NEACRP OCTOBRE 1979
L 235

WORK ON GAMMA THERMOMETER IN C.E.A.

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1 - INTRODUCTION -

This report explains,the work made in CEA during the last years in the gamma thermometer field. In order to dispose of incore instrumentation able to measure the local reactor power, the use of gamma thermometer wich measures the gamma energy absorbed in its steel part is planned by EDF (the national utility of France producing electricity. This report describes :

- the methods used for the calculation of the gamma thermometer heating
- the physical signification of the gamma thermometer heating
- the variation of the gamma thermometer response during several power diagrams
- the comparison between project calculations and Monte Carlo calculations
- the influence of gamma rays from five hundred KeV to one hundred KeV.

2 - THE METHOD USED FOR THE CALCULATION OF THE GAMMA THERMOMETER HEATIN

2.1. Sources taken into account

Let us examine the sources taken into account for the gamma thermometer heating. At this time, we have only considered the gamma heating. It is planned to estimate the neutron contribution by means of ANISN spectrum calculations. The gamma sources taken into account are the following for the standard assembly.

- gamma rays coming directly from fission
- gamma rays emitted by fission products
- gamma rays from captures in U^{238}
- gamma rays from captures in U^{235}
- gamma rays from neutrons captures in fuel cladding
- gamma rays emitted by neutrons captures in borated water
- gamma rays emitted by the gamma thermometer itself and its associated water.

Gamma rays from inelastic scattering will be evaluate. For an assembly containing control rods, we have also taken into account the gamma emitted by silver, indium-cadmium rods and by the steel rods.

We have also considered elements with poisons. The gamma spectra were defined in eleven groups given in table 1. The group number eleven contains also gamma rays wich energy is lower than five hundred KeV with conservation of the total energy emitted. We have made also calculations with three groups below five hundred KeV. This calculation will be explained later.

The gamma issued from fission products are evaluated by means of the PICFEE code. Let $f_j(t)$ be the number of gamma emitted per unit of time in the energy group j, where t is the cooling time after the elementary fission. Let W (t) be the power variation versus time t in fission rate per unit of time. The PICFEE code calculates the convolution product (1) for several cooling time t.

The result of the integration is the gamma spectrum emitted by the fission products.

$$(1) \qquad S_j(t) = \int_0^t W(\tau)\, f_j(t-\tau)\, d\tau$$

The functions are obtained by the following way.

For short cooling times, f_j (t) is given by Maienschein measurements for t between 0 and fifteen hundred seconds. After 1 500 seconds, the kernels f_j (t) are calculated by the code PEPIN which solves the differential equations satisfied by the fission product concentrations during the cooling time after the elementary fission (PEPIN treats also any power diagram). A PEPIN calculation involves six hundred thirty five fission products. For each fission product, the library of PEPIN contains capture cross section, half time, branching ratio, γ and β spectrum emitted by radioactive decay.

The PICFEE calculations don't take into account the neutron capture on fission products. To evaluate this approximation we have made a PEPIN calculation which take into account the neutron captures and a PICFEE calculation. The two calculations are made with the same power diagram. The difference between the two calculations is lower than one percent during the power operation and for short cooling times (thousand seconds).

The determination of the gamma sources from captures and fissions needs the knowledge of several reaction rates in all parts of the cell : captures in water, in boron, in fuel cladding, in U^{235} and U^{238}, fission density, captures in poisons and control rods and so on. For this pupose, we have used the cell code APOLLO which solves the Boltzmann equation by the collision probability method.

2.2. Gamma transport calculations

Two different gamma transport calculations were made to obtain the gamma thermometer heating.

1°) line of sight point attenuation kernel method
2°) Monte Carlo method

The line of sight point attenuation kernel method was used for all gamma contributions except for gamma coming from captures in the gamma thermometer itself and its associated water. MERCURE IV performs this calculation. MERCURE IV treats a three dimensional geometrical configuration. The geometry is composed of homogeneous volumes limited by plane or quadratic surfaces. The source distribution is also three dimensional. The linear attenuation coefficients are used in the multigroup structure defined in table I. The build up factors use the Kitazum formula, which takes into account the sequence of materials along the gamma path. The integration of the attenuation kernel is performed by a Monte Carlo method. The program calculates and adjusts itself importance values which are used for sampling source particles. For this calculation, we have described exactly the fuel rods, the control rods both with their cladding and the associated water.

The picture number 2 shows the geometry used in MERCURE IV calculations.

The Monte Carlo method was used to calculate the heating resulting from the captures in the gamma thermometer itself and in its associated water. We have used the code TRIPOLI a general, three dimensional Monte Carlo program, which treats the slowing down and the diffusion of neutrons and gamma in source problems (or critical problems for neutrons). The geometry is the same as MERCURE IV : it is described as a combination of volumes bounded by portions of first or second degree surfaces. The orientation in space of these volumes is quite arbitrary. Repetitive geometry by translation, symetry, rotation can be treated. For gamma calculations, the cross sections have a multigroup structure with 61 groups between 10 KeV and 10 MeV. The program can solve deep or not penetration problems by using variance reduction technics based on exponential transformation, and biasing of angular scattering laws. The distribution of sources can be any arbitrary function of space, energy and direction.

3 - PHYSICAL SIGNIFICATION OF THE GAMMA THERMOMETER HEATING

We give now some results obtained with our method.

First we take into account gamma radiation emitted by equilibrium fission products. The table 3 gives the percentage of heating in the gamma thermometer from several cell rows.

About 91 percent of the heating comes from the instrumented fuel element and 9 percent from the 8 surrounding elements.

The table 4 gives the decomposition of the gamma thermometer heating. 65 percent of the heating is directly proportionnal to power density or thermal flux, 35 percent comes from the fission products.

The heating due to the gamma issued from neutron captures in the gamma thermometer itself and its associated water amounts up to 7.4 percent additional.

4 - VARIATION OF THE GAMMA THERMOMETER RESPONSE DURING SEVERAL POWER DIAGRAMS

The first power diagram is shown on the picture 5. The diagram is periodical and the period is exactly one day. The power decreases or increases by a factor 3 during half an hour. The table 6 gives the corresponding results. The ratio between the gamma thermometer heating and the nuclear power is between 1.25 and 0.93. *

The picture number 7 shows another type of power diagram and the corresponding results.

For each diagram and for several times we have an importance map for each cell to the gamma heating.

It is possible to get an estimation of the value of the local power P_N (t) from the gamma thermometer heat measurement $i\gamma$ (t).

This comes from the existing relationship between heat measurement and local power. This relation is given by the convolution Volterra-type integral equation (2) :

$$(2) \qquad i\gamma(t) = \alpha P_N(t) + \int_0^t H(t-\tau)\, P_N(\tau)\, d\tau$$

The convolution product comes from the heating due to the fission products and α from the other sources. Many way for solving a Volterra equation are known as Hilbert method, Neumann series, degenerated kernel approximation. This resolution will give P_n (t).

* The ratio between gamma thermometer heating and power is normalized to 1 for t $\longrightarrow \infty$

5 - COMPARAISON BETWEEN MONTE CARLO METHOD AND LINE OF SIGHT POINT ATTENUATION KERNEL METHOD

We made TRIPOLI and MERCURE IV calculations with the same conditions for two fuel rods. The first fuel rod was very far from the gamma thermometer and the second was near. For each rod, we calculated the contribution of the 11 energy groups defined in table 1. Our Monte Carlo method can give a point wise estimation of the response for neutron but presently not for gamma. Then we have calculated the gamma heating in the central square of water.

The tables 8 and 8 bis give the results obtained with TRIPOLI and MERCURE IV for the gamma rays coming directly from fission. The agreement is good above 2.5 MeV. MERCURE IV over-estimates the heating below 2.5 MeV essentialy at 1 MeV. MERCURE IV over-estimate the total response of 15 percent for the distant fuel rod and of 11 percent for the nearest fuel rod. In view of the standard deviation, about 5 percent, the overevaluation is about the same for any rod.

We also calculated the contribution of :

- gamma rays emitted by fission products
- gamma rays from captures in U^{238}
- gamma rays from captures in U^{235}

The table 9 gives the relative contribution to the heating coming from the different sources. The agreement between TRIPOLI and MERCURE IV is very good. In this calculation we don't take into account the following gamma sources :

- captures in fuel cladding
- captures in borated water
- captures in gamma thermometer itself.

These gamma sources contribute for about 11 percent additionnal to the gamma heating.

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6 - INFLUENCE OF GAMMA RAY BELOW 500 KeV

With PICFEE we have computed the gamma spectrum from 8.5 MeV to 100 KeV with 2 groups below 500 KeV. For 8 fuel rods at different distance from the gamma thermometer, we have made two MERCURE IV calculations. In these two calculations the ten energy groups above 0.75 MeV are the same. In one calculation we have taken into account the exact gamma spectrum. In the other calculation we have only one group between .75 MeV and .5 MeV with conservation of the energy emitted below .75 MeV.

The table 10 give the results for several fuel rod nows.

The calculation with 11 groups over estimates the response of 0.4 %.

The calculation of the group number 11 is not good far from the gamma thermometer (40 %), but this contribution is unimportant.

TABLE 1

Number of group j	Uper energy (MeV)	Lower energy (MeV)
1	8.5	7.5
2	7.5	6.5
3	6.5	5.5
4	5.5	4.5
5	4.5	3.5
6	3.5	2.75
7	2.75	2.25
8	2.25	1.75
9	1.75	1.25
10	1.25	0.75
11	0.75	0.50

Figure 2

COMPARAISON MERCURE-4 / TRIPOLI

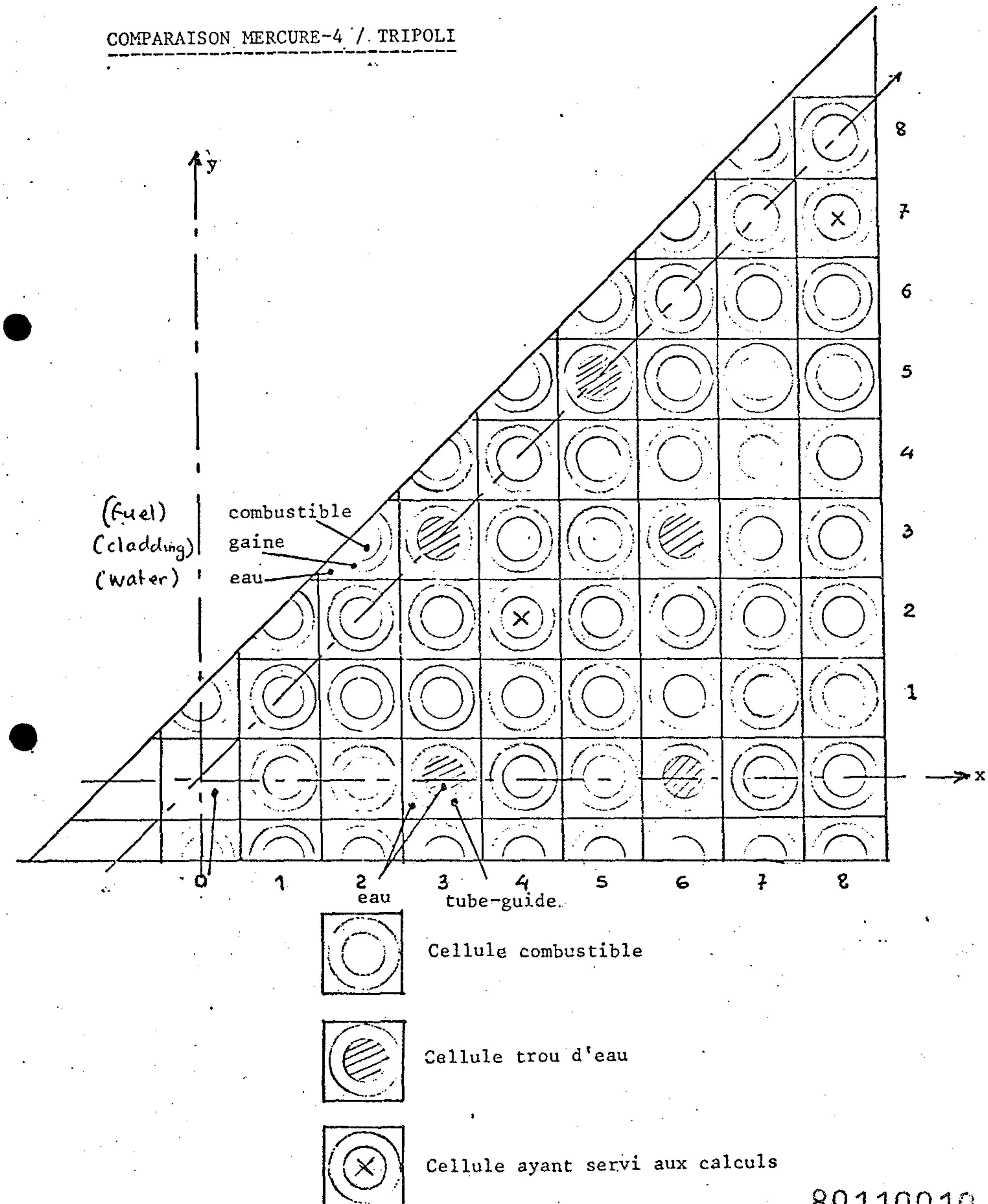

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TABLE 3

Row number from which the gamma are issued	Number of fuel rods	Number of water cell	Heating amount percent
1	8	0	29.90
2	16	0	22.24
3	16	8	11.36
4	32	0	10.82
5	36	4	6.57
6	36	12	4.04
7	56	0	3.75
8	64	0	2.83
9	72	0	2.47
10	80	0	1.80
11	76	12	1.28
12	84	12	0.84
13	104	0	0.73
14	80	32	0.42
15	120	0	0.45
16	128	0	0.33
17	104	32	0.17

TABLE 4

Gamma from fission ---------------------------- 38 %
Gamma from fission products ------------------- 35 %
Gamma from capture in U^{238} -------------------- 17 %
Gamma from capture in U^{235} -------------------- 6 %
Gamma from capture in fuel cladding ---------- 2 %
Gamma from capture in borated water ---------- 2 %

Neutron captures in gamma thermometer itself 7,4 % additional.

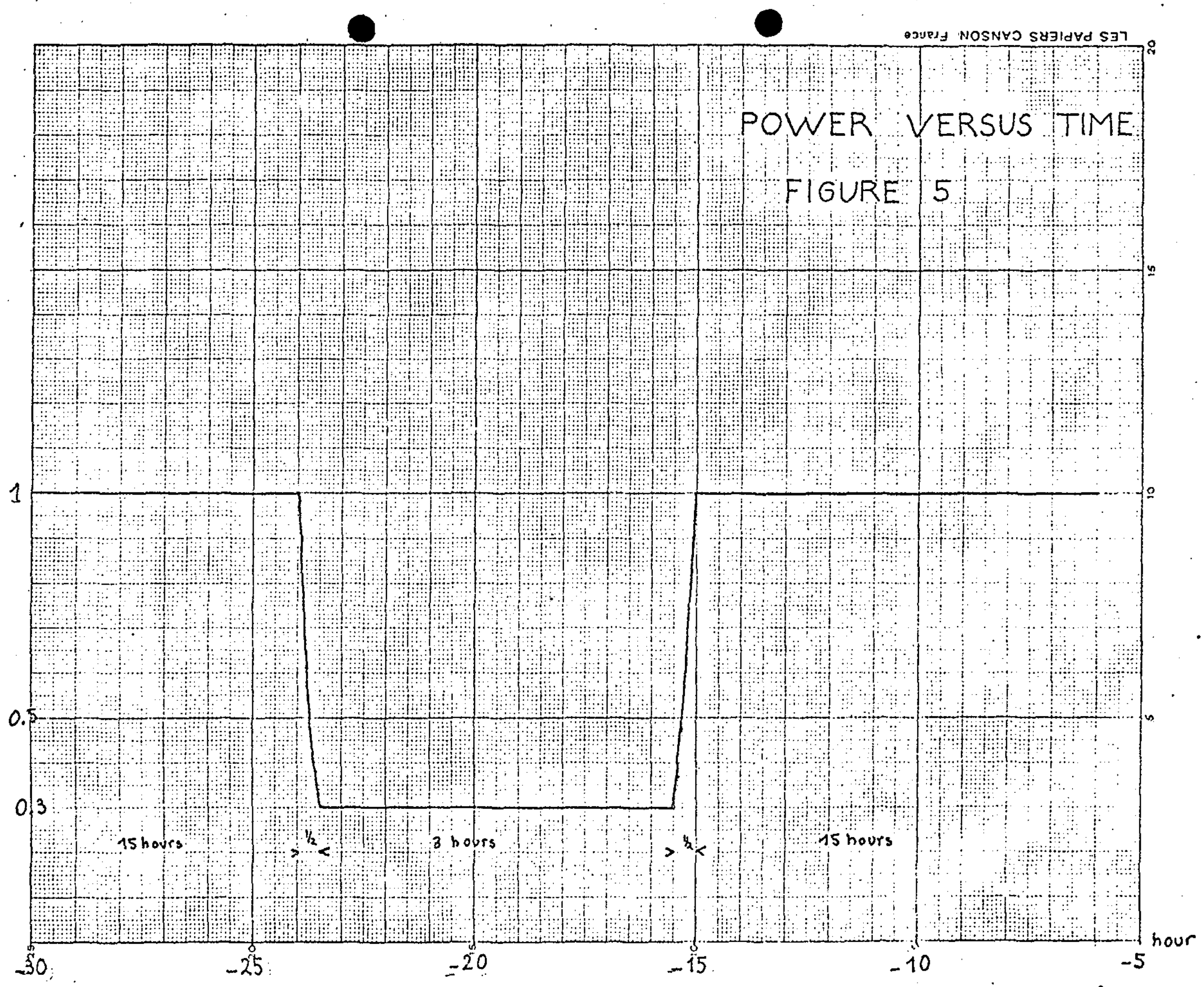
POWER VERSUS TIME
FIGURE 5
1
0.5
0.3
15 hours
½
3 hours
½
15 hours
hour
-30
-25
-20
-15
-10
-5

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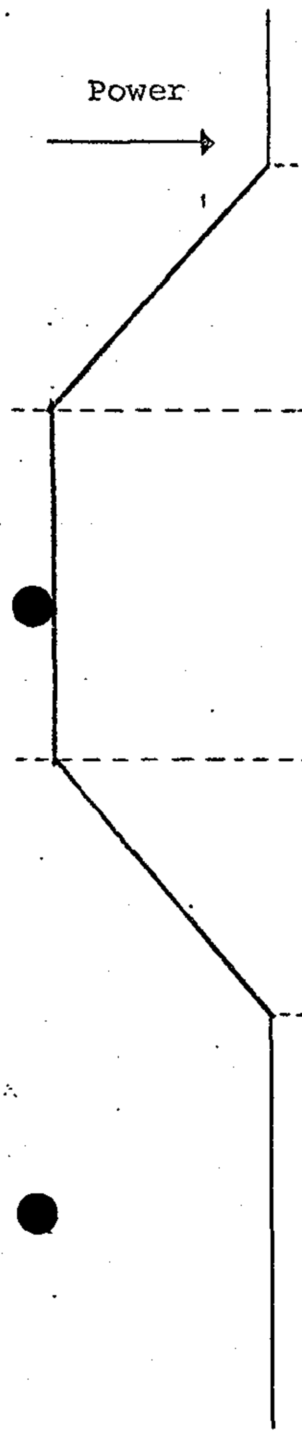
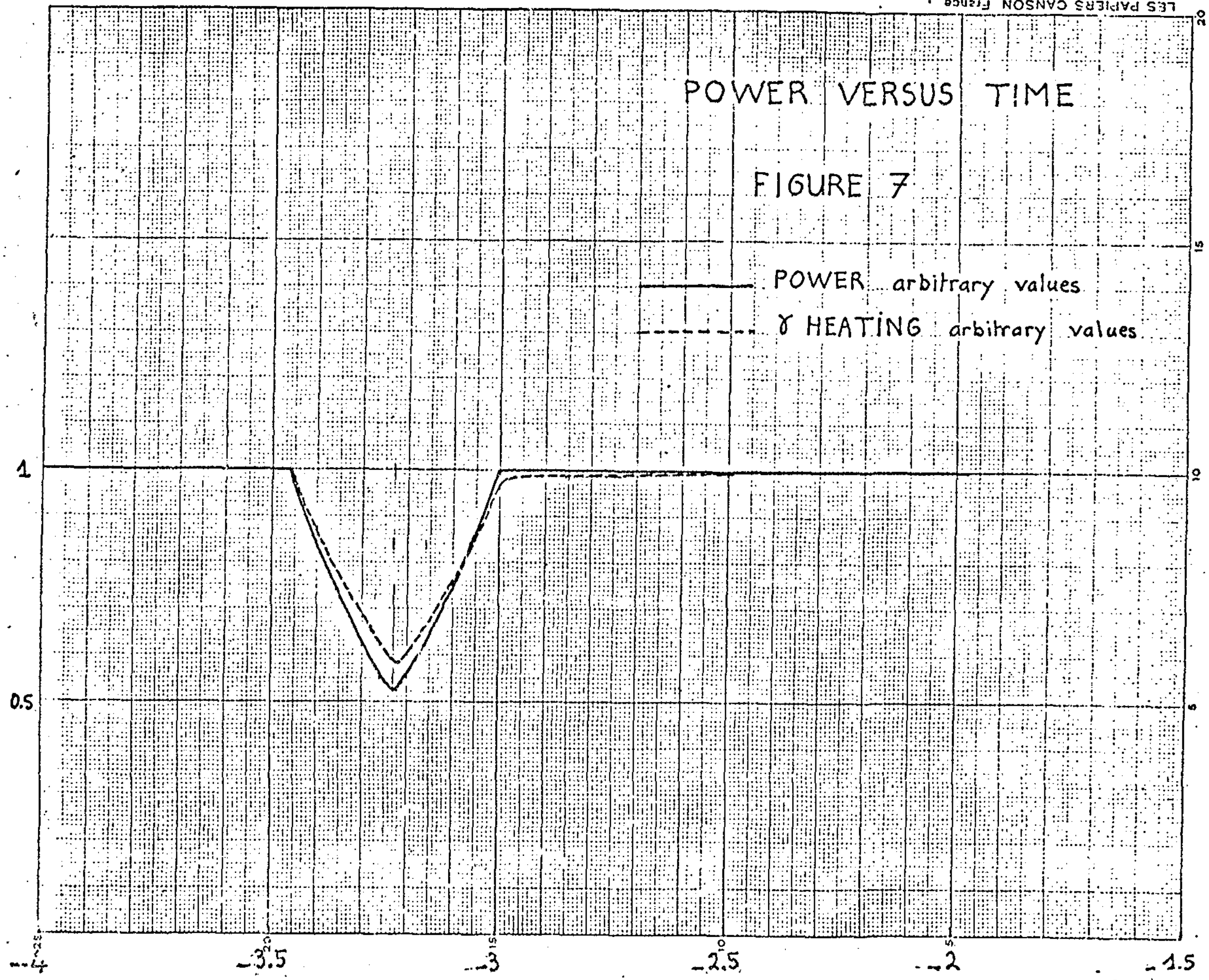
TABLE 6



Time in hours	Heating relatives values	Reactor power diagram	Ratio $\frac{\text{heating}}{\text{power}}$
-30	1.000	1.	1.
-28	1.000	1.	1.
-26	1.001	1.	1.001
-24	1.001	1.	1.001
-23.9	0.8236	0.7862	1.048
-23.8	0.6733	0.6180	1.090
-23.7	0.5516	0.4859	1.135
-23.6	0.4534	0.3820	1.187
-23.5	0.3742	0.3000	1.248
-23.25	0.3562	0.3000	1.187
-23.	0.3482	0.3000	1.161
-22.5	0.3394	0.3000	1.131
-22	0.3340	0.3000	1.114
-20	0.3240	0.3000	1.080
-18	0.3198	0.3000	1.066
-15.5	0.3170	0.3000	1.057
-15.4	0.3851	0.3820	1.008
-15.3	0.4753	0.4859	0.978
-15.2	0.5915	0.6180	0.957
-15.1	0.7404	0.7872	0.942
-15	0.9302	1.	0.930
-14.75	0.9568	1.	0.957
-14.5	0.9669	1.	0.967
-14	0.9766	1.	0.977
-13	0.9858	1.	0.986
-11	0.9933	1.	0.993
-10	0.9950	1.	0.995
- 8	0.9973	1.	0.997
- 6	0.9986	1.	0.999


POWER VERSUS TIME
FIGURE 7
POWER arbitrary values
γ HEATING arbitrary values
1
0.5
-4
-3.5
-3
-2.5
-2
-1.5

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Fuel rod 4.2 heating due to gamma prompt of fission

Energy group	Group	TRIPOLI Heating ± 2 σ	MERCURE IV Heating ± 2 σ	Ratio TRIPOLI / MERCURE IV
8.5				
7.5	1	3.535E-20 ± 13 %	3.597E-20 ± 3.5 %	0.983
6.5	2	1.041E-19 ± 10 %	9.565E-20 ± 1.6 %	1.088
5.5	3	3.360E-19 ± 9 %	2.869E-19 ± 0.7 %	1.171
4.5	4	6.294E-19 ± 8 %	5.783E-19 ± 4.3 %	1.088
3.5	5	1.767E-18 ± 9 %	1.572E-18 ± 1.9 %	1.124
2.75	6	2.663E-18 ± 9 %	2.413E-18 ± 1.7 %	1.104
2.25	7	2.638E-18 ± 10 %	2.667E-18 ± 1.8 %	0.989
1.75	8	3.311E-18 ± 8 %	3.649E-18 ± 1.6 %	0.907
1.25	9	4.299E-18 ± 9 %	5.047E-18 ± 1.1 %	0.852
0.75	10	4.334E-18 ± 8 %	5.797E-18 ± 0.9 %	0.748
0.50	11	2.748E-18 ± 12 %	3.307E-18 ± 1.7 %	0.831
	TOTAL	2.287E-17 ± 3.4 %	2.545E-17 ± 0.5 %	0.898

Normalization : 1 γ from fission per $cm^3.s$

σ : standard deviation due to Monte Carlo method

TRIPOLI code : exact Monte Carlo method

MERCURE IV code : line of sight point attenuation kernel method with build-up factors. Integration over the source performed by Monte Carlo method.

Fuel rod 8 - 7 heating due to gamma prompt of fission

FAREST FUEL ROD

Energy Group	Group	TRIPOLI Heating ±2 σ	MERCURE IV Heating ±2 σ	Ratio TRIPOLI / MERCURE IV
8.5	1	3.177E-21 ± 16 %	3.182E-21 ± 4.3 %	0.999
7.5	2	1.518E-20 ± 14 %	1.174E-20 ± 2.6 %	1.292
6.5	3	4.076E-20 ± 16 %	3.522E-20 ± 1.4 %	1.155
5.5	4	8.304E-20 ± 13 %	7.513E-20 ± 5.9 %	1.105
4.5	5	2.218E-19 ± 12 %	2.056E-19 ± 4 %	1.079
3.5	6	3.074E-19 ± 12 %	3.275E-19 ± 0.7 %	0.939
2.75	7	3.000E-19 ± 13 %	3.354E-19 ± 1.4 %	0.895
2.25	8	3.994E-19 ± 11 %	4.452E-19 ± 4.3 %	0.897
1.75	9	3.850E-19 ± 12 %	5.157E-19 ± 0.9 %	0.747
1.25	10	2.378E-19 ± 14 %	3.424E-19 ± 1.3 %	0.694
0.75	11	0.621E-19 ± 14 %	7.224E-20 ± 5.9 %	0.859
0.50				
	TOTAL	2.056E-18 ± 4.6 %	2.369E-18 ± 1 %	0.868

Normalization : 1 γ from fission per $cm^3.s$

σ : standard deviation due to Monte Carlo method

Different contributions to the gamma heating

1°) NEAREST FUEL ROD

	TRIPOLI	MERCURE IV	RATIO MERCURE IV / TRIPOLI
γ directly from fission	40.75 %	40.70 %	0.9988
γ from fission products	37.91 %	37.74 %	0.9955
γ captures on U^{235}	5.69 %	5.68 %	0.9982
γ captures on U^{238}	15.65 %	15.88 %	1.0147

2°) DISTANT FUEL ROD

	TRIPOLI	MERCURE IV	RATIO MERCURE IV / TRIPOLI
γ directly from fission	40.31 %	40.09 %	0.9945
γ from fission products	38.84 %	38.91 %	1.0018
γ captures on U^{235}	5.62 %	5.59 %	0.9947
γ captures on U^{238}	15.23 %	15.41 %	1.0118

TABLE 10

Fission Products Below 500 KeV

Cell rod number	Row number	With 11 energy groups (conservation of total energy)	With 13 energy groups	Ratio
1-1	1	3.790 E-15	3.7944 E-15	1.00042
2-1	2	1.8556 E-15	1.8496 E-15	1.00032
3-1	3	6.9808 E-16	6.9045 E-16	1.011
4-1	4	3.8760 E-16	3.8409 E-16	1.0091
5-1	5	2.3518 E-16	2.3355 E-16	1.0070
6-1	6	1.5021 E-16	1.4946 E-16	1.0050
7-1	7	1.0170 E-16	1.0132 E-16	1.0038
8-1	8	7.3009 E-17	7.2780 E-17	1.0031

Normalization : 1 fission per cm^3

Approximate Influence on the gamma themometer heating

With 11 groups ------------ 1.0787 E-13

With 13 groups ------------ 1.0741 E-13

Difference ---------- 0.43 %

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