Local Linear Heat Rate Ramps In The VVER-440 Transient Regimes.

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Abstract

The operation of the VVER-440 reactors must be accomplished in such a way that the fuel rods durability would be high enough during the whole operation period. The important factors determining the absence of fuel rod failures are the criteria limiting the core characteristics (fuel rod and fuel assembly power, local linear heat rate, etc.). For the transient and load follow conditions the limitations on the permissible local linear rate ramp are also introduced. This limitation is the result of design limit of stress corrosion cracking of the fuel cladding and depends on the local fuel burn-up.

The control rod motion is accompanied by power redistribution, which, in principle, can result in violating the design and operation limitations. Consequently, this motion have to be such as the core parameters, including the local ramps of the linear heat generation rates would not exceed the permissible ones.

The paper considers the problems of VVER-440 reactor control under transient and load follow conditions and the associated optimisation of local linear heat generation rate ramps. The main factors affecting the solution of the problem under consideration are discussed. Some recommendations for a more optimal reactor operation are given.

Introduction

Recently the efforts of specialists on the VVER reactors are focused on the increase in the VVER-440 reactor efficiency. In particular, the problems on power increase in the operating power units and transfer of the reactors to power load follow operation are solved, the modernized fuel cycles characterized by more economic use of nuclear fuel are introduced. Naturally, these actions lead to the reduction in the design and operational margins, decrease in the conservatism in choosing the characteristics of fuel cycles for the purpose of increasing the economic effect. As a consequence rise the requirements to the systems of reactor power monitoring and operation. The problem of optimal operation involve many questions. The methods for their solution depend in many respects on the problem stated (power increase, load following operation conditions, the former and the latter simultaneously, etc.). However, it is clear that any operation methods and algorithms are based on the requirements to meeting the limitations (limits) under all normal operation conditions.

At the RRC KI working on the creation of such methods for the VVER-440 reactors are being carried out. The first phase of this elaboration is developing an approach to the solution of the problem stated as well as the analysis of conditions of meeting the core limits under the normal operation conditions.

1. Target setting

As stated above the methods for power operation depend on the goal stated and may differ as applied to different reactors. For example, the operation method for the power unit operating in base load may be different from that required for the unit in load follow. The common feature for all the methods is the requirement of meeting the criteria and limits adopted. For the power variation conditions an important factor, determining the absence of damages in the fuel claddings, is the limit on the permissible local ramp of linear heat generation rate. This limit was obtained from experiments and thermomechanical calculations of fuel rods and depends on the local fuel burn-up (Fig.1 "limit curve 2").

As a rule, the reactor operation is accomplished with the participation of mechanical control rods whose motion affects significantly the power distribution over the core. The character of power redistribution is determined by many factors:

- range and rate of change in load;
- time of operation at lower power level;
- range and velocity of control rod motion;
- fuel loading pattern;
- distribution of fission products over the core, which, in turn, depends on many parameters, etc.

In the first phase of creation of power operation algorithms the problem is stated as follows: how the reactor must be operate so that the requirements on not exceeding the core limits would be met? The solution of this problem is essentially reduced to the determination and optimization of control rod motion range which permits the designing and operation limits to be met. The operation algorithm which will ensure the minimum power redistribution is optimal for this statement of the problem.

2. Definitions

For an unambiguous treatment of notions used in the paper some terms, characterizing the operation conditions, are given below.

Cycle of power change or loading cycle, means the power variation by the schedule 100%-N% (N<100)-100%.

Regime of the compensation is the change in the control rod position with no power change (critical state of the reactor is maintained at the expense of change in the boron concentration in the reactor coolant).

Start control bank position is the position in the steady state at nominal power at the moment of loading cycle beginning.

End control bank position is the position upon the completion of loading cycle or regime of the compensation.

Local linear heat rate ramp – local power change as result of loading cycle or regime of the compensation.

Permissible local linear heat rate ramp is a local power ramping for which the absence of propagation of technological detect of fuel cladding is justified.

Transient regime is the condition which is accompanied by the power redistribution in the core.

Permissible start position of control rods is the position in the steady state at nominal power, for which limitations on power (local, of the fuel rod and FA) are fulfilled.

Permissible end position of control rods is the position upon the completion of loading cycle or regime of compensation, for which the power limitation, local, fuel rod, FA) and local ramp limitations are fulfilled.

Effective control rod position in the burnout regime is a conditional constant in time position of control group, which forms the actual FP distribution over the core during the core campaign.

3. *Determination of the permissible moving range of control bank*

To maintain the control rod operability during the whole operation time the local power must not exceed the "limit curve 1", and the local ramps of the linear heat rate, induced by control rod motion and power redistribution during the transients must not exceed the "limit curve 2" in permissible ramps. The limits on the linear heat rate ramps for the PWR are similar [1-3]. In addition, the limits on the power of FAs and fuel rods are established. Let us consider the above listed limits as determining although, in principle, they may be added by others.

To determine the permissible range of control rod motion, with the problem stated in such a way, it is necessary to find the maximum deviation from the permissible values over the whole core volume in the process of transient.

$$dQ_{FA}^{max}=Q_{FA}^{max} - Q_{FA}^{perm} \tag{1}$$

$$dQ_{FR}^{max}=Q_{FR}^{max} - Q_{FR}^{perm} \tag{2}$$

$$dQ_l^{max}=(Q_l - Q_l^{perm}(B_1))^{max} \tag{3}$$

$$d(dQ_l)^{max}=((dQ_l - dQ_l^{perm}(B_2))^{max} \tag{4}$$

They characterize the regime. Here
- Q_{FA}^{perm} is the permissible fuel assembly power;
- Q_{FR}^{perm} is the permissible fuel rod power;
- $Q_l^{perm}(B_1)$ is the permissible local heat generation rate;
- $dQ_l^{perm}(B_2)$ is the permissible local linear heat rate ramp;
- B_1 is the fuel rod burn-up;
- B_2 is the local fuel burn-up.

The core states at which the conditions

$$Q_{FA}^{max} - Q_{FA}^{perm} \leq 0 \tag{5}$$

$$Q_{FR}^{max} - Q_{FR}^{perm} \leq 0 \tag{6}$$

$$(Q_l - Q_l^{perm} (B_1))^{max} \leq 0 \tag{7}$$

$$(dQ_l - dQ_l^{perm} (B_2))^{max} \leq 0 \tag{8}$$

are met determine the region of permissible extreme positions of control rods at the start condition specified. Formulas (1)-(4) can be added with formulas showing other criteria, in principal.

Since in expressions (1)-(8) the local fuel burn-up exists, the range of permissible positions must be established, in principle, individually for each fuel loading and different core life time intervals.

The approach proposed has been applied for the analysis of general regularities of power operation, determination of the main factors affecting the operation process. Basing on this analysis the recommendations for more optimal VVER-440 power operation have been worked out just now, before their implementation on the existing NPPs.

In the analysis of transients the question arises on the time of stress relaxation in the fuel claddings upon the local ramps of the linear heat rate. The answer to this question determines to the significant degree the approach to the solution of the problem considered.

The existing limitations on the linear heat generation rate (Fig.1, "limit curve 1") determine the level of possible values of the local linear heat rate under the conditions of normal operation. For example, for the third year fuel rods (burn-up range 25-35 MWD/kgU) this heat rate must be not higher than 270-280 W/cm, for the fourth year fuel rods (burn-up higher than 35 MWD/kgU) it must be not higher than 250-280 W/cm. The limitations must be fulfilled in the steady state and transient regimes. As follows from the thermomechanical calculations of the behaviour of fuel rods in the transients, the operating under these "temperate" heat rate levels is not practically accompanied by the relaxation of stresses in the fuel cladding upon possible local power ramps. Then in the such transients the dynamics of stresses in the cladding is determined by the local burn-up and local power value and, practically, is not depended on the time of operation at this power. Power redistribution can be then considered as oscillations near the distribution which was established in the process of burnout. Possible increase and decrease the cladding stresses will be determined by difference in the local rate levels during the transient regime and in the burnout regime (by local power ramps).

4. Calculation analysis

The calculation analysis was performed by the code package BIPR-7A-PERMAK-A [4,5], which, in addition to the above mentioned characteristics, permits the critical heat flux ratio, distributions of coolant temperature in the fuel assemblies and hot channels of the core as well as the temperatures of fuel and claddings to be calculated. This, in principle, makes it possible to control the limitations by all above parameters in the process of calculations.

The analysis was made of the effects of:

- start and end positions of the control rod group;
- operating time upon refuelling (T_{eff}=0-240 days);
- time of operation at lower power;
- depth of load following;
- effective position of the control rod group under the burnout conditions;
- fuel assembly loading patterns.

The conditions of power variations by the schedules 100%-10%-100%, 100%-50%-100% and the compensation regime were considered. As the control rod motion exerts the strongest influence on the power of fuel roods of the fuel assemblies surrounding the control rod group, two loading patterns (Figs. 2 and 3) were analyzed. By the first pattern the fuel assemblies of the second and third year operation were located around the VI group of control rods, by the second pattern only the fuel assemblies of the second year operation. Two versions of the effective position of the control rod group in the burnout regime, 175 cm and 195 cm, were considered. The region of permissible motions was determined in accordance with conditions (5)-(8). Then

- in the calculations of linear heat generation rates and their ramps the engineering factor for location power $k_m^{Ql} = 1.14$ was considered;
- the fuel assembly power was calculated with allowance for the engineering factor $k_m^{FA} = 1.05$;
- the fuel rod power was calculated with allowance for the engineering factor $k_m^{FR} = 1.08$;
- the start and end positions of control rods varied over the range 125-234 cm (141-250 cm by selsyn readings);
- the permissible start positions of control rods are those when power limitations (5)-(7) (FA, fuel rod, local) are fulfilled;
- the permissible end positions are determined from the conditions of fulfilment of criteria (5)-(8);
- a correction was introduced which accounts for the exponential character of the fall of axial power distribution in the fuel rods of the parts of the control rod *banks, which are under the core;*
- the non-uniformity of the control rod bank joint which gives an additional contribution to the change in the local power in the fuel rods of neighbour assemblies during the control rod movement was taken into account.

5. Results of calculation analysis

The main calculation results are given in Figs. 4-15 in the form of lines of equal levels by power ramps $(dQ_1\text{-}dQ_1^{perm}(B_2)^{max})$. In these figures the dashed lines show the isolines $(Q_1\text{-}Q_1^{perm}(B_1))^{max} = 0$. The region between them corresponds to not exceeding $Q^{perm}(B)_1$.

First of all, it follows from the calculations that for the fuel loadings and operation conditions considered the established limits on the power of fuel rods and fuel assemblies are *not violated within the whole range of control rod motion. It is important to note that in other* cases it is the limitations on the power of fuel assemblies and fuel rods that can be the factors restricting the control rod motion. First of all these restrictions can manifest themselves in forcing the power of the power unit or for the refuelling pattern of more "rigid" in-in-out than the considered ones.

The comparison of dependencies in Figs. 4 and 5 permits one to judge about the influence of the time of power unit performance upon refuelling, T_{eff}, on the permissible range of control rod motion. The determining factors are then the increase of fuel burn-up with the time and reduction in the boron concentration.

The comparison of the dependencies given in Figs. 5,6 and 7 shows how the operating-time at the low power affects the permissible range of control rod movement.

The comparison of Figs. 8,9 with Figs. 10,11 illustrates the influence of the effective position of control rods in the burnout regime on the permissible range of control rod motion during the transients.

From the comparison of Figs. 12-15 the extent of the influence of replacement of the third year operation FA located near the control rod group by the fuel assemblies of second year operation can be estimated.

6. Conclusions

The calculation analysis of the conditions of fuel rod and fuel assembly performance in the transient regimes of the four-year fuel cycle of VVER-440 reactor was carried out.

The following conclusions can be drawn from the calculation results:

- for the operation conditions and refuelling patterns considered the limits on the power of fuel assemblies and fuel rods are not violated;
- for other refuelling patterns or for the power unit performance at higher power the limitations on the FA power or fuel rod power may be factors restricting the control rod motion;
- in the transient regimes with or without a change of the reactor power there are restrictions on the control rod motion, determined by Q_1^{perm} and dQ_1^{perm};
- the range of permissible control rod positions reduces, as a rule, with the increase in the power load follow depth and with the increase in the power unit performance time upon refuelling;
- a prolonged time of reactor operating with the control rods in lower position is accompanied by non-uniform build-up of fission products, which leads to a significant power redistribution and decrease in the permissible range of control rod group motion during the transients;
- the recommended lower boundary of the effective control rod position under the burnout conditions is ~ 195 cm (or 210 cm by selsyn readings);
- - this position of control rods is preferable from the viewpoint of optimization of local linear heat rate ramps in the transients;
- allocation of the fuel assemblies with lower fuel burn-up near the control rod bank enables the optimization of local ramps of the linear rate.

Conclusion

The paper considers the problems associated with the power operation in the transient and load follow regimes of the VVER-440 reactors. Some recommendations on a more optimal operation are given.

The optimization of power operation must begin essentially in the phase of fuel loading designing. In particular, the allocation of fuel assemblies with lower burn-up near the control rod group favours the increase in the permissible range of control rod motion. An important factor affecting the character of non-steady state regimes is the choice of an effective position of control rod group under the burnout conditions. The higher position enabling the uniform build-up of fission products is characterized by a wider range of control rod movement.

The creation and implementation of power control codes on the operating power units will enable the increase in the efficiency of NPPs with the VVER-440 reactors. These codes are able to make a calculated forecast of the nearest core states taking into account its current state and history directly on the operating power unit. This will permit to the operator to make optimal decisions for control of the operating reactor. The creation of power operation codes for the unit computer seems to be also important as it is just impossible to foresee the character of all possible non-stationary conditions and to analyse them in the designing stage.

The paper shows the first stage of the elaboration. The list of parameters considered in the optimization will be subsequently extended. The calculation code set BIPR-7A-PERMAK-A used for the analysis permits one, in particular, to control the fulfilment of restrictions on the DNBR, coolant temperature in hot channels, fuel claddings and fuel pellets temperatures [6,7].

In addition, the question on the minimization of the amount of liquid radioactive wastes will be considered.

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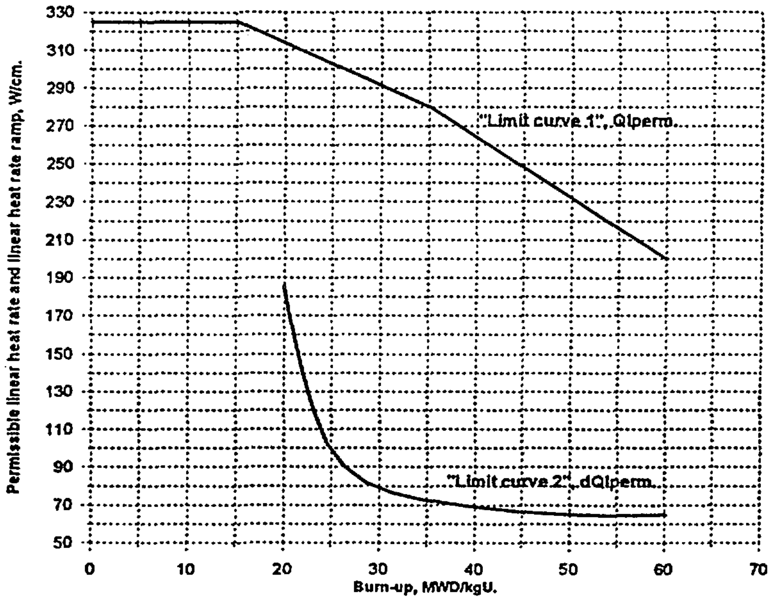

Fig. 1. Permissible linear heat rate and linear heat rate ramp.

Refuelling pattern 1.

Assemblies of the 2-d and 3-d years are placed around bank VI.

```
Nomber of assembies in 60°    59
Year                           4
Burn-up, MWD/kgU, BOC      36.27
Burn-up, MWD/kgU, EOC      39.57
                            57    58
                             1     4
                          0.00 35.28
                         10.42 39.97
                         1.036 0.489
                          53    54    55    56
                           2     1     4     4
                        9.79  0.00 34.35 36.22
                       22.53 11.78 40.27 39.38
                        48    49    50    51    52
                         2     2     1     1     4
                     13.40 10.42  0.00  0.00 36.21
                     25.68 23.21 10.13  9.79 40.12
                      42    43    44    45    46    47
                       3     2     3     1     2     4
                   25.72 13.39 22.53  0.00 11.78 35.95
                   36.22 25.74 33.74 13.27 21.21 39.86
                    35    36    37    38    39    40    41
                     3     1     3     3     1     1     4
                 25.76  0.00 25.68 24.43  0.00  0.00 36.27
                 36.21 13.40 36.27 35.26 13.27  9.79 39.42
                  28    29    30    31    32    33    34
                   1     4     3     3     3     1     4
                0.00 33.74 18.07 25.68 22.53  0.00 34.36
               13.39 43.28 26.87 36.27 33.74 10.13 40.28
                20    21    22    23    24    25    26    27
                 3     3     4     1     2     2     1     4
             23.22 24.61 33.74  0.00 13.39 10.42  0.00 35.27
             34.35 35.27 43.28 13.41 25.76 23.22 11.78 39.95
              11    12    13    14    15    16    17    18    19
               2     3     1     3     3     2     2     1     4
           12.85 23.21  0.00 25.75 25.37 13.39  9.79  0.00 36.21
           25.37 34.35 13.39 36.21 35.93 25.68 22.53 10.42 39.52
     1     2     3     4     5     6     7     8     9    10
     4     2     3     2     4     2     2     2     1     3
 25.40 11.77 21.21 10.13 32.73 13.27 10.13 13.27  0.00 20.16
 38.39 24.43 32.72 20.16 42.59 24.61 18.07 25.72 12.86 25.37
```

Fig. 2

Refuelling pattern 2.

Assemblies of the 2-d years are placed around bank VI.

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Nomber of assembies in 60°   59
Year                          4
Burn-up, MWD/kgU, BOC     35.70
Burn-up, MWD/kgU, EOC     39.00
                           57    58
                            1     4
                         0.00 35.94
                        10.34 40.54
                         53    54    55    56
                          2     1     4     4
                       9.65  0.00 34.27 36.45
                      22.32 11.62 40.11 39.55
                       48    49    50    51    52
                        2     2     1     1     4
                    13.46 10.35  0.00  0.00 36.09
                    25.74 22.87  9.94  9.63 39.94
                     42    43    44    45    46    47
                      2     3     3     1     2     4
                  13.64 25.55 22.30  0.00 11.65 36.34
                  25.75 36.33 33.21 13.01 20.94 40.18
                   35    36    37    38    39    40    41
                    3     1     3     3     1     1     4
                25.94  0.00 25.90 24.52  0.00  0.00 35.71
                36.67 13.41 36.19 35.09 13.02  9.64 38.84
                 28    29    30    31    32    33    34
                  1     4     3     3     3     1     4
               0.00 33.44 18.23 25.90 22.25  0.00 34.28
              13.62 43.11 26.98 36.20 33.17  9.95 40.13
               20    21    22    23    24    25    26    27
                3     3     4     1     3     2     1     4
            22.85 24.95 33.45  0.00 25.54 10.36  0.00 35.13
            34.20 35.72 43.12 13.42 36.34 22.89 11.64 39.78
             11    12    13    14    15    16    17    18    19
              2     3     1     3     2     2     2     1     4
          12.80 22.89  0.00 25.93 13.64 13.45  9.64  0.00 36.08
          25.52 34.24 13.62 36.66 25.76 25.74 22.31 10.35 39.38
    1     2     3     4     5     6     7     8     9    10
    4     2     3     2     4     2     2     2     1     3
30.40 11.63 20.96  9.96 32.55 13.02  9.94 13.02  0.00 20.21
38.51 24.48 32.67 20.18 42.68 24.91 18.21 25.53 12.80 25.40
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Fig.3

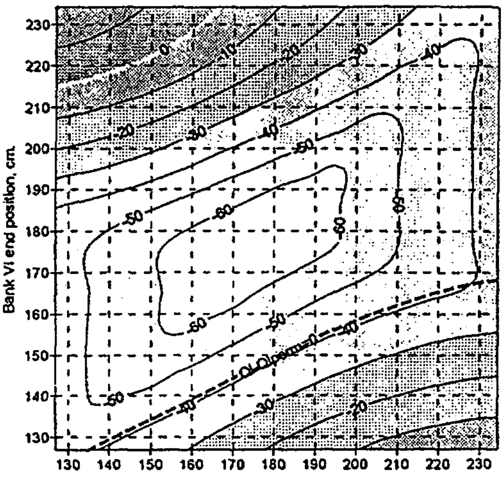

Fig. 4. Regime 100%-50%(2 hours)-100%, BOC, $\underline{H_{VI}^{eff}=175\ cm}$, assemblies of the 2-d and 3-d years are placed around bank VI.

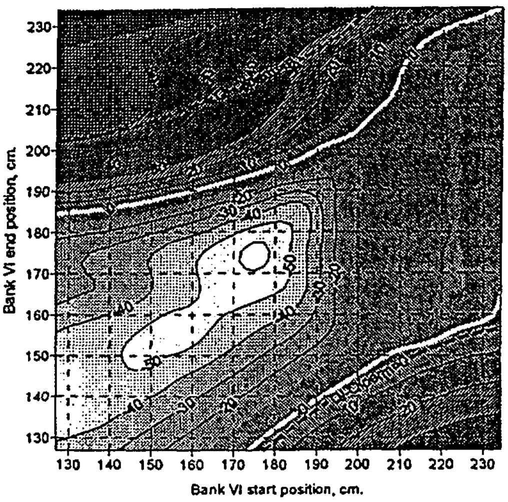

Fig. 5. Regime 100%-50%(2 hours)-100%, 240 EFD, $\underline{H_{VI}^{eff}=175\ cm}$, assemblies of the 2-d and 3-d years are placed around bank VI.

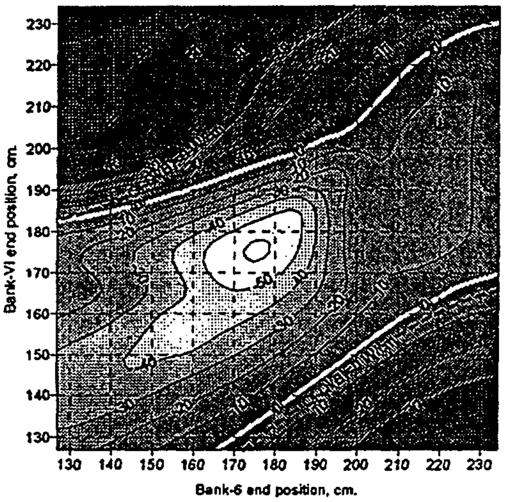

Fig. 6. Regime 100%-50%(6 hours)-100%, 240 EFD, $\underline{H_{VI}^{eff}=175\ cm}$, assemblies of the 2-d and 3-d years are placed around bank VI.

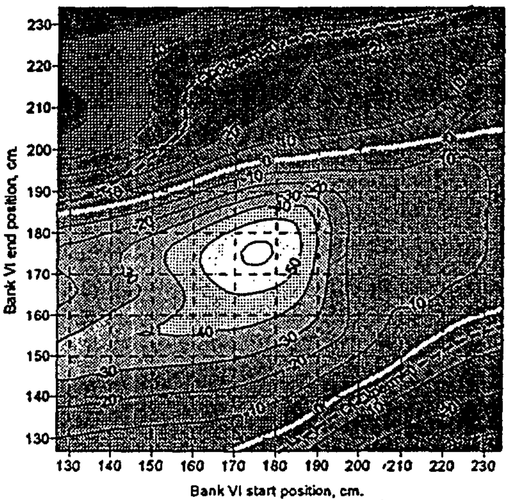

Fig. 7. Regime 100%-50%(12 hours)-100%, 240 EFD, $\underline{H_{VI}^{eff}=175\ cm}$, assemblies of the 2-d and 3-d years are placed around bank VI.

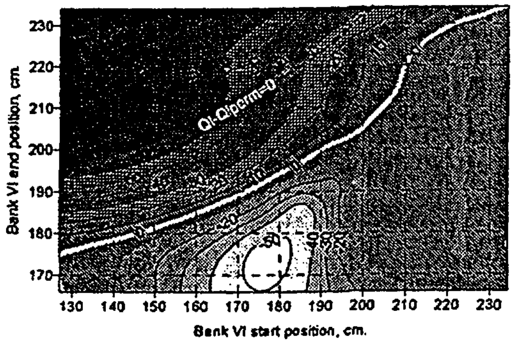

Fig. 8. Regime 100%-10%(6 hours)-100%, 240 EFD, $H_{VI}^{eff}=175$ cm, assemblies of the 2-d and 3-d years are placed around bank VI.

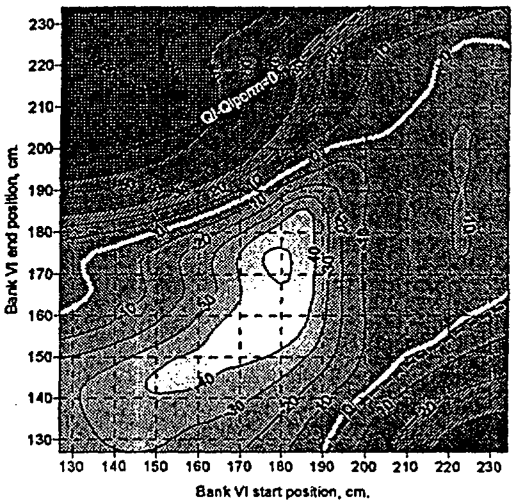

Fig. 9. Regime 100%-10%(12 hours)-100%, 240 EFD, $H_{VI}^{eff}=175$ cm, assemblies of the 2-d and 3-d years are placed around bank VI.

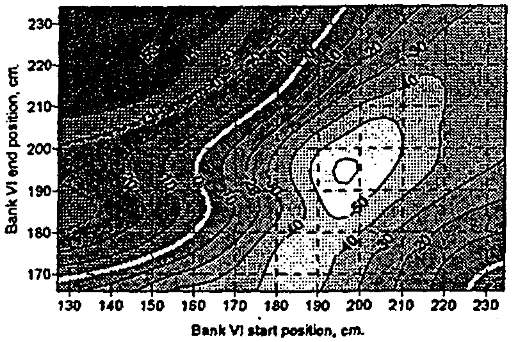

Fig. 10. Regime 100%-10%(6 hours)-100%, 240 EFD, $H_{VI}^{eff}=195$ cm, assemblies of the 2-d and 3-d years are placed around bank VI.

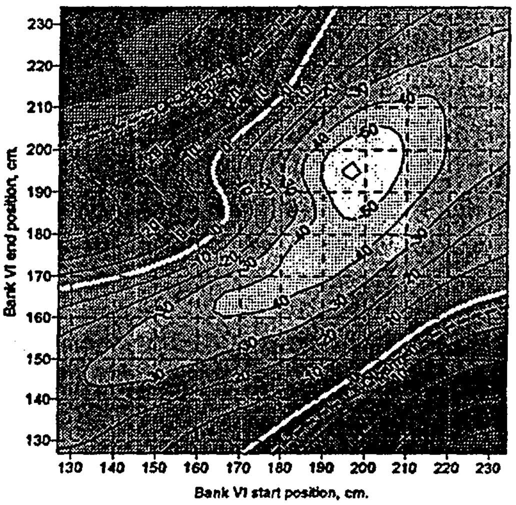

Fig. 11. Regime 100%-10%(6 hours)-100%, 240 EFD, $H_{VI}^{eff}=195$ cm, assemblies of the 2-d and 3-d years are placed around bank VI.

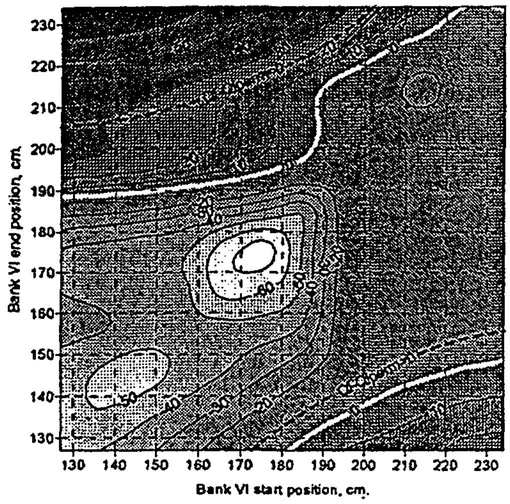

Fig.12. Regime of the compensation, 240 EFD, H_{VI}^{eff}=175 cm, assemblies of the 2-d and 3-d years are placed around bank VI.

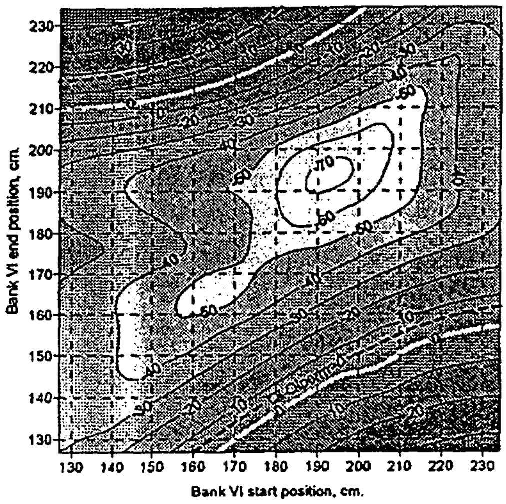

Fig. 13. Regime of the compensation, 240 EFD, H_{VI}^{eff}=195 cm, assemblies of the 2-d and 3-d years are placed around bank VI.

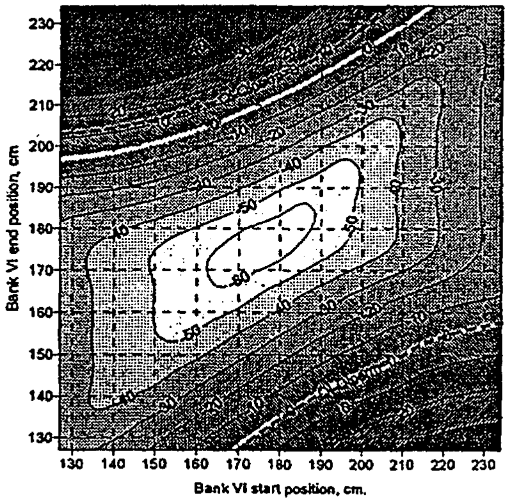

Fig.14. Regime of the compensation, 240 EFD, H_{VI}^{eff}=175 cm, assemblies of the 2-d year only are placed around bank VI.

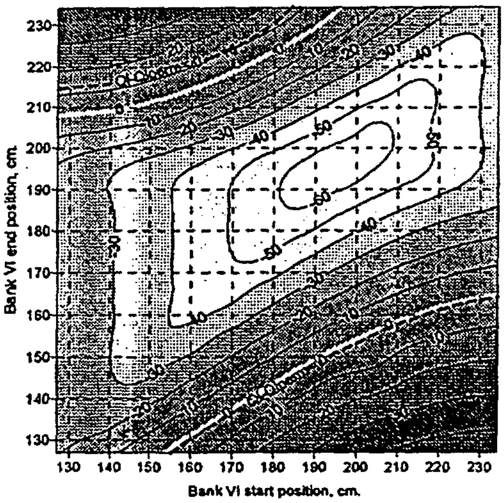

Fig.14. Regime of the compensation, 240 EFD, H_{VI}^{eff}=195 cm, assemblies of the 2-d year only are placed around bank VI.