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NEA NUCLEAR SCIENCE COMMITTEE

RINGHALS 1 STABILITY BENCHMARK

Final Report

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NUCLEAR ENERGY AGNECY
ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

Pursuant to Article 1 of the Convention signed in Paris on 14th December 1960, and which came into force on 30th September 1961, the Organisation for Economic Co-operation and Development (OECD) shall promote policies designed:

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— to contribute to sound economic expansion in Member as well as non-member countries in the process of economic development; and
— to contribute to the expansion of world trade on a multilateral, non-discriminatory basis in accordance with international obligations.

The original Member countries of the OECD are Austria, Belgium,Canada, Denmark, France, Germany, Greece, Iceland, Ireland, Italy, Luxembourg, the Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, the United Kingdom and the United States. The following countries became Members subsequently through accession at the dates indicated hereafter: Japan (28th April 1964), Finland (28th January 1969), Australia (7th June 1971), New Zealand (29th May 1973), Mexico (18th May 1994) the Czech Republic (21st December 1995) and Hungary (7th May 1996). The Commission of the European Communities takes part in the work of the OECD (Article 13 of the OECD Convention).

NUCLEAR ENERGY AGENCY

The OECD Nuclear Energy Agency (NEA) was established on 1st February 1958 under the name of the OEEC European Nuclear Energy Agency. It received its present designation on 20th April 1972, when Japan became its first non-European full Member. NEA membership today consists of all European Member countries of OECD as well as Australia, Canada, Japan, Republic of Korea, Mexico and the United States. The Commission of the European Communities takes part in the work of the Agency.

The primary objective of NEA is to promote co-operation among the governments of its participating countries in furthering the development of nuclear power as a safe, environmentally acceptable and economic energy source.

This is achieved by:

— *encouraging harmonization of national regulatory policies and practices, with particular reference to the safety of nuclear installations, protection of man against ionising radiation and preservation of the environment, radioactive waste management, and nuclear third party liability and insurance;*
— *assessing the contribution of nuclear power to the overall energy supply by keeping under review the technical and economic aspects of nuclear power growth and forecasting demand and supply for the different phases of the nuclear fuel cycle;*
— *developing exchanges of scientific and technical information particularly through participation in common services;*
— *setting up international research and development programmes and joint undertakings.*

In these and related tasks, NEA works in close collaboration with the International Atomic Energy Agency in Vienna, with which it has concluded a Co-operation Agreement, as well as with other international organisations in the nuclear field.

FOREWORD

Nuclear industries and licensing authorities need to be able to rely on the good performance of computer programs and nuclear data used in all important nuclear energy calculations. It is important that the methods and data issued should be internationally accepted. This is best achieved by validation and benchmarking on an international scale, with all countries concerned participating in the testing.

Benchmarks in which these codes are compared against sets of data from nuclear power plant operation or of specifically designed "clean" measurements have been organised and successfully concluded under the auspices of the OECD Nuclear Energy Agency on several topics. Thesebenchmark studies aim at verifying the correctness of computer codes and data, building confidence in methods and codes in areas where experiment is very expensive or lacking.

The present report summarises the work carried out in the frame of the Nuclear Science Committee activities concerning Boiling-water Reactor Stability. A task group addressing Light-water Reactor Core Transients has been set up under the former committee on Reactor Physics about five years ago. This activity has then been taken over by the Nuclear Science Committee. Apart from thebenchmark discussed in this report the following other benchmarks have been investigated or are in process of being initiated:

- H. Finnemann, H. Bauer, A. Galati, R. Martinelli: *Results of LWR Core Transients Benchmarks*, NEA/NSC/DOC(93)25, October 1993, comprising:
  - Six cases of a rod ejection accident in a PWR,
  - A cold water injection and core pressuration transient in a BWR;

- R. Fraikin: *PWR Benchmarks on Uncontrolled Rod Withdrawal at Zero Power*, NEA/NSC/DOC(96)20 – final draft June 1996;

- R. Fraikin: *Loss of Flow Accident (LOFA) Transients in a PWR* – in preparation;

- T. Lefvert: *BWR Time Series Analysis* – proposed 1996;

- K.N. Ivanov and A.J. Baratta: Proposal for a *Benchmark on Coupled Thermal-Hydraulic Spatial Kinetics Codes for LWR Analysis* (PWR Main Steam Line Break Benchmark) – proposed 1996.

The present work has been co-ordinated by Tomas Lefvert, Vattenfall AB, Sweden, who has also prepared the report. The benchmark specification and the data have been prepared by a team at the Ringhals 1 nuclear power plant.

This report is dedicated to the memory of Renato Martinelli, who was the initiator of this series of benchmark activity, and who has personally contributed in an essential way to its success.

The opinions expressed in this report are those of the authors only and do not necessarily represent the position of any Member country or international organisation. This report is published on the responsibility of the Secretary-general of the OECD.

CONTENTS

EXECUTIVE SUMMARY

There are several recent examples in OECD Member countries of inadvertent power oscillations in BWRs, an experience that has initiated activities in research and development as well as licensing and finding new core design and operation strategies. When such instability occurs the core can normally be expected to oscillate in one of two different modes (or, sometimes, with overlapping of the two modes). The fundamental mode is the in-phase, or global, mode where all fuel bundles oscillate together in phase; the other is the first harmonic mode, or out-of-phase, or regional, mode, where one half of the core oscillates out of phase against the other half. Both these modes have been observed in operating BWRs.

Computer programs have recently been developed by groups and institutes in several countries and more are under way. Data from instability events, notably in Caorso and La Salle, have been used widely in the past in order to tune and validate the various models and codes. Some BWR operators have performed stability measurements providing another, more reliable, source of data which, however, has not been generally available.

It was therefore concluded that a comprehensive and well defined set of data from such measurements assembled in an international Benchmark would be of interest to many code developers and could also be of value in the licensing efforts presently under way in some countries.

The present Benchmark thus has the purpose to enable code developers in member countries to test their codes and also to validate the predictive capability of their respective codes and models for stability analysis.

Data given come from measurements in BOC 14 and 15 in the Swedish BWR reactor Ringhals 1, designed by ABB Atom and owned and operated by Vattenfall AB. For these measurement campaigns the complete time series from the measurement is given as well as the usual evaluated stability parameters decay ratio and natural oscillation frequency for both the fundamental mode and the first harmonic mode. Measurements were also taken in cycles 16 and 17. Here all input data were given to perform the simulations but the measured data were not released in the first phase of the Benchmark. Thus the data from cycle 16 and 17 have served as blind tests for the predictive capability of the respective codes. The Benchmark comprises totally 41 state points from four cycles each with measured and evaluated decay ratios and natural frequencies. Moreover, in one of the BOC 14 measured state points regional oscillations were observed and measured offering an extended benchmark opportunity for those codes that operate in the time domain.

The time series data given in the Benchmark could also be used in validating and comparing models and algorithms used for evaluating data from noise measurements and for on-line monitoring of stability. This is, however, not the purpose of the present Benchmark but has been proposed to the NSC of NEA as a follow-up activity.

Different groups of data were given in the Benchmark specifications in order to be able to model the Ringhals 1 reactor in sufficient detail, to be able to adapt, or tune, the respective codes/models to the Ringhals 1 reactor and finally to predict stability parameters at BOC 16, 17.

The total amount of data given in the Benchmark was considerable and the work to assemble them made up a good part of the total effort.

The Benchmark attracted nine participants from eight countries featuring several different calculation models, some operating in the frequency domain and some in the time domain. The participating organisations and the codes used are listed below.

Organisation	*Code*	*Domain*
CSN/Univ. of Valencia, Spain	LAPUR	FD
NETCORP/SCANDPOWER, USA	LAPUR	FD
Nuclear Fuel Industries, Japan	STAIF-PK,DYNAS-2	FD,TD
Paul Scherrer Inst., Switzerland	RAMONA-3.5	TD
SCANDPOWER/ABB ATOM, Norway/Sweden	RAMONA-3	TD
SIEMENS, Germany	STAIF	FD
Toden Software Inc., Japan	TSI Stab.Eval.Syst.	FD
University of Pisa, DCMN, Italy	RELAP5/MOD2	TD

The report describes the methodology used and presents complete results in the form of tables and diagrams for all participants. When judging the reported results it is important to acknowledge for each participant and code the mode of application chosen in this Benchmark. For the purpose of this report we may distinguish between best estimate, conservative and basic validation applications. The codes used in validation may eventually be classified as either best estimate or conservative. The first two categories represent an established methodology for application of the respective code, while the last category show examples of code- and method validation at different levels.

The codes applied in the best estimate mode all come out with a very small bias in global decay ratio and with an uncertainty (one standard deviation) in the calculated decay ratio in the range 0.06 – 0.10. The codes under validation show higher fluctuation in both bias and uncertainty between cycles.

A standard deviation of less than 0.02 can be expected in the measured global oscillation frequencies for state points with decay ratio at least 0.3. All participants come close to this uncertainty in their calculated results, however, with a trend towards a systematic underestimation of the oscillation frequency.

Some of the participants also performed calculations for regional oscillation parameters. Both the bias and the standard deviation are higher than in the global oscillation case. The standard deviation of the results for the regional DR was in the range 0.08 to 0.14.

We may also conclude that the participating time-dependent codes can adequately reproduce the regional oscillations observed and registered in one of the measured state points.

In summary it may be stated that the calculation of the global stability characteristics of a BWR can today be performed with a precision rather close to that of the noise analysis methods used to evaluate the corresponding stability parameters from the raw data. This is true for frequency domain codes as well as for time domain codes but we have assumed that credit can be taken for tuning against a set of given evaluated data for the reactor in question.

As for the regional stability characteristics the picture is less clear and the methods for both time-series evaluation and calculation of oscillation parameters should be refined. A regional oscillation is potentially more troublesome for the present BWR core monitoring and core protection systems (however, means to handle this have been developed). At the same time the oscillatory behaviour of some BWRs, especially those with large cores, is normally dominated by the regional mode. The demand on precision in pre-calculations is therefore the same for the regional as for the global decay ratio. We also need a calculational tool to tell us with some confidence which core mode will be dominant in a certain reactor with given operating conditions and core design.

Chapter 1

INTRODUCTION

There are several recent examples in OECD Member countries of inadvertent power oscillations in BWRs, an experience that has initiated activities in research and development as well as licensing and finding new core design and operation strategies. When such instability occurs the core can normally be expected to oscillate in one of two different modes (or, sometimes, with overlapping of the two modes). The fundamental mode is the in-phase, or global, mode where all fuel bundles oscillate together in phase; the other is the first harmonic mode, or out-of-phase, or regional, mode, where one half of the core oscillates out of phase against the other half. Both these modes have been observed in operating BWRs.

According to the General Design Criteria (specifically GDC12) the BWR operator may either prove that oscillations will not occur, or that , if they do, he is sure to detect and safely suppress them. Whichever way he chooses to deal with BWR instability an analytical tool validated for predictive calculations is of great importance when e.g., evaluating a proposed core reload scheme or planning a start-up control rod sequence.

Computer programs have recently been developed by groups and institutes in several countries and more are under way. Data from instability events, notably in Caorso and La Salle, have been used widely in the past in order to tune and validate the various models and codes. Some BWR operators have performed stability measurements providing another, more reliable, source of data which, however, has not been generally available.

It was therefore concluded that a comprehensive and well defined set of data from such measurements assembled in an international Benchmark would be of interest to many code developers and could also be of value in the licensing efforts presently under way in some countries.

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The time series data given in the Benchmark could also be used in validating and comparing models and algorithms used for evaluating data from noise measurements and for on-line monitoring of stability. This is, however, not the purpose of the present Benchmark but has been proposed to the NSC of NEA as a follow-up activity.

It should be noted that there is another parallel NEA activity related to BWR stability, namely the State-of-the-art Report on *BWR Stability* promoted by the CSNI. The SOAR [1] will be available by the end of 1996.

Some milestones for the Benchmark are: Final specifications March 1994, Benchmark meeting at NEA headquarters in Paris May 1995 with participants for discussion of preliminary results and predictive results. This meeting also signified the end of the blind test since the evaluated stability parameters from cycles 16 and 17 were disclosed at that time. Dead-line for final results was October 1st, 1995.

In the following , we give in Chapter 2 a short summary of the information that was supplied in the Benchmark and is available also for future use. Chapter 3 outlines themethodology used by each participant and presents the results, whereas, in Chapter 4, we discuss and compare theresults from the various participants. Finally, Chapter 5 gives some concluding remarks and also discusses the need for future work.

A list of participants and contributors to the Benchmark is given in Appendix 2.

The data sets released together with the original Benchmark specification can be obtained from the OECD/NEA Data Bank. Their identification is:

ZZ-BWRSB-RINGHALS1	• Ringhals 1 reactor model data for cycles 14, 15, 16, 17 • measured data during cycles 14, 15
ZZ-BWRSB-RINGHALS2	• measured data during cycles 16, 17

Chapter 2

INFORMATION SUPPLIED IN THE BENCHMARK

The following groups of data were supplied in the Benchmark specifications [2,3]:

- To model the Ringhals 1 reactor:
  - General reactor data,
  - Reactor system geometry,
  - Core and fuel description,
  - Nuclear cross sections (fast and thermal groups),
  - Kinetic parameters (fast and thermal group),
  - Core thermal-hydraulic data,
  - Fuel rod data,
  - Heat transfer data,
  - Recirculation loop data,
  - Steam line data;
- To adapt codes/models to the Ringhals 1 reactor:
  - Measured data during tests at BOC 14 and 15 comprised of digital recordings in about 90 channels for about 11 minutes with sample frequency of 80 ms. data includes APRM and LPRM responses, coolant flows, feedwater flows etc.;
  - Evaluated decay ratio and natural oscillation frequency for all measured state points in cycle 14 and 15;
  - Cycle specific data for cycles 14 and 15 describing the core state at the time of the measurements, including control rod patterns, 3D power profiles etc.;
  - Operating history data for cycles 14,15;
- To predict stability parameters at BOC 16,17:
  - Cycle specific data describing the core state at the time of the measurements, including control rod patterns, 3D power profiles etc.;
  - Operating history data for cycles 16,17.

In parallel to the progress of the Benchmark there has been at Ringhals a further development of the methods used to evaluate the stability measurements. This resulted in a report [4] giving re-evaluated data for decay ratios and natural oscillation frequencies for the global and in–phase oscillation modes in cycles 14 – 17 as well as results from a new method to evaluate the same parameters for the regional mode (half core out-of-phase oscillations). The re-evaluated data are given in Tables 2.1 – 2.5 . The original, now obsolete, data for cycles 14 and 15 are given in Appendix 1.

Table 2.1 ***Ringhals 1 BOC cycle 14 stability test results***

Case	Power %	Core Flow kg/s	Global DR	*f (Hz)*	Regional DR	*f (Hz)*
1	65	4105	0.3	0.43	–	–
3	65	3666	0.69	0.43	0.57	0.43
4	70	3657	0.79	0.55	0.75	0.52
5	70	3868	0.67	0.51	0.6	0.5
6	70.2	4126	0.64	0.52	0.59	0.5
8	75.1	3884	0.78	0.52	0.79	0.5
9	72.6	3694	0.8	0.56	0.99	0.54
10	77.7	4104	0.71	0.5	0.63	0.49

Table 2.2 ***Ringhals 1 BOC cycle 15 stability test results***

Case	Power %	Core Flow kg/s	Global DR	*f (Hz)*	Regional DR	*f (Hz)*
1	64.7	4138	0.23	0.44	–	–
2	65.2	3881	0.24	0.42	–	–
3	65.1	3649	0.21	0.43	–	–
4	70.1	4165	0.33	0.44	–	–
5	70.1	3945	0.43	0.44	–	–
6	70.3	3775	0.59	0.47	0.39	0.47
8	75.2	3994	0.77	0.55	0.77	0.52
9	71.1	3633	0.67	0.53	0.67	0.52
10	77.3	4216	0.6	0.54	0.67	0.52

Table 2.3 ***Ringhals 1 BOC cycle 16 stability test results***

Case	Power %	Core Flow kg/s	Global DR	*f (Hz)*	Regional DR	*f (Hz)*
1	64.3	4112	0.54	0.48	–	–
2	64.6	3925	0.54	0.48	–	–
3	64.6	3698	0.69	0.47	0.55	0.45
4	70.2	4165	0.71	0.52	–	–
5	69.9	3932	0.67	0.49	0.51	0.49
6	69.5	3673	0.79	0.49	0.74	0.48
7	74.4	4081	0.72	0.5	0.5	0.49
8	74.9	3907	0.82	0.49	0.66	0.49
9	74.6	3678	0.87	0.48	0.82	0.47
10	76	4217	0.65	0.5	0.64	0.51
11	66.1	3653	0.66	0.48	0.55	0.45

Table 2.4 ***Ringhals 1 MOC Cycle 16 stability test results***

Case	Power	Core Flow	Global		Regional	
	%	*kg/s*	*DR*	*f (Hz)*	*DR*	*f (Hz)*
1	77.4	6588	0.35	0.68	–	–
2	75.6	6034	0.33	0.61	–	–
4	57.5	3815	0.73	0.51	0.58	0.49

Table 2.5 ***Ringhals 1 BOC Cycle 17 stability test results***

Case	Power	Core Flow	Global		Regional	
	%	*kg/s*	*DR*	*f (Hz)*	*DR*	*f (Hz)*
2	65.6	3954	0.24	0.46	–	–
3	65.6	3680	0.22	0.44	–	–
4	69.5	4166	0.32	0.46	–	–
5	69.9	4015	0.28	0.42	–	–
6	69.7	3758	0.34	0.46	–	–
7	74.9	4140	0.33	0.46	–	–
8	75.1	4020	0.41	0.48	–	–
9	75.4	3739	0.57	0.47	0.43	0.49
10	78.1	4058	0.49	0.49	–	–

Figure 2.1 shows where in the power-flow map of Ringhals 1 the stability measurements were taken. The solid line defines the present operating domain in the low flow-high power region.

Error estimates according to Table 2.6 are given for the new evaluation of the stability parameters of the global mode based on an optimal choice of model order in the analysis of sampled data. Note that this is the uncertainty due to the evaluation method only and does not include the measurement error. The uncertainty in Table 2.6 should be characterised as a maximum rather than a standard deviation.

Table 2.6 ***Uncertainty in estimating the DR due to model order selection***

Decay Ratio	*Uncertainty*
0.2	±0.15
0.4	±0.09
0.6	±0.07
0.8	±0.05

The data given in [4] is considered to be the best available evaluation of the measured data for this Benchmark and so the calculated results will be compared against this new set of evaluated data. The difference between the original (Appendix 1) and the new values (Tables 2.1 – 2.2) are sometimes larger than indicated by the measurement error as given in Table 2.6. The original values also contain a systematic error giving an underprediction of the DR.

It was emphasised in the Benchmark meeting in May 1995 that there is much more to be said about the evaluation of time series data of this type. Several different approaches are possible and have been successfully used in the past. A recommendation was given to study this important application in the field of signal analysis in a separate follow-up Benchmark activity of the Nuclear Science Committee. This was endorsed by the NSC in its 1996 plenary meeting.

The task for the participants in the Benchmark was to calculate the decay ratio and the natural resonance frequency of the global oscillation mode for each of the state points given in cycles 14, 15, 16 and 17, and, if possible, also the decay ratio and the natural resonance frequency of the first harmonic, regional oscillation mode.

The participants using a time domain code were asked to calculate also the average APRM response, the APRM-1 response and that of LPRMs 2, 13, 27 and 32 (lying close to a north-south core diagonal) on axial levels 2 and 4 in the case 9 of cycle 14. The APRM-1 signal is a sum over the signals from six LPRM strings, while the APRM signal is a sum over the APRM-n (n=1.4) signals thus being composed of 24 out of the 36 LPRMs.

Chapter 3

PARTICIPANTS AND METHODS

The Benchmark attracted nine participants from eight countries featuring several different calculation models, some operating in the frequency domain and some in the time domain, according to the overview in Table 3.1.

Table 3.1 ***Benchmark participants and methods***

Organisation	*Code*	*Frequency/ Time Domain*
CSN/UPV, Spain	LAPUR	FD
NETCORP/SCANDPOWER, U.S.A.	LAPUR	FD
NFI, Japan	STAIF-PK, DYNAS-2	FD,TD
PSI, Switzerland	RAMONA-3.5	TD
SCANDPOWER/ABB ATOM, Norway/Sweden	RAMONA-3	TD
SIEMENS, Germany	STAIF	FD
TSI, Japan	TSI Stab.Eval.Syst.	FD
University of Pisa, DCMN, Italy	RELAP5/MOD2	TD

3.1 CSN/UPV, Spain

This represents a joint participation from the Consejo de Seguridad Nuclear in Madrid and the Universidad Politecnica de Valencia, Departemento de Ingenieria Quimica y Nuclear. The Benchmark was performed as part of a larger program in the areas of signal analysis and reactor core modelling. This program is structured in different steps of which the first three falls within the present Benchmark. The fourth step is not planned within the schedule for this Benchmark.

i. Calculation of decay ratio (DR) of neutronic signals from cycles 14 and 15 in Ringhals 1. Intercomparison between different methods.
ii. Modes separation of the neutronic signal using nodal cross sections output from the 3D core simulator SIMULATE-3 [5]. The fundamental mode and the subcritical lambda modes are calculated. The neutronic signal is expressed as a linear combination of these modes and it will be possible to verify if the subcritical modes will be excited in case of instability.
iii. Setting up a LAPUR [6] model for the Ringhals 1 reactor. The DR associated with both in-phase and out-of-phase oscillations is calculated. Consistent kinetic parameters derived with SIMULATE-3.
iv. Setting up a TRAC model for the Ringhals 1 reactor. This will enable a transient stability analysis.

The results from the first step, although they were presented at the May 1995 Benchmark meeting and in [7], will not be discussed further in this report. We refer to the follow-up Benchmark in the field of signal analysis that was recommended partly as a result of this interesting Spanish work.

CSN/UPV did not participate in the blind test but have presented two sets of results from steps ii and iii, preliminary and final. The preliminary set of results, presented in [7], is not further discussed in this report.

The final results, given in [8], reflect several improvements. The neutronic model according to steps ii and iii was changed in order to improve the eigenvalue separation calculated from the nodal cross sections provided by SIMULATE-3. Basically, the core model was initialised using the fission power distributions from the data provided by Ringhals (instead of using equilibrium data). Improvements were also done to the axial reflector models and the correlation, required by the code, of the bypass flow fraction versus power and flow using the data from all the state-points in the four cycles. Furthermore, in calculations according to step ii, the two first azimuthal modes were determined, instead of only one, in order to know witch one is dominant.

The final results of [8] are shown in Tables 3.2 and 3.3 for step ii and step iii modelling, respectively. When discussing the results of Table 3.2 it should be kept in mind that there are limitations to the modal composition method separating the fundamental and the regional modes:

- The axial average power harmonic modes are not exactly orthogonal and also, the LPRMs are not in half-core radially symmetrical positions;.

- When the state point is far from the stability boundary the amplitude of the regional modes are much smaller than that of the global mode making difficult a proper separation of the modes. Therefore, the regional mode might be contaminated with the global mode.

Different noise analysis techniques were applied to calculate the DRs in the step ii modelling. However, the DRs obtained using the AR-Lyapunov approximation were considered to be more reliable and were therefore selected in the presentation of the results.

The values given in Table 3.2 are the averages of the DRs obtained with autoregressive models of orders 40, 50 and 60.

In Figures 3.1.a and 3.1.b. the global mode DRs and oscillation frequencies of Table 3.2 are compared with the given Benchmark data while, in Figures 3.2.a and 3.2.b, we compare the DRs and frequencies of the regional modes using the dominating regional mode from Table 3.2.

Referring to Table 3.3, the final LAPUR results have been obtained using a 6-region channel grouping based on the individual channel bulk coolant saturation elevations, in order to study the correlation between the DRs and this parameter (a strong correlation was found, see [5]). Some input data (gain factor and friction coefficients) were tuned to case 9 of cycle 14 with no new adjustments for the other state-points. The global mode DR results in Table 3.3 are compared with measured data in Figure 3.3 and the regional mode DRs in Figure 3.4.

3.2 NETCORP/SCANDPOWER, U.S.A.

Nuclear Engineering Technology Corporation participated in the post calculation part of the Benchmark together with Scandpower. Their report [9] gives the results of calculations with the LAPUR-K code. The LAPUR-K is a NETCORP propriety version of LAPUR5 [10].

Decay ratios and natural oscillation frequencies are calculated for both the global and the first regional mode.

3.2.1 Methodology

The methodology used for this study consisted of the two key ingredients:

i. A base LAPUR-K input deck was generated that contained all the non-case specific input cards. This deck was used along with the case specific cards that were generated by the auxiliary data processing codes to generate the case specific LAPUR-K input decks.

ii. The major assumptions were:
   a) The thermal hydraulic regions represented the active fuel length plus the unheated outlet section;
   b) The grouping of bundles per radial peaking factor and fuel type into thermal hydraulic regions was the same for all cases within a specific cycle. Seven thermal hydraulic regions were used for all cases;
   c) The hydraulic parameters for the thermal hydraulic regions that represented a mixture of different fuel types were weighted average values based on the number of bundles;
   d) The nominal built-in friction factor models of LAPUR5 were used;
   e) The spacer loss coefficients were explicitly represented;
   f) The flow was expended at the outlet of the thermal hydraulic regions;
   g) The gap heat transfer coefficient was based on the core average fuel temperature using the Thorn nucleate boiling heat transfer correlation;
   h) The recirculation loop gain and time constant were calculated from a model that accounted for the loop pressure drop (separators). the recirculation pump head assuming that all pumps were running at a reduced speed to balance the core pressure drop as calculated by LAPUR-K, and the loop fluid inertia;
   i) The neutronic data which included the density and fuel temperature reactivity coefficients, the delayed neutron parameters and the neutron life time were obtained from a model that was based on the nodal cross sections as determined from the information contained in the distribution files. All these parameters were treated on a core average basis assuming a power-squared weighting. The density reactivity coefficient was calculated as a function of density. The neutronic data corresponding to the least stable operating condition within a cycle was used for all cases in that cycle. Note that different neutronic data was used for the BOC and MOC 16 cases. The reactivity coefficients were calculated using a procedure that was based on the local reactivity with perturbation about the initial thermal hydraulic and neutronic conditions as determined from the distribution files;
   j) The global decay ratio calculation utilised the full complex plane search option with a convergence criterion of 0.01;
   k) The eigenvalue separations used for the regional mode decay ratio calculations were those reported by TSI (see [22]).

3.2.2 Results of the analysis

The results of the LAPUR-K benchmark calculations are shown in Table 3.4 and the calculated decay ratios and oscillation frequencies are compared with measured data in Figures 3.5.a and 3.5.b (global mode) and Figures 3.6.a and 3.6.b (regional mode).

3.3 NFI, Japan

Nuclear Fuel Industries have studied the Benchmark using two different methods, the frequency domain code STAIF-PK [11] and the 3D time domain code DYNAS-2. The STAIF-PK was used to calculate the decay ratios and natural resonance frequencies of all measured points for the global oscillation analysis and the decay ratio and frequency of the case 9 of cycle 14 for the regional oscillation analysis. The DYNAS-2 code was used to calculate the APRM- and LPRM transient response in case 9 of cycle 14. NFI report their results in [12].

3.3.1 Outline of the DYNAS-2 code

The DYNAS-2 code is comprised of four sub-models which include 3D neutron kinetics, fuel rod heat transfer, fuel channel thermal hydraulics and excore recirculation. The sub-models are coupled to each other by several variables: core power, heat flux, fuel temperature, channel void fraction, core inlet and exit flows, core pressure drop etc. The neutronics model calculates the transient neutron flux distribution by solving a 1-group coarse-mesh diffusion equation with one node per bundle and 12 to 25 nodes in the axial direction. The thermal-hydraulic model is based on axially 1D transient continuity and energy equations for the vapour and the mixture and a momentum equation for the mixture. The individual fuel channels in the core are grouped into several channel types independently from the neutronics noding. The fuel rod model solves a 1D radial heat transfer equation for each single rod representing the average heat generation rate of each thermal-hydraulic node. The ex-core recirculation loop system consists of upper plenum, steam separators, vessel dome and bulkwater, downcomer and recirculation pump system (internal and external jet pump), and lower plenum. The ex-core model solves mass, energy and momentum conservation equations for the mixture. The separator model incorporates an empirical equation to account for the rotational flow.

3.3.2 Outline of the STAIF-PK code

The frequency domain code STAIF-PK is comprised of four sub-models similar to the DYNAS-2 code, that is core neutronics, fuel rod heat transfer, fuel channel thermal hydraulics and excore recirculation. However, the STAIF-PK uses point kinetics instead of 3D kinetics and the transient equations are linearised by perturbation to a reference steady state and solved in the frequency domain by a Laplace transform.

The out-of-phase stability analysis by STAIF-PK is similar to the core-wide stability analysis, but some modifications were made for the reactivity to power transfer function, the nodal power perturbation and recirculation flow feedback according to a calculation method given in [13]. The higher harmonics analysis was performed by the higher harmonics analysis code, HARMO, a 1-group coarse mesh diffusion method. The higher mode flux vectors were obtained by a conventional iteration scheme starting from a random distribution and by subtracting the components of the orthogonal projection to the lower mode vectors after iteration. The stability analysis is performed by STAIF-PK using several grouped channels for which the power distribution was given by the fundamental mode, but the perturbation amplitude distribution was given by the first higher harmonics mode.

3.3.3 Calculated decay ratios and natural frequencies

The STAIF-PK analysis was carried out using 11 grouped channels and 3D power distributions given in the benchmark specification. The resulting DRs and natural frequencies for the global mode are given in Table 3.5 and a comparison with the corresponding data of the specifications in Figures 3.7.a and 3.7.b.

Regional oscillation analysis was performed for the case 9 of cycle 14 for which regional oscillation was detected by measurement. The first harmonic mode analysis by HARMO gave a subcriticality of 1.03$ for this harmonic. The STAIF-PK was carried out using 11 grouped channels and 3-D power distributions given in the Benchmark. The calculated decay ratio and natural oscillation frequency was 0.99 and 0.55, respectively, in close agreement with measured values.

3.3.4 Calculated APRM- and LPRM results

The results of the DYNAS-2 calculations showed a limit cycle for the case 9 of cycle 14 with an oscillation pattern in accordance with what was observed with regard to phase shift and damping. The results are illustrated in Figures 3.8 and 3.9 showing the calculated response of LPRM detectors placed on a line orthogonal to the symmetry line for the half-core oscillations.

3.4 PSI, Switzerland

Stability analysis is part of a larger research program at Paul Scherrer Institute. The RAMONA-3.5 code [14] has been chosen with the aim to develop an independent methodology to study the stability characteristics of the Swiss BWRs. The work is supported by HSK, the Swiss nuclear regulatory authority. The Benchmark has served the dual purpose of supporting the methodology development as well as providing an opportunity for code validation. In view of this, emphasis was put on post calculations, but for cycle 16 and some state points in cycle 17 pre-calculated results were reported at the Benchmark meeting in May 1995 [15].

3.4.1 Methodology

The methodology for stability analysis at PSI can be divided into three parts:

i. Calculation of macroscopic cross sections for the nodal mesh of the 3D core simulator in RAMONA-3.5. This is performed by the 2D lattice transport code CASMO-3 [16]. The results from CASMO-3 are transformed into the proper format for the simulator through intermediate coupling codes. Although CASMO cross sections were provided with the Benchmark they were recalculated by PSI from the CASMO input decks provided separately by Ringhals. This was done in order to test all parts of the PSI methodology.

ii. Calculation of the transient system response, including the reactor core. A plant model for RAMONA-3.5 was set up for Ringhals 1 based on the data given in the Benchmark. The RAMONA-3.5 code features a seven component model for the primary system plus special models for several safety systems. The neutron transport is solved with a 3D, 1.5 energy group nodal diffusion approximation. A 1D radial heat transport is performed for the pellet, gap and cladding regions of the fuel rod. The 4-equation thermohydraulic model includes two mass balance equations for water and steam and one equation each for the energy and momentum balance of the two-phase mixture.

iii. Signal analysis. The dynamic calculations result in time series simulating the response in each LPRM (there are 36 strings with 4 axial detectors each in Ringhals 1) and APRM.

These data are analysed using standard methods to find the decay ratio, natural oscillation frequency and phase shifts.

3.4.2 Results

Calculations were performed for 35 of the 41 state points given in the Benchmark. The results are given in Table 3.6 and a comparison with measured data in Figures 3.10.a and 3.10.b, and 3.11.a and 3.11.b for the global and regional decay ratios, respectively.

3.5 SCANDPOWER/ABB ATOM, Norway/Sweden

Using the RAMONA-3 code Scandpower and ABB Atom have participated jointly in the Benchmark. True predictions have been given of the stability parameters for all state points in cycles 16 and 17. Apart from core decay ratios and natural frequencies of all 41 points, case 9 of cycles 14 to 17 (the most limiting case of each cycle) was studied in detail calculating the time-evolution of the signals from the requested APRM and LPRM detectors.

3.5.1 Methodology

The RAMONA-3 is specifically designed [17] for transient modelling of BWR systems. Special emphasis is placed on the core modelling with full 3D neutron kinetics and explicit representation of each flow channel in the core. The RAMONA-3 plant model is shown in Figure 3.12. The coolant flow conditions are, inside the pressure vessel, calculated using a basic 4-equation model (cf. section 3.4). Constitutive relationships are given for non-equilibrium vapour generation and condensation, unequal phase velocities as well as wall friction and heat transfer.

RAMONA-3 automatically finds the steady state initial conditions according to the specified operating data. The numerical time integration is performed using an implicit predictor/corrector scheme for the neutronics and the fuel model and a 2nd order explicit integration method for the hydraulics. The input to RAMONA-3 for the Benchmark are given in all details in [18].

The work methodology was the following:

i. The fuel assembly lattice and nodal core distribution data supplied by NEA were converted to a format suitable for RAMONA-3.
ii. The plant model was set up as described in [18].
iii. Static 3D calculations were done to compare RAMONA-3's power distribution against that supplied by NEA. Nodal standard deviations of 6% or less were considered as acceptable.
iv. All test points were simulated in the dynamic mode. Symmetric reactivity (control rod) perturbations were simulated and the reactor response calculated during at least 30 seconds.
v. From the RAMONA-3 calculated reactor response decay ratios and oscillation frequencies for the global mode were derived.
vi. Some cases with a tendency to regional oscillations were analysed in more detail by either simulating asymmetric reactivity perturbations or letting the simulation run during long periods and observing oscillation patterns. For one case (case 9 in cycle 15) the decay ratio of the first harmonic could be estimated.

3.5.2 RAMONA-3 results

The RAMONA-3 results on decay ratios and oscillation frequency are shown in Table 3.7. For cycles 14 and 15 they represent post-calculations while for cycles 16 and 17 calculations were performed without previous knowledge of the measured stability data. The calculated values are compared with measured data in Figures 3.13.a and 3.13.b.

Cases no 9 of cycles 14-17 were studied in detail since they were the most limiting cases in each cycle. Results are presented in [17] showing, for each of these measuring points, the evolution in the time domain of the average APRM reading, of APRM-1 and of LPRM detectors no 2, 13, 27 and 32 at level 4 (bottom of the core).

RAMONA-3 results following a global reactivity perturbation at time zero in case 9 of cycle 14 are illustrated in Figure 3.14. Here are shown the calculated LPRM readings for detectors lying on a N-S axis. The oscillation pattern in the core changes after about 50 s with growing (decay ratio >1), out-of-phase oscillations with a 180° phase shift between the north and south core halves.

In case 9 of cycle 15 the global decay ratio was evaluated to 0.71 following a global reactivity perturbation. Here the oscillation pattern is changing after about 30s but without increase in the oscillation amplitude. To analyse the possibility of regional instabilities, the same case was re-run during 50s without any postulated perturbation. This shows that the core has a tendency to azimuthal oscillations although the decay ratio <1.0, since no amplitude increase could be observed.

From the information obtained in the previous calculations, an asymmetric perturbation was designed in order to initiate out-of-phase oscillations and RAMONA-3 was run during 30s. This gave clear indication of half-core regional oscillations with an E-W symmetry line. The decay ratio for the first harmonic was estimated to 0.90.

Case 9 of cycle 16 is of particular interest, showing a tendency to both global and regional instabilities. In a first run with a global initial reactivity perturbation no phase shift could be observed between LPRM detectors positioned along the core diagonals. The decay ratio for the global mode was evaluated to be 0.95. However, the global oscillation amplitude at the end of the simulation period was still too large to enable a possible change in oscillation pattern (cf. the results above for case 9 cycle 14). Therefore RAMONA-3 was rerun with an asymmetric reactivity perturbation which actually initiated a small amplitude azimuthal oscillation with a 180° phase shift between the N-W and the S-E core halves. The conclusion from these calculations was that the core is close to both the global and the out-of-phase instability limit, the decay ratio for both modes probably being about the same.

Finally, in case 9 of cycle 17, the results after a global perturbation (with global decay ratio of 0.64) revealed an asymptotic regional oscillation pattern where opposite core quadrants have a phase shift of 180°, while the phase shift between contiguous quadrants is about 45°. A decay ratio for the regional oscillations could not be evaluated since it was not possible to induce this kind of oscillations by means of asymmetric perturbations. It is therefore concluded that although the core has a tendency to regional oscillations the decay ratio for this mode must be close to or slightly below that of the global mode.

3.6 SIEMENS, Germany

Siemens participated using the well known frequency domain code STAIF providing predictive results for cycles 16 and 17 as well as post-calculations for cycles 14 and 15.

3.6.1 Outline of the STAIF code

The program STAIF (Stability Analysis in the Frequency Domain) incorporates a linearised model of the reactor core and recirculation loop. The individual model components of STAIF are briefly characterised below:

- *Neutron kinetics*: One-dimensional, one-group neutronics with axially variable void and Doppler feed-back, accounting for six groups of delayed neutrons;
- *Channel thermal hydraulics*: Multiple, parallel channels with independent geometry and axial power distribution, two mass equations, one energy and one momentum equation;
- *Fuel heat transfer*: Detailed fuel heat transfer for an average rod per channel using axially variable temperature-dependent properties;
- *Recirculation loop*: Detailed representation of all recirculation loop components like upper plenum, standpipes, separators, steam dome, bulkwater, and down-comer region, recirculation pumps and lower plenum.

All the above mentioned model components are considered for the calculation of the global mode. STAIF is also capable of the out-of-phase, regional mode [19,20], where the recirculation loop feed-back is cut off to maintain a constant core average pressure drop.

3.6.2 Methodology and input preparation

The generation of nodal nuclear cross sections is based on the 2D lattice cross sections, the 3D nodal distribution arrays and the control rod patterns supplied in the Benchmark specifications. Condensation of the 2-group neutronics data to the required 1-group data is then carried out. Channel grouping for partial radial condensation is based on the radial power distribution and the fuel assembly type.

For the channel thermal hydraulic calculations STAIF requires, per channel group, the geometrical characteristics of the respective fuel assembly including spacer and tie plate loss coefficients, which have all been taken from the specifications. The inlet orifice loss coefficients are also taken into account.

Volume and length of the various recirculation loop components mentioned above were also taken from given data and are used in STAIF to calculate the momentum balance for the entire loop. Also required are the corresponding loss coefficients which have been estimated. Pump coefficients have been generated for the external pump model in STAIF using the given pump curve.

For the regional mode calculations, static eigenmode analysis for the harmonic solutions of the neutron flux are carried out, after solving for the global mode. The global mode 3D solution was supplied in the Benchmark, and not calculated by the standard Siemens simulator code. In such a case it is difficult to arrive at a consistent harmonic solution. For this reason the regional mode calculations were not performed.

3.6.3 Results of the analysis

The results of the STAIF analysis for all four cycles are listed in Table 3.8 and compared with measured data in Figures 3.15.a and 3.15.b.

3.7 Toden Software Incorporated (TSI), Japan

TSI applied their newly developed Stability Analysis System to the Benchmark data. Although the final results for cycles 16 and 17 were delivered after the Benchmark meeting in May 1995, they are in fact truly predictive, since evaluated LPRM data from these cycles were not used. Two sets of data are given, one using the design base models of system and one using best fit models. The TSI Benchmark report is [21].

3.7.1 Evaluation procedure and analytical models

An outline of the TSI BWR stability evaluation system is given in Figure 3.16 showing the flow of information from design and other input data through the respective calculational models. Although some of the steps could have been omitted using the Benchmark data (e.g., two-group constants for the fuel and 3D power distributions in the core), those steps were also included in order to test all parts of the evaluation system. Also, the given model parameters for void-quality and two-phase multiplier differed significantly from those used in the corresponding TSI model. The Benchmark calculations were performed using the TSI parameters. Then the resulting core thermal hydraulic characteristics and power distributions were compared with those of the Benchmark specifications in the process of tuning the models against data from cycles 14 and 15.

Apart from the commercially available codes INTERPIN, CASMO and SIMULATE, the TSI stability analysis system also includes the TSI original codes ACCORD and CTCYCL as well as the TSI version of the LAPUR code.

- ACCORD is a two group higher neutron flux mode analysing model based on the finite difference method. However, the local flux shape around control rods makes the convergence slow unless a good initial guess is provided. To speed up convergence 2D harmonic fluxes are used to define a proper initial guess of the 3D modal fluxes.

- CTCYCL is a multi-channel core thermal hydraulic model which calculates the core flow distribution, bypass flow fraction and thermal margin (MCPR) in specified core states. Each channel consists of the active, the water rod and the channel paths which run in parallel. Two-phase effects are calculated using the following correlations:

– void-quality	EPRI Chexal-Lellouche
– two-phase friction multiplier	modified Martinelli-Nelson
– two-phase local loss multiplier	modified Romie

Finally, the LAPUR-TSI has evolved from the conventional frequency domain stability LAPUR model (see e.g., [6]) applied in the BWR core design licensing.

3.7.2 Evaluation results

Prior to the stability analysis TSI performed comparisons between supplied Benchmark data and their own results for some important parameters. The two-group CASMO constants for the various fuel types were judged to be equivalent for the purpose of this benchmark. The bundle wise relations between power and flow for different bundle types were calculated from CTCYCL with slight parameter adjustment to fit those of the NEA data. Furthermore, TSI performed their own core follow calculations, based on the supplied operating information, to arrive at radial power distributions for the stability test points. Again, the agreement was good when comparing with the Benchmark data although at BOC 15 the discrepancy was slightly higher than in the other cycles.

Finally, the higher mode analysis showed that the two first higher modes are those where one half of the core oscillates against the other half with either a "north-south" or a "east-west" neutral radial axis.

The models of the stability analysis system were tuned against the measured/evaluated stability data of the seventeen state points in cycles 14 and 15. In the design base model several input parameters, such as e.g., the void coefficient, are chosen to give conservative decay ratios over a wide range of operating conditions. In contrast, in the best fit approach, models and input data are based as far as possible on actual plant specifications and experimental data. Results for the global decay ratio and oscillation frequency are given in Figures 3.17.a and 3.17.b and 3.19.a and 3.19.b for the design base and the best fit models, respectively.

The regional decay ratios were also calculated for all test points, the results are given in Figures 3. 18.A and 3.18.b and 3.20.a and 3.20.b, respectively, for the two model approaches. There are, however, several uncertain factors in these calculations, notably the channel grouping and the relative amplitude of the higher mode (only one higher mode is kept). The interaction between different modes is another factor. Most of these problems are caused by the linear approximation to an inherently non-linear phenomenon and could be overcome by using a time domain model.

After the tuning against cycle 14 and 15 data the models were frozen and used to calculate the stability parameters of the measured state points in cycles 16 and 17. Therefore, those results are truly predictive even though the measured data had already been released. The results for cycles 16 and 17 are included in Figures 3.17 through 3.20. The complete results are also given in Tables 3.9 and 3.10 for the design base and the best fit models, respectively.

3.8 University of Pisa, Dept. DCMN, Italy

The benchmark activity was carried out with the main purpose to extend the validation area of the adopted code and of the applied methodology attempting to characterise the link between neutronics and thermal hydraulics.

A 1D frozen thermal hydraulic code (RELAP5/MOD2) including a 0D kinetic model was used. An independently developed 1D kinetic model has been coupled to the same code and applied to the Benchmark problem. DCMN has provided a main report [22] and a complementary report [23] explaining and discussing in more detail some of the predicted results in cycle 17.

3.8.1 Methodology and results

Five main phases should be distinguished as described below. Unless otherwise specified all the results and the assumptions are related to the use of the 0D neutronics.

i. *Nodalisation development.* Following standard criteria at DCMN nodalisation was performed for the Ringhals 1 BWR based on the given data. This resulted in 168 nodes using four parallel channels in the active part of the core, one bypass channel and totally 90 nodes for the whole core.

ii. *Nodalisation qualification.* Several separate steps were required for qualification of the thermal hydraulics and the neutronics part of the input deck. Thermal hydraulic steady state properties of the reactor at 110% power were found. Examples are given for core flow, lower plenum fluid temperature, steam line pressure and downcomer level both at 110% and in the state point corresponding to case 9 of cycle 14. Next the decay ratio versus void reactivity coefficient was studied in steady state neutronic calculations with best estimate input data. As a final procedure, before applying the nodalisation to the prediction of blind cases, a number of transient neutronic-thermal-hydraulic calculations were performed for the decay ratio in the domain defined by the cycle 14 and 15 cases. In this procedure the concept of "phenomenological area" (see [24]) was applied providing a means of selecting the cases in cycles 16 and 17 that belong to the validated area of application.

iii. *Sensitivity analysis*. Changing selected input parameters, one at a time, several series of calculations were carried out. From the results the following functions or diagrams were obtained:
   - Decay ratio vs. core power (constant core flow),
   - Decay ratio vs. core flow (constant power),
   - Decay ratio vs. pressure,
   - Decay ratio vs. feedwater temperature,
   - Decay ratio vs. input perturbations,
   - Decay ratio vs. linear power distribution.

iv. *Predictive calculations for cycles 16 and 17*. The appropriate cases were selected according to ii) above. The results of all calculations are given in Table 3.11 and compared with measured data in Fig. 3.21. The results in Figure 3.21 are true predictions in cycles 16 and 17. In [23] additional calculational results are given for two cases with exceptionally high deviation from measured values. This is discussed in more detail in Chapter 4 below.

v. A 1D neutronic code MODICO-AV solving the classical two group kinetic equations in the diffusion approximation has recently been coupled to RELAP5/MOD2. The Benchmark was considered as a good opportunity to start a validation of the code. However, since there is at present no validated procedure to collapse the 3D nodal data for Ringhals 1 only parametrical studies could be performed at the present stage which fall outside this report. See [22] for a discussion of these calculations.

Chapter 4

DISCUSSION

Before discussing the results presented in the previous chapter we look in Section 4.1 at theuncertainties in measured and calculated data and acknowledge in Section 4.2 the different status and mode of application of the various codes used in the Benchmark.

4.1 Uncertainty of stability parameters

4.1.1 Measured/evaluated parameters

The true values of the observed stability parameters (decay ratio and oscillation frequency) are not known. First there is an error in the measured detector time series data which have not been quantified. However, the influence of this error on the evaluated stability parameters is believed to be small since the sampling time for each measurement was relatively long and should provide data allowing a relatively accurate noise analysis. Then there is an error (believed to be dominant) due to the evaluation procedure of a given time series in order to get the stability parameters. This error, which can be characterised as a maximum deviation, has been estimated in [4] and is given in Table 2.6 of the present report for the particular noise analysis method chosen to define the measured stability parameters of this Benchmark. Note, that in the figures in Chapter 3 comparing measured and calculated global decay ratios we have indicated an uncertainty band according to Table 2.6. Calculated values inside this region are therefore consistent with measured data. (Values calculated by a conservative approach would first have to be shifted downwards by an amount corresponding to the degree of conservatism claimed).

It is interesting to observe that the global decay ratios evaluated by CSN/UPV by means of another well established noise analysis method (AR-Lyapunov), with very few exceptions, all lie inside the uncertainty band defined by Table 2.6 (see Figure 3.1.a). We can also derive from Table 3.2 that these decay ratios have a bias of 0.01 and a standard deviation of 0.07 over the 40state points in all cycles as compared to those given in the Benchmark. Assuming that the two methods have the same uncertainty, the standard deviation of each method over all cycles would therefore be about 0.05. This value would apply to evaluated decay ratios in the range 0.2-1. Looking instead at the subset (24 state points) in the range 0.5 – 1 the corresponding standard deviation of the evaluated decay ratio is about 0.03.

4.1.2 Calculated parameters

A recent study [25] has been performed by Scandpower, on behalf of a group of six European utilities, using RAMONA-3 to analyse in a systematic way the contributions to the total uncertainty from individual plant- and cycle-dependent parameters as well as different operating conditions. We give as an example the resulting relative ranking (Table 4.1) of the individual contributions to the uncertainty in Ringhals 1. The usefulness of such an approach to assess theuncertainties is obvious since it indicates those parameters and associated models one should focus on to get more accurate results.

The total error includes both systematic and random components. Tuning the code in post-calculations is a way to decrease or even eliminate systematic errors in the application to a certain reactor, or class of reactors. The errors displayed in section 4.3 below reflect this. An error assessment as in [25] is expected to lead to a higher uncertainty than given in 4.3 since it includes the systematic errors typical of a first application prediction to a reactor.

Table 4.1
Ringhals 1- predicted ranking of the contribution to the uncertainty from individual parameters

Parameter
Inlet throttling
Pump model
Power shape
Core flow
Inlet subcooling
Fuel gap conductance
Beta-effective
Outer loop pressure drop
Riser pressure drop
Total power
Outlet throttling
Spacer pressure drop
Fuel conductivity
Fuel heat capacity

4.2 Mode of application

When judging the results presented in Chapter 3 it is important to acknowledge for each participant and code the mode of application chosen in this Benchmark. For the purpose of this report we may distinguish between best estimate, conservative and basic validation applications. The codes used in validation may eventually be classified as either best estimate or conservative. The first two categories represent an established methodology for application of the respective code, while the last category show examples of code- and method validation at different levels. In Table 4.2 the previous Table 3.1 is incorporated with additional information on the mode of application. Furthermore, in the last column, /B indicates that blind results were delivered for cycles 16 and 17.

Table 4.2 ***Participants, codes and mode of application***

Organisation	*Code*	*Domain*	*Mode*
CSN/UPV, Spain	LAPUR	FD	Validation
NETCORP/SCANDPOWER, U.S.A.	LAPUR	FD	Validation
NFI, Japan	STAIF-PK, DYNAS-2	FD,TD	Best estimate/B
PSI, Switzerland	RAMONA-3.5	TD	Validation
SCANDPOWER/ABB ATOM, Norway/Sweden	RAMONA-3	TD	Best estimate/B
SIEMENS, Germany	STAIF	FD	Best estimate/B
TSI, Japan	TSI Stab.Eval.Syst.	FD	Cons./Best est./B
University of Pisa, DCMN, Italy	RELAP5/MOD2	TD	Validation

4.3 Discussion of results

In many respects the detailed presentation of the results given in Chapter 3 speaks for itself. In the following sub-sections we will focus on bias and uncertainty in the results, discuss the reliability in determining the regional decay ratio and comment on the predictive capability of some of the codes.

4.3.1 Global mode results

We summarise in Table 4.3 the average (bias) and the standard deviation of the difference between the calculated and the measured global decay ratio. These statistical parameters are given for each cycle, all cycles and, for those who delivered blind results, also for cycles 14+15 and 16+17, respectively.

Table 4.3
Average and standard deviation of the difference between calculated and measured global decay ratio

Cycle		Participant								
no of points		CSN/ UPV	NET-CORP	NFI	PSI	SCP/ ABB	SIE-MENS	TSI des	TSI be	Univ. PISA
14	bias	0.01	0.03	0.04	-0.03	-0.05	0.02	0.12	-0.10	
(8)	std.dev.	0.05	0.16	0.10	0.05	0.05	0.08	0.13	0.10	
15	*bias*	*0.04*	*0.03*	*0.03*	*-0.11*	*-0.03*	*0.03*	*0.17*	*-0.05*	*0.01*
(9)	*std.dev.*	*0.13*	*0.17*	*0.11*	*0.09*	*0.06*	*0.07*	*0.07*	*0.06*	*0.07*
16	bias	0.06	-0.11	0.00	0.06	0.01	-0.02	0.44	0.12	
(11+3)	std.dev.	0.07	0.10	0.06	0.07	0.07	0.05	0.10	0.05	
17	*bias*	*0.13*	*-0.03*	*0.07*	*-0.06*	*0.01*	*-0.07*	*0.12*	*-0.08*	
(9)	*std.dev.*	*0.07*	*0.07*	*0.13*	*0.08*	*0.05*	*0.04*	*0.07*	*0.05*	
14+15	bias			0.04		-0.04	0.02	0.14	-0.07	
(17)	std.dev.			0.10/ 0.10		0.06/ 0.06	0.07/ 0.07	0.10/ 0.10	0.08/ 0.08	
16+17	*bias*			*0.03*		*0.01*	*-0.04*	*0.32*	*0.04*	
(23)	*std.dev.*			*0.10/ 0.11*		*0.06/ 0.06*	*0.05/ 0.10*	*0.09/ 0.23*	*0.05/ 0.11*	
All	bias	0.07	-0.03	0.03	-0.01	-0.01	-0.01	0.24	-0.01	0.08
(40)	std.dev.	0.08/ 0.09	0.13/ 0.14	0.10/ 0.11	0.07/ 0.10	0.06/ 0.06	0.06/ 0.09	0.09/ 0.20	0.06/ 0.11	0.06/ 0.28

For standard deviations taken over more than one cycle two alternatives are given. The first entry refers to the assumption that the true standard deviation is the same in each cycle and that the cyclewise observed values are independent estimates of the true value. However, the bias is allowed to vary from one cycle to another. In calculating the standard deviation in the second entry all measuring points in the respective cycles are taken together and the deviation taken around the resulting mean value. Obviously, in the latter case, a fluctuation in the mean value between cycles tends to increase the calculated standard deviation.

The codes applied in the best estimate mode all come out with a very small bias in decay ratio and with an uncertainty (one standard deviation) in the difference between calculated and measured decay ratio in the range 0.06 – 0.10. The codes under validation show higher fluctuation in both bias and uncertainty between cycles.

We have no estimate for the uncertainty in measured natural oscillation frequency so the quality of the calculated results presented in Chapter 3 cannot be directly assessed in absolute terms. However, when consulting again the independent noise analysis results of CSN/UPV we find that, over all cycles, the difference between calculated and measured global oscillation frequency has a bias of -0.01 and a standard deviation of 0.02 (the two methods showing very large differences for small decay ratios, measuring points with decay ratio below 0.3 were left out). Consequently, an uncertainty of less than 0.02 can be expected in the measured oscillation frequencies for state points with decay ratio at least 0.3.

The results of the participants calculating the oscillation frequency are compared in Table 4.4. As can be seen, uncertainties in the calculated frequencies are small. In some cases there is a negative bias outside the range indicated by the uncertainty, that is, a systematic underestimation.

Table 4.4
Average and standard deviation of the difference between calculated and measured global oscillation frequency

Cycle		*Participant*						
		NET-CORP	NFI	PSI	SCP/ ABB	SIE-MENS	TSI des	TSI be
All	bias	-0.11	-0.02	-0.02	-0.02	-0.05	0.00	0.02
	std.dev.	0.02	0.03	0.02	0.01	0.02	0.03	0.03

4.3.2 Regional mode results

A new method [26] was applied by Ringhals in evaluating the regional decay ratio from the LPRM signals. There is no estimate of the uncertainty in this method other than the reasonable assumption that it is at least as high as that for the global decay ratio. Also, there is no independent evaluation of the regional stability characteristics that could by comparison give us an indication of the uncertainty of this type of noise analysis methods.

Table 4.5 presents a summary of the results of those participants who performed calculations for regional oscillation parameters. More detailed results are found in Chapter 3, e.g., the study performed by ScP/ABB Atom for three selected state points. Both the bias and the standard deviation are higher than in the global oscillation case, but since the corresponding parameters for the evaluation method are not known we can not assess the quality of the calculated data in an absolute sense. The standard deviation of the results is in the range 0.08 to 0.14.

Table 4.5
Average and standard deviation of the difference between calculated and measured regional decay ratio

Cycle		*Participant*					
		CSN/UPV AR-Lyap.	CSN/UPV LAPUR	NET-CORP	PSI	TSI des	TSI be
All	bias	0.03	0.08	0.30	0.06	0.15	0.04
	std.dev.	0.08	0.14	0.14	0.10	0.11	0.10

The calculated regional oscillation frequency is given in Figures 3.2.b (CSN/UPV AR-Lyapunov), 3.6.b (NETCORP), 3.11.b (PSI), 3.18.b (TSI design) and 3.20.b (TSI best fit). By inspection we conclude that the results with regard to trend and uncertainty are similar to those for the global oscillation frequency.

4.3.3 Time-dependent results

From the time-dependent results presented in Figures 3.8, 3.9 and 3.14 we may conclude that the codes DYNAS-2 from NFI and RAMONA-3 from Scandpower can adequately reproduce the regional oscillations observed in Ringhals 1 in case 9 of cycle 14. Furthermore, ScP/ABB Atom's study of the tendency towards regional oscillations in case 9 of cycles 15-17, described in Sub-section 3.5.2, is an interesting example of using a time-dependent code to separate oscillation modes. Perhaps this procedure could work faster, needing less trial and error, if combined with a compatible 3D neutron flux harmonics solver. This could provide information on how to trigger the regional oscillation.

4.3.4 Predictive capability

One purpose with the Benchmark was to allow participants to test the predictive capability of their codes in blind calculations against the measurements in cycles 16 and 17. NFI, ScP/ABB Atom, Siemens and TSI used this opportunity and the result can be judged from the corresponding figures in Chapter 3 comparing measured and calculated stability parameters as well as from Table 4.3. Averaging over cycles 14, 15 and 16, 17, respectively, Table 4.3 illustrates the predictive capability for the global decay ratio. We see that the uncertainty (defined as the standard deviation around the mean value in each cycle) for all four participants is practically the same in prediction as in post-calculation. The other measure of uncertainty, which according to 4.3.1, is sensitive to a cyclewise variation in systematic errors, shows a high degree of consistency for ScP/ABB Atom and NFI, but less so for the others.

Predictive calculations for the regional decay ratio are scarce and are presented only by TSI. Referring to Tables 3.9 and 3.10, we see that the uncertainty in predictions is comparable with that for post-calculations while both the design and the best fit methods give more conservative results in prediction. We point out that there is a rather limited amount of measured regional oscillation data. Over all four cycles only half as many as for the global data and for cycle 17 only one state point.

Chapter 5

CONCLUDING REMARKS

In addition to the conclusions already made in Chapter 4 it may be stated that the calculation of the global stability characteristics of a BWR can today be performed with a precision close to that of the noise analysis methods used to evaluate the corresponding stability parameters from the raw data. This is true for frequency domain codes as well as for time domain codes but we have assumed that credit can be taken for tuning against a set of given evaluated data for the reactor in question. For further improvement in calculational models and methods, especially to achieve robustness and reliability in the predictive mode, a systematic analysis of uncertainties along the lines discussed in [25] could be very useful.

As for the regional stability characteristics the picture is less clear. A regional oscillation is potentially more troublesome for the present BWR core monitoring and core protection systems (means to handle this are described in Chapter 5 of [1]). At the same time the oscillatory behaviour of some BWRs, especially those with large cores, is normally dominated by the regional mode. The demand on precision in pre-calculations is therefore the same for the regional as for the global decay ratio. We also need a calculational tool to tell us with some confidence which core mode will be dominant in a certain reactor with given operating conditions and core design.

The discussion in Chapter 4 indicates that we need better qualification of the applied noise analysis methods as a base for qualification of the calculational models for the regional stability parameters. The results shown in Table 4.5 and the corresponding figures in Chapter 3, are encouraging but the calculational accuracy in the regional case should be improved. In this process it is of particular interest to assess the limitations of the 1D frequency domain approach in calculation of regional stability parameters. Although the eigenvalue separation of the various modes of the neutron flux in the core is normally calculated by a 3D neutronic code, the stability analysis is performed in 1D.

It is against this background that we have proposed a follow-up Benchmark dedicated to the analysis of time series data and including the evaluation of both global and regional stability parameters.

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Furthermore, thanks are due to Enrico Sartori at OECD/NEA for his efficient administration of the Benchmark and support to the author and the participants.

Last, but not least, the author would like to express his gratitude to all the participants for their dedicated efforts in this Benchmark providing extremely interesting results from many different angles and model approaches as well as many useful comments in the preparation of this report.

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Appendix 1

Evaluated resonance frequencies and corresponding decay ratios-original data calculated from the average APRM-response

Case	Decay ratio	Frequency (Hz)
Cycle 14		
1	0.29	0.44*
3	0.36	0.44*
4	0.63	0.53
5	0.54	0.52
6	0.58	0.53
8	0.74	0.51
9	0.57**	0.54
10	0.67	0.51
Cycle 15		
1	0.18	0.40*
2	0.21	0.39*
3	0.14	0.41*
4	0.30	0.42
5	0.50	0.43
6	0.55	0.46
8	0.69	0.52
9	0.74	0.56
10	0.65	0.53

* Some frequency spectra did not show pronounced resonances. The corresponding value in Table 4 is marked with * and refers to a breakpoint in the spectrum rather than a resonance peak.

** In Case 9 of cycle 14 the core showed regional oscillations. The evaluated decay ratio for APRM-1 was in this case 0.72 and the maximum value for a single LPRM was 0.99.

Appendix 2

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Table 3.2 ***Final Noise Analysis (AR-Lyanpunov) Results for Cycles 14 to 17***

Ringhals 1 NEA Benchmark Results

Participant **CSN/UPV** — **Code** — **Modal analysis**

Meas. no	Oper. pow.%	Oper. flow %	Meas.DR global	Meas. freq.	Meas. DR reg	Meas. freq.	Calc. DR glob	Abs. dev.	Calc. freq.	Calc. DR reg	Abs. dev.	Calc. freq.
Cycle 14 (BOC)												
1	65.00	58.64	0.30	0.43			0.39	0.09	0.42	0.29		0.44
3	65.00	52.37	0.69	0.43	0.57	0.43	0.64	-0.05	0.42	0.50	-0.07	0.42
4	70.00	52.24	0.79	0.55	0.75	0.52	0.77	-0.02	0.54	0.77	0.02	0.52
5	70.00	55.26	0.67	0.51	0.60	0.50	0.67	0.00	0.52	0.66	0.06	0.52
6	70.20	58.94	0.64	0.52	0.59	0.50	0.68	0.04	0.52	0.52	-0.07	0.51
8	75.10	55.49	0.78	0.52	0.79	0.50	0.79	0.01	0.52	0.78	-0.01	0.50
9	72.60	52.77	0.80	0.56	0.99	0.54	0.8	0.00	0.56	1.00	0.01	0.54
10	77.70	58.63	0.71	0.50	0.63	0.49	0.71	0.00	0.50	0.56	-0.07	0.50
							Average	***0.01***			***-0.02***	
							Std.dev.	***0.04***			***0.05***	
Cycle 16 (BOC)												
1	64.30	58.74	0.54	0.48			0.60	0.06	0.49	0.49		0.46
2	64.60	56.07	0.54	0.48			0.58	0.04	0.49	0.44		0.46
3	64.60	52.83	0.69	0.47	0.55	0.45	0.71	0.02	0.47	0.61	0.06	0.46
4	70.20	59.50	0.71	0.52			0.73	0.02	0.52	0.54		0.49
5	69.90	56.17	0.67	0.49	0.51	0.49	0.69	0.02	0.50	0.59	0.08	0.48
6	69.50	52.47	0.79	0.49	0.74	0.48	0.82	0.03	0.49	0.77	0.03	0.47
7	74.40	58.30	0.72	0.50	0.50	0.49	0.73	0.01	0.50	0.64	0.14	0.50
8	74.90	55.81	0.82	0.49	0.66	0.49	0.83	0.01	0.49	0.72	0.06	0.49
9	74.60	52.54	0.87	0.48	0.82	0.47	0.88	0.01	0.48	0.82	0.00	0.47
10	76.00	60.24	0.65	0.50	0.64	0.51	0.67	0.02	0.50	0.67	0.03	0.50
11	66.10	52.19	0.66	0.48	0.55	0.45	0.68	0.02	0.48	0.65	0.10	0.46
								0.02			***0.06***	
								0.02			***0.04***	
Cycle 17 (BOC)												
2	65.60	56.49	0.24	0.46			0.13	-0.11	0.26	0.26		0.42
3	65.60	52.57	0.22	0.44			0.30	0.08	0.40	0.28		0.40
4	69.50	59.51	0.32	0.46			0.40	0.08	0.46	0.32		0.44
5	69.90	57.36	0.28	0.42			0.27	-0.01	0.40	0.32		0.41
6	69.70	53.69	0.34	0.46			0.43	0.09	0.44	0.27		0.38
7	74.90	59.14	0.33	0.46			0.34	0.01	0.44	0.40		0.46
8	75.10	57.43	0.41	0.48			0.28	-0.13	0.44	0.44		0.45
9	75.40	53.41	0.57	0.47	0.43	0.49	0.58	0.01	0.47	0.53	0.10	0.46
10	78.10	57.97	0.49	0.49			0.46	-0.03	0.48	0.46		0.48
								0.00				
								0.08				

Nominal power **2,064** **MWth** Nominal flow **7000** **kg/s**

Meas. no	Oper. pow.%	Oper. flow %	Meas.DR global	Meas. freq.	Meas. DR reg	Meas. freq.	Calc. DR glob	Abs. dev.	Calc. freq.	Calc. DR reg	Abs. dev.	Calc. freq.
Cycle 15 (BOC)												
1	64.70	59.11	0.23	0.44			0.12	-0.11	0.13	0.14		0.12
2	65.20	55.44	0.24	0.42			0.14	-0.10	0.11	0.11		0.12
3	65.10	52.13	0.21	0.43			0.17	-0.04	0.11	0.14		0.12
4	70.10	59.50	0.33	0.44			0.43	0.10	0.40	0.42		0.43
5	70.10	56.36	0.43	0.44			0.30	-0.13	0.32	0.48		0.42
6	70.30	53.93	0.59	0.47	0.39	0.47	0.55	-0.04	0.47	0.64	0.25	0.47
8	75.20	57.06	0.77	0.55	0.77	0.52	0.70	-0.07	0.53	0.69	-0.08	0.54
9	71.10	51.90	0.67	0.53	0.67	0.52	0.80	0.13	0.55	0.69	0.02	0.54
10	77.30	60.23	0.60	0.54	0.67	0.52	0.65	0.05	0.53	0.64	-0.03	0.52
								-0.02			***0.04***	
								0.09			***0.15***	
Cycle 16 (MOC)												
eq.	94.80	140.44										
1	77.40	94.11	0.35	0.68			0.38	0.03	0.64	0.41		0.70
2	75.60	86.20	0.33	0.61			0.52	0.19	0.61	0.38		0.64
4	57.50	54.50	0.73	0.51	0.58	0.49	0.75	0.02	0.51	0.60	0.02	0.49
								0.08				
								0.10				

Table 3.3 Final LAPUR Results for Cycles 14 to 17

Ringhals 1 Final NEA- Benchmark Results

Participant CSN/UPV — **Code** LAPUR

Meas. no	Oper. pow.%	Oper. flow %	Meas.DR global	Meas. freq.	Meas. DR reg	Meas. freq.	Calc. DR glob	Abs. dev.	Calc. freq.	Calc. DR reg	Abs. dev.	Calc. freq.
Cycle 14 (BOC)												
1	65.00	58.64	0.30	0.43								
3	65.00	52.37	0.69	0.43	0.57	0.43						
4	70.00	52.24	0.79	0.55	0.75	0.52	0.80	0.01		0.96	0.21	
5	70.00	55.26	0.67	0.51	0.60	0.50	0.72	0.05		0.72	0.12	
6	70.20	58.94	0.64	0.52	0.59	0.50	0.62	-0.02		0.52	-0.07	
8	75.10	55.49	0.78	0.52	0.79	0.50	0.86	0.08		0.91	0.12	
9	72.60	52.77	0.80	0.56	0.99	0.54	0.75	-0.05		1.01	0.02	
10	77.70	58.63	0.71	0.50	0.63	0.49						
							Average	***0.01***			***0.08***	
							Std.dev.	***0.05***			***0.11***	
Cycle 16 (BOC)												
1	64.30	58.74	0.54	0.48			0.52	-0.02		0.27		
2	64.60	56.07	0.54	0.48			0.64	0.10		0.41		
3	64.60	52.83	0.69	0.47	0.55	0.45	0.79	0.10		0.61	0.06	
4	70.20	59.50	0.71	0.52			0.63	-0.08		0.50		
5	69.90	56.17	0.67	0.49	0.51	0.49	0.76	0.09		0.67	0.16	
6	69.50	52.47	0.79	0.49	0.74	0.48	0.93	0.14		0.84	0.10	
7	74.40	58.30	0.72	0.50	0.50	0.49	0.77	0.05		0.68	0.18	
8	74.90	55.81	0.82	0.49	0.66	0.49	0.88	0.06		0.79	0.13	
9	74.60	52.54	0.87	0.48	0.82	0.47	1.02	0.15		0.92	0.10	
10	76.00	60.24	0.65	0.50	0.64	0.51	0.72	0.07		0.57	-0.07	
11	66.10	52.19	0.66	0.48	0.55	0.45	0.82	0.16		0.96	0.41	
								0.07			***0.13***	
								0.07			***0.14***	
Cycle 17 (BOC)												
2	65.60	56.49	0.24	0.46			0.31	0.07		0.05		
3	65.60	52.57	0.22	0.44			0.42	0.20		0.10		
4	69.50	59.51	0.32	0.46			0.31	-0.01		0.06		
5	69.90	57.36	0.28	0.42			0.38	0.10		0.10		
6	69.70	53.69	0.34	0.46			0.49	0.15		0.18		
7	74.90	59.14	0.33	0.46			0.48	0.15		0.21		
8	75.10	57.43	0.41	0.48			0.55	0.14		0.29		
9	75.40	53.41	0.57	0.47	0.43	0.49	0.78	0.21		0.58	0.15	
10	78.10	57.97	0.49	0.49			0.65	0.16		0.46		
								0.13				
								0.07				

Nominal power 2,064 MWth — Nominal flow 7000 kg/s

Meas. no	Oper. pow.%	Oper. flow %	Meas.DR global	Meas. freq.	Meas. DR reg	Meas. freq.	Calc. DR glob	Abs. dev.	Calc. freq.	Calc. DR reg	Abs. dev.	Calc. freq.
Cycle 15 (BOC)												
1	64.70	59.11	0.23	0.44			0.29	0.06		0.05		
2	65.20	55.44	0.24	0.42			0.34	0.10		0.07		
3	65.10	52.13	0.21	0.43			0.45	0.24		0.13		
4	70.10	59.50	0.33	0.44			0.39	0.06		0.11		
5	70.10	56.36	0.43	0.44			0.52	0.09		0.21		
6	70.30	53.93	0.59	0.47	0.39	0.47	0.70	0.11		0.50	0.11	
8	75.20	57.06	0.77	0.55	0.77	0.52	0.57	-0.20		0.62	-0.15	
9	71.10	51.90	0.67	0.53	0.67	0.52	0.65	-0.02		0.85	0.18	
10	77.30	60.23	0.60	0.54	0.67	0.52	0.51	-0.09		0.51	-0.16	
								0.04			***-0.01***	
								0.13			***0.18***	
Cycle 16 (MOC)												
eq.	94.80	140.44										
1	77.40	94.11	0.35	0.68			0.35	0.00				
2	75.60	86.20	0.33	0.61			0.33	0.00				
4	57.50	54.50	0.73	0.51	0.58	0.49	0.73	0.00		0.58	0.00	
								0.00				
								0.00				

Table 3.4 LAPUR-K Results for Cycles 14 to 17

Ringhals 1 NEA Benchmark — Nominal power 2,064 MWth — Nominal flow 7000 kg/s

Participant NETCORP/SCANDPOWER — **Code** LAPUR-K

Meas. no	Oper. pow.%	Oper. flow %	Meas.DR global	Meas. freq.	Meas. DR reg	Meas. freq.	Calc. DR glob	Abs. dev.	Calc. freq.	Calc. DR reg	Abs. dev.	Calc. freq.
Cycle 14 (BOC)												
1	65.00	58.64	0.30	0.43			0.52	0.22	0.30	0.31		0.35
3	65.00	52.37	0.69	0.43	0.57	0.43	0.58	-0.11	0.31	0.69	0.12	0.37
4	70.00	52.24	0.79	0.55	0.75	0.52	1.12	0.33	0.45	1.36	0.61	0.49
5	70.00	55.26	0.67	0.51	0.60	0.50	0.67	0.00	0.46	1.02	0.42	0.47
6	70.20	58.94	0.64	0.52	0.59	0.50	0.52	-0.12	0.44	0.74	0.15	0.46
8	75.10	55.49	0.78	0.52	0.79	0.50	0.8	0.02	0.44	1.23	0.44	0.47
9	72.60	52.77	0.80	0.56	0.99	0.54	0.82	0.02	0.42	1.28	0.29	0.44
10	77.70	58.63	0.71	0.50	0.63	0.49	0.62	-0.09	0.43	1.02	0.39	0.47
							Average	***0.03***			***0.35***	
							Std.dev.	***0.16***			***0.17***	
Cycle 16 (BOC)												
1	64.30	58.74	0.54	0.48			0.38	-0.16	0.36	0.41		0.42
2	64.60	56.07	0.54	0.48			0.44	-0.10	0.36	0.55		0.41
3	64.60	52.83	0.69	0.47	0.55	0.45	0.61	-0.08	0.37	0.82	0.27	0.41
4	70.20	59.50	0.71	0.52			0.46	-0.25	0.40	0.72		0.44
5	69.90	56.17	0.67	0.49	0.51	0.49	0.57	-0.10	0.39	0.87	0.36	0.43
6	69.50	52.47	0.79	0.49	0.74	0.48	0.76	-0.03	0.38	1.09	0.35	0.41
7	74.40	58.30	0.72	0.50	0.50	0.49	0.57	-0.15	0.38	0.92	0.42	0.43
8	74.90	55.81	0.82	0.49	0.66	0.49	0.7	-0.12	0.38	0.95	0.29	0.42
9	74.60	52.54	0.87	0.48	0.82	0.47	0.89	0.02	0.37	1.25	0.43	0.41
10	76.00	60.24	0.65	0.50	0.64	0.51	0.47	-0.18	0.38	0.80	0.16	0.44
11	66.10	52.19	0.66	0.48	0.55	0.45	0.75	0.09	0.42	0.95	0.40	0.44
								-0.10			***0.34***	
								0.10			***0.09***	
Cycle 17 (BOC)												
2	65.60	56.49	0.24	0.46			0.25	0.01	0.32	0.06		0.36
3	65.60	52.57	0.22	0.44			0.3	0.08	0.32	0.10		0.36
4	69.50	59.51	0.32	0.46			0.23	-0.09	0.34	0.06		0.38
5	69.90	57.36	0.28	0.42			0.28	0.00	0.34	0.10		0.39
6	69.70	53.69	0.34	0.46			0.34	0.00	0.34	0.18		0.39
7	74.90	59.14	0.33	0.46			0.32	-0.01	0.36	0.23		0.42
8	75.10	57.43	0.41	0.48			0.36	-0.05	0.37	0.33		0.42
9	75.40	53.41	0.57	0.47	0.43	0.49	0.46	-0.11	0.37	0.66	0.23	0.42
10	78.10	57.97	0.49	0.49			0.36	-0.13	0.38	0.52		0.44
								-0.03				
								0.07				

Meas. no	Oper. pow.%	Oper. flow %	Meas.DR global	Meas. freq.	Meas. DR reg	Meas. freq.	Calc. DR glob	Abs. dev.	Calc. freq.	Calc. DR reg	Abs. dev.	Calc. freq.
Cycle 15 (BOC)												
1	64.70	59.11	0.23	0.44			0.31	0.08	0.32	0.10		0.36
2	65.20	55.44	0.24	0.42			0.35	0.11	0.32	0.11		0.35
3	65.10	52.13	0.21	0.43			0.37	0.16	0.33	0.17		0.38
4	70.10	59.50	0.33	0.44			0.35	0.02	0.35	0.16		0.39
5	70.10	56.36	0.43	0.44			0.40	-0.03	0.35	0.27		0.40
6	70.30	53.93	0.59	0.47	0.39	0.47	0.51	-0.08	0.37	0.62	0.23	0.42
8	75.20	57.06	0.77	0.55	0.77	0.52	0.57	-0.20	0.44	0.98	0.21	0.48
9	71.10	51.90	0.67	0.53	0.67	0.52	1.03	0.36	0.45	1.23	0.56	0.49
10	77.30	60.23	0.60	0.54	0.67	0.52	0.48	-0.12	0.45	0.89	0.22	0.49
								0.03			***0.31***	
								0.17			***0.17***	
Cycle 16 (MOC)												
eq.	94.80	140.44										
1	77.40	94.11	0.35	0.68			0.10	-0.25	0.51	0.07		0.61
2	75.60	86.20	0.33	0.61			0.13	-0.20	0.5	0.15		0.60
4	57.50	54.50	0.73	0.51	0.58	0.49	0.71	-0.02	0.42	0.76	0.18	0.44
								-0.16				
								0.12				

Table 3.5 *STAIF-PK Global DRs and Frequencies for Cycles 14 to 17*

Ringhals 1 NEA Benchmark

Participant Nuclear Fuel Industries (NFI) | **Code** STAIF-PK

Nominal power 2,064 MWth | Nominal flow 7000 kg/s

Meas. no	Oper. pow.%	Oper. flow %	Meas.DR global	Meas. freq.	Meas. DR reg	Meas. freq.	Calc. DR global	Abs. dev.	Calc. freq.	Calc. DR reg	Abs. dev.	Calc. freq.
Cycle 14 (BOC)												
1	65.00	58.64	0.30	0.43			0.35	0.05	0.35			
3	65.00	52.37	0.69	0.43	0.57	0.43	0.57	-0.12	0.38			
4	70.00	52.24	0.79	0.55	0.75	0.52	0.94	0.15	0.55			
5	70.00	55.26	0.67	0.51	0.60	0.50	0.74	0.07	0.53			
6	70.20	58.94	0.64	0.52	0.59	0.50	0.56	-0.08	0.50			
8	75.10	55.49	0.78	0.52	0.79	0.50	0.88	0.10	0.53			
9	72.60	52.77	0.80	0.56	0.99	0.54	0.96	0.16	0.53	0.99	0.00	
10	77.70	58.63	0.71	0.50	0.63	0.49	0.70	-0.01	0.53			
							Average	***0.04***				
							Std.dev.	***0.10***				
Cycle 16 (BOC)												
1	64.30	58.74	0.54	0.48			0.55	0.01	0.44			
2	64.60	56.07	0.54	0.48			0.60	0.06	0.44			
3	64.60	52.83	0.69	0.47	0.55	0.45	0.68	-0.01	0.45			
4	70.20	59.50	0.71	0.52			0.64	-0.07	0.49			
5	69.90	56.17	0.67	0.49	0.51	0.49	0.72	0.05	0.48			
6	69.50	52.47	0.79	0.49	0.74	0.48	0.83	0.04	0.46			
7	74.40	58.30	0.72	0.50	0.50	0.49	0.74	0.02	0.48			
8	74.90	55.81	0.82	0.49	0.66	0.49	0.80	-0.02	0.48			
9	74.60	52.54	0.87	0.48	0.82	0.47	0.93	0.06	0.46			
10	76.00	60.24	0.65	0.50	0.64	0.51	0.74	0.09	0.47			
11	66.10	52.19	0.66	0.48	0.55	0.45	0.85	0.19	0.50			
								0.04				
								0.07				
Cycle 17 (BOC)												
2	65.60	56.49	0.24	0.46			0.12	-0.12	0.40			
3	65.60	52.57	0.22	0.44			0.20	-0.02	0.41			
4	69.50	59.51	0.32	0.46			0.18	-0.14	0.41			
5	69.90	57.36	0.28	0.42			0.43	0.15	0.43			
6	69.70	53.69	0.34	0.46			0.46	0.12	0.44			
7	74.90	59.14	0.33	0.46			0.52	0.19	0.44			
8	75.10	57.43	0.41	0.48			0.54	0.13	0.45			
9	75.40	53.41	0.57	0.47	0.43	0.49	0.74	0.17	0.47			
10	78.10	57.97	0.49	0.49			0.65	0.16	0.47			
								0.07				
								0.13				

Meas. no	Oper. pow.%	Oper. flow %	Meas.DR global	Meas. freq.	Meas. DR reg	Meas. freq.	Calc.DR global	Abs. dev.	Calc. freq.	Calc. DR reg	Abs. dev.	Calc. freq.
Cycle 15 (BOC)												
1	64.70	59.11	0.23	0.44			0.18	-0.05	0.39			
2	65.20	55.44	0.24	0.42			0.15	-0.09	0.38			
3	65.10	52.13	0.21	0.43			0.16	-0.05	0.39			
4	70.10	59.50	0.33	0.44			0.38	0.05	0.42			
5	70.10	56.36	0.43	0.44			0.52	0.09	0.42			
6	70.30	53.93	0.59	0.47	0.39	0.47	0.70	0.11	0.46			
8	75.20	57.06	0.77	0.55	0.77	0.52	0.71	-0.06	0.56			
9	71.10	51.90	0.67	0.53	0.67	0.52	0.91	0.24	0.56			
10	77.30	60.23	0.60	0.54	0.67	0.52	0.67	0.07	0.55			
								0.03				
								0.11				
Cycle 16 (MOC)												
eq.	94.80	140.44					0.01					
1	77.40	94.11	0.35	0.68			0.17	-0.18	0.6			
2	75.60	86.20	0.33	0.61			0.18	-0.15	0.61			
4	57.50	54.50	0.73	0.51	0.58	0.49	0.62	-0.11	0.49			
								-0.15				
								0.04				

Table 3.6 *RAMONA-3.5 DRs and Frequencies for Cycles 14 to 17*

Ringhals 1 NEA Benchmark

Participant: Paul Scherrer Institute (PSI) — **Code:** RAMONA-3.5

Nominal power 2,064 MWth — Nominal flow 7000 kg/s

Meas. no	Oper. pow.%	Oper. flow %	Meas.DR global	Meas. freq.	Meas. DR reg	Meas. freq.	Calc. DR glob	Abs. dev.	Calc. freq.	Calc. DR reg	Abs. dev.	Calc. freq.
Cycle 14 (BOC)												
1	65.00	58.64	0.30	0.43			0.39		0.43			
3	65.00	52.37	0.69	0.43	0.57	0.43	0.68	-0.01	0.42	0.64	0.07	0.42
4	70.00	52.24	0.79	0.55	0.75	0.52	0.76	-0.03	0.51			
5	70.00	55.26	0.67	0.51	0.60	0.50						
6	70.20	58.94	0.64	0.52	0.59	0.50						
8	75.10	55.49	0.78	0.52	0.79	0.50	0.79	0.01	0.50			
9	72.60	52.77	0.80	0.56	0.99	0.54	0.69	-0.11	0.52	1.00	0.01	0.51
10	77.70	58.63	0.71	0.50	0.63	0.49	0.68	-0.03	0.51			
							Average	***-0.03***				
							Std.dev.	***0.05***				
Cycle 16 (BOC)												
1	64.30	58.74	0.54	0.48			0.50	-0.04	0.44			
2	64.60	56.07	0.54	0.48			0.59	0.05	0.44			
3	64.60	52.83	0.69	0.47	0.55	0.45	0.75	0.06	0.44			
4	70.20	59.50	0.71	0.52			0.67	-0.04	0.47			
5	69.90	56.17	0.67	0.49	0.51	0.49	0.78	0.11	0.46	0.64	0.13	0.45
6	69.50	52.47	0.79	0.49	0.74	0.48	0.92	0.13	0.45			
7	74.40	58.30	0.72	0.50	0.50	0.49	0.80	0.08	0.48	0.69	0.19	0.48
8	74.90	55.81	0.82	0.49	0.66	0.49	0.89	0.07	0.47			
9	74.60	52.54	0.87	0.48	0.82	0.47	0.99	0.12	0.46	0.95	0.13	0.48
10	76.00	60.24	0.65	0.50	0.64	0.51	0.77	0.12	0.48	0.77	0.13	0.49
11	66.10	52.19	0.66	0.48	0.55	0.45	0.80	0.14	0.48	0.47	-0.08	0.51
								0.07			***0.10***	
								0.06			***0.10***	
Cycle 17 (BOC)												
2	65.60	56.49	0.24	0.46			*<0,2*					
3	65.60	52.57	0.22	0.44			0.25	0.03				
4	69.50	59.51	0.32	0.46			0.16	-0.16	0.47			
5	69.90	57.36	0.28	0.42			0.20	-0.08				
6	69.70	53.69	0.34	0.46			0.23	-0.11	0.46			
7	74.90	59.14	0.33	0.46			0.25	-0.08	0.48			
8	75.10	57.43	0.41	0.48			0.30	-0.11	0.42			
9	75.40	53.41	0.57	0.47	0.43	0.49	0.66	0.09	0.48			
10	78.10	57.97	0.49	0.49			0.45	-0.04	0.46			
								-0.06				
								0.08				

Meas. no	Oper. pow.%	Oper. flow %	Meas.DR global	Meas. freq.	Meas. DR reg	Meas. freq.	Calc. DR glob	Abs. dev.	Calc. freq.	Calc. DR reg	Abs. dev.	Calc. freq.
Cycle 15 (BOC)												
1	64.70	59.11	0.23	0.44								
2	65.20	55.44	0.24	0.42								
3	65.10	52.13	0.21	0.43			0.21	0.00	0.45			
4	70.10	59.50	0.33	0.44								
5	70.10	56.36	0.43	0.44								
6	70.30	53.93	0.59	0.47	0.39	0.47	0.51	-0.08	0.42			
8	75.20	57.06	0.77	0.55	0.77	0.52	0.51	-0.26	0.50			
9	71.10	51.90	0.67	0.53	0.67	0.52	0.58	-0.09	0.49	0.88	0.21	0.49
10	77.30	60.23	0.60	0.54	0.67	0.52	0.48	-0.12	0.51	0.69	0.02	0.50
								-0.11				
								0.09				
Cycle 16 (MOC)												
eq.	94.80	140.44					0.16		0.48			
1	77.40	94.11	0.35	0.68			0.25	-0.10	0.61			
2	75.60	86.20	0.33	0.61			0.39	0.06	0.63			
4	57.50	54.50	0.73	0.51	0.58	0.49	0.75	0.02	0.48			
								-0.01				
								0.08				

Table 3.7 ***RAMONA-3 Results for Cycles 14 to 17***

Ringhals 1 NEA Benchmark												
Participant	**SCANDPOWER**							**Code**	**RAMONA-3**			
Cycle 14 (BOC)												
Meas. no	Oper. pow.%	Oper. flow %	Meas.DR global	Meas. freq.	Meas. DR reg	Meas. freq.	Calc. DR glob	Abs. dev.	Calc. freq.	Calc. DR reg	Abs. dev.	Calc. freq.
1	65.00	58.64	0.30	0.43			0.36	0.06	0.41			
3	65.00	52.37	0.69	0.43	0.57	0.43	0.53	-0.16	0.41			
4	70.00	52.24	0.79	0.55	0.75	0.52	0.76	-0.03	0.50			
5	70.00	55.26	0.67	0.51	0.60	0.50	0.63	-0.04	0.49			
6	70.20	58.94	0.64	0.52	0.59	0.50	0.53	-0.11	0.48			
8	75.10	55.49	0.78	0.52	0.79	0.50	0.75	-0.03	0.49			
9	72.60	52.77	0.80	0.56	0.99	0.54	0.77	-0.03	0.51	>1,0		
10	77.70	58.63	0.71	0.50	0.63	0.49	0.65	-0.06	0.49			
							Average	***-0.05***				
							Std.dev.	***0.05***				
Cycle 16 (BOC)												
1	64.30	58.74	0.54	0.48			0.45	-0.09	0.44			
2	64.60	56.07	0.54	0.48			0.54	0.00	0.44			
3	64.60	52.83	0.69	0.47	0.55	0.45	0.70	0.01	0.44			
4	70.20	59.50	0.71	0.52			0.58	-0.13	0.46			
5	69.90	56.17	0.67	0.49	0.51	0.49	0.72	0.05	0.46			
6	69.50	52.47	0.79	0.49	0.74	0.48	0.84	0.05	0.45			
7	74.40	58.30	0.72	0.50	0.50	0.49	0.75	0.03	0.47			
8	74.90	55.81	0.82	0.49	0.66	0.49	0.83	0.01	0.46			
9	74.60	52.54	0.87	0.48	0.82	0.47	0.95	0.08	0.45			
10	76.00	60.24	0.65	0.50	0.64	0.51	0.69	0.04	0.47			
11	66.10	52.19	0.66	0.48	0.55	0.45	0.76	0.10	0.47			
								0.01				
								0.07				
Cycle 17 (BOC)												
2	65.60	56.49	0.24	0.46			0.21	-0.03	0.44			
3	65.60	52.57	0.22	0.44			0.30	0.08	0.43			
4	69.50	59.51	0.32	0.46			0.22	-0.10	0.45			
5	69.90	57.36	0.28	0.42			0.27	-0.01	0.45			
6	69.70	53.69	0.34	0.46			0.34	0.00	0.44			
7	74.90	59.14	0.33	0.46			0.35	0.02	0.47			
8	75.10	57.43	0.41	0.48			0.42	0.01	0.46			
9	75.40	53.41	0.57	0.47	0.43	0.49	0.64	0.07	0.46			
10	78.10	57.97	0.49	0.49			0.52	0.03	0.48			
								0.01				
								0.05				

Nominal power		**2,064**	**MWth**	Nominal flow			**7000**	**kg/s**				
Cycle 15 (BOC)												
Meas. no	Oper. pow.%	Oper. flow %	Meas.DR global	Meas. freq.	Meas. DR reg	Meas. freq.	Calc. DR glob	Abs. dev.	Calc. freq.	Calc. DR reg	Abs. dev.	Calc. freq.
1	64.70	59.11	0.23	0.44			0.21	-0.02	0.40			
2	65.20	55.44	0.24	0.42			0.23	-0.01	0.41			
3	65.10	52.13	0.21	0.43			0.26	0.05	0.42			
4	70.10	59.50	0.33	0.44			0.25	-0.08	0.44			
5	70.10	56.36	0.43	0.44			0.36	-0.07	0.44			
6	70.30	53.93	0.59	0.47	0.39	0.47	0.51	-0.08	0.46			
8	75.20	57.06	0.77	0.55	0.77	0.52	0.64	-0.13	0.51			
9	71.10	51.90	0.67	0.53	0.67	0.52	0.71	0.04	0.51	0.90		
10	77.30	60.23	0.60	0.54	0.67	0.52	0.59	-0.01	0.52			
								-0.03				
								0.06				
Cycle 16 (MOC)												
eq.	94.80	140.44					<0,1					
1	77.40	94.11	0.35	0.68			<0,2					
2	75.60	86.20	0.33	0.61			<0,2					
4	57.50	54.50	0.73	0.51	0.58	0.49	0.74	0.01	0.46			

Table 3.8 STAIF Results for Cycles 14 to 17

Ringhals 1 NEA Benchmark												
Participant	SIEMENS							Code	STAIF			
Cycle 14 (BOC)												
Meas. no	Oper. pow.%	Oper. flow %	Meas. DR glob	Meas. freq.	Meas. DR reg	Meas. freq.	Calc. DR glob	Abs. dev.	Calc. freq.	Calc. DR reg	Abs. dev.	Calc. freq.
1	65.00	58.64	0.30	0.43			0.39	0.09	0.37			
3	65.00	52.37	0.69	0.43	0.57	0.43	0.58	-0.11	0.37			
4	70.00	52.24	0.79	0.55	0.75	0.52	0.79	0.00	0.48			
5	70.00	55.26	0.67	0.51	0.60	0.50	0.68	0.01	0.47			
6	70.20	58.94	0.64	0.52	0.59	0.50	0.55	-0.09	0.47			
8	75.10	55.49	0.78	0.52	0.79	0.50	0.83	0.05	0.48			
9	72.60	52.77	0.80	0.56	0.99	0.54	0.93	0.13	0.50			
10	77.70	58.63	0.71	0.50	0.63	0.49	0.77	0.06	0.48			
							Average	***0.02***				
							Std.dev.	***0.08***				
Cycle 16 (BOC)												
1	64.30	58.74	0.54	0.48			0.53	-0.01	0.42			
2	64.60	56.07	0.54	0.48			0.61	0.07	0.43			
3	64.60	52.83	0.69	0.47	0.55	0.45	0.73	0.04	0.42			
4	70.20	59.50	0.71	0.52			0.63	-0.08	0.45			
5	69.90	56.17	0.67	0.49	0.51	0.49	0.72	0.05	0.44			
6	69.50	52.47	0.79	0.49	0.74	0.48	0.87	0.08	0.42			
7	74.40	58.30	0.72	0.50	0.50	0.49	0.76	0.04	0.45			
8	74.90	55.81	0.82	0.49	0.66	0.49	0.83	0.01	0.44			
9	74.60	52.54	0.87	0.48	0.82	0.47	0.98	0.11	0.42			
10	76.00	60.24	0.65	0.50	0.64	0.51	0.73	0.08	0.45			
11	66.10	52.19	0.66	0.48	0.55	0.45	0.69	0.03	0.46			
								0.04				
								0.05				
Cycle 17 (BOC)												
2	65.60	56.49	0.24	0.46			0.13	-0.11	0.39			
3	65.60	52.57	0.22	0.44			0.22	0.00	0.40			
4	69.50	59.51	0.32	0.46			0.19	-0.13	0.40			
5	69.90	57.36	0.28	0.42			0.23	-0.05	0.40			
6	69.70	53.69	0.34	0.46			0.28	-0.06	0.39			
7	74.90	59.14	0.33	0.46			0.24	-0.09	0.42			
8	75.10	57.43	0.41	0.48			0.31	-0.10	0.42			
9	75.40	53.41	0.57	0.47	0.43	0.49	0.53	-0.04	0.43			
10	78.10	57.97	0.49	0.49			0.46	-0.03	0.44			
								-0.07				
								0.04				

Nominal power			2,064	MWth	Nominal flow			7000	kg/s			
Cycle 15 (BOC)												
Meas. no	Oper. pow.%	Oper. flow %	Meas. DR glob	Meas. freq.	Meas. DR reg	Meas. freq.	Calc. DR glob	Abs. dev.	Calc. freq.	Calc. DR reg	Abs. dev.	Calc. freq.
1	64.70	59.11	0.23	0.44			0.23	0.00	0.38			
2	65.20	55.44	0.24	0.42			0.24	0.00	0.38			
3	65.10	52.13	0.21	0.43			0.37	0.16	0.39			
4	70.10	59.50	0.33	0.44			0.30	-0.03	0.41			
5	70.10	56.36	0.43	0.44			0.45	0.02	0.42			
6	70.30	53.93	0.59	0.47	0.39	0.47	0.59	0.00	0.42			
8	75.20	57.06	0.77	0.55	0.77	0.52	0.72	-0.05	0.49			
9	71.10	51.90	0.67	0.53	0.67	0.52	0.77	0.10	0.49			
10	77.30	60.23	0.60	0.54	0.67	0.52	0.65	0.05	0.50			
								0.03				
								0.07				
Cycle 16 (MOC)												
eq.	94.80	140.44					0.01		0.69			
1	77.40	94.11	0.35	0.68			0.12	-0.23	0.61			
2	75.60	86.20	0.33	0.61			0.18	-0.15	0.59			
4	57.50	54.50	0.73	0.51	0.58	0.49	0.46	-0.27	0.46			
								-0.22				
								0.06				

Table 3.9 ***TSI Design Base Model Results for Cycles 14 to 17***

Ringhals 1 NEA Benchmark												
Participant	**Toden Software Inc. (TSI)**							**Codes**	**TSI Stability Evaluation System (ACCORD,CTCYCL,SIMULATE-3,LAPUR)**			
Cycle 14 (BOC)												
Meas. no	Oper. pow.%	Oper. flow %	Meas.DR global	Meas. freq.	Meas. DR reg	Meas. freq.	Calc. DR glob	Abs. dev.	Calc. freq.	Calc. DR reg	Abs. dev.	Calc. freq.
1	65.00	58.64	0.30	0.43			0.68	0.38	0.43	0.32		0.43
3	65.00	52.37	0.69	0.43	0.57	0.43	0.89	0.20	0.42	0.52	-0.05	0.42
4	70.00	52.24	0.79	0.55	0.75	0.52	0.85	0.06	0.52	0.93	0.18	0.51
5	70.00	55.26	0.67	0.51	0.60	0.50	0.77	0.10	0.52	0.71	0.11	0.51
6	70.20	58.94	0.64	0.52	0.59	0.50	0.75	0.11	0.51	0.60	0.01	0.50
8	75.10	55.49	0.78	0.52	0.79	0.50	0.85	0.07	0.50	0.80	0.01	0.49
9	72.60	52.77	0.80	0.56	0.99	0.54	0.77	-0.03	0.53	0.94	-0.05	0.52
10	77.70	58.63	0.71	0.50	0.63	0.49	0.74	0.03	0.51	0.62	-0.01	0.50
							Average	***0.12***			***0.03***	
							Std.dev.	***0.13***			***0.09***	
Cycle 16 (BOC)												
1	64.30	58.74	0.54	0.48			0.99	0.45	0.46	0.54		0.45
2	64.60	56.07	0.54	0.48			1.07	0.53	0.45	0.65		0.44
3	64.60	52.83	0.69	0.47	0.55	0.45	1.22	0.53	0.44	0.85	0.30	0.43
4	70.20	59.50	0.71	0.52			1.17	0.46	0.46	0.77		0.46
5	69.90	56.17	0.67	0.49	0.51	0.49	1.28	0.61	0.45	0.93	0.42	0.45
6	69.50	52.47	0.79	0.49	0.74	0.48	1.37	0.58	0.44	1.04	0.30	0.43
7	74.40	58.30	0.72	0.50	0.50	0.49	1.29	0.57	0.45	0.94	0.44	0.45
8	74.90	55.81	0.82	0.49	0.66	0.49	1.32	0.50	0.45	0.97	0.31	0.44
9	74.60	52.54	0.87	0.48	0.82	0.47	1.45	0.58	0.43	1.08	0.26	0.43
10	76.00	60.24	0.65	0.50	0.64	0.51	1.21	0.56	0.46	0.81	0.17	0.45
11	66.10	52.19	0.66	0.48	0.55	0.45	1.15	0.49	0.48	0.95	0.40	0.46
								0.53			***0.33***	
								0.05			***0.09***	
Cycle 17 (BOC)												
2	65.60	56.49	0.24	0.46			0.29	0.05	0.52	0.03		0.53
3	65.60	52.57	0.22	0.44			0.38	0.16	0.50	0.05		0.51
4	69.50	59.51	0.32	0.46			0.32	0.00	0.51	0.03		0.51
5	69.90	57.36	0.28	0.42			0.34	0.06	0.50	0.05		0.51
6	69.70	53.69	0.34	0.46			0.45	0.11	0.49	0.09		0.49
7	74.90	59.14	0.33	0.46			0.54	0.21	0.48	0.14		0.48
8	75.10	57.43	0.41	0.48			0.59	0.18	0.48	0.19		0.47
9	75.40	53.41	0.57	0.47	0.43	0.49	0.74	0.17	0.46	0.37	-0.06	0.46
10	78.10	57.97	0.49	0.49			0.63	0.14	0.48	0.32		0.48
								0.12				
								0.07				

Nominal power		2,064 MWth	Nominal flow			7000 kg/s						
Cycle 15 (BOC)												
Meas. no	Oper. pow.%	Oper. flow %	Meas.DR global	Meas. freq.	Meas. DR reg	Meas. freq.	Calc. DR glob	Abs. dev.	Calc. freq.	Calc. DR reg	Abs. dev.	Calc. freq.
1	64.70	59.11	0.23	0.44			0.32	0.09	0.50	0.06		0.50
2	65.20	55.44	0.24	0.42			0.36	0.12	0.49	0.06		0.50
3	65.10	52.13	0.21	0.43			0.50	0.29	0.48	0.12		0.47
4	70.10	59.50	0.33	0.44			0.50	0.17	0.48	0.14		0.48
5	70.10	56.36	0.43	0.44			0.60	0.17	0.47	0.21		0.46
6	70.30	53.93	0.59	0.47	0.39	0.47	0.83	0.24	0.46	0.52	0.13	0.45
8	75.20	57.06	0.77	0.55	0.77	0.52	0.83	0.06	0.51	0.80	0.03	0.50
9	71.10	51.90	0.67	0.53	0.67	0.52	0.88	0.21	0.52	0.99	0.32	0.50
10	77.30	60.23	0.60	0.54	0.67	0.52	0.75	0.15	0.52	0.62	-0.05	0.51
								0.17			***0.11***	
								0.07			***0.16***	
Cycle 16 (MOC)												
eq.	94.80	140.44										
1	77.40	94.11	0.35	0.68			0.30	-0.05	0.64	0.08		0.66
2	75.60	86.20	0.33	0.61			0.36	0.03	0.62	0.13		0.64
4	57.50	54.50	0.73	0.51	0.58	0.49	1.08	0.35	0.47	0.69	0.11	0.46
								0.11				
								0.21				

Table 3.10 TSI Best Fit Model Results for Cycles 14 to 17

Ringhals 1 NEA Benchmark — Nominal power 2,064 MWth — Nominal flow 7000 kg/s

Participant: Toden Software Inc. (TSI) — Codes: TSI Stability Evaluation System (ACCORD,CTCYCL,SIMULATE-3,LAPUR)

Meas. no	Oper. pow.%	Oper. flow %	Meas.DR global	Meas. freq.	Meas. DR reg	Meas. freq.	Calc. DR glob	Abs. dev.	Calc. freq.	Calc. DR reg	Abs. dev.	Calc. freq.
Cycle 14 (BOC)												
1	65.00	58.64	0.30	0.43			0.43	0.13	0.43	0.20		0.46
3	65.00	52.37	0.69	0.43	0.57	0.43	0.53	-0.16	0.43	0.34	-0.23	0.45
4	70.00	52.24	0.79	0.55	0.75	0.52	0.6	-0.19	0.53	0.79	0.04	0.52
5	70.00	55.26	0.67	0.51	0.60	0.50	0.55	-0.12	0.53	0.62	0.02	0.53
6	70.20	58.94	0.64	0.52	0.59	0.50	0.5	-0.14	0.53	0.48	-0.11	0.53
8	75.10	55.49	0.78	0.52	0.79	0.50	0.65	-0.13	0.51	0.79	0.00	0.52
9	72.60	52.77	0.80	0.56	0.99	0.54	0.71	-0.09	0.50	0.89	-0.10	0.50
10	77.70	58.63	0.71	0.50	0.63	0.49	0.58	-0.13	0.52	0.63	0.00	0.53
							Average	***-0.10***			***-0.05***	
							Std.dev.	***0.10***			***0.10***	
Cycle 16 (BOC)												
1	64.30	58.74	0.54	0.48			0.63	0.09	0.48	0.33		0.49
2	64.60	56.07	0.54	0.48			0.68	0.14	0.47	0.41		0.48
3	64.60	52.83	0.69	0.47	0.55	0.45	0.75	0.06	0.46	0.52	-0.03	0.46
4	70.20	59.50	0.71	0.52			0.82	0.11	0.49	0.66		0.49
5	69.90	56.17	0.67	0.49	0.51	0.49	0.86	0.19	0.48	0.72	0.21	0.48
6	69.50	52.47	0.79	0.49	0.74	0.48	0.88	0.09	0.46	0.76	0.02	0.46
7	74.40	58.30	0.72	0.50	0.50	0.49	0.9	0.18	0.48	0.76	0.26	0.49
8	74.90	55.81	0.82	0.49	0.66	0.49	0.94	0.12	0.47	0.82	0.16	0.48
9	74.60	52.54	0.87	0.48	0.82	0.47	0.98	0.11	0.46	0.84	0.02	0.46
10	76.00	60.24	0.65	0.50	0.64	0.51	0.87	0.22	0.48	0.67	0.03	0.49
11	66.10	52.19	0.66	0.48	0.55	0.45	0.84	0.18	0.49	0.75	0.20	0.48
								0.15			***0.13***	
								0.05			***0.10***	
Cycle 17 (BOC)												
2	65.60	56.49	0.24	0.46			0.17	-0.07	0.53	0.02		0.57
3	65.60	52.57	0.22	0.44			0.21	-0.01	0.51	0.03		0.55
4	69.50	59.51	0.32	0.46			0.19	-0.13	0.53	0.02		0.57
5	69.90	57.36	0.28	0.42			0.2	-0.08	0.52	0.03		0.56
6	69.70	53.69	0.34	0.46			0.24	-0.10	0.51	0.05		0.54
7	74.90	59.14	0.33	0.46			0.32	-0.01	0.51	0.09		0.53
8	75.10	57.43	0.41	0.48			0.36	-0.05	0.50	0.13		0.52
9	75.40	53.41	0.57	0.47	0.43	0.49	0.42	-0.15	0.49	0.22	-0.21	0.50
10	78.10	57.97	0.49	0.49			0.41	-0.08	0.50	0.20		0.53
								-0.08				
								0.05				

Meas. no	Oper. pow.%	Oper. flow %	Meas.DR global	Meas. freq.	Meas. DR reg	Meas. freq.	Calc. DR glob	Abs. dev.	Calc. freq.	Calc. DR reg	Abs. dev.	Calc. freq.
Cycle 15 (BOC)												
1	64.70	59.11	0.23	0.44			0.19	-0.04	0.51	0.04		0.54
2	65.20	55.44	0.24	0.42			0.20	-0.04	0.51	0.04		0.55
3	65.10	52.13	0.21	0.43			0.25	0.04	0.49	0.06		0.52
4	70.10	59.50	0.33	0.44			0.27	-0.06	0.52	0.07		0.53
5	70.10	56.36	0.43	0.44			0.33	-0.10	0.5	0.11		0.52
6	70.30	53.93	0.59	0.47	0.39	0.47	0.47	-0.12	0.49	0.33	-0.06	0.50
8	75.20	57.06	0.77	0.55	0.77	0.52	0.65	-0.12	0.53	0.75	-0.02	0.52
9	71.10	51.90	0.67	0.53	0.67	0.52	0.66	-0.01	0.53	0.84	0.17	0.52
10	77.30	60.23	0.60	0.54	0.67	0.52	0.64	0.04	0.53	0.68	0.01	0.53
								-0.05			***0.03***	
								0.06			***0.10***	
Cycle 16 (MOC)												
eq.	94.80	140.44										
1	77.40	94.11	0.35	0.68			0.30	-0.05	0.68	0.10		0.71
2	75.60	86.20	0.33	0.61			0.37	0.04	0.65	0.15		0.67
4	57.50	54.50	0.73	0.51	0.58	0.49	0.75	0.02	0.5	0.47	-0.11	0.49
								0.00				
								0.05				

Table 3.11 ***RELAP5/MOD2 Results for Cycles 14 to 17***

Ringhals 1 NEA Benchmark | **Nominal power** | **2,064** | **MWth** | Nominal flow | **7000** | **kg/s**

Participant | **PISA UNIVERSITY/DCMN** | **Code** | **RELAP5/MOD2, MODICO-AV**

Meas. no	Oper. pow.%	Oper. flow %	Meas.DR global	Meas. freq.	Meas. DR reg	Meas. freq.	Calc. DR glob	Abs. dev.	Calc. freq.	Calc. DR reg	Abs. dev.	Calc. freq.
Cycle 14 (BOC)												
1	65.00	58.64	0.30	0.43								
3	65.00	52.37	0.69	0.43	0.57	0.43						
4	70.00	52.24	0.79	0.55	0.75	0.52	0.63	-0.16				
5	70.00	55.26	0.67	0.51	0.60	0.50						
6	70.20	58.94	0.64	0.52	0.59	0.50						
8	75.10	55.49	0.78	0.52	0.79	0.50						
9	72.60	52.77	0.80	0.56	0.99	0.54	0.72	-0.08				
10	77.70	58.63	0.71	0.50	0.63	0.49	0.67	-0.04				
								-0.09				
								0.06				
Cycle 16 (BOC)												
1	64.30	58.74	0.54	0.48								
2	64.60	56.07	0.54	0.48								
3	64.60	52.83	0.69	0.47	0.55	0.45						
4	70.20	59.50	0.71	0.52								
5	69.90	56.17	0.67	0.49	0.51	0.49						
6	69.50	52.47	0.79	0.49	0.74	0.48	0.75	-0.04				
7	74.40	58.30	0.72	0.50	0.50	0.49						
8	74.90	55.81	0.82	0.49	0.66	0.49	0.65	-0.17				
9	74.60	52.54	0.87	0.48	0.82	0.47	0.72	-0.15				
10	76.00	60.24	0.65	0.50	0.64	0.51						
11	66.10	52.19	0.66	0.48	0.55	0.45						
								-0.12				
								0.07				
Cycle 17 (BOC)												
2	65.60	56.49	0.24	0.46								
3	65.60	52.57	0.22	0.44			1.12	0.90				
4	69.50	59.51	0.32	0.46								
5	69.90	57.36	0.28	0.42								
6	69.70	53.69	0.34	0.46			0.73	0.39				
7	74.90	59.14	0.33	0.46								
8	75.10	57.43	0.41	0.48			0.65	0.24				
9	75.40	53.41	0.57	0.47	0.43	0.49	0.62	0.05				
10	78.10	57.97	0.49	0.49				***0.40***				
								0.36				

Meas. no	Oper. pow.%	Oper. flow %	Meas.DR global	Meas. freq.	Meas. DR reg	Meas. freq.	Calc. DR glob	Abs. dev.	Calc. freq.	Calc. DR reg	Abs. dev.	Calc. freq.
Cycle 15 (BOC)												
1	64.70	59.11	0.23	0.44								
2	65.20	55.44	0.24	0.42								
3	65.10	52.13	0.21	0.43								
4	70.10	59.50	0.33	0.44								
5	70.10	56.36	0.43	0.44			0.50	0.07				
6	70.30	53.93	0.59	0.47	0.39	0.47	0.55	-0.04				
8	75.20	57.06	0.77	0.55	0.77	0.52	0.69	-0.08				
9	71.10	51.90	0.67	0.53	0.67	0.52	0.74	0.07				
10	77.30	60.23	0.60	0.54	0.67	0.52	0.65	0.05				
							Average	***0.01***				
							Std.dev.	***0.07***				
Cycle 16 (MOC)												
eq.	94.80	140.44										
1	77.40	94.11	0.35	0.68								
2	75.60	86.20	0.33	0.61								
4	57.50	54.50	0.73	0.51	0.58	0.49						

Fig. 2.1 Benchmark Measuring Points in the Operating Domain at BOC 14-17.
(100% power=2064 MWth, 100% flow=7000 kg/s)

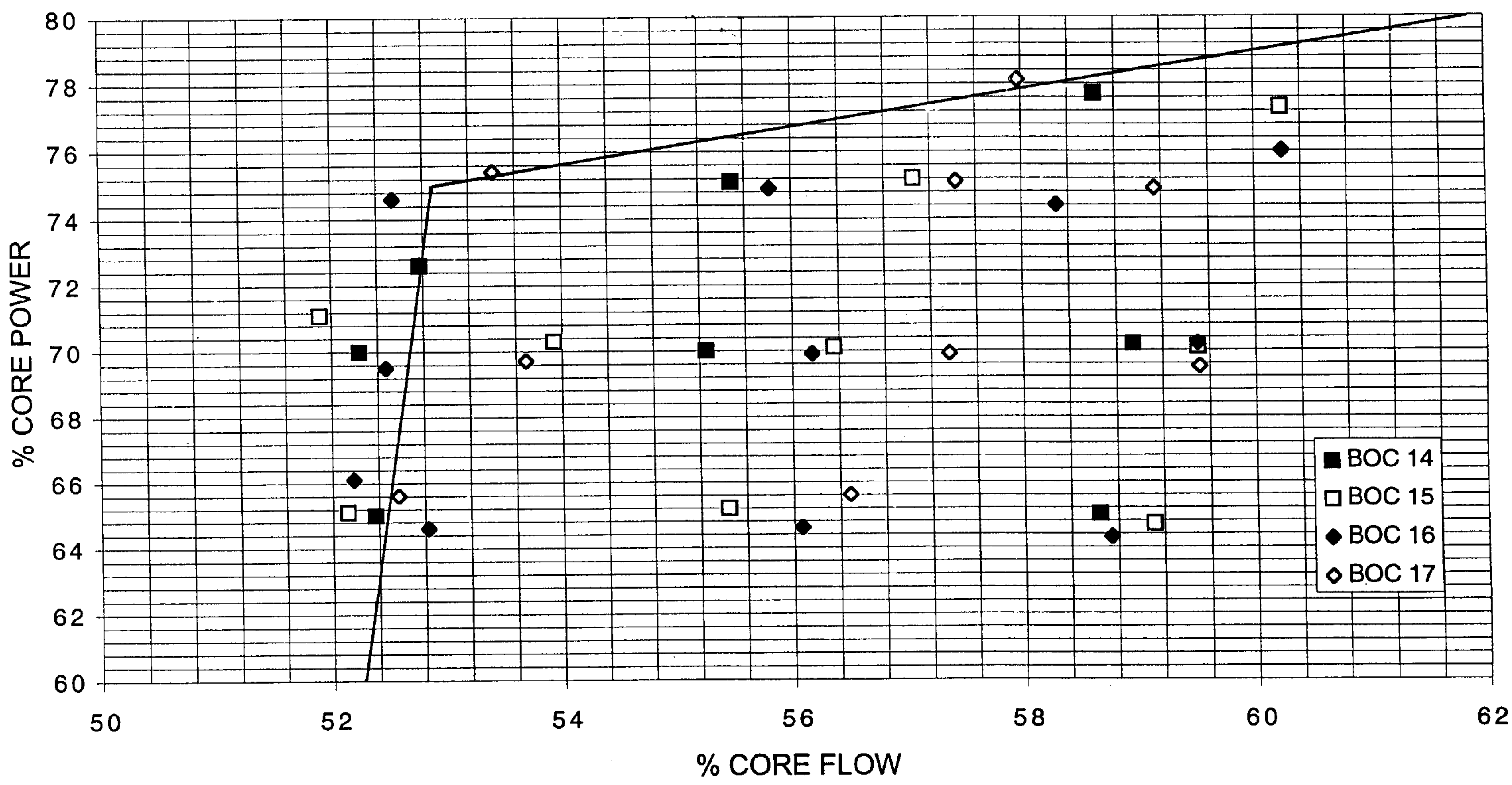


Fig. 3.1a CSN/UPV, AR-Lyapunov approximation, global decay ratio

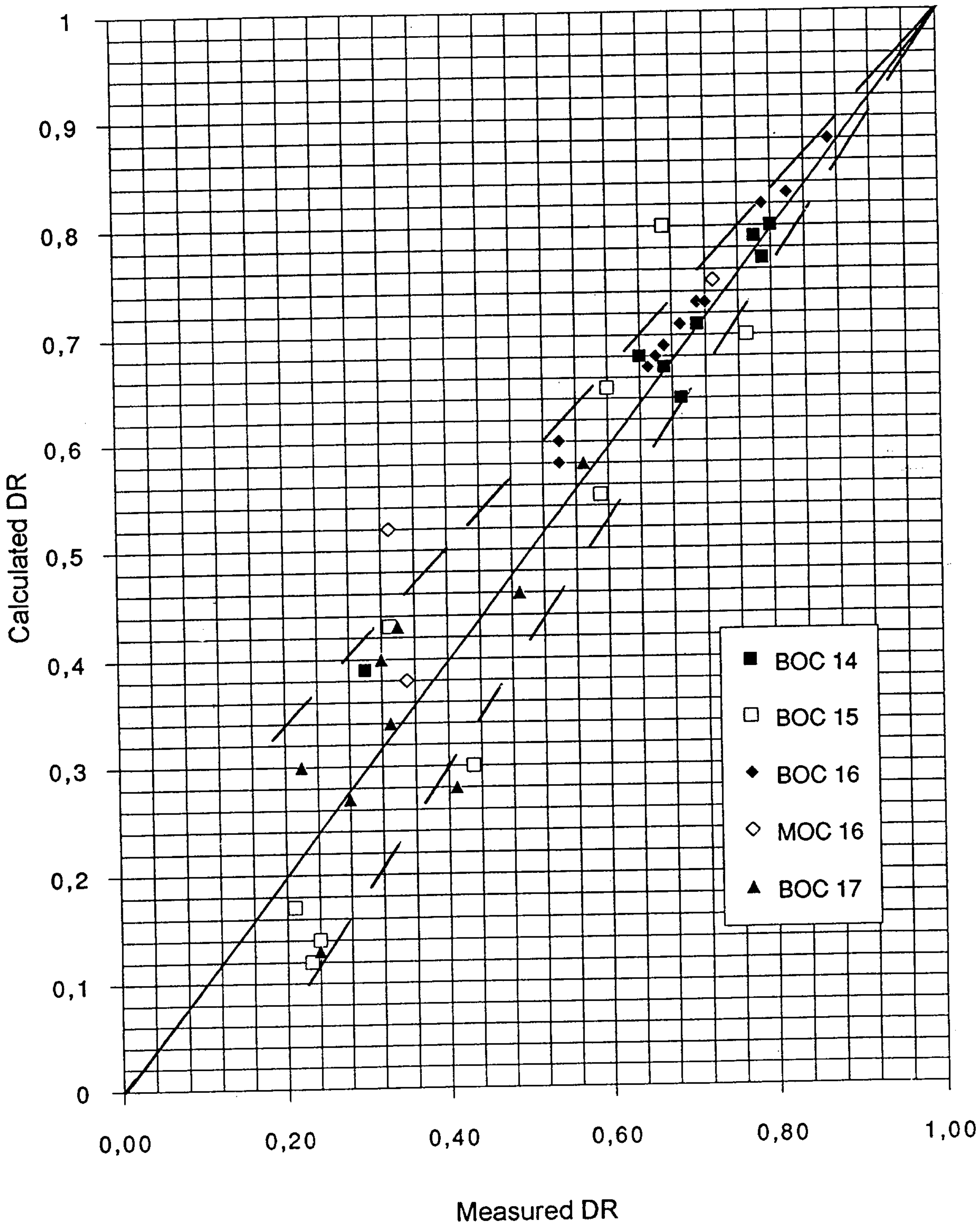


Fig. 3.1b CSN/UPV,AR-Lyapunov approximation, natural, global oscillation frequency

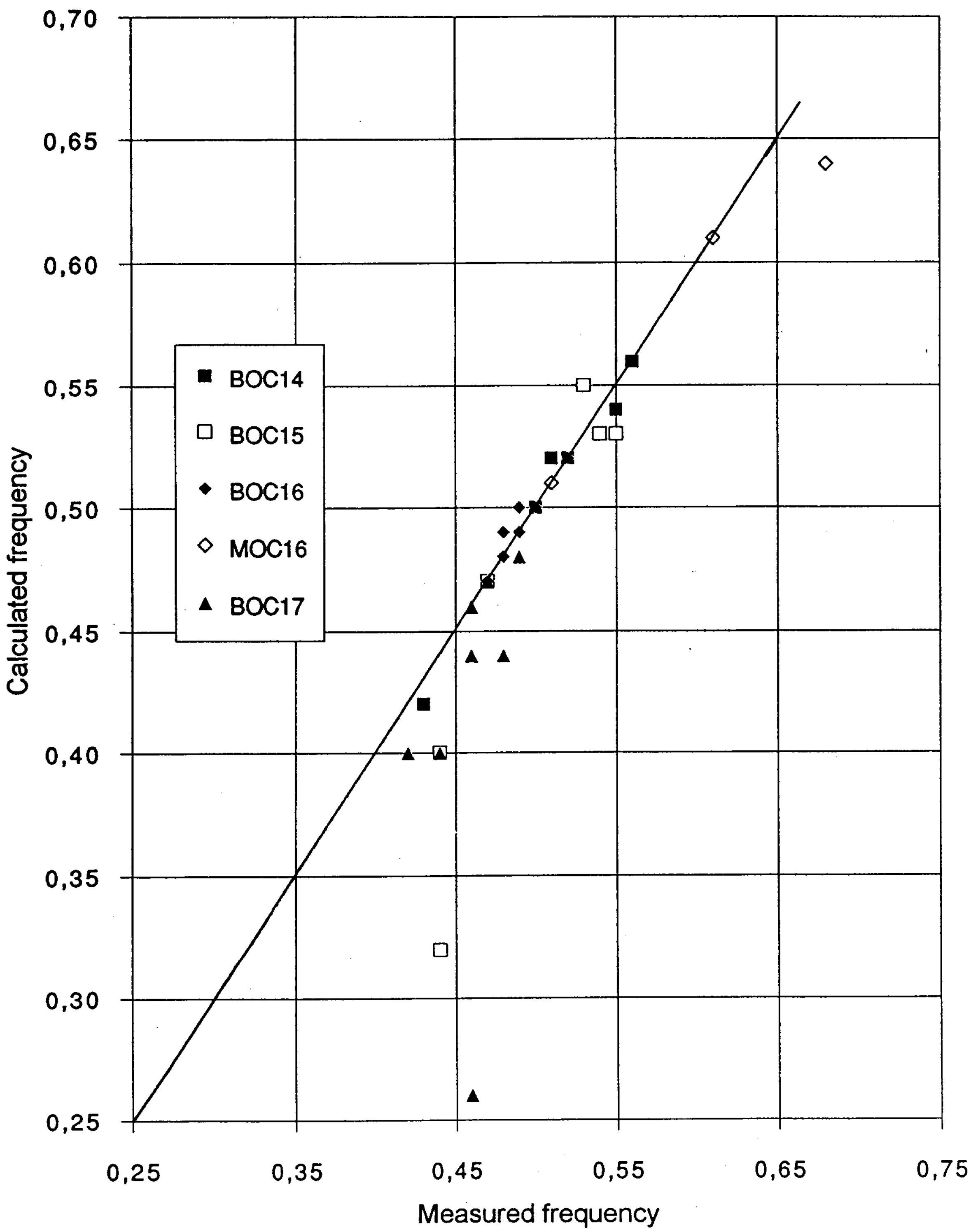


Fig. 3.2a CSN/UPV, AR-Lyapunov approximation, regional decay ratio

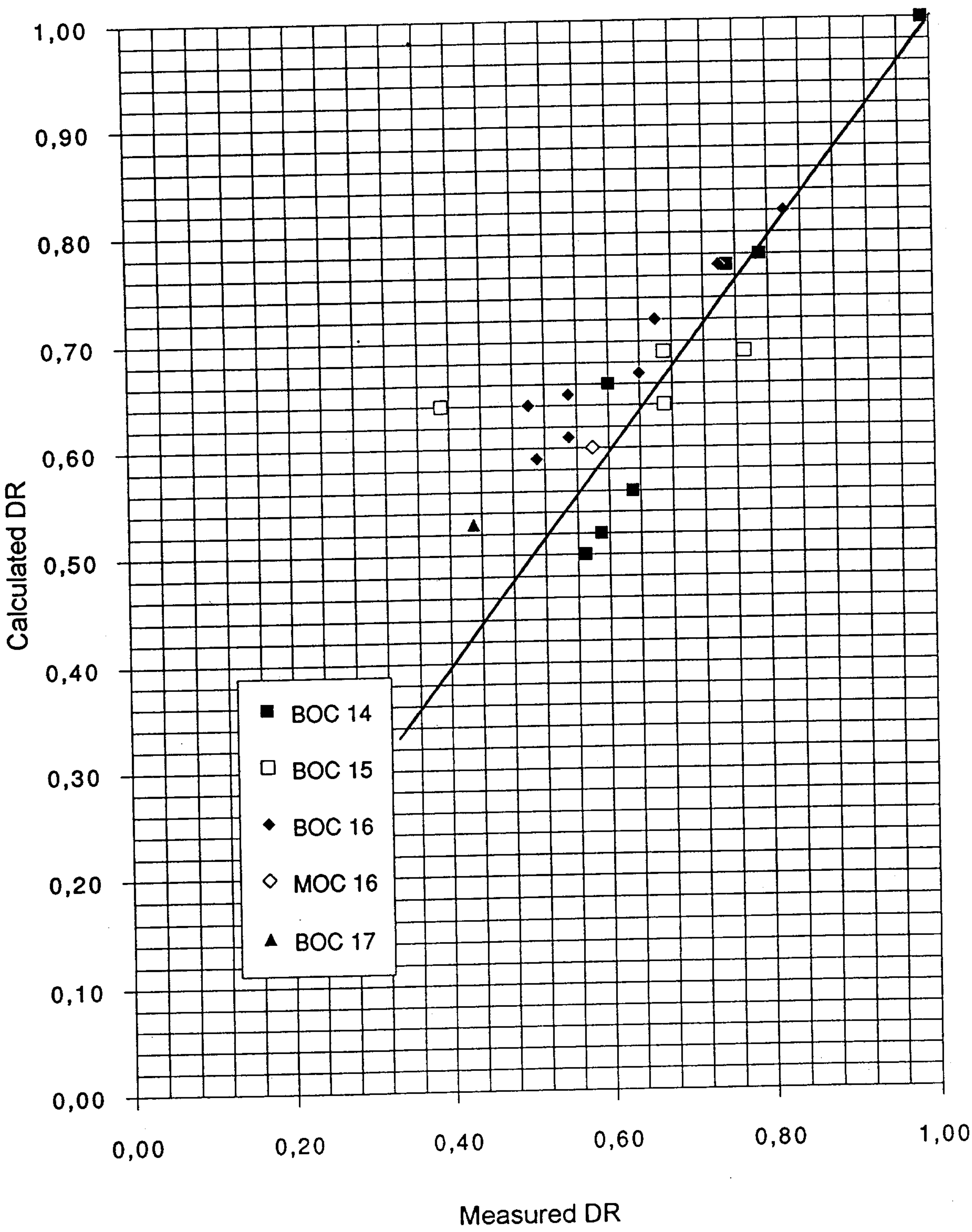


Fig. 3.2b CSN/UPV,AR-Lyapunov approximation, natural, regional oscillation frequency

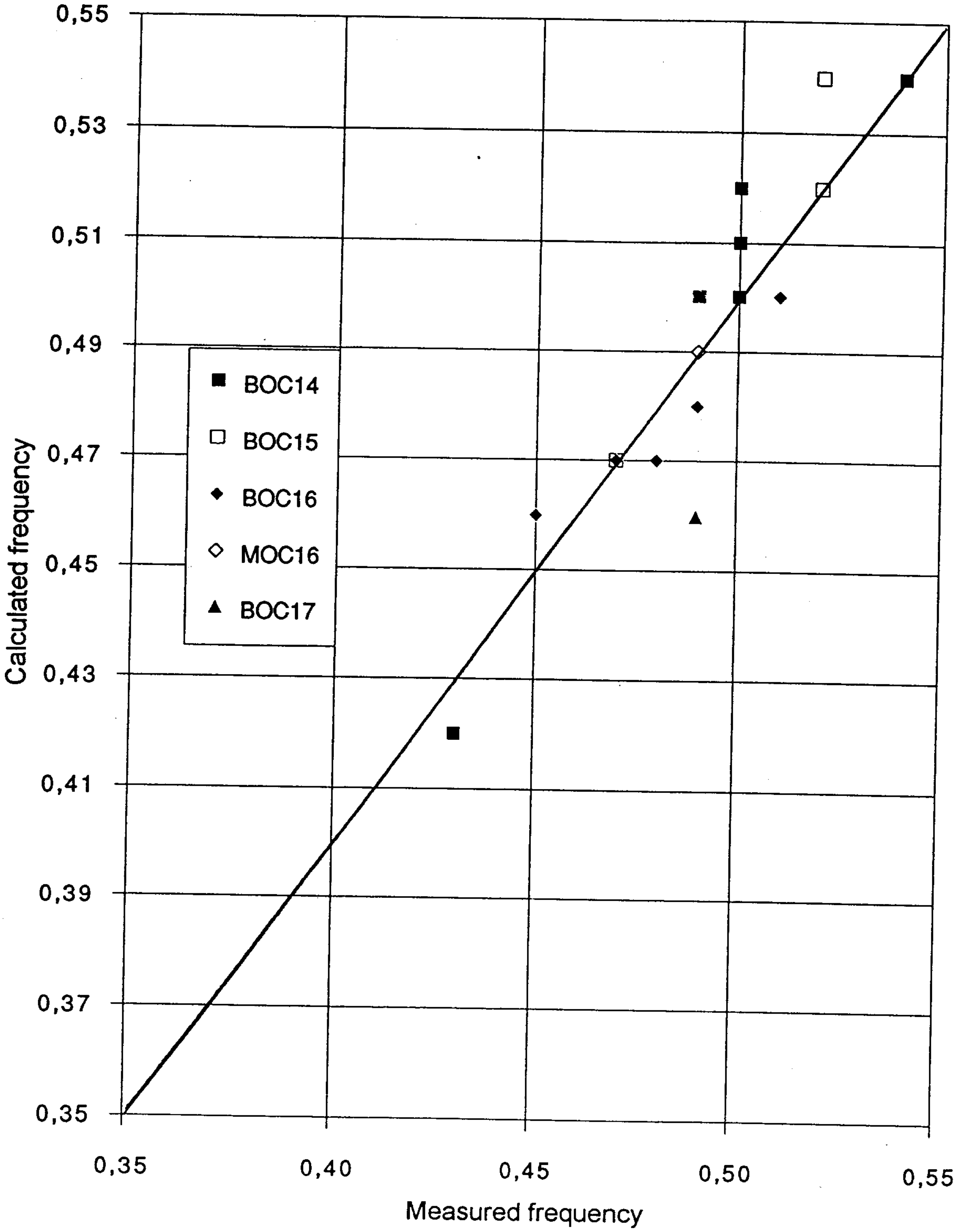


Fig. 3.3 CSN/UPV, LAPUR results, global decay ratio

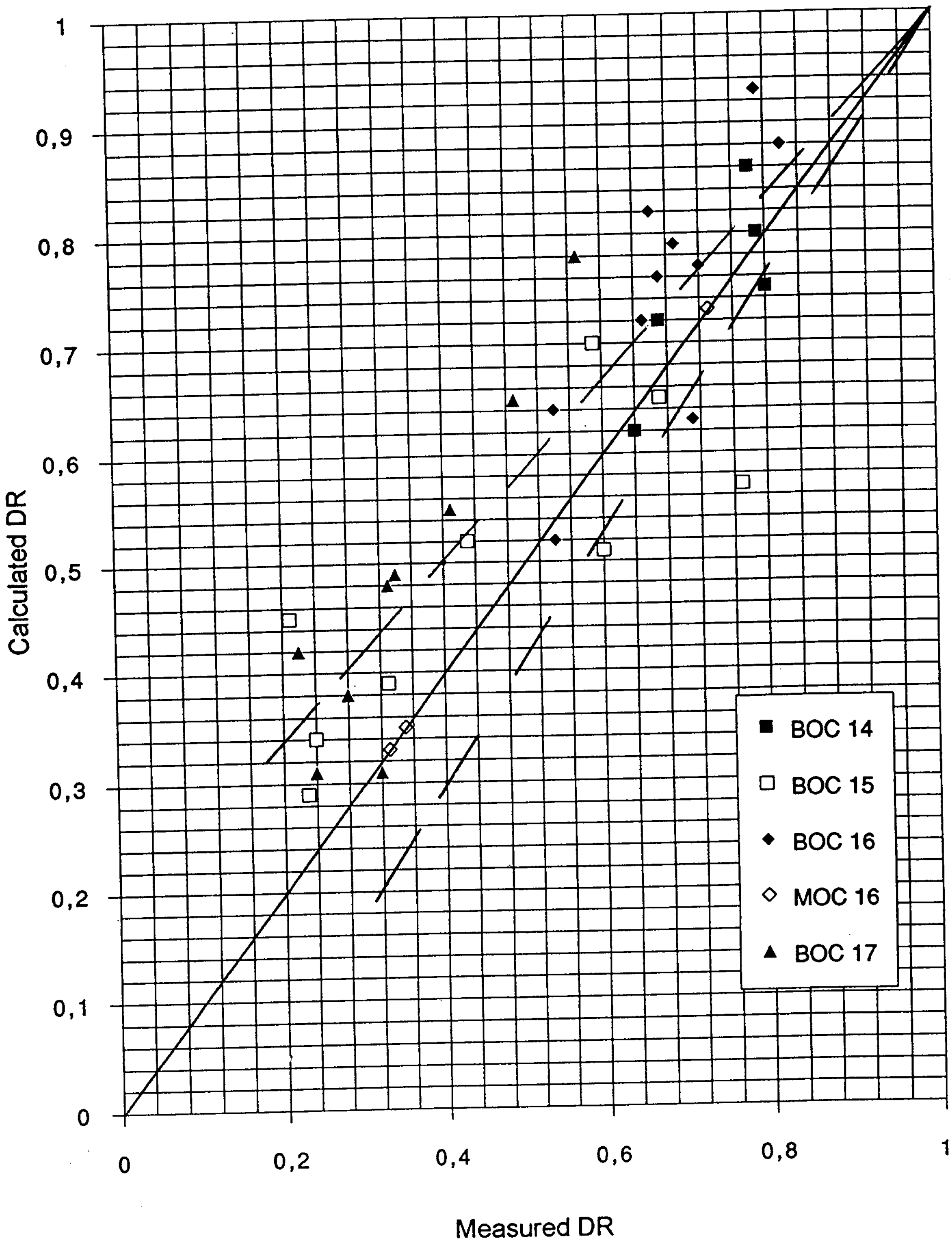


Fig. 3.4 CSN/UPV, LAPUR results, regional decay ratio

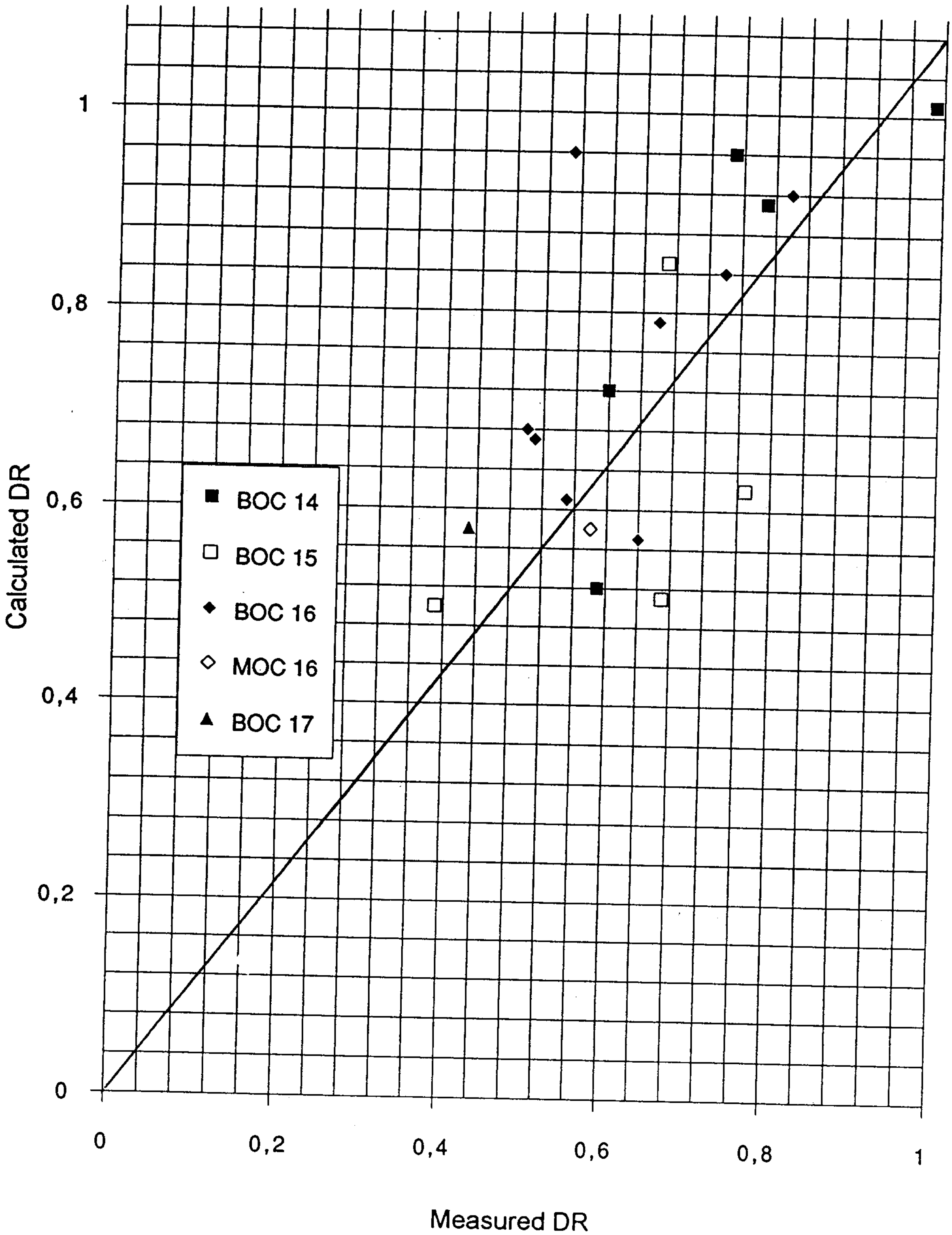


Fig. 3.5a NETCORP/SCANDPOWER LAPUR-K results, global decay ratio

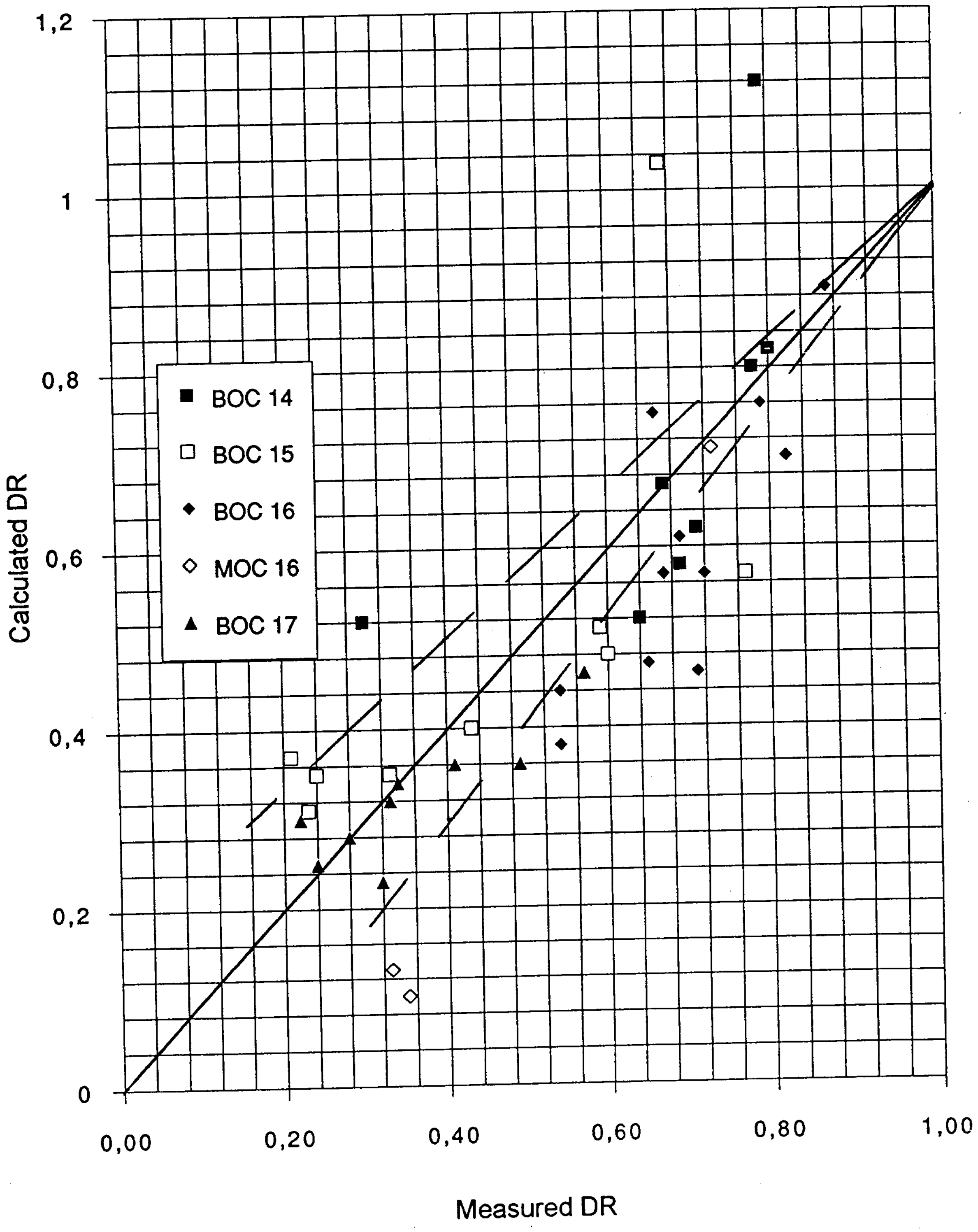


Fig. 3.5b NETCORP/SCANDPOWER LAPUR-K results, natural, global oscillation frequency

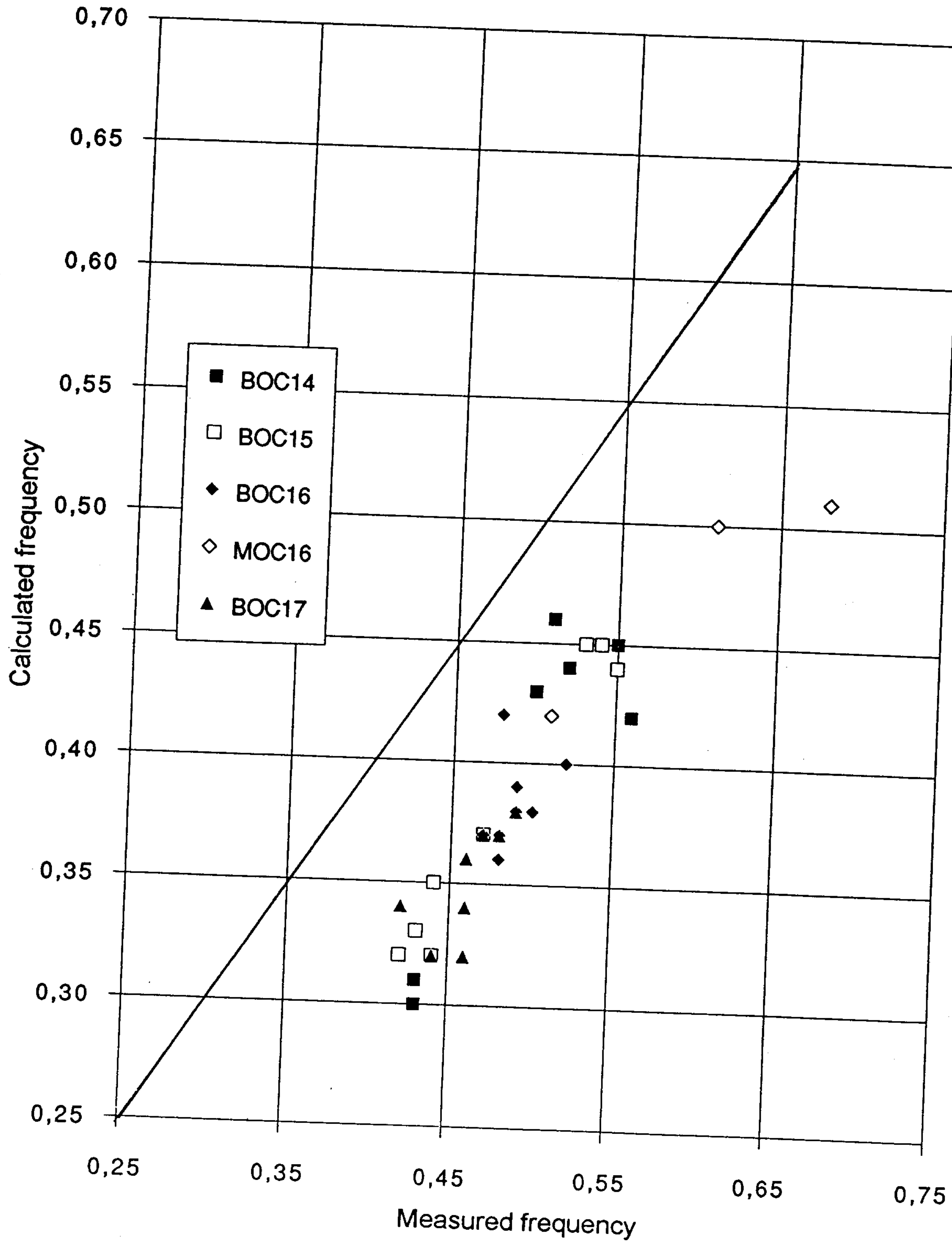


Fig. 3.6a NETCORP/SCANDPOWER LAPUR-K results, regional decay ratio

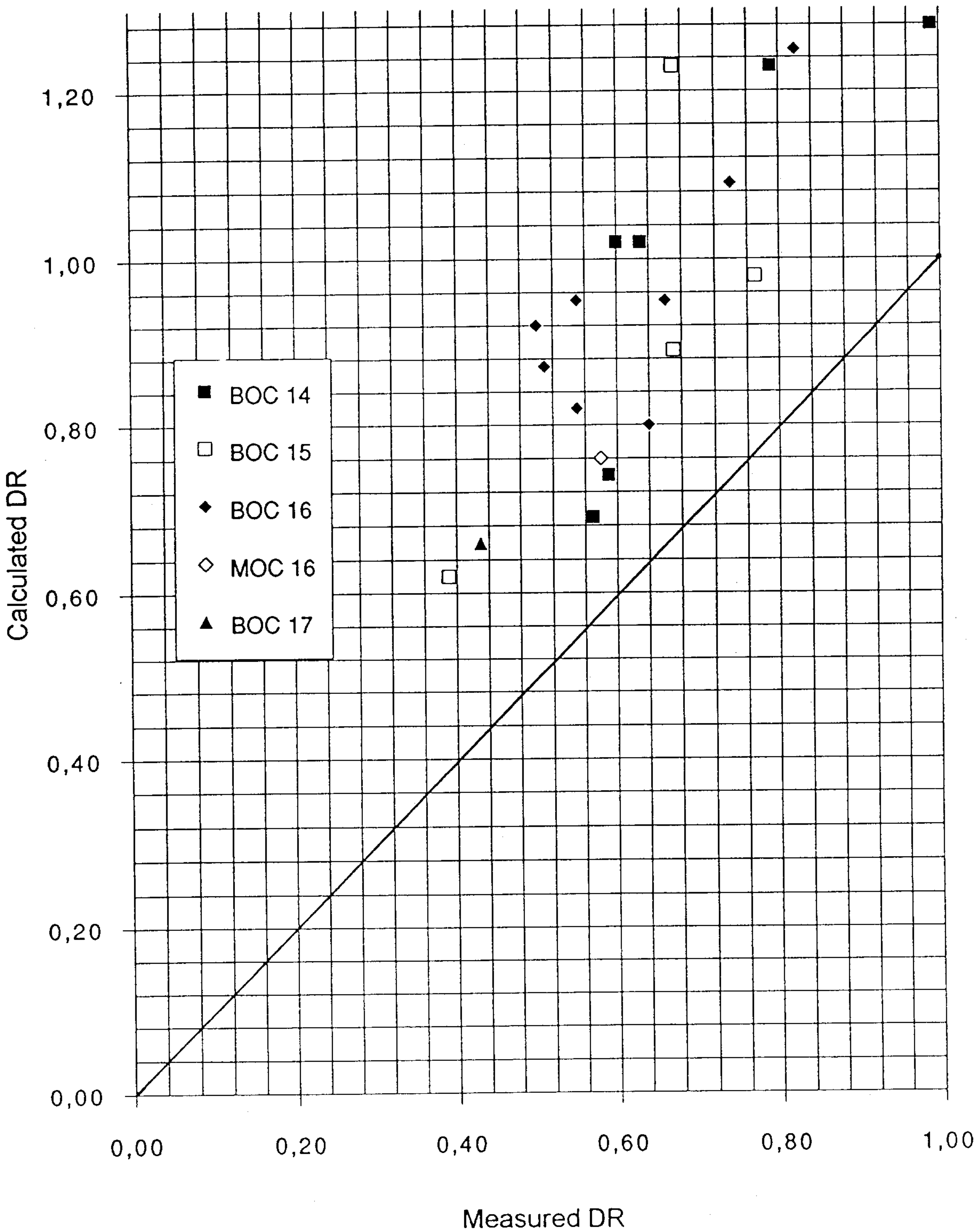


Fig. 3.6b NETCORP/SCANDPOWER LAPUR-K results, natural, regional oscillation frequency

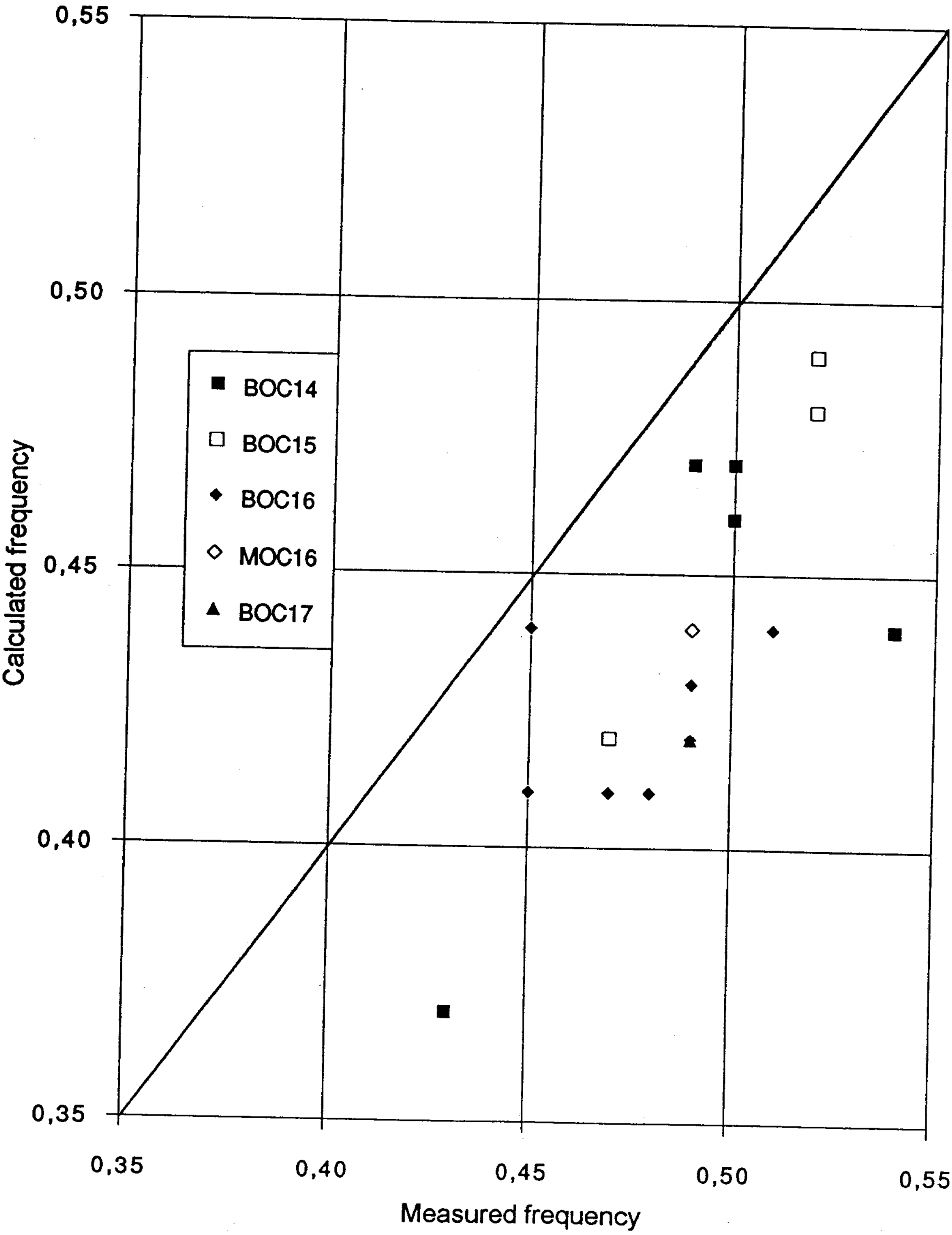


Fig. 3.7a NFI STAIF-PK results, global decay ratio

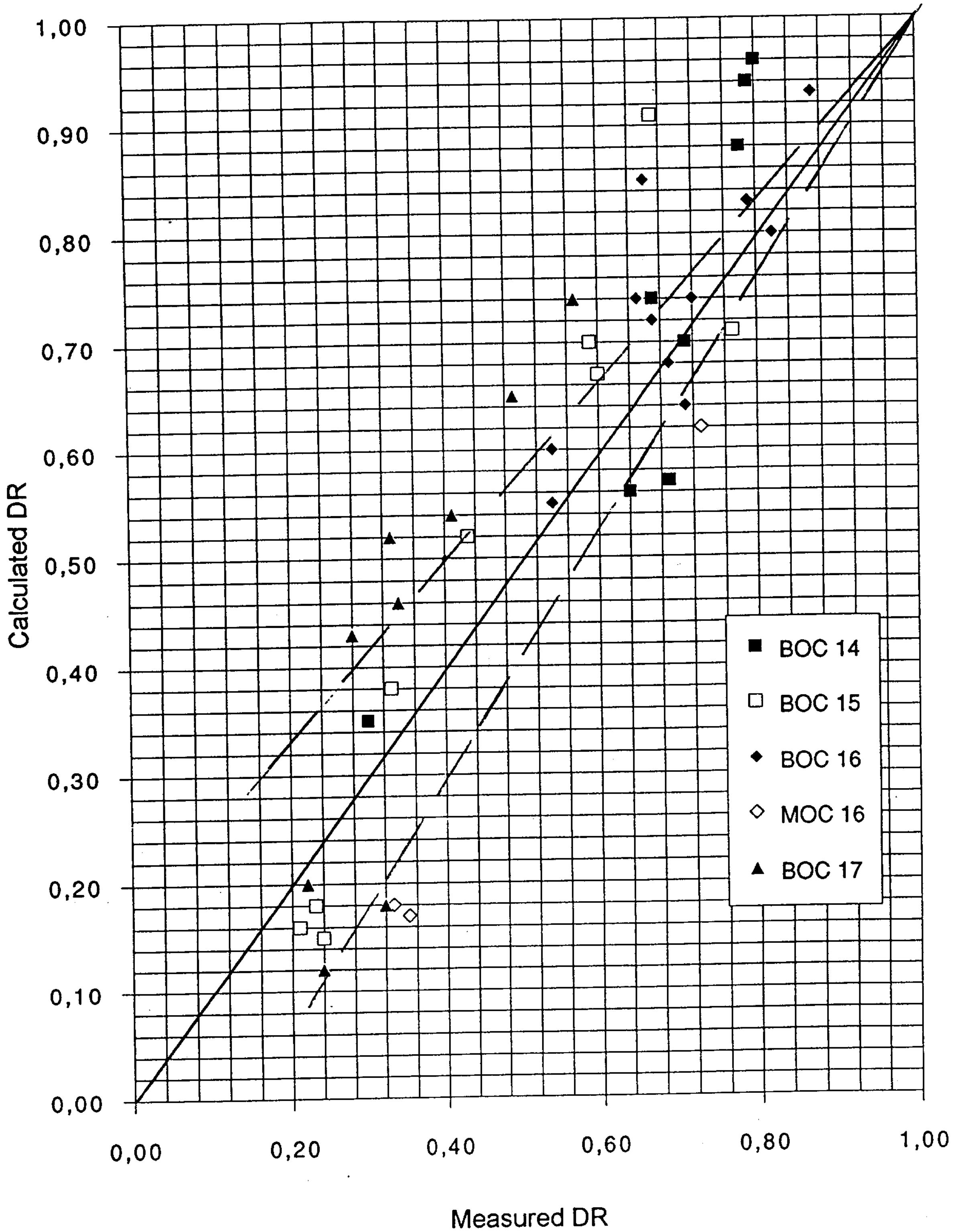
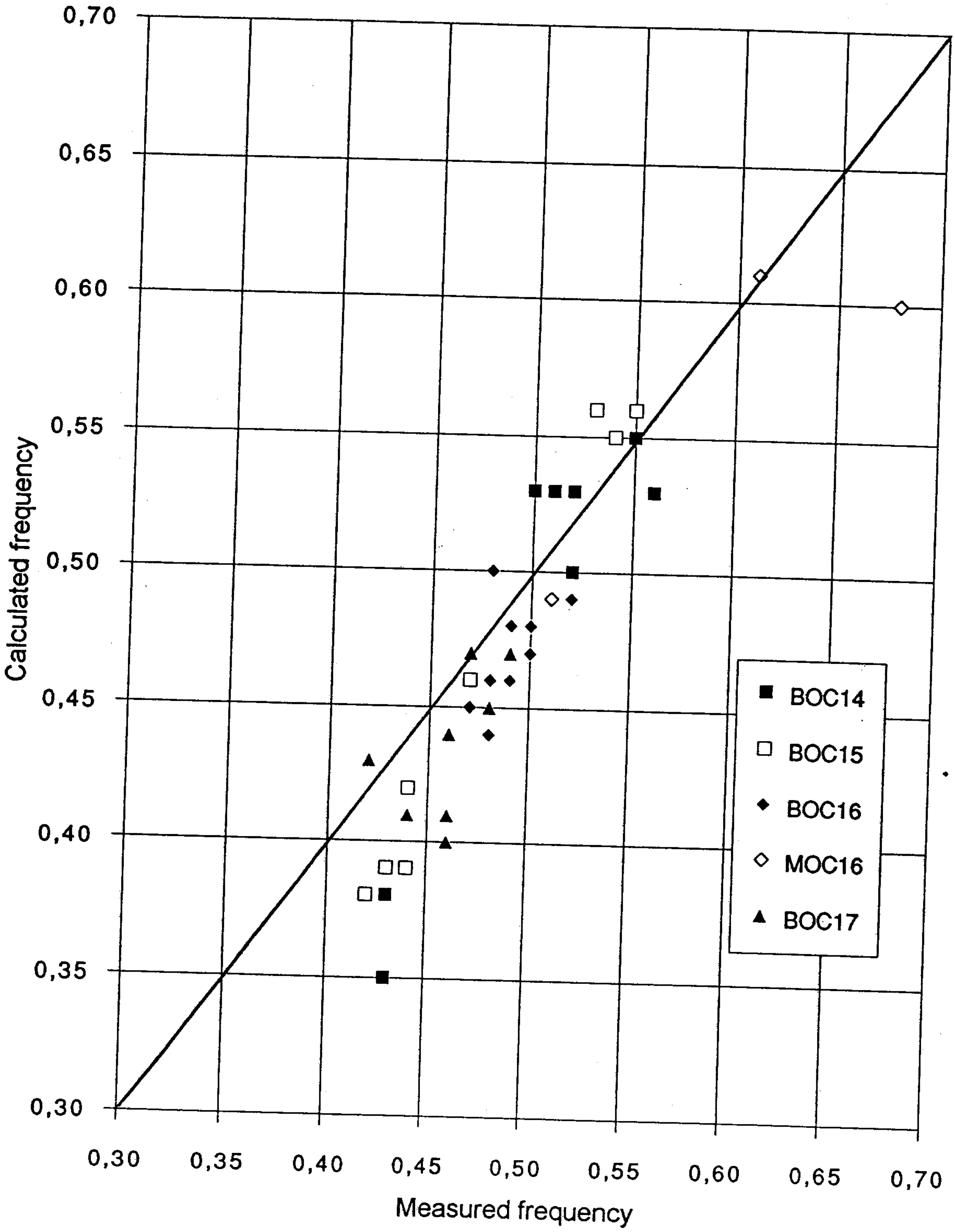


Fig. 3.7b NFI STAIF-PK results, natural, global oscillation frequency



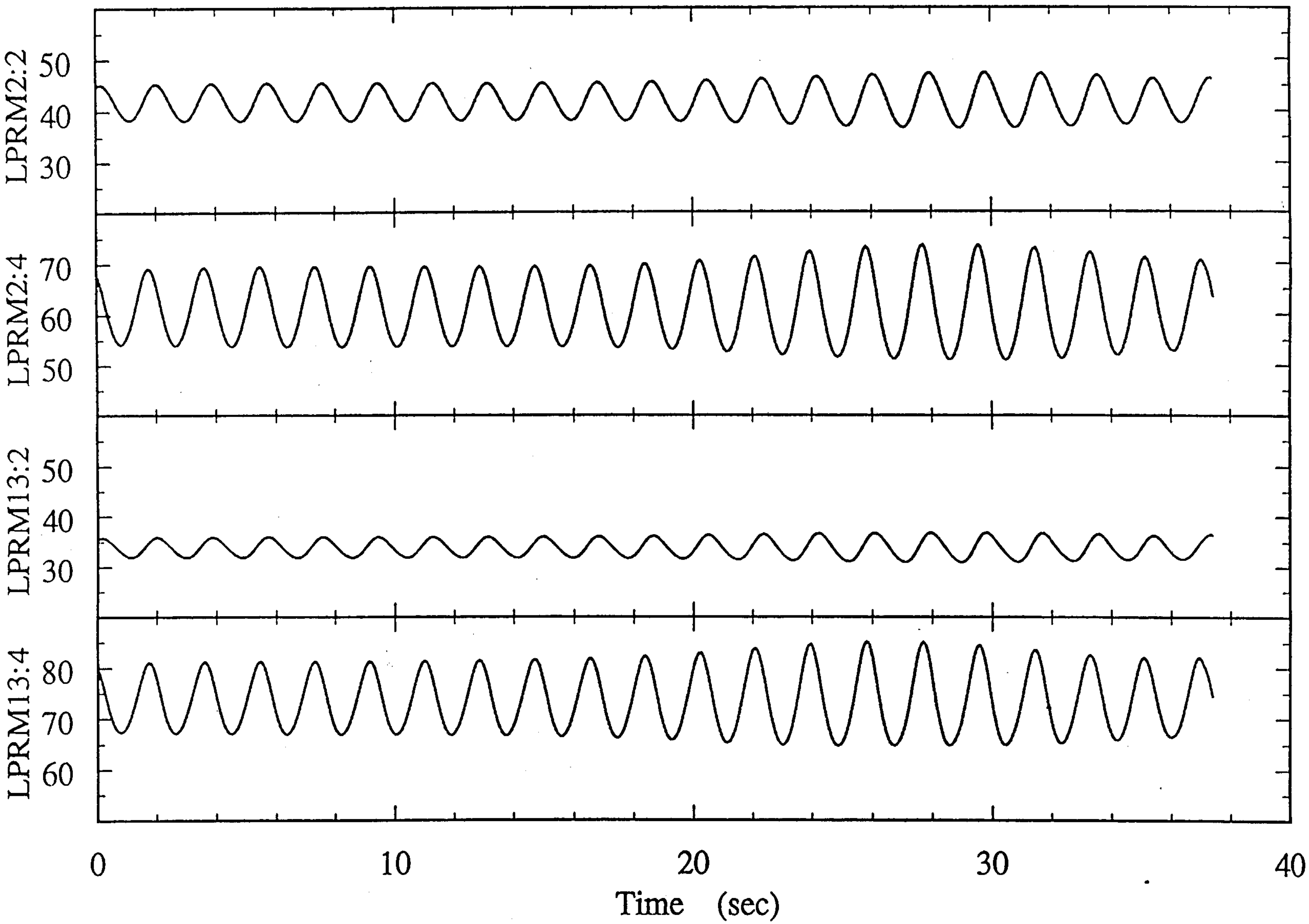


Fig. 3.8 Calculated LPRM Response of Cycle 14 Test 9 by DYNAS-2

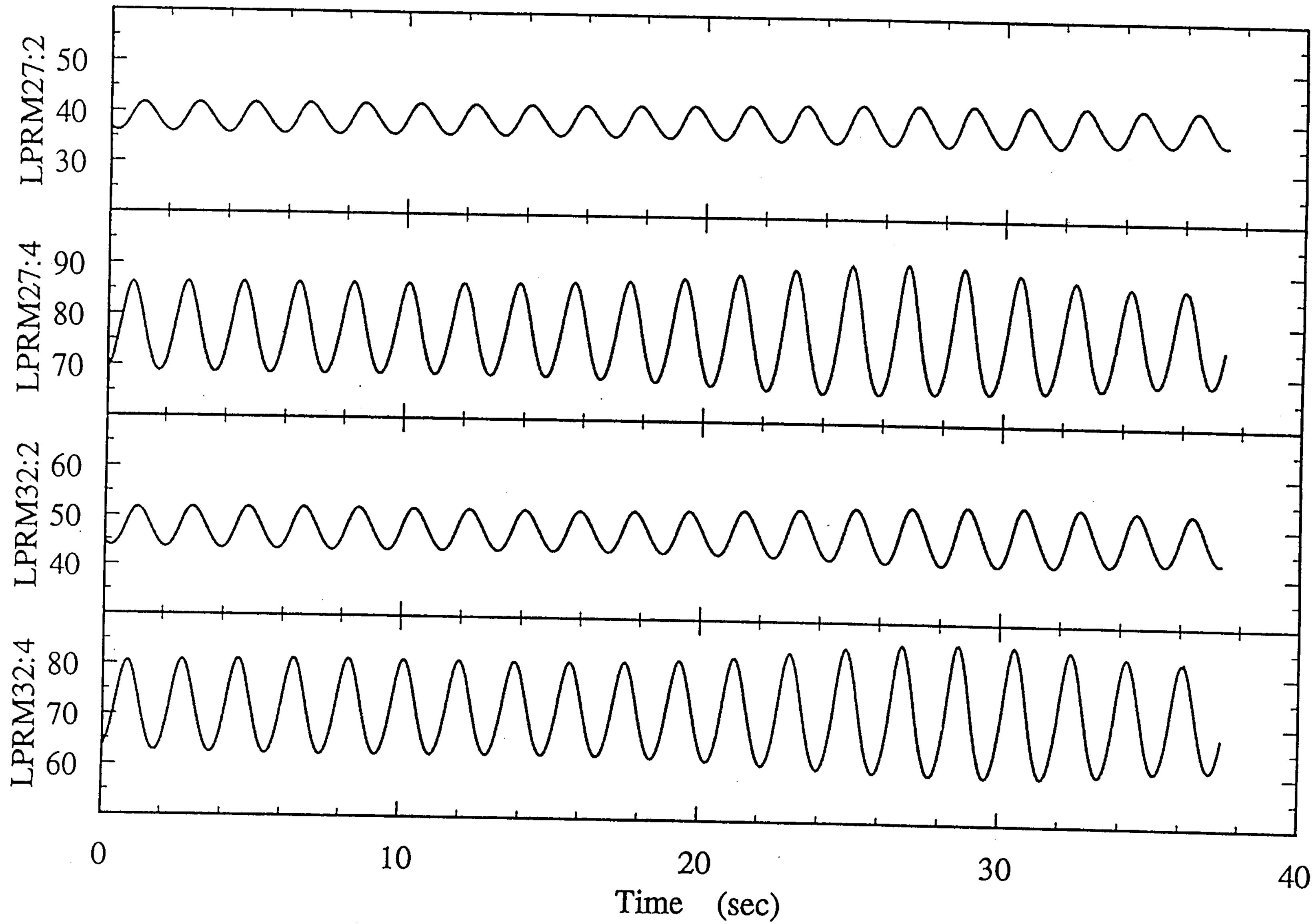


Fig. 3.9 Calculated LPRM Response of Cycle 14 Test 9 by DYNAS-2

Fig. 3.10a PSI RAMONA-3.5 results, global decay ratio

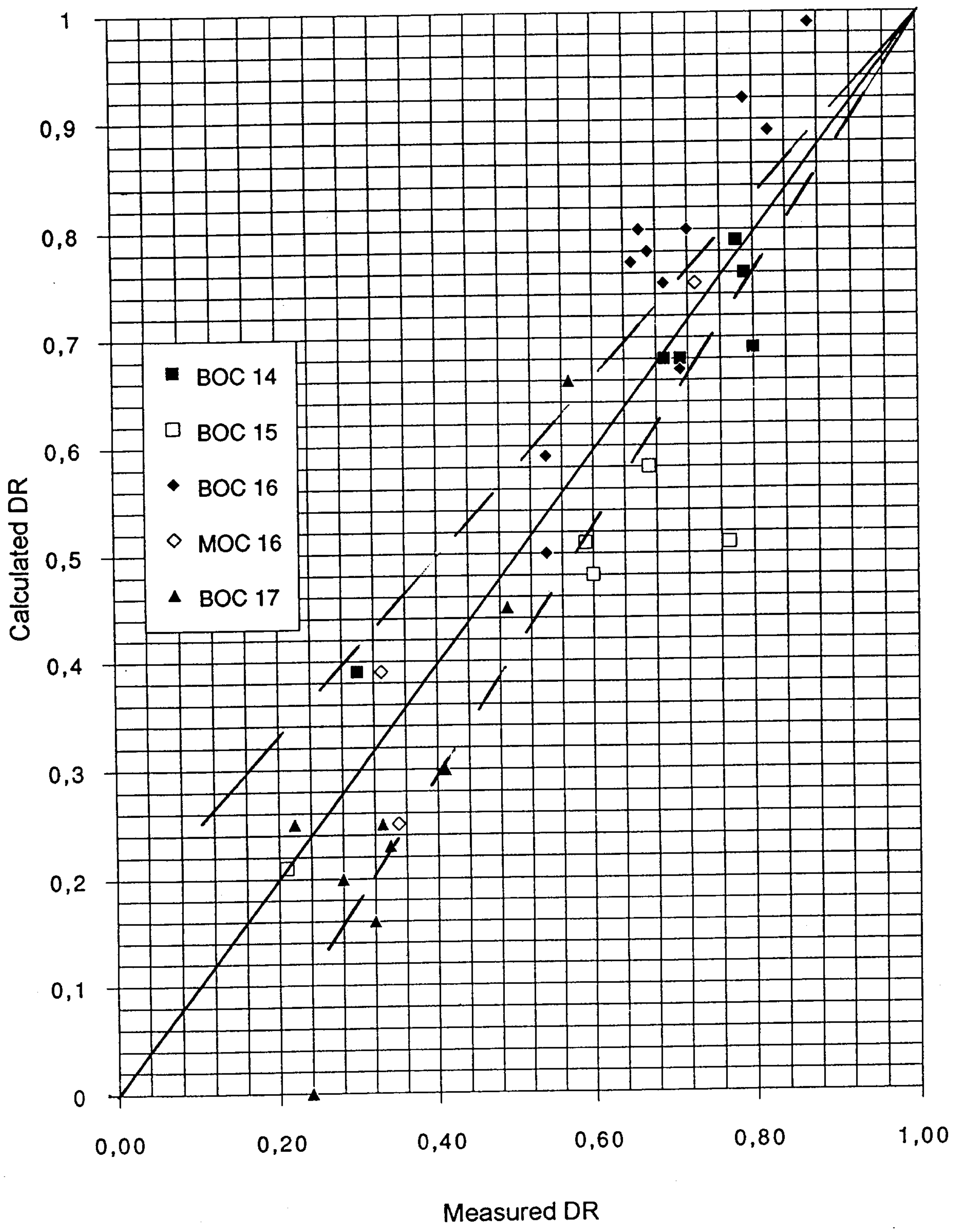


Fig. 3.10b PSI RAMONA-3.5 results, natural, global oscillation frequency

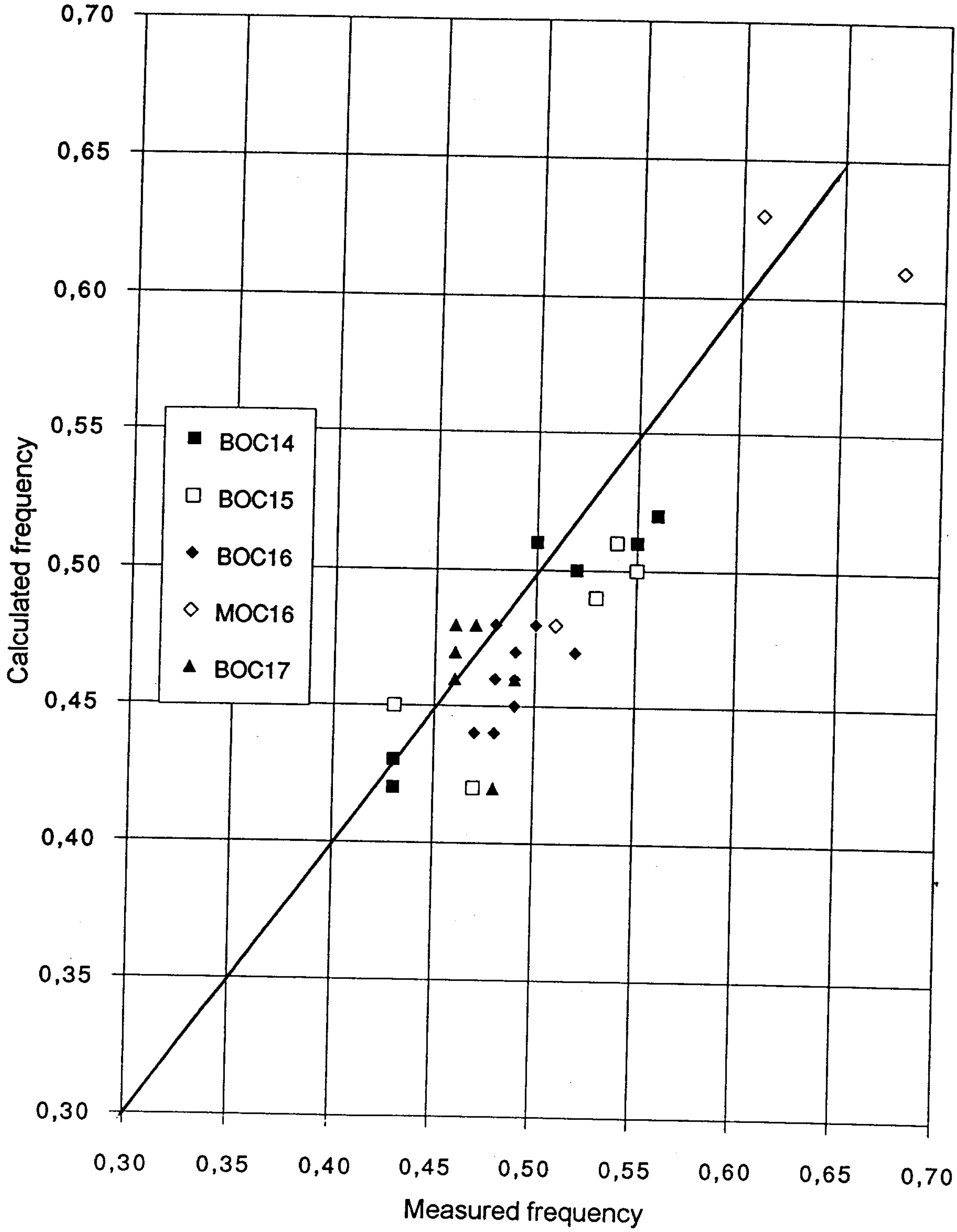


Fig. 3.11a PSI RAMONA-3.5 results, regional decay ratio

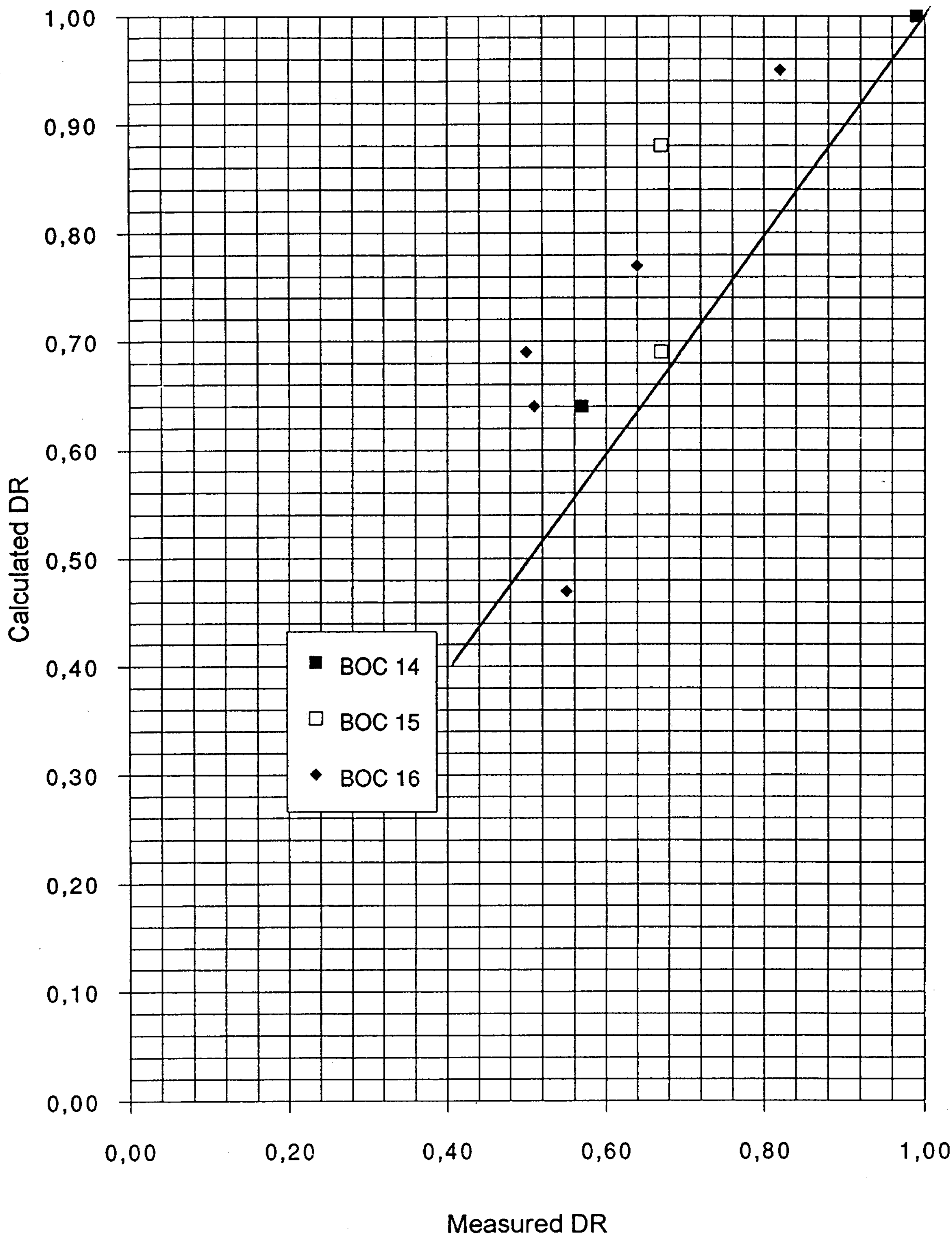
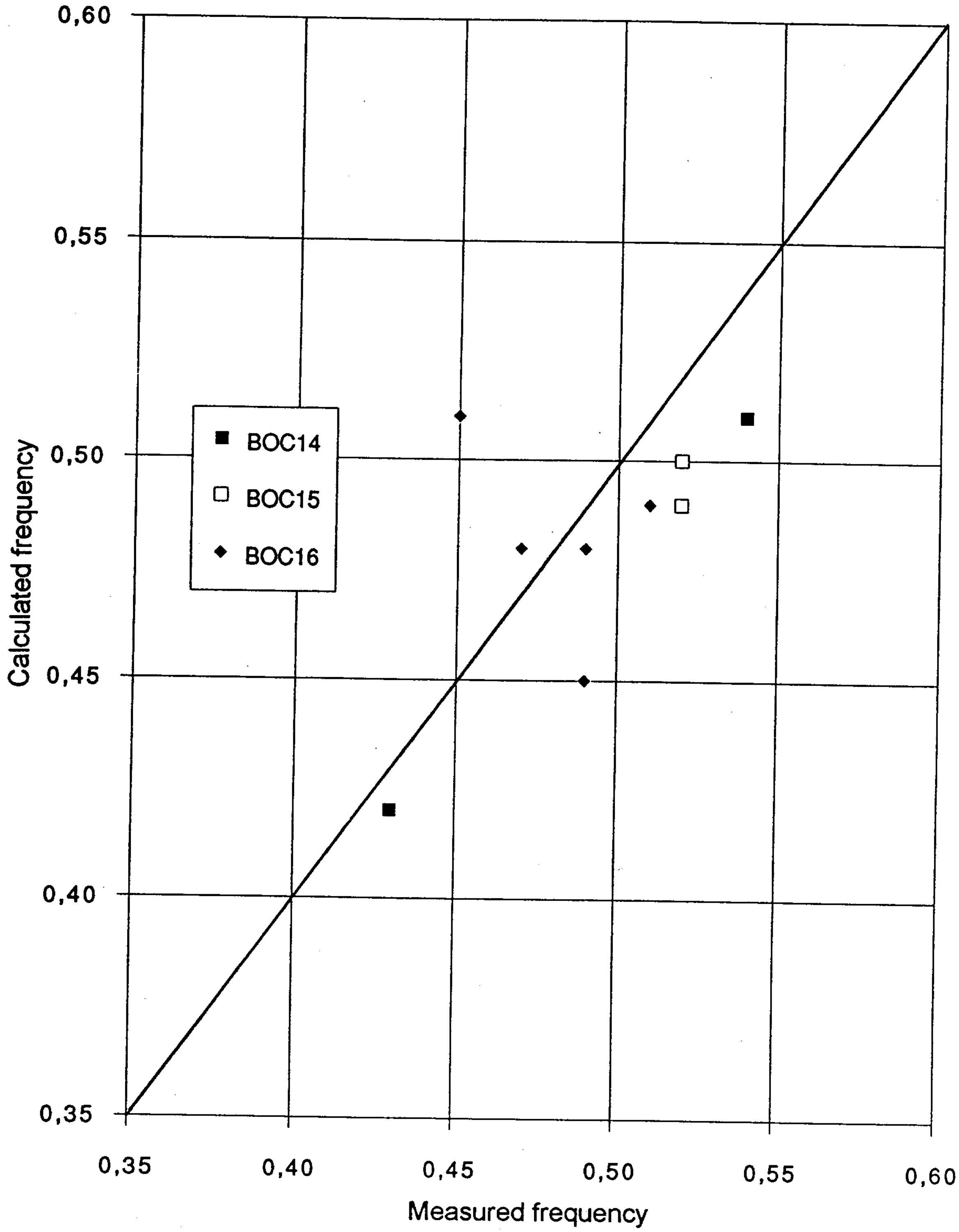


Fig. 3.11b PSI RAMONA-3.5 results, natural, regional oscillation frequency



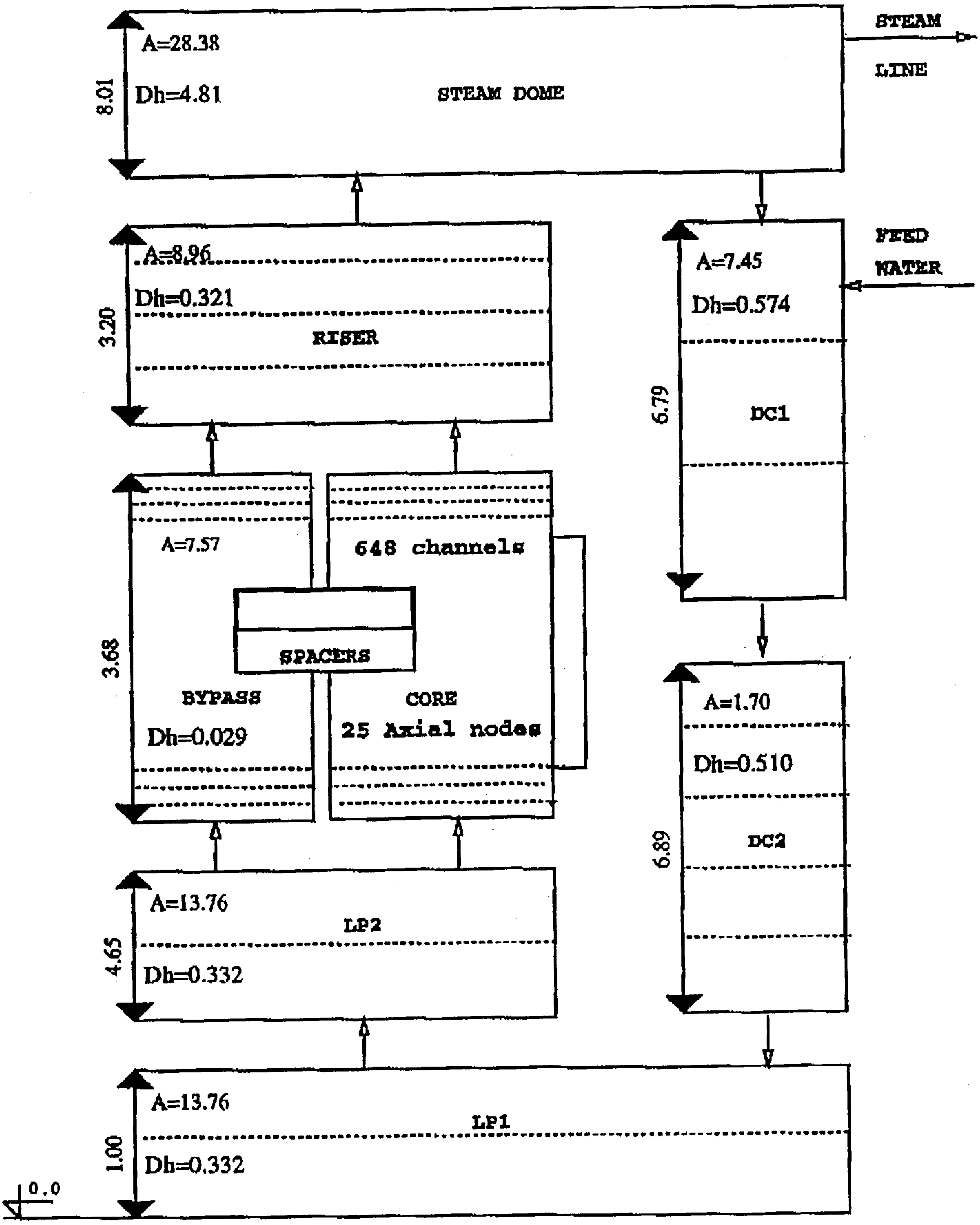


Fig. 3.12 RAMONA-3 Plant Model

Fig. 3.13a SCANDPOWER/ABB ATOM RAMONA-3 results, global decay ratio

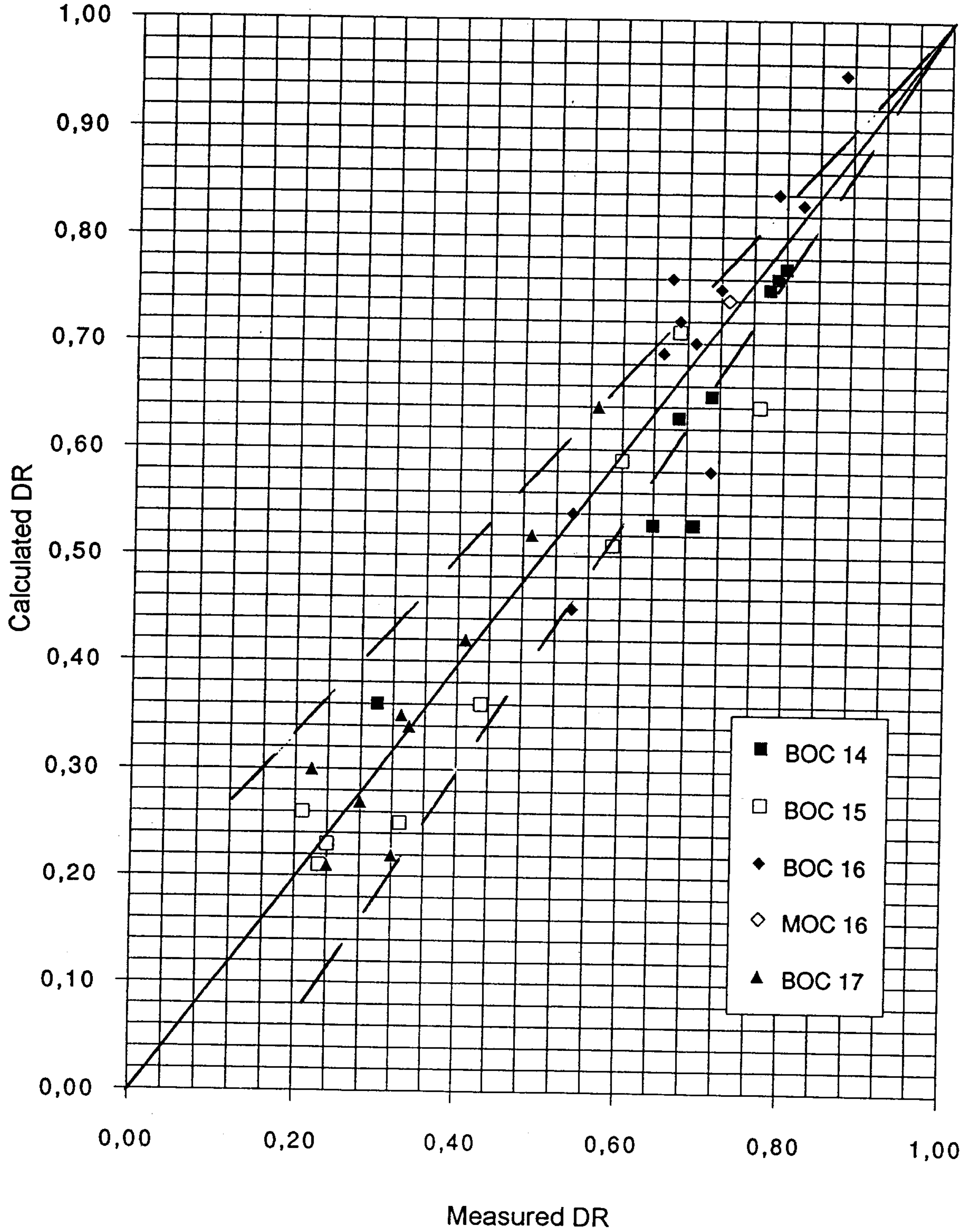
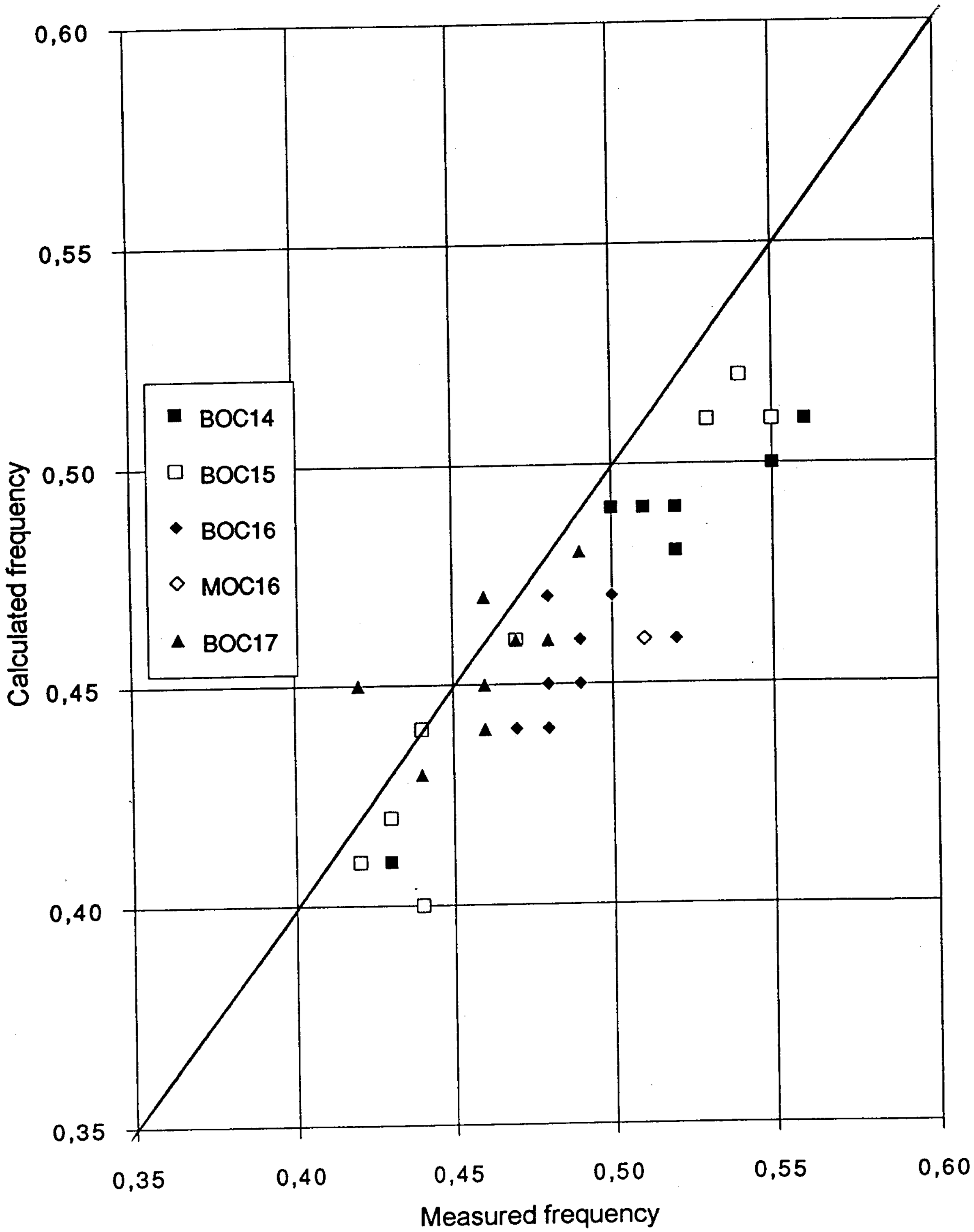


Fig. 3.13b SCANDPOWER/ABB ATOM RAMONA-3 results, natural, global oscillation frequency



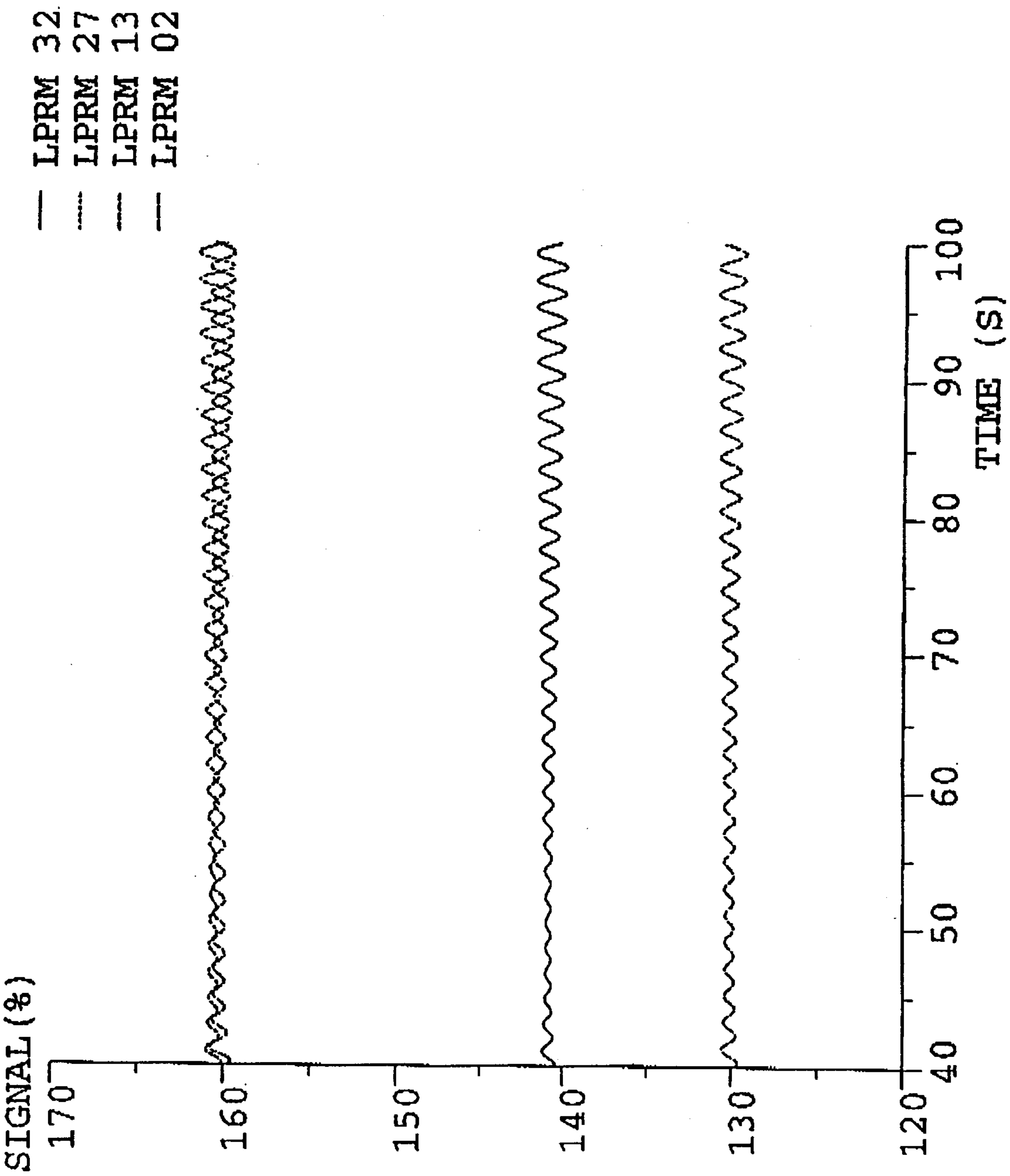


Fig. 3.14 Cycle 14, Case 9-LPRM Level 4 Responses

Fig. 3.15a Siemens STAIF results, global decay ratio

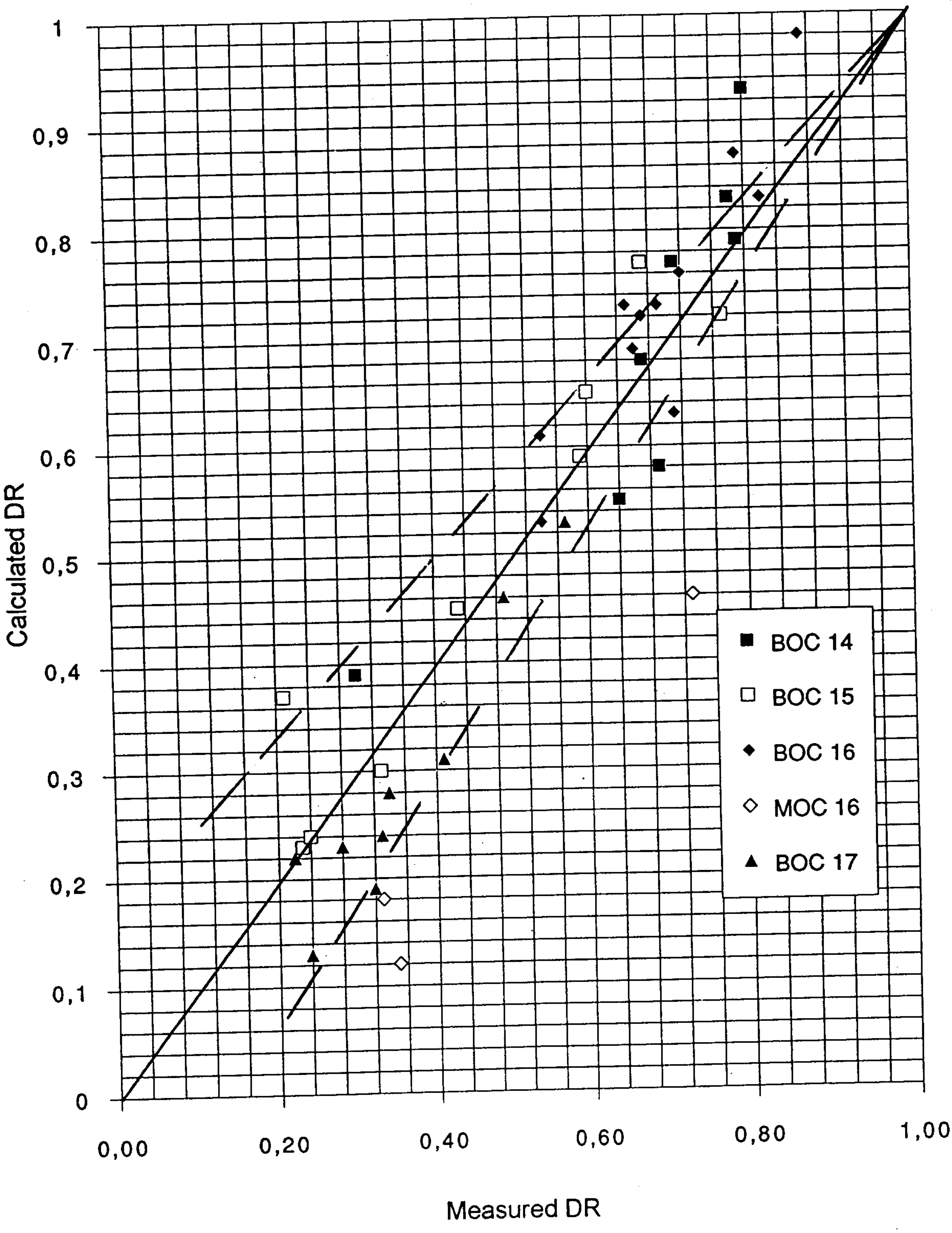
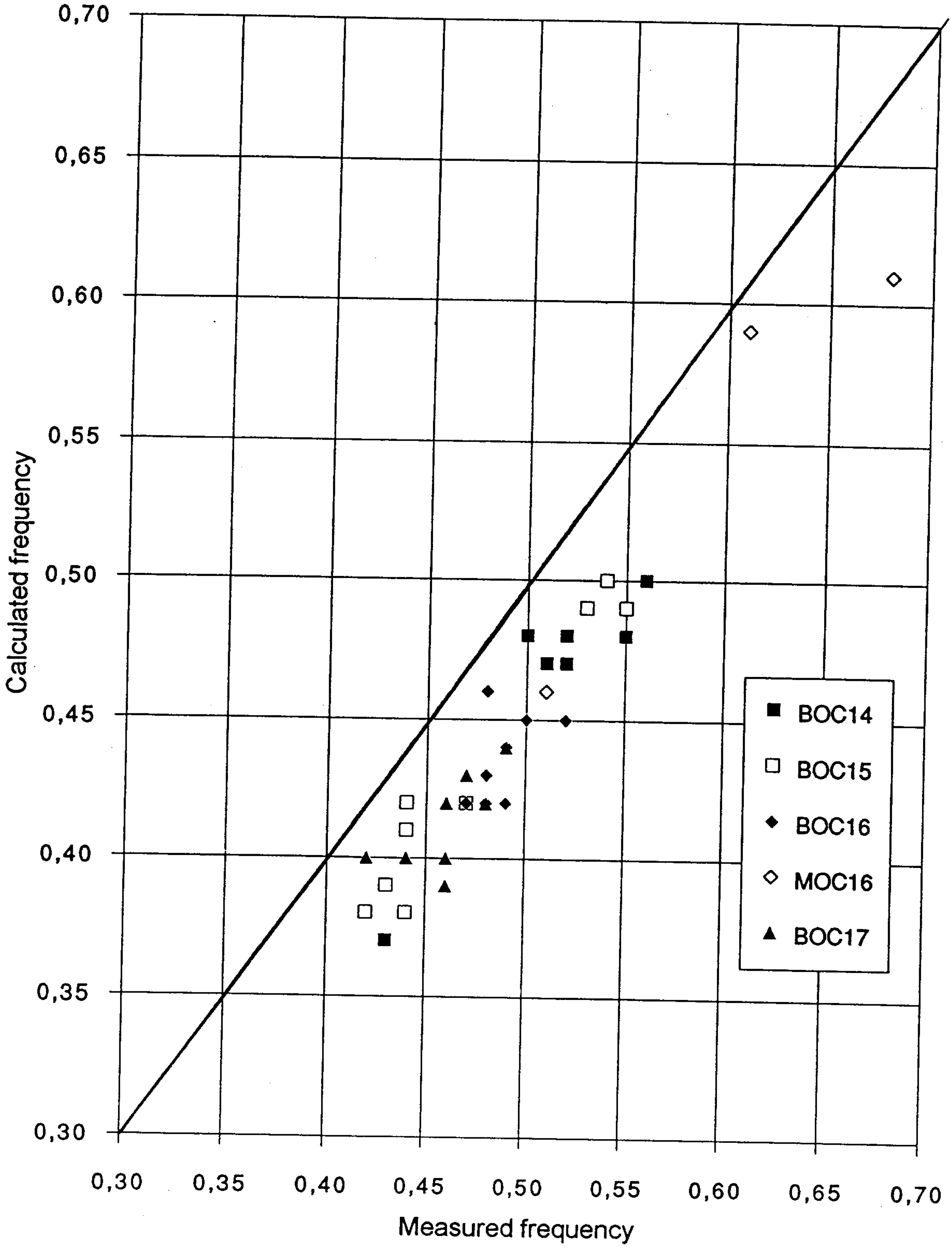


Fig. 3.15b Siemens STAIF results, natural oscillation frequency



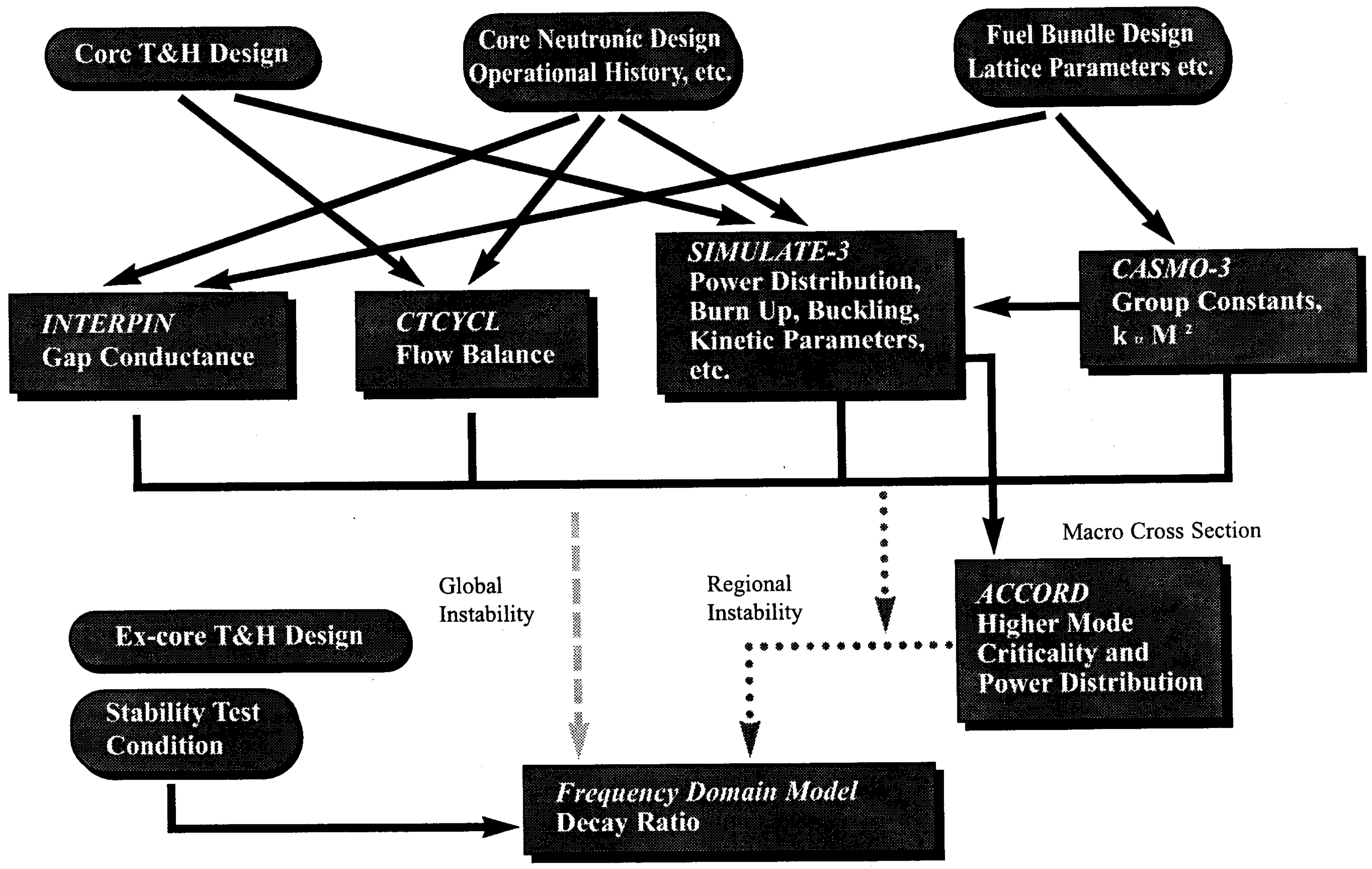


Fig. 3.16 TSI BWR Stability Evaluation System

Fig. 3.17a TSI results, global decay ratio, design base model

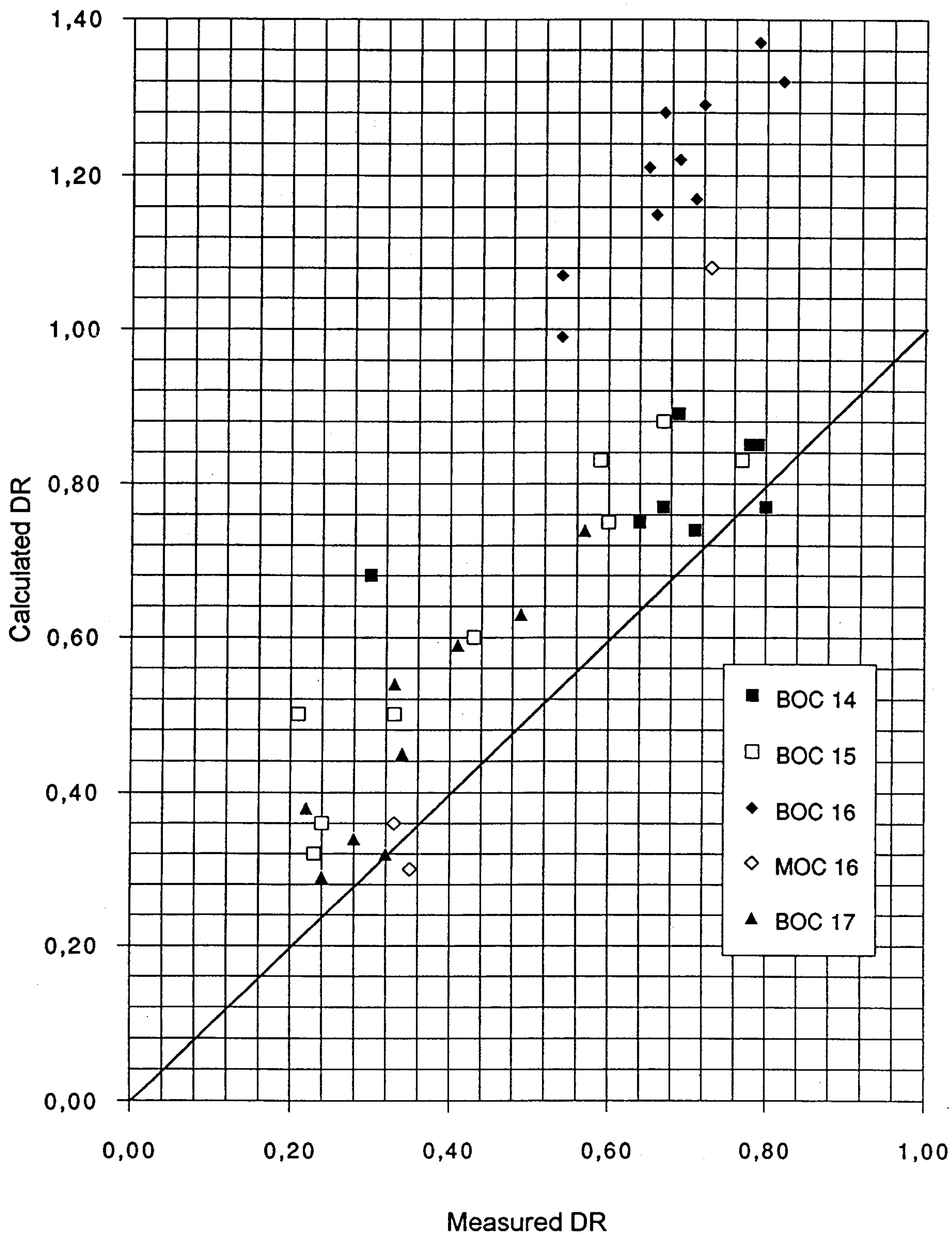


Fig. 3.17b TSI results, natural, global oscillation frequency, design base model

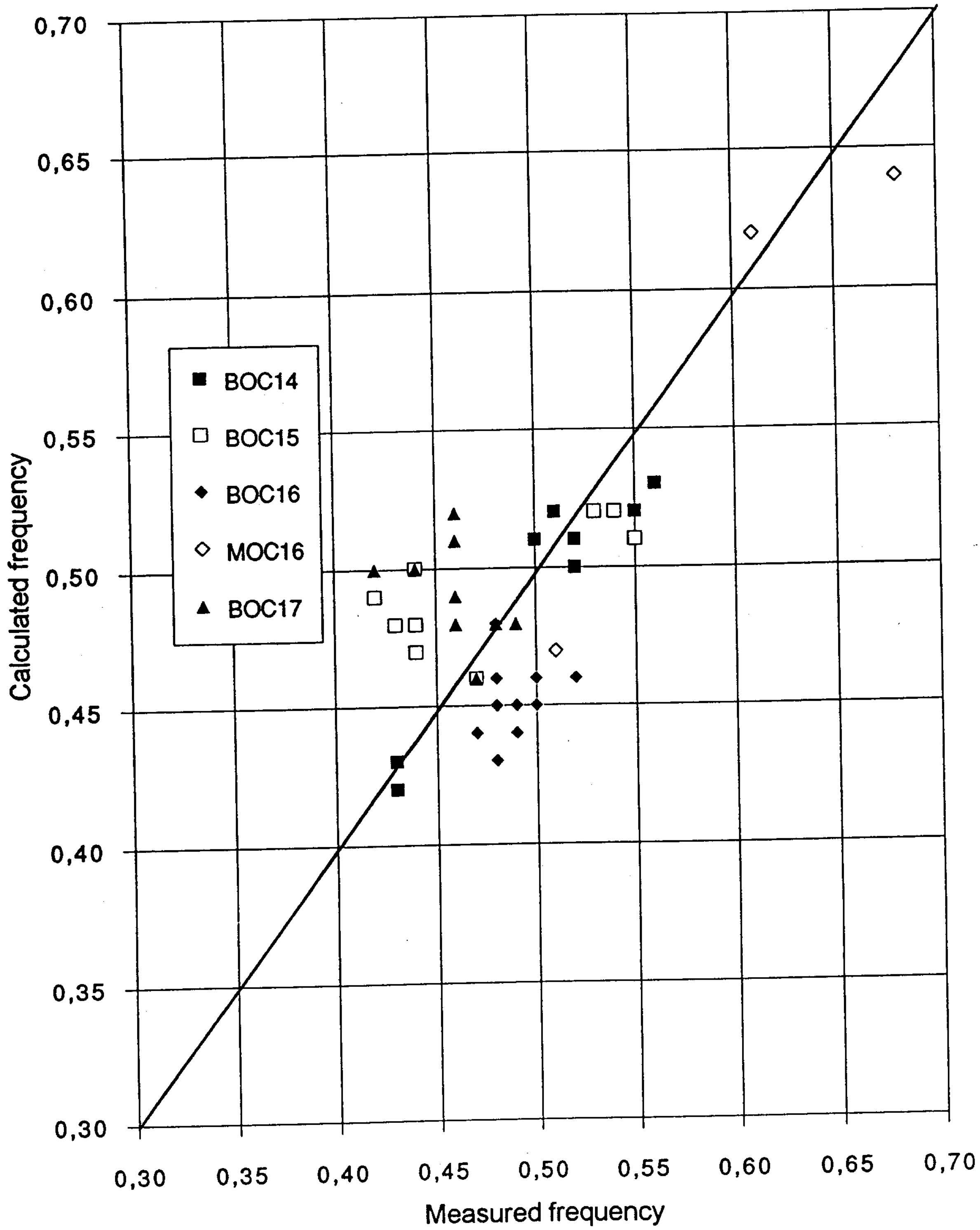


Fig. 3.18a TSI results, regional decay ratio, design base model

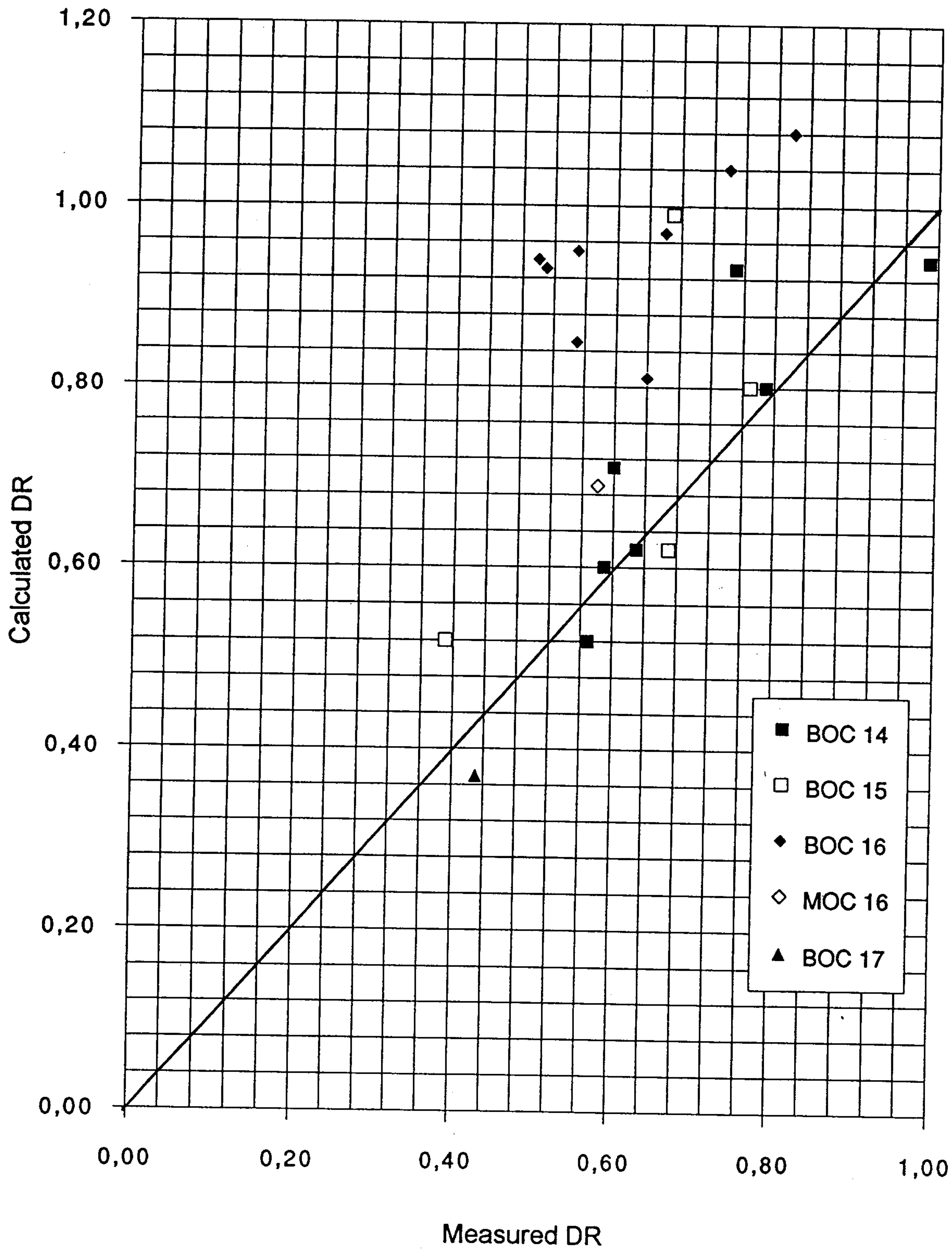


Fig. 3.18b TSI results, natural, regional oscillation frequency, design base model

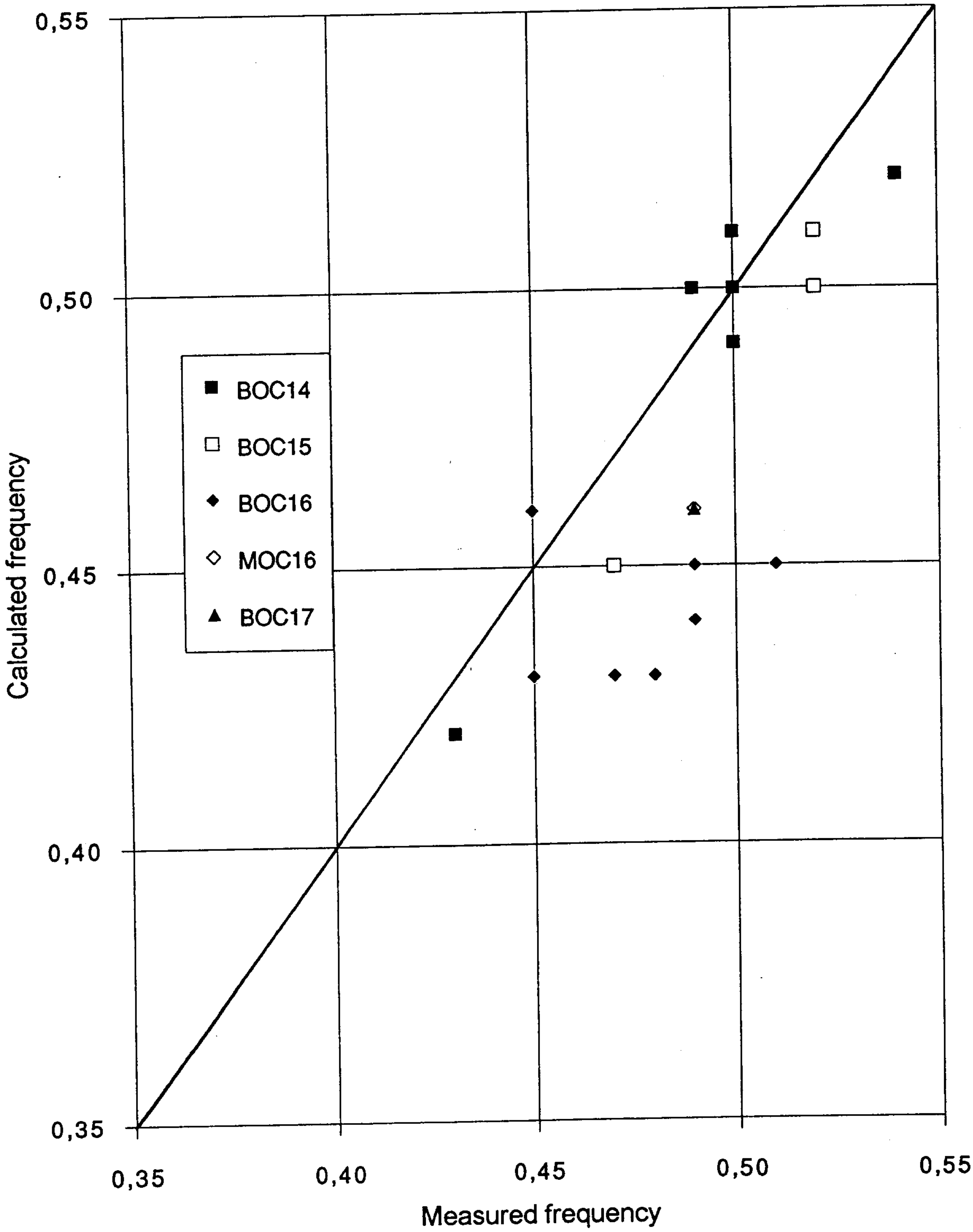


Fig. 3.19a TSI results, global decay ratio, best fit model

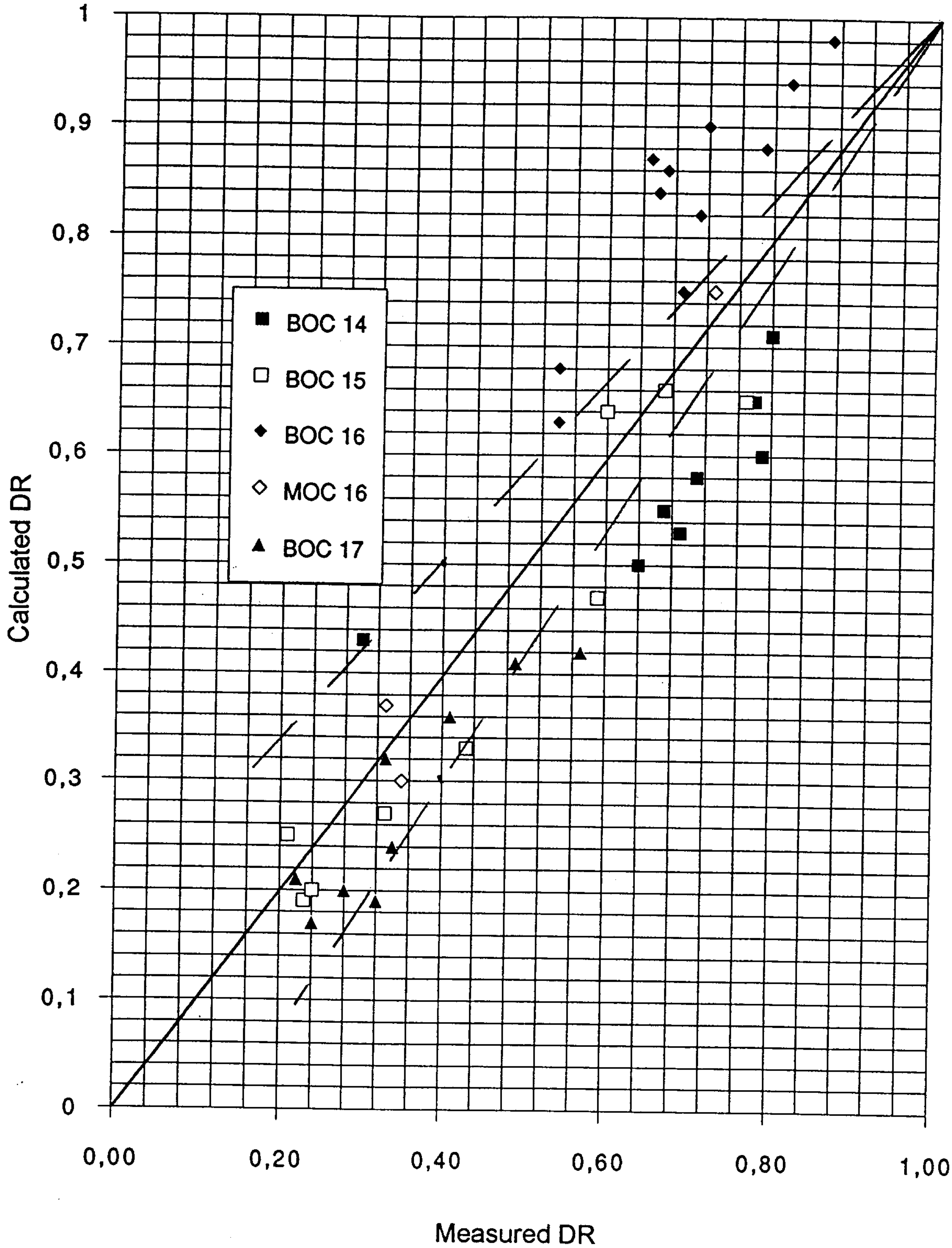


Fig. 3.19b TSI results, natural, global oscillation frequency, best fit model

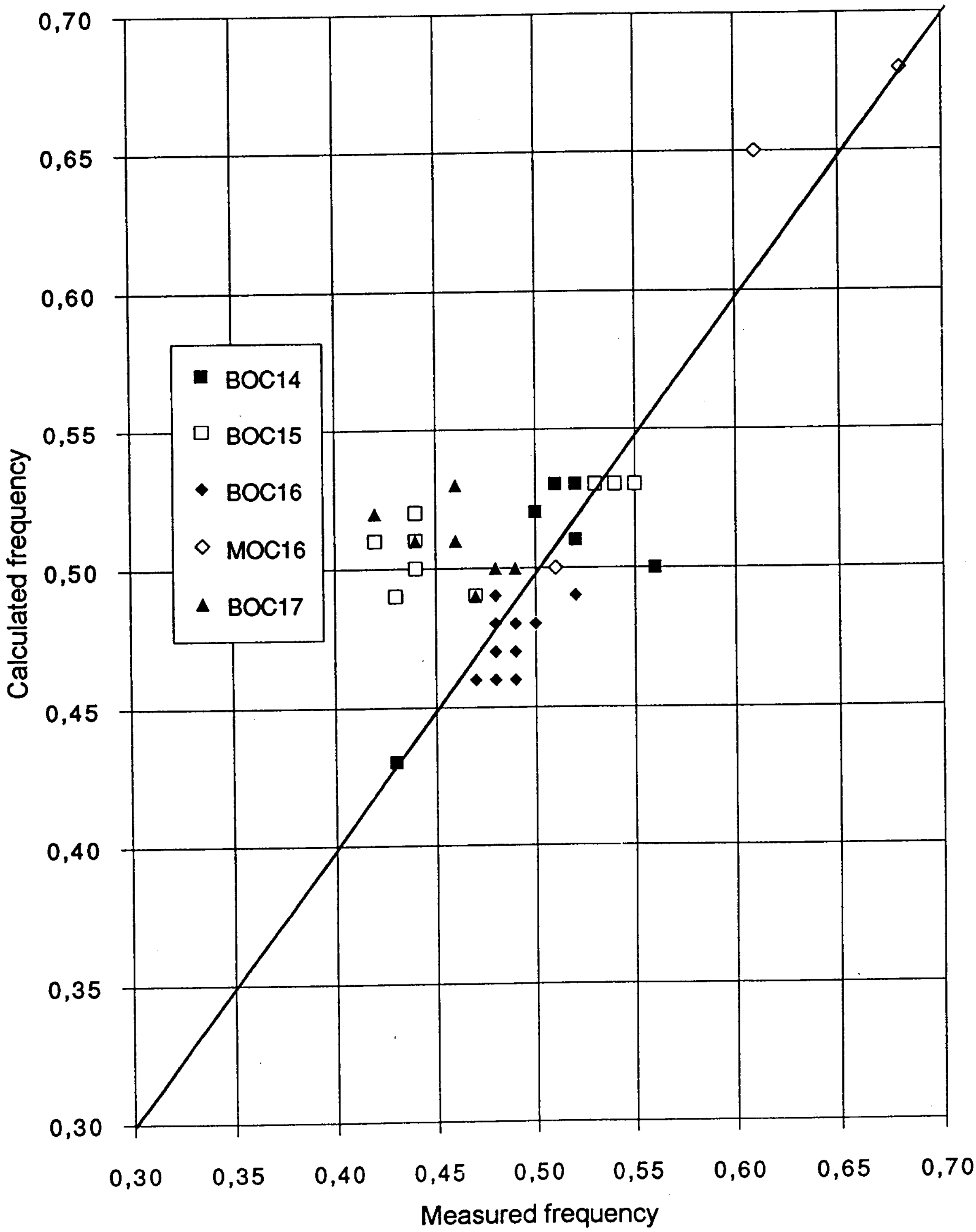


Fig. 3.20a TSI results, regional decay ratio, best fit model

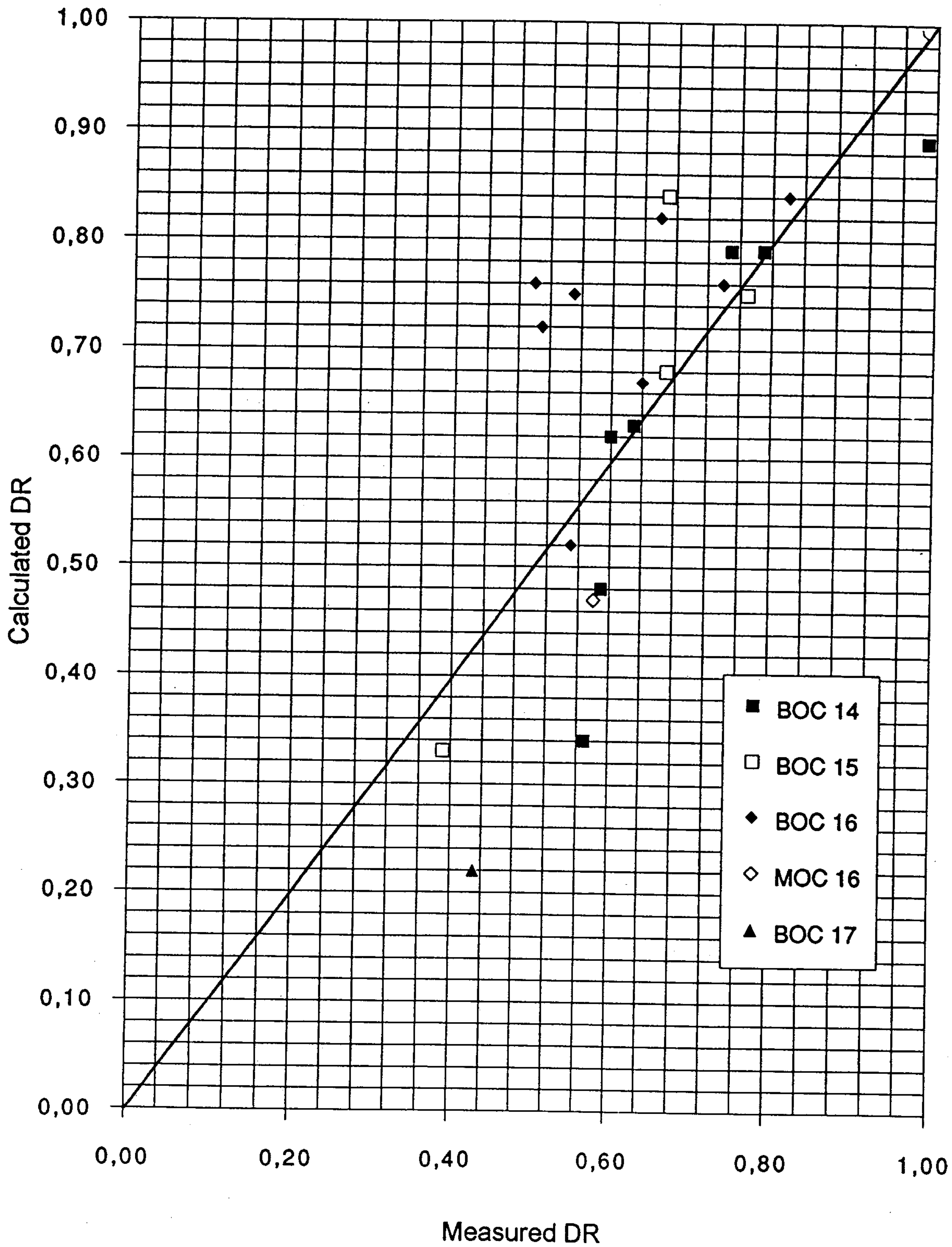


Fig. 3.20b TSI results, natural, regional oscillation frequency, best fit model

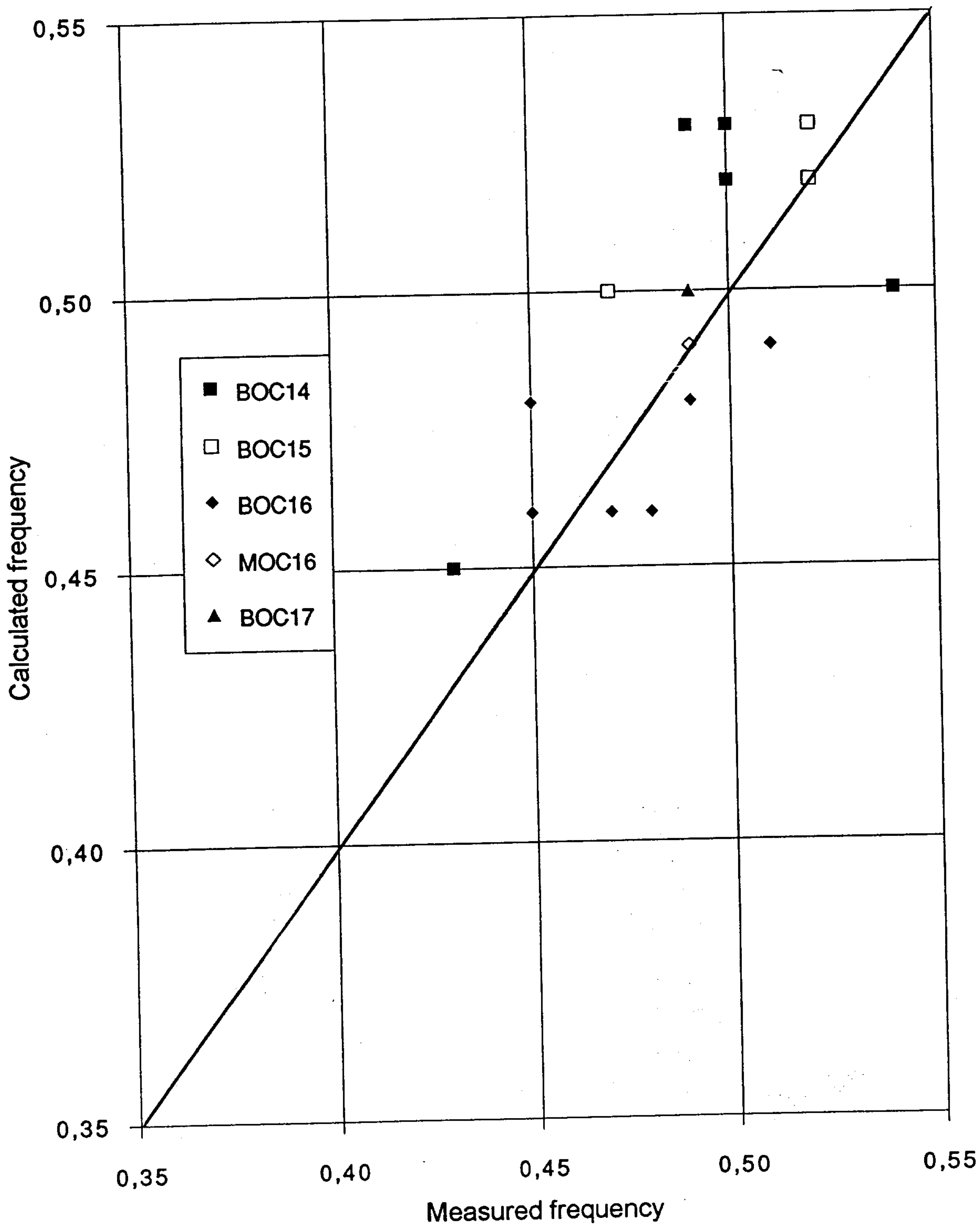


Fig. 3.21 DCMN RELAP5/MOD2 results, global decay ratio