POWER PEAK IN VICINITY OF WWER-440 CONTROL ROD AT END OF FUEL CYCLE

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ABSTRACT

This paper presents some results of the axial power distribution measurements carried out in a WWER-440 type core on the light-water, zero-power reactor LR-0 in the vicinity of the WWER-440 control rod (CR) model at zero boron concentration in moderator. Further presented information concern the description of the CR model, LR-0 core arrangement, specification of the fuel assemblies and measurement conditions. The aim of performed experiment is enlargement of the available "power peaking database" to enable the calculation codes validation also by means of data that correspond to the end of WWER-440 fuel cycle.

1. INTRODUCTION

It is well known that WWER-440 CR has a significant influence on the space power (fission density) distribution and can cause power peaks in adjacent fuel assemblies. This is a consequence of the butt joint design of the absorbing adapter (part) to the CR fuel part [1], that is, presence of the water cavity, the beginning of which is the upper level of steel inserts in fuel assembly (FA) and the end - in FA cap; presence of the given cavity results in a flash-up of thermal neutrons in periphery fuel pins (rods) of the adjacent operating assemblies.

Problems concerning the CR were discussed in the frame of the Technical Meeting on "WWER-440 Local Power Peaking Induced by Control Rods" organized by Nuclear Research Institute (NRI) Rez plc in co-operation with the International Atomic Energy Agency, held in Rez, 11 - 13 March 2002. Altogether 33 participants have represented the WWER-440 NPPs as well as the co-operating research institutes and other relevant organisations from Armenia, Bulgaria, Hungary, Finland, IAEA, Russian Federation, Slovakia, Switzerland, Ukraine and the host country - Czech Republic. Based on the presentations and discussions, the "Conclusions" from two Working Groups on computational and experimental aspects were presented to a final plenary meeting for consensus. For simplicity, a part of this consensus consists in the following [2]:

- The power peaking phenomenon is safety related and the criteria affected are maximum linear heat generation rate, as well as pellet cladding interaction through high power ramps for fuel surrounding the control rods. Both criteria become significant in the future if plants move to high burn-up, load following operation or power up rating.

- Proper experimental verification is however needed since safety margins monitoring relies on adequate codes / methods for pre-calculation. No direct monitoring is possible.
- The information presented in meeting is qualitatively consistent, though there are some small quantitative differences, which can be explained with varying experimental conditions. The design modification including a Hafnium plate will reduce the power peaking effect significantly, of the order of 60%.
- New measurements at low boron concentration are desirable as suggested during the meeting for future LR-0 experiments at NRI Rez.
- An extension of the Rez database is considered necessary, in particular for experiments with boric acid to compare the results against the Russian data.

From the point of view of boron acid concentration in moderator, the power peaking effect was investigated e.g. in two cases:

- First one with zero boron concentration, corresponding to the end of fuel cycle, by means of calculations presented by Russian specialists in 1999 [1] and
- Second one with boron acid concentrations about 5 g/l by means of:
    1. Experiment on LR-0 reactor at NRI Rez in 1994 with concentration 4.8 g/l in the frame of a contract with Hungarian NPP Paks [3] and
    2. Experiment at concentration 5.15 g/l and calculation studies carried out at RRC "Kurchatow Institute" published in 2000 [4].

Because of complicated geometry and material composition of the CR, the detailed calculations of power distribution are complicated too. Since the case corresponding the end of fuel cycle mentioned above was only investigated by calculations, it was suggested to add needed experimental information by means of measurements to be performed on the LR-0 reactor in appropriate WWER-440 type core at zero boron concentration and containing a WWER-440 CR model [5], to have in this important case both the calculation and experimental data. This suggestion is in accordance with "Conclusions" of the Technical Meeting mentioned above [2]. In such way desirable calculation and experimental information could be available for both zero and higher boron acid concentrations to validate computation codes. It is to be noted that detailed experimental space power distribution data cannot be obtained in the NPPs.

It can also be noted, to suppress neutron flash-up the plates of metallic Hafnium are arranged on the inner surface of the jacketed tube in the region of butt joint of the innovated CR; the performed physical calculations showed that in case of arrangement of Hafnium plates the neutron flash-up is prevented completely [1]. According to our information, some of NPPs are equipped with this "Hafnium innovation" (e.g., in the Russian Federation), another ones will be innovated in the near future; some of NPPs are operated with inserted CR, other ones not (e.g. Finnish NPP Loviisa).

We can stated, they are two situations concerning the code validation that ought to be taken into account: the first one corresponding to the end of fuel cycle, i.e. with zero-boron acid concentration in moderator, and the second one - at the start of fuel cycle, i.e. with this concentration being practically highest (at the conditions on the LR-0 reactor, i.e. the room temperature, atmospheric pressure, this concentration can be about 6.5 g/l). Of course, the investigation of these situations should also include both two variants - without and with Hafnium plates in CR, if possible.

2. AIM OF EXPERIMENT

The aim of presented experiment is enlargement of the available "power peaking database" to enable calculation codes validation also by means of measurement results obtained at zero boron concentration that correspond to the end of WWER-440 fuel cycle.

3. EXPERIMENTAL ARRANGEMENT AND CONDITIONS

It is to be noted that CR model on the LR-0 reactor is an "authentic" model, because it is made of original parts of a real CR, but in comparison with the original CR, the sequence of its height arrangement (the fuel, butt joint and absorbing parts) is reverse. It consists of three parts. The lower one contains 2 absorbing segments from the original WWER-440 CR: hexagonal rings with outer diameter of 136 mm, thickness - 6 mm and height - 102 mm with 6 perforations, 1 in the centre of each of their 6 sides (diameter 10 mm). These absorbing segments, made of borated steel (2.0 wt. %), are placed in a stainless steel hexagonal tube (thickness 2 mm). Inside of these 2 absorbing segments a stainless steel tube (outer diameter - 114.5 mm, thickness - 5 mm) is situated which has the following perforations: 6 apertures (60° symmetry) having diameter 10 mm being arranged in the rows with 100 mm distance between them. The upper part of the CR model is a 2.4 % enriched FA, placed in a hexagonal tube (thickness 1.5 mm) made of zirconium alloyed with niobium (2.5 wt.%). Between those two parts there is a butt joint that contains original parts of the WWER-440 CR, too. In Fig. 1 the main parts of the complicated WWER-440 CR model are demonstrated with their positions in this model (identified by corresponding numbers) [6]. The loading of the CR model into LR-0 core is shown in Fig. 2.

A shortened WWER-440 type fuel pins were used having a 1250 mm active fuel (uranium pellets) length with lower end situated 38 mm from the fuel pin end, excepting the 2.4% enriched pins of the CR model with their active length (uranium pellets) of 1073.6 mm and containing Zr tubes at their lower part (diameter 7.6/6.0 mm, length 56.7 mm, lower end 38 mm from the fuel pin end), continuing with stainless steel cylinder (diameter 7.5 mm, length - 119.7 mm) and finally continuing with active fuel pin part (uranium pellets). The hexagonal tubes of all FAs (excepting the 2.4 enriched one of CR model mentioned above) are made of aluminium (thickness 2 mm). In all FAs the standard type stainless steel spacing grids (height 10 mm) defining the hexagonal lattice of the fuel pins in CR model (denoted by SG-CR) and in 12 FAs of the core (denoted by SG-Co) were used (see Figs. 6 - 9) at positions with axial (vertical) coordinates having step of 240 mm. The coordinates of their centres (below the moderator critical height level) in 12 FAs were 148 mm, 388 mm, 628 mm and 868 mm and in CR model - 543 mm and 783 mm from the lower end of the active fuel part (uranium pellets) of 12 FAs. The axial coordinates of the core arrangement:

- -38.0 mm - Lower end of the fuel pins of 12 FAs
- 0.0 mm - Lower end of the active fuel part (uranium pellets) of 12 FAs
- 5.5 mm - Bottom of absorber segments at CR model
- 209.5 mm - Top of absorber segments at CR model
- 465.0 mm - Bottom of fuel pins at CR model
- 503.0 mm - Bottom of Zr tubes at fuel pins of CR model
- 559.7 mm - Top of Zr tubes and bottom of stainless steel cylinders at fuel pins of CR model
- 679.4 mm - Top of stainless steel cylinders and bottom of fuel active part (uranium pellets) of CR model

- 882.4 +/- 0.2 mm - Critical height in case of 600 - 900 keV gamma quanta measurements - the mean of 6 critical height values - see belov moderator temperature 16.0 +/-1.0 °C
- 882.9 +/- 0.3 mm - Critical height in case of La peak - 1596.5 keV gamma quanta measurements; moderator temperature 15.7 +/- 0.9 °C

To start the experiment preparation, some needed calculations were perfomed to determine core having suitable properties. By means of these calculations [7], following core has bei determined: it consist of the CR model placed in the core centre, around it - a ring of 6 F/ with fuel pins having 3.6% enrichment except their periphery rows where three pins in tl corners have enrichment of 3.0 % and finally next 6 periphery FAs of the same compositic around those ones mentioned above. Schematic arrangement of the FAs in the LR-0 core presented in Fig. 3 with FAs numbering in which the measurements were performed. Tl arrangement of the fuel pins in FAs in LR-0 core with WWER-440 CR model in its centre shown in Fig. 4. Finally the fuel pins numbering (needed below) in the FA (No 2 in Fig. 3) presented in Fig. 5 (it is the same as in [1]).

The critical height of this core is sufficient to investigate power peaking effect in the vicini of the CR model butt joint (see below). Such core represents a compromise between son NPPs conditions/needs (e.g. profiled enrichment of the fuel assemblies), LR-0 react possibilities (disposable fuel pins/assemblies) and suitable conditions for calculatioi (e.g. 60° symmetry).

4. MEASUREMENT METHODS

The measurements of axial power (fission density) distributions have been performed t means of two measurement methods, i.e. by gamma activity determination (gamma scannir method) of the irradiated fuel pins (selected parts), detecting gamma quanta:

1. In the energy range of 600 - 900 keV and
2. In La peak area - 1596.5 keV

In both cases two Na(Tl) scintillator crystals (one of them - monitor) with diameter of 40 mı were used, each of them in Pb shielding (thickness 150 mm). The measurement process wi performed automatically by means of PC connected with stepping motor and CAMA modules. The fuel pin rotated around its own axis during the gamma scanning.

In case of 600 - 900 keV gamma quanta detection, the activities of 10 mm fuel pin sectioı were determined by means of a rectangular collimator (dimensions 10x10 mm). Tł measurements were carried out by means of 6 irradiations using the fuel pins irradiate stepwise in 6 FAs No 1,...,6 (Fig. 3), namely (see Fig. 5):

- In 6 equivalent (with respect to CR model) fuel pin positions P_i ($i = 1,\ldots,6$) in tł centres of the periphery fuel pin rows adjacent to the WWER-440 CR model; in cas of FA No 2 - the fuel pin position No 119
- In 6 equivalent fuel pin positions M_i ($i = 1,\ldots,6$) situated in the middle part of FAs in the centre of the fifth rows from WWER-440 CR model; in case of FA No 2 - th fuel No 17.

It means, that by one irradiation, one pair of axial power distributions in position P_i and M_i in FA No i (i = 1,...,6) was determined using a fuel pin monitor irradiated simultaneously in middle position between M_i and P_i (in case of FA No 2 - in fuel pin position No 56). The measurements were realized in the axial coordinates range of 50 - 950 mm with variable step (10, 25 or 50 mm - see Tab. 1) in dependence on the supposed distribution shape and the importance of the separate distribution parts from the point of view of experiment aim. The fuel pins were measured one time (without repetition).

In case of the "La peak method" only one (intensive) irradiation was realized. The fuel pin sections of 20 mm length were measured using a rectangular collimator having dimensions 20x10 mm. The measurements were carried out by means of fuel pins irradiated in 6 FAs No 1,...,6 (Fig. 3) in the same positions P_i and M_i as in case above and further also (Fig. 5):

- In 6 equivalent fuel pin positions C_{ij} of the 3 FAs No j (i = 1, 2; j = 2, 4, 6), fuel pin positions situated in both (i = 1, 2) to the CR adjacent corners of the FAs No j (j = 2, 4, 6); in case of FA No 2 - C_{12} and C_{22} are the fuel pin positions No 116 and 122 respectively.

The measurements were realized in the axial coordinates range of 50 - 950 mm with 10 mm step.

It means, that by one irradiation the axial power distributions in all positions P_i, M_i and C_{ij} mentioned above were determined using one fuel pin monitor irradiated simultaneously in FA No 1 in fuel pin position equivalent to No 56 of FA No 2. Each fuel pin was measured two times - in "both axial coordinates order", i.e., 50,...,950 mm and 950,...,50 mm, to suppress eventual small non stabilities.

By means of 6 axial power distributions measured in each position P_i, M_i and C_{ij}, the weighted mean values and corresponding errors of the axial power distributions in (fictive) fuel pin positions P, M and C were determined for both measurement methods mentioned above (in case of FA No 2 these fuel pin positions are equivalent to the positions No 119, 17 as well as 116 and 122, respectively).

5. RESULTS

For simplicity the relative axial power (fission density) distribution values obtained by means of "600 - 900 keV gamma quanta measurement method" in fuel pin positions P and M are presented only in Tab. 1 and demonstrated in Fig. 6. Further the peaking factor of the power distribution in fuel pin position P regarding to the power distribution in position M was determined by means of the ratio of the power distribution values in position P and in position M, i.e. "P/M" distribution values in all measured axial coordinates (Fig. 7).

In case of measurements performed by means of "La peak method", the obtained results of power distributions in fuel pin positions P, C and M are demonstrated in Fig. 8. The peaking factors of the power distributions in fuel pin positions P and C regarding to the power distribution in position M (i.e. "P"/"M" and "C/M" values) are shown in Fig. 9.

6. CONCLUSIONS

The obtained experimental results enlarge the available "power peaking database" by values measured at zero boron concentration corresponding to the end of WWER-440 fuel cycle that enable validation of the codes also in this important case. This validation can improve the reliability of the calculation results of the power distribution in WWER-440 cores, re-loading schemes etc. More information about the power peaking phenomenon can be found in [2].

7. REFERENCES

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Tab. 1. Relative axial power (fission density) distributions in fuel pin positions P and M
Energy of detected gamma quanta: 600 - 900 keV
Normalization: (non weighted) average of 92 presented values in fuel pin positions P and M = 1

Axial coord. [mm]	Relative power (fission density) Position P Value	Position P Error [%]	Position M Value	Position M Error [%]
50	0.1845	1.80	0.2270	1.02
100	0.2504	2.00	0.3086	0.89
150	0.3228	2.30	0.3829	0.77
200	0.4462	1.72	0.5001	0.60
225	0.5705	1.31	0.5571	0.41
250	0.6914	1.11	0.6212	0.96
275	0.8140	0.58	0.6661	0.64
300	0.7944	0.70	0.7176	0.71
325	0.7899	0.83	0.7619	0.56
350	0.8304	0.97	0.7979	0.19
375	0.8977	1.57	0.8350	0.97
400	0.9684	1.43	0.8361	0.68
410	1.0381	1.51	0.8632	0.87
420	1.1050	1.08	0.9025	0.76
430	1.1875	1.08	0.9412	0.73
440	1.3199	0.93	0.9678	0.94
450	1.4586	0.45	0.9872	0.82
460	1.5974	0.33	1.0164	0.58
470	1.6936	0.38	1.0358	0.83
480	1.7741	0.63	1.0481	0.74
490	1.8076	0.53	1.0680	0.59
500	1.8603	0.35	1.0711	0.76
510	1.8893	0.41	1.0821	0.68
520	1.8851	0.57	1.1050	0.87

Axial coord. [mm]	Relative power (fission density) Position P Value	Position P Error [%]	Position M Value	Position M Error [%]
530	1.8733	0.23	1.1104	0.62
540	1.8201	0.27	1.1150	0.85
550	1.7499	0.62	1.1109	0.62
560	1.6989	0.44	1.1268	0.54
570	1.6596	0.74	1.1311	0.80
580	1.6448	0.45	1.1342	0.71
590	1.6000	0.86	1.1193	0.83
600	1.5841	0.65	1.1291	0.53
625	1.5573	0.69	1.1030	0.67
650	1.5406	1.14	1.0822	0.56
675	1.5323	1.28	1.1091	0.85
700	1.4638	0.60	1.1002	0.57
725	1.4171	1.26	1.0585	1.08
750	1.3314	1.38	0.9988	1.16
775	1.2343	1.28	0.9381	0.79
800	1.1222	1.15	0.8475	0.86
825	0.9798	1.04	0.7320	0.79
850	0.7666	1.68	0.5701	1.32
875	0.4612	0.92	0.3497	1.65
900	0.1786	1.43	0.1382	1.19
925	0.1032	2.61	0.0854	1.75
950	0.0744	2.97	0.0580	1.67
Mean value	1.1646	1.05	0.8358	0.83

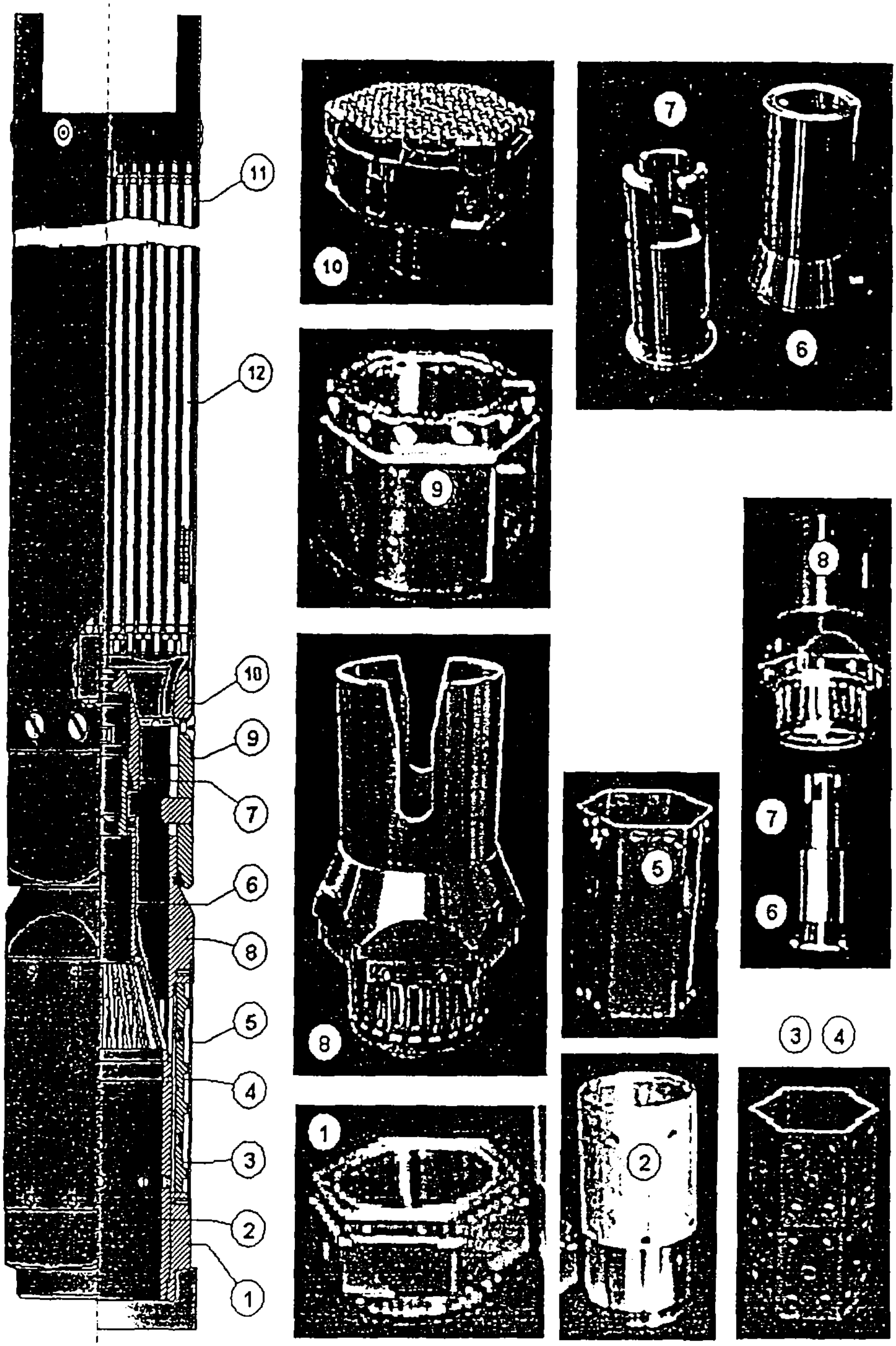

Fig. 1. Main parts of the WWER-440 CR model and their positions in this model

Fig. 2. WWER-440 CR model loading into LR-0 reactor core

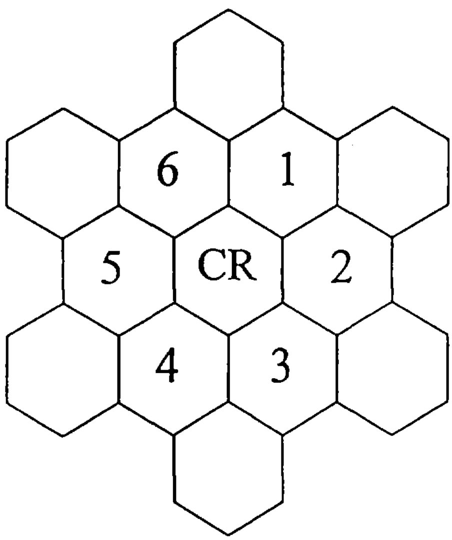

Fig. 3. Schematic arrangement of the LR-0 reactor core with WWER-440 CR model in its centre and the FAs numbering in which the measurements were performed

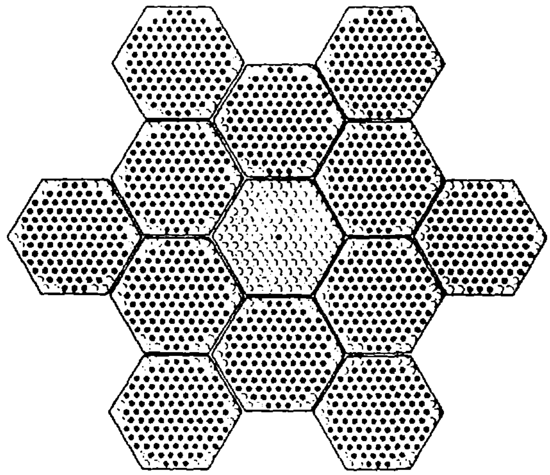

Fig. 4. Arrangement of the fuel pins in FAs in the LR-0 reactor core with WWER-440 CR model in its centre

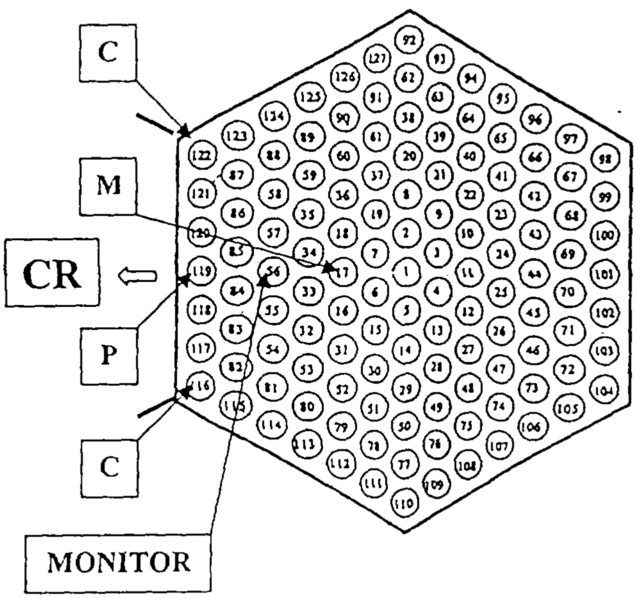

Fig. 5. Fuel pin positions numbering and denotation of the measured fuel pins positions P, M and C in the FA (No 2 in Fig. 3)

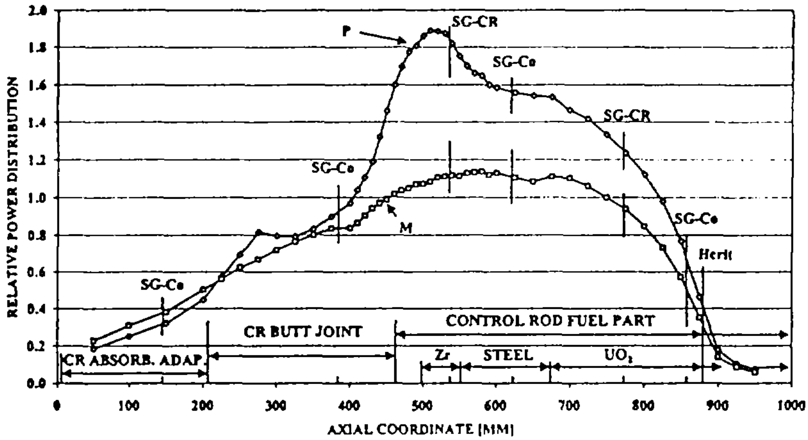

Fig. 6. Relative axial power distributions in fuel pin positions P and M
Energy of detected gamma quanta: 600 - 900 keV

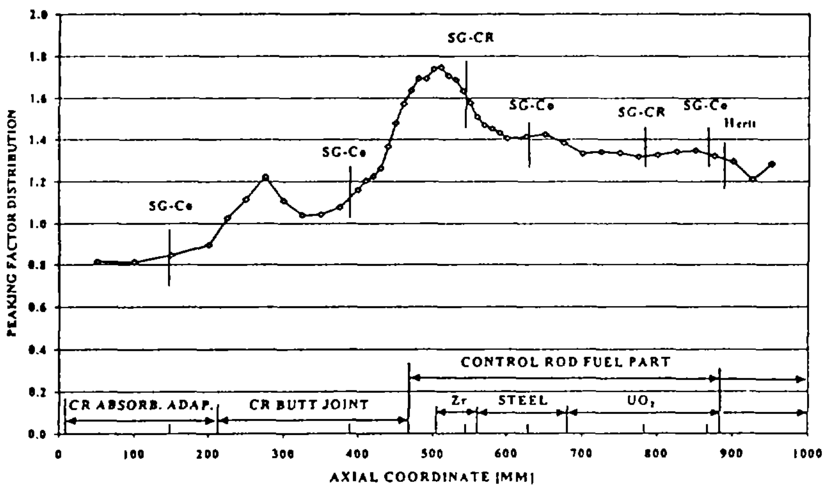

Fig. 7. Peaking factor of the axial power distribution in fuel pin position P regarding to the position M
Energy of detected gamma quanta: 600 - 900 keV

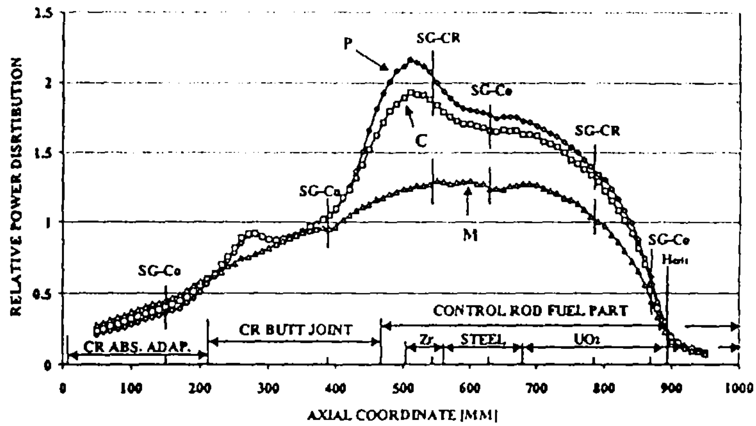

Fig. 8. Relative axial power distributions in fuel pin positions P, C and M
Energy of detected gamma quanta: La peak - 1596.5 keV

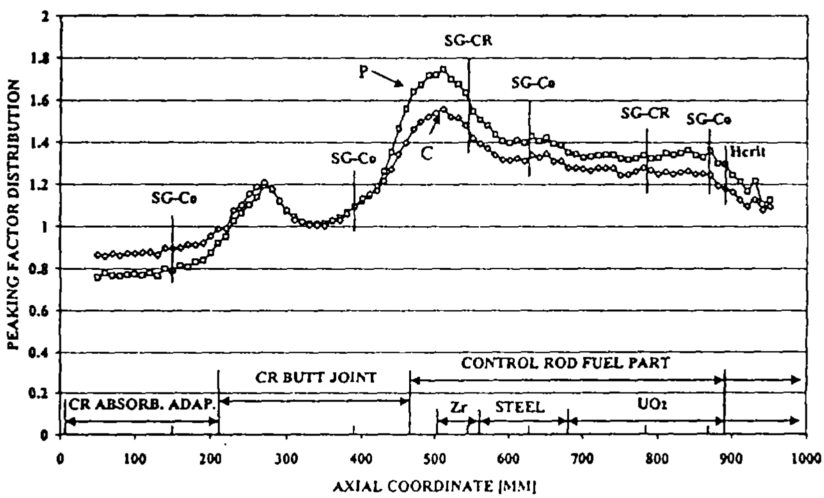

Fig. 9. Peaking factor of the axial power distribution in fuel pin positions P and C regarding to the position M
Energy of detected gamma quanta: La peak - 1596.5 keV