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NUCLEAR SCIENCE COMMITTEE
and
COMMITTEE ON THE SAFETY OF NUCLEAR INSTALLATIONS

OECD/NCR Benchmark based on NUPEC BWR Full-size Fine-mesh Bundle Tests (BFBT) Summary Record of the Third Workshop (BFBT-3)

26-27 April 2006
Pisa, Italy

English - Or. English

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NUCLEAR SCIENCE COMMITTEE
and
COMMITTEE ON THE SAFETY OF NUCLEAR INSTALLATIONS

OECD/NRC Benchmark based on NUPEC BWR Full-size Fine-mesh Bundle Tests (BFBT) Third Workshop (BFBT-3)

Pisa, Italy
26-27 April 2006

Hosted by
the University of Pisa

SUMMARY RECORD

Sponsorship

The third workshop for the OECD/NRC Benchmark based on NUPEC BWR Full-size Fine-mesh Bundle Tests (BFBT-3) was held from 26 to 27 April 2006 in Pisa Italy, and was a follow up to the first and second workshops. The second workshop for the BFBT benchmark (BFBT-2) was held from 27 to 29 June 2005 at State College, PA, USA, and was hosted by the Nuclear Engineering Program (NEP) of the Pennsylvania State University (PSU). The first workshop of the BFBT benchmark (BFBT-1) was held on 4th October 2004 and was hosted by the Japan Nuclear Energy Safety (JNES) Organization. The BFBT Benchmark is sponsored by the US Nuclear Regulatory Commission (NRC), the OECD, and the NEP of PSU. The experimental data were produced during a measurement campaign by the NUPEC, Japan and sponsored by the Japan Ministry of Economy, Trade and Industry (METI).

The international benchmark team is based on the collaboration between Japan and the USA. CEA-Saclay (France) proposed the introduction of an additional uncertainty analysis exercise to the benchmark and joined the benchmark team in defining and conducting the exercise. Further details relative to the structure and involvement of the different partners in this project can be found in the NEA/NSC/DOC(2004)15 – Summary of the First Workshop.

This workshop (BFBT-3) was held in conjunction with other meetings in order to facilitate co-ordination and sharing of work. These were held at the same place and during the same week in order to combine efforts in common areas such as CFD modelling and uncertainty analysis and to increase participation. The other meetings were the fourth workshop for the OECD/DOE/CEA VVER-1000 Coolant Transient (V1000CT) benchmark – V1000CT-4 – scheduled for 24-25 April 2006, and the NEA/OECD meeting on "Uncertainty Analysis in Modelling", scheduled for 28-29 April 2006.

Background and Purpose of the Benchmark Workshop

In the past decade, a large amount of effort has been made toward the direct simulation of the boiling transition (BT) for BWR fuel bundles. The most advanced sub-channel codes explicitly took into account droplets along with liquid and vapor. They predicted the dry-out process as disappearance of the liquid film on the fuel rod surface without employing any semi-empirical correlations. Through a series of benchmark

comparisons to full length/scale bundle data, it was verified that the codes were reliable in predicting the critical power of the conventional BWR fuel types. However, these sub-channel codes are not yet utilized in new fuel design. Adequacy of fuel lattice geometries, spacer configurations, etc., still has to be confirmed mainly by costly experiments using partial- and full-scale mock-ups. The main reason for this situation is a shortage of high resolution and full-scale experimental databases under actual operating conditions.

The detailed void distribution inside the fuel bundle is regarded as an important factor in the boiling transition in BWRs. With regard to the sub-channel wise void distribution, it is clear that the flow across the sub-channel gap dominates void distributions. Most of the well-known sub-channel codes still employ the classical Lahey's Void Drift Model or its modified models. Although there have been substantial efforts to establish a sound theoretical background of detailed void distributions, the numerical models that are verified in a wide range of geometrical and thermal-hydraulic conditions are not yet available. In this sense, this subject still remains the major unsolved problem in the two-phase flow of BWR fuel bundles. The main reason for this lack of resolution is the lack of reliable full bundle databases under operating conditions. Up to now, only partial bundle (3×3 or 4×4) test data under relatively low pressure ($\approx$ 1 MPa) conditions have been made available.

It was during the 4th OECD/NRC BWR TT Benchmark Workshop on 6 October 2002 in Seoul, Korea, that the need to refine models for best-estimate calculations based on good-quality experimental data was discussed. The need arising in this respect should not be limited to currently available macroscopic approaches but should be extended to next-generation approaches that focus on more microscopic processes. From 1987 to 1995, NUPEC (Nuclear Power Engineering Corporation) performed a series of void measurement tests using full-size mock-up tests for both BWRs and PWRs. Based on state-of-the-art computer tomography (CT) technology, the void distribution was visualized at the mesh size smaller than the sub-channel under actual plant conditions. NUPEC also performed steady-state and transient critical power test series based on the equivalent full-size mock-ups. Considering the reliability not only of the measured data, but also of other relevant parameters such as the system pressure, inlet sub-cooling and rod surface temperature, these test series supplied the first substantial database for the development of truly mechanistic and consistent models for void distribution and boiling transition. Consequently, the basis of this international benchmark is the data made available from the NUPEC database.

This international benchmark encourages advancement in this uninvestigated field of two-phase flow theory with very important relevance to the nuclear reactors' safety margins evaluation. Considering the immaturity of the theoretical approach, the benchmark specification is being designed so that it systematically assesses and compares the participants' numerical models for the prediction of detailed void distributions and critical powers. Furthermore, the following points were kept in mind while establishing the benchmark specification:

- As concerns the numerical model of void distributions, no sound theoretical approach applicable to a wide range of geometrical and operating conditions has been developed.

- In the past decade, experimental and computational technologies have tremendously improved though the study of the two-phase flow structure. Over the next decade, it can be expected that mechanistic approaches will be more widely applied to the complicated two-phase fluid phenomena inside fuel bundles.

- The development of truly mechanistic models for critical power prediction are currently underway. These models must include elementary processes such as void distributions, droplet deposit, liquid film entrainment, etc.

The BFBT benchmark is composed of two parts (phases), each part consisting of different exercises:

- Phase I – Void Distribution Benchmark

  Exercise 1 (I-1) – Steady-state sub-channel grade benchmark
  Exercise 2 (I-2) – Steady-state microscopic grade benchmark
  Exercise 3 (I-3) – Transient macroscopic grade benchmark
  Exercise 4 (I-4) – Uncertainty analysis of the steady state sub-channel benchmark

- Phase II – Critical Power Benchmark

  Exercise 0 (II-0) – Pressure drop benchmark
  Exercise 1 (II-1) – Steady-state benchmark
  Exercise 2 (II-2) – Transient benchmark
  Exercise 3 (II-3) – Uncertainty Analysis of the steady state critical power benchmark

The purpose of this benchmark is not only the comparison of currently available macroscopic approaches but above-all to encourage the development of novel next-generation approaches that focus on more microscopic processes. Thus, the benchmark problem includes both macroscopic and microscopic measurement data. In this context, the sub-channel grade void fraction data are regarded as the macroscopic data and the digitized computer graphic images are the microscopic data.

Scope and Technical Content of the Benchmark Workshop

The technical topics addressed at the workshop include:

- Review of the benchmark activities after the 2nd Workshop
- Discussion of the final version of the specifications and spacer's dimensions
- Presentation and discussion of modelling issues and comparison of submitted results for Exercise 1 of Phase I (I-1)
- Presentation and discussion of modelling issues and comparison of submitted results for Exercise 2 of Phase I (I-2)
- Presentation and discussion of modelling issues and comparison of submitted results for Exercise 0, Phase II (II-0)
- Presentation and discussion of modelling issues and comparison of submitted results for Exercise 1, Phase II (II-1)
- Discussion of the requested output and templates for submitting results for Exercises 3 and 4 of Phase I (I-3 and I-4), and Exercise 2 of Phase II (II-2)
- Discussion of Exercise 4 of Phase I (uncertainty analysis of I-1) and discussion of the introduction of Exercise 3 of Phase II (II-3) – uncertainty analysis of II-1
- Defining a work plan and schedule outlining actions to progress the two phases of the benchmark activities

Organization and Programme Committee of the Benchmark Workshop

A Programme Committee has made the necessary arrangements for the third Benchmark Workshop, organised the Sessions, and prepared the final programme. The general chair was Francesco D'Auria (University of Pisa) who is a member of CSNI which also hosted the workshop. The other members were Gene Rhee (US NRC) who is co-sponsoring this activity, José Aragonés (UPM), representing the NSC, Eric Royer (CEA), K. Ivanov (PSU) representing the benchmark team, and the OECD/NEA Secretariat.

Session 1 - Introduction and opening remarks

The meeting was opened by Francesco D'Auria of the University of Pisa that was hosting the meeting. He welcomed the participants on behalf of the University and wished them a successful work. He described the objectives of his department on Applications in Nuclear Energy, namely to maintain the competences and keeping the nuclear energy option alive in Italy. Enrico Sartori welcomed the participants on behalf of the NEA Secretariat and thanked in particular the local organizers for their hospitality. Gene Rhee welcomed participants on behalf of the US Nuclear Regulatory Commission and commented that the benchmark was a very timely undertaking. The entire modelling philosophy is moving toward the best-estimate analysis with uncertainty analysis included. This benchmark will contribute to this effort.

The agenda was approved with minor adjustments (see Annex I).

The meeting was attended by 41 participants from 11 countries representing 28 organisations or establishments (see Annex II). As pointed out by José Aragonés, these represent research, university, industry and regulators. This work advances the state-of-the-art in this field and in science and technology and helps transfer technology to the next generation through the presence of many PhD students. The interest in this benchmark is very large, though not all participants having committed themselves to provide results have participated. Overall, 46 experts from 26 organisations in 23 countries agreed to participate, from research (40%), university (30%) and industry (30%).

The benchmark team made presentations giving an overview and status of benchmark activities, summarising the major additions and modifications in the final BFBT benchmark specification and initiating a discussion of the estimation of spacer grid's dimensions and individual sub-channel loss coefficients. The estimated spacer grid's dimensions by the benchmark team as posted on the benchmark web-site are obtained using the original drawings and are recommended to be used by the participants. The use of individual loss coefficients, defined with the Rehme's method, does not improve the accuracy of the sub-channel void distribution predictions. It is recognized that the Rehme's method results in large differences between individual loss coefficients. Participants are encouraged to propose/use their own "in-house" methods for estimation of the individual loss coefficients based on the estimated spacer grid's dimensions.

Session 2

The benchmark team summarized, in four presentations, the comparisons of submitted results for Exercises I-1 and I-2 (macro- and microscopic steady state void distribution) as well as evaluation of the measured void distribution data and the suggested optimization approach of sub-channel void distribution predictions. In Exercise I-1 most of the participants had problems to predict the void fraction in the central sub-channel. In the follow-up discussion, suggestions were made by the participants which were subsequently accepted to be addressed in the future benchmark activities. The benchmark team is expected to complete the study on the non-symmetry bias in the measured void distribution data, to quantify the bias. It will be useful to supplement the sub-channel void distribution prediction comparisons with a comparison of results for the bundle-averaged void fraction and bundle equilibrium quality at several axial elevations. If the comparisons of absolute void fraction predictions are supplemented by normalized results (normalize the void fraction distribution of each participant by his/her predicted bundle-averaged void fraction), it will help to analyze better the observed deviations. For the same reason it was proposed to perform a code-to-code comparative analysis in addition to a code-to-data comparison. For exercise I-2, it was recommended to visualize the deviations between the predicted and measured values on a pixel level. A questionnaire will be prepared by the benchmark team for each exercise to collect the information related to the participants' modelling, such as calculation mesh, utilized spacer loss coefficients, etc. Participants will also provide a complete description of the physical models in their codes.

Sessions 3 and 4

In Sessions 3 and 4, the benchmark participants made 11 presentations on modelling and on the results for Exercises I-1 and I-2. The following modelling issues were discussed and suggestions made to the benchmark team:

a) Clarify and correct the statistical methodology utilized for comparative analysis of the participants' results;
b) Specify the water rod description and modeling;
c) Specify how and where the flow is entering the bundle;
d) Request information about the utilized axial nodalization from the participants;
e) Provide the coordinates for one pixel in relation to the center of the bundle;
f) Reverse the axes for Predicted/Measured comparisons;
g) Is it possible to provide 9 densitometer measurements in the horizontal plane for the specified axial locations? - if yes, utilize the steady state densitometer measurements at the 3 axial locations to compare with CFD results in Exercise I-2.

Session 5

Session 5 was devoted to discussion of the modelling issues and preliminary results of Exercises I-3 (transient void fraction distribution) and I-4 (uncertainty analysis of I-1). Based on the benchmark team experience in modelling I-3, it was recommended to prepare and provide to the participants one set of time-dependent smoothed boundary conditions (BCs) in order to avoid introducing discrepancies from the BC's approximations. There is a problem in comparing the sub-channel based results with the densitometer measurements at the 3 axial locations, which are more important for the transient comparisons in I-3. It was suggested that a correlation be developed for the sub-channel based models using the CT-scan and densitometer data for steady state void distribution, which can be applied for transient comparisons. For the code-to-data comparison, a simple method was suggested, namely to take the deviation from the steady state. It was also proposed, in addition to comparing time-history data, to introduce snapshots for the 2-D void distribution code-to-code comparison in I-3 (Note: the provided data is the bundle-averaged time-history).

Sessions 6 and 7

In Sessions 6 and 7, the benchmark team and participants presented comparisons of results submitted for Exercises II-0 (pressure drop) and II-1 (steady state critical power). The participants asked the benchmark team to check out the consistency of pressure drop comparisons. It was suggested also for critical power comparisons for II-1 to show all radial predicted frequencies, and to perform simultaneous summary analyses of the dry-out rod number for radial and axial predictions. Further, in Session 7, the benchmark team initiated a discussion of modeling issues and requested output for Exercise II-3 (transient critical power). The benchmark team proposed one set of smoothened time-dependent BCs II-2 to be provided to the participants. The benchmark team will provide a definition of the timing of the boiling transition, and the timing of rewetting in the templates for requested output for II-3. A practical method was suggested by one participant for defining the envelope of the analysed temperature time history.

Session 8 - Actions and Conclusions

The action items and schedule of benchmark activities were discussed. For the code-to-data comparison, it was recommended to take a quantity consisting of the predicted minus the measured value as a deviation and the predicted/measured value as the ratio. They are provided in the following list.

List of Agreed Actions

1. Send List of Actions and CD-ROM with the BFBT-3 Workshop Materials to the Benchmark Participants (Deadline – mid-May 2006)

2. Prepare Summary Record of the BFBT-3 Workshop (Deadline – end of May 2006)

3. Prepare Proposal for Complete Specifications of Uncertainty Analysis Exercises I-4 and II-3 (Deadline – end of August 2006)

4. Complete Exercise 1 of Phase I (I-1) and Exercise 0 (II-0) and Exercise 1 of Phase II (II-1) – Collect final results from the participants on these Exercises (Deadline – end of November 2006)
5. Collect the feedback from the participants and finalize the Complete Specifications of Uncertainty Analysis Exercises I-4 and II-3 (deadline – end of December 2006)

6. Collect preliminary results on all the cases of Exercise 2 of Phase 1, Exercise 3 of Phase I, and Exercise 2 of Phase II (Deadline – end of January 2007)

7. Collect first preliminary results of Exercises I-4 and II-3 (Deadline – end of March 2007)

8. Organize and conduct the 4th OECD/NRC BFBT Benchmark Workshop – May 8 to 10 2007, Paris, France

Proceedings of the Workshop an Publications

Copies of the presentations made were distributed free of charge to all participants at the meeting on CD-ROM together with the cumulative benchmark reports and documents in addition to this summary.

The status and plan for the NUPEC BWR Full Size Bundle Tests (BFBT) publications is as follows:

Volume I : Problem Specification	Printing Summer 2006
Volume II : Benchmark Results for Void Distribution	Printing Autumn 2007
Volume III : Benchmark Results for Critical Power	Printing Spring 2008

The next workshop (BFBT-4) is scheduled for the week of 7 May 2007 in conjunction with the V1000CT5 workshop also addressing CFD issues, but for single phase flow. Also a second meeting on Uncertainty Analysis in Modelling will be held in conjunction with this workshop. The venue will be Paris and Saclay.

Annex I

OECD/NRC Benchmark based on NUPEC BWR
Full-size Fine-mesh Bundle Tests (BFBT) – Third Workshop (BFBT-3)

Hosted by the
University of Pisa, Hotel Duomo, Pisa, Italy

26-27 April 2006

FINAL PROGRAMME [01]

Day 1: 26 April 2006

Session 1 – Session Chair – F. D'Auria

09:00-09:30 Introduction and opening remarks
University of Pisa
OECD-NEA
US NRC
Introduction of participants [02]

09:30-09:50. Overview and status of benchmark activities - *K. Ivanov[03]*

09:50-10:10 Summary of the major additions and modifications in the final BFBT benchmark specification – *K. Ivanov[04]*

10:10-10:30 Discussion of the estimation of spacer grid's dimensions and individual sub-channel loss coefficients – *M. Avramova, K. Ivanov, L. Hochreiter [05]*

10:30-11:00 Coffee Break

Session 2 – Session Chair – H. Utsuno

11:00-11:20 Evaluation of the void distribution measured data included in Exercise I-1
F. Aydogan, L. Hochreiter, K. Ivanov [06]

11:20-12:20 Summary of comparison and analysis of submitted results for Exercise I-1
B. Neykov, K. Ivanov, L. Hochreiter, M. Avramova [07]

12:20-12:40 Summary of comparison and analysis of submitted results for Exercise I-2
B. Neykov, K. Ivanov, L. Hochreiter, M. Avramova [08]

12:40-13:00 Optimization approach of sub-channel void distribution
M. Martin, F. Gaudier [09]

13:00-14:30 Lunch

Session 3 – Session Chair – A. Tentner

14 :30–16 .10 Participants' presentations on modelling and results for Exercises I-1 and I-2

- "COBRA-IE Evaluation by Simulation of the NUPEC BWR Full-Size Fine-Mesh Bundle Tests (BFBT)", *Christopher J. Burns, David L. Aumiller [10]*
- "Modeling and results for void distribution benchmark with a sub-channel analysis code TCAPE-INS/B", *H. Utsuno, Y. Masuhara and F. Kasahara [11]*
- "UNIPI Contribution to BFBT Benchmark Using RELAP5-3D System Code", *Alessandro Petruzzi, Carlo Parisi [12a]*
- Data Analysis by *Fabio Moretti, Maria Cristina Galassi [12b]*
- "Activities of KAERI BFBT Benchmark Team Using MATRA, MARS(COBRA-TF) and CFX", *D.H. Hwang, J.J. Jeong, W.K. In [13]*
- "CEA Results for Exercise I-1 Using FLICA4"*, M. Martin [14]*

16 :10-16 :30 Coffee Break

Session 4 – Session Chair – D. Aumiller

16 :30–18.30 Participants' presentations on modelling and results for Exercises I-1 and I-2

- "CFD Modelling and Results for Exercise I-2 using the STAR-CD code", *Adrian Tentner [15]*
- "Preliminary Applications of the NEPTUNE-CFD and CFX Codes at UNIPI" *Fabio Moretti, [16]*
- Exercise I-1 with F-COBRA-TF, *Markus Glück [17] [text 17b]*
- "Results of exercise I-1 with MONA-3", *C. Adamsson and H. Anglart [18]*
- "NUPEC BWR Bundle Test, Status of Multiphase Modelling Activities using CFX (and other tools)", *M. Böttcher, U. Imke [19], {5 Videos}*
- "Results of Ph-I/Ex-1 in NUPEC BFBT benchmark Based on NASCA", *Akitoshi Hotta [20]*

Day 2: 27 April 2006

Session 5 – Session Chair – A. Hotta

08:40-09:10 Discussion of modelling issues, preliminary results, requested output, and templates for Exercise I-3, *M. Avramova, K. Ivanov, L. Hochreiter [21]*

09:10-09:30 "Modelling and preliminary result for Exercise I-3", *M. Naitoh [22]*

09:30-09:50 Approach for uncertainty propagation and analysis (Exercise I-4) *F. Gaudier, M. Martin*. [23]

09:50-10:10 "Uncertainty analysis result (Exercise I-4)", *M. Naitoh [24]*

10:10-10:30 "Several Issues of Uncertainty Analysis (Ph-I/Ex-4) by NASCA", *Akitoshi Hotta [25]*

10:30-10:50 Coffee Break

Session 6 – Session Chair – E. Royer

10:50-11:30 Summary of comparison and analysis of submitted results for Exercise II-0
F. Aydogan, L. Hochreiter, K. Ivanov, M. Avramova [26]

11:30-12:10 Summary of comparison and analysis of submitted results for Exercise II-1
F. Aydogan, L. Hochreiter, K. Ivanov, M. Avramova [27]

12:10-13:10 Participants' presentations on modelling and results for Exercises II-0 and II-1
- "Modelling and Results of Critical Power Exercise with Neptune System Code", *Michel Valette*: [28]
- "Analysis of BFBT Exercise II-0 using MATRA", *D. H. Hwang and S. K. Moon [29]*
- "Exercise II-0 with F-COBRA-TF" *Markus Glück [30]*

13:10 – 14:30 Lunch

Session 7 – Session Chair – M. Glück

14:30-15:30 Participants' presentations on modelling and results for Exercises II-0 and II-1
- "Results of exercises II-0 and II-1 with MONA-3", *C. Adamsson and H. Anglart [31]*
- "IVA Simulations to the OECD/NRC Benchmarks based on NUPEC BWR Full-size Fine-mesh Bundle Tests", *Nikolay Ivanov Kolev [32a] [text 32b]*
- The Internal Characteristics of Boiling at Heated Surfaces, , *Nikolay Ivanov Kolev [32c]*
- "CEA Results for Exercises II-0 and II-1 Using FLICA4", *M. Martin [33]*

15:30-15:50 Presentations on related topics from participants
- "Modeling for liquid film dry-out prediction with a sub-channel analysis code TCAPE-INS/B", *H. Utsuno, Y. Masuhara and F. Kasahara [34]*

15:50-16:10 Presentation and discussion of the modelling issues and preliminary results for Exercise II-2, *M. Avramova, K. Ivanov, L. Hochreiter [35]*

16:10-16:30 "Modelling and preliminary result for Exercise II-2" *M. Naitoh [36]*

16:30-16:50 Coffee Break

Session 8 – Session Chair – J-M. Aragonés

16:50-17:10 Discussion of the introduction of Exercise 3 of Phase II (II-3) – uncertainty analysis of II-1, and definition of such exercise,
F. Aydogan, L. Hochreiter, G. Rhee, K. Ivanov [37]

17:10- 17:40 Action items and schedule of benchmark activities, next workshop (BFBT-4) and plans – *E. Sartori, K. Ivanov [38]*

17:40-18:00 Conclusions and closing remarks

Annex II

BFBT3 (Third OECD/NRC BWR BFBT Workshop, Pisa, 26-27 April 2006)

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