements. Systematic examinations should enable us to determine the origin, either a shield defect or swelling.

3.4. Consequences for operation

As the few initial incidents mentioned above never caused any real circuit contamination problems, there have been no severe radiological consequences affecting the personnel. On the contrary, the individual dosimeter readings show a general decline in the doses received by the pperating personnel, in relation to the period when the highly enriched U-Al fuel was used. This is caused essentially by the replacement of the aluminum shield by a zircaloy shield, which has meant a very large decline in the ^{24}Na activity of the water in the primary circuits and capacitors.

The performance losses in neutron flows found in irradiations confirm the experimental studies on Isis and the preliminary calculations. The consequences are quite limited for the testing program. The reduction of the fast neutron flow by about 9 percent has no disadvantage other than lengthening the duration of irradiations. The notable loss in thermal neutron flow inside the core causes no problems, as the corresponding sites are used for rapid flow irradiations. Externally, the average 8 percent loss in thermal neutron flow is compensated by the adjusted position of the irradiations and the increase in the number of high-flow sites.

IV Conclusion

This demonstration of the use of a slightly enriched fuel in a high-performance research reactor is a technical experiment of interest from all points of view.

Generally speaking, it seems that a research reactor, even one with performances as high as those of Osiris, does not necessarily need a highly enriched fuel. Of course, this reduction in enrichment is accompanied by a certain modification in the characteristics of the core in terms of the neutron flows. These modifications have not significantly hindered most of the irradiations.

In the particular case of the oxide plate fuel, known as Caramel, its behavior is quite satisfactory. The few defects found have been minor and the reactor can be used with a completely normal regularity. The change, from a radiological point of view, has been of benefit for the personnel.

This demonstration experiment successfully conducted with Osiris gives France an alternative solution for the highly enriched fuel used in its multipurpose research reactors. It strengthens France's position for exporting research reactors, as international trade in highly enriched uranium may in the future be tightly restricted.

It is certain that, for most of the existing reactors and announced projects, the irradiation conditions for this fuel would be much less stringent than those that have been tested at Saclay for almost 2 years.

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