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FRENCH LEU FUEL FOR RESEARCH REACTOR WITH EMPHASIS ON THE OSIRIS EXPERIENCE OF CORE CONVERSION AND REACTOR OPERATION WITH THE NEW FUEL

Jean-Marie CERLES *
Maria TROTABAS **
Ghislain DE CONTENSON **
Jacques DELAFOSSE ***

* Centre d'Etudes Nucléaires de Saclay, Services des Piles, OSIRIS
** Centre d'Etudes Nucléaires de Saclay, Division de Métallurgie et d'Etudes des Combustibles Nucléaires, Départemant de Technologie
*** Société Technicatome

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COMMISSARIAT A L'ENERGIE ATOMIQUE
DIVISION de METALLURGIE et d'ETUDES des COMBUSTIBLES NUCLEAIRES
DEPARTEMENT DE TECHNOLOGIE

SERVICES DES PILES DE SACLAY
OSIRIS

1. INTRODUCTION

One of the various activities carried out in France concerned with the design, fabrication and development of nuclear fuels was the development by the CEA of a plate type fuel (Caramel fuel). A Caramel fuel element is in the form of a plate consisting of two tight covering zircaloy sheets in which the UO_2 platelets are confined themselves within the network of a zircaloy grid. The plane geometry provides an effective means of overcoming the drawback of poor uranium oxide conductivity, and makes it possible to combine high specific power with low fuel temperature.

The different materials used in the Caramel type fuel assemblies i.e. UO_2 and Zy, are very well known after their extensive use in LWR's. Their physical properties, in pile behaviour, manufacturing features etc... are well mastered, and will therefore not be dealt with in this presentation.

The chief advantages of this fuel are the following :

(1) It is a very low enriched fuel. It can be used in research reactors demanding high volumetric powers and neutron fluxes, with a required enrichment significantly lower than 20 % ^{235}U.

The difference between the densities of UO_2 matrix and U-Al, 10.3 and 1.6 g/cm respectively, leads to a higher uranium charge, making it possible to reduce the enrichment to between 3 and 10 %.

(2) A second advantage of the Caramel fuel stems from its operating safety. Owing to its dispersion, any loss of tightness only puts a small amount of fissile materiel in contact with the coolant, thus limiting any contamination of the primary circuit.

Another safety factor is the operating temperature, which is considerably lower than the temperature at which fission gases are liberated.

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The earliest research conducted at the CEA was directed towards applications in power, heat and naval propulsion reactors, and used thick (4 mm) Caramels owing to the low volumetric powers required.

The thin Caramels investigated since 1977 as part of the non-proliferation programme (INFCE) found their application in research reactors for which volumetric power levels are very high (mean value about 1700 W/cm^3, maximum value 4300 W/cm^3).

Thanks to the use of the low-enriched uranium Caramel fuel, the Commissariat à l'Energie Atomique proceeded to convert the core of the high-performance research reactor Osiris, at Saclay. The new Caramel fuel core has operated sucessfully since December 1979.

The Caramel type fuel takes advantage of the experience gained in LWR operation which alleviates most uncertainties and additionnal R and D effort, contrary to the use of less-known fuels like U-Al, U_3O_8-Al or U_3Si-Al.

The following table summarizes the main characteristics of the reactors under-operation or in project (Thermos project) using Caramel type plate fuel elements.

Reactor	Power (MW)	Caramel thickness (mm)	Temperature of clad (°C)	Coolant pressure (bar)	Mean specific power (W/cm^3)	Maximum specific power (W/cm^3)
pool reactor (Osiris)	70	1,45	140	3	1 640	4 300
heat generator (Thermos)	100	2,25	160	11	275	1 070
ISIS	0,7	1,45	95	1,5	16	43

2. DESCRIPTION

The Caramel type Osiris fuel element is in the form of a plate 700 mm long, 80 mm wide and 2,25 mm thick. Figure 1 shows the different components of a Caramel plate of the Osiris reactor. The sintered UO_2 fuel is in the form of a square-section parallelepiped measuring 17,1 x 17,1 mm and 1,45 mm thick. It is placed in a regular array within a square-pitched grid and confined between two zircaloy sheets. This assembly, fitted with zircaloy edge and end pieces, undergoes a series of welding operations designed to guarantee the perfect tightness of each UO_2 platelet to the exterior and to its neighbours.

Simultaneously, good contact is achieved between the oxide and the cladding. The fuel assemblies consist of several plates (14 or 17) in parallel position, held rigidly by slotted side-plates. They are equipped with a foot for water supply and a handling head.

The Caramel fuel is distinguished from the standard fuel pin by :

. its plane geometry,

. the absence of free volume,

. good oxide/clad contact (no clearance)

The special features of the Caramel fuel impose specific operating conditions. Owing to the absence of voids (except for the open porosity of the fuel), the temperature of incipient fission gas evolution must never be exceeded. To achieve this condition, it is essential to guarantee excellent oxide/clad contact for the fuel element from the very beginning and to maintain this throughout its service life.

3. FABRICATION AND QUALITY CONTROL

3.1 Fabrication

The Caramel fuel is fabricated in workshops belonging to the CEA or its subsidaries. Some components such as the zircaloy sheets, castings and machined parts are supplied by industry. The fabrication sequence is shown in Figure 2.

Fabrication is subdivided into the following phases :

3.1.1 Fabrication of oxide platelets (Caramels)

These platelets are fabricated by sintering UO_2 powder obtained by the wet method. The process employs the double normal cycle. The material is sintered under hydrogen at a temperature near 1600°C. The density of the sintered Caramel is equel to 94 % of the theoretical density.

It should be noted that the fabrication of Caramel fuels benefits from the experience gained in this area with PWR fuels.

Deposit of anti-diffusion barrier

Each Caramel is covered by a layer of chromium deposited by cathodic sputtering. This chromium performs the role of a barrier, by preventing the diffusion of oxygen into the zircaloy, that is liable to occu during the diffusion welding operation, also called "marmitage" (marmite = HP cooking pan) and described below.

3.1.2 Plate fabrication

The component parts of a plate are the following (figure 1) :

. oxide platelets,
. zircaloy grid obtained by welding zircaloy wires,
. nickel foot that plays a role with respect to neutrons,
. zircaloy side pieces,
. zircaloy end pieces,
. zircaloy sheet cladding.

The Caramels are placed within the grid cavities. The assembly including the grid with its Caramel load, the side pieces and end pieces is placed between two zircaloy sheets and welded tight. The plate closure operations are performed in the following order.

After resistance spot welding of the different parts, the sides are welded by a resistance seam welding unit.

The end pieces are then welded by electron bombardment welding that also places the plate under vacuum.

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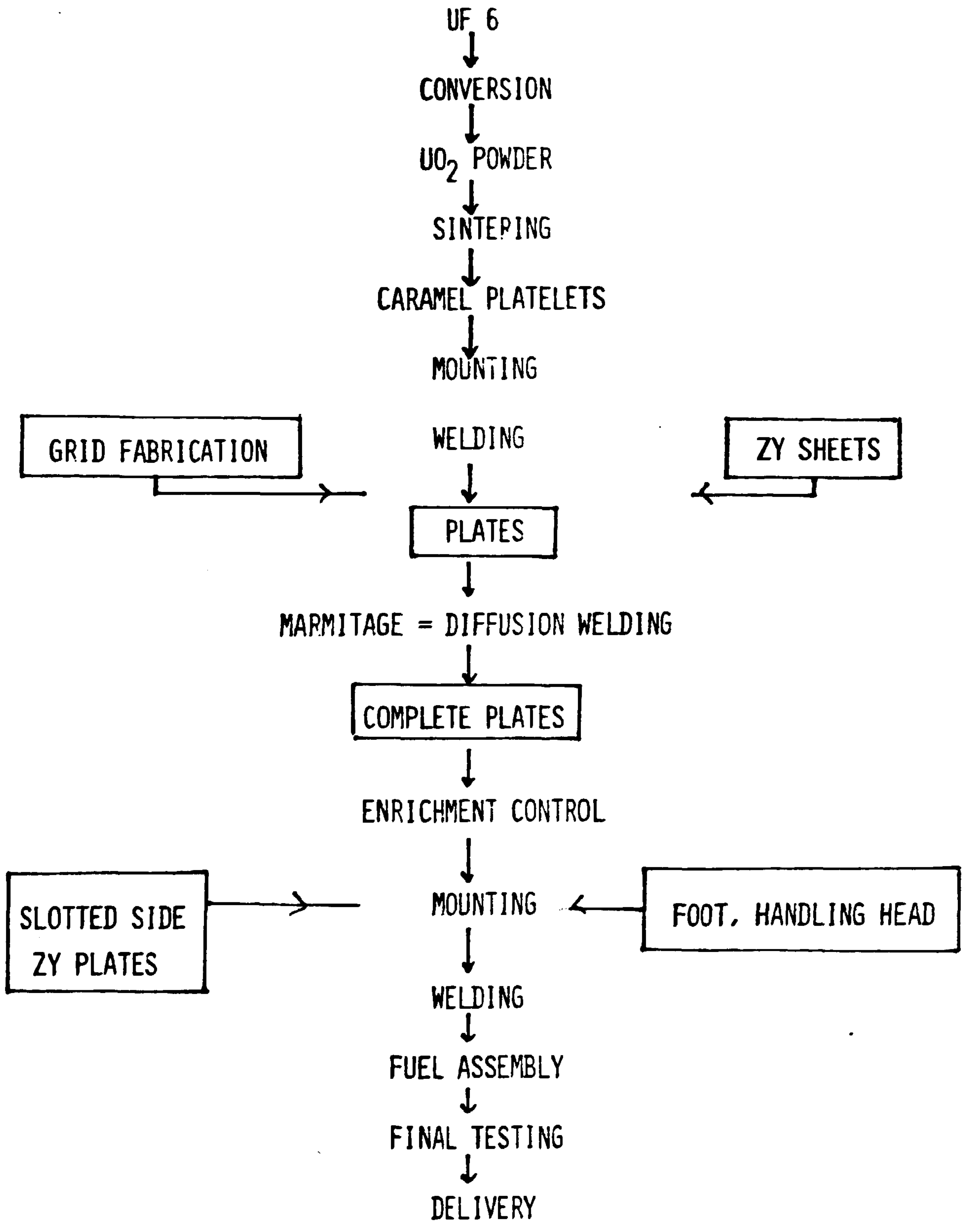
UF 6
CONVERSION
UO_2 POWDER
SINTERING
CARAMEL PLATELETS
MOUNTING
WELDING
GRID FABRICATION
ZY SHEETS
PLATES
MARMITAGE = DIFFUSION WELDING
COMPLETE PLATES
ENRICHMENT CONTROL
SLOTTED SIDE ZY PLATES
MOUNTING
FOOT, HANDLING HEAD
WELDING
FUEL ASSEMBLY
FINAL TESTING
DELIVERY

FIGURE 2

The closed plate is transferred to a diffusion welding enclosure and undergoes high temperature (greater than 900°C) and high pressure (≈ 1000 bar) treatment for four hours, also called "marmitage". This treatment guarantees the welding of all zircaloy components and especially between the grids and sheets, by ensuring the separation of each UO_2 platelet and good oxide/clad contact.

This marmitage treatment is followed by a control treatment under vacuum at 700°C.

The rough plates are then machined to the required dimensions. After undergoing the controls described in the next section, they are mounted on side plates. Electron bombardment welding is then used to join the Caramel plates and the side plates.

3.2 Quality control

All the materials and components are required to meet specifications.

Owing to its geometric characteristics and its operating conditions, the Caramel fuel must meet especially severe requirements, corresponding to specific control procedures.

These controls are carried out at all fabrication levels and include :
. metrology of components and of the assembly (e.g. metrology of channels)
. enrichment of each fuel platelet,
. quality of the weld between metal components,
. quality of oxide/clad contact.

These controls take place during fabrication as follows :

3.2.1 Controls in the fabrication of basic components

UO_2 platelet : metrology (length, width, thickness, density, visual appearence, chromium deposit inspection).

Tolerable surface defects have been defined on the basis of correlations between defect dimensions and the residual clad thickness after diffusion welding.

Zircaloy parts : metrology (surface condition after abrasion)

3.2.2 Controls applied to the finished plate

- Visual appearance
- Metrology
- Checking of the absence of occluded gases, by heat treatment at 700°C under vacuum, with free-standing plates
- Quality control of welds by micrography and corrosion test
- Enrichment test

The enrichment test of Caramel plates consists in the determination of the charge of ^{235}U per unit area by neutronometry. This check offers several advantages :

- overall checking of various Caramel fabrication tolerances :
  - enrichment,
  - uranium content of UO_2
  - density of UO_2 sinter
  - Caramel thickness
- possibility of systematic checking of all platelets making up a fuel plate
- speed of control in comparison with traditional methods,
- exact measurement of accounting for fabrication ranges,
- control of a characteristic (charge of ^{235}U per unit area) of direct use for the calculation of reactor performance,
- quality control of oxide/clad contact.

The quality of oxide/clad contact appears to be an important parameter in the design of the Caramel fuel. A thermal analysis method by infrared thermovision was developed for this purpose.

Actually it is not used, because the test performed at 800°C under vacuum serves to test the plates in conditions that are more severe than those of operation in a pool reactor. This test has proved highly satisfactory until now.

3.2.3 Control of finished assembly

. Overall metrology of assembly (passage through a gauge)
. Metrology of all channels
. Check of surface pollution

Control procedures and final acceptance are carried out by an organization that is independent of the fuel manufacturer. In addition, a quality assurance system is implemented, covering design, fabrication and tests.

A preirradiation characterization report is written for each fuel assembly. All the data related to the assembly are included in this report :

Data about assembly components : origin, fabrication procedure, mechanical characteristics, measurements, weight, chemical analyses.

Measurement results for each plate.

Remarks after visual examination for each plate.

Results of enrichment control performed on each UO_2 platelet

Measurement results of all water subchannels (a recording is made of each platelet row)

A few examples of data recorded for each fuel assembly and contained in the characterization report are annexed at the end of this paper.

Fabrication experience

Considerable fabrication experience has been gained, because aside from fabrications for experimental irradiations, a large number of assemblies has been fabricated, as summarized below.

Reactor	Number of assemblies	Number of plates	Number of UO_2 platelets	UO_2 weight (kg)
PAT	16	576	101 952	1 497
CAP	4	44	13 728	9 630
OSIRIS	200	3 400	462 400	2 019
TOTAL	220	4 020	478 080	13 146

CAP – Prototype Advanced Boiler. PWR type reactor of a power of 100 MWth, located at Cadarache.

PAT – Land Based Prototype. PWR type reactor used as a prototype for naval propulsion, located at Cadarache.

At present, the fabrication shops have a total capacity of 200 Osiris - type assemblies per year.

4. QUALIFICATION OF CARAMEL FUEL

An extensive programme involving experiments and qualification of the Caramel fuel has been undertaken and implemented in a broad range of specific powers and burnups. It was intended to determine initially the technological limits, and then the safe and reliable operating ranges for this type of fuel. This programme includes both parameter tests in irradiation test loops on specimens including a limited number of Caramels, and also irradiations of experimental assemblies carried out in the Osiris reactor and in the CAP and PAT prototype reactors.

The most important features of the programme are then exposed together with the main results obtained.

4.1 T I P programme

An exploratory programme was conducted during the 1965 to 1970 period with the EL 3 reactor at Saclay in order to define the technological limits of this fuel.

Seventeen test samples (containing 5 and 9 caramels) were irradiated at variable burnups and specific powers.

The specific power range explored ranged from 1000 to 3000 W/cm^3. The cladding temperature was between 280 and 340°C.

The results of these test showed that :
- it is possible to reach a burnup of 30000 MWD/T with specific powers as high as 3000 W/cm^3 without any deterioration of the fuel. Above 30000 MWD/T, if this specific power is retained, there is a risk that the platelets will swell and release gas. This phenomenon does not necessarily lead to cladding failure.
- if, on the other hand, the specific power is reduced at this stage of the irradiation, a burnup as high as 50000 MWD/T can be achieved without significantly modifying the structure of the UO_2 platelets.

4.2 SILOE programme (1976)

In this programme, two irradiations were performed without any external pressure in the pool reactor Siloé at Grenoble. Two small assemblies, each containing a few samples, were irradiated.

The following irradiation conditions were employed :

Specific power	1060 W/cm^3	and	1500 W/cm^3
Irradiation period	245 days	!	202 days
Burnup	18300 MWD/T	!	25100 MWD/T
Temperature	100°C	!	100°C

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<u>Results obtained</u> : Very good in-pile performance was obtained with the assemblies. Their appearance after irradiation was very satisfactory.

4.3 <u>Irradiation programme in the Osiris reactor</u>

As before, experimental test samples each containing few Caramels, were irradiated. The irradiations were carried out in the NaK loop at 300°C with an external pressure of 140 bars. Two series of irradiations were realized :

1973 - 1974 on 3 and 4 mm thick caramels

1975 - 1978 only on 4 mm thick caramels in order to define technological operating limits.

Specimens of the first series exhibited burnups exceeding 40000 MWD/T for the 3 mm thick caramels and 37500 MWD/T for the 4 mm thick caramels. The examinations carried out demonstrated that no gas had been released in the compartments and that the separators had performed very well.

The results obtained are related to :

- thermal conductivity of uranium oxide as a function of burnup,
- determination of the maximum normal service temperature,
- maximum temperature of separators,
- operating limits for the thicknesses of 3 and 4 mm.

Figure 3 shows an example of an operating limit for a 4 mm thick Caramel, up to a burnup of 50000 MWD/T . Since the maximum operating temperature of the fuel is known, it is possible to transpose these results to other Caramel geometries. Hence in the "equivalent" case of the Osiris reactor, maximum specific powers are greater than 5000 W/cm^3, whereas the maximum operating specific powers of Osiris are about 4000 W/cm^3 up to a burnup of 20000 MWD/T . They then decline to 2500 W/cm^3 at the maximum burnup of 30000 MWD/T .

Other test irradiations, were performed in loops in the Osiris reactor : these include two irradiations of the Irène programme carried out in a pressurized water loop reproducing real cooling conditions ; in one of these irradiations used for safety studies, a leak detection signal was generated ; the depositing of corrosion products under low flow rate conditions was studied in the other irradiation.

Power cycling studies were performed on 4 mm thick caramels in samples having reached a burnup of 30000 MWD/T in the Osiris reactor before it was shut down in July 1978. These cycles were carried out under the following conditions :

uppermost part 1250 W/cm^3
lowest part 375 W/cm^3
withdrawal and descent velocity : 400 $W.cm^{-3}mn^{-1}$
number of cycles 3634

Finally, the start-up of the new core of Osiris was preceeded by the qualification of three precursor assemblies in the previous core ; these tests widely covered the range of operating conditions encountered with Osiris.

5. CARINE EXPERIMENT CARAMEL FUEL CLADDING FAILURE FOLLOWUP

To appraise the operational safety of such a fuel regarding risks of fission product or fissile material release into the reactor primary system, a cladding failure followup test has been carried out under conditions corresponding to OSIRIS operation and using a test loop independent of the EL 3 reactor.

This cell, located in the D_2O tank of EL 3, forms a heavy-water cooling system separate from the reactor cooling system. The possible pollution of heavy water is thus limited to that system.

A cladding burst detection device using delayed neutrons with ^3He counters is installed in the system. This device is similar to that used in OSIRIS.

TEST CONDITIONS

The fuel element, manufactured by the same process as standard elements, comprised 32 UO_2 platelets enriched to 7 %.

The cladding defect is an ∿ $1mm^2$ circular hole. The fuel rating during irradiation was raised to 3050 W/cm^2, cooling being ensured by heavy water circulating at 10 m/s. These conditions are very like those encountered in OSIRIS.

The fuel element was installed in an aluminium sleeve channeling water on both sides of the fuel plate to cool it.

The power released in the fuel was measured by establishing a heat balance. The cooling water temperatures were recorded by three thermocouples at the inlet and three triple thermocouples at the outlet to limit uncertainties arising from uniform temperatures in a cross section. The flow rate was measured by a calibrated turbine inserted in the system.

Cladding failure was detected by two parallel systems ; one uses a BF 3 counter normally operated on the EL 3 independent cell installation ; the other, of higher performance and used on OSIRIS, is fitted with an ^3He counter.

TEST RESULTS

The evolution of the signal showing the amount of delayed neutrons during irradiation is given in fig. 4. It should be noted that 3 pseudo-plateaus of activity are present at increasing levels. Their duration is of about 5 h for the first, 30 h for the second, and 3 h for the third. During the first two pseudo-plateaus, fission product wafts have given rise to activity peaks whose amplitude is near the average signal.

Between these pseudo-plateaus, the evolution of the signal is faster and faster, following an exponential law. The time to double the signal value, 30 h during the first phase of fast evolution, goes down to 3 h during the second phase.

After the third pseudo-plateau, severe activity variations due to fission product wafts are recorded, the average signal first increasing very rapidly, then stabilizing for about 1 h, 40 min.

The delayed-neutron detection device used is completely representative of that installed in the OSIRIS reactor, which has allowed the time to determine when a cladding failure detection threshold is reached.

The results obtained show that this threshold is exceeded after the third pseudo-plateau and that irradiation still lasts for about 2 h in these conditions. Despite this fact, a very low level of activity of the radionuclides corresponding to fuel release was recorded.

The examinations carried out on the fuel after irradiation have shown that the hole previously drilled and the underlying fuel have not been spoiled significantly.

Moreover, the sequence of the experiment has proved the excellent behavior of the cladding failure detection system (CBD) installed on OSIRIS.

In conclusion the CARINE experiment has shown the excellent behavior of Caramel fuel in the case of a cladding failure and the possibility of detecting a failure in Osiris before serious pollution occurs in the reactor systems.

6. THE OSIRIS EXPERIENCE

6.1 Adaptation of the plant

The OSIRIS reactor has been chosen for this experience of a LEU fuel in a research reactor because of its very high performances. The fuel is thus used in severe conditions which are going well beyond the needs of research reactors on the whole.

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These severe conditions and the absence of margins,except those necessary to the safety, with the U-Al HEU fuel,mainly explain the necessity of the transformations of the core primary cooling circuit. It must indeed be remembered that this reactor was first designed for an operation at a rate of 50 MW ; the level of 70 MW was reached in 1968 only, after a small adaptation of the circulating pumps which were so driven to their limits.

The primary cooling system consisting of four groups of heat exchangers and pumps in parallel, each pump was associated with a heat exchanger. Three of these pumps were used simultaneously.

For the new fuel, the decrease of the number of plates of each fuel element (17 compared with 24 previously) had to be compensated by increasing the primary cooling flow rate to improve the removal conditions of the core power.

Because of the impossibility to increase the flow rate in each one of the exchangers, an adaptation of the main piping allows the connecting of the four exchangers to the outlet of each one of the four pumps. A main pipe connects the discharge of the pumps to the inlet of the heat exchangers. The pumps have been changed and their power increased. In this new situation the reactor is operated with three pumps and four heat exchangers.

The very works linked to the change of the fuel ran from the end of 1978 to August 1979. It was made use of a longer shutdown of the reactor for important maintenance works on the coatings of the storage capacities and of the decay tanks.

The other adaptations for the operation of the new oxide fuel were really lesser and limited to some strengthening of the structure of the dry storage tanks of the non irradiated fuels.

The modification of the cladding rupture detection system was already a project with U-Al fuel.

6.2 Changes in experimental conditions

For the experimental irradiations, the important parameters are the thermal and fast neutron fluxes levels. The gamma flux causes the liberation of additional heat energy which can be detrimental for the cooling. A certain quality of the neutron spectrum is aimed at for certain investigations of damage (better ratio of fast to thermal flux). We shall examine the irradiation conditions with the oxide fuel and compare them with the previous situation (U-Al).

The first calculations, then a serie of measurements taken in ISIS and at last, the experience of 18 month of OSIRIS operation provide us with an accurate idea of the changes in experimental conditions in OSIRIS.

6.2.1 The fast neutron flux (E > 1 MeV)

It was showed by the first calculations that the fast flux level was not modified with the new fuel if the core size was kept. This result has been verified from ISIS and OSIRIS. The loss in average fast flux level is indeed equal to the increase of the size of the core the number of fuel elements being passed from 39 to 44 because of the hydraulic and mechanical behavior of the reactor structures.

6.2.2 The thermal neutron flux

The very large absorption cross section of the new fuel, due to its high ^{235}U loading is reflected at an equivalent total power, by a significant drop in thermal flux in the network (35 to 40 % for these experiments). The spectrum quality is however better (gain of about 40 % in the fast / thermal flux ratio) for experiments on damage on structure materials.

The drop in thermal flux in the network has no detrimental consequences on the experimental program, the network being exclusively used for its characteristics in fast fluxes.

The loss on the thermal flux in the periphery of the core is, on an average, of 15 %. But here also, it has to be taken into account the increase of the size of the core and of the number of available experimental location on the external grids.

6.2.3 Gamma heating

Gamma heating decreases in the network and this is an advantage for some experiments. In the network irradiation locations
U-Al core : 10 to 15 Watt/g
oxide core : 4 to 8 Watt/g

6.3 State of the experience on OSIRIS

6.3.1 The reactor operation

The Osiris reactor was loaded with the new oxide LEU fuel in October 1979. A start-up test cycle took place in January/February 1980. From that time to July 1981, in addition of the start-up cycle, 12 cycles of roughly 4 weeks for each one took place. The total energy delivered by the reactor during this period is 21600 MWD at 70 MW.

The following table gives for each cycle, the ^{235}U loading in the beginning of the cycle the energy delivered by the reactor the number of EFPD of the cycle, the average burn-up of the unloaded fuel elements. It has to be pointed out that, for the first cycle, the average enrichment was only 6 % with fuel elements at 4,75 %, 5,62% and 7 %. The reloadings are done now with 7 % enriched fuel. At the end of 1982, this enrichment will be raised to 7,5 %

Cycle	^{235}U loading at the beginning of cycle	Energy delivered MWD	Number of EFPD	Average burn-up of the unloaded fuel elements MWD/T
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

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Each fuel element remains in the core for 5 or 6 cycles. At the end of each cycle it is proceeded to a partial refuelling and to a shuffling of the remaining fuels.

6.3.2 Working conditions of the fuel and statistics

The working conditions of the fuel are very hard. Particularly, the average and maximum specific powers in the oxide are well beyond those met in PWR reactors or of those for almost all the research reactors through out the world.

- average specific power in oxide : 1700 W/cm^3 of UO_2
- maximum specific power in oxide : 4300 W/cm^3 of UO_2

To make sure of the satisfactory behaviour of the fuel in the reactor, a programme of systematic non-destructive testing was undertaken. This involved testing the water channels, performed by a system of strain gauges, and a comparison with measurements taken after fabrication. It covered all the assemblies unloaded after the first six operating cycles, and half of the assemblies unloaded after the subsequent six cycles, making 90 assemblies in all.

This programme, currently under way, will be supplemented by destructive testing of one of the most irradiated assemblies, which has reached a burnup of 30000 MWD/T .

The overall measurements thus taken serve to provide a global estimate that is statistically representative of the changes in the characteristics and of the behaviour of the Osiris Caramel element under irradiation.

At the start-up with the oxide fuel, the licensing conditions allowed 20000 MWD/T average burn-up for a fuel element. This limit was raised to 25000 MWD/T in November 1980 and up to 30000 MWD/T in February 1981. These improvements were founded upon the good behavior of the fuel confirmed by the systematic non-destructive testings on unloaded irradiated elements. For the moment this average burn-up

(30000 MWD/T) is not reached on the whole of the elements. It needs to raise the enrichement to 7,5 %.

Presently 63 elements have got an average burn-up above 20 000 MWD/T ; among, them, 26 have passed beyond 25000 MWD/T and 8 have reached an average burn-up between 28000 and 30000 MWD/T.. It has to be pointed out that at an average burn-up of 30000 MWD/T corresponds to a maximum burn-up of 40000 to 43000 MWD/T for the most irradiated platelets.

7. THE CASE OF OTHER RESEARCH REACTORS

The performance of the fuel in Osiris are high enough to cover all the possibilities of research reactors.

On the other hand, the adaptation of Osiris is not representative of the majority of the existing reactors, the power of which is of the order of the MW or a few MW. In those cases, the change of the fuel might be done without any important modification and with a shorter shut-down time than for Osiris. An exemple for a low power reactor is given by ISIS, the neutronic mock-up of OSIRIS, the power of which is limited to 700 KW. The change of the fuel has been realized without any modification of the core structures of the cooling circuit or of the control. The work has been limited to a strengthening of the structures of the storage racks. As for the shut-down time, it was limited to the time necessary to the unloading of the old fuel, to the reloading with the new fuel and to the measurements of the core parameters for a safe operation (rods efficiency, power mapping, neutron flux). OSIRIS and ISIS are clearly situated at the two ends of the scale. Between the two, all the situations are possible and each case is a particular one.

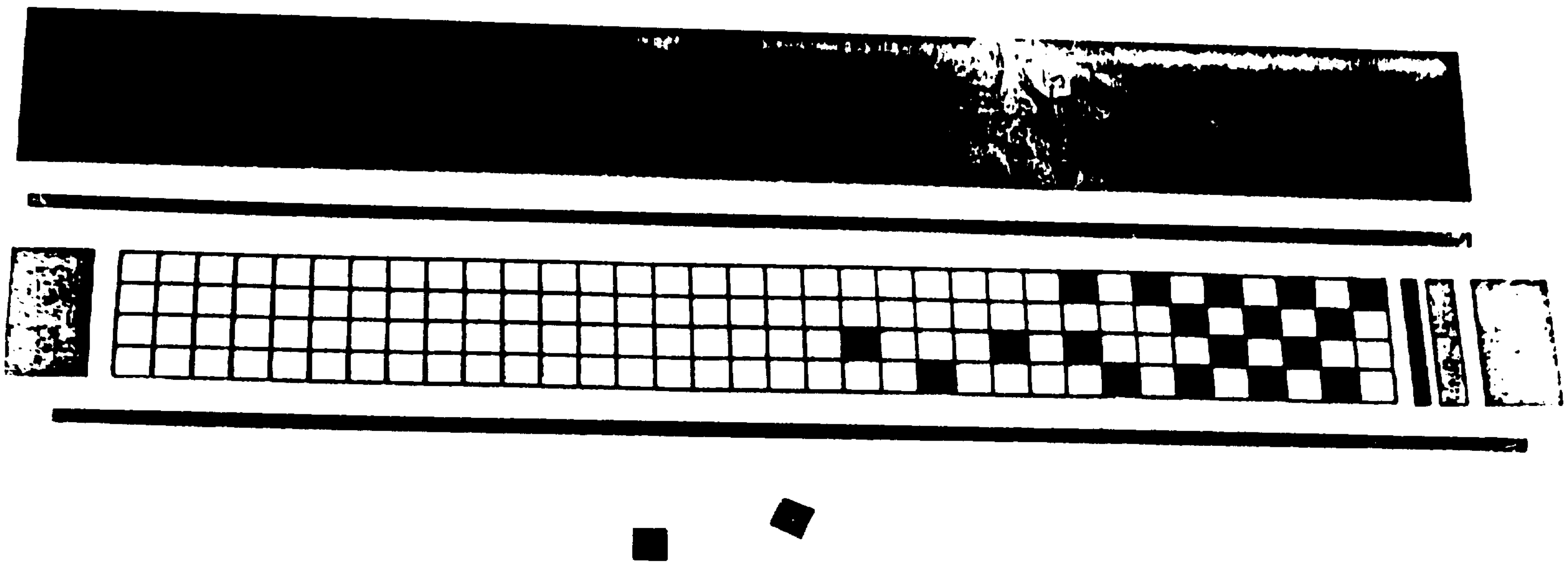


Fig. 1 – Components of a Caramel plate.

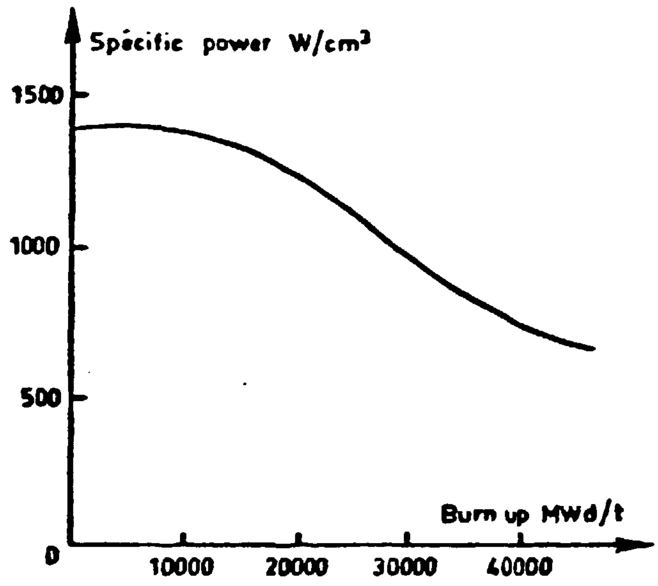


Fig. 3 - Operating limits of 4 mm thick Caramel fuel.

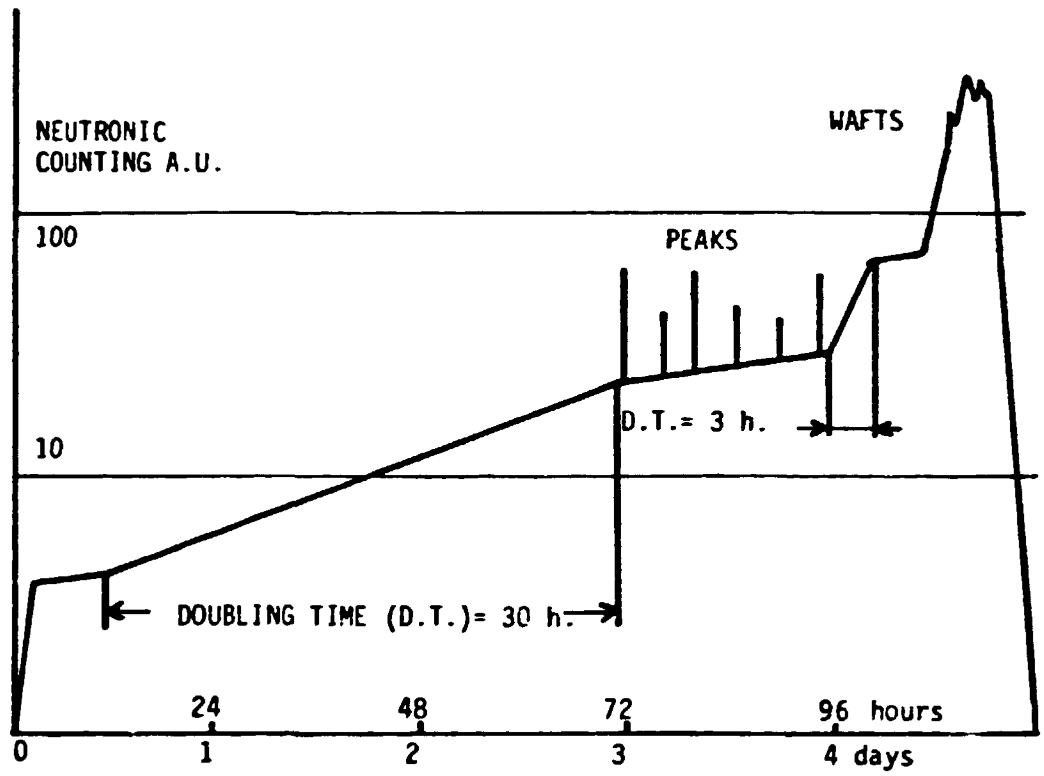


Fig. 4 - CARINE - delayed-neutron counting evolution during the irradiation.

ELEMENT OSIRIS STANDARD DAES/004

METROLOGIE DES CANAUX

	PISTE 1			PISTE 2			PISTE 3			PISTE 4					
	MAX	MIN	MOY	MAX	MIN	MOY	MAX	MIN	MOY	MAX	MIN	MOY	MOY-CANAL	ECART	%
CANAL 1	2.78	2.58	2.67	2.81	2.63	2.73	2.86	2.65	2.77	2.86	2.65	2.74	2.73	0.07	2.4
CANAL 2	2.76	2.49	2.66	2.74	2.50	2.62	2.70	2.46	2.62	2.75	2.53	2.64	2.63	-0.03	-1.0
CANAL 3	2.74	2.56	2.63	2.76	2.58	2.66	2.80	2.54	2.67	2.85	2.65	2.72	2.67	0.01	0.3
CANAL 4	2.75	2.57	2.65	2.66	2.49	2.58	2.63	2.40	2.53	2.56	2.36	2.46	2.55	-0.11	-4.0
CANAL 5	2.70	2.55	2.63	2.76	2.59	2.69	2.82	2.61	2.72	2.81	2.60	2.70	2.68	0.02	0.8
CANAL 6	2.79	2.61	2.68	2.77	2.54	2.66	2.71	2.53	2.64	2.76	2.57	2.66	2.66	-0.00	-0.1
CANAL 7	2.74	2.48	2.60	2.72	2.49	2.60	2.74	2.50	2.63	2.76	2.49	2.61	2.61	-0.05	-2.0
CANAL 8	2.73	2.41	2.59	2.76	2.50	2.63	2.74	2.50	2.62	2.71	2.49	2.60	2.61	-0.05	-2.0
CANAL 9	2.85	2.57	2.66	2.85	2.57	2.69	2.90	2.60	2.74	2.86	2.61	2.74	2.71	0.05	1.7
CANAL 10	2.76	2.54	2.67	2.76	2.56	2.66	2.76	2.51	2.64	2.69	2.53	2.61	2.64	-0.02	-0.7
CANAL 11	2.77	2.45	2.59	2.85	2.51	2.64	2.82	2.48	2.64	2.83	2.62	2.70	2.64	-0.02	-0.8
CANAL 12	2.86	2.65	2.75	2.83	2.63	2.72	2.82	2.60	2.70	2.77	2.53	2.64	2.70	0.04	1.5
CANAL 13	2.87	2.57	2.69	2.83	2.51	2.68	2.84	2.51	2.66	2.86	2.58	2.71	2.68	0.02	0.8
CANAL 14	2.79	2.56	2.69	2.82	2.55	2.67	2.78	2.55	2.66	2.82	2.54	2.66	2.67	0.01	0.3
CANAL 15	2.77	2.62	2.70	2.84	2.61	2.71	2.85	2.59	2.69	2.76	2.51	2.63	2.68	0.02	0.8
CANAL 16	2.84	2.59	2.70	2.81	2.55	2.71	2.83	2.55	2.72	2.83	2.62	2.72	2.71	0.05	1.9

MOY GENE 2.66

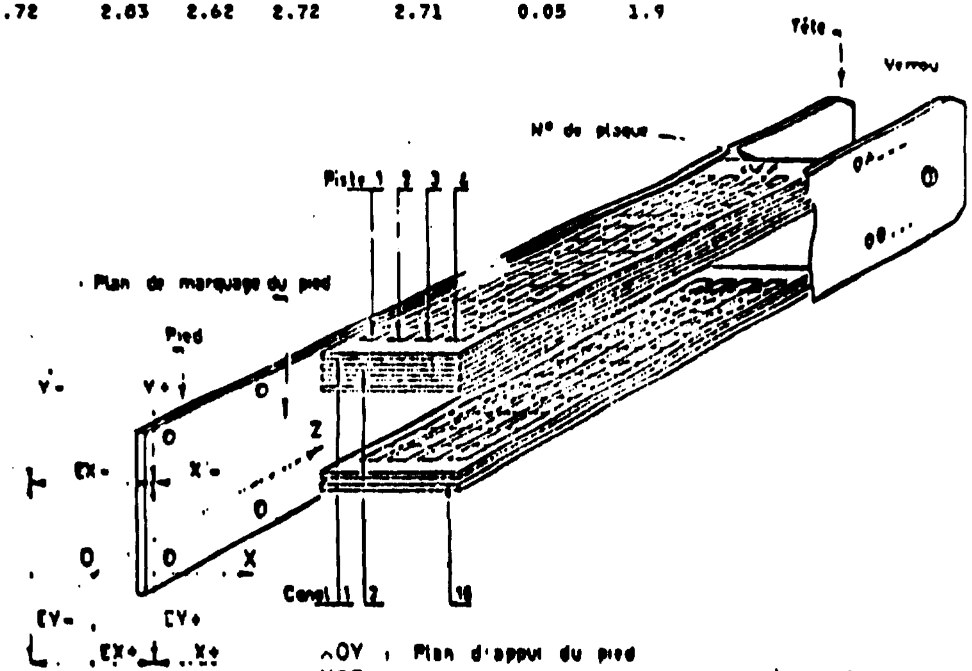
ECART TYPE 0.079

METROLOGIE EXTERNE

Z	X-	X+	EX-	EX+	Y-	Y+	EY-	EY+
30.	41.06	41.03	82.09	82.08	41.14	41.14	82.30	82.28
110.	41.00	40.93	82.00	82.06	41.17	41.19	82.34	82.27
190.	41.18	41.08	82.16	82.19	41.05	41.10	82.36	82.29
270.	41.17	41.10	82.15	82.20	41.02	41.09	82.37	82.35
350.	41.14	41.10	82.16	82.20	41.01	41.08	82.41	82.35
430.	41.12	41.13	82.17	82.22	41.03	41.08	82.43	82.36
510.	41.09	41.11	82.17	82.23	41.02	41.00	82.45	82.38
590.	41.09	41.13	82.18	82.21	41.02	41.08	82.45	82.30
670.	41.07	41.12	82.20	82.23	41.04	41.08	82.47	82.42
750.	41.07	41.14	82.21	82.25	41.04	41.05	82.50	82.40
830.	41.04	41.13	82.15	82.21	41.06	41.06	82.50	82.44
910.					42.16	42.15	84.32	84.30

TOLERANCE* SUR EX-,EX+ 82.20 +/- .20
EY-,EY+ 82.40 +/- .20
84.40 -.05/-.1 POUR Z=910.

* PASSAGE SUR CALIBRE SECS : OUI
* PASSAGE SUR GABARIT SPS : oui



OY : Plan d'appui du pied
XOZ : Plan de symétrie du faisceau parallèle au plan des plaques
YOZ : Plan de symétrie du faisceau perpendiculaire

[illegible]

CARAMEL PLATES - CHARGE OF ^{235}U PER UNIT AREA CONTROL

PLATE NUMBER : OS 2645 S T

NOMINAL CHARGE : 90.5 MG $^{235}U/CM^2$ (E = 7.00 %)
AVERAGE MESURED CHARGE : 91.8 MG $^{235}U/CM^2$ (+ - 0.5)
CORESPONDING DEVIATION : 1.4 %

DEVIATION + - %	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

DEVIATION MIN = - 0.3 MAX = 3.3 % NOMINAL CHARGE

CHARGE $^{235}U/CM^2$ HOMOGENOUS PLATE