The Database "EDUDBase" for Validation of Neutron-Physics Codes Used to Analyze the VVER-440 Cores

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ABSTRACT

The program and data system EDUDBase for validation of reactor computing codes was developed at NRI. It is designed for validation and evaluation of the precision of different computer codes used for VVER core analyses. The main goal of this database is to provide data for comparison with calculation results of tested codes and tools for statistical analysis of differences between the calculation results and the test data.

The benchmark data sets are based on in-core measurements performed on VVER-440 reactors of Dukovany NPP. The initial data from NPP are verified, errors and inaccuracies are eliminated and data are transferred to a form, which is suitable for comparison with results of calculations. A special reduced operating history data set is created for each operating cycle ("Benchmark Operation History") to be used as an input data for calculation. It contains values of some integral quantities for each time point: effective time, integral thermal power, boron concentration, position of working group control assemblies (group 6) and inlet coolant temperature. At present, sets are available for all completed cycles up to: (unit/cycle) 1/17, 2/16, 3/15, 4/15.

Power distribution is described for approx. 40 time steps during each operating cycle. 2D-power distributions are transferred into 60-degree core symmetry sector of reactor core. At present, such data sets are available only for later cycles starting with: (unit/cycle) 1/7, 2/6, 3/5, 4/5 (in other words last 11 cycles for each unit).

1. INTRODUCTION

Database EDUDBASE /4/ provides selected core operation data from Dukovany NPP used to validate neutron codes for VVER-440 core analysis, mainly the two of the core basic characteristics:

- Critical boron concentration (H_3BO_3) throughout the various states of operating cycles (boron letdown curve). Measured values of CB_exp(t) were determined from various methods of chemical analysis of primary coolant measurements at the plant and then averaged to daily mean value. These data were archived on magnetic media from the very beginning of Dukovany NPP operation. Further data reduction and averaging over the longer operating periods was performed as a part of validation data case preparation.
- Radial power distribution in VVER-440 core in various operating states at or close to the nominal power level. Reference measured data are represented by FA integral power Pw_exp(k) (as determined by VK3 CMS) in the FA positions instrumented by core exit temperature measurement thermocouple averaged over a symmetrical locations (converted into 60° RC symmetry FA average relative power). These data are available on magnetic media beginning from Cycle 5 of Unit 3 (since 1991).

Sources of measured data are described in /2/. This reference also describes in detail methods used for an independent verification of the data prior to their input into the database. Enhanced methods used for reference case power distribution preparation are described in /5/. Current status, data content, of the EDUDBASE database is documented in /4/.

Thorough analysis of validation case results is an important part of the data verification feedback process. Such analysis allows to identify individual measurement anomalies in the experimental data as well as systematic bias in some core characteristics behavior, which could be caused by improper function of some database input data preparation sequence (starting from data acquisition on NPP units through their further processing manual or by VK3 system). MOBY-DICK computer code is used for data analysis as a standard tool.

This paper presents excerpts of /6/ results for EDU Unit 1 obtained from validation case evaluation. The reference document also contains links to other reports documenting several data verification cycles during the 1992 to 2001 period.

2. VALIDATION CASE

All computer codes officially used in CR for neutron analysis of the reactor core characteristics have to pass through the code licensing procedure – evaluation by SONS expert group. The review process is controlled by SONS regulation and the topical report on code prediction accuracy evaluated on validation case composed from Czech plant operating data (for WWER-440 - EDU) is required as a part of the procedure.

2.1 EDUDBASE database

Based on the contract with SONS NRI had in cooperation with Dukovany NPP prepared validation case for MOBY-DICK and BIPR code standardization. This case is based on plant core operation data from EDUDBASE database /1,2,3,4/. The goal was to establish one of the basic operation benchmarks for VVER-440 core analysis codes to be used in the licensing process of these computer codes.

Database contains following files (kk – cycle number, b – unit number) with test case input data:

LOADPCkk.DUb - core loading description.

- Loading pattern,
- FA operating history (location of FA in previous cycles).

COHISCkk.DUb - Description of core operating history during the cycles.

- Effective time **Teff** (90 to 150 values),
- Critical boron concentration **H3BO3 CB**, (used as a reference – not as an input),
- CFA control group position (**CFA6** and **CFA0**),
- Reactor core thermal power **N**,
- Coolant inlet temperature **tin**.

Critical boron concentration (See COHIS) and fuel assembly power values from the data are used as a reference. These are archived for time points corresponding to and identified in COHIS file in which the core operation was sufficiently stable and equilibrium. The reference values are archived in the following files:

INDEXCkk.DUb - list of time points (20 to 40) of the given cycle for which FA power and additional RC characteristics are archived.

P2S36Ckk.DUb - 2-D relative FA power distribution in the core.

2.2 Core Analysis Results

Computer code calculation results of cycle history segments for **Teff**, **N**, **CFA6**, (**CFA0** if separated) and **tin** are requested for validation case evaluation. Each cycle is divided into 90 to 150 time intervals (including reactor shutdown periods with zero power). Maximum time interval duration is 7 calendar days, minimum 1 day (cycle history is reconstructed/condensed based on daily average values and data reduction is allowed for stable core operation periods). Xenon and Samarium are considered to be in equilibrium (except for zero power cases).

Results of **CB** and **Pw(k)** are then compared to measured data in EDUDBASE.

Note 2.1: As demonstrated earlier, 60° RC symmetry can be used for calculation. All analysis results presented in this paper are for 60° RC symmetry segment and it should be so understand whenever RC is mentioned in this paper.

MS Access based tools are used for data evaluation. They provide useful queries, forms, graphs and reports allowing to analyze the data according to specific needs of the user and to prepare suitable graphical presentation of the analysis results (tables, graphs).

2.3 Validation Case/Benchmark Scope

Validation case was calculated for all units of Dukovany NPP and all cycles finished by the end of the year 2001. Prediction accuracy analysis was performed for the following parameters, units and cycles:

Unit	Cycle	Parameter
1	1 to 16	Critical boron concentration at power H3BO3
2	1 to 15	
3	1 to 14	
4	1 to 14	
1	7 to 16	FA radial power distribution Paw(k) and Kq
2	6 to 15	
3	5 to 14	
4	5 to 14	

This paper presents only excerpts of /6/ results from validation case evaluation. Particular examples of EDU Unit 1 are presented to illustrate possibilities of the database analysis tools and analysis results.

3. DEFINITION OF PARAMETERS AND STATISTICS EVALUATED FOR THE VALIDATION CASE

Definition of the validation case isl documented in Ref. /1,2,3/. Only partial information important for understanding of the results presented in this paper is given here. Detailed information can be found in the references above.

3.1 General rules used in parameter and its statistic notation

X selected parameter (CB, Pw, Kq)

X_exp(i) i-th measured value of the given parameter X (out of **n** values)

X_eval(i) i-th calculated value of the given parameter X (out of **n** values)

Avg(X) average value of X

$$\mathrm{Avg}(X) = \frac{1}{n}\sum X(i)$$

Index i abbrev. for several independent indexes (see 3.2)

Note 3.1: When comparing the measured and calculated values of power distribution they are normalized over all instrumented FAs (CFA are excluded) such that the average value is equal to 1. Then:

$$\mathbf{Avg(Pw\_exp)} = \frac{1}{52}\sum \mathbf{Pw\_exp(i)} = \mathbf{Avg(Pw\_eval)} = \frac{1}{52}\sum \mathbf{Pw\_eval(i)} = 1,$$

Where sum is only over instrumented 52 FAs positions (see Figure 9).

Note 3.2: Trivial consequence of the definition above is that average of the differences equals zero.

dX(i) measured vs. calculated difference

$$dX(i) = X\_\exp(i) - X\_\mathrm{eval}(i)$$

Avg(dX) average value of dX(i)

$$\mathrm{Avg}(dX) = \frac{1}{n}\sum dX(i)$$

|dX(i)| absolute value of the difference dX(i)

Avg(|dX|) avg. of |dX(i)|

Max(dX) maximum positive difference

Min{dX} maximum negative difference

SD(dX) standard statistical deviation between measured and predicted value

$$\mathrm{SD}(dX) = \left(\frac{1}{n}\sum (dX(i) - \mathrm{Avg}(dX))^2\right)^{1/2}$$

3.2 Indexes

3.2.1 Data Indexes

b	EDU unit number (1-4)
c	cycle number
t	time point index in the given cycle (1 through n)
k	FA index in the 60°core segment (either 1 to 59 or only 1 to 52, see Figure 9)

Note 3.3: Two different sets of time point values **t** are mentioned in the analysis:

- For boron concentration CB is the **t** set given by points in COHIS.... file which is 90 to 150 points depending on cycle power history complexity.
- For radial power distribution Pw(k) and Kq is the **t** set given by number of points in INDEX.... file, which consists typically of 20 to 40 points. This set is a sub-set of the above.

Throughout the paper text simple term of set **t** is used, but it has to be distinguished accordingly depending on context.

For the purpose of this paper the indexes **b, c** were merged into one named in the graphs and tables as "Unit-Cycle". This allows more convenient presentation of statistic evaluation results (see 3.3). A name EDU is used for all four units. Index Unit–Cycle can have the following values:

Unit-Cycle = **EDU, 1, 2, 3, 4,** and one of the two following alternatives: a) For **CB** analysis: **1-01** to **1-16, 2-01** to **2-15, 3-01** to **3-14, 4-01** to **4-14.** b) For **Pw** and **Kq** analysis: **1-07** to **1-16, 2-06** to **2-15, 3-05** to **3-14, 4-05** to **4-14.**

3.2.2 Indexing of sub-sets

Statistical analysis of the data sub-sets (summaries) can provide the influence of different parts of the cycle or core locations on statistical behavior. For this purpose additional indexes are introduced **t, k**.

Note 3.4: Following index values are used in tables and graphs presented in this paper:

- Cycle = all **t** or **k** values belong to the given cycle,
- Unit = all **t** or **k** values belong to the all cycles of given unit,
- EDU = all **t** or **k** values belong to the all cycles and units of Dukovany NPP analyzed.

Following subsets were defined for this paper:

1. Index **t** is divided into three sub-sets for Teff:
   BOC = beginning of cycle (Teff <= 100 FPD),
   MOC = middle of cycle (100 FPD < Teff < 200 FPD),
   EOC = end of cycle (Teff >= 200 FPD).
   This auxiliary index is denoted as **POC** (= part of cycle).
   POC possible values are:
   POC = **EDU, Unit, Cycle, BOC, MOC, EOC.**
2. Index **k** is divided into subsets according to FA location in the core into three subsets as well:
   1 = FA surrounding CFA6 (total 7 FA),
   2 = other (inner) FA (total 35 FA),
   3 = Core periphery FA (total 10 FA).

Assignment/positions of FA for different groups is given in Figure 9.
This auxiliary index is denoted as **POZ** (= position).
POZ possible values are:
POZ = EDU, Unit, Cycle, 1, 2, 3, 4.

3.3 Presented statistics

Large sets of data are statistically compared and evaluated depending on different indexes (see 3.2). Statistic characteristics (Min, Max, Avg, StDev) characterize different data subset. Definitions are presented above in 3.2.2. Following statistics are provided:

3.3.1 Cb difference analysis

Difference dCB depends on index: Unit-Cycle, **t** (independent on **k**). POC index is to analyze different parts of the cycle (see 3.2). Following statistics are then calculated:

1. *POC statistics*: Fixed Unit-Cycle over **t** in POC.
2. *Cycle statistics*: Fixed Unit-Cycle (except EDU, 1, 2, 3, 4) over **t**.
3. *Unit statistics*: Fixed Unit-Cycle (= 1, 2, 3, 4) over **t**.
4. *EDU statistics*: Fixed Unit-Cycle (= EDU) over all **t**.

3.3.2 Kq difference analysis

dKq difference is the only single value for each time point over indexes **Unit-Cycle, t.** Same statistics as in 3.3.1 can be used, however, difference in meaning of **t** has to be recognized (see Note 3.3).

3.3.3 FA power Pw difference analysis

dPw difference depends on **Unit-Cycle, t,** and **k** indexes. Summary over **t** or over **k** was determined first for practicality and then processed in a standard way. Following summary characteristics were finally determined:

1. *POC statistic*: Fixed Unit-Cycle over t in POC and ovewr all **k**.
2. *Cycle statistic*: Fixed Unit-Cycle (except EDU, 1, 2, 3, 4) over all corresponding **t** and all **k**.
3. *Unit statistic*: Fixed Unit-Cycle (= 1, 2, 3, 4) over all corresponding **t** and all **k**.
4. *EDU statistic*: Fixed Unit-Cycle (= EDU) over all corresponding **t** and **k**.
5. *FA location (POZ) statistic*: Fixed Unit-Cycle over **k** in POZ and all **t**.
6. *Statistic 5 is also determined for index values (Cycle, Unit, EDU)*. For similarity in definitions they are not presented here explicitly.

Note 3.5: As follows from Note 3.2 the average over FAs is trivial Avg(dPw(k)) = 0 and therefore it is not presented. Instead Avg(|dPw|) statistics are used in Table 3 and 4.

4. CRITERIA FOR ACCURACY EVALUATION

As it follows from /1,2,3/ accuracy evaluation is based on statistical evaluation of time average difference values of parameters in question. This approach is chosen to avoid significant impact of single point disagreement on overall evaluation.

Some criteria used in /1,2,3/ appear to be suitable also for this presentation. The values are used as discrimination levels for data evaluation. This allows to identify existing trends in MOBY-DICK computer code predictions.

Three such criteria same as in /1,2,3/ are used in this chapter 4:

- Avg(dCB) = 0.20 g H_3BO_3/kg at power
- Max(dPw) = 0.07, Min(dPw) = -0.07
- Max(dKq) = 0.05, Min(dKq) = -0.05

In addition, following critical values used for evaluation in Chapter 6 have been identified based on existing experience from the work with the database:

- StDev(dCB) = 0.15
- Min(dCB) = Avg – 3*StDev
- Max(dCB) = Avg + 3*StDev
- Avg(|dPw|) = Avg(dPw) = 0.024
- StDev(dPw) = 0.032
- Avg(dKq) = 0.030
- StDev(Kq) = 0.030

Values outside the criteria boundary are marked with **x** in Tables.

5. Reference Code

All calculations were performed using <u>**MOBY-DICK , code version mob608 with WIE72G4G cross-section library,**</u> using two different methods. Results of evaluation for both methods are presented here.

<u>**Calculation method**</u>:	
<u>**Coarse mesh**</u>:	24 nodes per FA x-section (triangles), 40 nodes per core height.
<u>**Pin-wise**</u>:	Mesh of regular 126 hexagons per FA corresponding to fuel pin cells, 40 nodes for assembly shroud and gap and 40 nodes per core height.
<u>**Reactor core (RC)**</u>:	height = 244 cm , axial node height = 6.1 cm (= 40 nodes), Fuel stack height in CFA = 231.8 cm (= 38 nodes)
<u>**X-section library**</u>:	WIE72G4G: 2 groups (thermal group energy boundary 0.625eV) prepared by WIMS 8a. Diffusion data parameterized using APRO code.
<u>**Boundary conditions**</u>:	γ - matrices prepared by HECON code and corrected against MCNP results were used for radial and axial reflector as well as for absorber region of CFA.

Details are documented in /7/. Validation case calculation results were provided for evaluation on media through /8/.

6. Evaluation of Validation Case Results

<u>Note 6.1</u>: As it can be seen from presented tables and figures, the differences between coarse-mesh and pin-wise calculations are very small and therefore in most cases they are not distinguished in this chapter.

6.1 H_3BO_3 critical boron concentration at power

Table 1: Unit 1, N>1000 MWt

Avg(dCB) exceeds criterion only for the beginning of first cycle up to 200 FPD, which could be explained by very non-equilibrium operation of the core during this

	period of time and plant commissioning. Criteria is met with significant margin for the rest of the cycles
Min a Max	isolated values outside the criteria can be identified in different cycles, however, as can be seen from Figure 1, frequency of such cases is very low.
StDev	behaves similarly as Avg.

Table 2: Unit 1, N>0 MWt

Avg(dCB)	Behaves similarly as in case for N> 1000 MWt, criterion is met in most cases.
Min a Max	Increase of high difference frequency and thus StDev can be clearly identified.

Figure 1: Unit 1, N>1000 MWt

Frequency distribution shows well difference behavior. Maximum frequency for unit 1 corresponds to ~ -0.05. Contribution of different cycle periods can be seen from the picture as well.

Figure 2: All 4 units, N>1000 MWt

Shows contribution of different cycle periods to the overall statistics for all 59 cycles included in evaluation.

Figure 3: All 4 units, N>0 MWt

Shows contribution of different cycle periods to the overall statistics for all 59 cycles included in evaluation. It can be seen that Unit 4 exhibits negative bias. Higher negative differences were identified when low power cases are included into evaluation, however their frequency is very low.

Conclusion on critical boron concentration prediction evaluation:

1. dCB differences do meet criteria in the wide range of analyzed values.
2. Isolated larger differences were identified, however, they are of low statistical significance.
3. Insignificant differences between used methods were noted but in general both methods predict almost identical values.

6.2 Radial power distributions

6.2.1 dPw summary over FAs in time period subsets

Table 3: Unit 1, instrumented FAs (CFA excluded)

Avg(|dPw|)	absolute value is used for comparison since Avg(dPw) = 0 (see Note 3.2).

All statistics meet criteria used for all time points and cycles.

Table 4: Unit 1, all FAs (including CFA)

Avg(|dPw|)	slightly increased values compare to Table 3, but criterion met.
Min a Max	significant change, criteria not met for most of the cycles.
StDev	similar as for Avg.

Conclusion 1 for power difference analysis:

These results confirm the appropriateness of excluding CFAs from evaluation. While the agreement on instrumented FAs is excellent (Table 3), prediction for CFA powers exhibit significant differences, which is primarily believed to be attributable to VK3 system algorithms used to calculate "measured" CFA power.

Figure 4: Unit 1, instrumented FAs (CFA excluded)

This graph illustrates meeting the criteria with maximum difference frequency at ~ 0 or -0.005 depending on the method. Contribution of different cycle periods can also be seen. No practical dependence seen.

Figure 5: All 4 units, instrumented FAs (CFA excluded)

This graph illustrates meeting the criteria with maximum difference frequency at ~ 0.005 or 0 depending on the method. Contribution of different cycle periods can also be seen. No practical dependence seen.

Conclusion 2 for power difference analysis:

Figures 4 and 5 show that difference distribution is independent on time point in the cycle. All criteria are met.

6.2.2 Summary of dPw over time points for different FA groups

Table 5: Unit 1, over all measured FAs (CFA excluded)

All statistics meet given criteria for the whole range of time points and cycles.

Figure 6: Unit 1. over all measured FAs (CFA excluded)

Illustates well that criterion is met, maximum frequency is at ~ -0.005. Both methods behave in a similar way. FA location is also analysed in this figure.

Figure 7: All units over all measured FAs (CFA excluded)

Illustates well that criterion is met, maximum frequency is at ~ -0.005 or 0 depending on the method. FA location influence is also analysed in this figure.

Conclusion on FA groups power distribution:

Figures 6 through 8 show behavior of assembly power prediction accuracy depending on FA core location. FAs next to CFA6 have difference distribution shifted to negative values, peripheral FAs to positive values and the rest has normal distribution around zero.

6.2.3 Summary of dKq over cycles

Table 6: Unit 1., summary over all cycles and unit

Avg(dKq)	none of 10 values does not exceed criterion.
Min a Max	none of 20 values does not exceed criterion.
StDev(dKq)	none of 10 values does not exceed criterion.

Figure 8: all 4 Units

Difference distribution for both methods is insignificant. Maximum frequency corresponds to ~ -0.005. However differences > 0.05 exist.

Conclusion on Kq difference analysis over time intervals:

dKq differences and their statistics meet corresponding criteria very well.

7. CONCLUSIONS FROM MOBY-DICK CODE EVALUATION

7.1 H_3BO_3 Critical boron concentration at power

1. Difference dCB meet criteria in the wide range of analyzed values.

2. There are single differences exceeding criteria, but statistically they are not significant.

3. Differences between two different methods do exist, however they are marginal and both methods predict practically the same values.

7.2 Radial power distribution and Kq

1. All statistics meet the criteria in cycle sub-intervals.

2. Figure 3 and 4 demonstrate practical independence of power distribution accuracy on the time in the cycle.

3. Figure 7 and 8 show difference behavior depending on FA location in the core. FA next to CFA6 have the maximum differences in negative direction. Peripheral FAs have maximum differences in positive direction. Differences for the rest of the core have normal distribution around zero.

4. dKq difference and its statistics meet the criteria very well.

7.3 Conclusion notes

Database content is significantly larger than presented in this paper. It also contains data of thermocouple measurements, SPND signals, spatial power distributions, data from BOC criticality etc. Evaluated computer code had to be capable to provide required characteristics.

When performing some comparisons between code calculations and SPND measurement it was discovered that conversion of SPND currents to power needs to be clarified. Therefore the evaluation results for this parameter were not published yet. However, there is still influence of SPND data on "measured" 3D power distribution through their relative axial profile.

Difficulties of codes were identified also for predictions of the hot zero power critical CB after shutdown and outage periods. More thorough analysis of differences in measured and predicted data still remains to be performed to identify cause and propose some solution.

Temperature measurement analysis as documented in /5/ was very successful and confirmed possibility to perform comparison of FA power based on FA exit temperature rather than based on temperature rise measurements.

Database is regularly maintained and updated by new operation data and their verification. Work on similar database for Temelin NPP data ETEDBASE was already commenced.

8. List of Nomenclature

Physical quantities

Teff	Effective time [FPD]
N	Reactor thermal power [MWt]
CB	Boron concentration (H_3BO_3) [g/kg]
tin	Inlet coolant temperature [°C]
Pw(k)	Relative fuel assembly power [-]
Kq	Fuel assembly peaking factor [-]

$$Kq = \frac{\max(Pw(k))}{Avg(Pw)}$$

Other abbreviations

CFA	control fuel assembly

CFA6	position of working CFA group (Group 6) [cm]
CFA0	position of central CFA in case it is separated from Group 6 [cm]
FA	fuel assembly
RC	reactor core
EDU	Dukovany NPP
ETE	Temelín NPP
SONS	State Office for Nuclear Safety
VK3	original Russian design core surveillance system of EDU
CR	Czech Republic

Additional abbreviations used in validation cases are defined in Article 3.1.

9. REFERENCES

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/7/ Krýsl V., Mikoláš P., Švarný J., Vlachovský K.: **Preparation of few group diffusion data library for advanced fuel with Gd burnable absorbers (Part 1. – Library preparation).** Ae 10770/Dok, Rev. 0, Pilsen, November 2002, (in Czech)

/8/ Krýsl V., Mikoláš P., Švarný J., Vlachovský K.: **Validation case results calculated using MOBY-DICK code.** Private communication, 2002, (in Czech)

Table 1 Statistical analysis of H3BO3 concentration differencies (measurement - calculation) for the 1. unit EDU at time points with thermal power >1000 MWt. x marks values out of criteria (see text).

Unit-Cycle	Subset of time points	Number of events	Coarse mesh ΔCB (g H3BO3/kg)				Pin-wise ΔCB (g H3BO3/kg)			
			Min	Avg	Max	StDev	Min	Avg	Max	StDev
1	Teff<=100	428	-0.399	-0.027	0.655 x	0.159 x	-0.404	-0.006	0.663 x	0.153 x
1	100<Teff<200	463	-0.388 x	0.027	0.559 x	0.125	-0.377 x	0.028	0.561 x	0.122
1	200<=Teff	467	-0.282	-0.034	0.285 x	0.103	-0.273	-0.048	0.263 x	0.100
1	Unit history	1358	-0.399	-0.011	0.655 x	0.133	-0.404 x	-0.009	0.663 x	0.130
EDU	Teff<=100	1662	-0.677 x	-0.073	0.655 x	0.162 x	-0.641 x	-0.053	0.663 x	0.157 x
EDU	100<Teff<200	1655	-0.693 x	-0.007	0.690 x	0.139	-0.676 x	-0.004	0.695 x	0.135
EDU	200<=Teff	1815	-0.486 x	-0.074	0.472 x	0.137	-0.464	-0.088	0.458 x	0.135
EDU	EDU history	5132	-0.693 x	-0.052	0.690 x	0.149	-0.676 x	-0.049	0.695 x	0.146
1-01	Teff<=100	25	0.059	0.402 x	0.655	0.170 x	0.070	0.410 x	0.663	0.168 x
1-01	100<Teff<200	28	0.218	0.344 x	0.559 x	0.070	0.204	0.341 x	0.561 x	0.073
1-01	200<=Teff	35	0.002	0.159	0.285	0.073	-0.023	0.134	0.263	0.077
1-01	Cycle history	88	0.002	0.287 x	0.655	0.152 x	-0.023	0.278 x	0.663	0.163 x
...										
1-16	Teff<=100	28	-0.180	-0.016	0.494 x	0.123	-0.136	0.015	0.543 x	0.122
1-16	100<Teff<200	30	0.025	0.071	0.168	0.037	0.031	0.082	0.170	0.035
1-16	200<=Teff	37	-0.164	-0.011	0.102	0.071	-0.163	-0.019	0.098	0.074
1-16	Cycle history	95	-0.180	0.013	0.494 x	0.091	-0.163	0.023	0.543 x	0.093

Table 2 Statistical analysis of H3BO3 concentration differences (measurement – calculation) for the 1. unit EDU at time points with thermal power >0 MWt. x marks values out of criteria (see text).

Unit-Cycle	Subset of time points	Number of events	Coarse mesh ΔCB (g H3BO3/kg)				Pin-wise ΔCB (g H3BO3/kg)			
			Min	Avg	Max	StDev	Min	Avg	Max	StDev
1	Unit history	1577	-0.969 x	-0.010	1.367 x	0.183 x	-0.950 x	-0.006	1.360 x	0.179 x
EDU	EDU history	5883	-1.533 x	-0.054	1.903 x	0.195 x	-1.522 x	-0.050	1.904 x	0.192 x
1-01	Cycle history	136	-0.217	0.289 x	1.367 x	0.232 x	-0.237	0.284 x	1.360 x	0.236 x
...										
1-16	Cycle history	95	-0.180	0.013	0.494 x	0.091	-0.163	0.023	0.543 x	0.093

Table 3 Statistical analysis of power differences (measurement – calculation) for measured fuel assemblies only (i.e. without CFA) of the 1.unit EDU.
x marks values out of criteria (see text).

Unit-Cycle	Subset of time points	Number of events	Coarse mesh ΔPw (Relative unit)				Pin-wise ΔPw (Relative unit)			
			Min	Avg (|ΔPw|)	Max	StDev	Min	Avg (|ΔPw|)	Max	StDev
1	Teff<=100	4680	-0.064	0.014	0.050	0.017	-0.067	0.014	0.053	0.018
1	100<Teff<200	5512	-0.049	0.013	0.050	0.016	-0.052	0.013	0.046	0.016
1	200<=Teff	5668	-0.049	0.013	0.044	0.015	-0.049	0.012	0.046	0.015
1	Unit history	15860	-0.064	0.013	0.050	0.016	-0.067	0.013	0.053	0.016
EDU	Teff<=100	18772	-0.069	0.016	0.091 x	0.020	-0.077 x	0.018	0.102 x	0.022
EDU	100<Teff<200	21060	-0.063	0.014	0.077 x	0.018	-0.063	0.015	0.091 x	0.018
EDU	200<=Teff	21632	-0.063	0.014	0.069	0.018	-0.061	0.014	0.084 x	0.018
EDU	EDU history	61464	-0.069	0.015	0.091 x	0.019	-0.077 x	0.016	0.102 x	0.019
1-07	Teff<=100	468	-0.057	0.015	0.050	0.018	-0.061	0.017	0.051	0.020
1-07	100<Teff<200	780	-0.037	0.013	0.046	0.016	-0.039	0.014	0.043	0.017
1-07	200<=Teff	728	-0.039	0.012	0.044	0.014	-0.037	0.012	0.046	0.015
1-07	Cycle history	1976	-0.057	0.013	0.050	0.016	-0.061	0.014	0.051	0.017
...										
1-16	Teff<=100	364	-0.047	0.012	0.042	0.016	-0.044	0.013	0.049	0.017
1-16	100<Teff<200	364	-0.047	0.013	0.039	0.017	-0.045	0.013	0.039	0.017
1-16	200<=Teff	364	-0.045	0.014	0.041	0.018	-0.048	0.014	0.038	0.017
1-16	Cycle history	1092	-0.047	0.013	0.042	0.017	-0.048	0.013	0.049	0.017

Table 4 Statistical analysis of power differences (measurement – calculation) for all fuel assemblies (i.e. with CFA) of the 1. unit EDU.
x marks values out of criteria (see text).

Unit-Cycle	Subset of time points	Number of events	Coarse mesh ΔPw (Relative unit)				Pin-wise ΔPw (Relative unit)			
			Min	Avg (|ΔPw|)	Max	StDev	Min	Avg (|ΔPw|)	Max	StDev
1	Unit history	17995	-0.659 x	0.017	0.242 x	0.028	-0.642 x	0.017	0.259 x	0.028
EDU	EDU history	69738	-0.659 x	0.019	0.242 x	0.028	-0.642 x	0.020	0.259 x	0.029
1-07	Cycle history	2242	-0.139 x	0.018	0.107 x	0.025	-0.140 x	0.019	0.120 x	0.026
...										
1-16	Cycle history	1239	-0.125 x	0.016	0.042	0.023	-0.119 x	0.016	0.049	0.023

Table 5 Statistical analysis of power differences (measurement – calculation) for measured fuel assemblies only (i.e. without CFA) of the 1.unit EDU from the point of view of fuel assembly position in the core.
x marks values out of criteria (see text).

Unit-Cycle	Subset of FA positions	Number of events	Coarse mesh ΔPw (Relative unit)				Pin-wise ΔPw (Relative unit)			
			Min	Avg	Max	StDev	Min	Avg	Max	StDev
1	Inner FAs	10675	-0.064	0.000	0.050	0.016	-0.067	0.001	0.053	0.016
1	Periphery FAs	3050	-0.045	0.003	0.050	0.017	-0.048	0.001	0.047	0.017
1	FAs near CFA6	2135	-0.059	-0.005	0.033	0.013	-0.060	-0.005	0.051	0.014
1	All FAs	15860	-0.064	0.000	0.050	0.016	-0.067	0.000	0.053	0.016
EDU	Inner FAs	41370	-0.064	0.000	0.085 x	0.018	-0.067	0.001	0.102 x	0.019
EDU	Periphery FAs	11820	-0.063	0.008	0.075 x	0.018	-0.063	0.006	0.076 x	0.019
EDU	FAs near CFA6	8274	-0.069	-0.011	0.091 x	0.016	-0.077 x	-0.011	0.074 x	0.017
EDU	All FAs	61464	-0.069	0.000	0.091 x	0.019	-0.077 x	0.000	0.102 x	0.019
1-07	Inner FAs	1330	-0.057	-0.002	0.030	0.013	-0.061	-0.002	0.037	0.015
1-07	Periphery FAs	380	-0.041	0.006	0.050	0.022	-0.040	0.003	0.047	0.022
1-07	FAs near CFA6	266	-0.042	0.003	0.031	0.013	-0.043	0.006	0.051	0.018
1-07	All FAs	1976	-0.057	0.000	0.050	0.016	-0.061	0.000	0.051	0.017
...										
1-16	Inner FAs	735	-0.047	0.005	0.042	0.017	-0.045	0.006	0.049	0.016
1-16	Periphery FAs	210	-0.045	-0.012	0.007	0.014	-0.048	-0.014	0.006	0.014
1-16	FAs near CFA6	147	-0.040	-0.007	0.012	0.011	-0.040	-0.009	0.011	0.010
1-16	All FAs	1092	-0.047	0.000	0.042	0.017	-0.048	0.000	0.049	0.017

Table 6 Statistical analysis of peaking factor Kq differences (measurement – calculation) for the 1. unit EDU.
x marks values out of criteria (see text).

Unit-Cycle	Subset of time points	Number of events	Coarse mesh ΔKq (-)				Pin-wise ΔKq (-)			
			Min	Avg	Max	StDev	Min	Avg	Max	StDev
1	Teff<=100	90	-0.028	-0.002	0.028	0.018	-0.027	-0.001	0.026	0.017
1	100<Teff<200	106	-0.017	-0.001	0.024	0.010	-0.015	0.000	0.021	0.009
1	200<=Teff	109	-0.030	-0.005	0.021	0.011	-0.027	-0.005	0.017	0.009
1	Unit history	305	-0.030	-0.003	0.028	0.013	-0.027	-0.002	0.026	0.012
EDU	Teff<=100	361	-0.035	0.003	0.094 x	0.026	-0.039	0.001	0.094 x	0.026
EDU	100<Teff<200	405	-0.039	-0.001	0.084 x	0.017	-0.034	-0.001	0.087 x	0.017
EDU	200<=Teff	416	-0.056 x	-0.006	0.064 x	0.018	-0.063 x	-0.006	0.069 x	0.018
EDU	EDU history	1182	-0.056 x	-0.001	0.094 x	0.021	-0.063 x	-0.002	0.094 x	0.021
1-07	Cycle history	38	-0.017	-0.009	0.006	0.005	-0.009	0.001	0.016	0.006
...										
1-16	Cycle history	21	-0.004	0.008	0.019	0.006	-0.009	0.006	0.019	0.008

Figure 1.A EDU 1. unit, coarse mesh.

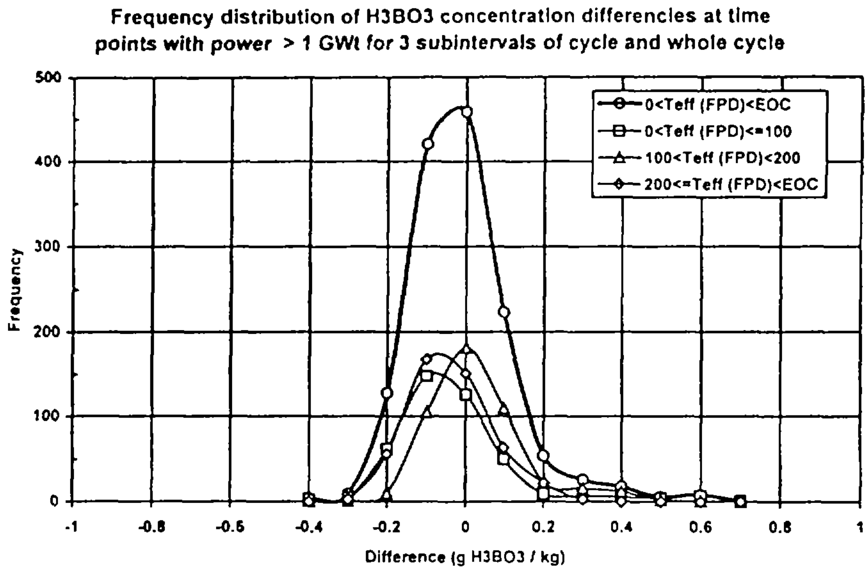


Figure 1.B EDU 1. unit, pin-wise.

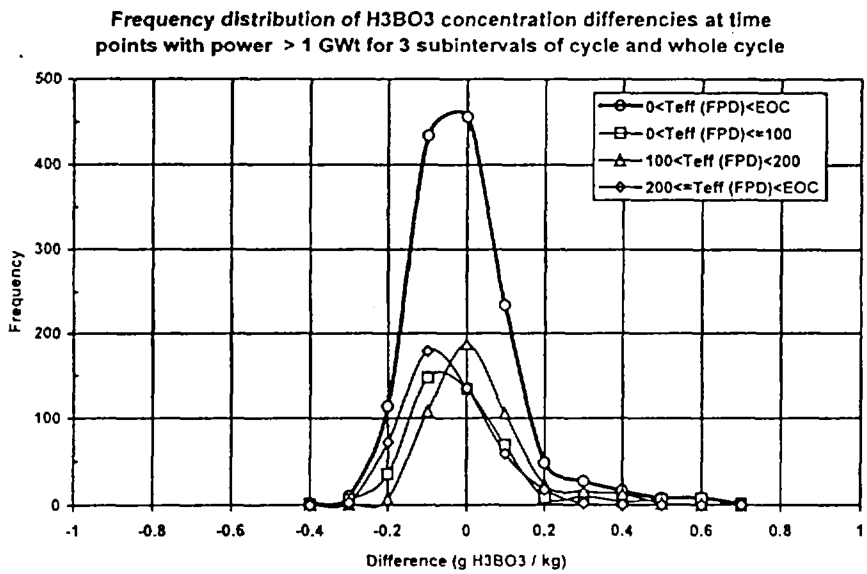


Figure 2.A .All four units EDU together , coarse mesh.

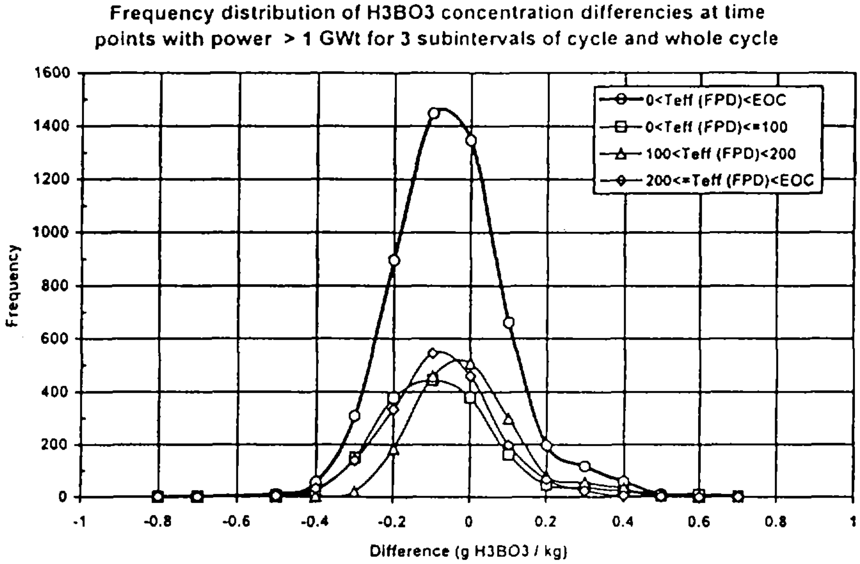


Figure 2.B All four units EDU together , pin-wise.

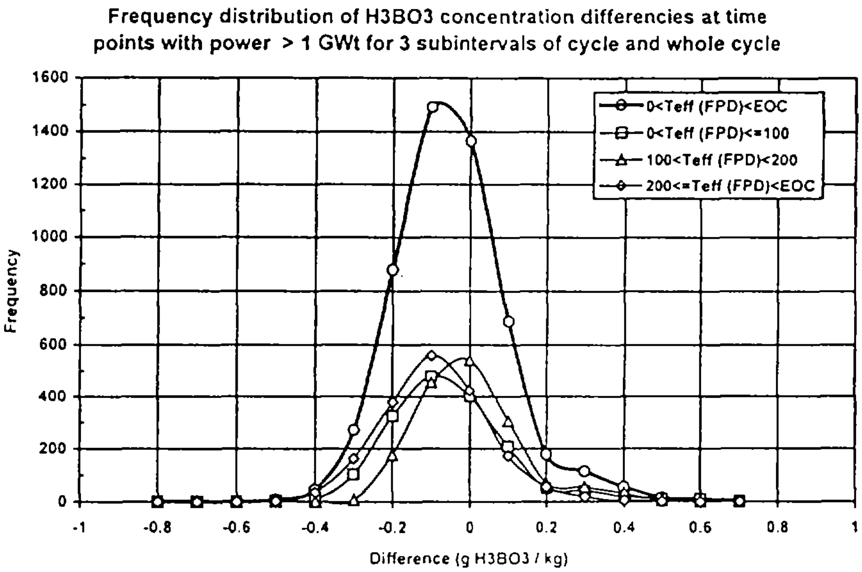


Figure 3.A All four units EDU together, coarse mesh.

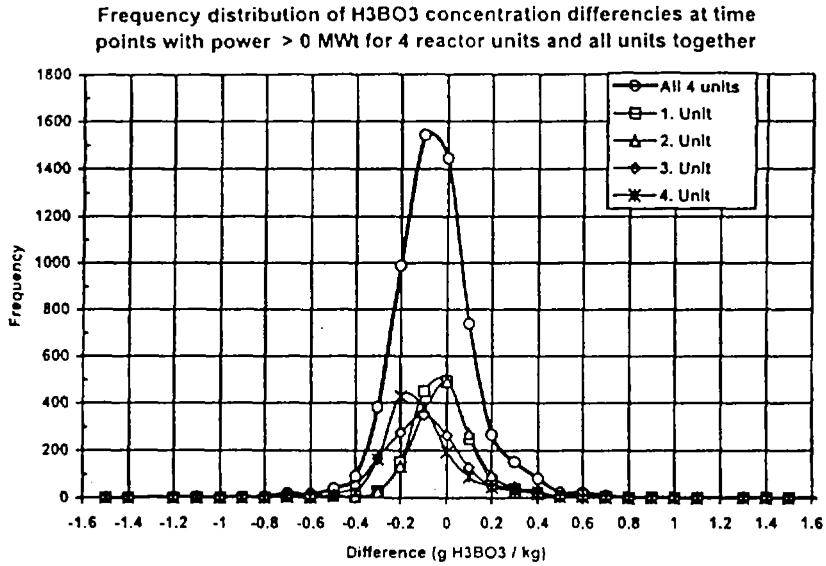


Figure 3.B All four units EDU together, pin-wise.

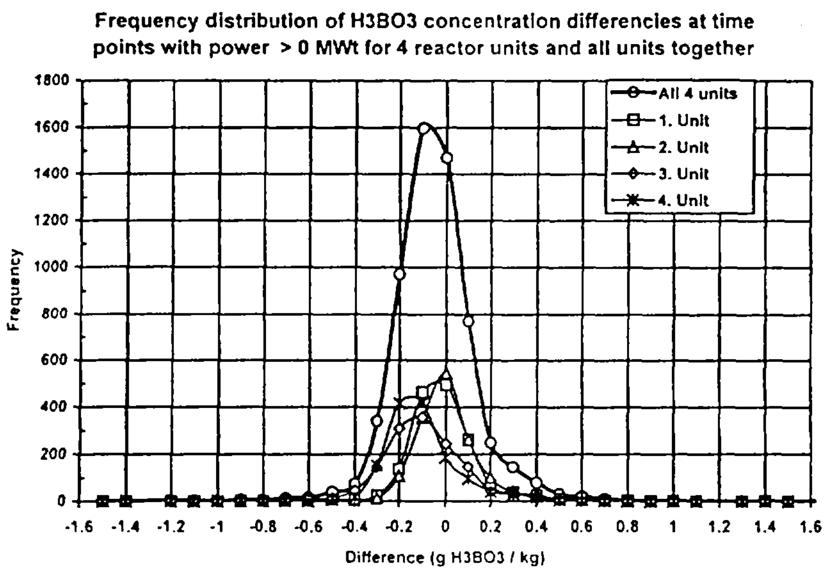


Figure 4.A EDU 1. unit, coarse mesh.

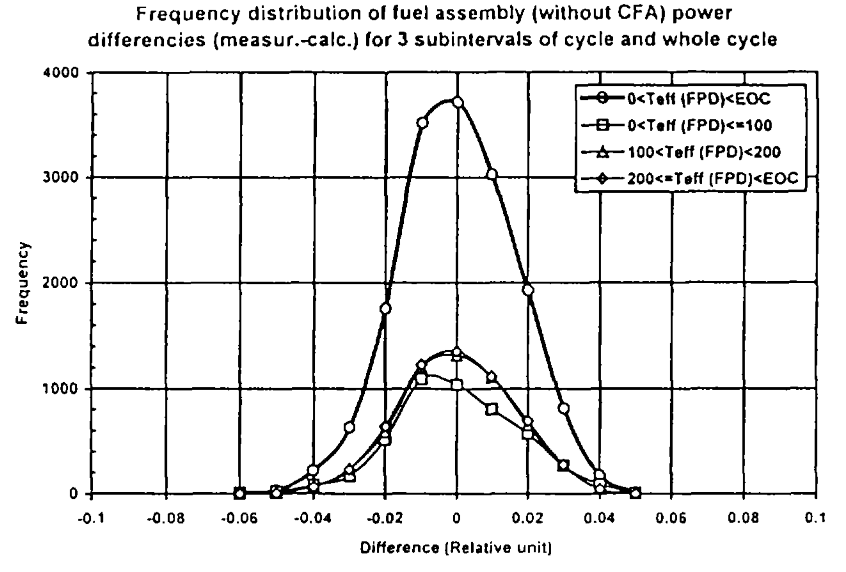


Figure 4.B EDU 1. unit, pin-wise.

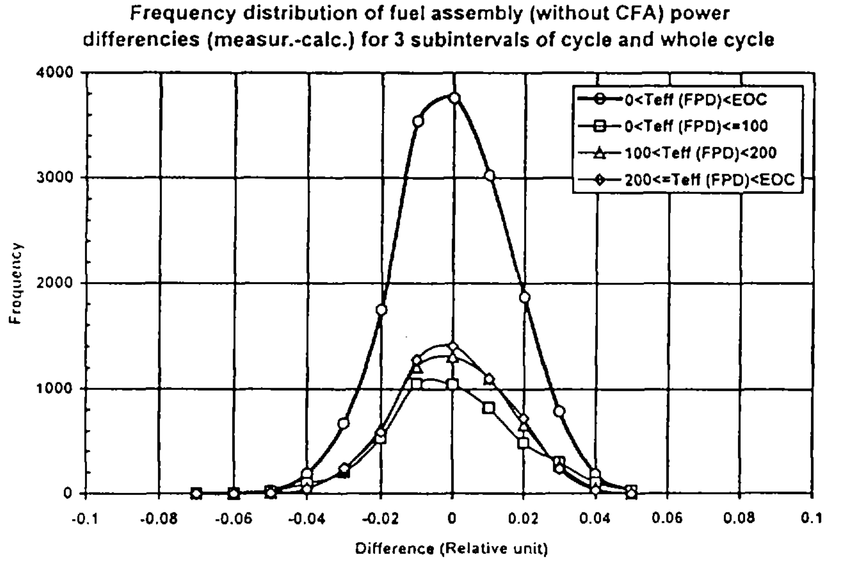


Figure 5.A All four units EDU together , coarse mesh.

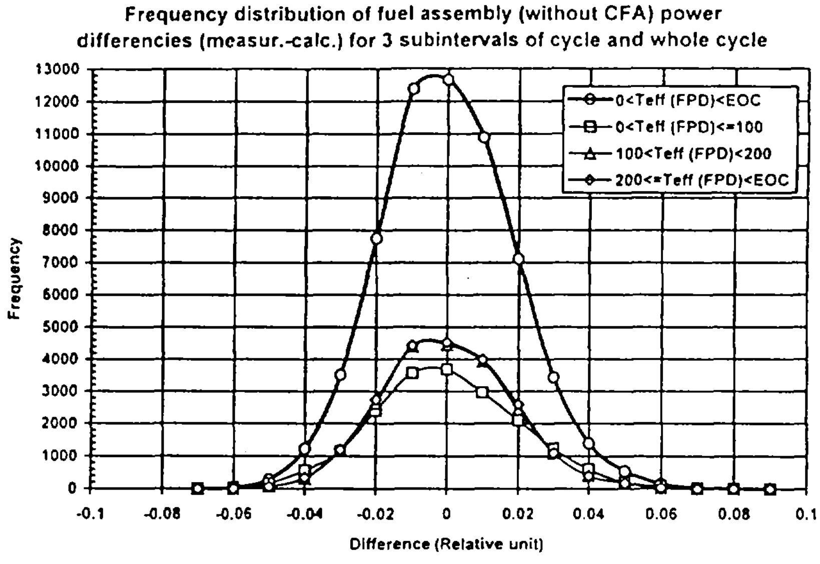


Figure 5.B All four units EDU together , pin-wise.

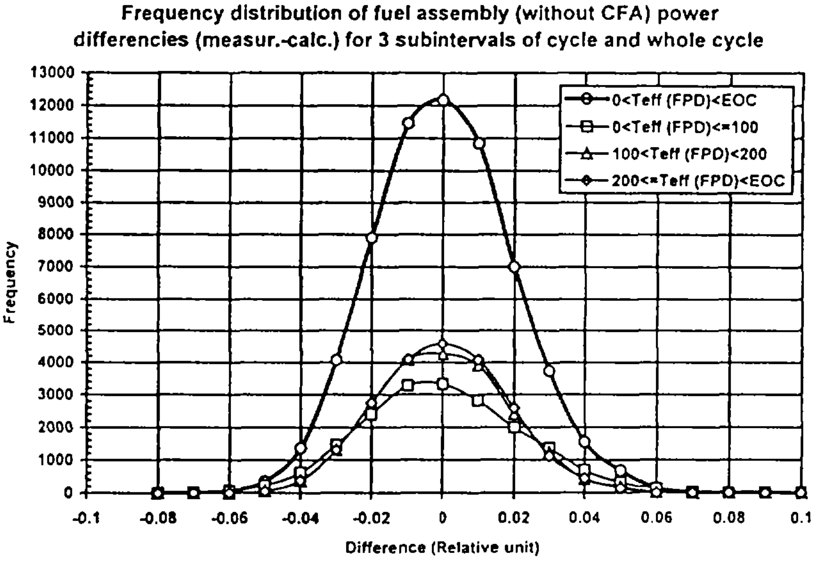


Figure 6.A EDU 1. unit, coarse mesh.

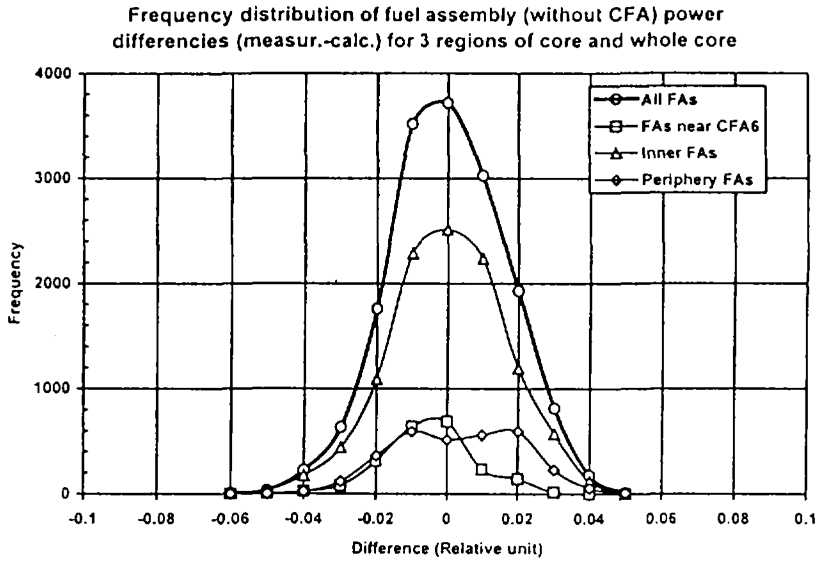


Figure 6.B EDU 1. unit, pin-wise.

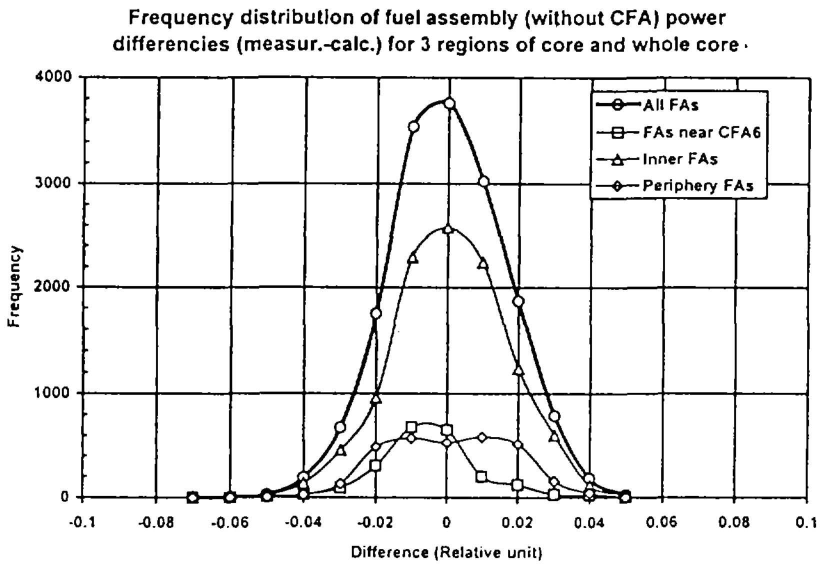


Figure 7.A All four units EDU together, coarse mesh.

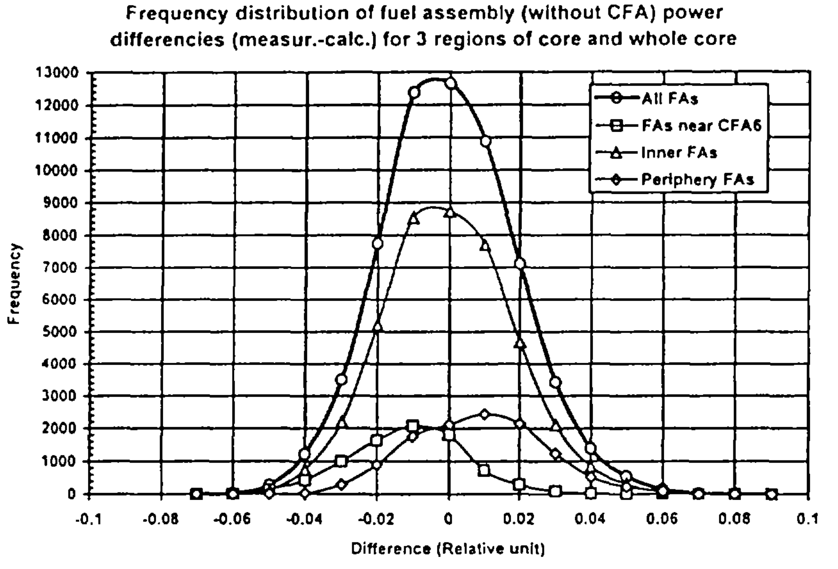


Figure 7.B All four units EDU together, pin-wise.

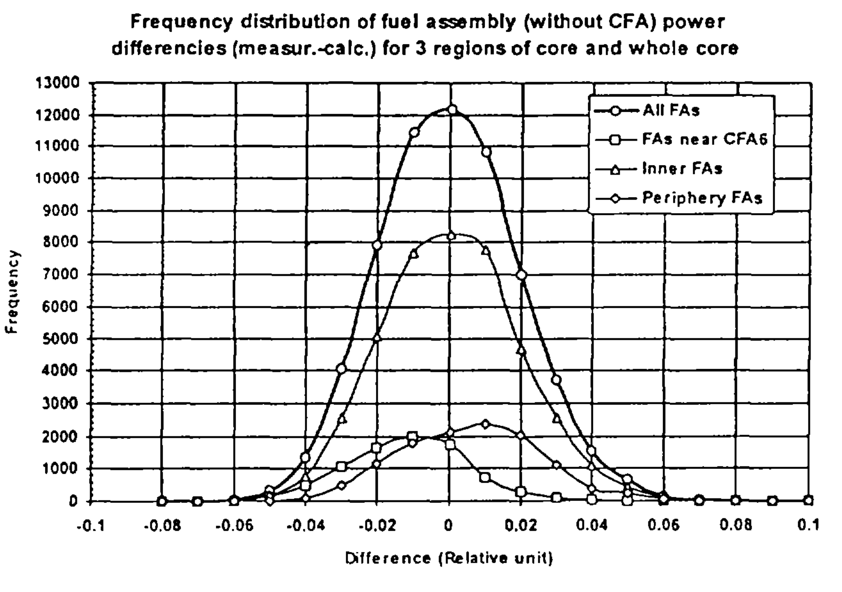


Figure 8.A All four units EDU together , coarse mesh.

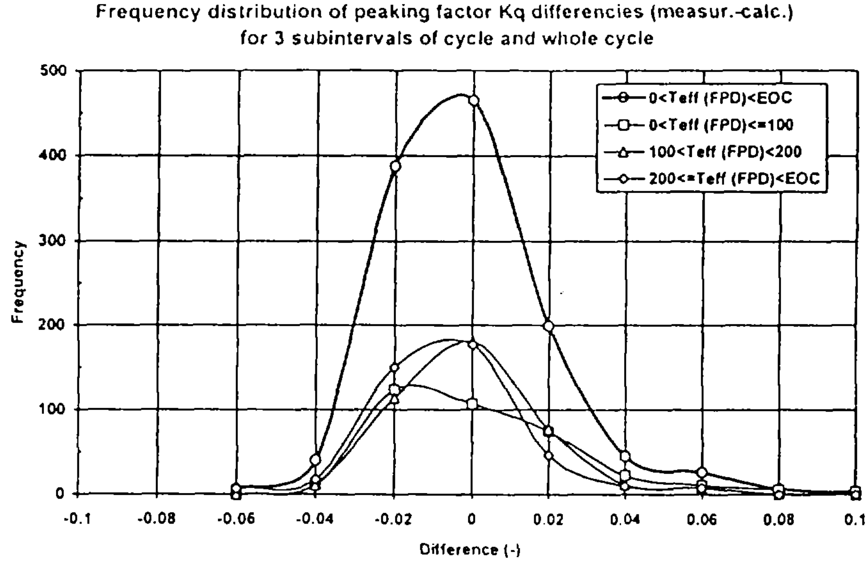
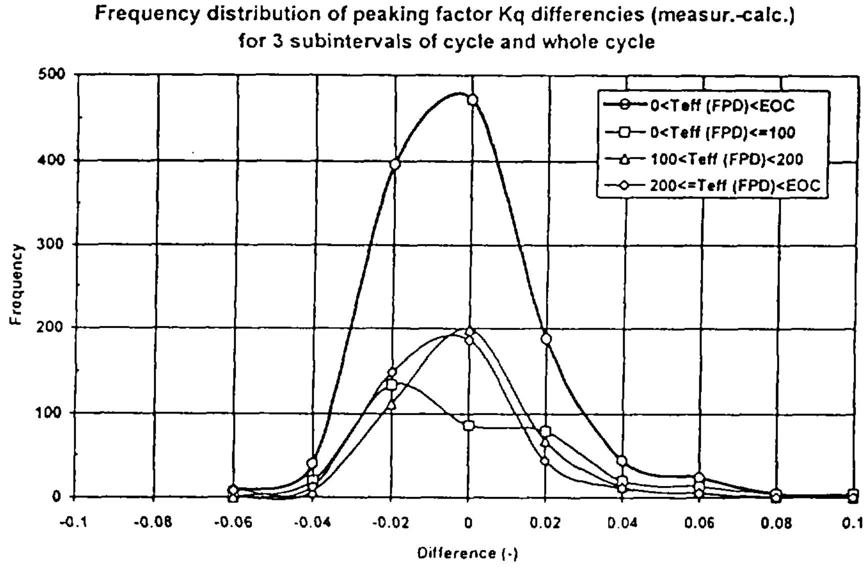


Figure 8.B All four units EDU together , pin-wise.



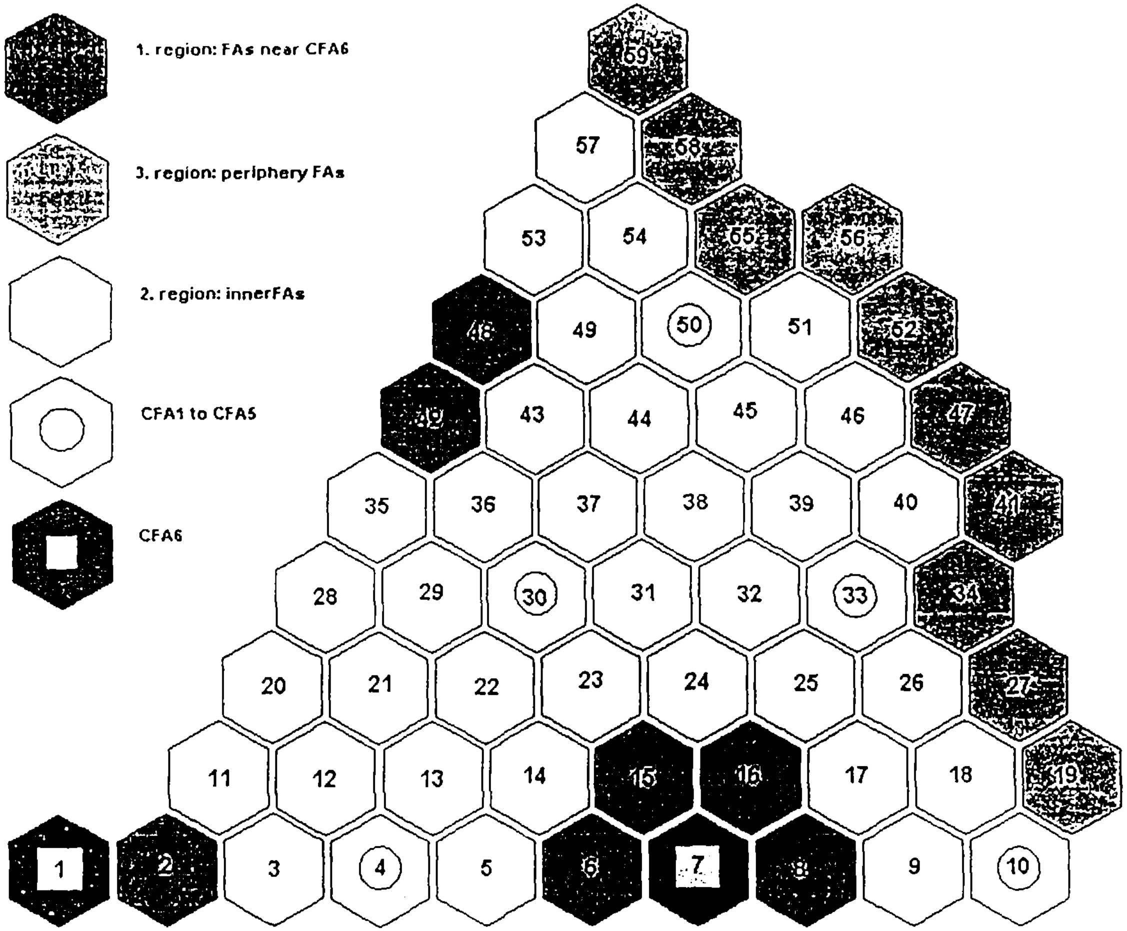


Figure 9

Scheme of core sector (60 degree symmetry). Three regions used for statistical analysis of position dependence of power differencies are marked out.

Region	Position	Count
1	FAs near CFA6	7
2	Inner FAs	35
3	Periphery EAs	10
Sum		52

Comment: All 6 groups of CFA (7 assemblies in sector 60°) are not used in statistical analyses of power differencies, because they are not measured.