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Commission of the
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SEPTEMBER 1974

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## ABSTRACT

Reactivity effects of burnt fuel clusters were measured in the $D_2O$ moderated critical facility ECO using the pile oscillation technique.

Results are given for three $UO_2$ cluster types and in three burn-up steps from 0 to 9500 MWd/t, at three lattice pitches for air, $D_2O$ and $H_2O$ coolants. The reactivity effects were measured with an inverse neutron kinetics technique, which took into account the decay of the delayed neutron precursors in the fuel element part which was temporarily outside the reactor.



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Luxembourg, September 1974 - 30 Pages - 11 Figures - B.Fr. 50,—



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## 1. INTRODUCTION

Reactivity effects of burnt fuel clusters with 7, 13 and 19 rods were measured in the $D_2O$ moderated critical facility ECO of the CCR Ispra.
Data are given for $D_2O$ and $H_2O$ coolants and a voided coolant channel at 3 different square lattice pitches. The fuel rods for the test subassembly were taken from irradiated NPD-fuel subassemblies with known isotopic composition of fissile and fertile material.

The available rods permitted determination of the reactivity effect of a 19 rod subassembly up to nominal burn-up of 5500 MWd/t. Seven and thirteen rod clusters were investigated up to 9500 MWd/t and 9000 MWd/t respectively.

The reactivity effect was measured by the pile oscillation technique using a fuel element with a length of about twice the extrapolated critical height of the reactor. This oscillation element has a reference section of natural $UO_2$ and a test section of the same geometry but with either fresh or burnt fuel rods. The reactivity difference of the two clusters was measured with an inverse neutron kinetics method. This technique takes into account the production and decay of the delayed neutrons for the fuel part of the oscillation element inside and outside the core.

## 2. EXPERIMENTAL INSTALLATION

### 2.1. Reactor and fuel element oscillator

The $D_2O$ moderated critical facility ECO (Ref.1) was equipped with a fuel element oscillator permitting a periodic rapid exchange of the fuel in the central axis of the core according to a trapezoidal time law (Ref.2, 3). Fig.2.1 gives a principal view of the reactor with the installed oscillator. The oscillation device consists of three main components :the oscillation tube, the drive mechanism of the fuel element with its control units and an emergency braking system with the $D_2O$ collector.

The Al oscillation tube has an external/internal diameter of 122 mm/110 mm and a length of about 11 m. It is aligned with the core axis, supported on the rotating cover plate and guided by the lattice pitch mechanism and the bottom plug. Inside this tube the fuel element assembly of about 6 m length is coupled to the rack, and moved by the oscillator drive mechanism. The maximum oscillation amplitude can be set to 3 m, with a maximum average speed of 1 m/sec. The reproducibility of the fuel element rest position was better than $\pm 2$ mm. The drive control unit permits period settings between 0 and 200 sec with an error of $\pm 0.2$ sec. An emergency braking system is foreseen to limit damage to the oscillation element in the case that this should become accidentally separated from the drive mechanism. In case of damage to the oscillation tube this safety device avoids loss of $D_2O$.

## 2.2. Fuel elements

During all measurements the ECO core was loaded with 76 ECO-reference fuel elements U/19/12-air (Fig.2.2). The lavout of the oscillation element is shown in Fig.2.3. It is guided inside the oscillation tube with spring loaded rollers mounted on the upper and lower extensions. This element is axially subdivided into 10 cluster subassemblies each about 50 cm long inside an Al tube of $\emptyset_a/\emptyset_i$ = 97 mm/93 mm. Two of them are the test and reference subassemblies, housed inside a leak tight Al container of $\emptyset_a/\emptyset_i$ = 91 mm/84 mm. Two assemblies are arranged above the reference sample and three were mounted below the reference and test samples.

The geometry of the cluster was identical in all 10 subassemblies. The fuel cross sections of the 7, 13 and 19 rod clusters are given in Fig.2.4, 2.5 and 2.6 respectively.

The $UO_2$ diameter of all rods was 14.4 mm with a Zy-2 cladding thickness of about 0.4 mm. 190 fresh fuel rods were made available for the experiments by the AECL. These rods differed from spacers and end cap designs. The fuel density of the $UO_2$ was specified in the range of 10.3 $g/cm^3 \leq \delta \leq$ 10.7 $g/cm^3$. For these reasons it was not possible to mount an oscillation element with identical composition in all subassemblies. This suggested a measurement with fresh fuel in the position of the test cluster in order to obtain the same environment conditions for fresh and burnt fuel.

For this reason a subassembly with fresh fuel was mounted in the position of the test zone of the oscillation element. All reactivity effects of the burnt fuel clusters have to be referred to this zero burn-up cluster.

2.3. Fuel materials

The isotopic composition of the irradiated NPD fuel rods available for the oscillation experiments are given in Table 2.1. The relative abundances of the U and Pu isotopes were determined from destructive analysis of other NPD fuel rods irradiated under the same conditions. These analyses were performed at the laboratories of the CEA (Ref.4).

The fuel rods were assembled to 7, 13 and 19 rod clusters of different nominal burn-up. Table 2.2 gives for each of the 9 test fuel sections the type and number of rods used in the three radial cluster positions.

## 3. MEASUREMENT AND ANALYSIS METHOD

### 3.1. Theory

In the oscillation experiment with complete fuel elements the test element is periodically exchanged against the reference element between an out of core and an in core position. The upper part of the oscillation element with the reference subassembly in its centre is defined as the reference element. The lower part with the exchangeable test subassembly is the test element.

Both elements have as rest position in the core the zone of maximum importance. The out of core position has zero importance. During an oscillation cycle the transfer time of the elements is small as compared to their rest time in or outside the reactor.

In the element outside the core the delayed neutron precursors are decaying and no production occurs during this time.
If this element is oscillated back into the core, its delayed neutron precursor population has become smaller than that of an element in the same position and exposed to the complete pile history. This effect requires treatment of the kinetic equations with time dependent sources of negative sign, expressing the lack of delayed fission neutron production rate.
Only in the case of two identical fuel elements, the source terms of reference and test element are identical. Already small flux depression differences caused by a changed design of the test element alters its delayed fission neutron production rate as compared to the reference element. This means that a fundamental mode Fourier Analysis of the neutron population is no longer applicable in this case, because the perturbation of the neutron balance equation is no longer an even multiple of the fundamental mode.

In order to measure the reactivity difference between test and reference element, a conventional inverse neutron kinetics technique can only be applied for oscillation periods which are longer than the decay time of the longest lived delayed neutron emitter of the above mentioned negative delayed neutron source term. In $D_2O$ moderated reactors the required oscillation periods would become unreasonably long. For this reason the existing inverse kinetics program (Ref.5) was modified so that the delayed neutron balance during the oscillation experiment was treated more correctly.

By means of a perturbation theory, two kinetic equation systems were derived, one for the reference element (state 0) and one for the test element (state 1) inserted into the core. It was assumed that the reactor was operated for a certain time with the reference element inserted to maximum importance. Then oscillation state 1 is reached from state 0 via a step function. The neutron population in the initial phase of state 1 is determined by the multiplication of the delayed neutrons emitted from the delayed neutron precursor distribution of state 0 of the reactor excluding the zone of the oscillation element. No delayed neutron emitters were previously formed in the test element. Only during the first half cycle, a delayed neutron precursor population is formed in the reference zone of the reactor and the test element according to the neutron distribution of state 1.

In the second and all following half cycles, delayed neutron source terms are present in the reference zone of the reactor, formed by a neutron distribution of states 0 and 1. In the reference and test element only delayed neutron precursors are present according to reactor states 0 and 1 respectively. The obtained kinetic equation has the following form :

$$\rho_\mu(t) = \frac{\Lambda_\mu(t)\,\alpha P_\mu(t)}{P_\mu(t)\,\alpha t} - \frac{b_\mu \Lambda_\mu(t)}{P_\mu(t)} + \bar{\beta}_\mu \qquad (1)$$

$$- \sum_{i=1}^{I} \lambda_i \beta_i (1-\eta_\mu) \int_{-\infty}^{t} e^{-\lambda_i (t-t')} \left[ \frac{\varepsilon_{i\mu R} f_\mu(t') P_\mu(t') + \varepsilon_{i\mu\nu R} \chi_{\mu\nu} f_\nu(t') P_\nu(t')}{f_\mu(t)\, P_\mu(t)} \right] dt'$$

$$- \sum_{i=1}^{J_\mu} \lambda_i \beta_i \eta_\mu \int_{-\infty}^{t} e^{-\lambda_i (t-t')} \frac{\varepsilon_{i\mu T} f_\mu(t') P_\mu(t')}{f_\mu(t)\, P_\mu(t)} dt'$$

$$\bar{\beta}_\mu = (1-\eta_\mu) \sum_{1}^{I} \beta_i \varepsilon_{i\mu R} + \eta_\mu \sum_{1}^{J_\mu} \beta_i \varepsilon_{i\mu T}$$

The indices $\mu$ and $\nu$ are conditioned by :

$\mu = 0$ then $\nu = 1$ (reference element in the core) and

$\mu = 1$ then $\nu = 0$ (test element in the core)

$P_\mu(t)$= reactor power with element $\mu$ inserted

$\Lambda_\mu(t)$= neutron generation time

$\overline{\beta_\mu}$ = effective delayed neutron fraction

$b_\mu$ = time constant source term

$\beta_i$ = delayed neutron fraction of group i

$\lambda_i$ = " " decay constant of group i

$\varepsilon_i$ = weighting factors for delayed neutrons

$x_{\mu\nu}$= fission rate of reference zone of reactor with element $\nu$ inserted, normalized on the same fission rate but with element $\mu$ inserted

$\gamma_\mu$= fission rate in test zone of reactor, normalized on the fission rate of the reactor

R = reference zone of reactor

T = test zone of reactor

I = number of delayed neutron groups in reference zone of reactor

$J_\mu$ = number of delayed neutron groups in test zone of reactor

The first term of equation 1 describes the prompt decay and has little influence on $\rho$. In the second term the source background due to spontaneous fission neutrons and of $\beta^+ - n$ reactions from long lived fission products are taken into account. The fourth term gives the reactivity contribution of the delayed neutrons emitted in the reference zone of the core. The reactivity contribution of the delayed neutrons generated in the test zone is considered in the last term.

Equation 1 was programmed on an IBM 360 computer, permitting an adjustment of $b_0$, $\eta_0$ and $\eta_1$ (Ref.6). With $\eta_0=0$ and $\eta_1=0$ equation 1 leads to the conventional inverse kinetics equation.

In the practical application $P_\mu(t)$ was put equal to the current of an ionisation chamber, located in a reflector position. The neutron generation time was derived from cell and criticality codes. For the fast and thermal fission $\lambda_i$ and $\beta_i$ -values, the data of Ref.7 were utilized. The fission rate ratio $x_{\mu\nu}$ was put arbitrarily at 1. In the calculation of the effective delayed neutron fraction the following simplified relation was utilized. For thermal fission isotopes :

$$\varepsilon_{i\mu R} = \frac{1}{\varepsilon} \frac{N_j \sigma_j \nu_j}{\sum_{j=1}^{J} N_j \sigma_j \nu_j} \qquad (2)$$

for fast fission isotopes

$$\varepsilon_{i\mu R} = \frac{\varepsilon - 1}{\varepsilon} \frac{N_k \sigma_k \nu_k}{\sum_{k=1}^{K} N_k \sigma_k \nu_k} \qquad (3)$$

$\varepsilon-1$ = extra number of fast neutrons generated in the cluster per original fast neutron of the fuel cluster

N = number of fissile atoms of type $j$ or $k$ per unit volume of fuel cluster

$\sigma$ = fission cross section

$\nu$ = number of neutrons produced per fission

$j$ = index for thermal fission isotopes

$k$ = " " fast " "

$\varepsilon_{i\mu T}$ and $\varepsilon_{i\mu DR}$ use the same relations. Both expressions assume an identical prompt and delayed neutron spectrum. The number of fissile atoms N per unit volume of the cluster was obtained from table 2.1, giving the isotopic fuel fractions of irradiated NPD fuel rods. Table 2.2 indicates the type and position of the fuel rod inside a particular cluster type. No weighting procedure was introduced taking into account the fast and thermal fission distribution inside the fuel cluster. The fast fission factor $\xi$ was determined with a cell code (Ref.8) for each cluster type, coolant and burn-up state, independent of the lattice pitch. The efficiency of the delayed photoneutrons was derived from step reactivity experiments at each of the three lattice pitches and was put equal in test and reference element. For the delayed photoneutron $\beta_i$-values of the Pu isotopes, the following assumption was made:

$$\beta_{iPu} = \frac{\beta_{Pu}}{\beta_{U5}} \beta_{iU5} \qquad (4)$$

$\beta_{Pu}$ = delayed neutron fraction for fast or thermal fission in a particular Pu isotope

$\beta_{U5}$ = delayed neutron fraction for thermal fission in $U^{235}$

$\beta_{iU5}$ = delayed photo-neutron fraction of group i for thermal fission in $U^{235}$

$\beta_{iPu}$ = delayed photo-neutron fraction of group i for fast or thermal fission in a particular Pu isotope

## 4. EXPERIMENTAL PROCEDURE

The reactivity effects of the elements were measured with a static and a kinetic method. The static method expresses the reactivity difference between test and reference element in units of the critical height difference. By the other method the reactivity difference is directly measured for the oscillations assuming a correct value of $\beta$.

### 4.1. The static method

In the static method the critical height $H_c$ was determined for various axial positions $Z_{\mu i}$ of the test and reference subassembly near the core midplane. The purpose of this experiment was to determine the core midplane position of the test and reference subassemblies $Z_{\mu i}$ and the corresponding critical heights $H_c(Z_{\mu i})$. A least square parabola fit on the i experimental values $H_c(Z_{\mu i})$ and $Z_{\mu i}$ lead to the constants $a_\mu$, $b_\mu$ and $c_\mu$ for both cases :

$$H_c(Z_{\mu i}) = a_\mu + b_\mu Z_{\mu i} + c_\mu Z_{\mu i}^2 \qquad (5)$$

$Z_{\mu i}$ = axial position reading on oscillator position indicator with test or reference subassembly near core midplane.

The core midplane position of the interesting subassemblies is obtained from :

$$Z_\mu = -\frac{b_\mu}{2c_\mu} \qquad \mu = 0,1 \qquad (6)$$

The critical height difference is given by

$$\Delta H_c = H_c(Z_1) - H_c(Z_0) \qquad (7)$$

Fig.4.1 shows the experimental results of such a measurement for a test element $UO_2/19/14.4$ - air - 1250 at a lattice pitch of 23.5 cm. The critical height $H_c$ is expressed as function of the axial rest position of the oscillation element in digit units (1 bit = 0.391 mm) read on the position indicator.

4.2. The dynamic method

In the dynamic method the fuel assembly was oscillated between the two positions $Z_o$ and $Z_1$ at a waterlevel, which was very close to $H_{osc} \cong 0.5 \left[ H_c(Z_1) + H_c(Z_o) \right]$. With some test subassemblies the extreme values for $H_c$ at $Z_1$ were not well defined. This affected not the critical height difference but the erros of $Z_1$. For this reason the stroke of the oscillator

$$\Delta Z = Z_1 - Z_o = 203.3 \text{ cm}$$

was taken from the design of the fuel assembly.

The experiment was started with the reference subassembly at $Z_o$ and a slightly supercritical waterlevel $H_p(Z_o)$. After extraction of the horizontal control plates the reactor diverged with a constant reactivity. The reactor was balanced after the desired power level was reached. Twenty minutes later the critical water level $H_c(Z_o)$ was measured. The reactor power was recorded throughout the experiment in equal subsequent time intervals. The reactivity was calculated OFF LINE with the special inverse neutron kinetics theory described in chapter 3. The reactivity coefficient of the water level was determined using the relation

$$\left( \frac{\Delta \varrho}{\Delta H} \right)_{H_c} = \frac{\varrho_p - \varrho_c}{H_p(Z_o) - H_c(Z_o)} \qquad (8)$$

After an adjustment of the waterlevel to $H_{osc}$ the fuel element was oscillated between the two positions $Z_o$ and $Z_1$. A series of at least 10 oscillations was performed one with a period of about 110 sec and the other with 50 sec. The reactivity difference

$$\Delta\rho_{10} = \bar{\rho}(z_1) - \bar{\rho}(z_o) \tag{9}$$

was determined using a mean value of the reactivity with the subassembly 1 and 0 close to core midplane. These mean values were obtained omitting the reactivity values of the first 14 and the last 4 seconds within each half oscillation cycle. The reactivity difference $\Delta\rho_{10}$ is much influenced by the value chosen for $\beta$. The reactivity variation given in equation 9 can be transformed into a critical height variation using equation 8 :

$$\Delta H_\rho = -\left(\frac{\Delta H}{\Delta\rho}\right)_{H_{osc}} \left[\bar{\rho}(z_1) - \bar{\rho}(z_o)\right] \tag{10}$$

$\frac{\Delta H}{\Delta\rho}$ is for a given lattice pitch a function of the $D_2O$ level. For this reason all measured $\left(\frac{\Delta H}{\Delta\rho}\right)$ - values obtained at different critical water levels at a particular pitch were fitted on a linear function of the type

$$\left(\frac{\Delta H}{\Delta\rho}\right)_i = a + bH_i \tag{11}$$

From this relation the $\frac{\Delta H}{\Delta\rho}$ value was derived at the $D_2O$ water level $H_{osc}$ during the fuel element oscillation. $\Delta H_\rho$ is directly comparable with the critical height difference $\Delta H_c$ obtained with the static method.

The error introduced into this experimental result is dominantly influenced by the error of the waterlevel difference measurement and not by the reactivity measurements.

## 5. EXPERIMENTAL RESULTS

Critical height variations and reactivity values are given as a measure characterizing the difference between a test and a reference subassembly. In addition the $D_2O$ moderator level which was maintained during the oscillation is quoted. The square lattice pitches investigated were 18.8 cm, 23.5 cm and 28.05 cm. Results are quoted for a zero, medium and a high burn-up state in the test subassembly.

Table 5.1 gives the results of a seven rod cluster subassembly with a burn-up of 0,5400 , 9500 MWd/t, using air and $H_2O$ coolants. At larger pitches the effects become nearly identical. Increasing negative reactivity effects were measured with increasing burn-up state. At the smallest lattice pitch and air coolant the effects are more pronounced.

The results of the 13 rod cluster measurements with 0, 5050 and 9000 MWd/t burn-up (table 5.2) show the same tendency as the 7 rod cluster data. However the reactivity effects with increasing burn-up are larger in this case. Due to a technical mistake found after the measurements no reactivity effects are quoted for a burn-up with 5050 MWd/t and air codant. Measurements with 19 rod clusters (table 5.3) were performed with test subassemblies of 0, 1250 and 5500 MWd/t with the coolants air, $D_2O$ and $H_2O$.

The largest reactivity differences exist with air and the smallest with $H_2O$ coolant. The effects increase with increasing lattice pitch. Due to the relative smaller coolant cross section of the 19 rod cluster, the coolant effects are less important than those of 13 and 7 rod clusters.

In all tables the reactivity values of the zero burn-up test element is positive with respect to the reference element. As already explained in chapter 2.2 this effect is due to the axial inhomogeneity of the oscillation element in the reactor. For this reason it is necessary to refer the reactivity values with burnt fuel to the zero burn-up reactivity value quoted in the tables, and not directly to the reference element.

The quoted errors of the reactivity effects are standard deviations of the results of at least 10 oscillations with a 110 sec oscillation period. Measurements with 60 sec periods lead to the same results. All $\Delta H_\rho$ values were obtained from $\frac{\Delta H}{\Delta \rho}$ - values with an accuracy of about 1%. Good agreement exist in general between the $\Delta H_\rho$ and the directly measured critical height variations $\Delta H_{stat}$ whose error is about $\pm 0.2$ mm.
All experimental results are summarized in the Fig.5.1, 5.2 and 5.3 for the different lattice pitches.

CONCLUSIONS

The specification of the burnt fuel rods were known with much better accuracy then those of the unburnt $UO_2$ rods. Additional measurements would have been useful to investigate the axial inhomogeneity of the oscillation element. Because of the closure of the critical facility ECO on the 10.6.72 due to a program decision of the Council of

Ministers the number of burn-up steps and coolants in the experimental program had to be reduced considerably.

ACKNOWLEDGEME''TS

The support of the AECL and the CEA are gratefully acknowledged, providing the essential means for the execution of the experiments. Many thanks are due to the ECO reactor staff for good cooperation.

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TABLE 2.1 : ISOTOPIC FUEL FRACTIONS OF IRRADIATED NPD FUEL RODS

| EUR Index | $U^{235}$ | $Pu^{239}$ | $Pu^{241}$ | $U^{236}$ | $U^{238}$ | $Pu^{240}$ | $Pu^{242}$ | notation of irradiated NPD fuel rods |
|---|---|---|---|---|---|---|---|---|
| 1 | 0.0036051 | 0.0020955 | 0.0000741 | 0.0005760 | 0.9931536 | 0.0004841 | 0.0000113 | 922-B |
| 2 | 0.0029898 | 0.0022746 | 0.0001094 | 0.0006854 | 0.9932950 | 0.0006255 | 0.0000202 | 922-C |
| 3 | 0.0015510 | 0.0025950 | 0.0002486 | - | 0.9942350 | 0.0012793 | 0.0000911 | 955-B |
| 4 | 0.0010042 | 0.0026945 | 0.0003320 | - | 0.9942946 | 0.0015116 | 0.0001630 | 955-C |
| 5 | 0.0062114 | 0.0006851 | 0.0000029 | 0.0001986 | 0.9928638 | 0.0000382 | 0.0000002 | 1022-B |
| 6 | 0.0059844 | 0.0008235 | 0.0000041 | 0.0001984 | 0.9921123 | 0.0000535 | 0.0000002 | 1022-C |
| 7 | 0.0023642 | 0.0024139 | 0.0001586 | 0.0007649 | 0.9933750 | 0.0008835 | 0.0000401 | 1052-B |
| 8 | 0.0017285 | 0.0025829 | 0.0002299 | 0.0008643 | 0.9934169 | 0.0011029 | 0.0000746 | 1052-C |
| 9 | 0.0020166 | 0.0025033 | 0.0001963 | 0.0007947 | 0.9933919 | 0.0010389 | 0.0000583 | 1092-B |
| 10 | 0.0014219 | 0.0026349 | 0.0002751 | - | 0.9943059 | 0.0012595 | 0.0001028 | 1092-C |
| 11 | 0.0028309 | 0.0023144 | 0.0001192 | 0.0006953 | 0.9933053 | 0.0007105 | 0.0000243 | 1096-B |
| 12 | 0.0022153 | 0.0024637 | 0.0001754 | 0.0007749 | 0.9934276 | 0.0008968 | 0.0000463 | 1096-C |
| 13 | 0.0058185 | 0.0009393 | 0.0000066 | 0.0002383 | 0.9929232 | 0.0000736 | 0.0000003 | 1129-B |
| 14 | 0.0054813 | 0.0011399 | 0.0000106 | 0.0002770 | 0.9929835 | 0.0001068 | 0.0000007 | 1129-C |
| 15 | 0.0046474 | 0.0016286 | 0.0000303 | 0.0004171 | 0.9930346 | 0.0002394 | 0.0000026 | 1530-B |
| 16 | 0.0041711 | 0.0018472 | 0.0000465 | 0.0004866 | 0.9931203 | 0.0003233 | 0.0000050 | 1630-C |
| 17 | 0.0072000 | 0 | 0 | 0 | 0.9928000 | 0 | 0 | Unat |

TABLE 2.2 : COMPOSITION OF FUEL CLUSTERS

| Rods per Bundle | Cluster Nr. | Nominal Burnup Mwd/t | EUR Index | Notation of irr. NPD Fuel Rods | Central Rod | Number in 1st Ring | Number in 2nd Ring |
|---|---|---|---|---|---|---|---|
| 19 | 1 | 0 | 17 | | 1 | 6 | 12 |
| | 2 | 1250 | 5 | 1022-B | 1 | 1 | 1 |
| | | | 6 | 1022-C | | 5 | 1 |
| | | | 13 | 1129-B | | | 3 |
| | | | 14 | 1129-C | | | 5 |
| | | | 15 | 1630-B | | | 1 |
| | | | 16 | 1630-C | | | 1 |
| | 3 | 5500 | 1 | 922-B | | 3 | |
| | | | 2 | 922-C | | 3 | 3 |
| | | | 7 | 1052-B | | | 3 |
| | | | 11 | 1096-B | | | 3 |
| | | | 12 | 1096-C | | | 3 |
| | | | 16 | 1630-C | 1 | | |
| 13 | 4 | 0 | 17 | | 1 | 6 | 6 |
| | 5 | 5050 | 1 | 922-B | | 3 | |
| | | | 2 | 922-C | | 3 | 3 |
| | | | 11 | 1096-B | | | 3 |
| | | | 16 | 1630-C | 1 | | |
| | 6 | 9000 | 3 | 955-B | | | 2 |
| | | | 4 | 955-C | | | 1 |
| | | | 8 | 1052-C | 1 | 3 | |
| | | | 9 | 1092-B | | 3 | |
| | | | 10 | 1092-C | | | 3 |
| 7 | 7 | 0 | 17 | | 1 | 6 | |
| | 8 | 5400 | 2 | 922-C | | 6 | |
| | | | 11 | 1096-B | 1 | | |
| | 9 | 9500 | 3 | 955-B | | 2 | |
| | | | 8 | 1052-C | 1 | | |
| | | | 10 | 1092-C | | 4 | |

TABLE 5.1 : CRITICAL HEIGHT AND REACTIVITY VARIATIONS OF 7 ROD CLUSTERS

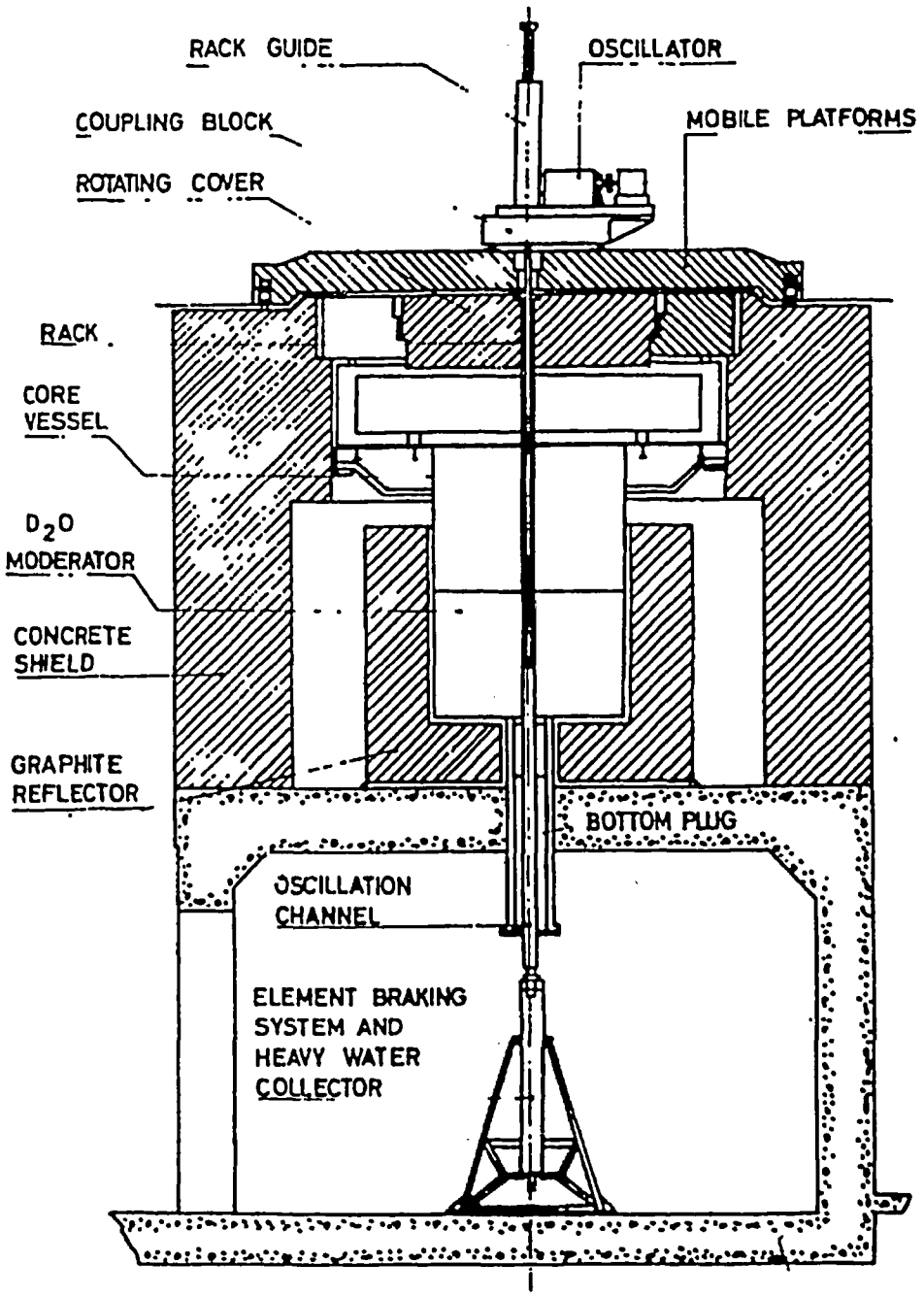
| pitch (cm) | coolant | burn-up (MWd/t) | $\Delta\rho$ ($10^{-5}$) | $\delta\Delta\rho$ ($10^{-5}$) | $\Delta H_\rho$ (mm) | $\Delta H_{stat}$ (mm) | $H_{osc}$ (mm) |
|---|---|---|---|---|---|---|---|
| 18.8 | | | +15.036 | ±0.044 | -2.755 | -2.6 | 1714.0 |
| 23.5 | air | 0 | +18.526 | ±0.036 | -1.641 | -1.6 | 1368.2 |
| 28.05 | | | +17.763 | ±0.027 | -1.666 | -1.7 | 1505.3 |
| 18.8 | | | -20.225 | ±0.041 | 3.720 | 3.8 | 1716.8 |
| 23.5 | air | 5400 | -25.879 | ±0.040 | 2.294 | 2.3 | 1368.8 |
| 28.05 | | | -27.354 | ±0.045 | 2.566 | 2.6 | 1505.5 |
| 18.8 | | | -58.443 | ±0.078 | 10.700 | 11.0 | 1713.9 |
| 23.5 | air | 9500 | -79.780 | ±0.039 | 7.058 | 7.0 | 1366.3 |
| 28.05 | | | -85.423 | ±0.213 | 7.995 | 7.5 | 1503.4 |
| 18.8 | | | +8.862 | ±0.029 | -1.849 | -1.7 | 1807.8 |
| 23.5 | $H_2O$ | 0 | +7.901 | ±0.032 | -0.750 | -0.8 | 1418.7 |
| 28.05 | | | +6.451 | ±0.026 | -0.649 | -0.7 | 1563.3 |
| 18.8 | | | -12.041 | ±0.026 | 2.522 | 2.4 | 1810.3 |
| 23.5 | $H_2O$ | 5400 | -13.199 | ±0.022 | 1.251 | 1.2 | 1418.6 |
| 28.05 | | | -12.098 | ±0.050 | 1.215 | 1.3 | 1563.2 |
| 18.8 | | | -36.385 | ±0.039 | 7.598 | 7.7 | 1808.4 |
| 23.5 | $H_2O$ | 9500 | -38.505 | ±0.044 | 3.656 | 3.8 | 1419.8 |
| 28.05 | | | -34.058 | ±0.033 | 3.430 | 3.5 | 1565.4 |

TABLE 5.2 : CRITICAL HEIGHT AND REACTIVITY VARIATIONS OF 13 ROD CLUSTERS

| pitch (cm) | coolant | burn-up (MWd/t) | $\Delta\rho$ ($10^{-5}$) | $\delta\Delta\rho$ ($10^{-5}$) | $\Delta H_\rho$ (mm) | $\Delta H_{stat}$ (mm) | $H_{osc}$ (mm) |
|---|---|---|---|---|---|---|---|
| 18.8 | air | 0 | +12.639 | ±0.018 | -2.290 | -2.3 | 1705.2 |
| 23.5 | | | +16.264 | ±0.027 | -1.414 | -1.4 | 1353.6 |
| 28.05 | | | +16.302 | ±0.088 | -1.493 | -1.5 | 1484.6 |
| 18.8 | air | 9000 | -102.498 | ±0.055 | 18.859 | 18.6 | 1714.6 |
| 23.5 | | | -140.558 | ±0.073 | 12.342 | 12.0 | 1359.9 |
| 28.05 | | | -146.089 | ±0.197 | 13.515 | 13.7 | 1492.6 |
| 18.8 | $H_2O$ | 0 | +9.888 | ±0.012 | -1.925 | -1.9 | 1759.3 |
| 23.5 | | | +9.673 | ±0.056 | -0.884 | -1.0 | 1392.2 |
| 28.05 | | | +8.510 | ±0.042 | -0.824 | -0.8 | 1532.9 |
| 18.8 | $H_2O$ | 5050 | -35.123 | ±0.055 | 6.895 | 6.9 | 1765.3 |
| 23.5 | | | -41.342 | ±0.049 | 3.785 | 3.9 | 1393.1 |
| 28.05 | | | -40.101 | ±0.035 | 3.891 | 3.9 | 1534.4 |
| 18.8 | $H_2O$ | 9000 | -87.021 | ±0.053 | 17.120 | 16.7 | 1766.8 |
| 23.5 | | | -97.895 | ±0.087 | 9.008 | 9.3 | 1396.9 |
| 28.05 | | | -92.195 | ±0.047 | 8.970 | 9.3 | 1536.7 |

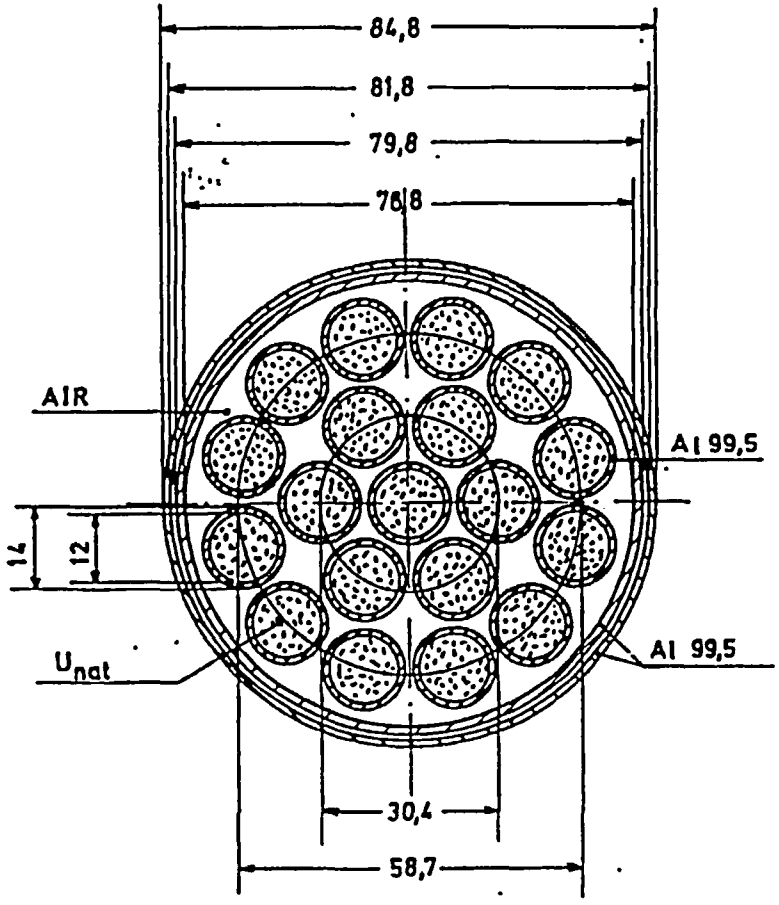
TABLE 5.3 : CRITICAL HEIGHT AND REACTIVITY VARIATIONS OF 19 ROD CLUSTERS

| pitch (cm) | coolant | burn-up (MWd/t) | $\Delta\rho$ ($10^{-5}$) | $\delta\Delta\rho$ ($10^{-5}$) | $\Delta H_\rho$ (mm) | $\Delta H_{stat}$ (mm) | $H_{osc}$ (mm) |
|---|---|---|---|---|---|---|---|
| 18.8 | air | 0 | +11.309 | ±0.040 | -2.035 | -2.0 | 1699.9 |
| 23.5 | | | +14.901 | ±0.071 | -1.282 | -1.3 | 1345.3 |
| 28.05 | | | +14.411 | ±0.051 | -1.302 | -1.2 | 1472.2 |
| 18.8 | air | 1250 | -1.198 | ±0.061 | 0.224 | 0.1 | 1699.3 |
| 23.5 | | | -0.528 | ±0.051 | 0.046 | 0 | 1347.2 |
| 28.05 | | | -0.917 | ±0.077 | 0.083 | 0 | 1473.8 |
| 18.8 | air | 5500 | -71.241 | ±0.069 | 12.890 | 12.7 | 1704.1 |
| 23.5 | | | -97.263 | ±0.080 | 8.420 | 8.3 | 1350.4 |
| 28.05 | | | -103.219 | ±0.202 | 9.388 | 9.2 | 1478.8 |
| 18.8 | $H_2O$ | 0 | +8.145 | ±0.029 | -1.052 | -1.4 | 1729.7 |
| 23.5 | | | +5.697 | ±0.070 | -0.507 | -0.6 | 1371.5 |
| 28.05 | | | +4.229 | ±0.085 | -0.398 | -0.6 | 1507.5 |
| 18.8 | $H_2O$ | 1250 | -2.013 | ±0.052 | 0.377 | 0.3 | 1731.6 |
| 23.5 | | | -4.944 | ±0.067 | 0.440 | 0.4 | 1371.6 |
| 28.05 | | | -6.548 | ±0.088 | 0.616 | 0.6 | 1508.1 |
| 18.8 | $H_2O$ | 5500 | -70.364 | ±0.102 | 13.226 | 13.1 | 1733.4 |
| 23.5 | | | -83.442 | ±0.028 | 7.452 | 7.7 | 1374.4 |
| 28.05 | | | -82.419 | ±0.073 | 7.774 | 7.8 | 1510.2 |
| 18.8 | $D_2O$ | 0 | +12.698 | ±0.058 | -2.300 | -2.4 | 1705.2 |
| 23.5 | | | +12.475 | ±0.082 | -1.078 | -1.0 | 1349.0 |
| 28.05 | | | +10.277 | ±0.097 | -0.934 | -1.0 | 1477.9 |
| 18.8 | $D_2O$ | 1250 | +2.303 | ±0.039 | -0.417 | -0.4 | 1705.2 |
| 23.5 | | | +4.607 | ±0.047 | -0.399 | -0.4 | 1350.2 |
| 28.05 | | | +4.553 | ±0.071 | -0.414 | -0.5 | 1478.5 |
| 18.8 | $D_2O$ | 5500 | -69.277 | ±0.017 | 12.640 | 12.4 | 1710.7 |
| 23.5 | | | -88.094 | ±0.085 | 7.672 | - | 1355.1 |
| 28.05 | | | -92.895 | ±0.116 | 8.435 | 8.6 | 1481.9 |

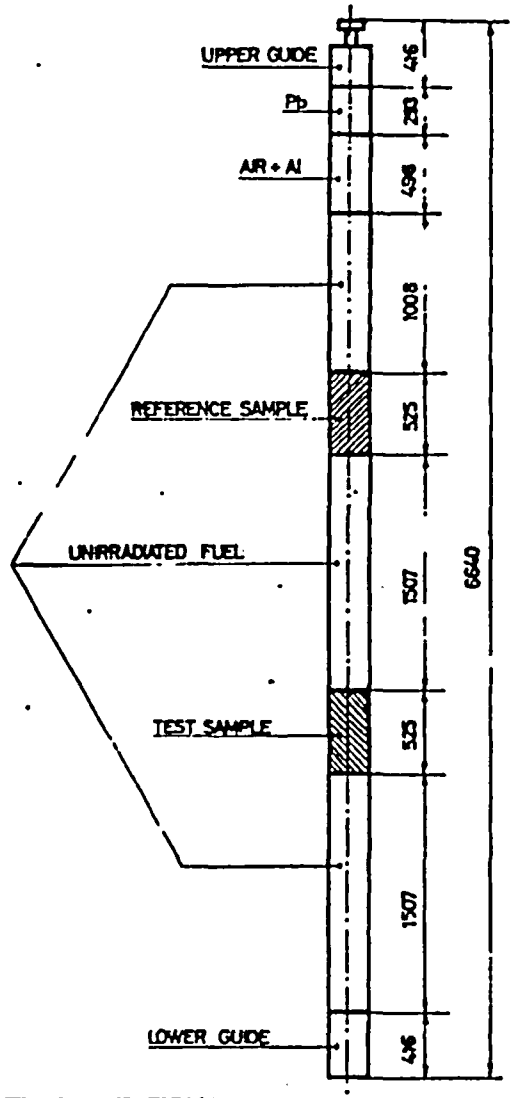



ECO REACTOR WITH THE FUEL ELEMENT OSCILLATOR

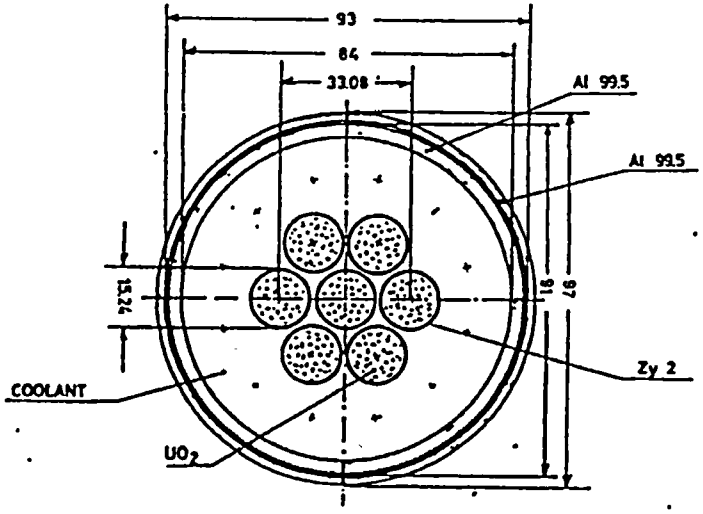
FIG. 2.1



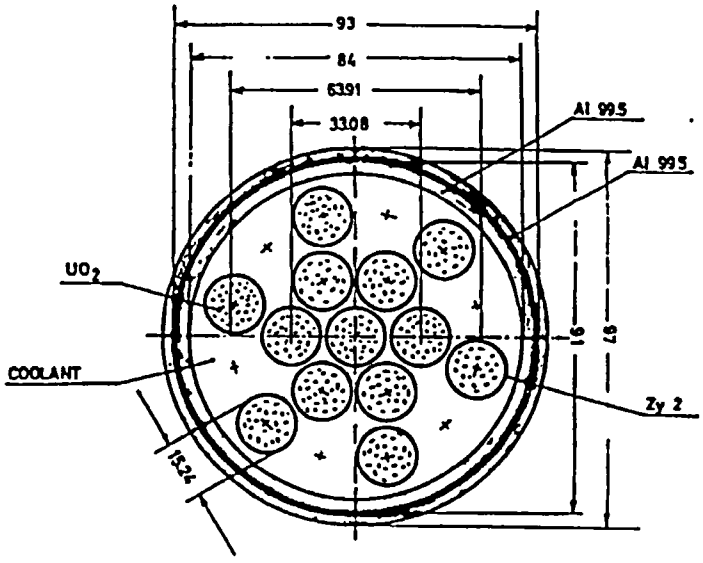

ECO REFERENCE FUEL ELEMENT U/19/12-AIR FIG. 2.2



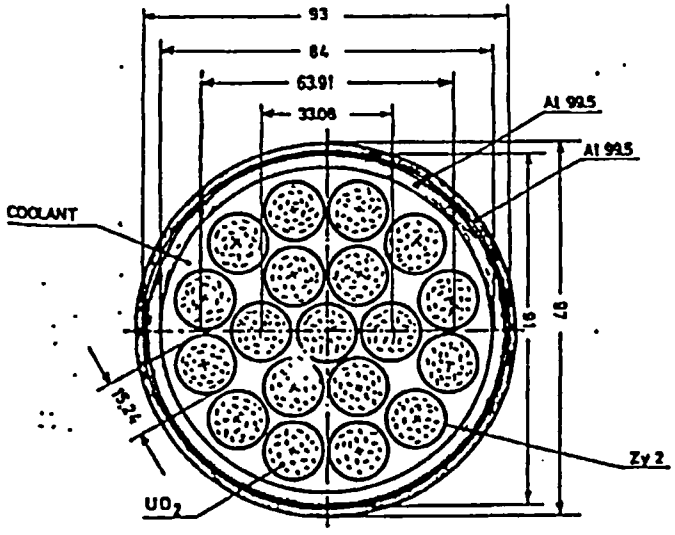

FUEL SECTIONS ARRANGEMENT OF THE OSCILLATION ELEMENT FIG. 2.3



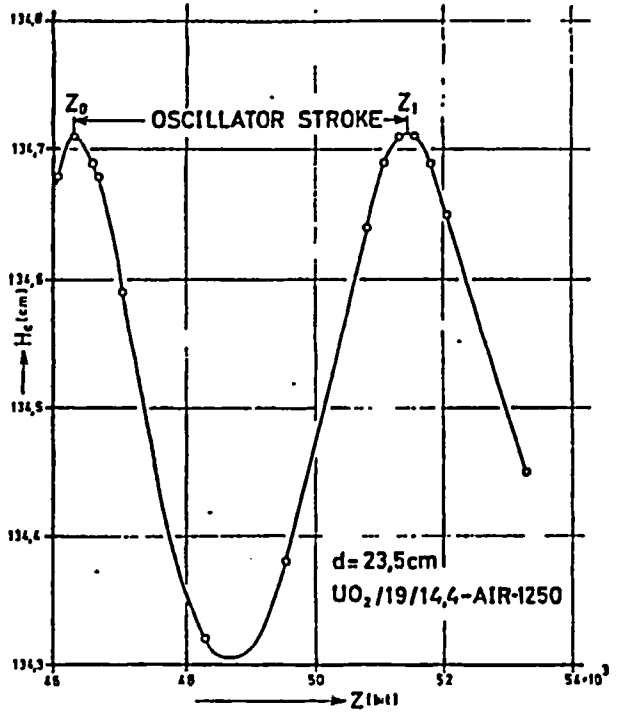

OSCILLATION ELEMENT $UO_2$/7/14.4 FIG. 2.4



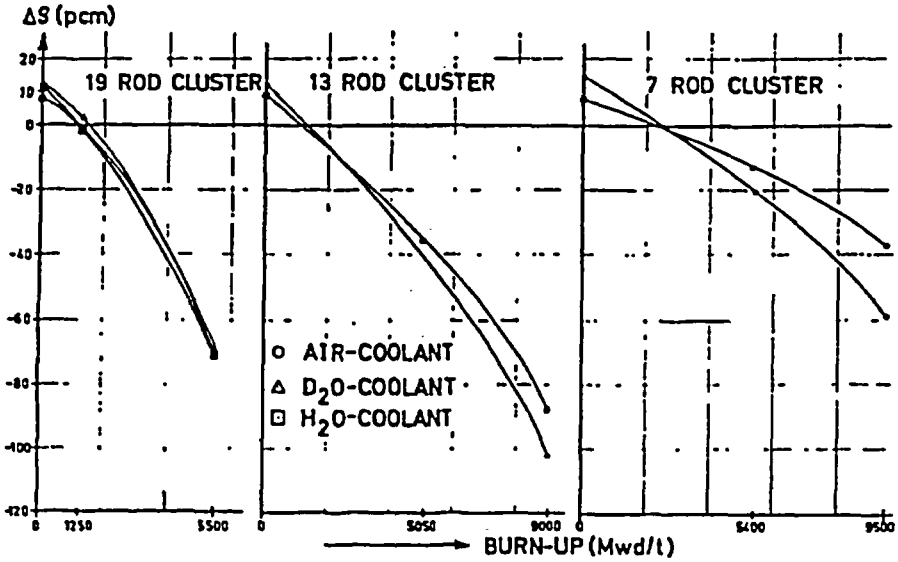

OSCILLATION ELEMENT $UO_2$/13/14.4 FIG. 2.5




OSCILLATION ELEMENT $UO_2$/19/144 FIG. 2.6

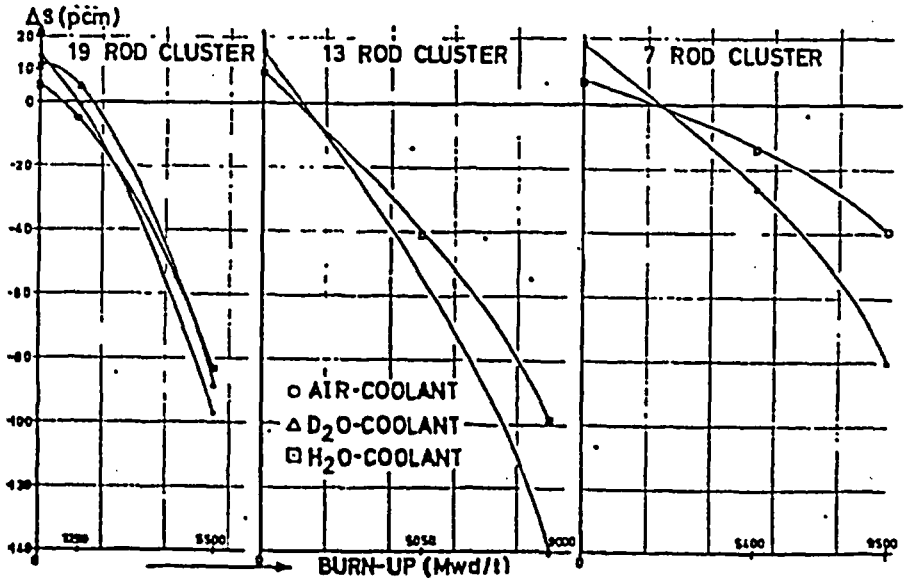



CRITICAL HEIGHT AS FUNCTION OF AXIAL OSCILLATION ELEMENT POSITION FIG. 4.1



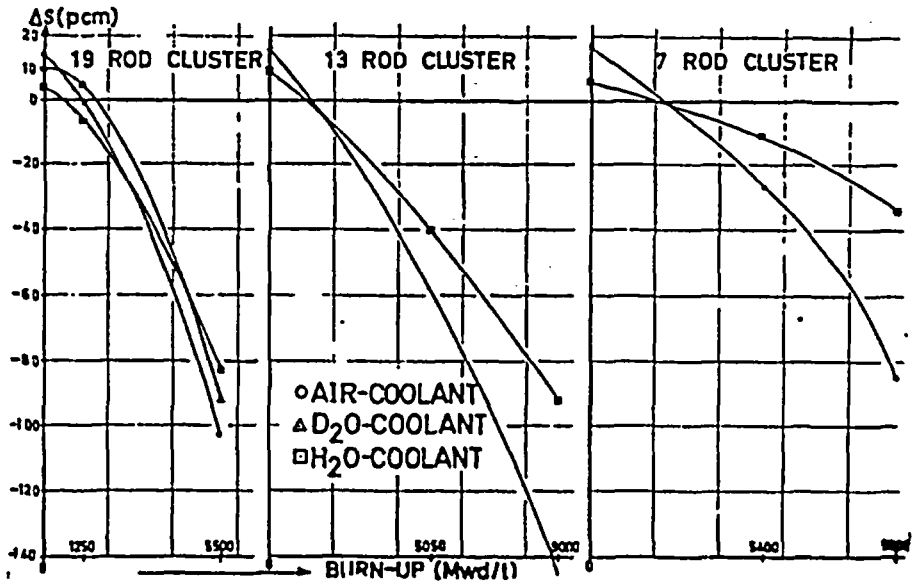

REACTIVITY EFFECT AS FUNCTION OF BURN-UP
LATTICE PITCH : 18,8 cm

FIG. 5.1




REACTIVITY EFFECT AS FUNCTION OF BURN-UP
LATTICE PITCH : 23,5 cm

FIG. 5.2




REACTIVITY EFFECT AS FUNCTION OF BURN-UP
LATTICE PITCH: 28,05 cm

FIG. 5.3

[redacted]

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