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**NUCLEAR ENERGY AGENCY
NUCLEAR SCIENCE COMMITTEE**

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**OECD/NRC Benchmark based on NUPEC BWR
Full-size Fine-mesh Bundle Tests (BFBT)
Sixth Workshop (BFBT-6)**

SUMMARY RECORD

**University Park / State College, PA, USA
27-28 April 2009**

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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)
Sixth Workshop (BFBT-6)

In memory of late Prof. L. Hochreiter

University Park / State College, PA, USA
April 27-28 2009

Hosted by
The Pennsylvania State University (PSU)
USA

SUMMARY RECORD

**OECD/NRC Benchmark based on NUPEC BWR
Full-size Fine-mesh Bundle Tests (BFBT) – Sixth Workshop
(BFBT-6)**

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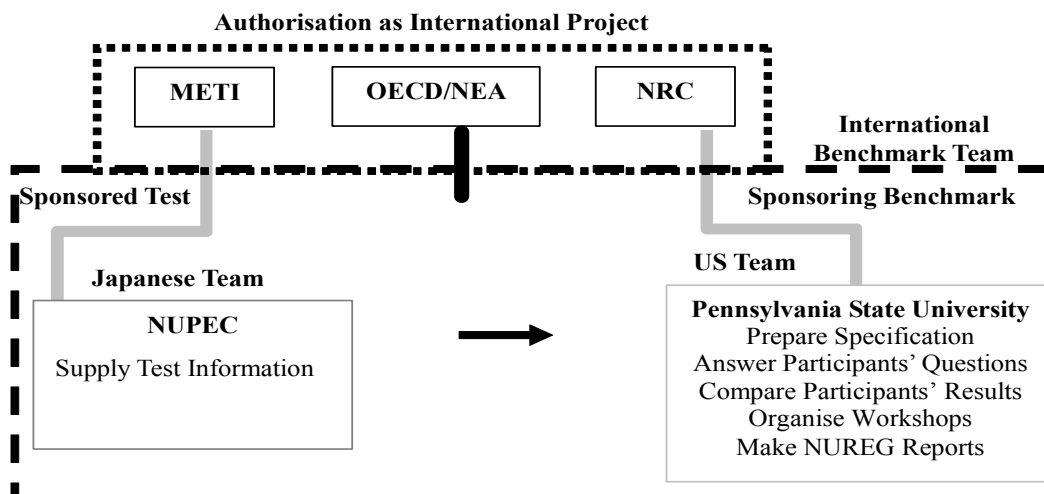
Sponsorship

The Sixth workshop for the OECD/NRC Benchmark based on NUPEC BWR Full-size Fine-mesh Bundle Tests (BFBT-6) was held on April 27-28 2009 in University Park / State College, PA, USA, and was a follow up to the first five workshops:

1. First workshop (BFBT-1) held on 4 October 2004, hosted by the Japan Nuclear Energy Safety (JNES) Organisation;
2. Second workshop, (BFBT-2) held from 27 to 29 June 2005 at State College, PSA, USA, hosted by the Nuclear Engineering Program (NEP) of the Pennsylvania State University (PSU);
3. Third workshop (BFBT-3) held on 26 and 27 April 2006, at Pisa, Italy, hosted by the University of Pisa.
4. Fourth workshop (BFBT-4) held on 8 and 9 May 2007 in Paris, France, hosted by CEA-Saclay and OECD/NEA.
5. Fifth workshop (BFBT-5) held on 31 March and 1 April 2008 in Garching, Germany, hosted by GRS mbH.

The BFBT-6 workshop was dedicated to Dr. Lawrence E. Hochreiter, Professor of Nuclear and Mechanical Engineering, to commemorate his contributions to the field of nuclear reactor thermal-hydraulics and safety.

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 organised based on the collaboration between Japan and the USA as shown in the figure below. At BFBT-2, CEA-Saclay (France) proposed the introduction of an additional uncertainty analysis exercise to the benchmark and joined the benchmark team in defining and conducting such an exercise.



This workshop (BFBT-6) was held in conjunction with other meetings, in order to facilitate co-ordination and sharing of work. The two other meetings 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 make the participation more efficient. The meetings concerned were the Third Workshop for the OECD Uncertainty Analysis in Modelling (UAM) Light Water Reactor (LWR) benchmark UAM-3, which took place on April 29 - May 1 2009; in parallel with the BFBT-6 meeting the First OECD Kalinin-3 VVER-1000 Benchmark Workshop was held at the same premises as well. There was also a special session on LWR UAM in multi-physics multi-scale simulations at the M&C 2009 Conference in Saratoga Springs, NY, USA. The M&C 2009 conference took place on May 3-7 2009 (the week after the Benchmark workshops at PSU).

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 take into account droplets along with liquid and vapor. They predict 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 are 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., have still 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, the subject still remains the major unsolved problem in the two-phase flow of BWR fuel bundles. The main reason 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 (≈ 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 needs 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 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 the uninvestigated fields of the 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 on 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 that can be applied to a wide range of geometrical and operating conditions has been developed.
- In the past decade, experimental and computational technologies have tremendously improved through 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 is currently underway. These models must include elementary processes such as void distributions, droplet deposit, liquid film entrainment, etc.

The BFBT benchmark is made up 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 critical power benchmark

It should be recognized that the purpose of this benchmark is not only to compare 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 included:

- Review of the benchmark activities after the 5th Workshop
- Discussion of the report on Phase I
- Participants' presentations on their models and results for Exercises I-1, I-2 and I-3
- Discussion of the report on Phase II
- Participants' presentations on their models and results for Exercises II-0, II-1 and II-2
- Presentation and discussion of the results submitted for the uncertainty analysis exercises
- Participants' presentations on their models and results for Exercises I-4 and II-3
- Introduction and presentation of the new OECD benchmark based on NUPEC PWR Sub-channel and Bundle Tests (PSBT) (as follow-up benchmark activities of the OECD/NRC BFBT benchmark): database, specification and schedule.

- Status of the NED special issue with participants' BFBT papers
- 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

An Organization and Programme Committee has made the necessary arrangements for the fifth Benchmark Workshop, organized the Sessions, and prepared the final program. The general chair was M. Avramova (PSU) and PSU also hosted the workshop. The other members were José Aragonés (UPM), representing the NSC, Francesco D'Auria, representing CSNI, Eric Royer (CEA-Saclay), Adrian Tentner (ANL), Utsuno (JNES), A. Hotta (TEPSYS), K. Ivanov (PSU), and E. Sartori, representing the OECD/NEA Secretariat.

Opening Session – Introduction and opening remarks

The meeting was opened by J. Brenizer, chair of the Nuclear Engineering Program (NEP) at PSU that was hosting the meeting. He presented the NEP activities and accomplishments, welcomed the participants on behalf of the PSU and wished them a successful work. S. Bajorek welcomed the participants on behalf of the US NRC and underlined the importance of such benchmarks for improving the reliability of nuclear safety evaluations. E. Sartori presented the structure of working party on scientific issues in reactor systems at the Nuclear Science Committee (NSC) of the NEA/OECD, and welcomed the participants on behalf of the NEA Secretariat. K. Ivanov acknowledged the contributions of the late Prof. L. Hochreiter and asked the participants to observe one minute of silence in his memory.

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

The workshop was attended by 40 participants from 21 organizations in 9 countries (see Annex II). The interest in this benchmark is very large as shown by the participation from research institutions, universities and industry with sub-channel, CFD, porous media and system thermal-hydraulic codes.

S. Kim made two presentations on the overview of the research performed at the advanced multi-phase flow laboratory and spacer grid thermal-hydraulic program at PSU.

K. Ivanov, on behalf of the benchmark team, made a presentation giving an overview and status of the BFBT benchmark activities. A special issue in Nuclear Engineering and Design journal is being devoted to this benchmark.

Technical Sessions on Phase I – Void Distribution Benchmark

Sessions 1 to 3 were devoted to the four exercises of Phase I of the BFBT benchmark. The benchmark team summarized, in four presentations, the outstanding issues of code-to-data comparisons (rod displacement issues, chordal averaged void fraction measurements, and updated densitometer correlation) as well as the report on Phase I, containing the comparisons of submitted results for Exercises I-1 and I-2 (macro- and microscopic steady state void distribution) and for Exercise I-3 (sub-channel transient void distribution). Based on these presentations the following issues were discussed and decisions made for the final report:

- a) PSU will perform independent studies confirming the direction of rotation for the assembly type 4. Based on the results of these studies and methodology proposed by ANL the benchmark team will provide guidelines to the participants for correcting the pixel data. However, in the final report the original pixel data will be used for code-to-data comparisons;

- b) The negative void fraction values reported by the chordal measurements will be regarded as zero values for the code-to-data comparisons in the report. However, it was pointed out by A. Tentner that it is important to study in the future the effect of the inlet sub-cooling on densitometer signal. H. Utsuno confirmed that the accuracy of the chordal average void fraction measurement is 2% absolute void fraction value.
- c) PSU will smooth the improved densitometer correlation (based on experimental data for the region of 20 to 80 % void fraction and CFD results for the region below 20 % void fraction). This final correlation can be used for both steady-state and transient code-to-data comparisons for assembly type 4.

Participants made ten presentations on their models and results obtained for the Exercises of Phase I.

Technical Sessions on Phase 2 – Critical Power Benchmark

Sessions 4 and 5 were devoted to the four exercises of Phase II of the BFBT benchmark. The benchmark team summarized in one presentation the report on Phase II, containing the comparisons of submitted results for steady state Exercises II-0 (pressure drop) and II-1 (critical power), and for the transient Exercise II-2 (critical power).

Participants made four presentations on their models and obtained results for the Exercises of Phase II.

The deadline for submitting results for Exercises I-4 and II-3 is the end of March 2009.

Conclusions, Actions and Schedule for completing the BFBT benchmark

Some organizations indicated their intention to submit new/updated results for the Exercises of Phase I (CSA and AECL), Phase II (TEPSYS and Chalmers University) and Uncertainty Analysis (McMaster University and KTH).

The action items and schedule to complete BFBT benchmark activities were discussed. They are provided in the following list:

List of Agreed Actions on BFBT

1. The BFBT-6 workshop summary will be prepared by the benchmark team and distributed by the end of May 2009.
2. End of May 2009 – deadline for submission of final results relative to Exercises I-1, I-2, I-3, II-0, II-1, II-2.
3. End of May 2009 – deadline for submission of papers for the special BFBT issue of NED journal.
4. End of June 2009 - deadline for submission of the reports on Phase I and Phase II to the reviewers.
5. End of August 2009 – deadline for completing reviews of the reports on Phase I and Phase II.
6. End of September 2009 - deadline for submission final results on Uncertainty Analysis Exercises I-4 and II-3 (these results will be compared in a separate report).

Technical Sessions on the new OECD benchmark based on NUPEC PWR Sub-channel and Bundle Tests (PSBT)

The benchmark team summarized in three presentations the experimental facility and measurement techniques utilized by NUPEC for performing PWR Sub-channel and Bundle Tests (PSBT), assembly specifications and benchmark database as well as the proposed benchmark specification and schedule. In the follow up discussions it was clarified that the following assumptions should be adapted in test facility modelling:

- a) heat losses are negligible;
- b) the heater rod gap is filled with a non-active gas (such as nitrogen);

It was decided that the benchmark team will work to obtain more data for specifying spacer dimensions for the three types of spacers used in the tests. Majority of the participants attending the BFBT-6 workshop indicated that they will participate in the PSBT benchmark activities. The benchmark team has received also e-mails from many other organizations interested in participating in the PSBT benchmark activities.

The action items and schedule to start PSBT benchmark activities were discussed. They are provided in the following list:

List of Agreed Actions on BFBT

- 1. End of October 2009 – draft of the PSBT specification will be distributed to the participants.
- 2. Mid-March 2009 – deadline for submission preliminary results on Phase I
- 3. The PSBT-1 workshop will be held on April 12-13, 2010.

The PSBT-1 workshop will be held in conjunction with other meetings, in order to facilitate co-ordination and sharing of work. The three other meetings will be held at the same place and during the same week in order to combine efforts in common areas such as thermal-hydraulic modelling and uncertainty analysis and to make the participation more efficient. There are two options for location of the four workshops in April 2010 – one is in the NEA/OECD, Paris, France (room reservations have been made) and the other is University of Pisa, Pisa, Italy. The NSC committee will decide on the location of the four workshops. The meetings concerned are the fourth workshop on the OECD Uncertainty Analysis in Modelling (UAM) Light Water Reactor (LWR) benchmark (UAM-4) and AER Working Group D workshop (VVER dynamics and safety), which will take place on April 14-16, 2010. In parallel with the BFBT-6 meeting the second workshop on the Kalinin-3 VVER coupled code benchmark will be held at the same premises. The objectives of the PSBT-1 workshop will be the following:

- a) Discussion of the draft PSBT specification
- b) Discussion of support studies performed by the benchmark team
- c) Discussion of preliminary results submitted for Phase I exercises
- d) Discussion of final results submitted for BFBT uncertainty analysis exercises

Acknowledgments

The OECD/NEA Secretariat and Benchmark Participants expressed their great appreciation to the Ministry of Economy, Trade and Industry of Japan, and the Japan Nuclear Safety Organisation (JNES), for making these most valuable experimental data available to the international community, and the Pennsylvania State University (PSU) for their efforts for co-ordinating the work connected with it.

Annex 1
**OECD/NRC Benchmark based on NUPEC BWR
Full-size Fine-mesh Bundle Tests (FBFT) – Sixth Workshop (FBFT-6)**

Hosted by
The Pennsylvania State University (PSU), USA
April 27-28 2009

PROPOSED PROGRAMME [B601]

Day 1: April 27 2009 - Regency B Room at the Atherton Hotel

Opening Session – Chair M. Avramova

8:30-8:45 Introduction and opening remarks and list of participants [B602]

- Prof. Jack Brenizer, Chair of Nuclear Engineering Program, PSU [B603]
- Dr. S. Bajorek, US NRC [B604]
- Dr. E. Sartori, OECD/NEA [B605]

8:45-8:55 Remembering late Prof. L. Hochreiter

- K. Ivanov [B606]

8:55-9:20 Research Overview at the Advanced Multiphase Flow Laboratory at Penn State

- Seungjin Kim [B607]

9:20-9:45 Spacer Grid Thermal Hydraulics (SGTH) Program

- Seungjin Kim [B608]

9:45-10:00 Overview and status of benchmark activities

- K. Ivanov [B609]

10:00 -10:15 Coffee Break

Technical Sessions on Phase I – Void Distribution Benchmark

Session I – Chair S. Bajorek

10:15-10:35 Answer to rod displacement issues in FBFT Benchmark

- H. Utsuno [B610]

10:35-10:55 Chordal averaged void fraction measurements

- H. Utsuno [B611]

10:55-11:05 Discussion of updated densitometer correlation

- B. Neykov [B612]

11:05-12:00 Presentation of the report on Phase I
- B. Neykov [B613]

12:00-13:00 Lunch – Tarragon restaurant at the Atherton Hotel

Session II – Chair – M. Glück

13:05-13:30 Steady-state sub-channel void benchmark with VIPRE-W
- K. Brynjell-Rahkola, J.-M. Le Corre and C. Adamsson (presented by Y. Sung)
[B614]

12:05-12:30 Steady-state sub-channel void benchmark with VIPRE-W
- K. Brynjell-Rahkola, J.-M. Le Corre and C. Adamsson (presented by Y. Sung)
[B614]

13:30 -13:55 Preliminary 3D Calculations of 2 BFBT tests with CATHARE 3
- M. Valette [B615]

13:55-14:20 Status of FZK/INR Investigations of the BFBT BWR Benchmark
- V.H. Sanchez de Espinosa, U. Imke, M. Thieme and R. Gomez (presented by K. Ivanov) [B616]

14:20-14:45 Status of steady-state and transient void fraction calculation using the POLCA-T system code
- A. Hernandez [B617]

14:45-15:10 ASSERT-PV Subchannel code Against the NUPEC BFBT
- Yanfei Rao, A. Nava-Dominguez, G. Waddington [B618]

15:10-15:35 VIPRE01 BFBT Exercise I Benchmark Summary
- G. Gose [B619]

15:35-15:50 Coffee Break

Session III – Chair – H. Utsuno

15:50-16:15 STAR-CD Simulation of BFBT void measurement tests: the influence of sub-channel scales on CDF void distribution
- David Pointer, Adrian Tentner [B620]

16:15-16:40 CFD modelling capabilities at ARL, PSU
- R. Kuntz [B621]

16:40-17:05 CIAU Uncertainty Analysis of BFBT Void Distribution Benchmark (Exercise I-4). Analysis of the geometrical uncertainties in the mock-up.
- A. Petrucci, K. Leung, F. D’Auria, D. Novog [B622]

- 17:05-17:30 Uncertainty Analysis of COBRA-TF Void Distribution Predictions for the OECD/NRC BFBT Benchmark
- M. Avramova, K. Ivanov, B. Krzykacz-Hausmann, K. Velkov, A. Pautz, Y. Perin [B623]

19:00 - Banquet - Regency A room at the Atherton Hotel

Day 2: April 28 2009 – Regency B Room at the Atherton Hotel

Technical Sessions on Phase 2 – Critical Power Benchmark

Session IV – Chair A. Tentner

- 08:30-09:30 Presentation of the report on Phase II
- B. Neykov [B624]
- 09:30-10:00 Steady-state pressure drop benchmark with VIPRE-W
- J.-M. Le Corre (Presented by Y. Sung) [B625]

10:00 -10:15 Coffee Break

Session V – Chair A. Petruzzi

- 10:15-10:40 Status of steady-state pressure drop and critical power calculations using the POLCA-T system code
- A. Hernandez [B626]
- 10:40-11:05 Enhancement of NASCA Component Models based on Partial Size Bundle Test and Validation in BFBT
- K. Nozaki, A. Hotta [B627]
- 11:05-11:30 Steady-state critical power benchmark with MEFISTO
- C. Adamsson and J.-M. Le Corre (Presented by Y. Sung) [B628]

11:30-12:00 Discussions and conclusions on Phases I and II

12:00-13:00 – Lunch – Regency A room at the Atherton hotel

Technical Sessions on the new OECD benchmark based on NUPEC PWR Sub-channel and Bundle Tests (PSBT) (as follow-up benchmark activities of the OECD/NRC BFBT benchmark):

Session VI – Chair D. Caruge

- 13:05-13:30 Action items and schedule of completing benchmark activities – report on the BFBT uncertainty analysis exercises, and the special journal issue.

13:30 -13:50 Pamphlet of Takasago Engineering Laboratory (NUPEC)

- H. Utsuno [B629]

13:50-14:35 OECD/NEA Benchmark based on NUPEC PWR Sub-channel and Bundle Tests (PSBT), Assembly Specifications and Benchmark Database, Volume I

- H. Utsuno [B630]

14:35-14:55 Proposed benchmark specification and schedule

- M. Avramova [B631]

14:55-15:20 Application of a subchannel code to predicting CHF in PWR rod bundles

- D. Hwang [B632]

15:20-15:40 Action items, schedule, First workshop (PSBT-1) and plans

15:40-15:45 Conclusions and closing remarks

15:45-18:30 Visit to Advanced Multi-Phase Flow Laboratory and TRIGA research reactor at PSU

Annex 2

**OECD/NRC Benchmark based on NUPEC BWR
Full-size Fine-mesh Bundle Tests (BFBT)
Sixth Workshop (BFBT-6)**

University Park / State College, PA, USA
April 27-28 2009

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