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CONFERENCIA INTERNACIONAL SOBRE UTILIZACION DE REACTORES
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PHYSICS OF GRAPHITE LATTICES WITH PLUTONIUM BEARING FUELS

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1. INTRODUCTION

1.1. The economics of a nuclear power plant highly depend on the fuel utilization. It is necessary to predict with great accuracy the burn-up level at which the fuels have to be rejected, the maximum irradiation level, in order to achieve the best fuel management (radial or axial shuffling, unloading, type of fuel to be reloaded, etc...). Thus one must be able to compute, under all conditions encountered in the reactor life, the various physical phenomena varying with the fuel composition : plutonium build-up, isotopic changes, depletion of the uranium 235, fission product formation, variation of the neutron spectrum and of the effective cross sections of the various present nuclei, variation of the total reactivity, variation of temperature coefficients.

1.2. The Commissariat à l'Energie Atomique has carried out since 1958 a set of theoretical and experimental studies in order to increase our knowledge of all these problems. The theoretical studies have mainly been directed to develop a

synthetical model for representing neutron thermalization. This allows to take into account the neutron spectrum in the thermal range with a high accuracy and to compute the effective cross sections of heavy nuclei, as often as necessary so as to follow the variation of the isotopic composition [1], [2], [3], [4]. Such a method is particularly adapted to the systematic work which is required to interpret experimental results.

1.3. Due to the great number of phenomena involved in fuel burn-up, the numerous uncertainties on the fundamental data, and the various approximations introduced in the computation, it is necessary to compare the theoretical methods developed to experiments. Various types of experiments and of methods for doing this comparison and for studying the physics of plutonium-fuels may be considered ; in fact they are complementary and it is not possible to "shunt" one or the other of these methods if a complete study of the physics of plutonium lattices is to be fully performed.

a) First idea. Measurements "in situ" in power reactors

At first sight, such measurements could be considered as sufficient, since they allow us to follow on the reactor itself : Reactivity changes, variation of temperature coefficients and fuel loading policy.

But, if these measurements are useful for the reactor operation, they cannot be applied without difficulties to other reactors, as soon as one modifies such parameters as temperature, lattice and fuel geometry, or loading policy. Measurements on power reactors allow to check computation models, but not to develop them. Therefore we will not deal here with this type of measurements.

b) Second idea. Measurements on irradiated fuels

In order, to have a better understanding of the measurements made on power reactors, some direct experiments on irradiated fuels, under well defined conditions, are necessary. Two types of measurements are possible : On one hand, isotopic analyses so as to know the variation with burn-up of the isotopic composition of heavy nuclei.

On the other hand, critical measurements are useful to correlate reactivity changes and variations of the fuel composition. Critical experiments on irradiated fuels are obviously difficult to perform (fuel handling problems) and to interpret (knowledge of burn-up conditions, heterogeneous distribution of plutonium, ...).

c) Third idea. Measurements on "reconstituted" fuels.

To develop and to check the computation methods as well as the fundamental data used, it is necessary to resort to experiments of a more basic character, in particular on "synthetic" fuels, plutonium-uranium alloys, which allow to reproduce under conditions easy to calculate, the composition of irradiated fuels. In varying the plutonium-uranium ratio and the isotopic composition of both elements (mainly the U^{235} and the Pu^{240} contents), it becomes possible to study the related effects on reactivity, temperature coefficient, spectrum, effective cross sections...

2. ANALYSES OF IRRADIATED FUELS

An accurate analysis of the fuel composition and of its variation during burn-up gives essential informations, provided that the burn-up conditions, and in particular the moderator temperature and the neighbouring spectrum are well known. Those conditions are often poorly known, due to variations of power during the reactor life. It is then necessary to analyze a rather great number of fuels so as to have accurate results as a function of the various irradiation parameters : fuel geometry, lattice geometry, surrounding spectrum, irradiation level.

An important program of irradiated fuel analyses is now being done ; it has already given accurate results [5] which allow us to check the new burn-up codes. A number of analyses have been made, over a large range of parameters :

- natural uranium fuels, 28 mm dia. rod from G2 (graphite lattice), irradiated with moderator temperatures from 200 to 350 °C, their burn-up varying from 200 to 4500 MWD/T.

- 1.6 % enriched uranium fuels, tube 23.3 x 29.5 mm, from EL 3 (heavy water lattice) ; burn-up from 700 till 8000 MWD/T.

- natural uranium fuels, tube 35 x 14 mm, from EDF 1, outer zone (pitch 224 mm) ; burn-up from 300 to 1500 MWD/T.

- natural uranium fuels, tube 40 x 18 mm, from EDF 2, burn-up from 500 to 3500 MWD/T.

All these analyses have been made with the greatest possible accuracy, in order to be able to deduce with a sufficient precision the physical parameters of burn-up, i.e the effective cross sections. The methods used and the accuracy obtained are the following :

a) Uranium analysis

A high accuracy is required to be able to use the U^{235} depletion as a measurement of the irradiation level.

The analysis is made with a UF_6 spectrometer and the accuracy on the U^{235}/U^{238} ratio normalized to unity for natural uranium is 5.10^{-4} . The U^{236}/U^{238} ratio is measured to 5.10^{-6} .

b) Plutonium analysis

The isotopic analysis of plutonium is made with a thermoionic source mass spectrometer. The accuracy on the 240/239 ratio is about 1 % : the 241 and 242 isotopes are also determined, with an accuracy depending on their concentration.

c) Plutonium/uranium ratio

For this measurement, the technique of the double isotopic dilution is used with one tracer, which is a mixture of U^{233} and Pu^{242} . The Pu/U ratio is obtained to 1 %.

A number of results have been presented to the EAES Symposium at Karlsruhe (June 27-29, 1966) [5]. Table I recalls these results, obtained on irradiated fuels in the graphite-gas reactor G2. Table II gives the deviation in % between these measurements and the value calculated with the spectrum method, mentioned in the introduction.

3. EXPERIMENTS ON PLUTONIUM-URANIUM LATTICES

A great number of experiments on natural uranium lattices has led to the establishment of a coherent set of formulae relative to non irradiated lattices. One of the main difficulties encountered in burn-up studies is the uncertainty on effective cross sections of the plutonium isotopes.

We have seen that an analytical study of these properties requires series of experiments performed on plutonium-uranium alloys, so-called "reconstituted fuels". These fuels have the advantage over the irradiated ones of being manufactured at will. They are exempt from fission products and present a homogeneous distribution of plutonium.

The fuels have been studied with two experimental methods : a progressive replacement method, or substitution, and an oscillation method. Spectral index measurements have also been done.

3.1. Studied fuels

The substitution technique requires an amount of fuel in the order of one ton ; we have therefore limited ourselves to the study of three sets with different contents :

1 P set : natural uranium + 0.05 % of Pu containing
6 % of Pu ²⁴⁰

2 P set : 0.22 % depleted uranium + 0.30 % of Pu containing
8 % of Pu ²⁴⁰

3 P set : natural uranium + 0.05 of Pu containing
25 % of Pu ²⁴⁰

The oscillation technique has the advantage of requiring only one fuel element, or sample ; however difficulties inherent to this type of experiment lead to consider this method as complementary to the substitution technique, the latter giving better absolute values.

Therefore samples from the three sets of substitution have been measured with the oscillation technique. A large range of samples allowing a better study of the variation of the effective cross sections with the total content of plutonium and its isotopic content has been measured with this method too.

The samples are listed in Table III.

In all cases, these uranium-plutonium fuels have the same geometry : they are rods of dia. 29.2 mm and height 29.25 cm, with Mg cans in CESAR experiments.

3.2. The substitution method

a) Basis of the method

The basis of the method which has been used to study the three sets 1, 2, 3 P in AQUILON (at 20 °C), MARIUS (at 20 °C) and CESAR (at elevated temperature) reactors is classical : the fuel elements of the "reference" lattice (studied by buckling measurements) are progressively replaced by the fuel elements of the lattice to be studied. The number of substitution channels is chosen so as to maintain the best possible symmetry in the central area.

The variations of the critical size are determined in the case of CESAR by changing the number of channels loaded at the boundary core-reflector. Measurement of the doubling time are performed for each different loading. Extrapolation to zero reactivity gives the critical radius. In a reactor such as AQUILON, the critical size variation is deduced from the variation of the critical height of heavy water. Thus, at every step, the variation of critical size (amounting to a reactivity variation) is measured. It is the sum of two terms : i) a main term due to the differences between the fundamental properties of the two lattices, ii) a secondary term which refers to the interaction between the two lattices. In the present case, both lattices have the same geometry, and the second term is small.

To improve the accuracy of the results, a calibration of the critical assembly to a perturbation is previously made with known fuels : rods of the same geometry as the reference fuel, slightly enriched in uranium 235 (0.83 % and 0.87 %) or depleted 0.69 %

The reference (natural U) and substituted (Uranium-Plutonium) lattices have the same values of ϵ and p , since their geometry is identical ; the deviations between the calculated and experimental thermal fission factors η , can then be deduced from experiments of progressive replacement. The variations of the disadvantage factor are small and may be calculated with accuracy. It is nevertheless interesting to complete the substitution measurements with fine structure measurements, in particular to check the temperature coefficient on f , and with spectral index measurement so as to define the mean spectrum in the cell.

b) Programme

The experiments made in spring 1966 dealt with the three sets 1 P, 2 P, 3 P at 20 °C, 100 °C and 200 °C in CESAR. At the same time, a programme of measurement of fine structures and spectral indices was carried on.

This series of measurements will proceed in september 1967, when will be studied levels at 300 and 450 °C.

c) Results

The following tables give the relative deviation between experiment and calculation, on the thermal fission factor η . Detailed results are given in a communication of R. NAUDET [6]

1 P set

	Aquilon	César (hexagonal pitch) 225 mm		
T °C	20	20	100	200
$\frac{\Delta \eta}{\eta}$ Exp-Calc (10 ⁻⁵)	10 ± 40	- 10 ± 60	41 ± 60	- 24 ± 60

The experimental values of the η_9/η_5 ratio at 2200 m/sec which can be deduced from these experiments are respectively :

	Aquilon	Cesar (hexagonal pitch) 225 mm		
T °C	20	20	100	200
$\frac{\eta_9}{\eta_5}$ (experiment) η_5 (2200 m/sec)	1.0195 ± 0.004	1.018 ± 0.006	1.023 ± 0.006	1.017 ± 0.006

An excellent agreement can be noticed with the value taken for the calculation (1.019). The results do not depend on temperature, within the experimental errors.

3 P set

	Aquilon	Cesar (hexagonal pitch) 225 mm		
T °C	20	20	100	200
$\frac{\Delta\eta}{\eta}$ (Exp-Calc) (10 ⁻⁵)	- 145 $\pm$ 40	- 160 $\pm$ 60	- 230 $\pm$ 60	- 206 $\pm$ 60

The 3 P set differs from the 1 P set only by the Pu²⁴⁰ content (Pu²⁴⁰/Pu²³⁹ = 6 % for 1 P set and 25 % for 3 P set). It thus seems that the capture of Pu²⁴⁰ is underestimated by about 15 %.

2 P set

	Aquilon	Cesar (hexagonal pitch) 225 mm		
T °C	20	20	100	200
$\frac{\Delta\eta}{\eta}$ (Exp-Calc) (10 ⁻⁵)	- 500 $\pm$ 100	- 720 $\pm$ 120	- 870 $\pm$ 120	- 952 $\pm$ 120

At low temperatures a deviation of about 600.10⁻⁵ is observed. The underestimation by 15 % of the absorption of Pu²⁴⁰ would explain half of this effect. A deviation of 300.10⁻⁵ remains which can be due :

- either to an overestimation of the self-shielding of the Pu²³⁹ resonance when Pu²³⁹ is present in large amount

- or to an overestimation by about 1 %, of the product $\nu_g \sigma_{fg}$ (η_g remaining unchanged).

At higher temperatures, the deviation between experiment and calculation increases by . 3 %. It would thus be necessary to assume that the variation of the effective fission cross-section of Pu^{239} is overestimated by about 0.7 %. The Pu/U spectral indices confirm this result (see 3.4).

On the other hand, direct measurements of the temperature coefficient by total reactivity variations between 20 and 40 °C, 100 and 120 °C, 200 and 220 °C have been made on the 2 P set. The results are briefly given below :

T °C	30	110	210
Exp. $10^{-5}/^{\circ}\text{C}$	8 ± 2.4	13 ± 1.5	16 ± 1.6
Calcul. $10^{-5}/^{\circ}\text{C}$	11	15	19

We find again, in conformity with the results of substitution measurements, a deviation of 2 to $3 \cdot 10^{-5}/^{\circ}\text{C}$ between experiment and calculation.

Finally, it can be noted that :

i) The adopted value of the η_g/η_5 ratio at 2200 m/sec (1.019) is in good agreement with the experiment

ii) The Pu^{240} absorption is underestimated by about 15 %.

iii) The values chosen for the microscopic cross-sections of Pu^{239} (Adjustement Westcott 1960 on BNL 325, 1958 ed.) lead to a temperature coefficient of the 2 P set overestimated by 3 pcm/°C.

Let us recall that this set corresponds to a graphite-natural uranium lattice with a burn-up of about 4000 MWD/T.

3.3. The oscillation method

a) Fundamentals

In a critical reactor, a standard cartridge of the central channel is replaced by a "sample" of the same geometry. Small amounts of absorbing or fissile material have been added to the reference fuel sample (usually natural uranium). The central channel loading thus modified is subjected to sinusoidal oscillations and two signals are measured :

- A reactivity signal proportional to the amplitude of the movement of a control rod. This control rod is automatically driven by a monitor so as to cancel the reactivity perturbation continuously.

- A local signal which is detected by an annular boron chamber (or, in Cesar, a fission chamber) around the central channel.

Each of these signals can be considered, in a first order approximation, as a linear combination of the variations of the absorption Σ_a and of the neutron production $\nu\Sigma_f$ cross sections in the perturbed samples. Conversely, the effective cross sections variation can be deduced from the measurement of these signals.

The direct interpretation of the measured values in terms of cross sections is difficult. Therefore the measured sample is considered to be equivalent to a natural uranium sample to which a well defined amount of U^{235} and of Boron would have been added and the results consequently expressed. This leads in the practice to measure with a great accuracy samples enriched or depleted in U^{235} and Boron samples. Thus, by means of this equivalence, the equivalences U^{235} -Boron for each U-Pu sample can be obtained through the results given by the measurement of reactivity and local signals.

Knowing the equivalences, the η of plutonium and the effective cross sections Σ_a and $\nu\Sigma_f$ are directly deduced.

b) Interpretation of the experiments

- In the system of the reactivity and local axis, any vector (G_p , L_p) characterizing a U-Pu sample can be expressed as the sum of two components : one vector along the U^{235} axis and the other along the Boron axis.

Therefore, at any point U-Pu of the diagram correspond two numbers of equivalent nuclei δN_5 and δN_B .

- It can then be written that the macroscopic cross sections are equal for Plutonium and its equivalents.

$$\begin{aligned}\sum a_p &= \sigma_{a5} \delta N_5 + \sigma_{aB} \delta N_B \\ \nu \sum f_p &= \nu_5 \sigma_{f5} \delta N_5\end{aligned}$$

Therefore, if the U^{235} and B cross sections are supposed well known, the Pu cross section can be deduced from the measurement.

Recall that for a sample depleted in U^{235} , and strongly loaded in plutonium, it is sufficient to add ΔN_5 , depletion in U^{235} , to δN_5 and to write :

$$\begin{aligned}\sum a_p &= \sigma_{a5} (\delta N_5 + \Delta N_5) + \sigma_{aB} \delta N_B \\ \nu \sum f_p &= \nu_5 \sigma_{f5} (\delta N_5 + \Delta N_5)\end{aligned}$$

- The calculation of the microscopic cross sections involves then the plutonium contents measured by analysis.

Conversely, η for plutonium is directly obtained from the measured equivalences.

$$\text{If : } \eta_p = \frac{\nu \sigma_{fp}}{\sigma_{ap}} = \frac{\nu \sum f_p}{\sum a_p}$$

It is practical to introduce

$$\eta_5 = \frac{\nu_5 \sigma_{f5}}{\sigma_{a5}}$$

Thus :

$$\eta_5/\eta_P - 1 = \frac{\sigma_{aB}}{\sigma_{a5}} \frac{\delta N_B}{\delta N_5}$$

and for the depleted fuels :

$$\eta_5/\eta_P - 1 = \frac{\sigma_{aB}}{\sigma_{a5}} \frac{\delta N_B}{\delta N_5 + \Delta N_5}$$

So taking into account the known cross sections of U^{235} and Boron, we can deduce finally

- the Pu effective macroscopic cross sections
- the η_P/η_5 ratio

- It may be considered as particularly interesting to check the coherence of the results : it is then convenient to shift from the measured values relative to sample to the same values relative to Pu^{239} . By means of spectrum and effective cross section calculations, the Pu^{239} contribution can be identified and the values at 2200 m/sec be deduced from effective values.

The results presented here have been obtained by this so called "calculated proportions method" which has the advantage of involving (for η as for the Σ) only the well known Pu isotopic contents.

c) Discussion of the method. Interpretation of the results

In this oscillation technique, there are some specific problems :

- First, the sample is different of surrounding fuels and the spectrum specific of the sample is perturbed by the other cells.

- Secondly, another perturbation of the spectrum is produced by the presence of the local chamber, surrounding the fuel. A two-group theory is not sufficient for an exact interpretation of the local signal which cannot be directly expressed in terms of effective cross sections.

- lastly, a first order interpretation of the equivalences is not satisfying and the measured effect of the flux perturbation in the rod must be taken into account, to refine the interpretation.

These different problems are now being studied : they prove that the results given by both methods (oscillation and substitution) must be interpreted in close correlation, the perturbation problems being less important for the second one.

By the oscillation method, the η of plutonium is directly obtained and may be compared to the substitution results. But, in order to know the microscopic cross sections σ_a and $\nu\sigma_f$, it is necessary to know with a great accuracy the total plutonium content and its isotopic content : for the synthetic fuels, the problem of the analyses is again encountered : we have already mentioned its importance for irradiated fuels.

d) Measurement programme

The samples we have described have been oscillated at low temperature, in MINERVE, MARIUS and CESAR. The results show that a great experimental accuracy can be reached, specially on U^{235} depleted fuels.

The programme will proceed with high temperature experiments in CESAR (100, 200, 300, 400 °C) which will begin next year, in order to better determine the values of the temperature coefficients.

e) Results

From a series of measurements made in 1965 in MARIUS we have obtained the following results.

i) η of plutonium

natural uranium bearing samples : The values of η_9/η_5 deduced from the measured values of η/η_5 do not show significant deviations as a function of the Pu^{240} content. From 13 samples, an average value and a standard deviation are obtained

$$\eta_9/\eta_5 = 0.957$$

$$\sigma = 0.005$$

Hence, using the calculation of the spectrum in the rod, a 2200 m/sec value of

$$(\eta_9/\eta_{5_0}) = 1.013 \quad \sigma = 0.005$$

The calculated values are respectively

$$\frac{\eta_9}{\eta_5} = 0.962 \text{ and } (\eta_9/\eta_{5_0}) = 1.019$$

Depleted uranium bearing samples : Samples with 0.22 depleted U give a very coherent set of results

$$\frac{\eta_9}{\eta_5} = 0.963 \quad \sigma = 0.0012$$

hence, the 2200 m/sec value : $(\eta_9/\eta_{5_0}) = 1.008 \quad \sigma = 0.0012$

We must notice the accuracy of the results, because those samples bear a large amount of Plutonium than the first.

ii) Plutonium absorption and fission cross sections

The coherence of the results is connected with the calculation of effective cross-sections which allow to identify the Pu^{239} cross-sections. The microscopic cross-sections, σ_a and σ_{f9} , then their 2200 m/sec values are obtained by dividing by the number of nuclei given by the analysis.

For the determination of the cross sections, the number of Plutonium nuclei plays an important role ; it has been necessary to improve the first analyses in order to have better coherence in the results. The following results show that the precision is still in excess of 1 %.

$$(\sigma_{a9_0}) = 1022 \text{ barns} \quad \sigma = 13.4 \text{ barns}$$

$$(\sigma_{f9_0}) = 741 \text{ barns } (\eta_9 = 2.989) \quad \sigma = 8.4 \text{ barns}$$

Samples with depleted U :

$$(\sigma_{a9_0}) = 1056 \text{ barns} \qquad \sigma = 13 \text{ barns}$$

$$(\sigma_{f9_0}) = 763 \text{ barns} \qquad \sigma = 9 \text{ barns}$$

A programme of analyses aiming to a 0.3 % accuracy on the plutonium content is presently carried out and will end in july 1967.

The values presently used in the calculations are :

$$(\sigma_{a9_0}) = 1014.5 \text{ barns} \qquad (\sigma_{f9_0}) = 740.5 \text{ barns}$$

3.4. Spectral index measurements

a) Fundamentals

By means of the spectral index, the variation of the effective cross section of an element can be determined as a function of the spectrum in which it is placed, and therefore the validity of the model can be tested.

These measurements are based, as it is well known, on the comparison of an element with a marked resonance in ther thermalization range to an element with a cross section which follows the $1/v$ law . To avoid multiple causes of error, the ratio obtained is compared to the same ratio in a thermal spectrum.

The Pu/U indices can be directly used for lattices containing Pu²³⁹. The effect of Pu²⁴⁰, which presents a resonance at 1 eV, can be studied by In/Mn indices, due to the 1.47 eV resonances of Indium 115.

b) Results

The experiments performed on Cesar with cold and heated lattices on 29.2 mm dia. fuels : natural uranium, 1 P, 2 P, 3 P sets, show an excellent agreement with calculation, in the

following tables on Pu/U measurements :

Pu/U Measurements

CESAR ϕ 29.2 mm

Hexagonal pitch 225 mm

Natural uranium

T°C	Exper.	Calcul.	Exper.	Calcul.
	Fuel		Moderator*	
20	1.292	1.278	1.181	1.186
100	1.347	1.379	1.277	1.277
200	1.545	1.549	1.423	1.428

1 P

20	1.262	1.271	1.196	1.195
200	1.517	1.530	1.421	1.439

2 P

20	1.176	1.177	1.184	1.182
100	1.252	1.257	1.289	1.274
200	1.366	1.386	1.416	1.429

3 P

20	1.253	1.274	1.198	1.197
100	1.346	1.369	1.270	1.287
200	1.510	1.530	1.430	1.438

* Average indices in the fuel and the moderator. The experimental errors are from 1 to 1.5 %.

It must be noted that the spectrum and the effective cross sections are here calculated for a fuel containing homogeneously distributed plutonium. The development of spectrum calculations on every point of the rod should afford a means for an accurate check of the theories and for their application to practical cases where the plutonium is not uniformly distributed.

The analyses of the isotopic composition of irradiated fuels already give a global check of calculations.

4. EXPERIMENTS ON IRRADIATED FUELS

4.1. The oscillation technique is a convenient method for the physical study of irradiated fuels, since it deals with a single sample and allows a systematic study of various fuel cartridges irradiated in power plants under various conditions of temperature, spectrum and irradiation levels. The measurement of the reactivity signal can be simply interpreted as the reactivity change between the new fuel and the irradiated fuel.

The interpretation of the local signal is related to fine problems of plutonium distribution in the rod and to resonant absorption phenomena.

Up to now, measurements have been performed only with reactivity signal.

4.2. Programme

a) Measurements have been made :

- in MINERVE, on 1.6 % enriched samples irradiated in the heavy water reactor EL 3, with radiation levels from 500 up to 1000 MWD/T. The samples were tubes 23.3 x 29.5. mm.

- in MARIUS, on natural uranium samples irradiated in the graphite reactor G2, rods of 28 mm dia., irradiated between 500 and 4500 MWD/T.

b) The measurement programme will proceed

- in 1967, in MARIUS, with systematic measurements (at 20 °C) on samples from cartridges irradiated in the graphite reactors G2, G3, EDF 1 and EDF 2.

- and, from 1968, in CESAR, at higher temperatures, on samples of the same type.

c) Results of the measurements

Fuel elements from a G2 channel were oscillated in MARIUS. The natural uranium fuel element has the shape of rods, of 28 mm dia. and 30 cm height ; the irradiation levels are in the range of 500 to 4500 MWD/T for moderator temperatures between 200 and 300 °C.

If the fission cross section is supposed to be well calculated, the variation of the absorption cross section between a natural uranium sample and an irradiated sample can be deduced from the reactivity signal. Burn-up calculations are made taking as an auxiliary variable the depletion in U^{235} ; the burn-up conditions are known from flux and temperature measurements made during the whole burn-up period.

The fig. 1 shows the comparison made on $\delta\Sigma_a^*$; in a further step of the interpretation, the fission products absorption can be deduced from these measurements, as the plutonium effective cross sections are studied and measured with homogeneous uranium-plutonium fuels, and the isotopic composition in heavy nuclei is accurately known by analyses.

* $\delta\Sigma_a$: variation of the absorption cross section, including fission products absorption, between a natural uranium sample and the irradiated fuel element.

TABLE I

Experimental results of analyses of irradiated fuels

Fuel position	Sample	Tmod. °C	Burn-up (MWD/T)	1- α	Pu9/U8 %	Pu0/Pu9 %	Pu1/Pu9 %	Pu2/Pu9 %	U6/U8 %
3	4	347	1029	0,1519	0,0789	9,15	0,72	0,029	0,0178
	5			0,1429	0,0751	8,55	0,63	0,023	0,0170
5	4	343	1501	0,2086	0,1040	12,55	1,27	0,070	0,0241
	5			0,1993	0,0985	11,70	1,15	0,056	0,0232
7	4	336	1916	0,2486	0,1176	15,00	1,76	0,13	0,0283
	5			0,2515	0,1183	15,30	1,76	0,13	0,0288
9	4	327	2290	0,2876	0,1327	17,87	2,19	0,20	0,0330
	5			0,2903	0,1322	18,04	2,26	0,21	0,0340
10	4	319	2495	0,3048	0,1391	18,5	2,49	0,23	0,0363
	5			0,3140	0,1393	19,0	2,50	0,24	0,0373
12	4	310	2830	0,3430	0,1550	21,45	3,10	0,34	0,0400
	5			0,3409	0,1510	20,87	2,98	0,31	0,0392
14	4	295	3540	0,4091	0,1710	24,95	3,93	0,54	0,0480
	5			0,4025	0,1705	25,60	3,99	0,56	0,0490
16	4	279	4100	0,4488	0,1816	27,8	4,43	0,72	-
	5			0,4557	0,1819	28,45	4,72	0,76	0,0525
20	4	243	4620	0,4897	0,1945	29,40	5,16	0,89	0,0555
	5			0,4999	0,1951	30,30	5,29	0,96	0,0559
22	4	221	4458	0,4831	0,1945	27,80	4,81	0,80	0,0559
	5			0,4870	0,1965	28,00	4,84	0,82	0,0551
24	4	196	3529	0,4142	0,1848	21,50	3,53	0,45	0,0484
	5			0,4117	0,1826	21,10	3,43	0,43	0,0474

TABLE II

Discrepancies (Calcul.-Exp.)/Exp. %

on isotopic compositions

Fuel position	Sample	Tmod. °C	Burn-up (MWD/T)	Pu9/U8	Pu0/Pu9	Pu1/Pu9	Pu2/Pu9	U6/U8
3	4	347	1029	+ 1,6	+ 2,8	- 2,7		+ 1,1
	5			+ 1,3	+ 2,9	- 0,7		- 0,6
5	4	343	1501	+ 0,5	+ 4,4	- 3,4		+ 2,4
	5			+ 2,3	+ 6,3	- 1,7		+ 1,6
7	4	336	1916	+ 2,2	+ 4,9	- 6,3		+ 3,7
	5			+ 2,5	+ 4,3	- 4,6		+ 3,1
9	4	327	2290	+ 1,4	+ 2,6	- 9,1	+ 0,7	+ 2,6
	5			+ 2,4	+ 2,8	- 8,9	- 1,2	+ 0,5
10	4	319	2495	+ 1,2	+ 5,1	- 6,6	+ 3,1	- 1,3
	5			+ 3,0	+ 6,3	- 1,8	+ 8,8	- 1,0
12	4	310	2830	- 0,9	+ 2,5	- 10,4	- 1,8	+ 0,6
	5			+ 1,3	+ 4,5	- 7,8	+ 5,6	+ 2,0
14	4	295	3540	+ 1,6	+ 7,1	- 3,8	+ 5,4	- 0,5
	5			+ 0,9	+ 2,1	- 8,1	- 3,9	- 4,1
16	4	279	4100	+ 2,4	+ 5,1	- 5,9	+ 3,1	
	5			+ 3,0	+ 5,0	- 5,0	+ 3,0	+ 0,9
20	4	243	4620	+ 3,5	+ 3,8	- 6,7	+ 2,3	+ 1,9
	5			+ 4,4	+ 3,8	- 5,3	+ 2,2	+ 3,2
22	4	221	4458	+ 4,5	+ 2,9	- 6,3	+ 2,1	- 0,4
	5			+ 4,0	+ 3,3	- 5,5	+ 2,5	+ 1,8
24	4	196	3529	+ 1,0	+ 3,5	- 8,4	+ 1,0	- 1,2
	5			+ 1,9	+ 4,6	- 6,8	+ 3,6	+ 0,3

TABLE III

U ²³⁵ en %	Pu en %	Pu ⁴⁰ /Pu ³⁹ en %						
		1	4	6	8	14	20	25
0.71	0.05	x	x	1 P set x		x	x	3 P set x
	0.07		x	x	x	x		x
0.65	0.05		x		x			
	0.07		x		x			
0.45	0.15				x			
	0.20				x			
0.22	25		x					x
	30		x	2 P set x				x
	35		x	x				

CONCLUSION

The program carried on by the CEA to increase our knowledge of the burn-up level in power reactors has allowed us to develop calculation methods specially well adapted to this type of studies.

Experimental results have already enable us to check these methods of calculation. They have also stressed out some possible errors which could be included in quoted calculations.

The results specially concern :

- The initial conversion factor and the change of isotopic composition versus burn-up. We recall that isotopic composition has been obtained through analysis of irradiated fuels.
- The effective cross sections of plutonium bearing fuels, which are deduced from critical experiments on homogeneous U-Pu fuels.
- The variation of reactivity with burn-up obtained through measurements on power-reactors, and the temperature coefficient deduced from critical experiments performed in CESAR.

This program is now being carried on. The main studies will include : a) Systematic measurements on fuels irradiated in various conditions and analysis of their isotopic composition, b) Oscillations in temperature in CESAR so as to precise the effect of fission products and isotopic changes on reactivity.

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Figure 1

Oscillations de combustibles irradiés dans G2

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