TIC Benchmark Analysis

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Joint IAEA-ICTP Workshop on Nuclear Reaction Data for Advanced Reactor Technologies

AIM:

To understand physics properties of VVER type Lattices and validate the code EXCEL (Lattice code).

Nu Power, Vol.16 ,No. 1-2 (2002).

TIC: Temporary International Collective

Established by 7 CMEA member states in 1972

1. Bulgaria 2. Czechoslovakia 3. Germany
4. Hungary 5. Poland 6. Romania
7. Union of Soviet Socialist republics (USSR)

AIM of TIC:

--- to perform Experimental Reactor physics investigations into VVER-type lattices.

--- to collect neutron physics operational data of VVER-type power reactors in start-up and in steady state condition for checking codes.

Ref: "Theoretical investigations of the physical properties of WWER-type uranium-Water Lattices", Akademiai kiado, Budapest(1994), final volume.

TIC (contd..)

--- performed a wide range of experimental investigations including measurements of criticality parameters, spectral ratios, reaction rate distributions, kinetic parameters of VVER-type fuel lattices as a function of uranium enrichment, lattice pitch, boron concentration in the moderator, etc.

--- the Experimental Results presented in vol-1 of the final report of TIC are based on measurements carried out on the critical assembly ZR-6.

Ref: “Theoretical investigations of the physical properties of WWER-type uranium-Water Lattices”, Akademiai kiado, Budapest(1994), final volume.

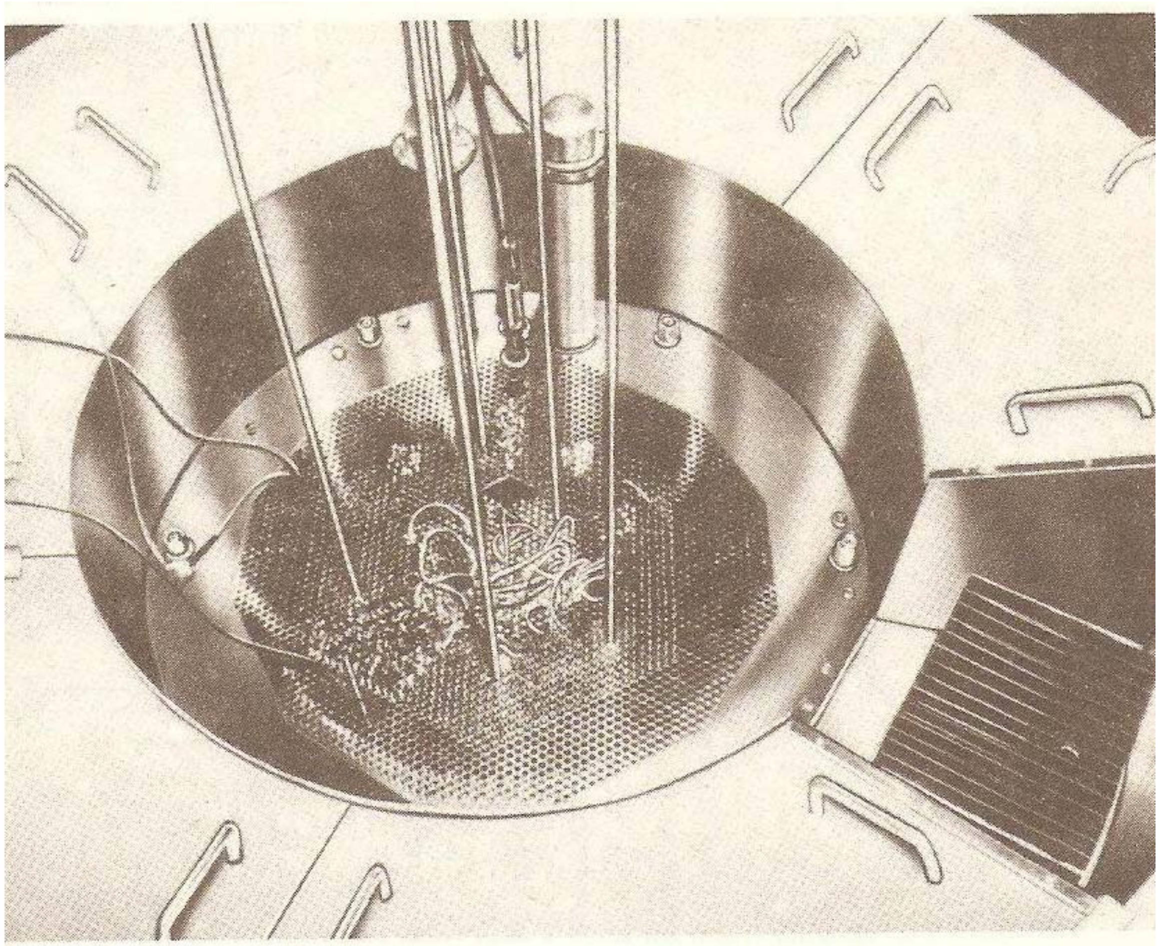
ZR-6 critical Facility

--- operated by the Central Research Institute for Physics (CRIP) of Hungarian Academy of Sciences, Budapest.

--- zero power clean critical facility

--- around 150 benchmark problems were investigated and reported in Final report of TIC vol.-1.

General view of the critical facility



Tank(SS) Dia: 1.8 m

ZR-6 critical Facility (Contd..)

--- lattice type: Hexagonal (pitch:1.27cm, 1.1 cm)

---fuel rod are identical with VVER-type power reactor except central hole (missing here) and their length (125 cm here) while 250 cm for VVER-400 and 350 cm for VVER-1000.

--- fuel: Enriched Uranium (UO_2)(Enrichment, atom%: 1.6, 3.6, 4.4)

--- moderator: Borated light water (C_B(g/l): 0, 0.64, 1.41, 1.85, 4.0, 7.2)

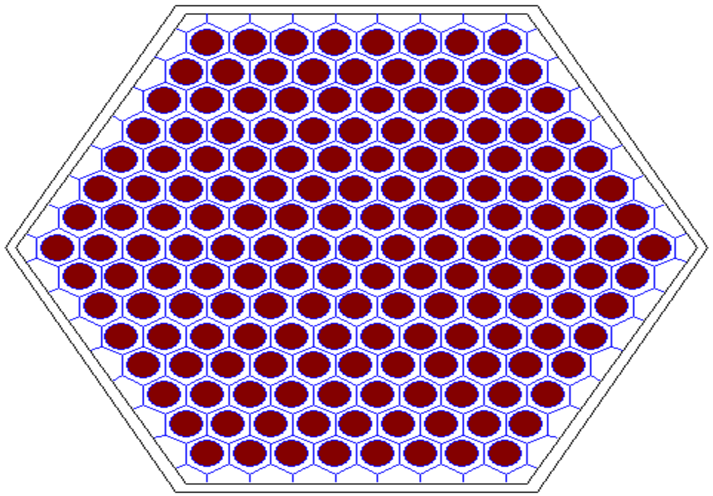
--- moderator nominal temp.: 22 ^{0}C

--- Criticality achieved by varying moderator height.

--- core configuration: Pitch(mm)/enr(at%)/cb(g/l)

Type of lattices were investigated:

- **Regular one region cores**
    - Pitch:12.7mm. 11 mm(for Enr=3.6%)
    - •Enrichment: 1.6%, 3.6%, 4.4%
    - • Boron conc.(g/l): 0, 0.64, 1.41, 1.85, 4.0, 7.2
    - •No.of investigated problems: 46

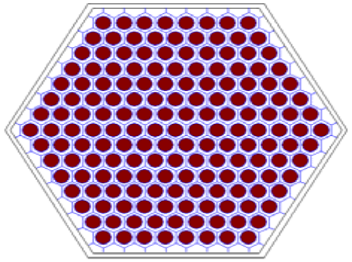


One region cores

Method of solution:

• Infinite regular lattice will give identical neutron multiplication factor as one pincell with reflective boundary condition. For finite lattice leakage factor (DB^2, depending on buckling) have to be considered.

• For same core configuration (Pitch/Enr/B Conc.) many experiments were carried out with different no. of fuel pins of regular lattice at different critical moderator height.



Regular one region lattice

• For same core configuration of regular lattice only one problem is analyzed to generate few group CXS (5 groups: 19.6MeV to 9.118KeV, 9.118KeV to 4eV, 4eV to 0.625eV, 0.625eV to 0.14eV and 0.14eV to 0.00001eV) parameters with help of EXCEL.

Five group parameters: $\Sigma_f, \Sigma_a, \nu\Sigma_f, \Sigma_{tr}, D, \Sigma_{gg'}$

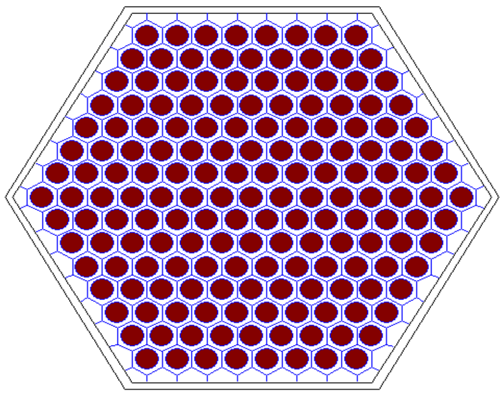
EXCEL: A hexagonal lattice Burn-up code

• Solves 1D transport equation for pincell and gives 172 groups fluxes using 172 groups basic CXS library by collision probability method.

• CXS of a super cell:group of pincell, are homogenized and collapsed into 5 groups CXS by considering flux and volume weighting.

• 5 group CXSs are used to solve 2D Diffusion equation and Assembly wise 5 groups CXS parameters $\Sigma_f, \Sigma_a, \nu\Sigma_f, \Sigma_{tr}, D, \Sigma_{gg'}$ are generated.

• Zero dimensional Diffusion equation is solved to get effective neutron multiplication factor with considering proper neutron leakage from the system.



Regular one region lattice

Zero dimension Diffusion equation

Diffusion equation:

$$D\nabla^2\phi - \Sigma_a\phi + \frac{\chi}{k_{eff}}\upsilon\Sigma_f\phi = 0$$

$$\nabla^2\phi + B^2\phi = 0$$

$$DB^2\phi + \Sigma_a\phi = \frac{\chi}{k_{eff}}\upsilon\Sigma_f\phi$$

$$B^2 = \left(\frac{2.405}{R_{eq}+\lambda_r}\right)^2 + \left(\frac{\pi}{H_{cr}+\lambda_z}\right)^2$$

Normalization of fission neutron

$$\sum_{g=1}^{5}\upsilon\Sigma_{fg}\phi = 1.0$$

5 group diffusion equation:

$$D_1B^2\phi_1 + \Sigma_{R1}\phi_1 = \chi_1$$

$$D_2B^2\phi_2 + \Sigma_{R2}\phi_2 + \Sigma_{12}\phi_1 = \chi_2$$

$$D_3B^2\phi_3 + \Sigma_{R3}\phi_3 + \Sigma_{13}\phi_1 + \Sigma_{23}\phi_2 = \chi_3$$

$$D_4B^2\phi_4 + \Sigma_{R4}\phi_4 + \Sigma_{14}\phi_1 + \Sigma_{24}\phi_2 + \Sigma_{34}\phi_3 = \chi_4$$

$$D_5B^2\phi_5 + \Sigma_{R5}\phi_5 + \Sigma_{15}\phi_1 + \Sigma_{25}\phi_2 + \Sigma_{35}\phi_3 + \Sigma_{45}\phi_4 = \chi_5$$

$$\Sigma_{Rg} = \Sigma_{trg} - \Sigma_{gg}$$

Matrix form of 5 group Diffusion equation:

$$\begin{bmatrix} \Sigma_{R1}+D_1B^2 & 0 & 0 & 0 & 0 \\ \Sigma_{12} & \Sigma_{R2}+D_2B^2 & 0 & 0 & 0 \\ \Sigma_{13} & \Sigma_{23} & \Sigma_{R3}+D_3B^2 & 0 & 0 \\ \Sigma_{14} & \Sigma_{24} & \Sigma_{34} & \Sigma_{R4}+D_4B^2 & 0 \\ \Sigma_{15} & \Sigma_{25} & \Sigma_{35} & \Sigma_{45} & \Sigma_{R5}+D_5B^2 \end{bmatrix} \begin{bmatrix} \phi_1 \\ \phi_2 \\ \phi_3 \\ \phi_4 \\ \phi_5 \end{bmatrix} = \begin{bmatrix} \chi_1 \\ \chi_2 \\ \chi_3 \\ \chi_4 \\ \chi_5 \end{bmatrix}$$

Calculation of:

$$K_\infty = \frac{\sum_{g=1}^{5} \upsilon\Sigma_{fg}\phi_g}{\sum_{g=1}^{5} \Sigma_{ag}\phi_g}$$

$$K_{eff} = \frac{\sum_{g=1}^{5} \upsilon\Sigma_{fg}\phi_g}{\sum_{g=1}^{5} \Sigma_{ag}\phi_g + \sum_{g=1}^{5} D_g B_g^2 \phi_g}$$

$$M^2 = \frac{K_\infty / K_{eff} - 1}{B^2}$$

$$\frac{EPF}{THF} = \frac{\phi_1 + \phi_2 + \phi_3}{\phi_4 + \phi_5}$$

Program, Input & Output

Compaq Visual Fortran - [TIC5003...]

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```
            else
            A(i,j)=-c(i,j+5)
            endif
         end do
      end do
      !write(2,*)((A(i,j),j=1
      ! calculation of flux b
            DO i=1,4
               I1=i+1
               DO j=I1,6
                  A(i,j)=A(i,
               ENDDO
               DO j=I1,5
                  DO  k=I1,6
                      A(j,k)=
                  ENDDO
               ENDDO
            ENDDO
               B(5)=A(5,6)/A(
               DO k=2,5
               i=5-k+1
               I1=i+1
               Z=0.0
                  DO j=I1,5
                  Z=Z+A(i,j)*
                  ENDDO
               B(i)=A(i,6)-Z
               ENDDO
      eph=B(1)+B(2)+B(3)
      thp=B(4)+B(5)
      ratio=eph/thp
      ! calculation of keff
      do i=1,5
```

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```
0.3979E-01 0.5782E-01 0.9696E-01 0.8352E+00 0.3991E+00 0.2419E-05 0.9994E-02 0.2732E+00 0.4186E+0
0.9951E-01 0.1405E+00 0.2425E+00 0.1589E+01 0.2097E+00 0.5632E-06 0.2885E-02 0.4963E-01 0.3560E+0
```

Results:

Core ID	flux1	flux2	flux3	flux4	flux5	epf/thf	Kinf	M^2	Buckling	Keff
2020	15.3924	6.0669	1.2578	1.1838	2.8597	5.618	1.40330	41.236	0.01011	0.99239
0303	15.4488	6.0944	1.2639	1.1897	2.8744	5.612	1.40335	41.215	0.00996	0.99258
1003	15.3963	6.0688	1.2583	1.1842	2.8607	5.618	1.40334	41.221	0.01010	0.99253
4703	15.4162	6.0785	1.2604	1.1863	2.8659	5.616	1.40334	41.221	0.01005	0.99253
1752	15.4502	6.0951	1.2641	1.1898	2.8748	5.612	1.40335	41.215	0.00995	0.99258
4821	15.4283	6.0844	1.2617	1.1875	2.8691	5.614	1.40335	41.214	0.01001	0.99259
1742	15.4568	6.0983	1.2648	1.1905	2.8765	5.611	1.40336	41.211	0.00993	0.99262
1542	15.5165	6.1275	1.2712	1.1968	2.8921	5.604	1.40339	41.203	0.00977	0.99270
5322	15.5217	6.1301	1.2717	1.1973	2.8935	5.604	1.40341	41.196	0.00975	0.99276
1732	15.5444	6.1412	1.2742	1.1997	2.8994	5.601	1.40342	41.189	0.00969	0.99282
0505	15.5061	6.1224	1.2700	1.1957	2.8894	5.605	1.40343	41.185	0.00980	0.99285
5223	15.5035	6.1212	1.2698	1.1954	2.8887	5.606	1.40344	41.183	0.00980	0.99287
172A	15.5078	6.1233	1.2702	1.1959	2.8898	5.605	1.40345	41.180	0.00979	0.99290
1722	15.5066	6.1227	1.2701	1.1957	2.8895	5.605	1.40345	41.178	0.00980	0.99291
5124	15.5033	6.1210	1.2697	1.1954	2.8886	5.606	1.40346	41.177	0.00980	0.99293
171A	15.5037	6.1213	1.2698	1.1954	2.8888	5.606	1.4			
1712	15.5050	6.1219	1.2699	1.1956	2.8891	5.606	1.4			
0404	15.4835	6.1114	1.2676	1.1933	2.8835	5.608	1.4			
1702	15.4758	6.1076	1.2668	1.1925	2.8815	5.609	1.4			
5050	15.4581	6.0990	1.2649	1.1906	2.8769	5.611	1.4			
1692	15.4178	6.0793	1.2606	1.1864	2.8664	5.615	1.4			

```
Average value of epf/thf:   5.609097
Average value of K-inf:   1.403410
Average value of M2:   41.19398
Average value of Buckling:   9.8871076E-03
Average value of K-eff:   0.9927732
```

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```
21
2020 685  1.27 89.50 13.39 7.65
0303 720  1.27 81.80 13.39 7.65
1003 720  1.27 76.00 13.39 7.65
4703 720  1.27 78.08 13.39 7.65
1752 721  1.27 81.60 13.39 7.65
4821 766  1.27 67.08 13.39 7.65
1742 769  1.27 68.59 13.39 7.65
1542 805  1.27 60.22 13.39 8.06
5322 807  1.27 60.23 13.39 8.06
1732 811  1.27 60.94 13.39 8.06
0505 865  1.27 54.20 13.39 7.91
5223 919  1.27 49.55 13.39 7.91
172A 919  1.27 49.70 13.39 7.91
1722 919  1.27 49.66 13.39 7.91
5124 1075 1.27 41.47 13.39 7.91
171A 1075 1.27 41.48 13.39 7.91
1712 1075 1.27 41.51 13.39 7.91
0404 1218 1.27 37.00 13.39 7.85
1702 1459 1.27 32.58 13.39 7.85
5050 1469 1.27 32.21 13.39 7.85
1692 1957 1.27 27.53 13.39 7.85
```

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```
1.7180E-03  3.0362E-03  4.7021E-03  2.2040E-01  1.5124E+00  1.7075E-01  0.0000E+00  0.0000E
5.3848E-03  2.7370E-02  1.3110E-02  5.0453E-01  6.6068E-01  4.6588E-02  3.9295E-01  0.0000E
9.8941E-03  1.8034E-02  2.4100E-02  5.6408E-01  5.9093E-01  1.6891E-05  7.1335E-02  2.2322E
3.9791E-02  5.7825E-02  9.6959E-02  8.3516E-01  3.9912E-01  2.4187E-06  9.9939E-03  2.7319E
9.9509E-02  1.4052E-01  2.4247E-01  1.5893E+00  2.0973E-01  5.6316E-07  2.8847E-03  4.9630E
```

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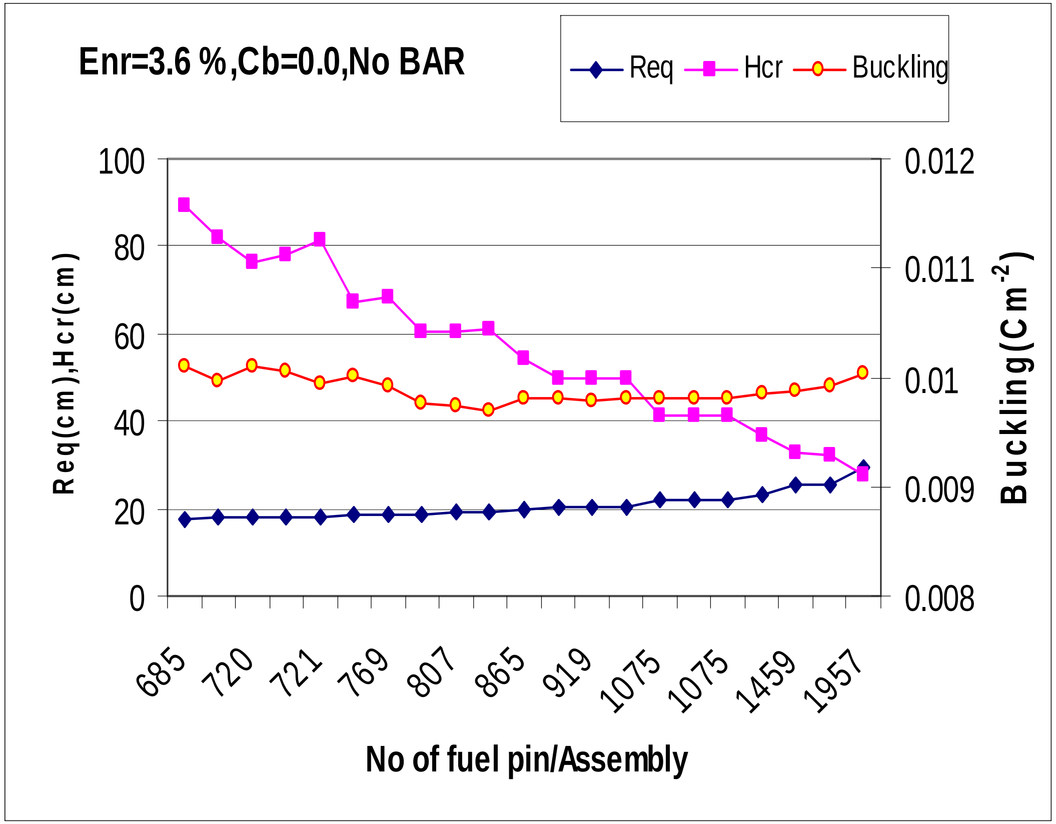
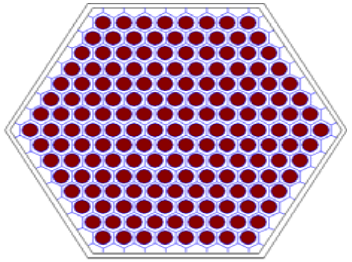
Analysis of regular lattices

- Core configuration 1.27/3.6/0.0.
- Total 21 cases analysed
- Req is increasing with no of fuel pin.
- Hcr is decreasing with no of fuel pin.
- Buckling is almost constant
- Average K-eff is 0.9972



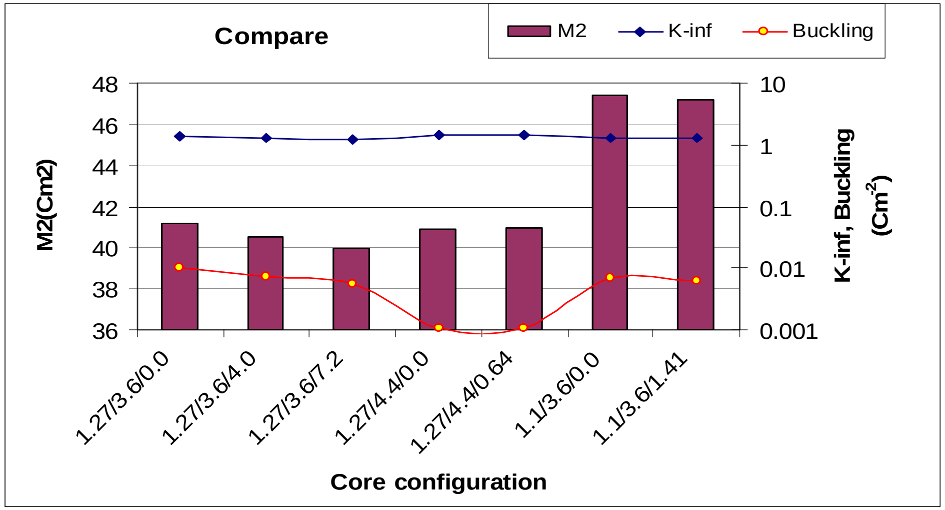
Variation of R_{eq}, H_{cr} and Buckling with number of fuel pins

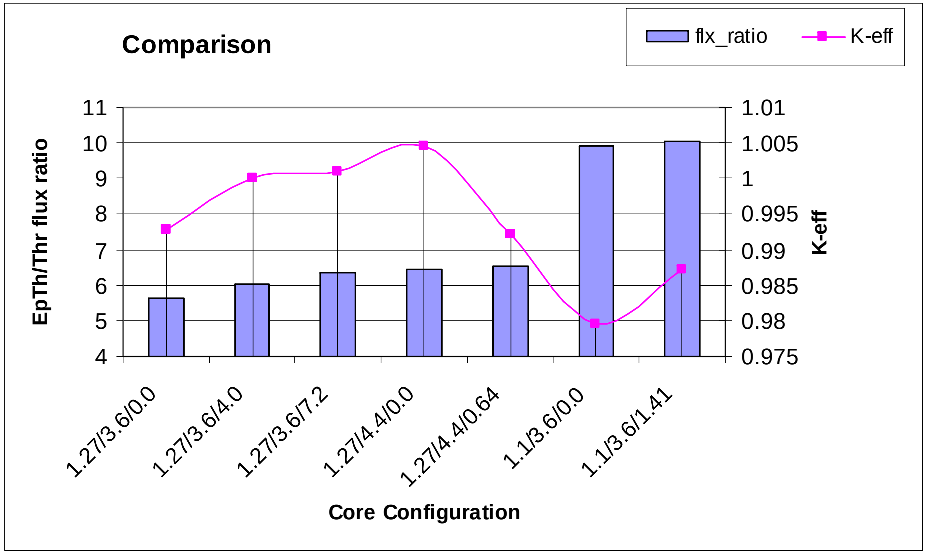


Regular one region lattice

Analysis of other core configuration

Config.	coreID	K-Inf	K-Eff
1.27/3.6/4.0	2727	1.29163	0.99994
	3333	1.29165	0.99998
	3434	1.29166	1.00002
	182B	1.29166	1.00003
	2828	1.29166	1.00005
	3232	1.29167	1.00007
	3636	1.29168	1.00009
	3131	1.29168	1.00012
	3030	1.29169	1.00015
	2626	1.29170	1.00017
	142B	1.29171	1.00022
	122A	1.29173	1.00027
	2929	1.29174	1.00030
1.27/3.6/7.2	3838	1.21648	1.00085
	3737	1.21652	1.00099
1.27/4.4/0.0	1102	1.44184	1.00403
1.27/4.4/0.64	1112	1.42422	0.99213
1.1/3.6/0.0	4141	1.29371	0.97970
	3939	1.29363	0.97949
	4040	1.29361	0.97946
1.1/3.6/1.41	4240	1.27275	0.98719





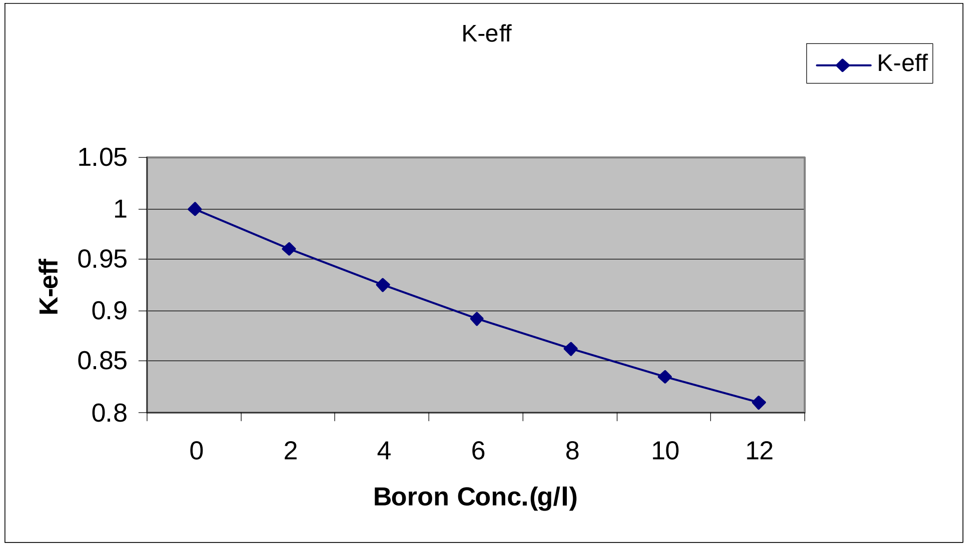
Borated water effect in criticality

Config.	Cb	CoreID	Fpins	Buckling	K-eff	Epi/Thm
1.27/3.6/*	0	174/174	769	0.00993	0.99928	6.034
	4.0	32/32	1302	0.0075	1.00037	6.401
	7.2	38/38	1801	0.00558	1.00776	6.687

- Lattice will be critical with less number of fuel pins when boron in moderator is less.

- If boron is in the moderator excess reactivity have to be supplied.

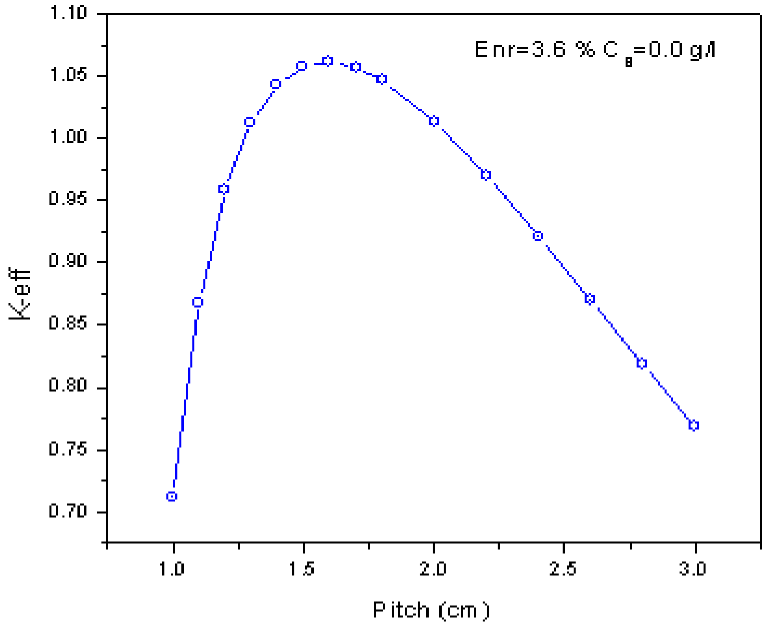
- K-eff is decreases with boron concentration.
- For 1 g/l change k-eff will change ~15mk



Lattice pitch effect on criticality

Config.	Pitch	CoreID	Fpins	Buckling	K-eff	Epi/Thm
*/3.6/0.0	1.27	174/174	769	0.00993	0.99928	6.034
	1.10	41/41	1597	0.00663	0.98119	10.890

Changing of lattice pitch effects on moderator thickness around fuel pin. It can be under moderation or over moderation. Both reduces on neutron population as well as on criticality also. To make those lattices critical excess reactivity have to be provided.



Conclusions

1. The computed keff values for both regular one-region lattices are overall in good agreement with the benchmark values.
2. Smaller lattice pitch there is some disagreement in the computed results compared to benchmark values. This zero dimensional diffusion equation may not be adequate to calculate fast neutron leakage from the core. Higher dimensional diffusion equation may give better result.


Thank You!

Table 7. Design parameters for a VVER-1000

Fuel density	10.13 g/cc
Fuel material	UO_2
Enrichment	1.6 – 4.4 % ^{235}U
Radius of fuel (in/out)	0.115/0.3775 cm
Fuel Clad radius (in/out)	0.386/0.4582
Clad and central tube material	Zr (1% Nb, 0.03% Hf)
Clad density	6.45 g/cc
Central tube radius (in/out)	0.45/0.515 cm
Burnable absorber material	Al:91.75%; B:1.25%; Cr:3%; Ni:2%; Zr:2%
Burnable absorber radius	0.35 cm
Burnable absorber density	2.9 g/cc
BA cladding and tube material	Zr (1% Nb, 0.03% Hf)
BA cladding and tube density	6.45 g/cc
BA clad radius (in/out)	0.35/0.41 cm
BA tube radius (in/out)	0.55/0.63 cm
Lattice element pitch	1.275 cm
Moderator density	0.69 g/cc
Typical power level	45 MW(th)/t
Fuel temperature	966 K
Clad temperature	630 K
Moderator temperature	578 K
Typical burnup	45,000 MW(th)d/t