Investigation of neutronphysical features of VVER-440 assembly containing differently enriched pins and Gd burnable poison

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Abstract

In this paper different pin-distributions of VVER-440 fuel assembly are examined. Assemblies contain 3 Gd-dopted pins (Hungarian design), 6 Gd-dopted pins near the assembly corners (Russian design) and differently profiled U5-enrichment in different pins. The main neutronphysical characteristics of this assemblies - as the function of burnup – are calculated using HELIOS code. The calculated parameters of different assembly designs are analyzed from the standpoint of fuel cycle economy and refueling design practice.

1. Introduction

The application of VVER fuel for longer operation time and higher burnup is recently a topic of development works. 4-batch refueling strategies for the VVER-440 fuel has been introduced in most of VVER user countries and utilities are looking for the further improvement of fuel cycle strategies. The fuel providing the opportunity of (partially of fully) 5-batch refueling strategy should have higher U-235 enrichment and burnable poison. Higher U-235 enrichment supply the reactivity reserve for higher burnup, the burnable poison makes possible to decrease BOC reactivity of fuel. Fuel suppliers offer Gd_2O_3 as burnable poison, integrated into the pellet.

In different papers of Russian and Czech authors [1,2,3] some design of different arrangement of VVER-440 fuel containing Gd_2O_3 burnable poison has been published. We examined two of them having approximately 4.4 and 4.2 % U-235 average enrichment. Using the idea developed during development work of BNFL VVER-440 fuel design we formed and examined two alternative pattern design having the same enrichment but different amount of Gd-pins then original Russian versions.

2. Method of calculation

For the calculation we used HELIOS code 1.6 version with k=3 option using 45-group hy045n18g16a library. One assembly structure was calculated according to Fig. 3. geometry. At the outer border white albedo boundary condition was used. For normal fuel pins hole, fuel, gap and tube parts were distinguished, moderator region of pincells were divided into 6 parts. For side- and corner cells further non-fuel regions such as shroud and gap between assemblies has been added (Fig.1). The pins containing Gd divided into 8 concentric rings and horizontally 6 sectors, each part (48 pellet-part at all) handled separately during burnup calculations (Fig.2) . The burnup steps of calculation were 500 MWd/tU up to 10000, 1000 MWd/tU from 10000 to 20000 and 2000 MWd/tU from 20000 to 40000 MWd/tU burnup level. For the fresh fuel the natural isotopic content of Gd was supposed. The boron concentration during full calculation was 500 ppm, the moderator temperature is 555.5 , the fuel temperature is 843.2 K. The power of system is 32 W/g (initial heavy metal) , equilibrium xenon is supposed.

3. Examined configurations

As a starting point we calculated the neutronphysical features of two Russian design of VVER-440 fuel with Gd burnable poison see on Fig. 3 and 4. The first one (called RUS-1 in the followings) have 4.38% the second (RUS-2) design 4.21% average U-235 enrichment. The enrichment of (1 or 3) corner pins is 3.6%, the side pins is: 4%. 6 pins containing 3.35% Gd_2O_3 and 4 % U-235 enriched fuel are placed next to corner pin. The U5 enrichment of inner pins are : 4.6 % in RUS-1 and 4.4% in RUS-2 design.

A VVER-440 fuel assembly pattern containing Gd burnable poison was developed earlier and published in [4]. Following the basic idea of that pattern two alternative designs of Russian fuel assemblies was investigated (called HUN-1 and HUN-2). All geometric and material properties of HUN designs are the same as RUS variant except U5 and Gd enrichment distribution. In HUN design we used the same enrichment of pins (both U5 and Gd enrichment) as it was used in RUS designs, but distributed differently.

HUN-1 pattern is the alternative of RUS-1 , HUN-2 is alternative for RUS-2 design. Both HUN-1 and HUN-2 have only 3 pins containing Gd. The Gd pins surround the assembly center in 120 degree. Gd content removed from the corner vicinity. The U5 enrichment of Gd pins is 4%, the Gd_2O_3 content is 3.35%. The average U5 enrichment of HUN design is approximately the same (slightly lower) then the appropriate RUS versions.

4. Studied parameters

For the mentioned cases we calculated the k_{inf} values and the pin power distribution as a function of burnup. As additional parameters the followings has been calculated :

- k_{inf} (as function of burnup) for the "*reference*" fuel. Reference fuel have the same U5 enrichment but no Gd.
- k_{inf} value at 0 burnup for the "*standard*" fuel. Standard fuel have 3.6% enrichments in each pins. For the calculated case we got k_{inf}=1.24539 (boron, temperatures , etc. see above)

For the detailed analysis if neutronphysical behavior we chosed the examination of following parameters :

- pin power distribution at 0 at 10000 MWd/tU burnups – representing 1st cycle BOC and EOC state of fuel
- k_{inf} as function of burnup for the examined and for it's reference fuel
- maximal pin power of the examined fuel as the function of burnup
- pin power of the Gd-pind as the function of burnup

5. *General characteristics*

5.1. RUS-1 design

Figures 7-10. show the calculated parameters of RUS-1 version. The pin power distribution within the assembly is very flat, the maximal pin power changes slowly up to 12 000 MWd/tU. The power of Gd-pin remains under the average, never become limiting, but there is low difference between the maximal and Gd-pin power. The k_{inf} value is increasing up to 10000 MWd/tU burnup level, then reaches the reference curve, showing the Gd has depleted. The maximum value of k_{inf} is considerable lower then the k_{inf} of standard fuel.

5.2. RUS-2 design

Figures 11-14. show the calculated parameters of RUS-2 version. The pin power distribution within the assembly is flat enough, the maximal pin power decreases into low value up to 12 000 MWd/tU. The power of Gd-pin remains under the average, never become limiting, but there is low difference between the maximal and Gd-pin power. The k_{inf} value is increasing up to 10000 MWd/tU burnup level, then reaches the reference curve, showing the Gd has depleted. The maximum value of k_{inf} is considerable lower then the k_{inf} of standard fuel.

5.3. HUN-1 design

Figures 15-18. show the calculated parameters of HUN-1 version. The pin power distribution within the assembly is flat enough, the maximal pin power decreases into low value up to 12 000 MWd/tU. The power of Gd-pin remains under the average, never become limiting. The asymmetry caused by 3 Gd-pins is negligible at the edge of assembly so the assembly orientation because of Gd pins is ambiguous. The k_{inf} value is slowly but decreasing up to 10000 MWd/tU burnup level, then reaches the reference curve, showing the Gd has depleted. The maximum value of k_{inf} is lower then the k_{inf} of standard fuel.

5.4. HUN-2 design

Figures 19-22. show the calculated parameters of HUN-2 version. The pin power distribution within the assembly is flat enough, the maximal pin power decreases into low value up to 12 000 MWd/tU. The power of Gd-pin remains under the average, never become limiting. The asymmetry caused by 3 Gd-pins is negligible at the edge of assembly so the assembly orientation because of Gd-pins is ambiguous. The k_{inf} value is slowly but decreasing up to 10000 MWd/tU burnup level, then reaches the reference curve, showing the Gd has depleted. The maximum value of k_{inf} is lower then the k_{inf} of standard fuel.

6. Comparison of different variants

6.1. Depletion of Gd

The burnable poison in the fuel is usually required to burn out during the 1st cycle, otherwise it decrease the cycle length making economy poorer. To examine this parameter we compared $k_{inf} - k_{inf}^{ref}$ values of different versions. Fig. 23. shows that up to the end of 1st cycle (10-12000 MWd/tU) Gd is effectively burning out for all variants.

6.2. k_{inf} behaviour

For all varians k_{inf} remains under the k_{inf} of standard (3.6 % enriched) fresh fuel. It means that reactivity problems related to storage-transportation and BOC state (high boron, positive $d\rho/dT_{mod}$) are automatically solved. The difference is : the k_{inf} of RUS variants is increasing with the burnup at the beginning of burnup process. This makes the criticality calculations difficult : one should follow burnup as well to calculate maximal reactivity state for that fuel. For HUN versions k_{inf} is continuously decreasing with burnup, the fresh state limits the reactivity for the full burnup process.

6.3. Pin power

As it was stated, the power of Gd-pin is lower then the maximum for all versions. But for RUS designs the power of Gd-pin is higher. Taking into account that the temperature of Gd-dopted fuel is relatively higher then those of normal fuel, it is possible to require separate handling. For HUN variants Gd pins never limit the pin temperature as well.

The maximal pin power values – normalized to assembly average – can be compared on the base of Fig. 24. HUN versions and RUS-2 behavior are close to each other, RUS-1 shows nicely flat power shape during the supposed 1st cycle. But – if we step one up on grade – the assembly power itself increasing during the cycle because of the depletion of Gd. We estimated the changing of assembly power on the base of [5], it is shown on Fig. 25. The growth of assembly power is two times higher in case of RUS version because of more Gd-pins. Pin powers normalized to full core are shown on Fig.26. In case of HUN variants the pin power practically constant during the cycle, for RUS versions it is increasing, making the core refueling design very uncomfortable.

The validity of nodal flux and power calculation models may be problematic in case of RUS variants because of possible high burnup-tilting between different Gd-pins. In case of HUN designs Gd-pins are close to each other, nodal modeling can be used without considerable problems.

7. Summary

On the base of calculated parameters all examined variants of VVER-440 assembly with Gd burnable poison seemed to be suitable to achieve 5-batch refueling strategy and high burnup. Possible problems related to the high reactivity of fresh fuel are solved. Pin power distribution of assemblies is flat enough. During refueling design procedure the handling of RUS versions are more uncomfortable because of growing assembly and pin powers during the 1st cycle. The modeling of RUS versions in different calculations is harder task. The expected fuel cycle cost using HUN variants is lower because the fewer applied Gd pins.

References :

[1] S. Stech, R. Vespalec , I. Tinka : Dukovany Core Design and Licensing Procedures, International Topical Meeting on VVER Technical Innovations for the Next Century, Prague, Czech Republic, 2000.

[2] A. Grishakov et al. : The Ways of WWER-440 Reactor Assemblies and Fuel Cycles Design Improvements , International Seminar on WWER Fuel Performance and Experimental Support, Pamporovo, Bulgaria, 1999.

[3] P. Mikolas : Preliminary analyses of WWER-440 FA with Gd Burnable absorber, AER WG A and B Meeting, Modra, Slovakia, 2000.

[4] Nemes I. et. al. : VVER-440 fuel with Gd Burnable Poison, AER Symposium, Germany, 1997.

[5] Inner materials, personal informations

Fig.1
Geometry of pins and cells in HELIOS calculation

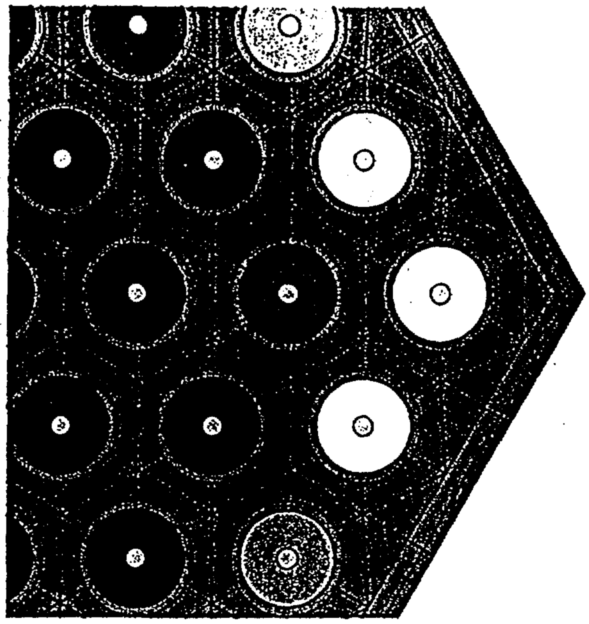


Fig.2.
Geometry of Gd pin in HELIOS calculation

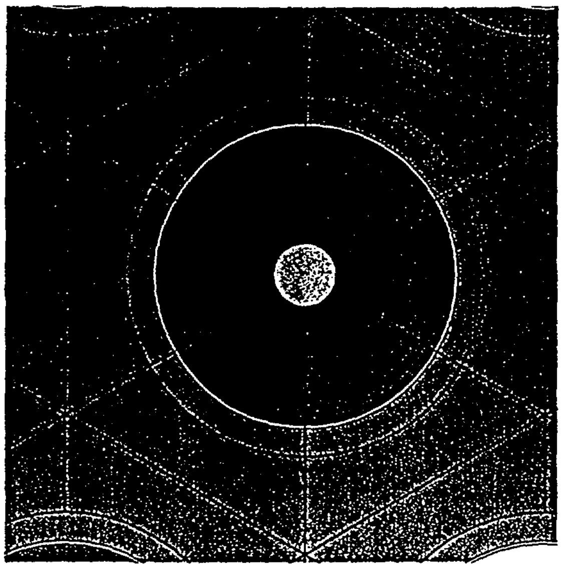


Fig. 3.
RUS-1 assembly design

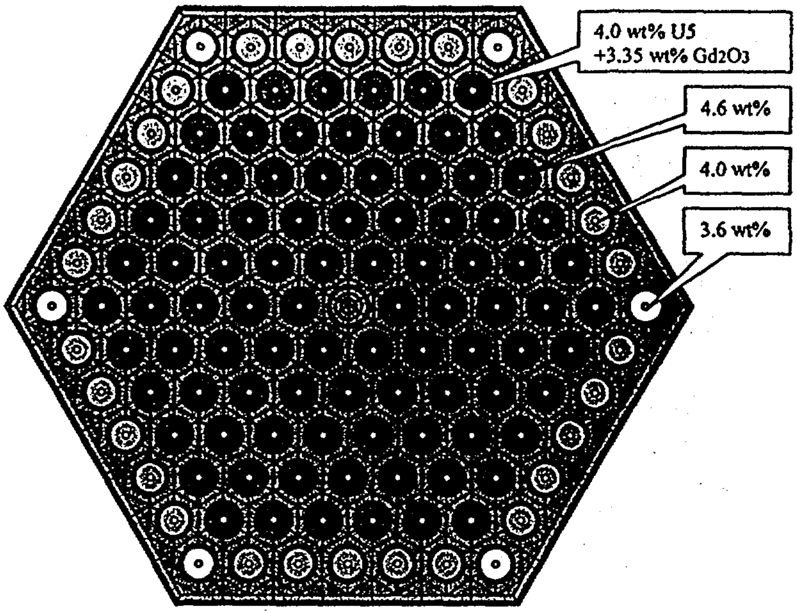


Fig. 4
RUS-2 assembly design

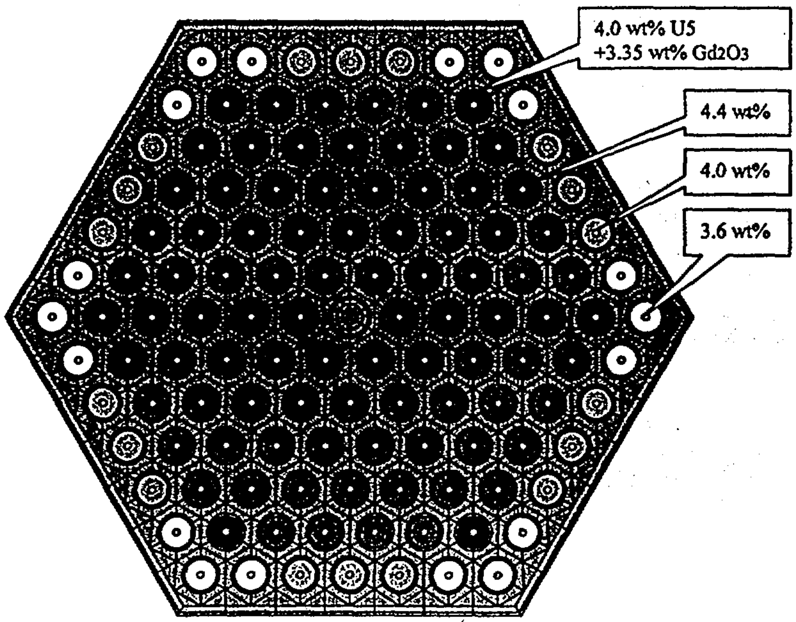


Fig. 5
HUN-1 assembly design

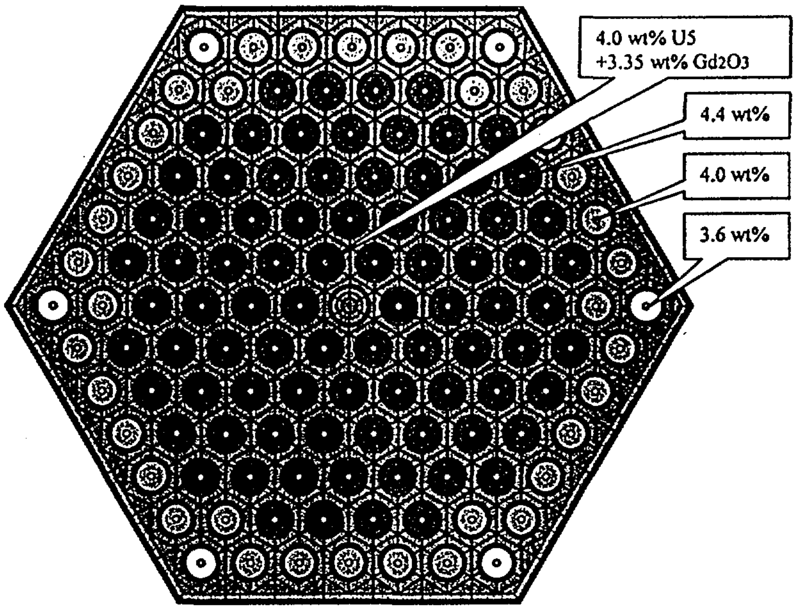


Fig. 6
HUN-2 assembly design

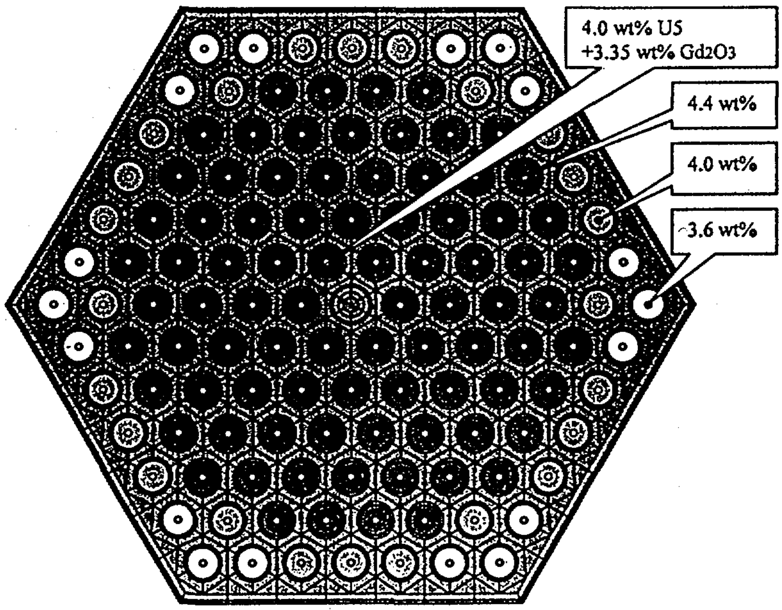


Fig. 7. Normalised pin power distribution of RUS-1 design at 0 burnup

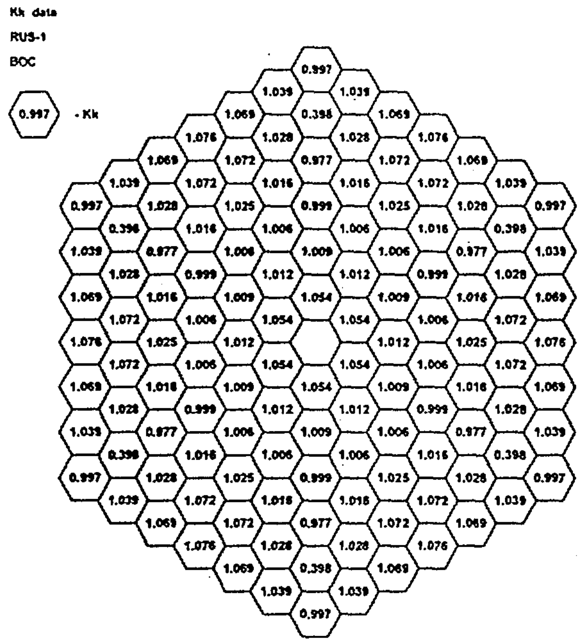


Fig. 8. Normalised pin power distribution of RUS-1 design at 10000 MWd/tU burnup

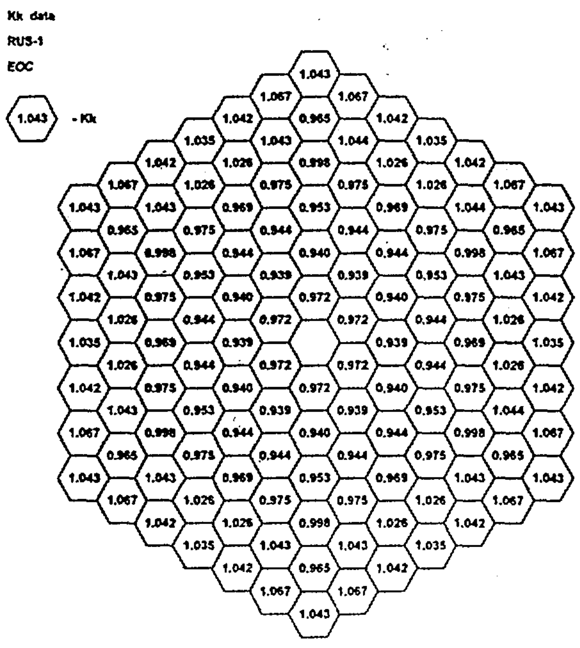


Fig. 9.
K-inf curve and the "reference" k-inf as function of burnup

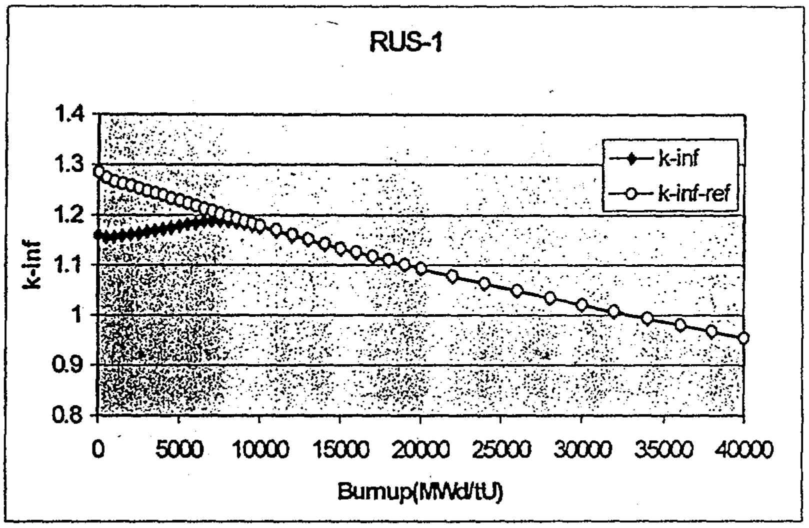


Fig. 10.
Maximal pin power and the power od Gd-pin as function of burnup

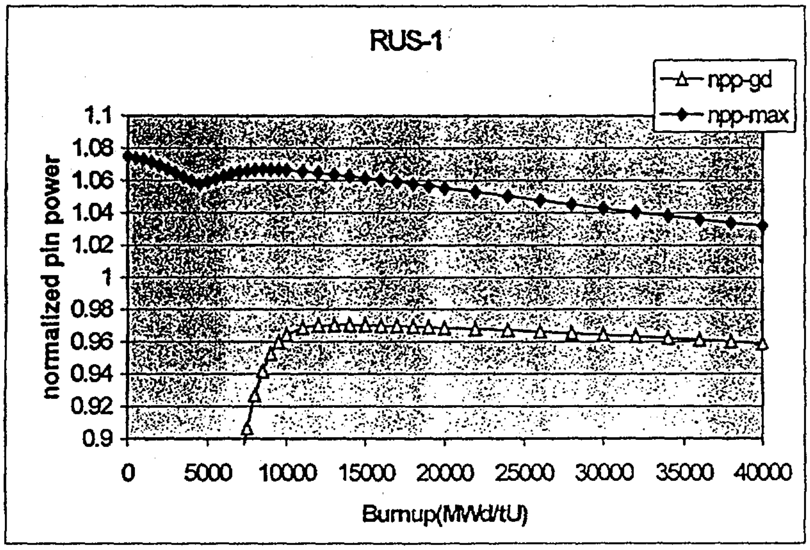


Fig. 11. Normalised pin power distribution of RUS-2 design at 0 burnup

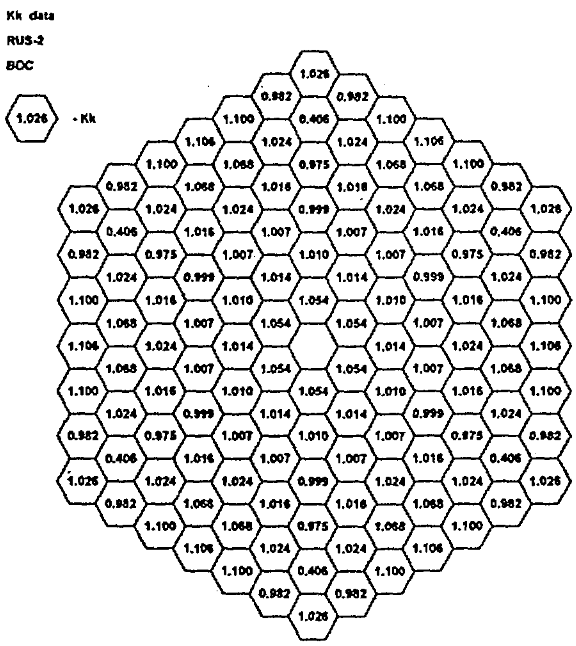


Fig. 12. Normalised pin power distribution of RUS-2 design at 10000 MWd/tU burnup

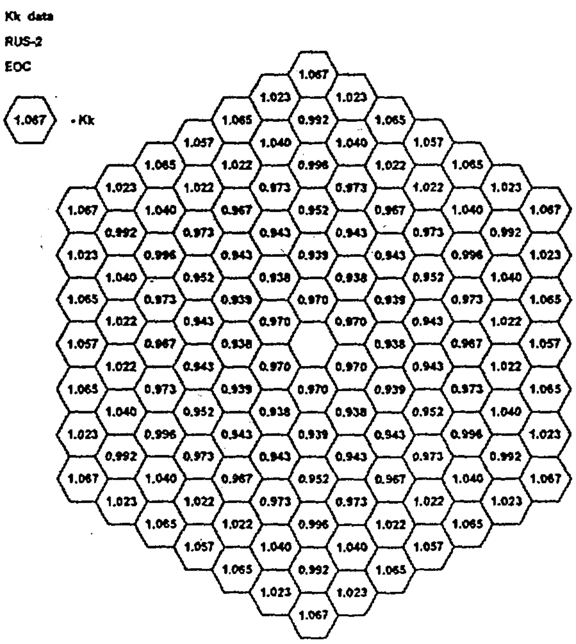


Fig. 13.
K-inf curve and the "reference" k-inf as function of burnup

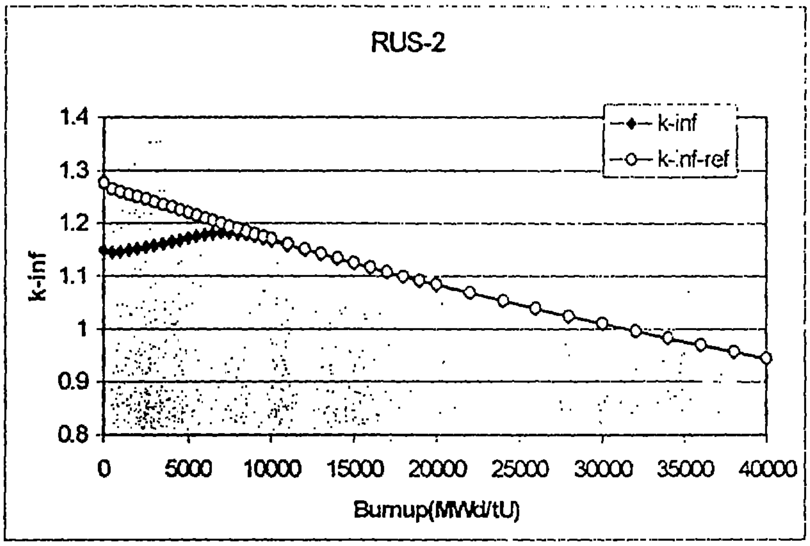


Fig. 14.
Maximal pin power and the power od Gd-pin as function of burnup

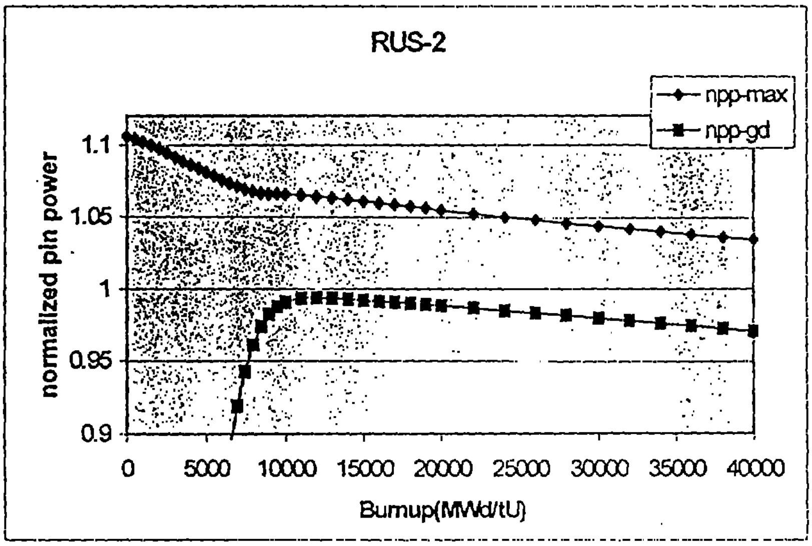


Fig. 15. Normalised pin power distribution of HUN-1 design at 0 burnup

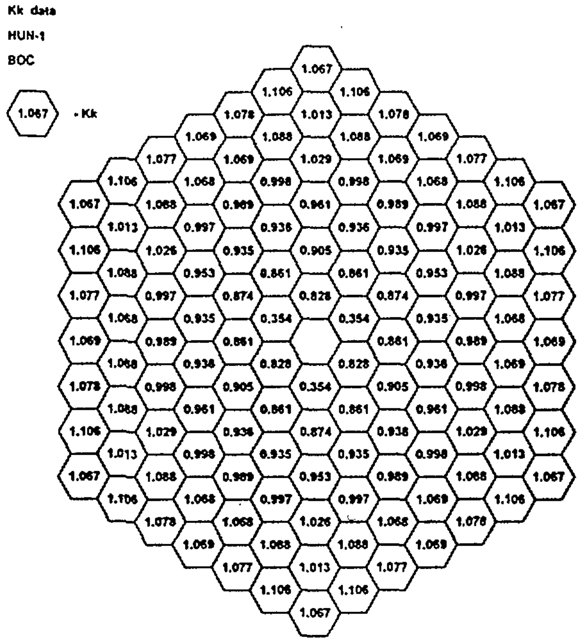


Fig. 16. Normalised pin power distribution of HUN-1 design at 10000 MWd/tU burnup

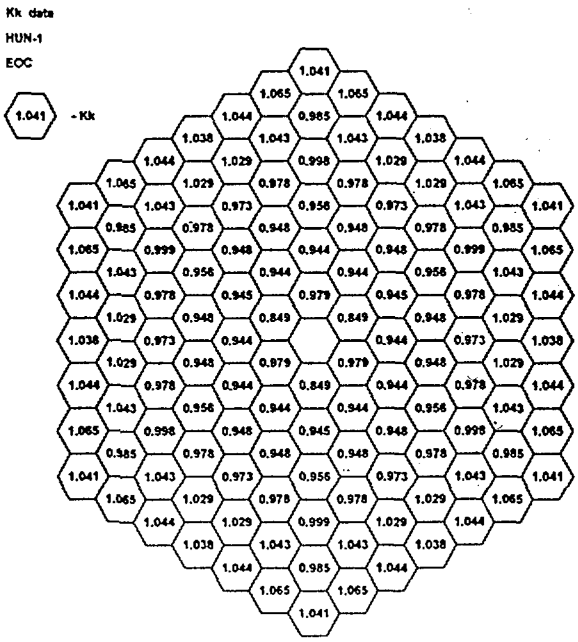


Fig. 17.
K-inf curve and the "reference" k-inf as function of burnup

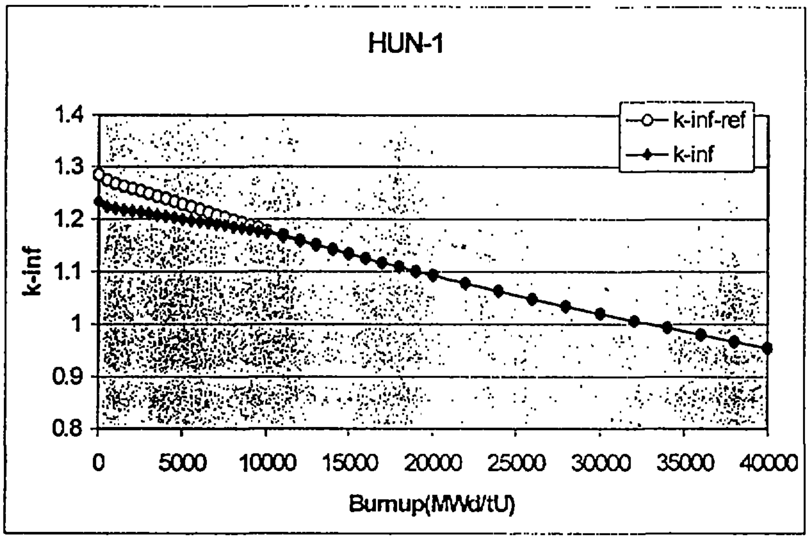


Fig. 18.
Maximal pin power and the power of Gd-pin as function of burnup

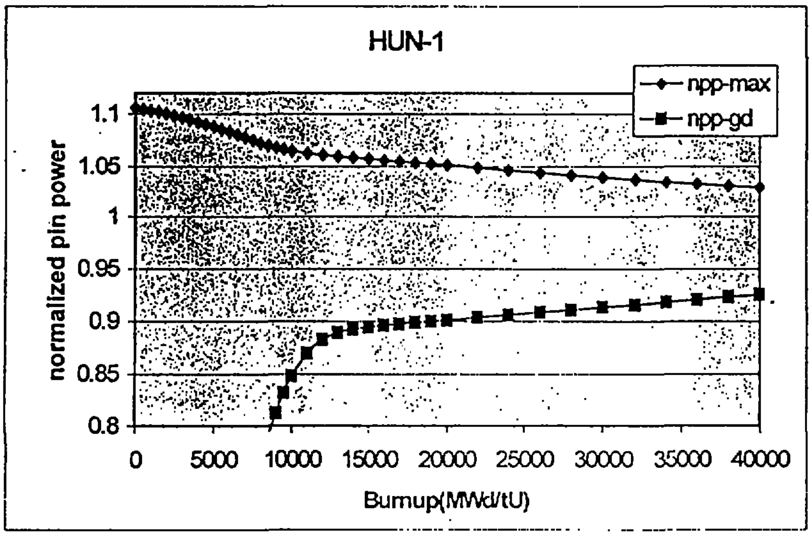


Fig. 19. Normalised pin power distribution of HUN-2 design at 0 burnup

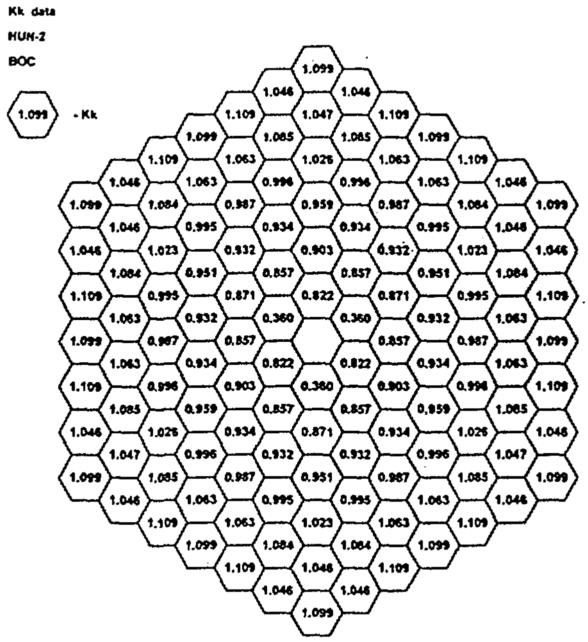


Fig. 20. Normalised pin power distribution of HUN-2 design at 10000 MWd/tU burnup

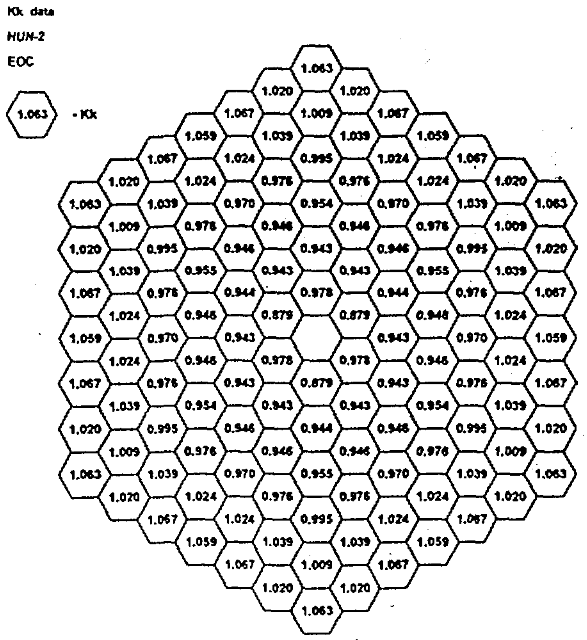


Fig. 21.
K-inf curve and the "reference" k-inf as function of burnup

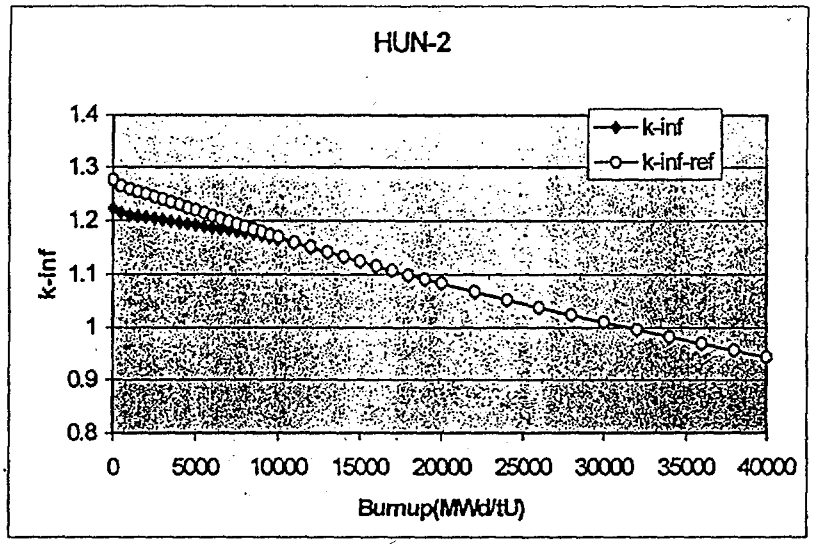


Fig. 22.
Maximal pin power and the power of Gd-pin as function of burnup

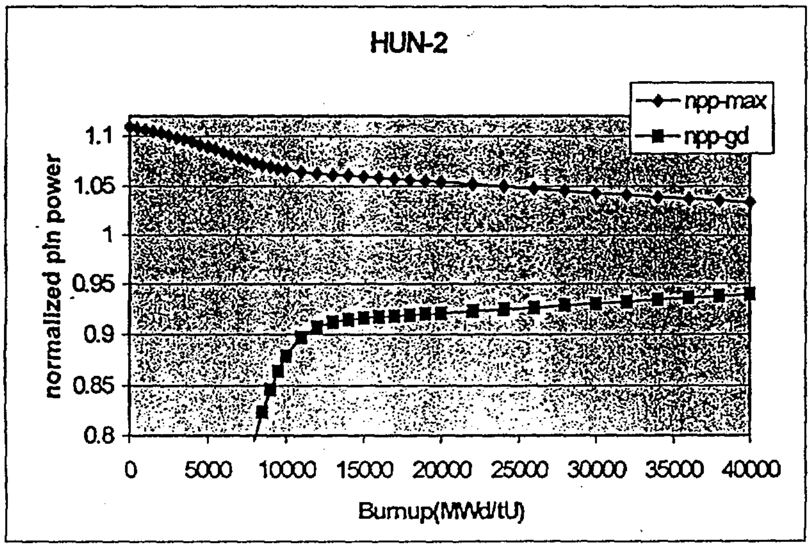


Fig. 25.

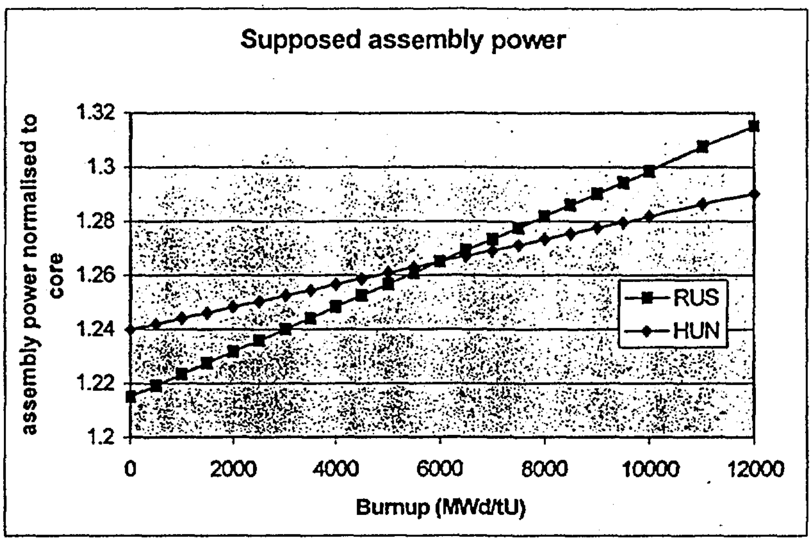

Supposed assembly power
assembly power normalised to core
1.32
1.3
1.28
1.26
1.24
1.22
1.2
0
2000
4000
6000
8000
10000
12000
Burnup (MWd/tU)
RUS
HUN

Fig. 26.

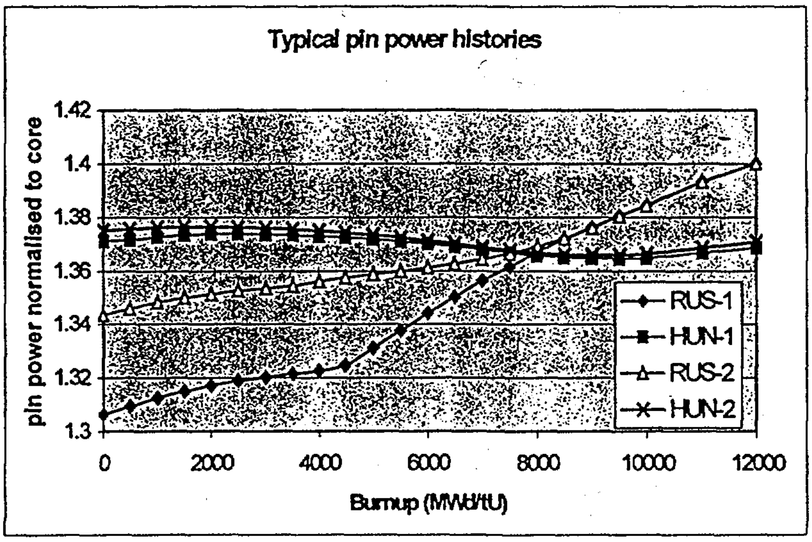
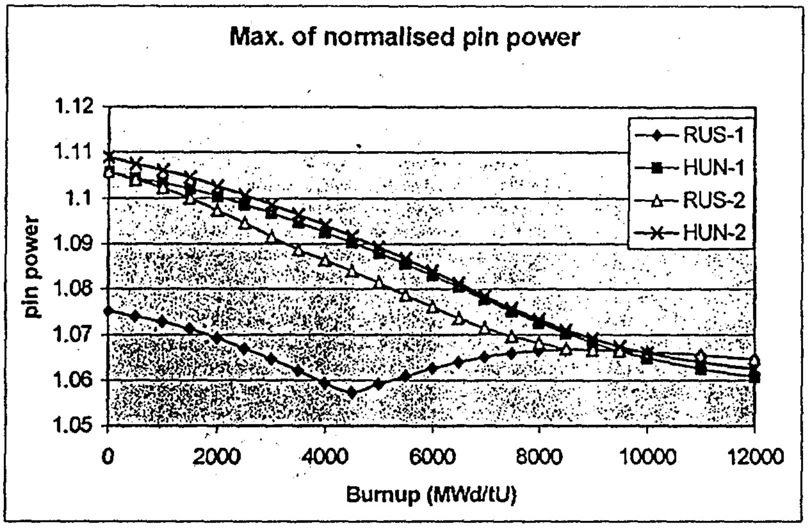
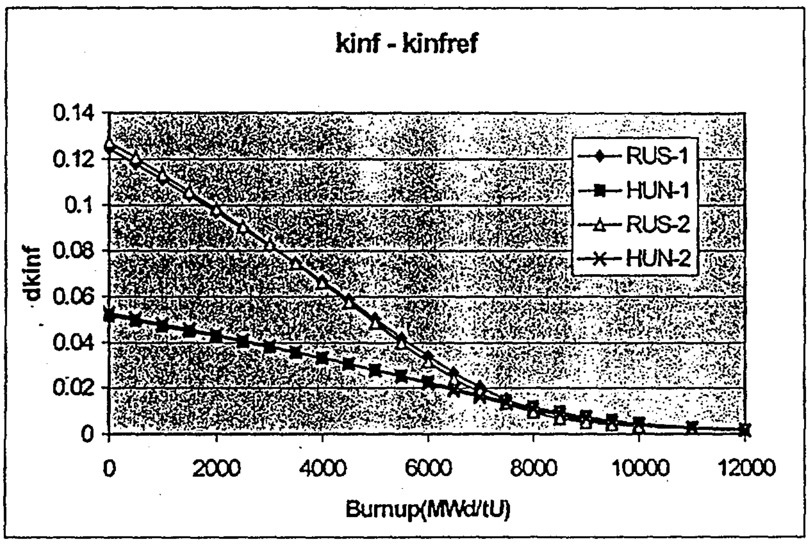

Typical pin power histories
pin power normalised to core
1.42
1.4
1.38
1.36
1.34
1.32
1.3
0
2000
4000
6000
8000
10000
12000
Burnup (MWd/tU)
RUS-1
HUN-1
RUS-2
HUN-2

Fig. 23.



Max. of normalised pin power
1.12
1.11
1.1
1.09
1.08
1.07
1.06
1.05
pin power
0
2000
4000
6000
8000
10000
12000
Burnup (MWd/tU)
RUS-1
HUN-1
RUS-2
HUN-2

Fig. 24.



kinf - kinfref
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
dkinf
0
2000
4000
6000
8000
10000
12000
Burnup(MWd/tU)
RUS-1
HUN-1
RUS-2
HUN-2