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Comparison of VNEM to Measured Data
from Ringhals Unit 3 IACIP
NKS-R-2008-61

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The results can be summarized as:

$$\text{core eigenvalue} = 0.99711 \pm 0.00067$$

Excellent agreement was obtained in the comparison of the neutron detector readings as observed in Phase 1 (2008).

The computing (CPU) time was measured to be 7.5 min. / case, which is about 1/3 of the prototype VNEM code. This is because of the sophisticated coding of VNEM module in CYGNUS and the convergence acceleration effect of the feedbacks.

Key words

CYGNUS, VNEM, Ringhals, unit 3, PWR, neutron detector, keff, IACIP:
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Comparison of VNEM to Measured Data from Ringhals Unit 3 IACIP, NKS-R-2008-61

Purpose

According to the agreement between NKS-R program management and Institutt for Energiteknikk (IFE), a verification study of the transport variational nodal expansion method (VNEM) has been performed based on the specification in the activity plan. This report presents the results of the study in detail.

Abstract

Comparisons have been made of a LWR core simulator CYGNUS with VNEM neutronics module to the measured data obtained from Ringhals unit 3 NPP at the hot-operating condition at its beginning of cycle 1 (core average burnup = 0 through 500MWD/MT).

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Excellent agreement was obtained in the comparison of the neutron detector readings as observed in Phase 1 (2008).

The computing (CPU) time was measured to be 7.5 min. / case, which is about 1/3 of the prototype VNEM code. This is because of the sophisticated coding of VNEM module in CYGNUS and the convergence acceleration effect of the feedbacks.

Additional calculations with more energy groups and without cell-homogenization will soon be made to achieve more accuracy.

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1 Introduction

This report shows the results of the comparisons of a light water reactor core simulator *CYGNUS* to the plant data obtained from Ringhals-3 pressurized water reactor (PWR) at the beginning of its 1st cycle.

In the year 2008 the verification of nodal transport code VNEM (Variational Nodal Expansion Method) was performed by comparing it to the plant data from Ringhals-3 PWR in a hot stand-by condition without feedback effects (the thermal-hydraulic, burnup, Xenon, Doppler, etc.) at the beginning of its life. The results of the comparisons were excellent as reported in Ref.[1.1].

In the year 2009 VNEM has been implemented in a light water reactor core simulator *CYGNUS* (PWR version) to include the feedback effects. Comparisons of *CYGNUS* to plant data from Ringhals-3 have been made for hot-operating cases from the beginning of life of the core up to the average burnup of about 500MWD/T where the *burnup tilt* effect (the effect of the difference of intra-assembly spatial burnup distribution from the infinite-lattice case on the neutron cross sections - this effect is planned to be included in *CYGNUS* in the year 2010) is not significant.

In Chapter 2 the calculation methods of the feedback effects are described. In Chapter 3 the generation and reproduction of VNEM coefficients are described. Chapter 4 shows the iterative solution method of *CYGNUS* with the feedback effects. Chapter 6 describes calculations performed in the comparison work, and Chapter 6, the results of comparisons.

1.1 References

- [1.1] M. Tsuiki and W. H. Beere: "Comparison of VNEM to Measured Data from Ringhals Unit 3," AR-VNEM-RH-01-08 (r1), 2008.

2 Calculation of Feedback Effects

In the PWR version of CYGNUS the following feedback effects on the neutron cross sections are included:

- Burnup
- Historical Boron
- Instantaneous Boron
- Fuel temperature
- Moderator density
- Xe135 concentration
- Sm149 concentration

Each of these will be explained in the following sections.

In VNEM, as in the usual *nodal codes*, the core is divided into a number of geometrically identical volume segments called a *node*. The nodes are numbered by 3-dimensional integer indices k , i and j (see Fig.5.1). Here k indicates the axial position of the node, and (i, j) , the radial position. As a node corresponds an assembly in the radial direction, (i, j) also indicate an assembly position. The feedback effects are assumed to be dependent only on the average of the above parameters over the volume of a node.

2.1 Burnup

The average burnup over the volume of a node (k, i, j) in the core at time t : $E_{k,i,j}(t)$ is defined by:

$$E_{k,i,j}(t) = \int_{t'=0, t} P_{k,i,j}(t') \rho(t') dt' / d_{ift} \quad (2.1)$$

where

$P_{k,i,j}(t')$: average power density over node (k, i, j) relative to core average at time t'
$\rho(t')$: average power density over the whole core volume at time t'
d_{ift}	: initial smeared density of the heavy elements for fuel type ift
ift	: fuel type index of node (k, i, j)

2.2 Historical Boron

The intra-assembly neutron cross sections are dependent on the neutron spectrum history during the burnup. As the Boron concentration significantly affects on the neutron spectrum, CYGNUS estimates this effect by using the *historical Boron* of a node:

$$BH_{k,i,j}(E) = \int_{E'=0, E} B_{k,i,j}(E') dE' / \int_{E'=0, E} dE \quad (2.2)$$

where E is the average burnup over the volume of node (k, i, j) used to represent the elapsed on-power time, and $B_{k,i,j}(E)$ is the instantaneous Boron at burnup E . At the beginning of the life the historical Boron becomes the same as the instantaneous Boron.

2.3 Instantaneous Boron

The instantaneous Boron is either the user's input parameter or calculated by CYGNUS so that the core becomes critical.

2.4 Fuel Temperature

The average fuel temperature $TF_{k,i,j}$ in node (k, i, j) is calculated by Halden correlation^[2.1] derived from the accumulated data obtained from PWR-type fuel experiments in Halden boiling water reactor (HBWR):

$$TF_{k,i,j} = TM_{k,i,j} + CHAL_{ift} ALHR_{k,i,j} \quad (2.3)$$

where

$TM_{k,i,j}$: moderator temperature at node (k, i, j)
 $CHAL_{ift}$: correlation coefficient (user's input data) for fuel type ift ,
 $= 1.83$ was commonly used for all the fuel types in the
present comparison

and the average linear heat generation rate is defined by:

$$ALHR_{k,i,j} = P_{k,i,j} \rho V_{node} / N_{rod} / delz \quad (2.4)$$

where

$P_{k,i,j}$: average power density over node (k, i, j) relative to core
average
 ρ : average power density over the whole core volume
 V_{node} : volume of a node
 N_{rod} : number of fuel rods in a node
 $delz$: height of a node

The burnup dependence of the coefficient $CHAL$ will be implemented later.

2.5 Moderator Density

The moderator density in node (k, i, j) is calculated in the following way. First the coolant flow $W_{i,j}$ in an assembly at position (i, j) is calculated by:

$$W_{i,j} = W_{av} \{ ffit(1, iat) + [ffit(2, iat) + ffit(3, iat) dP_{i,j}] dP_{i,j} \} \quad (2.5)$$

where

$$W_{av} = W_{tot} / N_a \quad (2.6)$$

$$dP_{i,j} = P_{i,j} - 1 \quad (2.7)$$

and

W_{tot} : total coolant flow in the active core (user's input data)
 N_a : total number of assemblies in the core
 iat : assembly type index of assembly (i, j)
 $ffit(1:3, iat)$: fitting coefficient of coolant flow in an assembly of type iat
 $P_{i,j}$: average power density over assembly (i, j), relative to core average

The assembly flow $W_{i,j}$ calculated by Eq.(2.5) is normalized so that the summation over all the assemblies becomes W_{tot} . In the present comparison we assume uniform assembly flow distribution, i.e.

$$\begin{aligned} ffit(1, iat) &= 1 \\ ffit(2:3, iat) &= 0 \end{aligned}$$

Then the enthalpy increase $dH_{k,i,j}$ of the coolant at node (k, i, j) is obtained by:

$$dH_{k,i,j} = P_{k,i,j} \rho V_{node} / W_{i,j} \quad (2.8)$$

Therefore the coolant enthalpy $HO_{k,i,j}$ at the outlet of node (k, i, j) becomes:

$$HO_{k,i,j} = H_{in} + \sum_{k'=1,k} dH_{k,i,j} \quad (2.9)$$

where H_{in} is the core inlet enthalpy calculated by

$$H_{in} = stmtbl_h_t(Pres, T_{in}) \quad (2.10)$$

with

$stmtbl_h_t$: steam table function to calculate enthalpy from temperature of subcool water
 $Pres$: core pressure (user's input parameter)
 T_{in} : core inlet temperature (calculated from the core thermal power)

We assume that the average coolant enthalpy $H_{k,i,j}$ in node (k, i, j) can be well approximated by:

$$H_{k,i,j} = (HO_{k-1,i,j} + HO_{k,i,j}) / 2 \quad (2.11)$$

Then finally the moderator density $MD_{k,i,j}$ at node (k, i, j) is obtained by:

$$MD_{k,i,j} = stmtbl_d_h(Pres, H_{k,i,j}) \quad (2.12)$$

where $stmtbl_d_h$ is steam table function to calculate density from enthalpy of subcool water.

2.6 Xenon-135 Concentration

The concentrations of Xe-135 and its precursor, I-135, are calculated by solving the equations:

$$\partial I(t) / \partial t = Y_I F(t) - \lambda_I I(t) \quad (2.13)$$

$$\partial X(t) / \partial t = Y_X F(t) + \lambda_I I(t) - \{ \sum_g \sigma_{X,g} \phi_g(t) + \lambda_X \} X(t) \quad (2.14)$$

where

- t : time
- I(t) : concentration of I-135
- X(t) : concentration of Xe-135
- Y_I : fission yield of I-135
- Y_X : fission yield of Xe-135
- λ_I : decay constant of I-135
- λ_X : decay constant of Xe-135
- $\sigma_{X,g}$: microscopic absorption cross section cross section of Xe-135
- g : neutron energy group index
- F(t) : fission rate
- $\phi_g(t)$: neutron scalar flux
- \sum_g : summation over all energy groups

For convenience, we define

$$SF(t) = \sum_g \sigma_{X,g} \phi_g(t) \quad (2.15)$$

The equilibrium concentrations, X^∞ and I^∞ , of Xe-135 and I-135 for constant values at $t = 0$: $F(t) = F(0)$ and $SF(t) = SF(0)$ are obtained by setting time derivative terms of Eqs.(2.13) and (2.14) to zero:

$$I^\infty(0) = Y_I F(0) / \lambda_I \quad (2.16)$$

$$X^\infty(0) = (Y_X + Y_I) F(0) / \{ SF(0) + \lambda_X \} \quad (2.17)$$

In a non-equilibrium case, Eqs.(2.13) and (2.14) are solved in a time domain $t \in [0, t]$. We first assume that the core is stationary in the time domain. Equations (2.13) and (2.14) become:

$$\partial I(t) / \partial t = Y_I F(0) - \lambda_I I(t) \quad (2.18)$$

$$\partial X(t) / \partial t = Y_X F(0) + \lambda_I I(t) - \{ SF(0) + \lambda_X \} X(t) \quad (2.19)$$

From (2.18) we obtain

$$I(t) = \beta \exp(-\lambda_I t) + I^\infty(0) \quad (2.20)$$

where

$$\beta = I(0) - I^\infty(0) \quad (2.21)$$

From this and Eq.(2.14) we obtain

$$X(t) = \kappa \exp(-\alpha t) + \{ \beta \lambda_I / (\alpha - \lambda_I) \} \exp(-\lambda_I t) + X^\infty(0) \quad (2.22)$$

where

$$\alpha = SF(0) + \lambda_X \quad (2.23)$$

$$\kappa = X(0) - \beta \lambda_I / (\alpha - \lambda_I) - X^\infty(0) \quad (2.24)$$

From Eqs. (2.20) and (2.22), one can calculate $I(t)$ and $X(t)$ if the initial values $I(0)$, $X(0)$, $F(0)$ and $SF(0)$ are given.

To increase the accuracy of Xe-135 concentration calculation, CYGNUS has an option of solving Eqs.(2.13) and (2.14) assuming $F(t)$ and $SF(t)$ are changing linearly with time. Reference [2.2] describes this method in detail. Though in this reference the method is applied to a 2-point core model, the same method can also be used for a 3-dimensional, node-by-node calculation of Xenon concentration, as in CYGNUS code.

2.7 Samarium-149 Concentration

The concentrations of Sm-149 and its precursor, Pm(Promethium)-149, are calculated the equations:

$$\partial Pm(t) / \partial t = Y_N F(t) - \lambda_{Pm} Pm(t) \quad (2.25)$$

$$\partial Sm(t) / \partial t = \lambda_{Pm} Pm(t) - \sum_g \sigma_{Sm, g} \phi_g(t) Sm(t) \quad (2.26)$$

where

$Pm(t)$: concentration of Pm-149

$Sm(t)$: concentration of Sm-149

Y_N : cumulative fission yield of Nd(Neodymium)-149 and Pm-149

λ_{Pm} : decay constant of Pm-149

$\sigma_{Sm, g}$: microscopic absorption cross section cross section of Sm-149

For convenience, we define

$$SFM(t) = \sum_g \sigma_{Sm, g} \phi_g(t) \quad (2.27)$$

The equilibrium concentrations, Sm^∞ and Pm^∞ , of Sm-149 and Pm-149 for constant values at $t = 0$: $F(t) = F(0)$ and $SFM(t) = SFM(0)$ are obtained by setting time derivative terms of Eqs.(2.25) and (2.26) to zero:

$$Pm^\infty(0) = Y_N F(0) / \lambda_{Pm} \quad (2.28)$$

$$Sm^\infty(0) = Y_N F(0) / SFM(0) \quad (2.29)$$

In a non-equilibrium case, Eqs.(2.25) and (2.26) are solved in a time domain $t \in [0, t]$. We first assume that the core is stationary in the time domain. Equations (2.25) and (2.26) become:

$$\partial Pm(t) / \partial t = Y_N F(0) - \lambda_{Pm} Pm(t) \quad (2.30)$$

$$\partial Sm(t) / \partial t = \lambda_{Pm} Pm(t) - SFM(0) Sm(t) \quad (2.31)$$

From (2.30) we obtain

$$Pm(t) = \beta_{Pm} \exp(-\lambda_{Pm} t) + Pm^{\infty}(0) \quad (2.32)$$

where

$$\beta_{Pm} = Pm(0) - Pm^{\infty}(0) \quad (2.33)$$

From this and Eq.(2.31) we obtain

$$Sm(t) = \kappa_{Sm} \exp\{-SFM(0).t\} + \{ [Pm(0) - Pm^{\infty}(0)] / [SFM(0) / \lambda_{Pm} - 1] \} \exp(-\lambda_{Pm} t) + Sm^{\infty}(0) \quad (2.34)$$

where

$$\kappa_{Sm} = Sm(0) - [Pm(0) - Pm^{\infty}(0)] / [SFM(0) / \lambda_{Pm} - 1] - Sm^{\infty}(0) \quad (2.35)$$

From Eqs. (2.33) and (2.34), one can calculate Pm(t) and Sm(t) if the initial values Pm(0), Sm(0), F(0) and SFM(0) are given.

2.8 References

- [2.1] E. Kolstad: Private communication, 16.11.2009.
- [2.2] S. Hval: "A Description of the Two-Point Model Used as Strategy Generator in the Core Surveillance System SCORPIO," HWR-79, 1982.

3 Generation and Reproduction of VNEM Coefficients

The group neutron transport equations are solved based on the VNEM in the neutronics module of CYGNUS code, to calculate the group neutron flux and the power density distributions in the reactor core and the core eigenvalue (effective multiplication factor). The coefficients of the equations depend on the parameters listed at the beginning of Chapter 2.

To include the effects of parameters on the coefficients, as in the existing many of the systems, the whole calculation process is divided into 2 stages: the single-assembly, infinite-lattice calculation stage (Stage 1) and the global, full core calculation stage (Stage 2).

In Stage 1, by using a lattice burnup code like HELIOS^[3.1] and *VCOEF-VTABLE* codes, tables of the coefficients are parametrically generated.

Stage 2 is performed by CYGNUS code. In the coefficients reproduction module of CYGNUS the coefficients are reproduced node-by-node depending on the values of the feedback parameters of a node, by using the tables of the coefficients generated in Stage 1.

Figure 3.1 shows the codes and data involved in generating and reproduction of the coefficients. *As pointed out in Section 1.3 of Ref.[1.1], we have removed FCM2D code from the generation of the coefficients. This drastically reduces the computing time of the coefficient generation.*

In this chapter the method of generating and reproducing of the coefficients are described. The detailed description of the equations and their coefficients are given in Appendix A of Ref.[1.1].

3.1 Generating Coefficients

The coefficients are generated by a code VCOEF based on the macroscopic neutron cross sections and the scalar fluxes calculated by a lattice burnup code (see Appendix A of Ref. [1.1]) for all the fuel types of the nodes in the core (the nodes are classified into *fuel types* according to their geometrical structure and compositions).

In addition to the coefficients generated by VCOEF code, we need:

Y_I	: fission yield of I-135
Y_X	: fission yield of Xe-135
$\sigma_{X,g}$: microscopic absorption cross section cross section of Xe-135
Y_N	: cumulative fission yield of Nd(Neodymium)-149 and Pm-149
$\sigma_{Sm,g}$: microscopic absorption cross section cross section of Sm-149

to calculate concentrations of Xe-135 and Sm-149.

For convenience we write:

$\Theta(\mathbf{sp})$ = a set of all the coefficients at a state-point \mathbf{sp} for a fuel type

where a state-point vector \mathbf{sp} is a set of specific values for the parameters on which the coefficients depend (listed at the beginning of Chapter 2):

$$\mathbf{sp} = (E, BH, BI, TF, MD, Xe, Sm)$$

where

E	: burnup
BH	: historical Boron
BI	: instantaneous Boron
TF	: fuel temperature
MD	: moderator density
Xe	: Xe135 concentration
Sm	: Sm149 concentration

The code VCOEF calculates $\Theta(\mathbf{sp})$ for a given state-point \mathbf{sp} for a given fuel type. The code VTABLE compiles $\Theta(\mathbf{sp})$ for needed state-points and generates tables of them which are used by CYGNUS code to reproduce the coefficients.

3.1.1 Base Coefficients Matrix

First we calculate the *base coefficients matrix* $\Theta_{\text{base}, iE, iBH}$:

$$\Theta_{\text{base}, iE, iBH} = \Theta(\mathbf{sp}_{\text{base}, iE, iBH}) \quad (3.1)$$

where

$$\mathbf{sp}_{\text{base}, iE, iBH} = (E_{iE}, BH_{iBH}, BI = BH_{iBH}, TF_{\text{base}}, MD_{\text{base}}, Xe_{\text{base}}, Sm_{\text{base}}) \quad (3.2)$$

Here we also set the power density in a node to be a base value (the nominal value is recommended), ρ_{base} , though the coefficients are not explicitly dependent on it. The burnup and the historical Boron points

$$\begin{aligned} E_{iE}, & \quad iE = 1, 2, \dots, iEM \text{ (indexing order: } E_{iE} < E_{iE+1} \text{)} \\ BH_{iBH}, & \quad iBH = 1, 2, \dots, iBHM \text{ (indexing order: } BH_{iBH} < BH_{iBH+1} \text{)} \end{aligned}$$

should be taken so that the range $E \in [E_1, E_{iEM}]$ and $BH \in [BH_1, BH_{iBHM}]$ sufficiently covers the possible values of (E, BH) of the nodes in the core. The coefficients are interpolated with respect to E and BH (see Section 3.2) by a quadratic formula, these points should be fine enough so that the interpolation gives enough accuracy.

The parameters TF_{base} and MD_{base} are base values (the nominal values are recommended) for the fuel temperature and the moderator density.

The parameters Xe_{base} and Sm_{base} are the equilibrium concentrations corresponding to the base power density ρ_{base} .

3.1.2 Branch-off Calculations

The coefficients corresponding to the parameters deviated from the base coefficient matrix are generated by the *branch-off calculations*, which are to generate:

$$\Theta_{iBI, iEb, iBHb} = \Theta(\mathbf{sp}_{iBI, iEb, iBHb}), \quad iBI = 1, \dots, iBIM \quad (3.3)$$

$$\Theta_{iTF, iEt, iBHt} = \Theta(\mathbf{sp}_{iTF, iEt, iBHt}) \quad , iTF = 1, \dots, iTFM \quad (3.4)$$

$$\Theta_{iMD, iEm, iBHM} = \Theta(\mathbf{sp}_{iMD, iEm, iBHM}) \quad , iMD = 1, \dots, iMDM \quad (3.5)$$

$$\Theta_{iXe, iEx, iBHx} = \Theta(\mathbf{sp}_{iXe, iEx, iBHx}) \quad , iXe = 1, \dots, iXeM \quad (3.6)$$

$$\Theta_{iSm, iEs, iBHs} = \Theta(\mathbf{sp}_{iSm, iEs, iBHs}) \quad , iSm = 1, \dots, iSmM \quad (3.7)$$

where

$$\mathbf{sp}_{iBI, iEb, iBHb} = (E_{iEb}, BH_{iBHb}, BI = BI_{iBI}, TF_{base}, MD_{base}, Xe_{base}, Sm_{base}) \quad (3.8)$$

$$\mathbf{sp}_{iTF, iEt, iBHt} = (E_{iEt}, BH_{iBHt}, BI = BH_{iBHt}, TF_{iTF}, MD_{base}, Xe_{base}, Sm_{base}) \quad (3.9)$$

$$\mathbf{sp}_{iMD, iEm, iBHM} = (E_{iEm}, BH_{iBHM}, BI = BH_{iBHM}, TF_{base}, MD_{iMD}, Xe_{base}, Sm_{base}) \quad (3.10)$$

$$\mathbf{sp}_{iXe, iEx, iBHx} = (E_{iEx}, BH_{iBHx}, BI = BH_{iBHx}, TF_{base}, MD_{base}, Xe_{iXe}, Sm_{base}) \quad (3.11)$$

$$\mathbf{sp}_{iSm, iEs, iBHs} = (E_{iEs}, BH_{iBHs}, BI = BH_{iBHs}, TF_{base}, MD_{base}, Xe_{base}, Sm_{iSm}) \quad (3.12)$$

The number of the burnup and the historical Boron points in Eqs.(3.8 through 3.12):

$$\begin{aligned} E_{iEb}, iEb &= 1, 2, \dots, iEMb; & BH_{iBHb}, iBHb &= 1, 2, \dots, iBHMb \\ E_{iEt}, iEt &= 1, 2, \dots, iEMt; & BH_{iBHt}, iBHt &= 1, 2, \dots, iBHMt \\ E_{iEm}, iEm &= 1, 2, \dots, iEMm; & BH_{iBHM}, iBHM &= 1, 2, \dots, iBHMm \\ E_{iEx}, iEx &= 1, 2, \dots, iEMx; & BH_{iBHx}, iBHx &= 1, 2, \dots, iBHMx \\ E_{iEs}, iEs &= 1, 2, \dots, iEMs; & BH_{iBHs}, iBHs &= 1, 2, \dots, iBHM s \end{aligned}$$

can be independently defined for each of the branch parameters, and can be less than the base coefficient matrix if interpolation accuracy is maintained.

3.2 Reproduction of Coefficients

To reproduce the coefficients for a node in CYGNUS, we assume that their dependence on parameters other than the burnup and the historical Boron concentration can be expanded into 1st order Taylor series around the base state point $\mathbf{sp}_{base, iE, iBH}$:

$$\begin{aligned} &\Theta(E, BH, BI, TF, MD, Xe, Sm) \\ &= \Theta(E, BH, BI = BH, TF_{base}, MD_{base}, Xe_{base}, Sm_{base}) \\ &+ \delta\Theta_{BI}(E, BH, BI) \\ &+ \delta\Theta_{TF}(E, BH, TF) \\ &+ \delta\Theta_{MD}(E, BH, MD) \\ &+ \delta\Theta_{Xe}(E, BH, Xe) \\ &+ \delta\Theta_{Sm}(E, BH, Sm) \end{aligned} \quad (3.13)$$

where (E, BH, BI, TF, MD, Xe, Sm) are the parameter values of the node.

The 1st term of the right side of Eq.(3.13) is calculated by 2-dimensional quadratic table-interpolation at (E, BH) of the base coefficient matrix using 9 points:

$$(iE, iE + 1, iE + 2) \times (iBH, iBH + 1, iBH + 2)$$

where iE is the maximum of the integer for which $E_{iE} < E$, and $iBH, BH_{iBH} < BH$.

The other terms are obtained from the branch-off calculations. For example, the 3rd term of the right side of Eq.(3.13) is calculated in the following manner. From the branch-off calculations, we obtain at state-point $(E_{iEt}, BH_{iBHt}, BI = BH_{iBHt}, TF_{iTF}, MD_{base}, Xe_{base}, Sm_{base})$

$$\delta\Theta_{TF}(E_{iEt}, BH_{iBHt}, TF_{iTF}) = \Theta(\mathbf{sp}_{iTF, iEt, iBHt}) - \Theta(\mathbf{sp}_{base, iE, iBH}) \quad (3.14)$$

where the burnup and the historical Boron values must be matched for indices (iE, iBH) and (iEt, iBHt). Then we find an maximum index iFT such that $TF_{iFT} < TF$, and find the values:

$$\delta\Theta_{TF}(E, BH, TF_{iTF}), iTF' = iTF, iTF + 1, iTF + 2 \quad (3.15)$$

by a 2-dimensional quadratic interpolation at (E, BH) of table $\delta\Theta_{TF}(E_{iEt}, BH_{iBHt}, TF_{iTF})$. Then finally we obtain $\delta\Theta_{TF}(E, BH, TF)$ by a quadratic interpolation of $\delta\Theta_{TF}(E, BH, TF_{iTF'})$ of Eq.(3.15).

3.3 References

- [3.1] F. D. Giust, R. J. J. Stamm'ler, and A. A. Ferri: "HELIOS1.7 User Guide and Manual," Studsvik and Scandpower, 2001.

4 Iterative Solution of VNEM Including Feedback Effects

The solution of VNEM module in CYGNUS code must include the effects of feedbacks shown in Chapter 2. This is performed by an iterative manner as described in this Chapter.

4.1 Calculation Flow

The calculation flow of CYGNUS is:

1. Start
2. Read input data
3. Initialize:
 - set nodal power distribution = initial guess
 - set flux moment expansion coefficients = initial guess
 - set iteration counter = 1
4. Calculate burnup and historical Boron (Sections 2.1 and 2.2)
5. Calculate concentration of Xe-135, I-135, Pm-149 and Sm-149 (Sections 2.6 and 2.7)
6. Calculate moderator density and fuel temperature (Sections 2.4 and 2.5)
7. Reproduce coefficients of VNEM (Section 3.2)
8. Solve VNEM transport equations (see Ref.[1.1])
9. Calculate core eigenvalue and nodal power distribution (see Ref.[1.1])
10. Convergence check of nodal power distribution and core eigenvalue
11. If *not* converged then:
 - convergence acceleration by coarse-mesh rebalancing
 - criticality adjustment if requested
 - increase iteration counter by 1
 - go back to step 4
12. Calculate pin power distribution
13. Write output results
14. End

The core eigenvalue is calculated by Rayleigh quotient algorithm^[4.1]. The convergence check of nodal power distribution is made by:

$$\max.\{P_{k,i,j}(L+1)/P_{k,i,j}(L)\} - \min.\{P_{k,i,j}(L+1)/P_{k,i,j}(L)\} < 2\varepsilon \quad (4.1)$$

where as in Section 2.1 the *nodal power* $P_{k,i,j}$ is average power density over node (k, i, j) relative to the core average, max. and min. mean the maximum and the minimum in the core. The parameter ε is user's input criterion of the convergence. As the iterative process shown above becomes linear after sufficient number of iterations, the criterion ε is interpreted as the maximum in modulus of the deviation of nodal power $P_{k,i,j}$ relative to the theoretically converged value.

The convergence of the iterative process defined above can efficiently be accelerated by using the coarse-mesh rebalancing method^[4.2]. The basic idea of this method is to accelerate the decay of the lower modes included in the errors of the initial guess for the nodal power distribution.

As the iterative process is a sort of the power method, the higher modes decay out quickly, but the lower modes remain alive and require much iteration to die out.

4.2 References

- [4.1] http://en.wikipedia.org/wiki/Rayleigh_quotient_iteration
- [4.2] http://wwwsoc.nii.ac.jp/aesj/publication/JNST2004/No.8/41_781-789.pdf

5 Comparison Calculations

Core follow calculations of Ringhals-3, Cycle 1 were performed from 02:00 hrs of 20.07.1980 (the beginning of Cycle 1) through 05:00 hrs. of 21.12.1980. As the present study in the year 2009 is focused around the beginning of life so that the effect of the burnup tilt is not significant. The actual calculation methods are described in this chapter.

5.1 Cases for Comparison

The calculation points (or cases) of CYGNUS were taken as:

1. 20:00 17.10.1980 (case number. hour: minutes date. month, year)
2. 06:29 04.11.1980 map7
3. 08:00 05.11.1980
4. 06:00 16.11.1980
5. 08:00 25.11.1980
6. 20:00 30.11.1980
7. 08:00 05.12.1980
8. 04:00 11.12.1980
9. 09:00 15.12.1980
10. 06:00 20.12.1980 map9
11. 05:00 21.12.1980

The core eigenvalue at each of the points is compared to the measured value of 1.0. At case numbers 2 (map7) and 10 (map9), the measured detector readings are given for octant symmetric core to which we can compare the calculated readings. Table 5.1 shows the operation parameters of the core at these points.

The types of fuel in the core and the loading pattern of assemblies are the same as shown in Ref.[1.1]. The node structure of the core is shown in Fig.5.1.

Figure 5.2 shows the Boron concentration, core thermal power and core average burnup at all the given points in the core follow calculation period.

5.2 Coefficients Generation

The coefficients of VNEM equations (described in Chapter 3) are generated in the following manner. As the "base" values we take:

$$\begin{aligned}\rho_{\text{base}} &= 113 \text{ (KW/L)} \\ \text{TF}_{\text{base}} &= 616 \text{ (C)} \\ \text{MD}_{\text{base}} &= 757 \text{ (KG/M}^3\text{)} \\ \text{Xe}_{\text{base}} &= \text{equilibrium with } \rho_{\text{base}} \\ \text{Sm}_{\text{base}} &= \text{equilibrium with } \rho_{\text{base}}\end{aligned}$$

It is assumed that the historical Boron is the same as the instantaneous Boron because the burnup of the fuel is less than 1000MWD/MT.

Then the base coefficients matrix is generated based on ENDFB-6 cross sections library by HELIOS^[3,1] and VCOEF codes for:

$$E_{iE, iE=1, 2, \dots, 7} = 0, 1, 200, 400, 600, 800, 1000 \text{ (MWD/MT)}$$

$$BH_{iBH=1, 2, 3, 4} = 800, 1000, 1200, 1400 \text{ (PPM)}$$

It should be noted here that the coefficients at $E_{iE=1} = 0$ are not used in reproduction of the coefficients, because at this burnup the Xe-135 concentration is 0 (it jumps to the equilibrium at $E_{iE=2} = 1$) and the quadratic interpolation may cause serious error if we include this point.

The branch-off calculations are made for:

$$TF_{iTF=1, 2, 3, 4} = 200, 516, 716, 1000 \text{ (C)}$$

$$MD_{iMD=1, 2} = 657, 707 \text{ (KG/M}^3\text{)}$$

$$Xe_{iXe=1, 2, 3} = 0.0, 0.5 \times \text{equilibrium}, 1.5 \times \text{equilibrium}$$

$$Sm_{iSm=1} = 0.0$$

for all the base matrix points (iE, iBH). We assume that the additional parameters:

- Y_I : fission yield of I-135
- Y_X : fission yield of Xe-135
- $\sigma_{X, g}$: microscopic absorption cross section cross section of Xe-135
- Y_N : cumulative fission yield of Nd(Neodymium)-149 and Pm-149
- $\sigma_{Sm, g}$: microscopic absorption cross section cross section of Sm-149

can well be reproduced only from the base matrix without the branch-off calculations.

For the axial and the radial reflectors, we assume that the coefficients depend only on the water density and the instantaneous Boron concentration. The reflectors do not burn nor generates any fission products. Therefore the coefficients is generated for

$$BI_{iBI=1, 2, 3} = 0, 1000, 2000 \text{ (PPM)}$$

$$MD_{iMD=1, 2, 3} = 657, 707, 757 \text{ (KG/M}^3\text{)}$$

The way to generate coefficients is in principle the same as that in Ref.[1.1] with the following exceptions.

The number of energy groups is assumed to be 5 (7 in Ref.[1.1]), based on the results obtained in preliminary analysis. The group boundaries are:

group	upper boundary		lower boundary
1	∞		to 1 MeV
2	1 MeV	to	9.119 KeV
3	9.119 KeV	to	3.9279 eV
4	3.9279 eV	to	0.27052 eV
5	0.27052 eV	to	0 eV

The 2D transport code FCM2D is not used to generate the infinite-lattice scalar neutron flux distributions. Instead of FCM2D, the output from HELIOS code is directly used in VCOEF.

5.3 Xenon Effect

As shown in Fig.5.3, Xe-135 is far from stable during the period of core follow calculations. Though CYGNUS can make a 3D Xenon-transient calculation, it would take too much computing time because the whole period is about 2.5 months long. Therefore we used a point kinetics model to estimate the transient effect of Xe-135.

In this model we assume that the spatial power density distribution in the core is uniform and is the same as the average power density over the whole core. With this assumption Eqs.(2.13) and (2.14) can be solved for each of the fuel types in the core to obtain the concentration of Xe-135, $X(t)$, through the whole period of core follow calculation, assuming the initial values $I(0)$ and $X(0)$ are = 0. At the same time we can calculate the equilibrium values of the concentration of Xe-135, $X^\infty(t)$.

In the core follow calculation of CYGNUS we assume that the concentration of Xe-135 is equilibrium with the power density, and make a correction:

$$Xe_{k,i,j} = Xe_{k,i,j}^\infty X_{ift}(t) / X_{ift}^\infty(t) \quad (5.1)$$

where

$Xe_{k,i,j}$: corrected concentration of Xe-135 to be used to reproduce coefficients of VNEM in CYGNUS at node k, i, j
$Xe_{k,i,j}^\infty$: originally calculated equilibrium Xe-135 concentration by CYGNUS at node k, i, j
$X_{ift}(t)$: transient Xe-135 concentration at core follow point of time t obtained from point Xe-kinetics model, ift = fuel type index of node k, i, j
$X_{ift}^\infty(t)$: equilibrium Xe-135 concentration at core follow point of time t obtained from point Xe-kinetics model, ift = fuel type index of node k, i, j

Figure 5.4 shows the equilibrium, the transient and the ratio of transient to equilibrium of Xe-135 for fuel type w211-00. One can see from this figure that the transient (actual) Xe-135 is less than the equilibrium except for the 8th point.

5.4 Miscellaneous

The burnup from case n to n + 1 (n = 0, 1, ..., 10) is calculated by Eq.(2.1) assuming that the average power density over node (k, i, j) is the same as that of case n + 1.

The historical Boron concentration of case n + 1 is calculated by Eq.(2.2) assuming that the instantaneous Boron concentration is the same as that of case n + 1. The feedback to the coefficients of VNEM is calculated by assuming that the historical Boron concentration is the same as the instantaneous Boron (input to CYGNUS from the operating data specified by Ringhals).

The fuel temperature is calculated by Halden correlation (2.3) with coefficient

$$CHAL_{ift} = 1.83$$

As shown in Section 2.5, the coolant flow is assumed to be distributed uniformly for all the assemblies. The total coolant flow and the method of calculating the inlet coolant temperature are specified by Ringhals.

The nodal concentration of Xe-135 is calculated by assuming the equilibrium with the nodal power density with the correction of Eq.(5.1).

The concentration of Sm-149 is assumed to be 0 as the core is at the beginning of the life and its effect is much less than Xe-135.

The followings are the same as Ref.[1.1]:

- method of calculating the control rod effect
- method of calculating the detector readings including the axial alignment correction
- core loading pattern
- problem domain = 1/4 core, mirror symmetry
- boundary condition at the outer boundary of the problem domain
- parameters in VNEM modules (degree of expansion polynomials etc.)

6 Results of Comparisons

The results of the comparisons are shown in this chapter.

6.1 Core Eigenvalue (keff)

The core eigenvalue of CYGNUS at the calculation points are:

no.	date, time	burnup(MWD/MT)	eigenvalue
1.	20:00 17.10.1980	38.0	0.99823
2.	06:29 04.11.1980 map7	91.8	0.99619
3.	08:00 05.11.1980	103.7	0.99668
4.	06:00 16.11.1980	172.4	0.99732
5.	08:00 25.11.1980	195.3	0.99749
6.	20:00 30.11.1980	247.5	0.99718
7.	08:00 05.12.1980	296.0	0.99802
8.	04:00 11.12.1980	363.9	0.99715
9.	09:00 15.12.1980	403.9	0.99704
10.	06:00 20.12.1980 map9	459.8	0.99583
11.	05:00 21.12.1980	478.0	0.99704
average			0.99711
root-mean-square deviation			0.00067

Figure 6.1 shows the eigenvalue in graphs.

The root-mean-square deviation is a measure of fluctuation of eigenvalue by cases, and is quite small. However the average is about 0.28% smaller than expected from the results from Ref.[1.1]. The cause for this may be:

- insufficient number of groups
- insufficient correction for cell homogenization

We will improve these insufficiencies by increasing the number of groups and making cell-heterogeneous calculations in VCOEF.

6.2 Detector Readings

The results of the comparisons of detector readings are summarized as, for

Map7:

Fig.6.2: Core average relative axial readings

Fig.6.3: Assembly average relative radial readings

Fig.6.4: Readings in assembly H4 ($i = 8, j = 4$), where the maximum reading is observed in Map7.

Map9:

Fig.6.5: Core average relative axial readings

Fig.6.6: Assembly average relative radial readings

Fig.6.7: Readings in assembly F6 ($i = 10, j = 6$), where the maximum reading is observed in Map9.

The errors of the maximum readings are:

Map	CYGNUS	MEASURED	ERROR
Map7	1.929	1.887	2.2%
Map9	1.890	1.928	-2.0%

The results of comparisons at all the measuring points of Maps7 and 9 are shown in the figures in Appendices A1 and A2, respectively. In these figures, the upper and the lower bounds of the measured readings are taken from the maximum and the minimum readings of assemblies at octant-symmetric positions.

6.3 Computing Time

The computing time is measured by using a PC:

PC: HP Compaq dx6100
 OS: Windows XP professional
 CPU: Pentium-4 (3GHz)
 RAM: 2.99GHz / 1.49GB

The computing time of CYGNUS is:

no.	date, time	CPU time(min.)
1.	20:00 17.10.1980	8.8
2.	06:29 04.11.1980 map7	7.5
3.	08:00 05.11.1980	4.6
4.	06:00 16.11.1980	9.2
5.	08:00 25.11.1980	9.6
6.	20:00 30.11.1980	8.7
7.	08:00 05.12.1980	7.5
8.	04:00 11.12.1980	7.9
9.	09:00 15.12.1980	7.4
10.	06:00 20.12.1980 map9	5.8
11.	05:00 21.12.1980	5.3
average		7.5

This is much faster than the calculation of VNEM3D for cases of Ringhals-3 without the feedback effects^[1,1]. The reasons are (1) more sophisticated coding in VNEM module in CYGNUS, and (2) the convergence acceleration effect of the feedbacks.

7 Conclusions

Comparisons were made of a PWR core simulator CYGNUS with VNEM neutronics module to measured data from Ringhals-3, hot-operating at the beginning of cycle 1.

The core eigenvalue from core average burnup = 0 through 500MWD/MT was 0.99711 ± 0.00067 . The deviation is small, however, the value is a bit smaller than expected from the results of Ref.[1.1]. This may be because of the difference of the number of energy groups and cell homogenization. We will urgently make 7 groups calculation (as in Ref.[1.1]) without the cell homogenization.

The results of the comparisons of the detector readings showed almost the same accuracy as in Ref.[1.1]. As for the core eigenvalue, this may be somewhat improved in the 7-group calculations without cell-homogenization.

8 Tables and Figures

Table 5.1 Operation parameters at core follow calculation points

case	DD.MM.YY	HH:MM	BORON	D	T	CTP	CTP%	burnup	bar	DR
	-----	-----	-----	---	-----	-----	-----	-----	---	-----
1	17.10.80	20:00	1188.0	198	298.2	708	25.5	38.0	154	
2	04.11.80	6:29	*1085.5	196	295.4	819	29.5	91.8	154	map7**
3	05.11.80	8:00	1055.0	197	295.5	832	30.0	103.7	154	
4	16.11.80	6:00	1056.0	182	295.1	957	34.5	172.4	154	
5	25.11.80	8:00	1096.0	204	295.2	1010	36.4	195.3	154	
6	30.11.80	20:00	1030.0	187	295.6	1152	41.5	247.5	154	
7	05.12.80	8:00	1051.0	194	294.1	796	28.7	296.0	154	
8	11.12.80	4:00	1001.0	203	294.8	821	29.6	363.9	154	
9	15.12.80	9:00	1016.0	198	295.7	1096	39.5	403.9	154	
10	20.12.80	6:00	997.0	199	296.4	1387	50.0	459.8	154	map9**
11	21.12.80	5:00	*972.5	204	296.5	1374	49.5	478.0	154	

DD.MM.YY : date, month, year of the point
HH.MM : hour, minutes of the point
BORON : instantaneous Boron concentration (PPM)
D : D-bank control rod position (STEPS)
T : core average coolant temperature (C)
CTP : core thermal power (MW)
CTP% : core thermal power (%)
burnup : core average burnup (MWD/MT)
bar : core pressure (bar)
DR : detector readings map number

* : BORON is not given at case 2 and 11. The values are obtained from 2 nearest neighbours where BORON is given by linear interpolation.

** : Measure detector readings are given at cases 2 and 10, named map7 and map9, respectively.

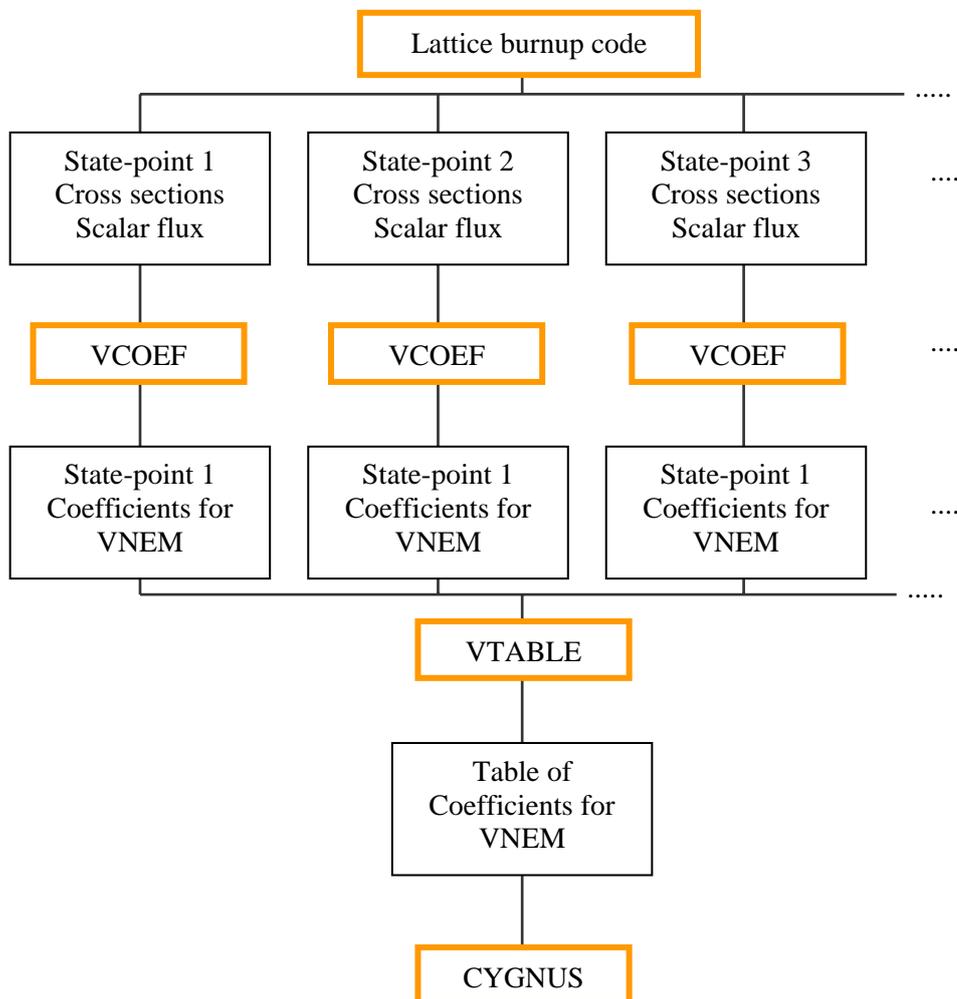
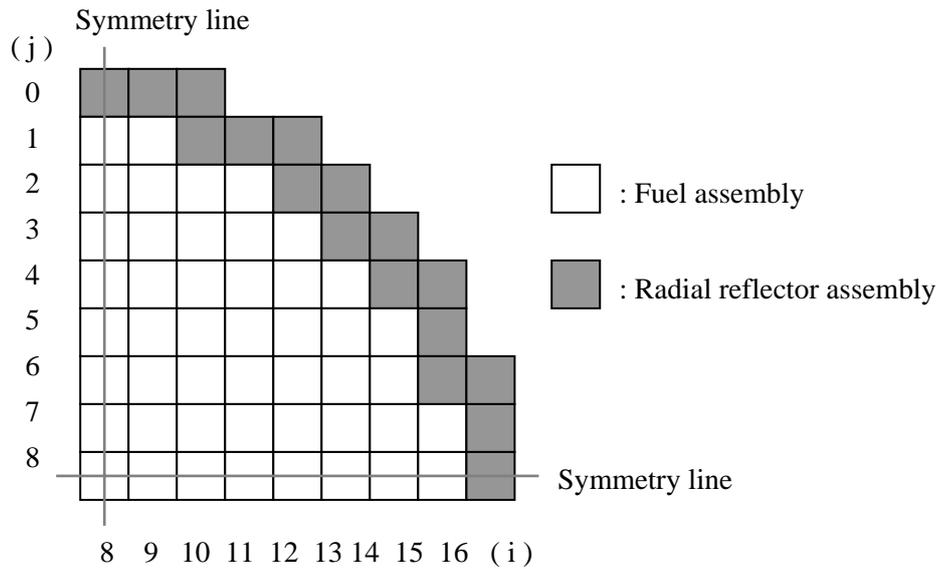
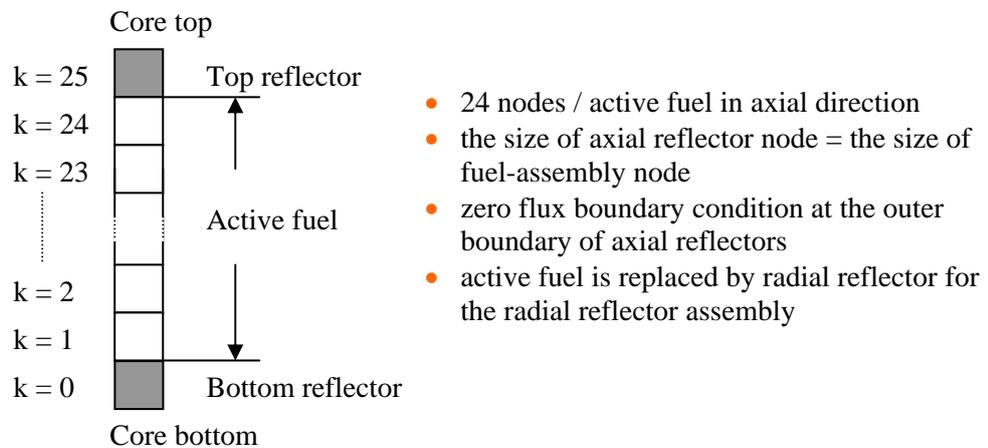


Fig.3.1 Generating table of coefficients of VNEM



- 1 node / assembly in radial direction
- the size of radial reflector assembly = the size of fuel assembly
- zero flux boundary condition at the outer boundary of radial reflectors

(a) Radial view



(b) Axial view

- height of active fuel = 365.76 cm
- width of fuel assembly = width of node = 21.42 cm
- height of node = $365.76 / 24 = 15.24$ cm

Fig.5.1 Core geometry modelling

Boron (PPM)

Burnup (MWD/MT)

Core thermal power (%)

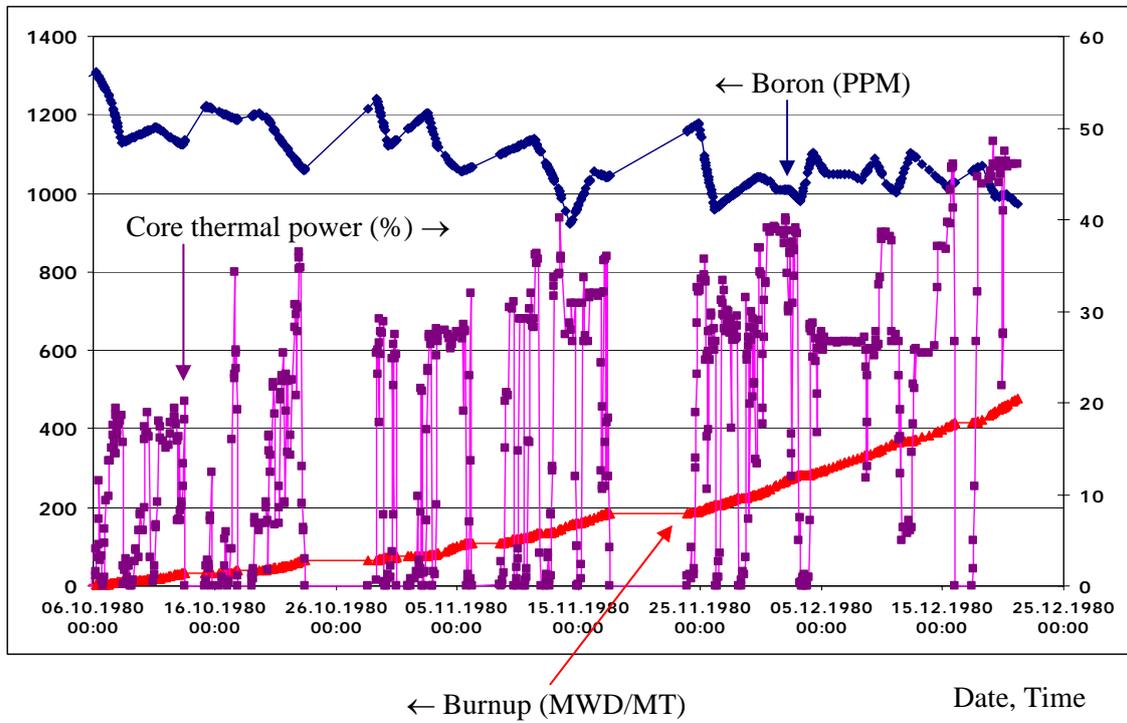


Fig.5.2 Boron concentration, core thermal power and core average burnup in tracking period.

Relative Xe-135 Concentration

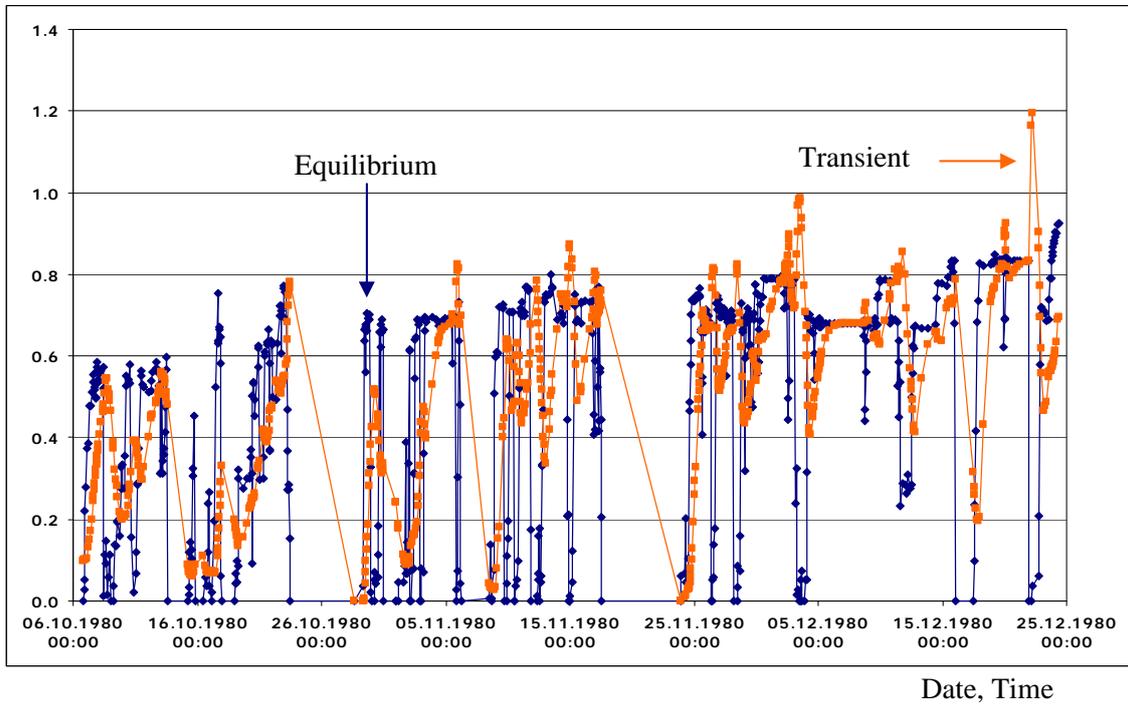


Fig.5.3 Comparison of equilibrium and transient Xe-135 concentrations relative to the equilibrium concentration at the base power density $\rho_{\text{base}} = 113$ (KW/L), fuel type = w211-00.

Relative Xe-135 Concentration

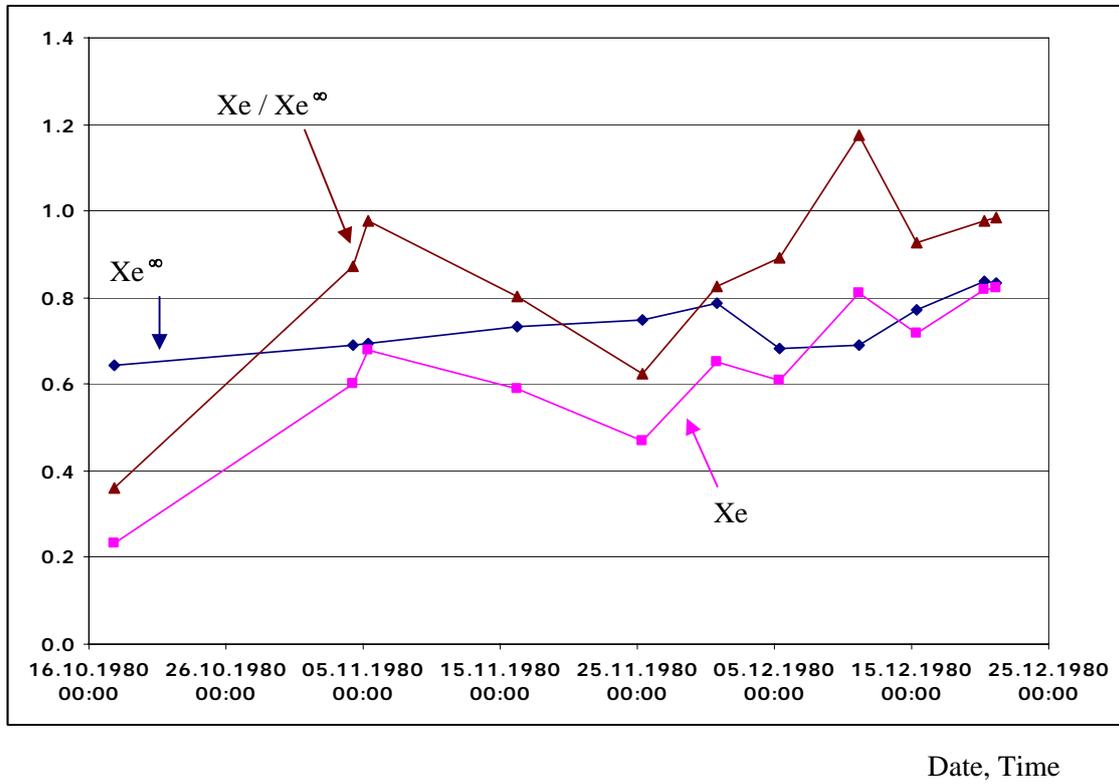


Fig.5.4 Xenon-135 concentration at core follow calculation points, relative to the equilibrium value for the nominal power density.
 Fuel type : w211-00
 Xe^∞ : equilibrium
 Xe : transient

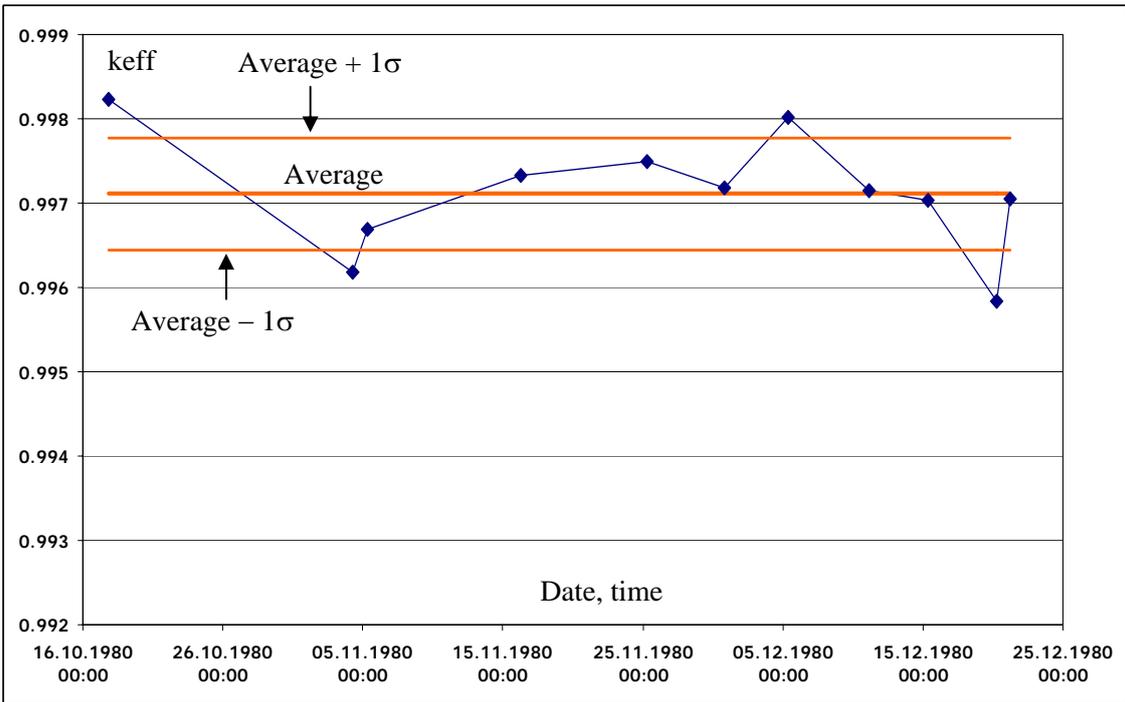
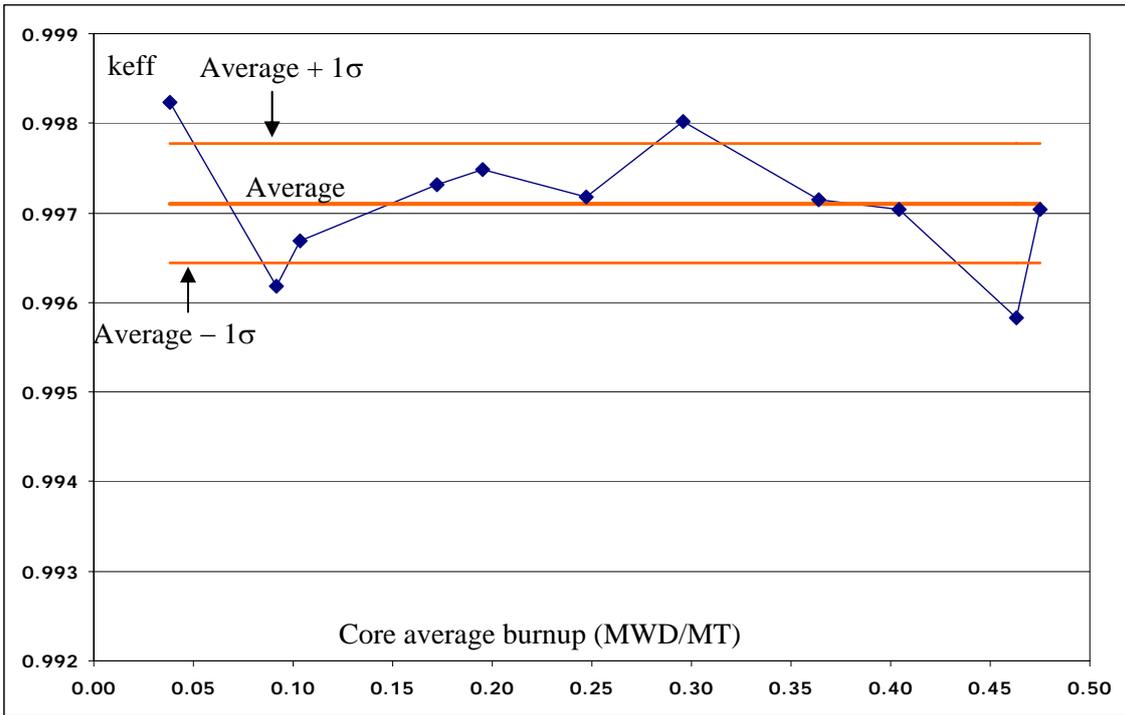


Fig.6.1 Core eigenvalue

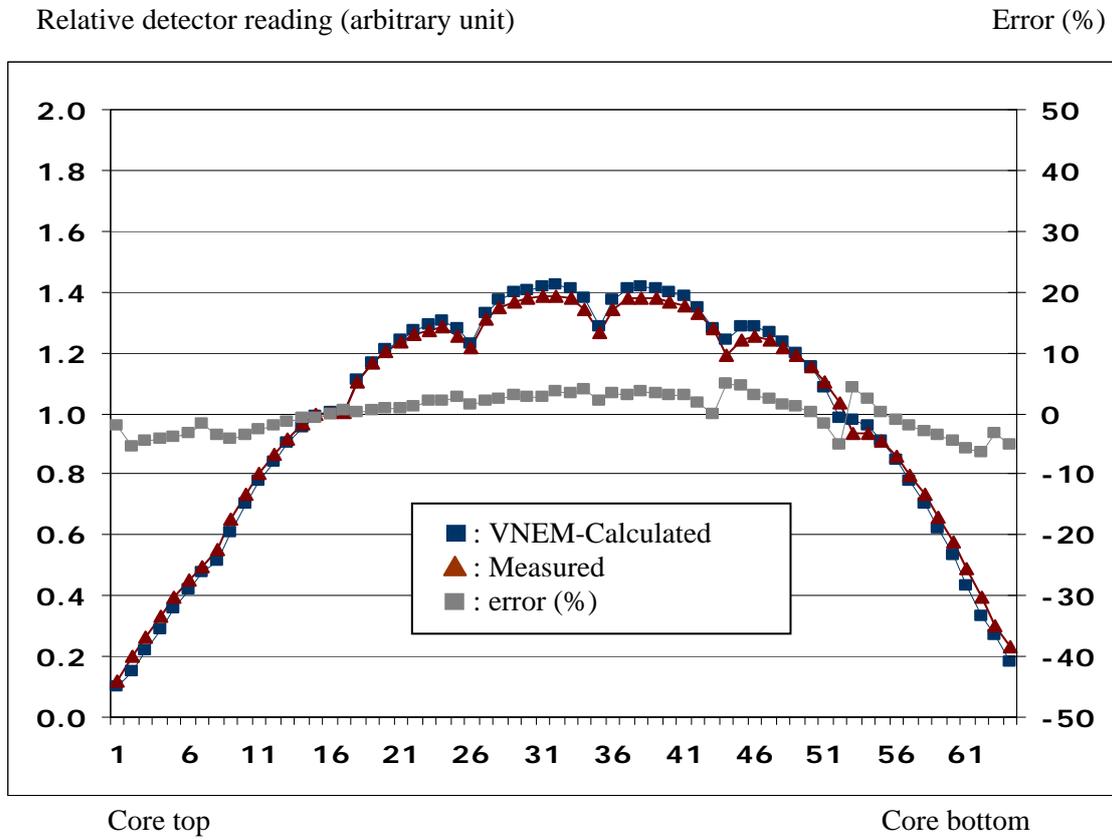
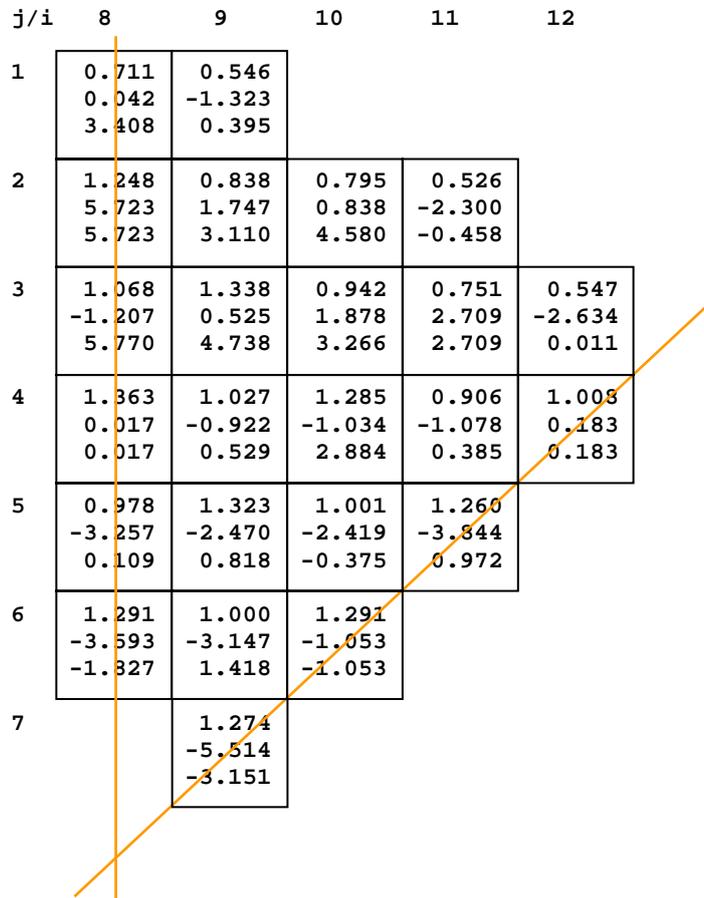


Fig.6.2 Comparison of core average axial detector readings, map7. The readings are relative to their average.



Octant symmetry lines

Fig.6.3 Comparison of assembly average radial detector readings, map7. The readings are relative to their average.

- Line 1: Calculated reading by CYGNUS
- Line 2: CYGNUS – Upper bound of measured in %
- Line 3: CYGNUS – Lower bound of measured in %

The upper and the lower bounds are taken from the maximum and the minimum readings of assemblies at octant-symmetric positions.

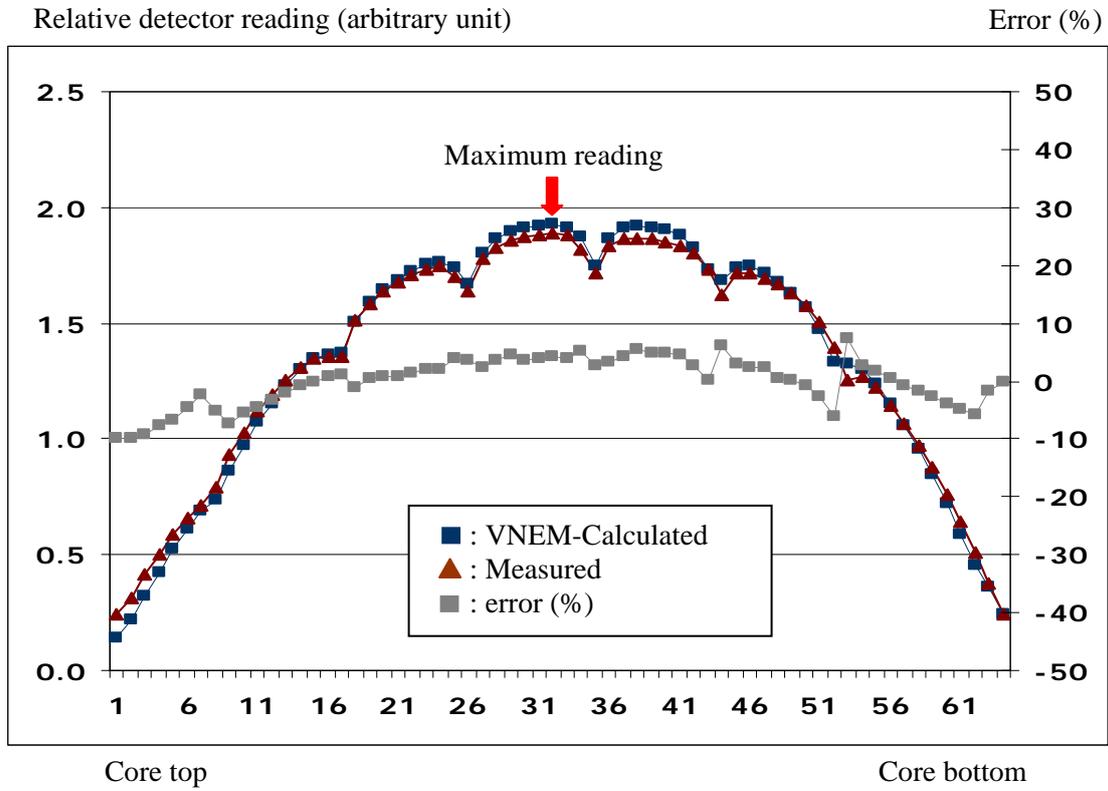


Fig.6.4 Comparison of detector readings in assembly H4, where the maximum reading is observed in map7.

The readings are relative to their average over all the measured positions in the core.

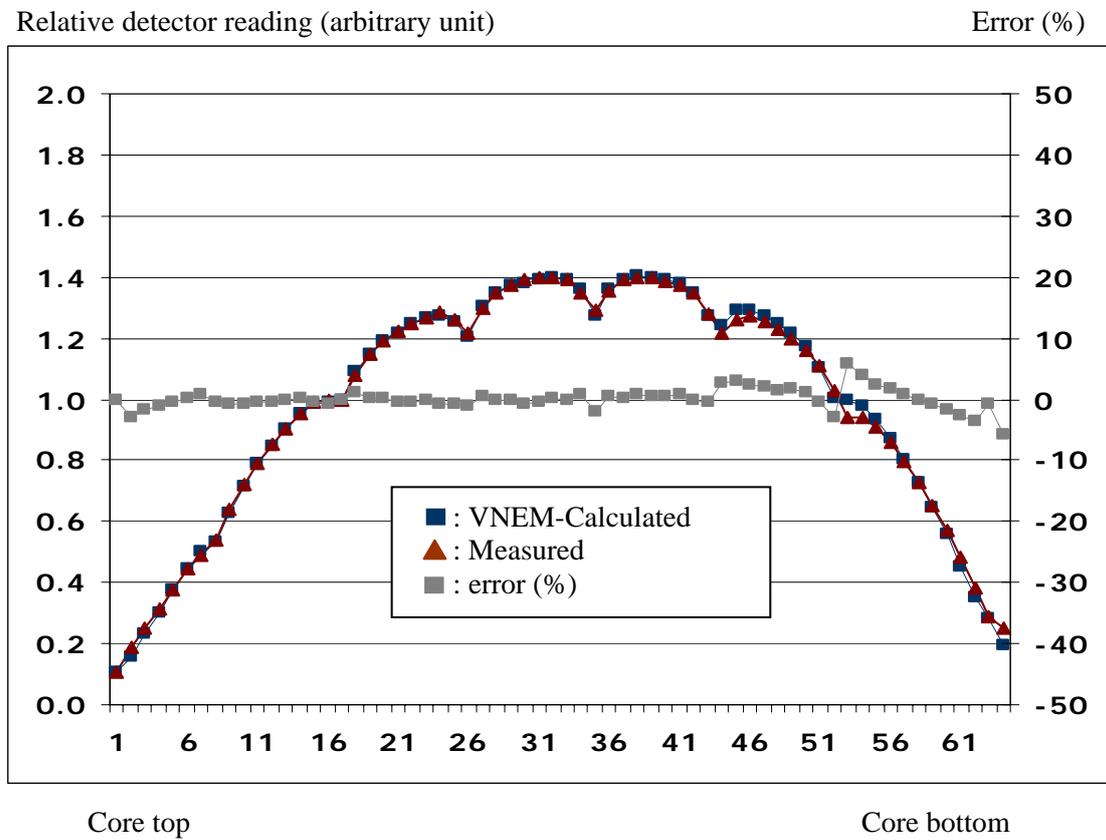


Fig.6.5 Comparison of core average axial detector readings, map9.
The readings are relative to their average.

j/i	8	9	10	11	12
1	0.599 0.547 2.480	0.539 -1.753 -0.053			
2	1.233 8.346 8.346	0.822 1.045 3.414	0.779 0.669 2.404	0.520 -1.084 0.000	
3	1.057 0.261 4.331	1.325 3.213 5.984	0.930 1.664 2.897	0.740 2.141 2.141	0.544 -2.232 -0.558
4	1.364 0.326 0.326	1.027 -2.440 0.093	1.283 0.757 3.674	0.902 0.184 1.575	1.005 0.448 0.448
5	0.988 -2.387 -0.965	1.337 -2.788 -0.978	1.009 -3.115 -0.862	1.265 -2.233 1.665	
6	1.313 -4.907 -2.287	1.016 -3.987 -2.624	1.316 -1.459 -1.459		
7		1.301 -5.860 -3.125			

Octant symmetry lines

Fig.6.6 Comparison of assembly average radial detector readings, map9. The readings are relative to their average.

- Line 1: Calculated reading by CYGNUS
- Line 2: CYGNUS – Upper bound of measured in %
- Line 3: CYGNUS – Lower bound of measured in %

The upper and the lower bounds are taken from the maximum and the minimum readings of assemblies at octant-symmetric positions.

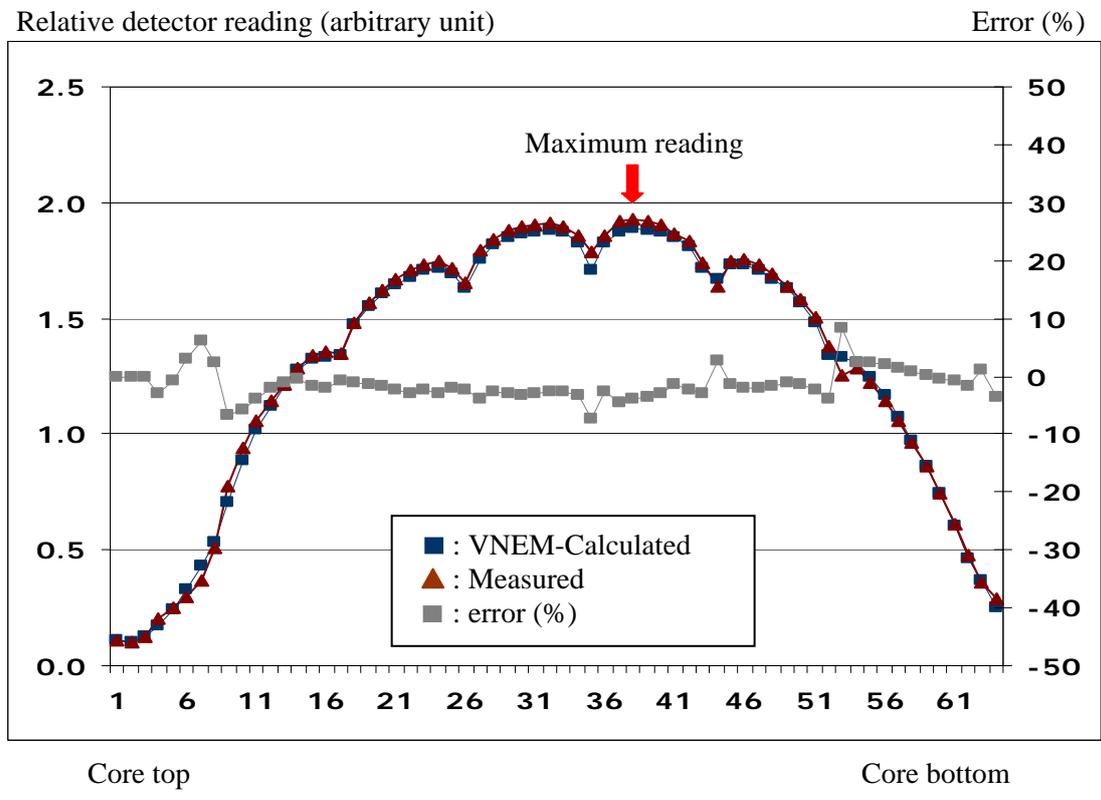


Fig.6.7 Comparison of detector readings in assembly F6, where the maximum reading is observed in map9.

The readings are relative to their average over all the measured positions in the core.

9 Appendix A: Comparison for All Thimbles

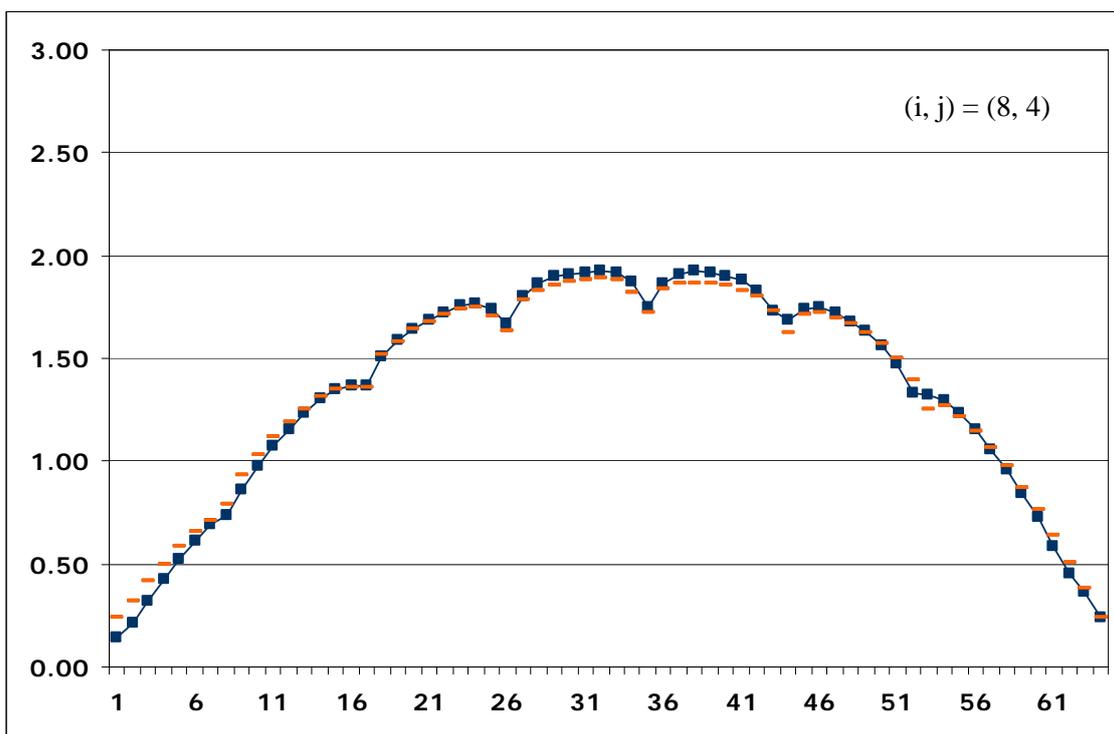
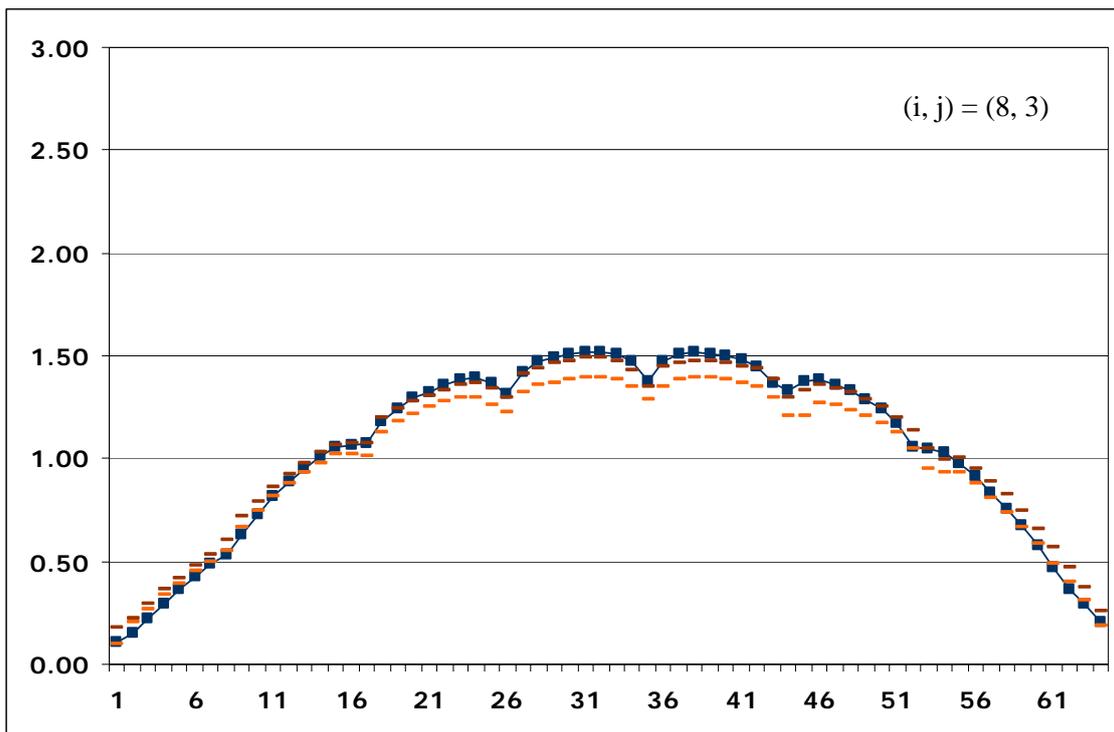
9.1 A.1 Map7

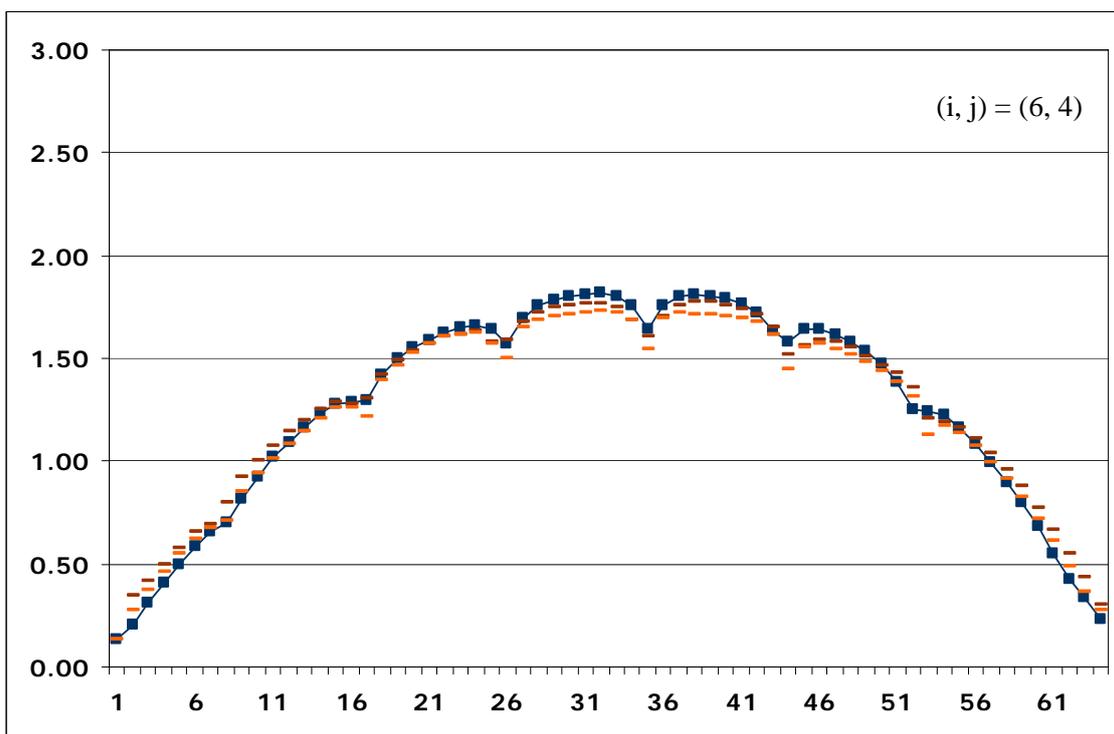
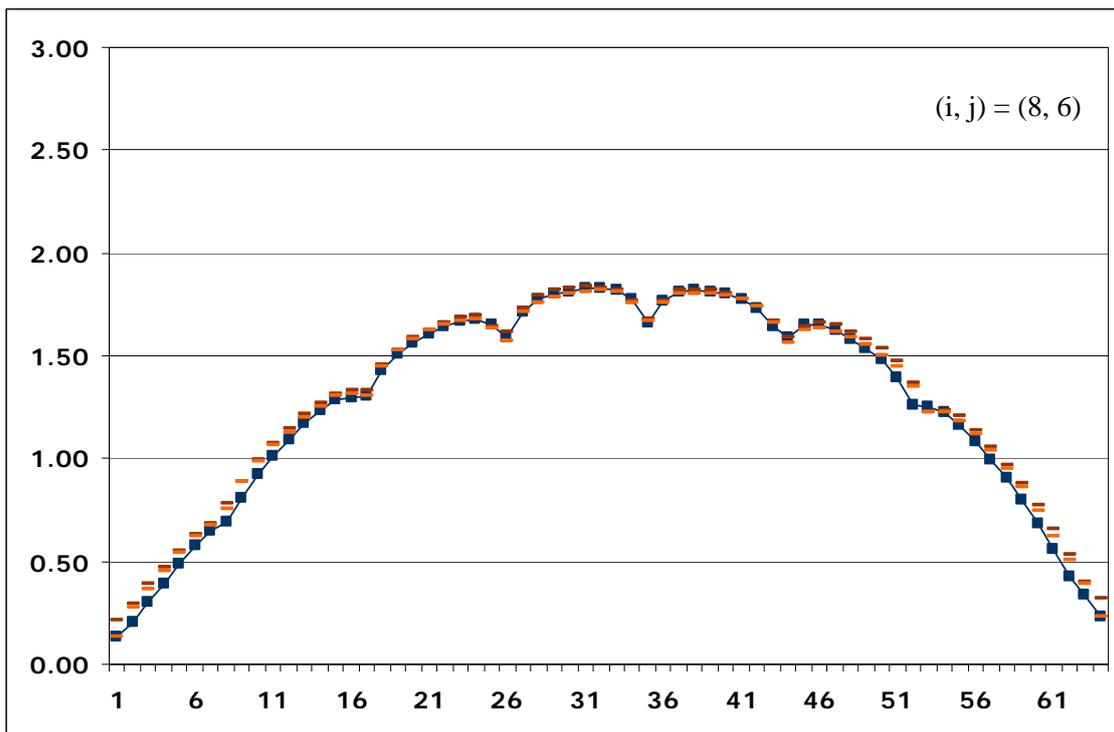
The following figures show the comparison of the measured and CYGNUS-calculated relative detector readings. Both are independently normalized so that the spatial average of the readings over all the measuring points becomes 1.0. Here in the figures:

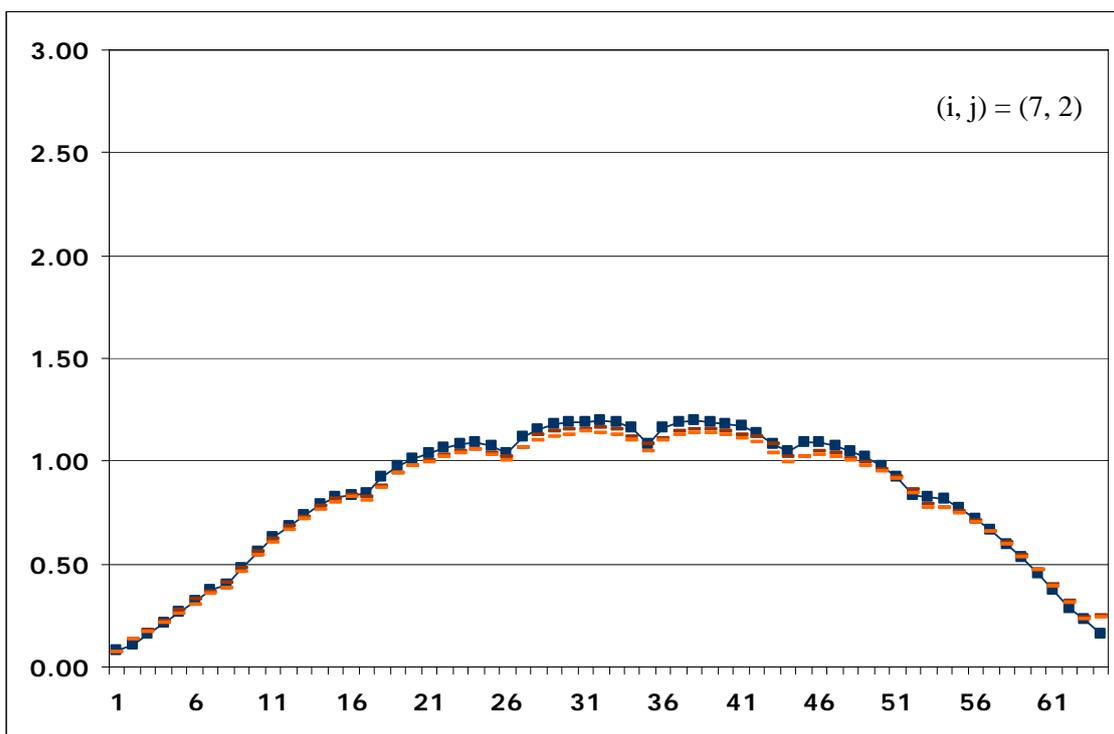
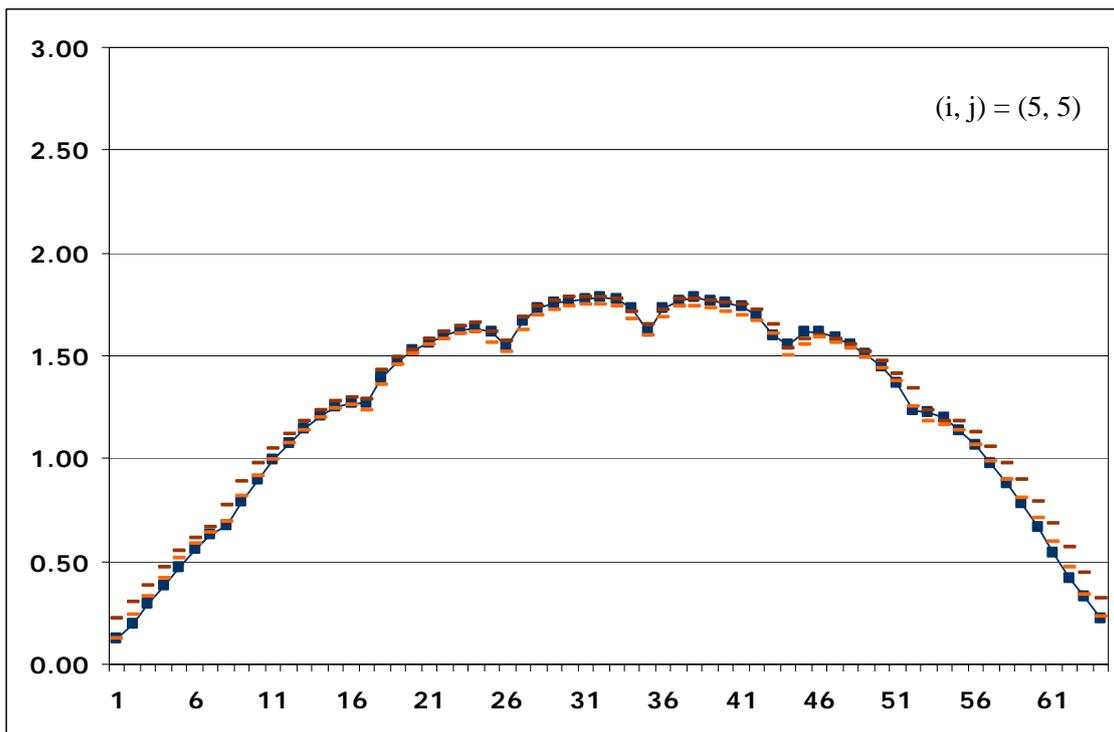
- : VNEM-calculated relative readings
- : Upper bound to the measured readings
- : Lower bound to the measured readings

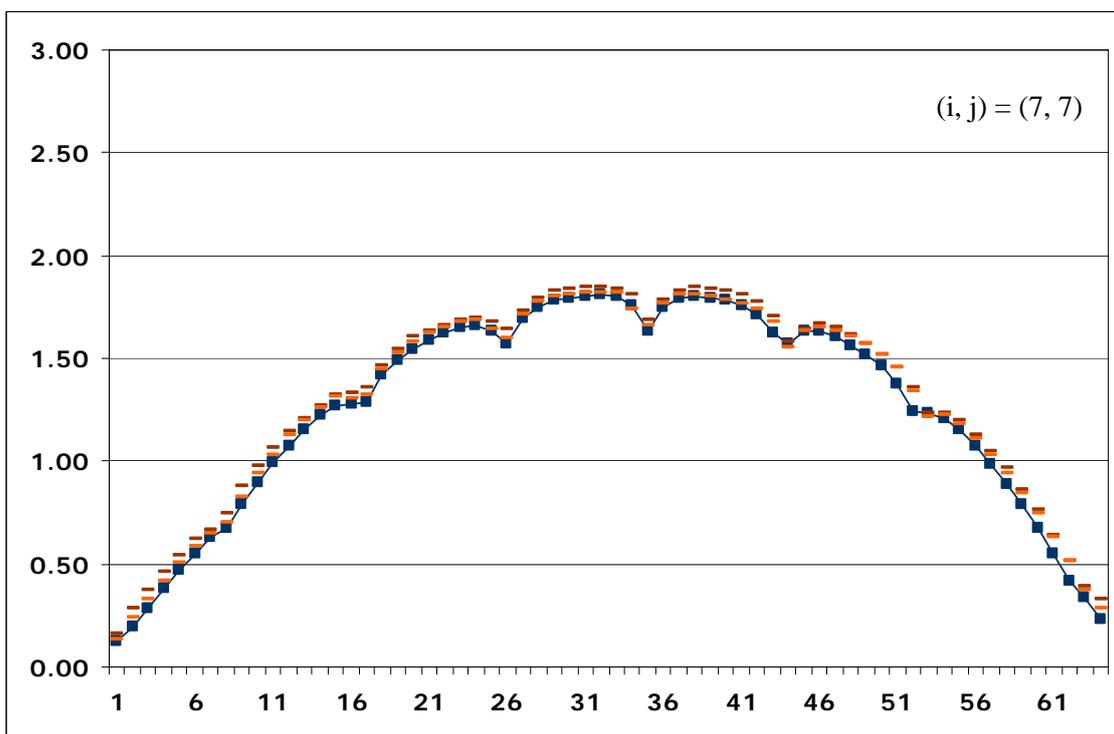
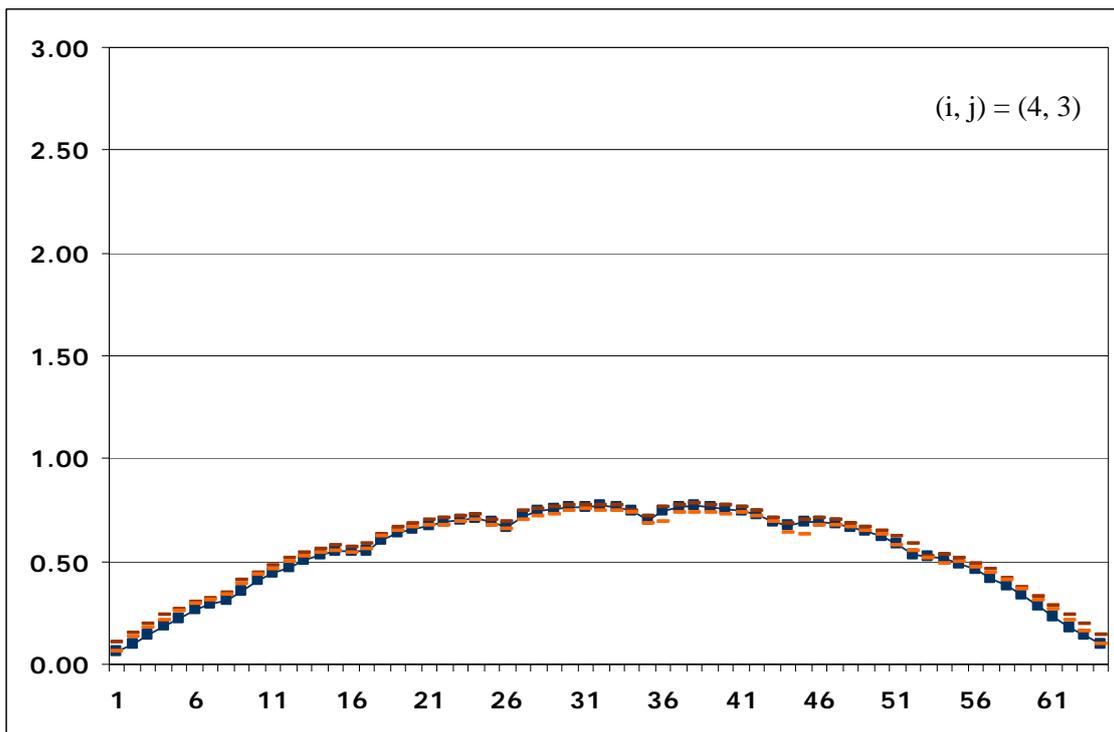
The upper / lower bounds of the measured readings are defined by the maximum / minimum of the readings of the assemblies at the octant-symmetric positions in the core. The representative of the octant-symmetric positions (i, j) in the core is taken from the north-north-east portion (shown in Fig.6.3).

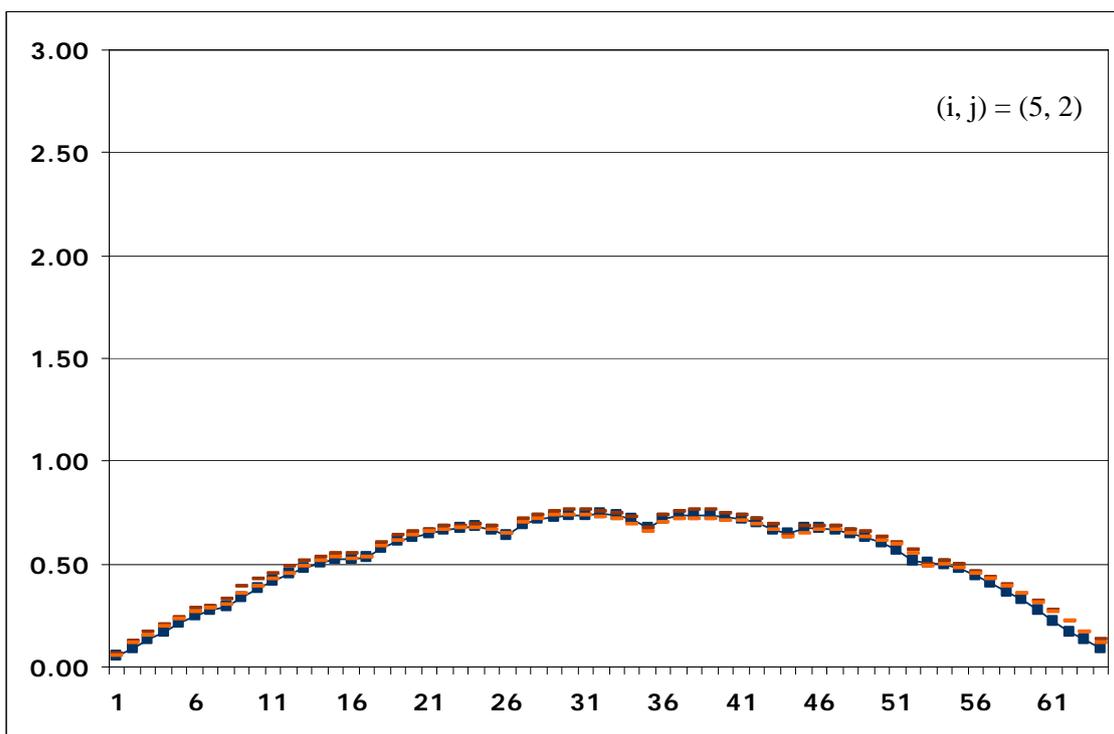
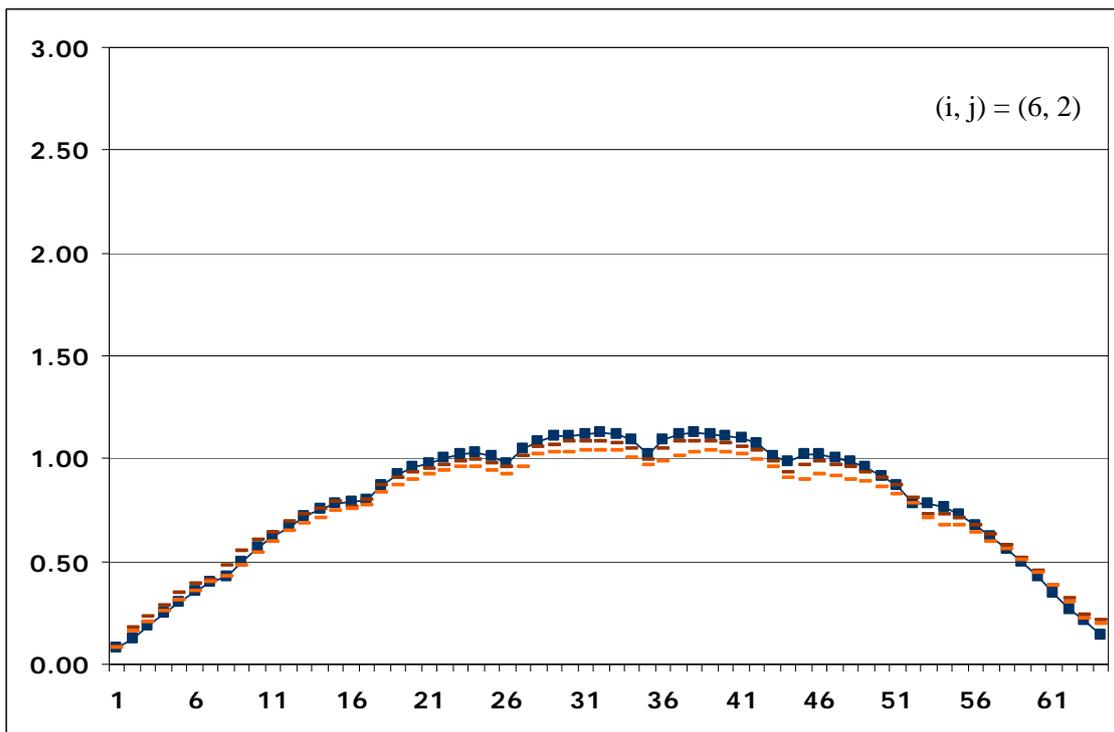
The horizontal axis indicates the axial measuring positions along a thimble that are numbered 1 through 64 from the top to the bottom of the core. The vertical axis indicates the relative detector readings in an arbitrary unit.

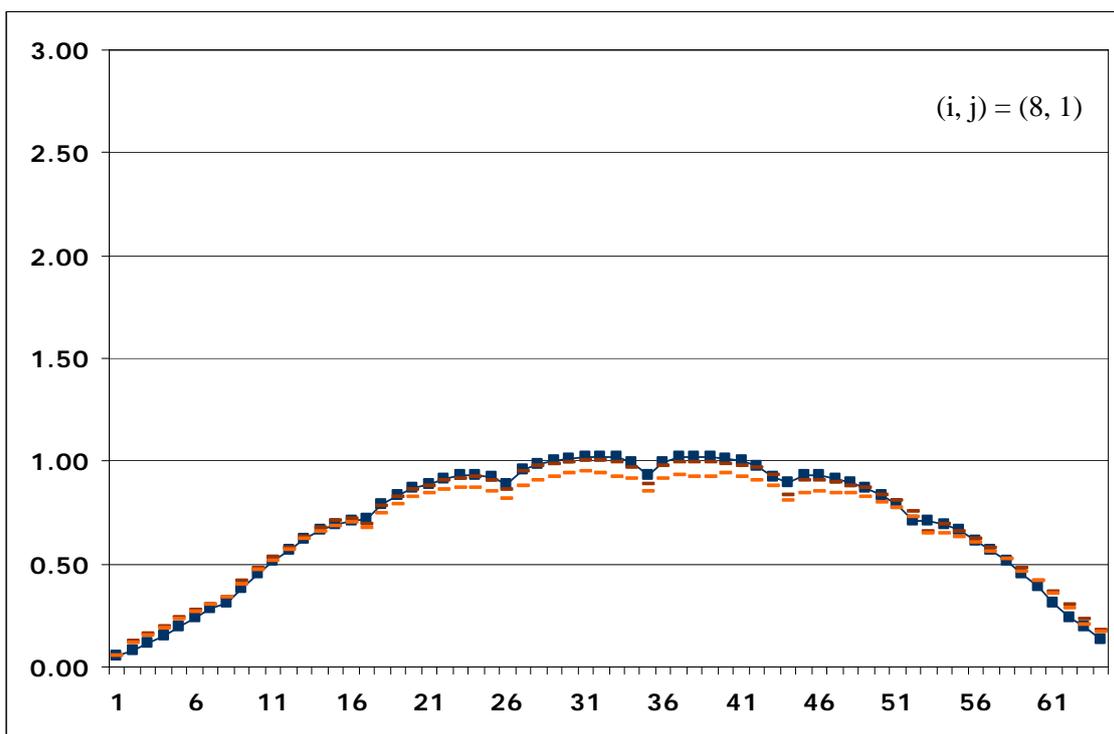
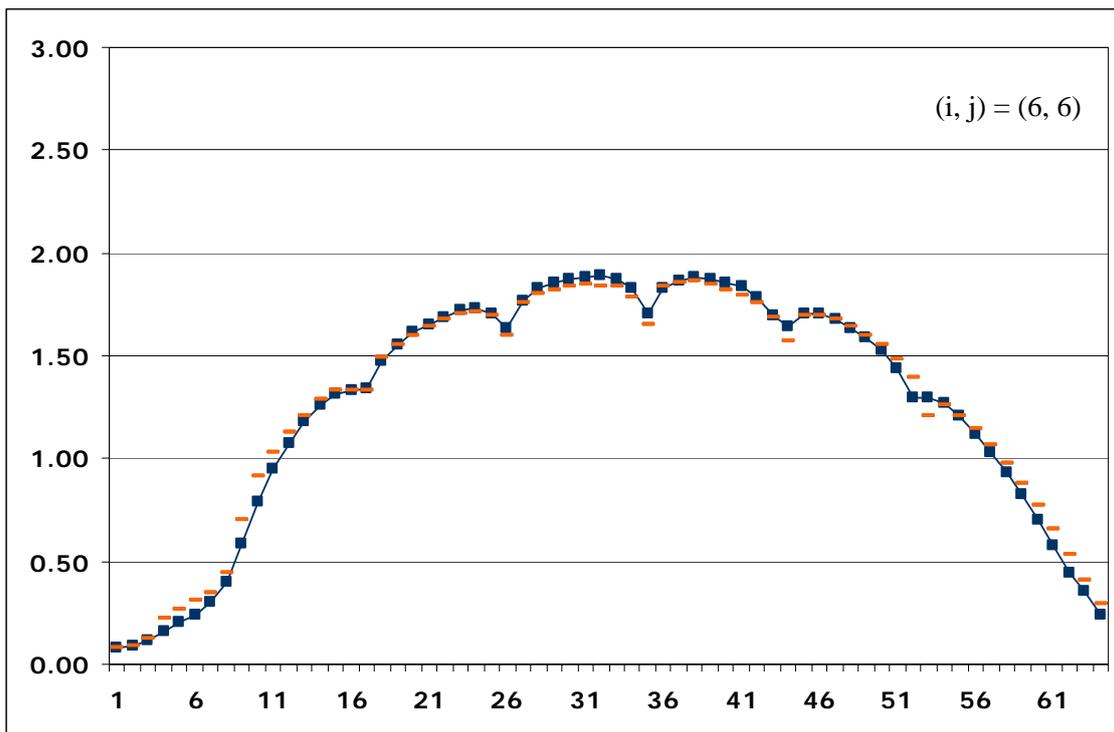


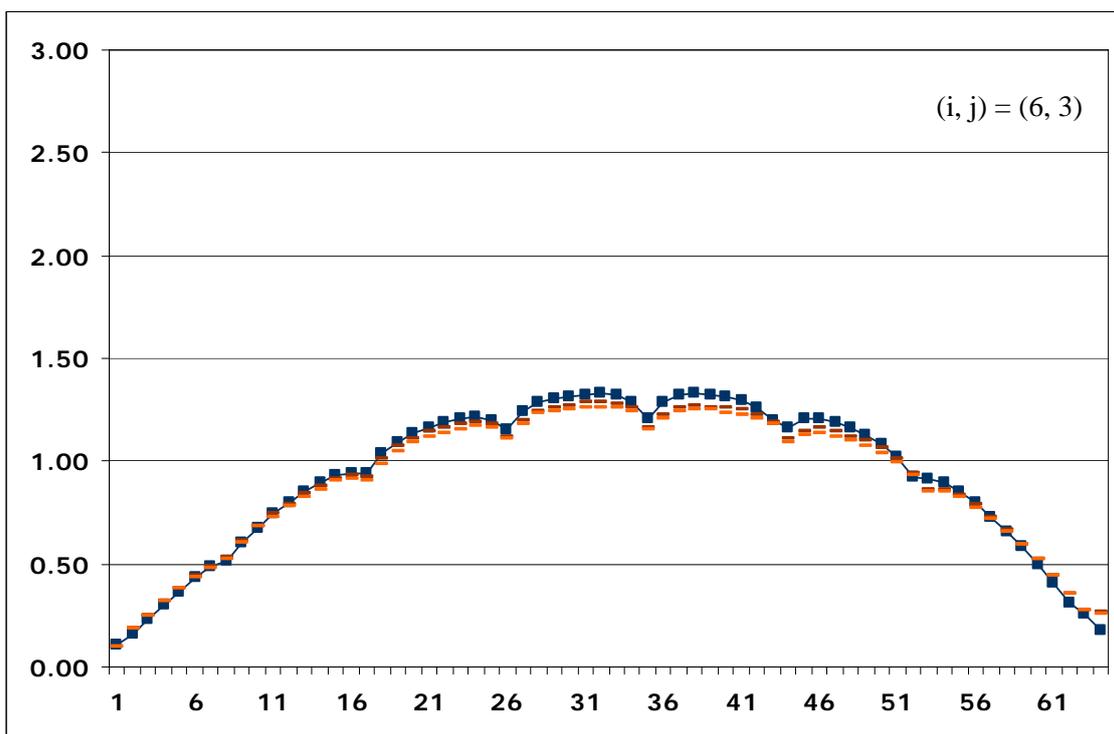
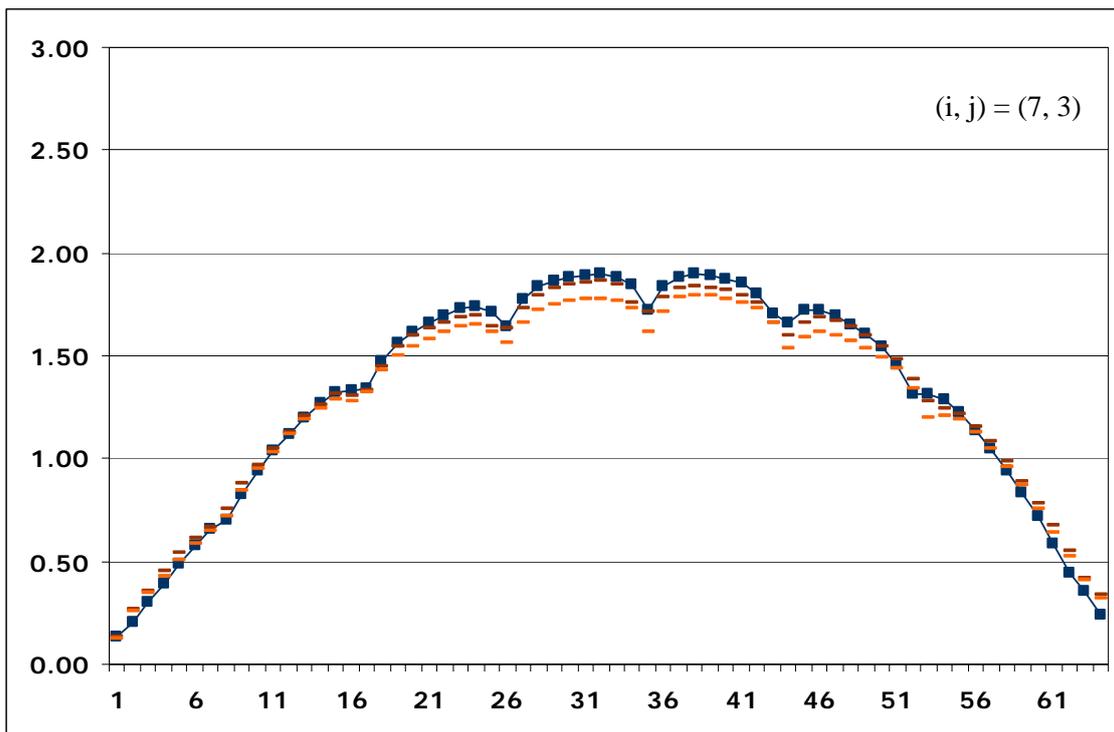


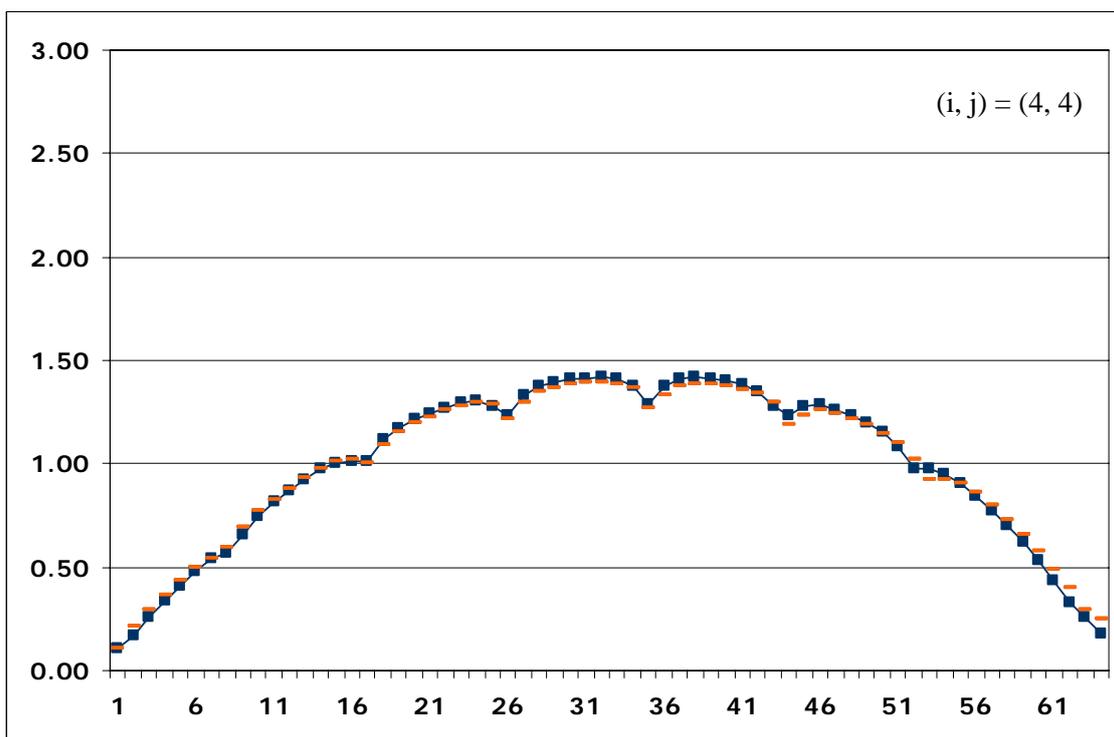
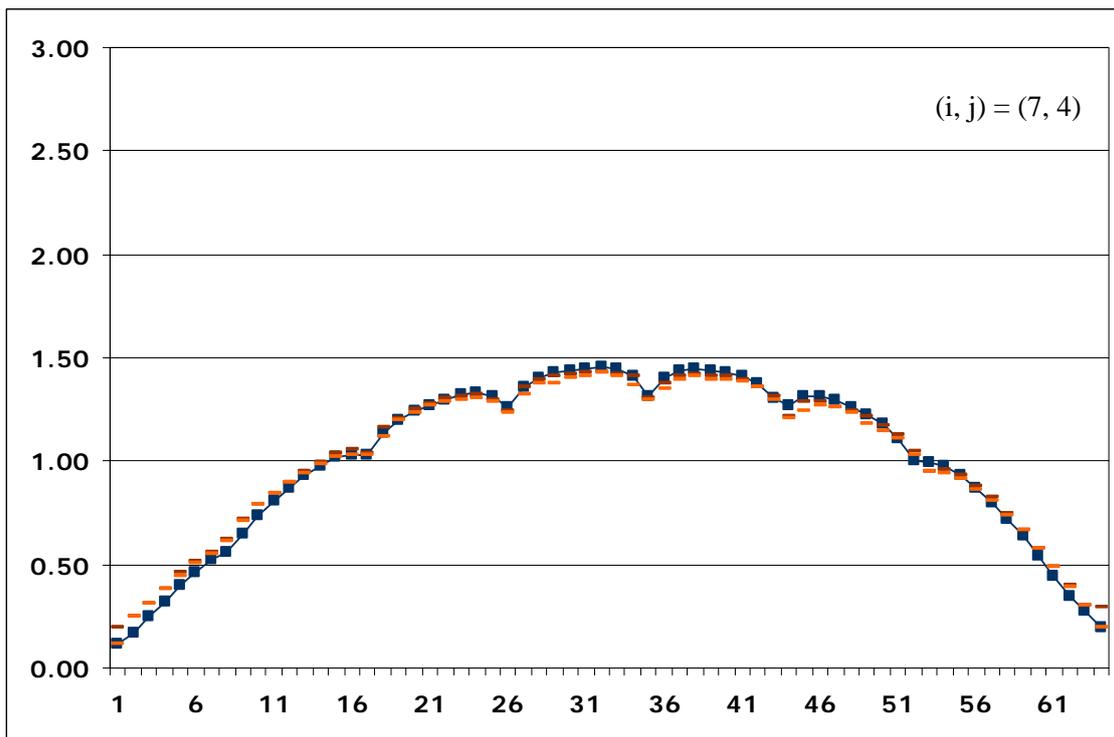


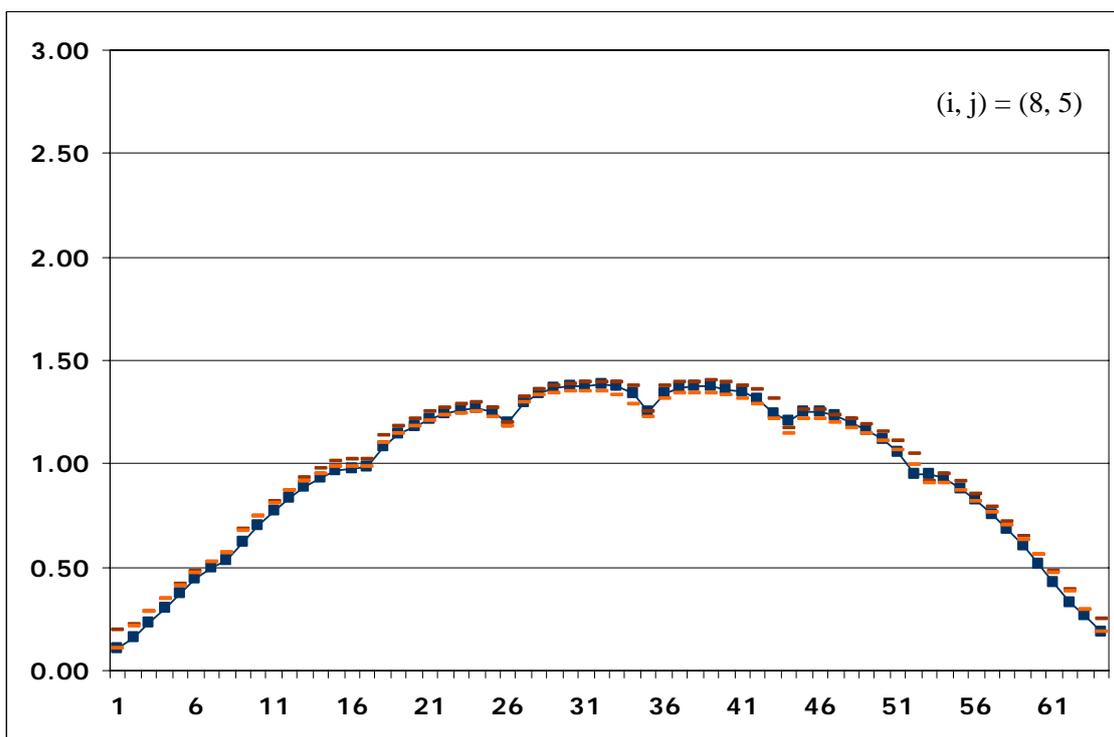
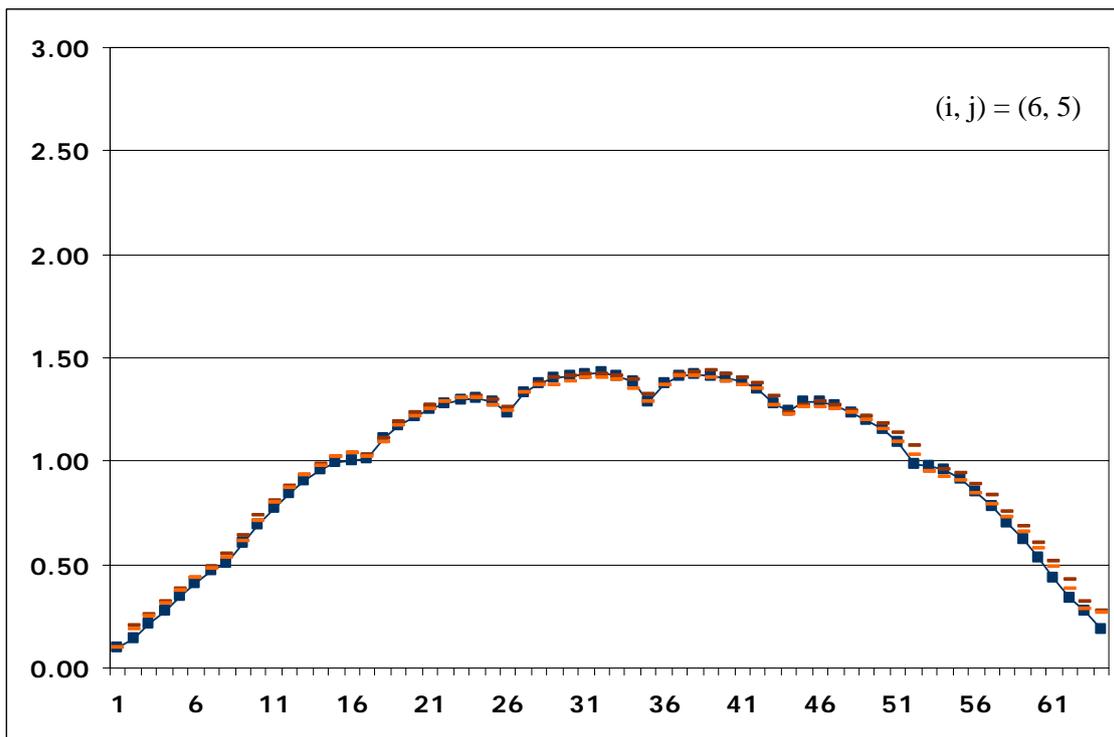


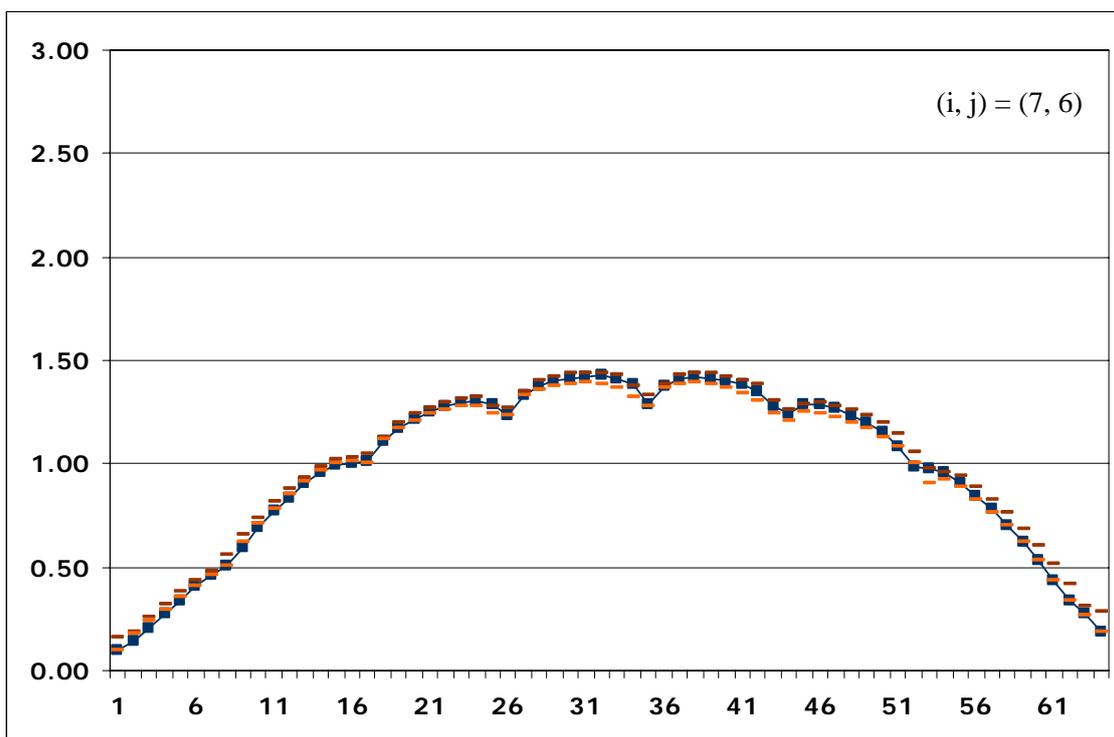
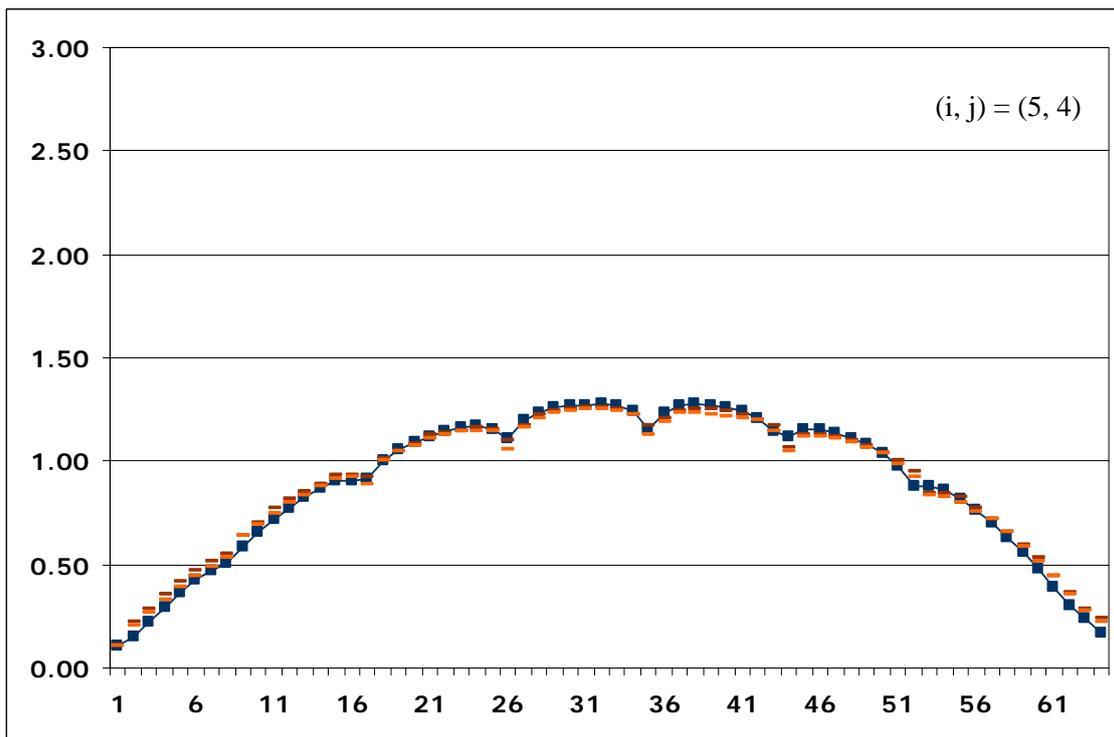


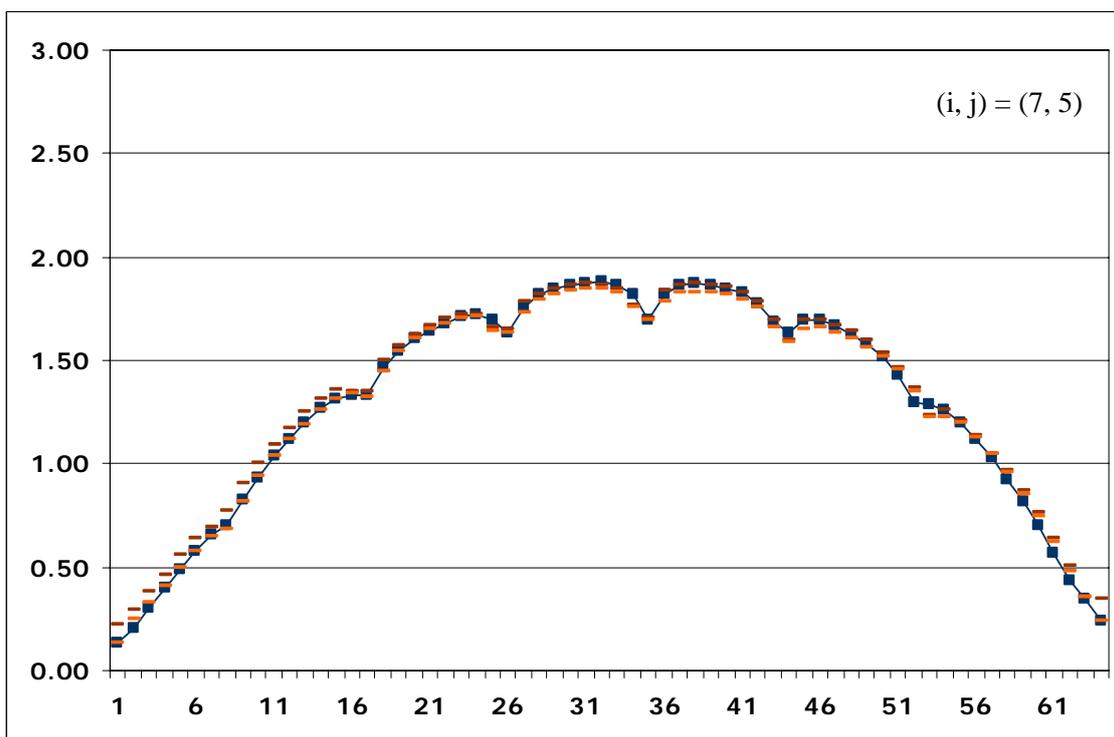
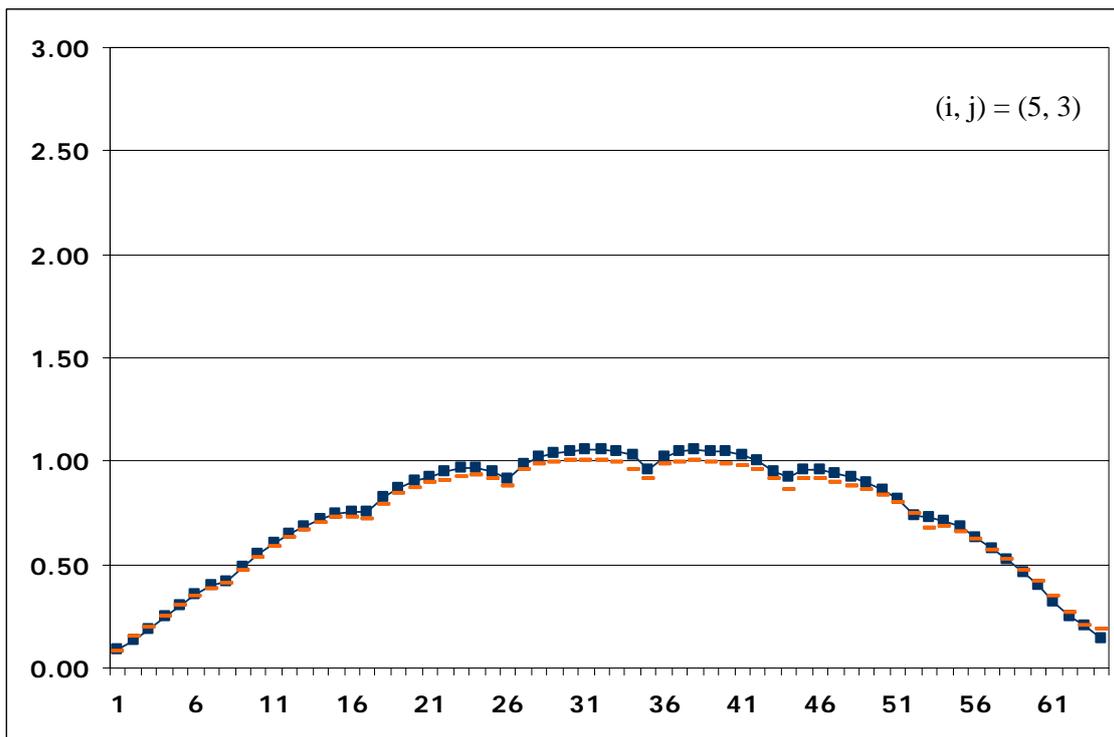


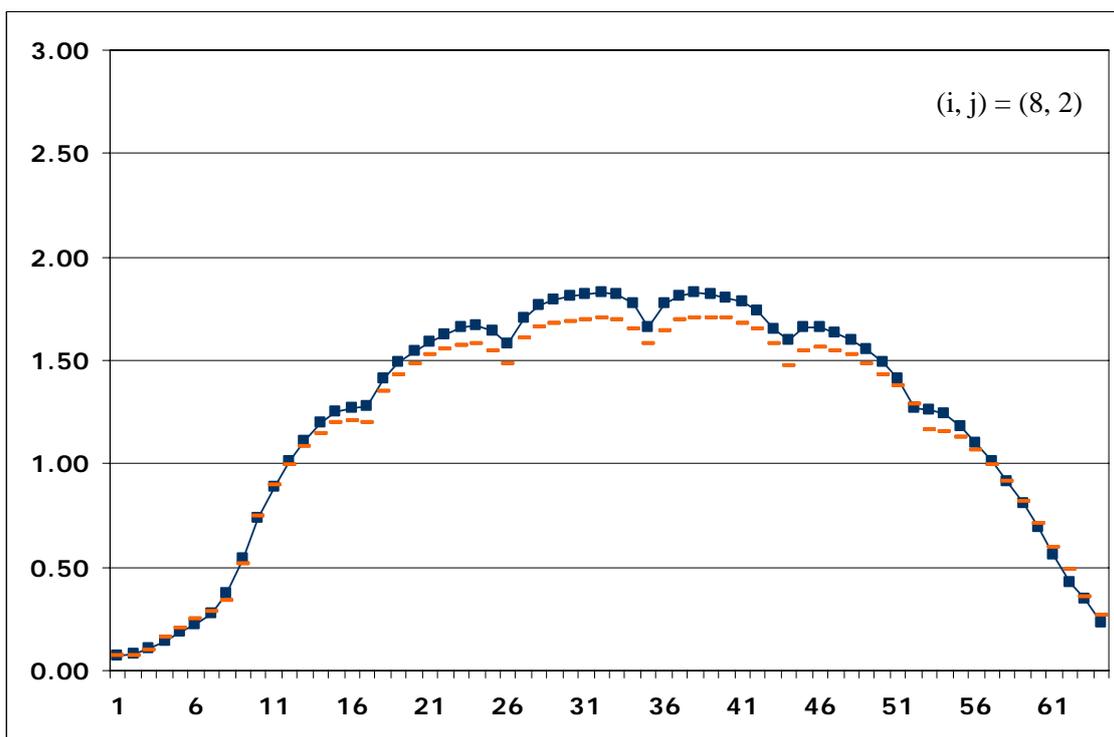
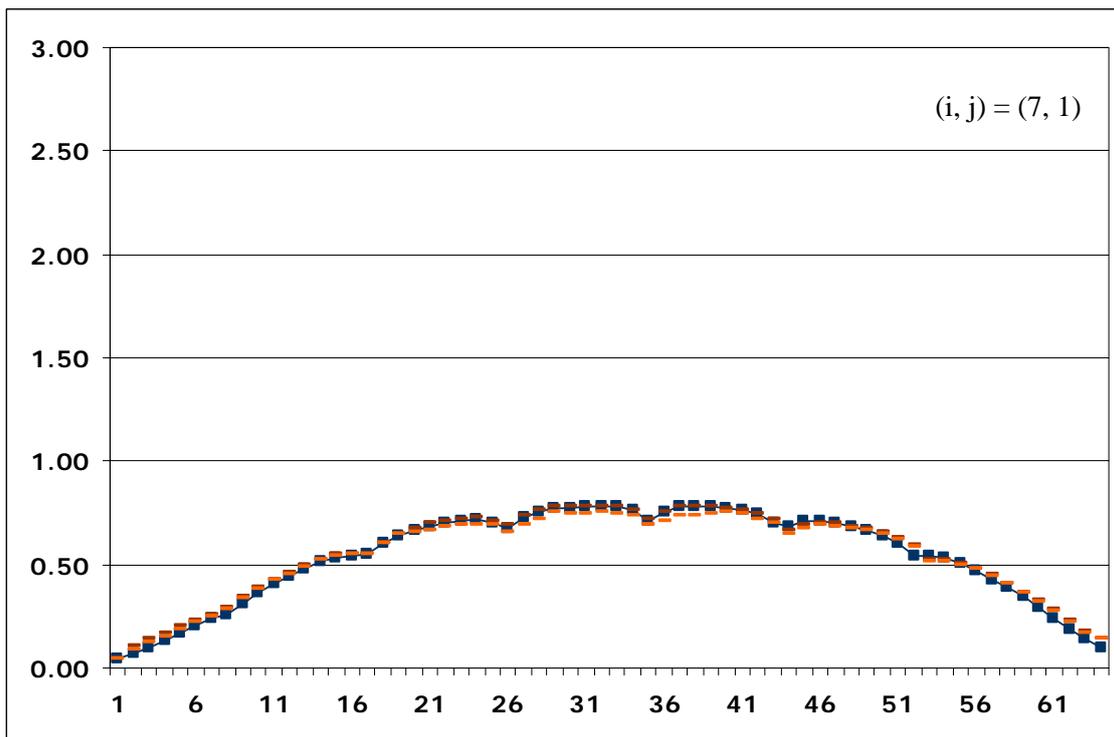












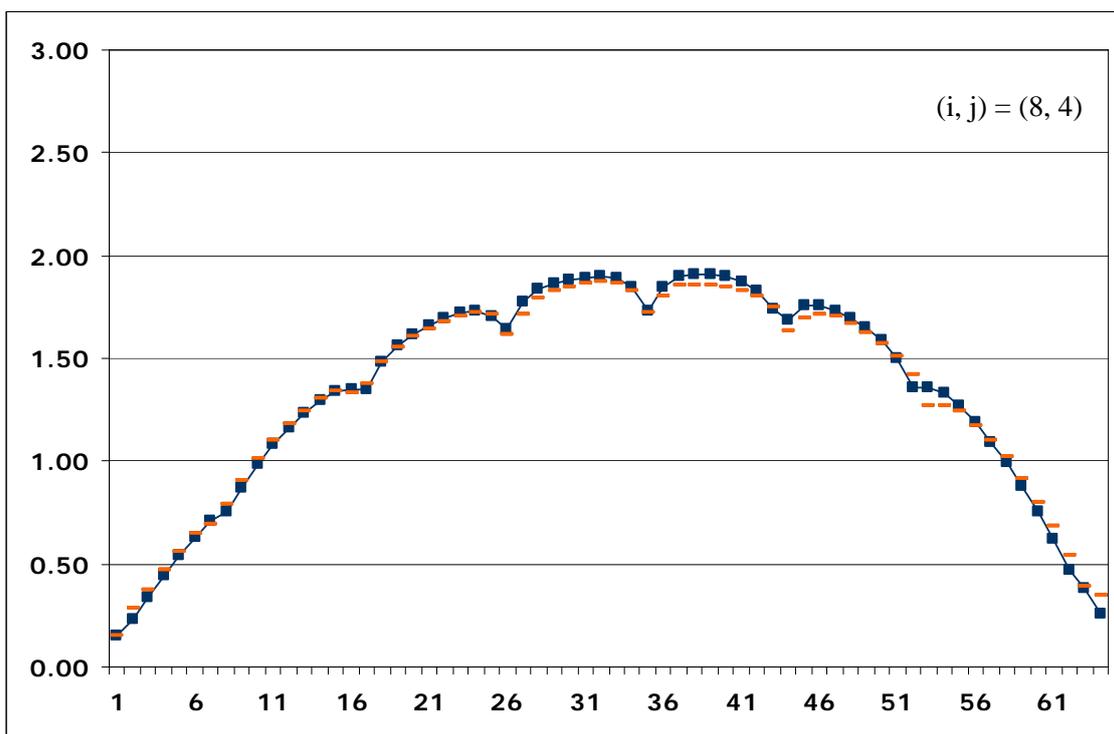
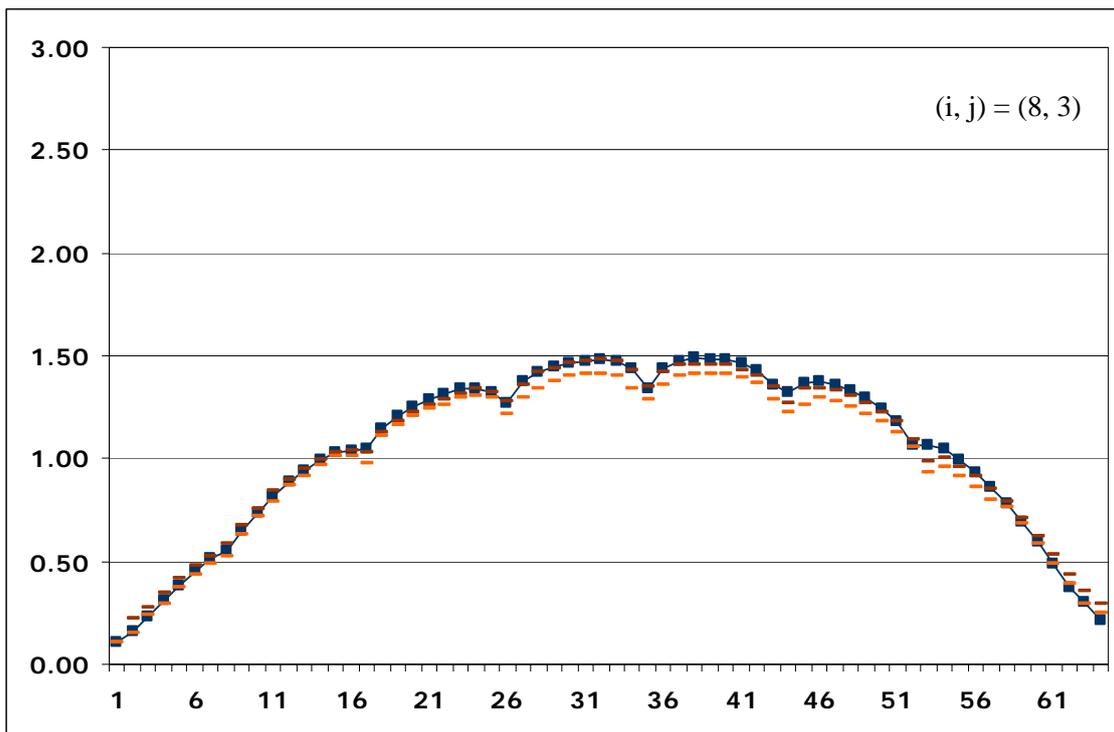
9.2 A.2 Map9

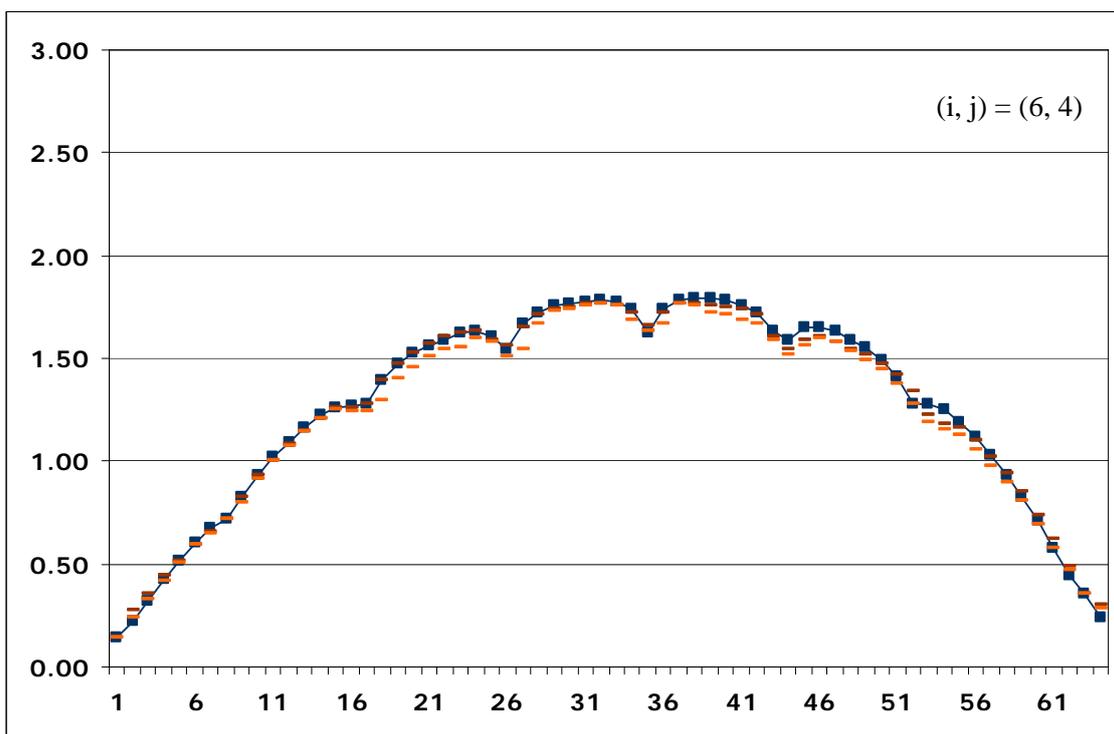
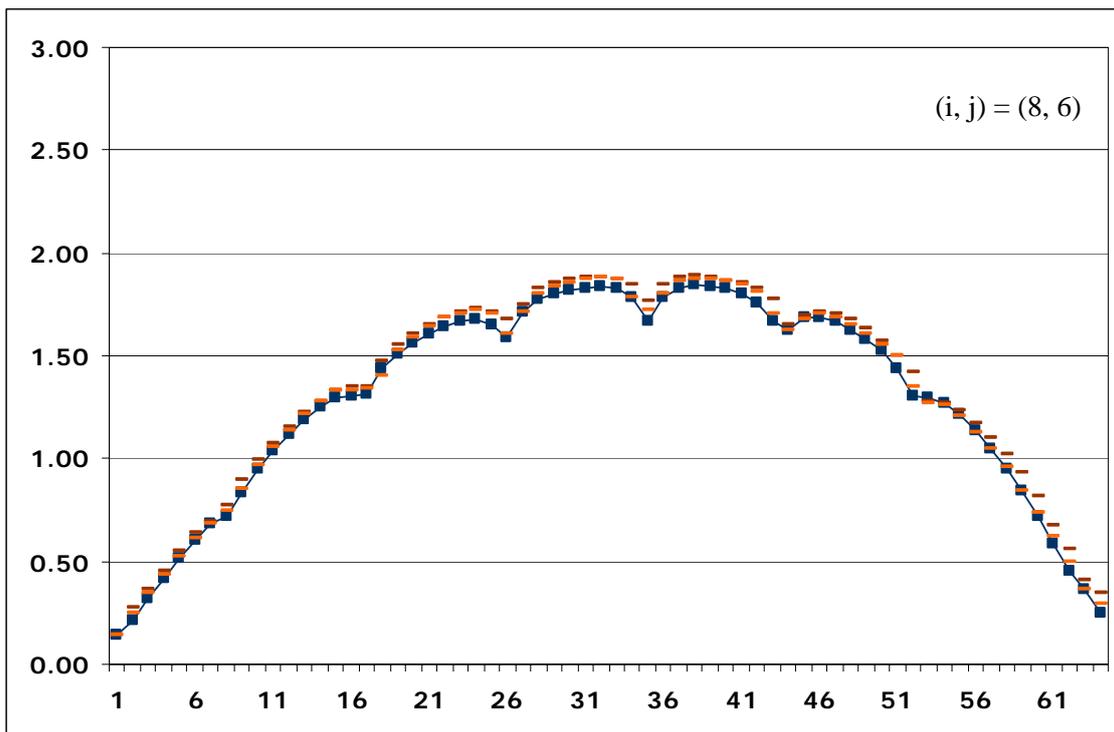
The following figures show the comparison of the measured and CYGNUS-calculated relative detector readings. Both are independently normalized so that the spatial average of the readings over all the measuring points becomes 1.0. Here in the figures:

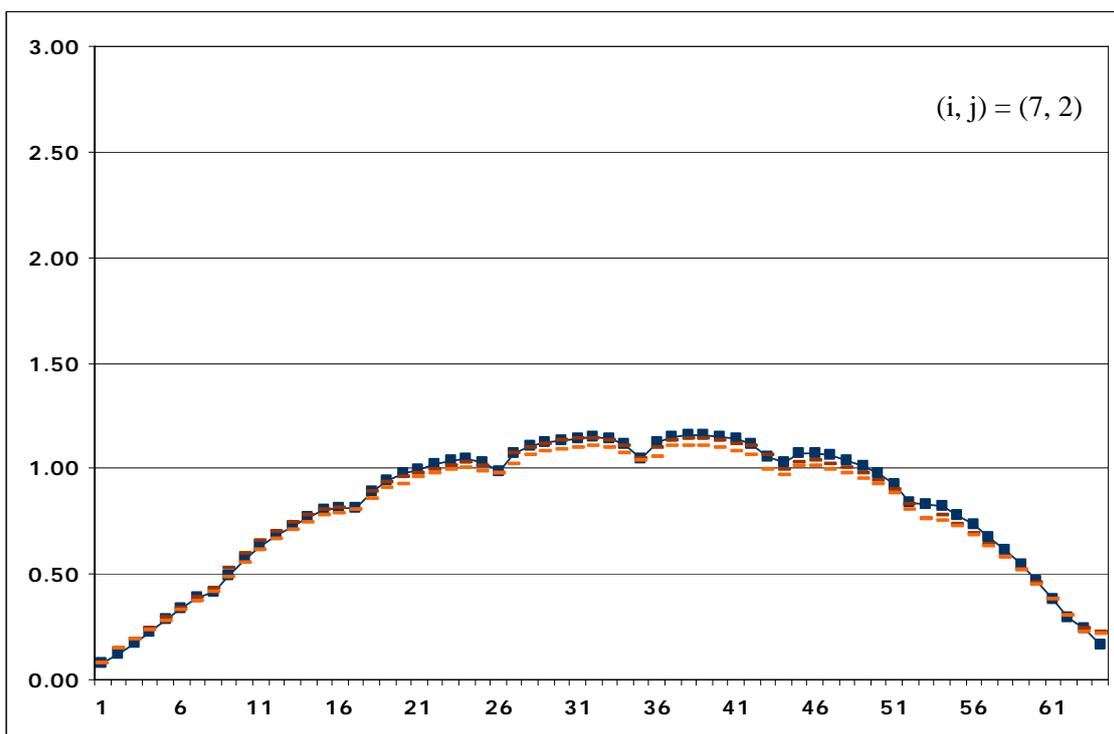
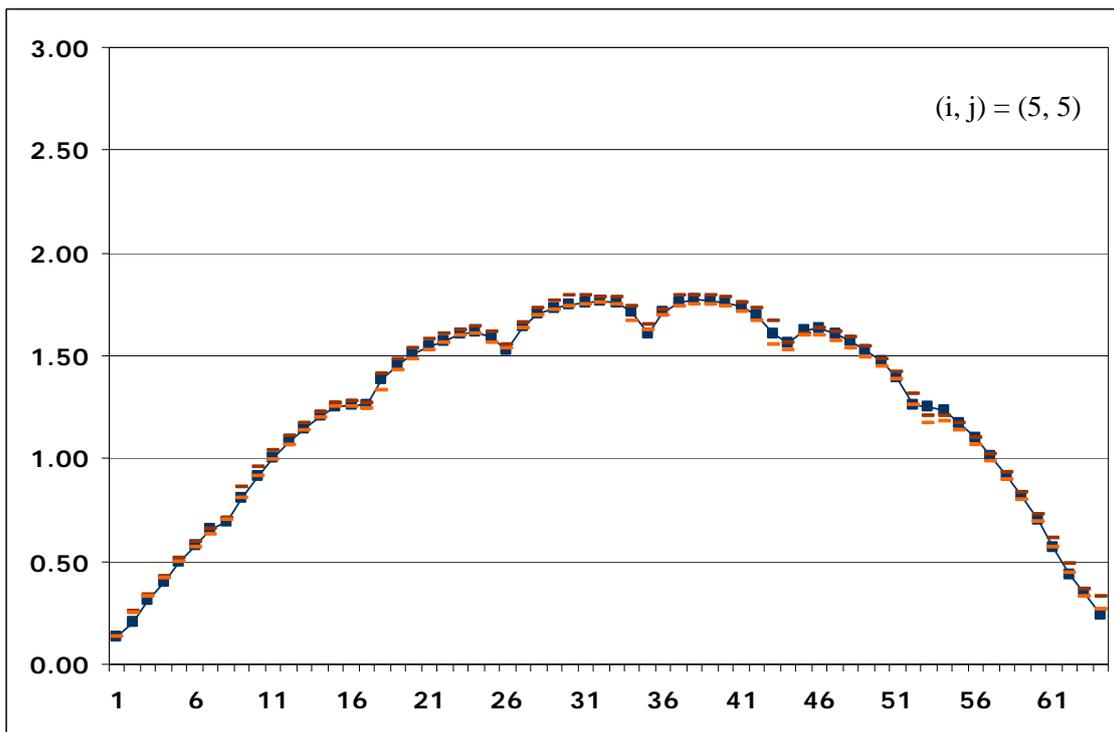
- : VNEM-calculated relative readings
- : Upper bound to the measured readings
- : Lower bound to the measured readings

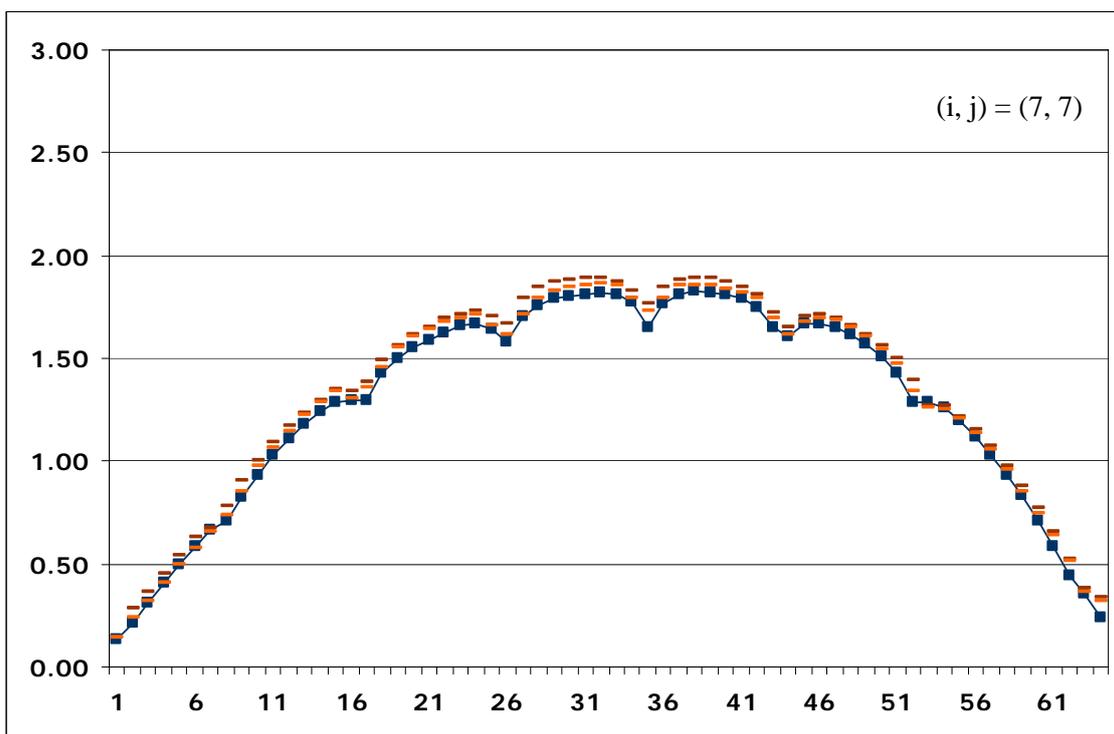
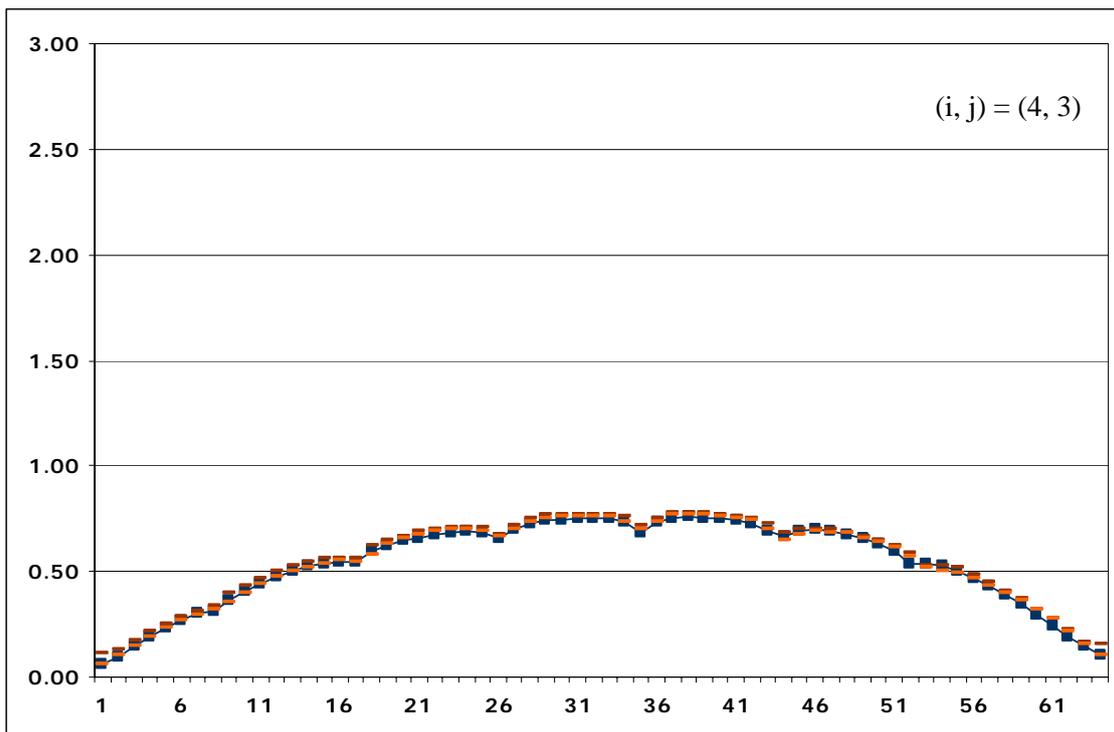
The upper / lower bounds of the measured readings are defined by the maximum / minimum of the readings of the assemblies at the octant-symmetric positions in the core. The representative of the octant-symmetric positions (i, j) in the core is taken from the north-north-east portion (shown in Fig.1.5.2).

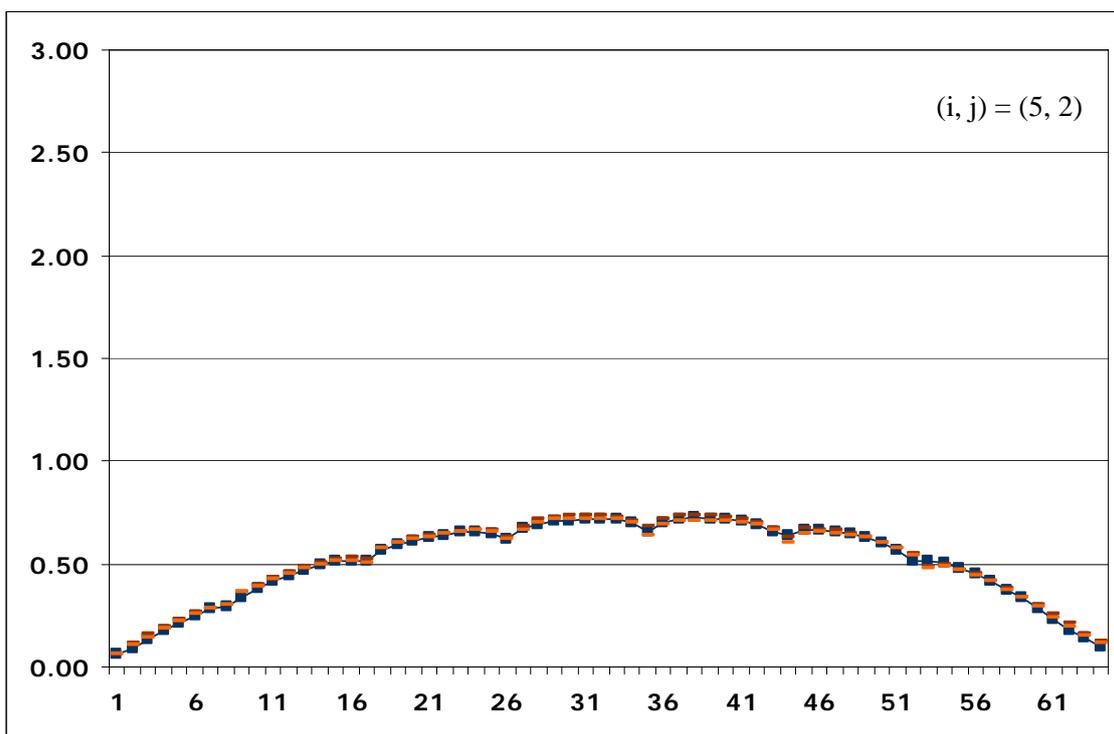
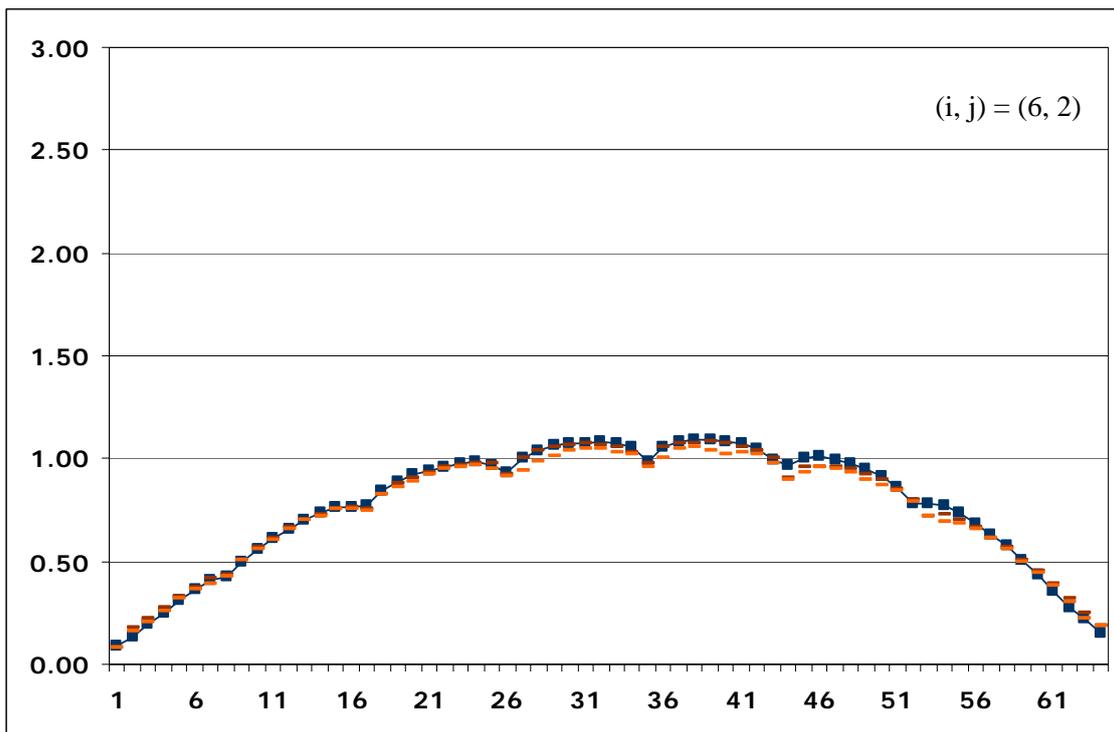
The horizontal axis indicates the axial measuring positions along a thimble that are numbered 1 through 64 from the top to the bottom of the core. The vertical axis indicates the relative detector readings in an arbitrary unit.

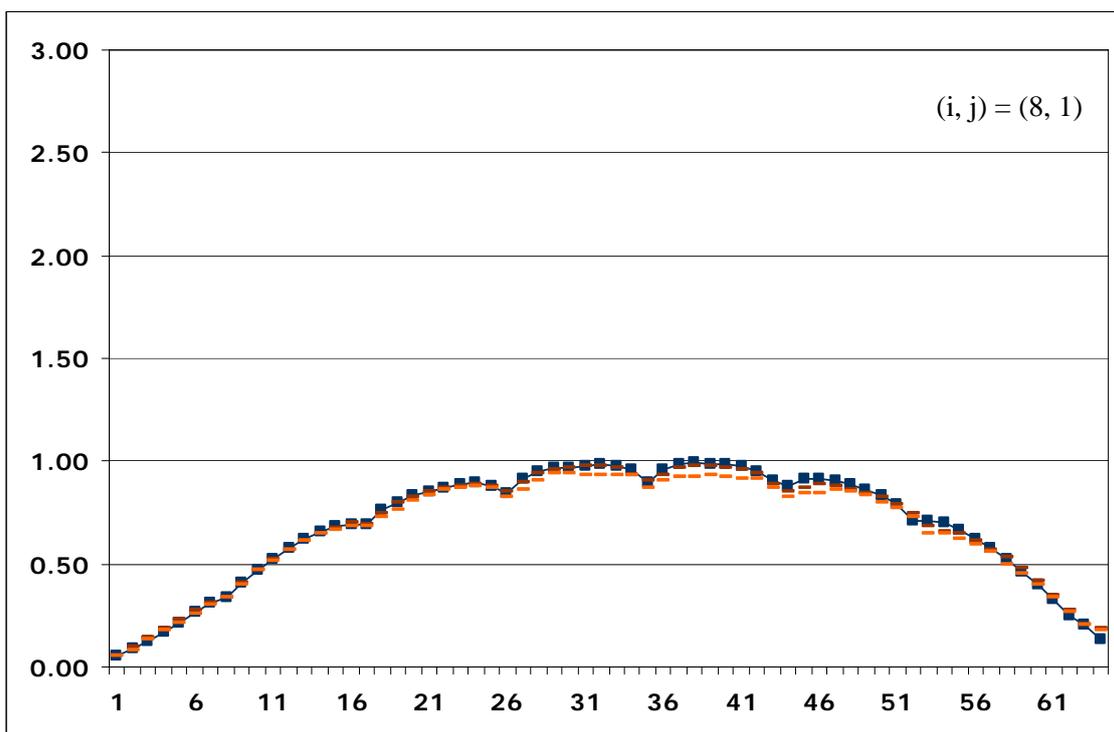
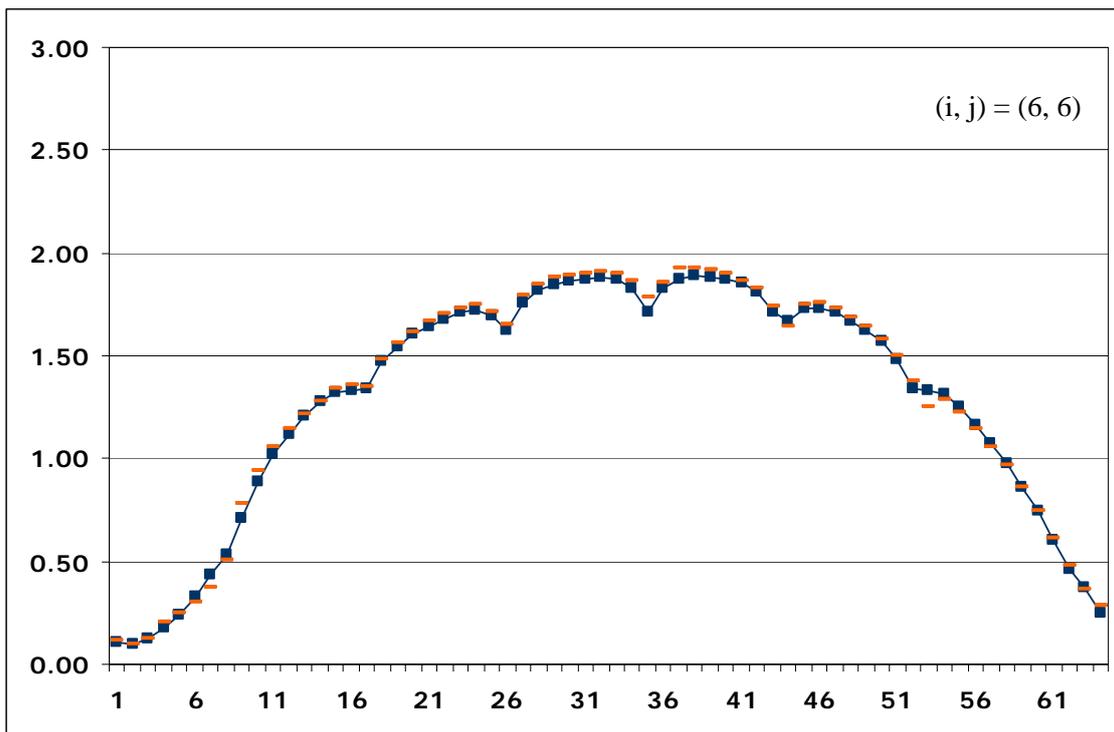


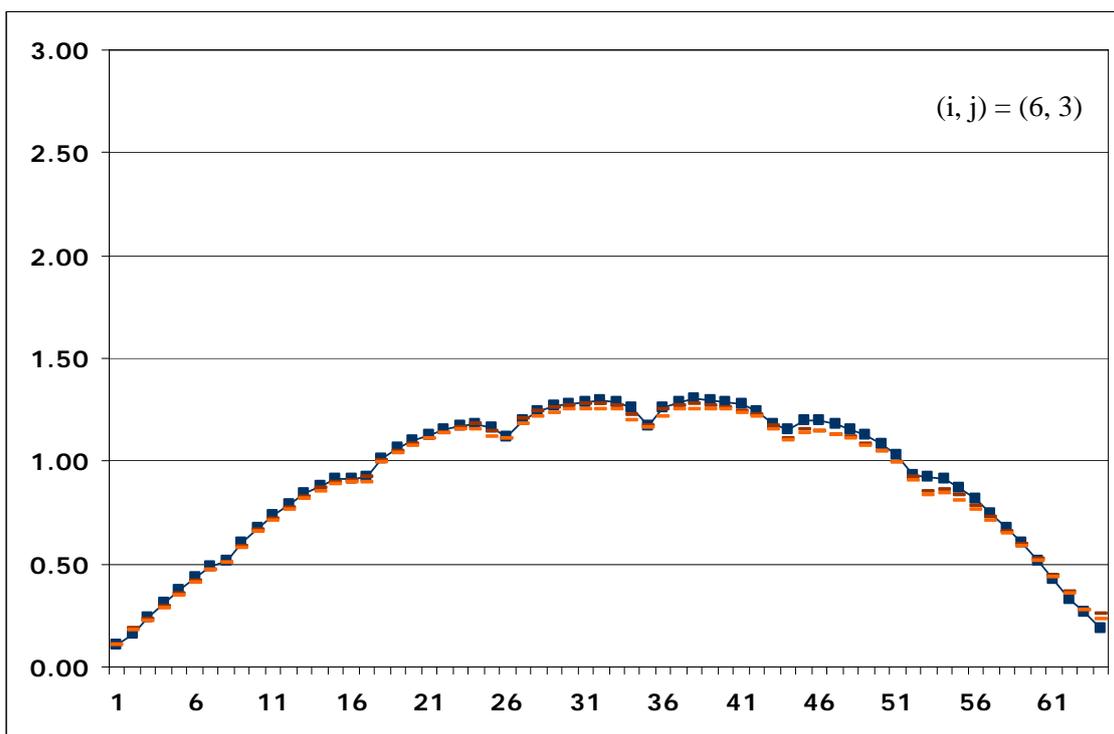
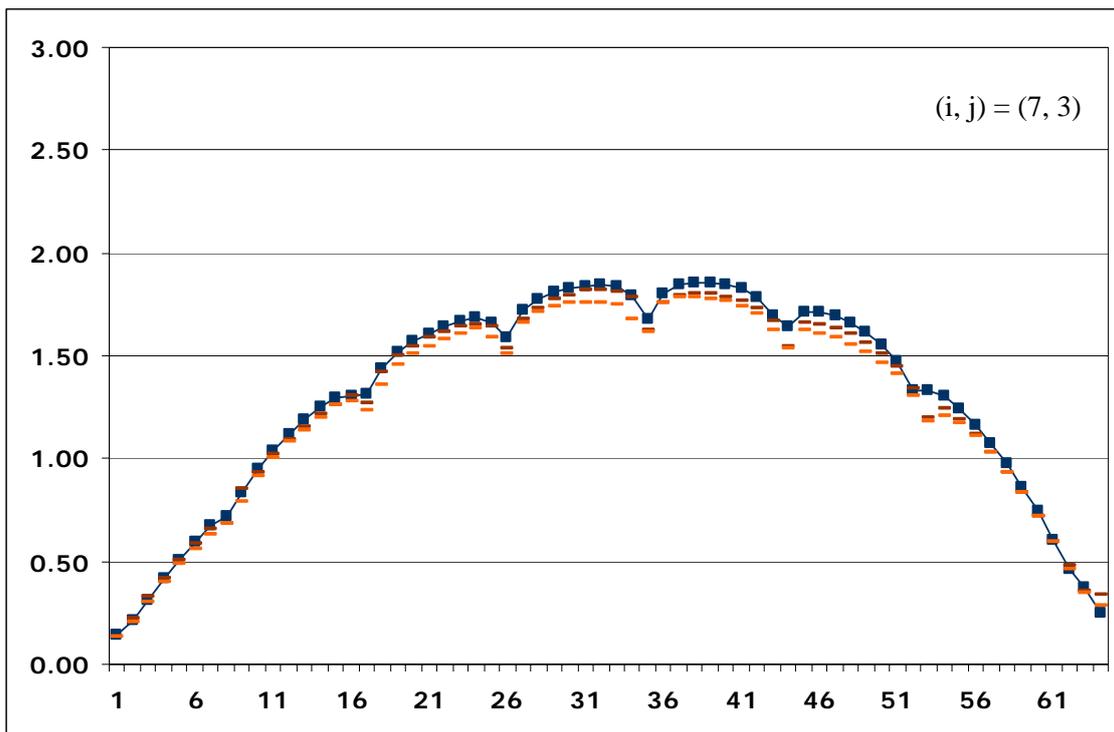


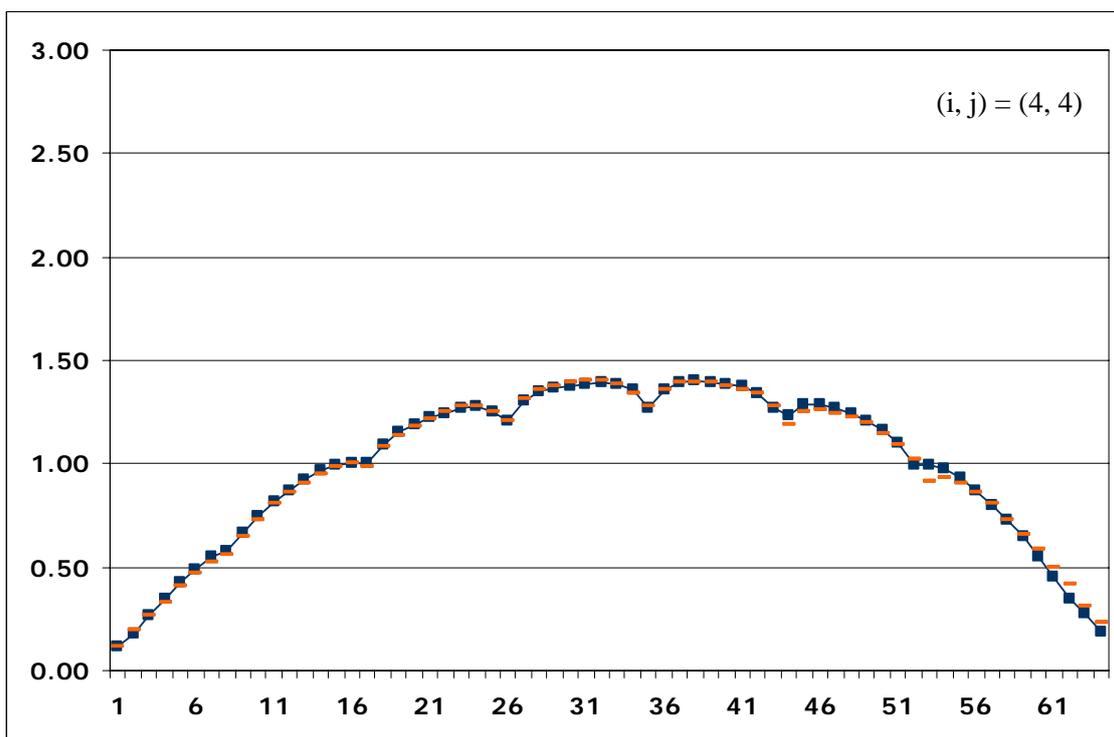
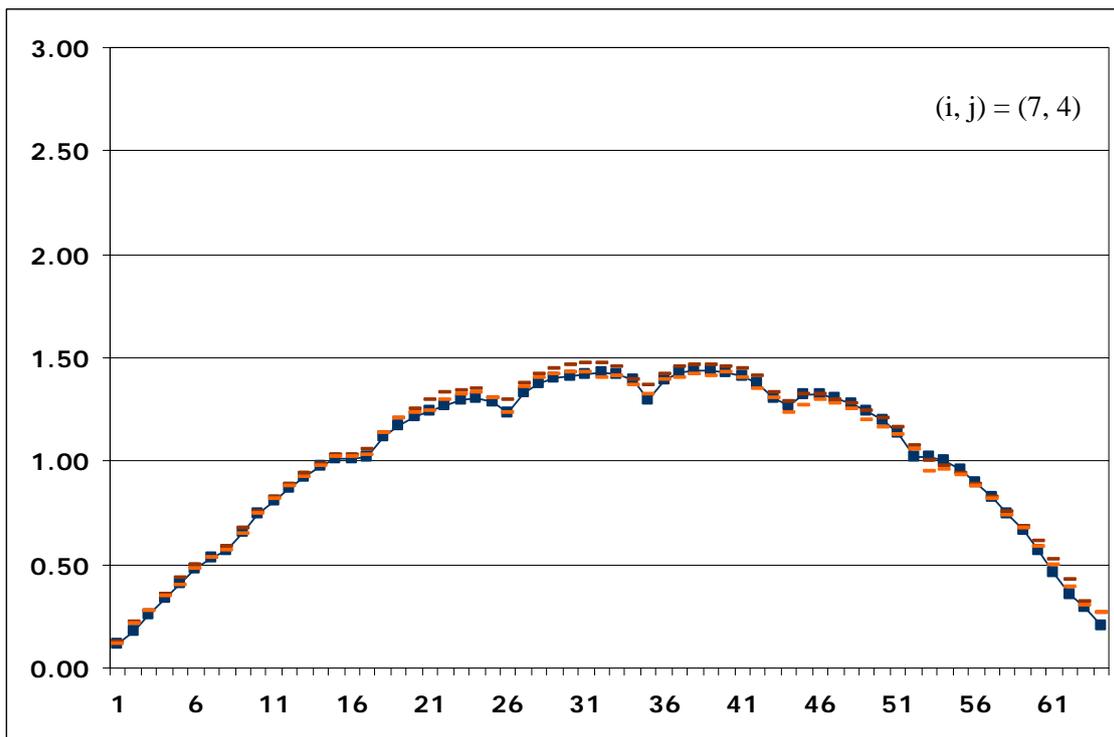


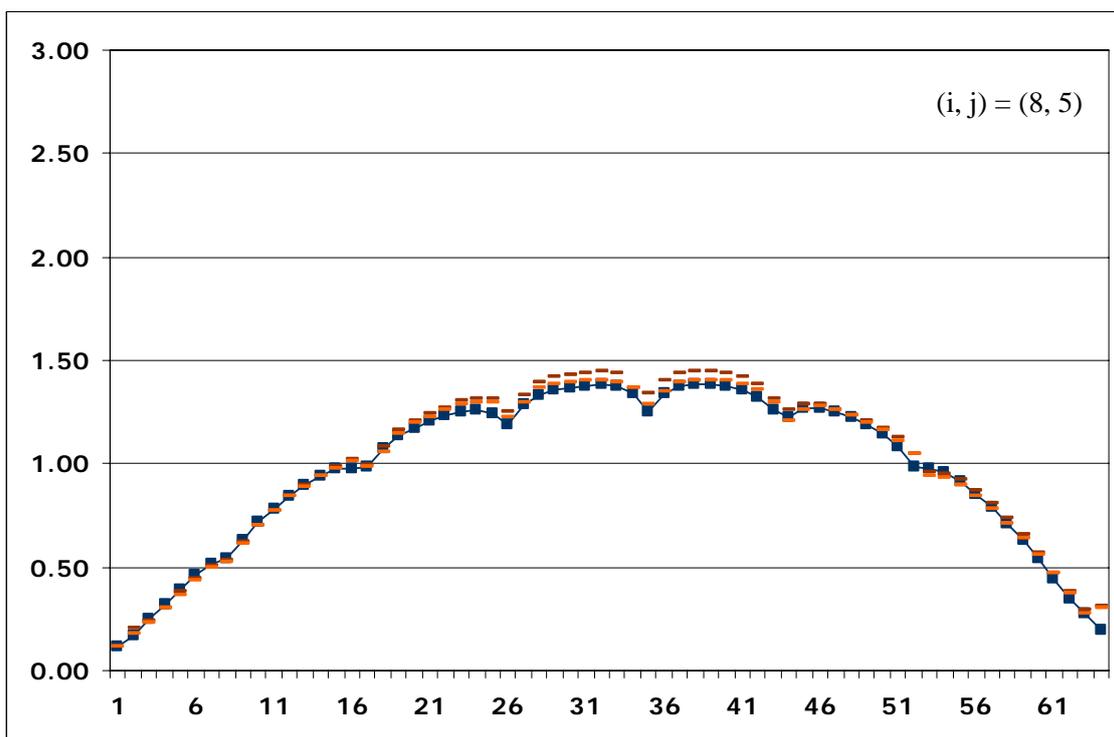
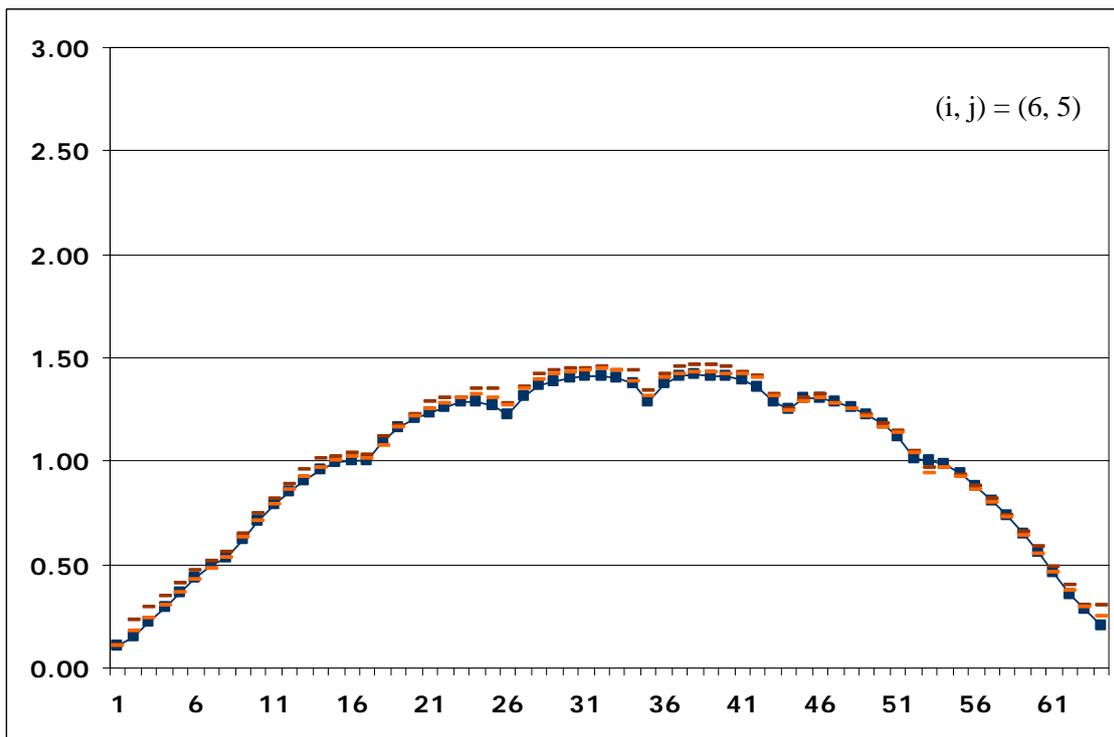


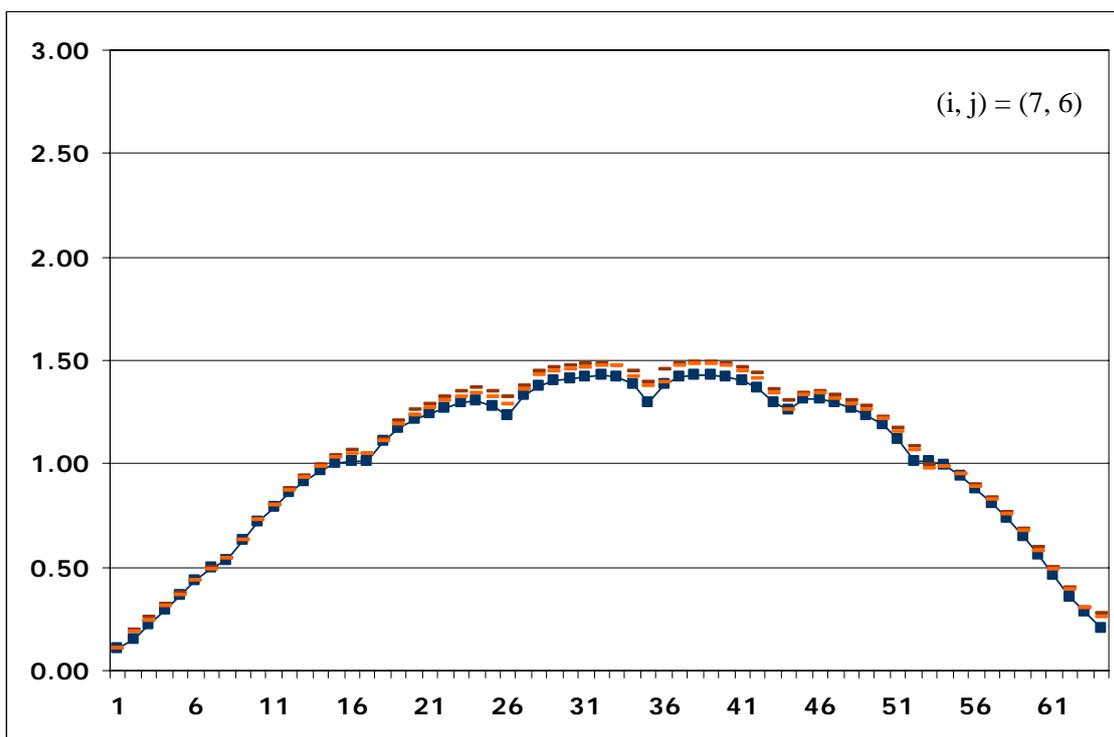
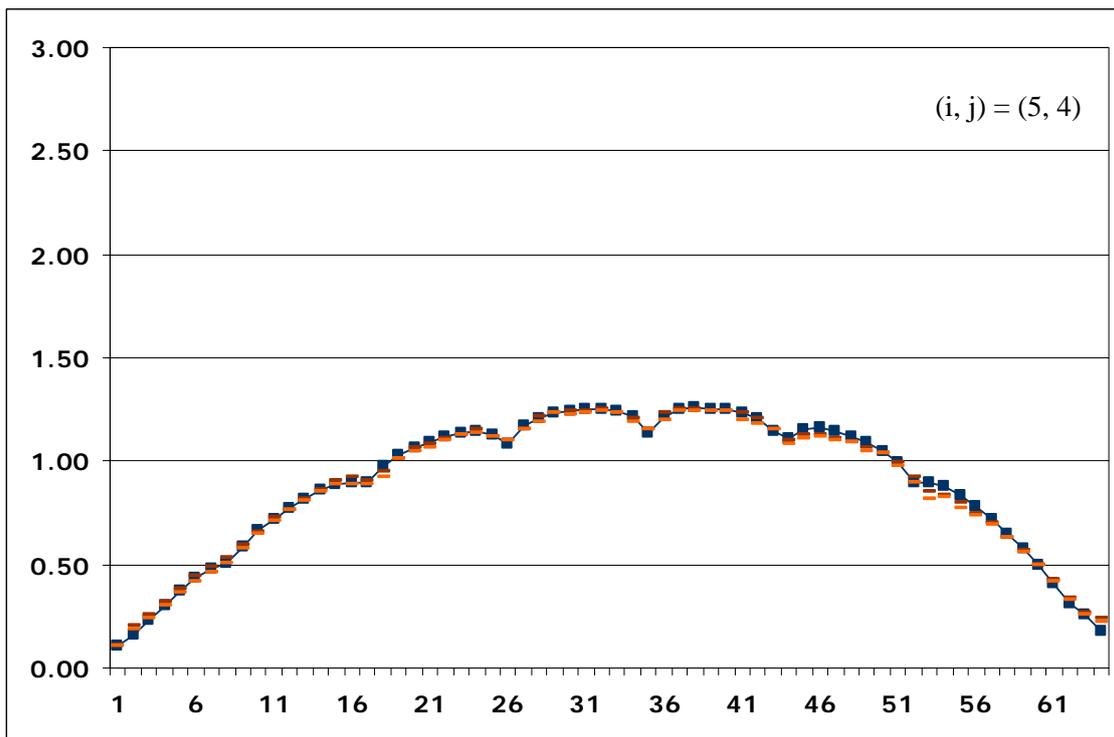


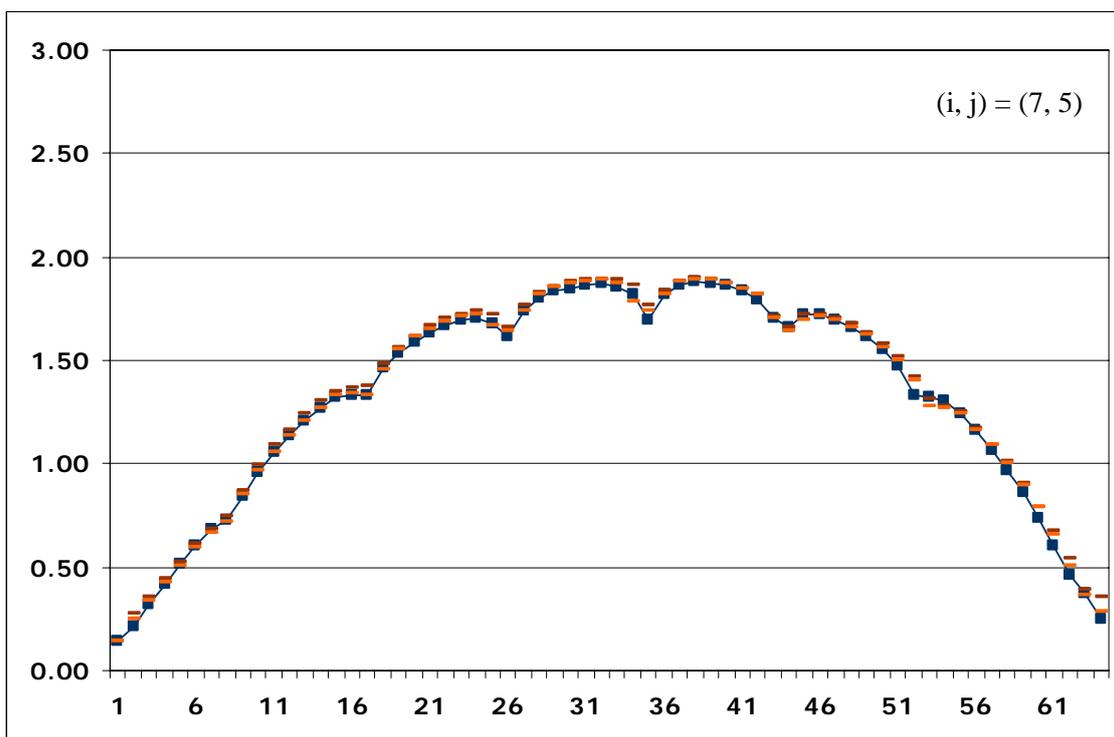
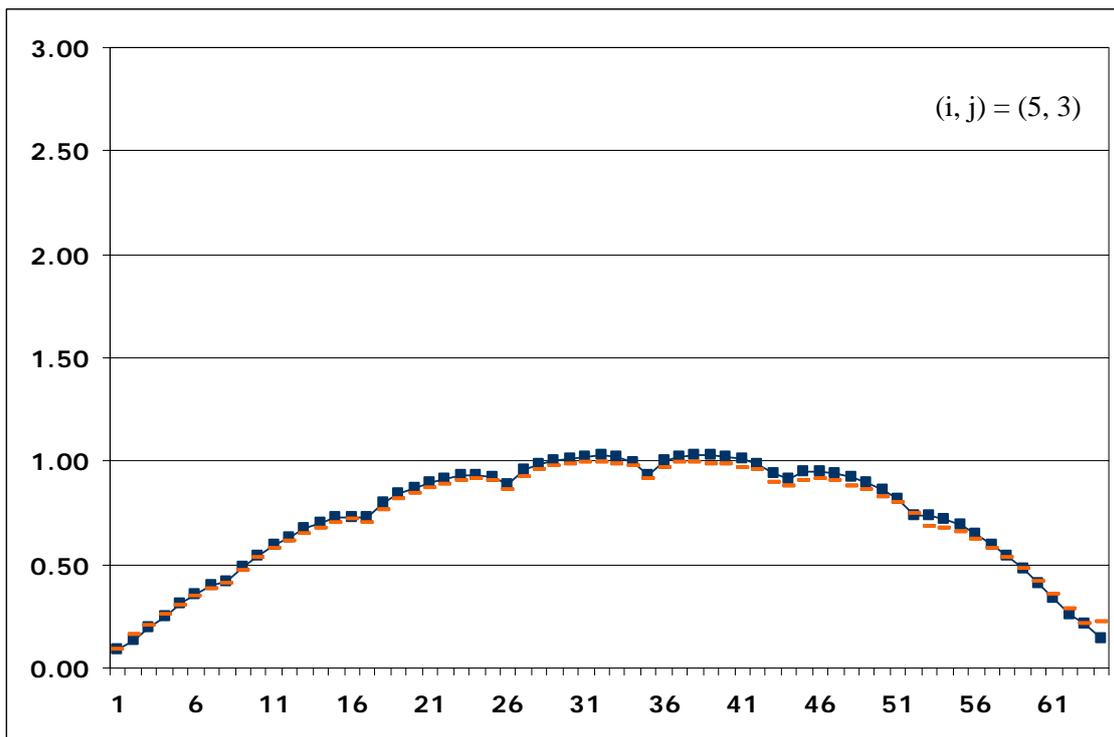


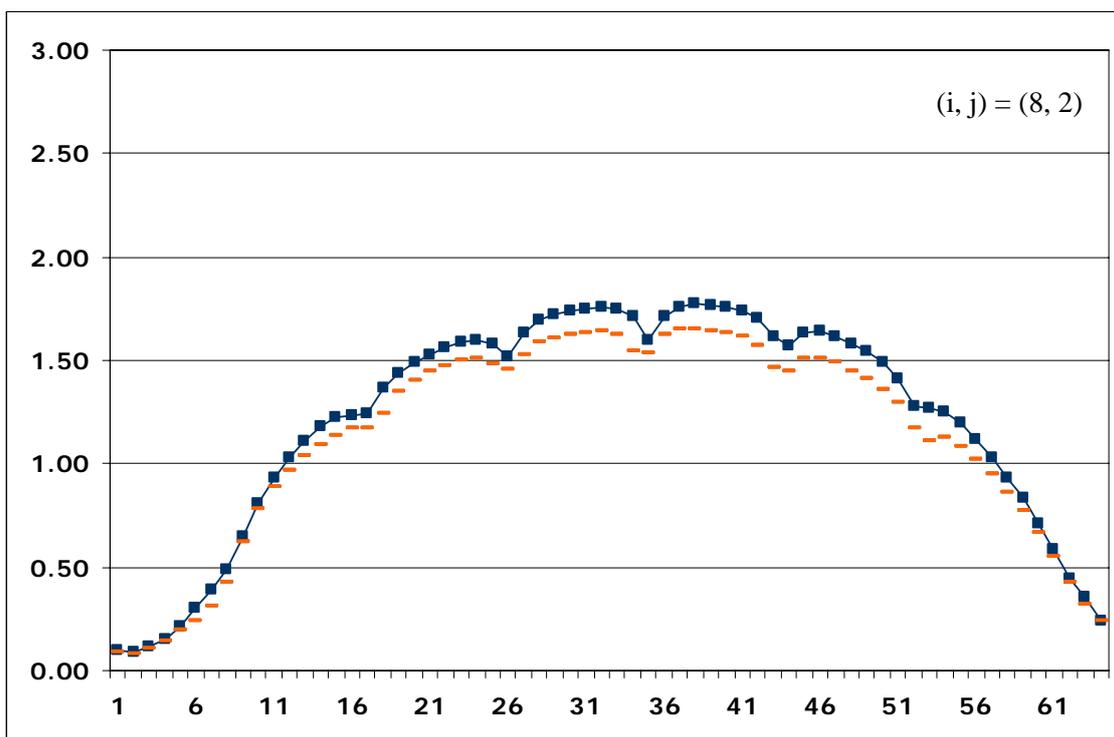
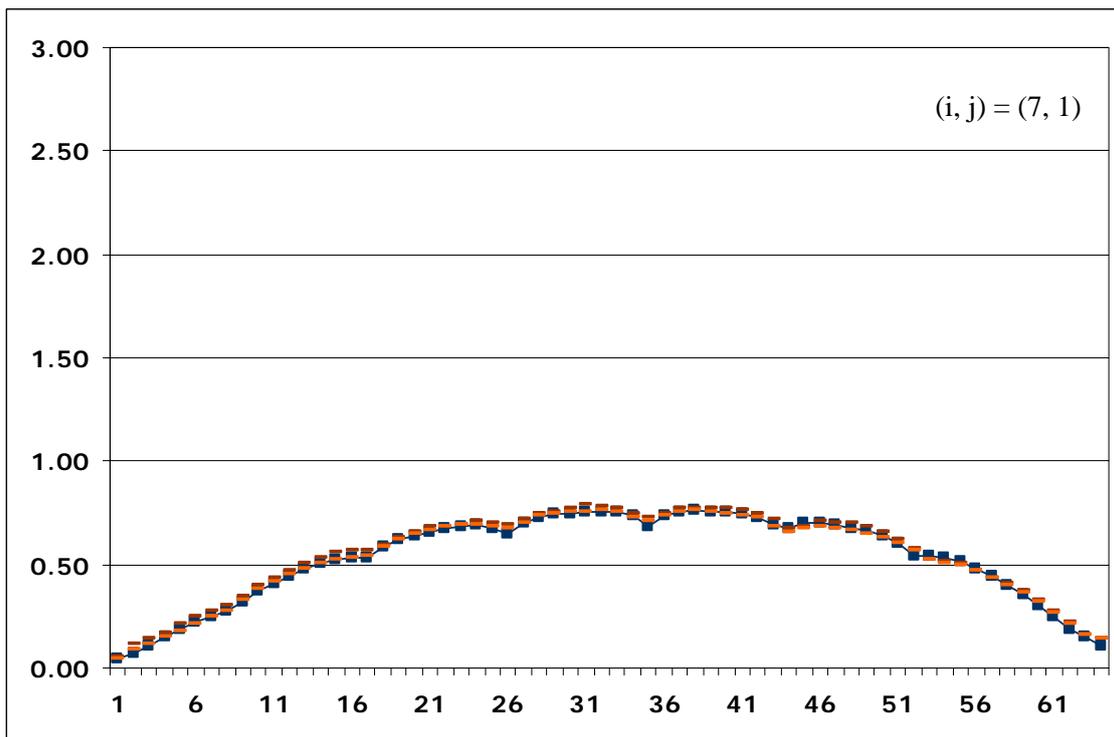












Title	Comparison of VNEM to Measured Data from Ringhals Unit 3 IACIP, NKS-R-2008-61
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No. of references	6
Abstract	<p>Comparisons have been made of a LWR core simulator CYGNUS with VNEM neutronics module to the measured data obtained from Ringhals unit 3 NPP at the hot-operating condition at its beginning of cycle 1 (core average burnup = 0 through 500MWD/MT).</p> <p>The results can be summarized as:</p> <p style="text-align: center;">core eigenvalue = 0.99711 +/- 0.00067</p> <p>Excellent agreement was obtained in the comparison of the neutron detector readings as observed in Phase 1 (2008).</p> <p>The computing (CPU) time was measured to be 7.5 min. / case, which is about 1/3 of the prototype VNEM code. This is because of the sophisticated coding of VNEM module in CYGNUS and the convergence acceleration effect of the feedbacks.</p>
Key words	CYGNUS, VNEM, Ringhals, unit 3, PWR, neutron detector, keff, IACIP: NKS_R_2008_61