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

Summary Record of the Fifth Workshop (BFBT-5)

31 March-1 April 2008
Garching, Germany

English - Or. English

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OECD/NRC Benchmark based on NUPEC BWR
Full-size Fine-mesh Bundle Tests (BFBT)
Fifth Workshop (BFBT-5)

Garching, Germany
31 March 2008 - 1 April 2008

Hosted by
Gesellschaft für Anlagen und Reaktorsicherheit (GRS)
Germany

SUMMARY RECORD

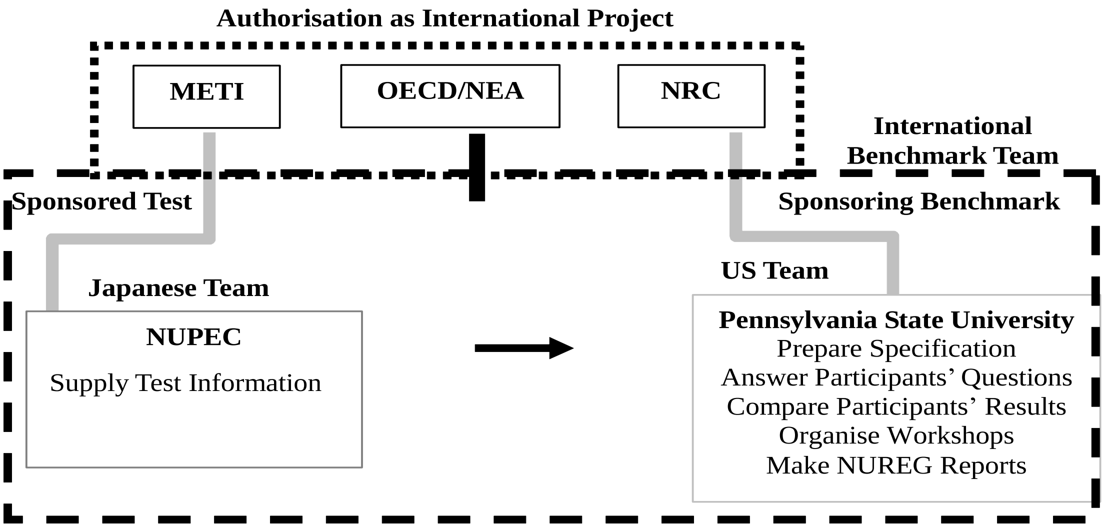
Sponsorship

The fifth workshop for the OECD/NRC Benchmark based on NUPEC BWR Full-size Fine-mesh Bundle Tests (BFBT-5) was held on 31 March and 1 April 2008 in Garching, Germany, and is a follow up to the first four workshops as follows:

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.

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-5) 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 are the second workshop for the OECD Uncertainty Analysis in Modelling (UAM) Light Water Reactor (LWR) benchmark, which took place on 2-4 April

2008; in parallel with the BFBT-5 meeting also the annual meeting of Working Group D involved in VVER reactor dynamics and safety research was held at the same premises. For further details of the latter meeting please contact Soeren Kliem at s.kliem@fzd.de.

Background and Purpose of the Benchmark Workshop

In the past decade, a large amount of effort has been devoted to 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. The adequacy of fuel lattice geometries, spacer configurations, etc., has 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 ($\approx$ 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 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 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 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 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 state 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 to be addressed at the workshop include:

- Review of the benchmark activities after the 4th Workshop
- Presentation and discussion of summary of comparisons of final submitted results for Exercise 1 of Phase I (I-1); for Exercise 0 of Phase II (II-0); and for Exercise 1 of Phase II (II-1)
- Presentation and discussion of comparison of final submitted results for Exercise 2 of Phase I (I-2)
- Presentation and discussion of comparison of final submitted results for Exercise 3 of Phase I (I-3)
- Presentation and discussion of comparison of final submitted results for Exercise 2 of Phase II (II-2)
- Presentation and discussion of preliminary uncertainty results for Exercise 4of Phase I (I-4)
- Presentation and discussion of preliminary uncertainty results for Exercise 3 of Phase II (II-3)
- Preparing a special issue in a journal with participants' BFBT papers
- Defining a work plan and schedule outlining actions to advance 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 S. Langenbuch (GRS) and he also hosted the workshop. The other members were Michael Rubin (US NRC) who is cosponsoring this activity, José Aragonés (UPM), representing the NSC, Francesco D'Auria, representing CSNI, Eric Royer (CEA-Saclay), L. Hochreiter (PSU), H. Utsuno (JNES), A. Hotta (TEPSYS), K. Ivanov (PSU), representing the benchmark team, and the OECD/NEA Secretariat.

Opening Session – Introduction and opening remarks

The meeting was opened by Andreas Pautz of the GRS that was hosting the meeting. He welcomed the participants on behalf of the GRS and wished them a successful work. Enrico Sartori welcomed the participants on behalf of the NEA Secretariat. Kostadin Ivanov of PSU welcomed the participants on behalf of the benchmark team. He asked the participants to acknowledge the memory of the famous reactor physicist Dr. Rudy Stamm'ler (who has passed away on March 20 2008) with one minute of silence.

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

The workshop was attended by 29 participants from 19 organizations in 10 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.

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 will be devoted to this benchmark.

Technical Sessions on Phase I – Void Distribution Benchmark

Sessions 1 to 3 and part of Session 4 were devoted to the first three exercises of Phase I of the BFBT benchmark. The benchmark team summarized, in three presentations, the comparisons of submitted results for Exercises I-1 and I-2 (macro- and microscopic steady state void distribution) as well as for Exercise I-3 (sub-channel transient void distribution). Based on these presentations the following issues were discussed and suggestions made to the benchmark team:

a) In the final report add to the figures of comparisons a picture with marked sub-channels for which the results are being compared;
b) To draw final conclusions, it is suggested to base the comparative analysis discussion on the models rather than on the codes. For instance, the performance of the drift flux model can be compared with two-fluid model, or CFD modelling with the sub-channel approach. The trend observed in the comparisons should be discussed, taking into account the physics and models in order to make conclusions;
c) For Exercise I-2 (CFD results) it is proposed to compare directly the pixel data after correction for the geometry rotation;
d) On the figures of comparisons, put the experimental data in a brighter color to be easily distinguished and visible;
e) For the transient time-histories, correct densitometer measured curves with the developed densitometer correlation.

Participants made eight presentations on their models and results obtained for Exercises I-1, I-2 and I-3.

The benchmark team presented a summary of the major conclusions of the continuation of the study performed by the benchmark team on developing correlation for the transient densitometer void distribution measurements. Void fraction experimental measurements in transient conditions were discussed since there are discrepancies between the two techniques of measurement (CT scanner and X-ray densitometer). A correction was developed by the benchmark team in order to achieve a more consistent comparison of the computed results against experimental data. At the BFBT-4 workshop the AREVA NP GmbH presentation demonstrated that the developed correction seems to be practicable for void fractions higher than 20 %. ANL provided to the benchmark team detailed CFD results (as data of numerical experiment) at the 3 axial elevations where the densitometers are located. These data were used to develop an improved correlation covering the whole range of conditions of interest. This linear correction should not be applied to extreme values of void fraction, i.e. below 20% and above 80% because there are not sufficient data and no correction should be used when reaching 0 and 100%. M. Glück from AREVA NP proposed to utilize in a different way the new extended data by dividing the whole range of conditions into two areas and developing the lumped sum of two linear correlations:

- High void fraction area (from 20 % to 100%) which can be based on the previous correlation and should end at 100% void fraction;
- Low void fraction area (from 0 % to 20 %) which will be a new correlation based on the CFD results. ANL will provide more CFD results for this area to support the development of this correlation by the benchmark team.

To summirise Phase I, since the previous workshop in Paris, significant progress has been made by the participants. The final deadline for submission of results and answers to questionnaires for Exercises I-1, I-2 and I-3 is the end of August, 2008, in order to start preparing the report on Phase I (without uncertainty). Participants are requested to provide more information about the physical models used by the code, so the conclusions can focus on physics to analyze the results. Reviewers for the report will be A. Tentner (ANL), N. Kolev (AREVA NP) and M. Glück (AREVA NP).

Technical Sessions on Phase 2 – Critical Power Benchmark

Sessions 6 and 7 were devoted to the first 3 exercises of Phase II of the BFBT benchmark. The benchmark team summarized in three presentations 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). The DP303 measurements are questionable (no consistency with other measurements for single-phase conditions). As a result, code predictions seem to be over-predicted. Comparison of dry-out locations should be extended to fuel rods without experimental detection. The information provided by participants about their models will be used for the physical analysis, particularly the criteria for dry-out. The spacer grid modelling is also very important for the critical power location predictions.

Participants made four presentations on their models and obtained results for Exercises II-0. To summarise Phase II, since the previous workshop in Paris, significant progress has been made by the participants for Exercises II-0 and II-1 for which many sets of results were submitted. Initial steady-state conditions of transient (Exercise I-1) are important to reduce discrepancies between experiments and code predictions. Exercise II-2 has only 3 sets of submitted results since it is more complex (transient phenomena). All of the results submitted for Exercise II-2 are from system codes (TRACE, RELAP5, and RELAP3D). The participants proposed and agreed upon a deadline for submission of the final results for Exercises I-0, I-1 and I-2 - end of January, 2009, in order to start preparing the report on Phase II (without uncertainty). Reviewers of this report will be M. Valette (CEA), A. Hotta (TEPSYS) and D. Panayotov (Westinghouse).

Technical Sessions on Uncertainty Analysis Exercises

A part of Session 4, Sessions 5 and 8 were devoted to uncertainty analysis exercises I-4 (uncertainty analysis of steady state void distribution predictions) and II-3 (uncertainty analysis of steady state critical power predictions). M. Martin presented the results of the analysis of the geometrical uncertainties: rod misplacements and mock-up rotation, which should be taken into account in the uncertainty analysis. In order to improve the consistency of the code-to-experiments comparisons at the sub-channel level (Exercise I-1), the benchmark team should clarify the averaging procedure used to produce the "experimental" sub-channel void fraction distribution from the measured pixel data.User effect and computer type may affect significantly the results and should be assessed and compared to other uncertainties. Two approaches for uncertainty analysis were presented and discussed. The first approach considers separately the effect of the boundary conditions, the geometry and the physical models (code dependent). In the case of drift flux model it is assumed that most sensitive models are sub-cooled condensation rate, vaporization heat flux, and relative velocity. The second approach propagates simultaneously uncertainties on boundary conditions, geometry (flow section) and physical models based on expert judgement. The low pressure and low power test cases are difficult for sub-channel codes to achieve convergence. . It is possible to change the experimental conditions selected for Exercise I-4 if this is confirmed by other participants. Near the corners and the central water rod, the coverage ratio is 0% while it is almost 100% everywhere else. If the experimental uncertainty is increased to 8% (instead of 3%), there are many more sub-channels with 100% coverage ratio.

N. Kolev suggested reviewing the developed Phenomena Identification and Ranking Tables (PIRTs) for void distribution and critical power. Drag coefficients for several intermediate flow regimes are not included in the ranking. The splitting of the heat to liquid and vapor is also very important and should be added in the ranking tables (especially for low mass flow it is a subject of uncertainty). In this regard participants need to provide more detailed description for the sub-cooled boiling models. In a saturation boiling regime, the splitting is not relevant. The drag coefficient is very important in the film boiling regime. The wall drag force is also very important and should be considered. The precise modeling of phenomena as the film drag, entrainment, and deposition is crucial for the correct prediction of the CHF/dry-out location. However, the currently used correlations/models significantly differ from each other. It is even possible to obtain better prediction of the dry-out location without deposition modeling. This is not because the phenomenon is less important for the dry-out occurrence, but because the experimental data used for derivation of the current correlations/models are measured at atmospheric pressure and adiabatic conditions. Therefore, when performing uncertainty analyses more alternative correlations/models have to be examined with an equal ranking.

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

Conclusions, Actions and Schedule

In summary, at the BFBT-5 workshop the benchmark team presented in total 13 presentations supplemented by 12 presentations from the participants. A special journal issue of Nuclear Engineering and Design is planned for the OECD/NRC BFBT benchmark. Papers have to be submitted by December, 2008, and the reviewing is expected by March, 2009.

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

List of Agreed Actions

1. The BFBT-5 workshop summary will be prepared by the benchmark team and distributed by the end of April 2008.

2. Participants are expected to confirm by the end of April 2008 their intention to submit a paper to K. Ivanov (kni1@psu.edu) for the planned benchmark special issue of the Nuclear Engineering and Design (NED) journal.

3. End of August 2008 – deadline for submission of final results relative to Exercises I-1, I-2 and I-3 for preparation of the report on Phase I.

4. End of December 2008 - deadline for submission of final results relative to Exercises II-0, II-1 and II-2 for preparation of the report on Phase II.

5. End of December 2008 – submission of papers for the special NED journal issue on OECD/NRC BFBT benchmark.

6. End of March 2009 - deadline for final results on Uncertainty Analysis Exercises I-4 and II-3.

7. The sixth workshop (BFBT-6) will be held on 27 and 28 April 2009, and will be hosted by the Pennsylvania State University (PSU), USA.

The BFBT-6 workshop will be held in conjunction with other meetings, in order to facilitate co-ordination and sharing of work. The two 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. The meetings concerned are the third workshop on the OECD Uncertainty Analysis in Modelling (UAM) Light Water Reactor (LWR) benchmark (UAM-3), which will take place from 29 April to May 1, 2009; in parallel with the BFBT-6 meeting. Also the first workshop on the Kalinin-3 VVER coupled code benchmark will be held at the same premises. The objectives of the next workshop (BFBT-6) will be the following:

a) Discussion of the report on Phase I
b) Discussion of the report on Phase II
c) Discussion of the results submitted for the uncertainty analysis exercises

Annex 1

OECD/NRC Benchmark based on NUPEC BWR
Full-size Fine-mesh Bundle Tests (BFBT) – Fifth Workshop (BFBT-5)

Hosted by
Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) mbH, Germany
31 March 2008 - 1 April 2008

PROGRAMME [B501]

Day 1: 31 March 2008

Opening Session – Chair S. Langenbuch

9:00 –9:15 Introduction and opening remarks – A. Pautz (GRS), E. Sartori (OECD/NEA) [B502]

9:15-9:30 Overview and status of benchmark activities – K. Ivanov [B503]

Technical Sessions on Phase I – Void Distribution Benchmark

Session I – Chair H. Utsuno

09:30 – 10:15 Summary of comparison and analysis of final submitted results for Exercise I-1
– B. Neykov, M. Avramova, K. Ivanov, L. Hochreiter [B504]
10:15 – 11:00 Summary of comparison and analysis of submitted results for Exercise I-2.
– B. Neykov, M. Avramova, K. Ivanov, L. Hochreiter [B505]

11:00 -11:15 Coffee Break

Session II – Chair – E. Royer

11:15 – 11:45 Summary of the major conclusions of the continuation of the study performed by the benchmark team on developing correlation for the transient densitometer void distribution measurements - F. Aydogan, L. Hochreiter, K. Ivanov [B506]
11:45 – 12:30 Comparative analysis of participants' results for Exercise I-3
- B. Neykov, M. Avramova, K. Ivanov, L. Hochreiter [B507]

12:30 – 14:00 Lunch

Session III – Chair - M. Glück

Participants' presentations on modelling and results on Phase I.

14:00 – 14:20 Analysis of the geometrical uncertainties in the mock-up, M. Martin [B508]
14:20 – 14:40 Recent BFBT CFD analyses with STAR-CD: the effect of interphase forces on void distribution - W. David Pointer, Adrian Tentner [B509]
14:40 – 15:00 TRACE simulation of void fraction tests - M. Thieme [B510]
15:00 – 15:20 Transient void prediction by CATHARE 2 code - L.Sabotinov, E.Georgieva [B511]
15:20 – 15:40 PSU modeling and results for Exercises II-0, I-1 and I-3
- M. Avramova, K. Ivanov, L. Hochreiter [B512]
15:40 – 16:00 Progress on activities performed at UNIPI on Void Distribution Prediction by means of CFD methods - M.C. Galassi, F. Moretti, F. D'Auria [B513]

16:00 – 16:15 Coffee Break

Session IV – Chair A. Tentner

16:15 – 16:35 FLUENT modeling and results for the BFBT benchmark
- B. Neykov, E. Popov, K. Ivanov, L. Hochreiter [B514]

16:35–16:50 Porosity PORFLO development for the BFBT benchmark calculations
- Jaakko Miettinen [B515]

16:50 – 17:10 Uncertainty analysis on void distributions - E. Royer, M. Martin [B516]
17:10 - 17:30 Uncertainty analysis of COBRA-TF void distribution predictions using GRS methodology – S. Langenbuch, B. Krzykacz-Hausmann, M. Avramova, K. Ivanov [B517]

Day 2: 1 April 2008

Session V – Chair A. Petruzzi

09:00 – 09:25 PSU methodology for uncertainty analysis - F. Aydogan, L. Hochreiter, K. Ivanov [B518]
09:25 – 09:50 PSU analysis and results for Exercise I-4 - F. Aydogan, L. Hochreiter, K. Ivanov [B519]
09:50 – 10:25 Discussions on Phase I

10:25 – 10:40 Coffee Break

Technical Sessions on Phase 2 – Critical Power Benchmark

Session VI – Chair D. Panayotov

10:40 – 11:25 Comparative analysis of participants' results for Exercise II-0
- B. Neykov, M. Avramova, K. Ivanov, L. Hochreiter [B520]

11:25 – 12:10 Comparative analysis of participants' results for Exercise II-1
- F. Aydogan, L. Hochreiter, M. Avramova, K. Ivanov, B. Neykov [B521]

12:10 – 12:40 Comparative analysis of participants' results for Exercise II-2
- F. Aydogan, L. Hochreiter, M. Avramova, K. Ivanov, B. Neykov [B522]

12:40 – 14:00- Lunch

Participants' presentations on modelling and results on Phase II.

Session VII – Chair L. Sabotinov

14:00 – 14:25 Modification of Droplet Generation Model of NASCA and Application to NUPEC BFBT Benchmark - Kenichiro Nozaki, Akitoshi Hotta, Hiromasa Chitose, Hideaki Ikeda [B523]
14:25 – 14:50 ASSERT-PV IST: Sub-channel Thermal-hydraulics Code for the CANDU Industry - Matt Krause Yanfei Rao [B524]
14:50 – 15:15 BFBT Results by RELAP5-3D© code - A. Kovtonyuk, A. Petruzzi, F. D'Auria [B525]
15:15 – 15:40 TRACE simulation of critical power tests - M. Thieme [B526]
15:40 – 16:00 Uncertainty and sensitivity analysis applied to simulation of the Swedish BWRs, Ch. Demazière [B527]

16:00 -16:10 Coffee Break

Session VIII – K. Ivanov and E. Sartori

16:10 – 16:30 PSU analysis and results for Exercise II-3 - F. Aydogan, L. Hochreiter, K. Ivanov [B528]

16:30 – 16:40 Discussion on Phase 2

16:40 – 16:50 Discussion of special issue in a journal with participants' BFBT papers

16:50 – 17:05 Action items and schedule of benchmark activities, next workshop (BFBT-6) and plans

17:05 – 17:15 Conclusions and closing remarks

Annex 2

BFBT-5 (Fifth OECD/NRC BFBT Workshop, Garching, 31.03. -1.04.2008)

List of Participants

CANADA

RAO, Yanfei	Tel: +1 613 584 3311 X 6346
Thermalhydraulics Branch	Fax: +1 613 584 8296
AECL Chalk River Laboratories,	Eml: raoy@aecl.ca
Station KEYS	
Chalk River	
Ontario K0J 1J0	

FINLAND

MIETTINEN, Jaakko	Tel: +358 20722 5032
VTT	Fax: +358 20722 5000
P.O. Box 1000 Tietatie 3 Espoo	Eml: jaakko.miettinen@vtt.fi
FIN-02044 VTT	

FRANCE

MARTIN, Matthieu	Tel: +33 1 69 08 81 55
Lab. d'Etudes Thermiques des Réacteurs	Fax: +33 1 69 08 85 68
Service Fluides numeriques,	Eml: matthieu.martin@cea.fr
Modelisation et Etudes (SFME)	
CEA Saclay	
91 191 Gif sur Yvette Cedex	
ROYER, Eric	Tel: +33 1 69 08 21 61
Centre d'Etudes de Saclay	Fax: +33 1 69 08 85 68
CEA/DEN/DM2S/SFME	Eml: eric.royer@cea.fr
91191 Gif-sur-Yvette Cedex	
SABOTINOV, Luben	Tel: +33 1 58 35 71 59
Institut de Radioprotection et de	Fax: +33 1 58 35 96 02
Surete Nucleaire	Eml: luben.sabotinov@irsn.fr
IRSN DSR/ST3C/BATH	
B.P. 17	
92262 Fontenay-aux-Roses Cedex	
VALETTE, Michel	Tel: +33 4 38 78 55 37
CEA-Grenoble	Fax: +33 4 38 78 94 53
SSTH/LMDL	Eml: michel.valette@cea.fr
17 avenue des Martyrs	
38054 GRENOBLE CEDEX 9	

GERMANY

GLUECK, Markus	Tel: +49 9131 900 5694
AREVA NP	Fax: +49 9131 900 4082
FGTT	Eml: markus.glueck@areva.com
Paul Gossen str. 100	
D-91052 ERLANGEN	
KOLEV, Nikolay Ivanov	Tel: +49 9131 189 6340
Senior Expert	Fax: +49 9131 189 4345
AREVA NP GmbH	Eml: nikolay.kolev@areva.com
NE R&D	
P.O. Box 1109	
91001 Erlangen	
KRZYKACZ-HAUSMANN, Bernard	Tel: +49-89 32004 325
Gesellschaft für Anlagen- und	Fax: +49 89 32004 599
Reaktorsicherheit (GRS) mbH	Eml: Bernard.Krzykacz-Hausmann@grs.de
Forschungsinstitute	
Postfach 1328,	
D-85748 Garching	

LANGENBUCH, Siegfried
Gesellschaft fuer Anlagen und
Reaktorsicherheit mbH
Forschungsinstitute
Postfach 13 28
D-85748 GARCHING
Tel: +49 89 3200 4424
Fax: +49 89 3200 4599
Eml: Siegfried.langenbuch@grs.de

PELLACANI, Filippo
Lehrstuhl für Nukleartechnik,
TU München
Boltzmannstr. 15
85748 Garching
Tel: +49 89 289 156 24
Fax: +49 89 289 156 22
Eml: pellacani@ntech.mw.tum.de

SCHEUERER, Martina
Gesellschaft für Anlagen- und Reaktorsich
Forschungsinstitute
D-85748 Garching
Tel: +49 89 32004 401
Fax: +49 89 32004 599
Eml: Martina.Scheuerer@grs.de

SCHMIDT, Klaus-Dieter
Gesellschaft fuer Anlagen und
Reaktorsicherheit
GRS mbH
Forschungsinstitute
D-85748 Garching
Tel: +49 89 3200 4430
Fax: +49 89 3200 4599
Eml: smk@grs.de

THIEME, Marc
Institute of Reactor Safety (IRS)
Forschungszentrum Karlsruhe GmbH
Hermann-von-Helmholtz-Platz 1
D-76344 Eggenstein-Leopoldshafen
Tel: +49 7247 82 2997
Fax: +49 7247 82 3718
Eml: marc.thieme@irs.fzk.de

ITALY

GALASSI, Maria Cristina
Università di Pisa
DIMNP
Via Diotisalvi 2
56126 PISA
Tel: +39 050 2210361
Fax: +39 050 2210384
Eml: mc.galassi@ing.unipi.it

KOVTONYUK, Andriy
Univerity of Pisa –
San Piero a Grado Nuclear Research Group
via Diotisalvi, 2 56122 PISA
Tel: +39 050 2210394
Fax: +39 050 2210384
Eml: a.kovtonyuk@ing.unipi.it

PETRUZZI, Alessandro
Universita di Pisa
DIMNP
Via Diotisalvi 2
56126 PISA
Tel: +39 050 2210377
Fax: +39 050 2210384
Eml: a.petruzzi@ing.unipi.it

JAPAN

NOZAKI, Kenichiro
TEPCO SYSTEMS Corporation
Shibusawa City Place Eitai
2-37-28 Eitai
Koto-ku
Tokyo 135-0034
Tel: +81 3 6364 1375
Fax: +81 3 5245 8401
Eml: nozaki-kenichirou@tepsys.co.jp

UTSUNO, Hideaki
Safety Analysis and Evaluation Division
Japan Nuclear Energy Safety Organization
Kamiya-cho MT Bldg.,
4-3-20, Toranomon, Minato-ku,
Tokyo, 105-0001
Tel: +81 3 4511 1536
Fax: +81 3 4511 1597
Eml: utsuno-hideaki@jnes.go.jp

RUSSIAN FEDERATION

BOYARINOV, Victor F.
Institute of Nuclear Reactors
RRC "Kurchatov Institute"
Kurchatov Sq. 1
Moscow 123182
Tel: +7 499 19 69 409
Fax: +7 499 196 7621
Eml: boyarinov@dhtp.kiae.ru

SPAIN

ARAGONES BELTRAN, Jose Maria | Tel: +34 91 336 3109
Dpto. Ingenieria Nuclear (DIN) | Fax: +34 91 336 3002
Univ. Politecnica de Madrid (UPM) | Eml: arago@din.upm.es
Jose Gutierrez Abascal, 2
E-28006 MADRID

JIMENEZ ESCALANTE, Javier | Tel: +34 91336 3108
Dpto. Ingenieria Nuclear | Fax: +34 91 336 3002
Univ. Politecnica de Madrid | Eml: jimenez@din.upm.es
Jose Gutierrez Abascal 2
E-28006 MADRID

SWEDEN

CADINU, Francesco | Tel: +46 8 5537 8825
Royal Institute of Technology | Fax: +46 8 5537 8830
ALBANOVA University Center | Eml: francesco@safety.sci.kth.se
KTH Nuclear Power Safety
Roslagstullsbacken 21
SE - 106 91 Stockholm

PANAYOTOV, Dobromir | Tel: +46 21 347 743
Westinghouse Electric Sweden | Fax: +46 21 347 580
Finslatten | Eml: dobromir.panayotov@se.westinghouse.com
Fuel Engineering
SE-721 63 Vasteras

UNITED STATES OF AMERICA

IVANOV, Kostadin | Tel: +1 814 865 0040
Head of RDFMG | Fax: +1 814 865 8499
Nuclear Engineering Program | Eml: kni1@psu.edu
The Pennsylvania State University
206 Reber Bldg
University Park, PA 16802

NEYKOV, Boyan | Tel: +1 814 441 3849
Ph.D. Student, Nuclear Engineering | Fax: +1 814 865 8499
Dept. of Mech. and Nucl.Engineering | Eml: bsn120@psu.edu
The Pennsylvania State University
334 Reber Building
University Park PA 16802

POINTER, W. David | Tel: +1 630 252 1052
Nuclear Engineering Division | Fax: +1 630 252 4500
NE-208 | Eml: dpointer@anl.gov
9700 S Cass Ave.
Argonne, IL 60439

TENTNER, Adrian | Tel: +1 630 252 8454
Argonne National Laboratory | Fax: +1 630 252 3361
9700 S. Cass Avenue | Eml: tentner@anl.gov
Argonne, IL 60439

International Organisations

SARTORI, Enrico | Tel: +33 1 45 24 10 72 / 78
OECD/NEA Data Bank | Fax: +33 1 45 24 11 10 / 28
Le Seine-Saint Germain | Eml: sartori@nea.fr
12 boulevard des Iles
F-92130 Issy-les-Moulineaux