A SUMMARY OF 50th OECD/NEA/CSNI INTERNATIONAL STANDARD PROBLEM EXERCISE (ISP-50)

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This paper describes a summary of final prediction results by system-scale safety analysis codes during the OECD/NEA/CSNI ISP-50 exercise, targeting a 50% Direct Vessel Injection (DVI) line break integral effect test performed with the Advanced Thermal-Hydraulic Test Loop for Accident Simulation (ATLAS). This ISP-50 exercise has been performed in two consecutive phases: “blind” and “open” phases. Quantitative comparisons were performed using the Fast Fourier Transform Based Method (FFTBM) to compare the overall accuracy of the collected calculations. Great user effects resulting from the combination of the possible reasons were found in the blind phase, confirming that user effect is still one of the major issues in connection with the system thermal-hydraulic code application. Open calculations showed better prediction accuracy than the blind calculations in terms of average amplitude (AA) value. A total of nineteen organizations from eleven countries participated in this ISP-50 program and eight leading thermal-hydraulic system analysis codes were used: APROS, ATHLET, CATHARE, KORSAR, MARS-KS, RELAP5/MOD3.3, TECH-M-97, and TRACE.

KEYWORDS : ISP-50, ATLAS, DVI line break, SB-LOCA, APR1400

1. INTRODUCTION

1.1 Background

An integral effect large scale thermal-hydraulic test loop, Advanced Thermal-Hydraulic Test Loop for Accident Simulation (ATLAS) has been utilized by Korea Atomic Energy Research Institute (KAERI) to establish a wide range of integral effect test database for APR1400 (Advanced Power Reactor, 1400MWe), since its construction in 2007 [1, 2]. The obtained experimental data can be used to resolve safety issues, to prove new design concepts and to validate system-scale safety analysis codes. In particular, the ATLAS can provide the unique test data for the 2 (hot legs) x 4 (cold legs) reactor coolant system with a direct vessel injection (DVI) of emergency coolant; this will significantly expand the currently available data bases for code validation.

The DVI of emergency coolant is a new advanced design feature believed to ensure more safety injection water reaches the reactor core and it has been adopted by Generation III+ nuclear power plants; AP1000, US-APWR, VVER-1000, and APR1400. As the emergency coolant is introduced directly to the annular downcomer region through nozzles on the reactor pressure vessel (RPV), the thermal hydraulic phenomena in the RPV downcomer is

regarded as more complicated than the conventional cold leg injection method. The key safety-relevant phenomena challenging code model developers include the multi-dimensional coolant mixing, condensation, the counter current flow limitation, inventory distribution, and interaction between the core and downcomer region.

Due to such safety significances, an international standard problem (ISP-50) exercise with the ATLAS facility was approved by OECD/NEA/CSNI in December 2008 and was numbered by ISP-50. The main objectives of the ISP-50 was to contribute to the enhancement of understanding on the behavior of nuclear reactor systems with the DVI and to the assessment of existing and new thermal-hydraulic analysis codes such as TRACE, CATHARE, RELAP, TRAC, ATHLET, CATHENA and MARS.

Among the integral effect test database established by ATLAS, a 50% break scenario of the DVI nozzle, equivalent to a 6-inch break SBLOCA, was determined by considering technical importance and by incorporating with comments from the participants. Utilities recommend that a core uncover should be prevented for a SB-LOCA up to an equivalent break diameter of 6 inches by a best-

estimate thermal-hydraulic analysis [3]. The DVI line break is an important accident scenario for several advanced PWRs but relevant data is very limited. Both regulators and industry require relevant experimental data and reliable prediction tools.

1.2 History of the Program

The ISP-50 was progressed in two serial phases: “blind” and “open” phases. The first “blind” phase started by holding a kick-off meeting in April, 2009. In the first workshop (kick-off meeting), where 11 organizations attended, the ISP-50 specifications were proposed. Afterwards, an ISP-50 working page was constructed and opened under the NEA web site in May, 2009. The ISP-50 specifications were finalized by incorporating answers to the questions and comments on the proposed specifications and it was distributed in June, 2009. The agreed test was successfully performed by the operating agency, KAERI in July, 2009. An Information document on actual test conditions and procedures was distributed in August, 2009. The experimental data were not released until the calculation results were made available for a comparison. All participants were requested to submit their calculation results to the operating agency for a comparison by the end of 2009.

In the “blind” phase, a total of 17 calculation results were submitted from 13 organizations. In particular, KOPEC and Hidropress submitted two and four different calculation results, respectively. CIAE was the latest to join the “blind” calculation of the ISP-50 and contributed to the ISP-50 by submitting their calculation results with the RELAP5/MOD3.3 code. A few participants showed their intentions to join the “open” phase due to lack of available resources. Seven leading safety analysis codes were used in the “blind” phase, including RELAP5/MOD3, TRACE, MARS-KS, KORSAR, TECH-M-97, APROS, and ATHLET. As an output specification, 86 parameters considered to be worthy of comparison were selected and requested.

The second workshop was held at the OECD headquarters in May 25-26, 2010 to present and to discuss the blind calculation results and future steps. Experimental results and overview of the comparison of the calculation results were presented by the operating agency. Quantitative comparison results of the submitted calculations by FFTBM were also presented and discussed. The participants discussed the parameters for which a comparison of calculated and experimental results would be interesting as well as the physical phenomena in the downcomer and loop seal clearing. In particular the 3-D phenomena such as temperature distribution, flow in the downcomer were of prime interest. JAEA and NRC accepted to help KAERI to point out the 3-D behavior in the downcomer and in the core. Some participants expressed the need for additional information in order to improve their understanding and interpretation of the test and hence in order to improve

their calculation results in the post-test phase. In addition, the importance of the upper head to the downcomer bypass and its role in loop seal clearing as well as the 3-dimensional nature of the flow in the upper part of the downcomer was highlighted.

The “open” phase followed the “blind” phase right after the second workshop. In response to the request for additional experimental data, the operating agency released the detailed experimental information as well as the detailed cladding temperature distribution. A total of 269 parameters for major thermal hydraulic variables were open to the participants. Detailed cladding temperatures for 264 different locations inside the core were also distributed to the participants. In addition, the operating agency delivered revised specifications for output submission, where 144 of 269 parameters were requested to examine the 3-D phenomena in the reactor pressure vessel as well as the asymmetric loop behavior. PSI and KFKI/AEKI took part in this “open” phase.

The “open” calculation results were collected from October, 2010 to March, 2011. A total of 16 calculation results were gathered from 11 countries. The number of codes used in the ISP-50 was seven: RELAP5/MOD3, TRACE, MARS-KS, KORSAR, APROS, CATHARE, and ATHLET. In order to apply the FFTBM, which can quantify the improvement of the “open” calculation against the “blind” calculation, 12 more cladding temperature data were additionally requested. Thanks to the help and cooperation of the participants, the requested additional data was successfully collected in due time. A final integration report was prepared with the help of the participants by the operating agency to incorporate the results in the “blind” phase. The final integration report was reviewed by WGAMA members and finally approved by NEA/CSNI in December 2011 [4]. A summary of the major milestones of the ISP-50 exercise is shown in Table 1.

1.3 Objectives

The co-existing of upward and downward flows in the downcomer above the cold leg are one of the important phenomena specific to the APR1400 because its DVI nozzles are located above the elevation of the cold leg. However, a systematic effort dealing with such complex thermal hydraulic phenomena occurring in the upper downcomer region was rare due to a lack of an available integral effect database. Thus, the ISP-50 exercise aims at a better understanding of thermal-hydraulic phenomena in the upper annulus downcomer region during the DVI period and a comprehensive investigation of the possible limitation of the existing best-estimate safety analysis codes. The first “blind” phase takes aim at assessing capability of the current-leading safety analysis codes in reproducing the overall thermal-hydraulic phenomena for the DVI line break scenario and investigating how much “user effects” the safety analysis codes have. The following

Table 1. Major Milestones of the ISP-50 Exercise

Date	Events/Actions
February 2009	Distribution of draft specification of ISP-50
April 21, 2009	The 1 st workshop to kick off ISP exercise Comments on the ISP specification Provide the facility summary report
May 2009	Freeze ISP-50 specifications
June 2009	Perform the agreed test by operating agency
August 2009	Provide detailed information on actual test conditions and procedures
December 2009	Complete blind calculation (Phase 1) by all participants
January 2010	Collect calculation results from all participants
February 2010	Provide test report and draft comparison report on blind calculations
May 25~26, 2010	The 2 nd workshop to discuss the draft comparison report Distribution of experimental results
September 2010	Presentation to GAMA
End of December 2010	Complete open calculation (Phase 2) by all participants
End of February 2011	Provide final draft report
May 25~26, 2011	Final workshop
Early July 2011	Final report
Sept-Oct. 2011	Review and GAMA endorsement Submission to PRG/CSNI for approval
December 2011	Final integration report was approved by CSNI

“open” phase is targeting at examining how much the “user effects” can be reduced for given integral effect data, assessing the capability of the current-leading safety analysis codes in capturing the multi-dimensional behavior observed in the ISP-50 test, especially in the upper annulus downcomer region when the safety injection water is introduced through the DVI nozzle above the cold leg, and finally finding limitation of the safety analysis codes and thus suggesting an area and/or directions where further code improvement is required.

2. ORGANIZATION OF THE ISP-50

The ATLAS ISP-50 was led by KAERI in collaboration with the OECD/NEA. As an operating agency, KAERI was responsible for the general coordination of the ISP-50, data provision, information on the ATLAS and the ISP-50, code calculations, receipt of submissions, results comparison, progress meetings, the final workshop, and a comparison report. A total of nineteen organizations joined the ATLAS ISP-50 program as listed in Table 2. A few organizations joined the “open” phase followed by the “blind” phase. Each signed organization had an obligation to perform a calculation with their system analysis codes

within the calculation period by using the test results which were provided by the operating agency. All the participants were also requested to write their analysis results in an assigned section of a final comparison report.

It was agreed in the kick-off meeting on April, 2009 that the steady state input deck of the ATLAS facility can be provided to participants who want to have it with a notification to the other participants. Thus, a code input deck for RELAP5/MOD3.3 prepared by the operating agency was delivered to eight organizations who requested the input deck. The organizations who have received the input deck from the operating agency are JNES, NRI, Univ. of Pisa, GRS, KTH, NRC, CIAE and PSI. Most Korean participants who are familiar with the ATLAS facility already have the RELAP5/MOD3.3 input deck. Such a provision provided the participants who were not familiar with the ATLAS facility with the opportunity of easy participation. Nonetheless, most organizations made the best use of their own code experience and expertise to analyze the test scenario as closely as possible.

Among 1,250 measuring parameters, a total of 86 parameters were requested to participants for a comparison with the data in the first “blind” phase. As one of the main objectives of the “blind” phase was to assess the capability of safety analysis codes in reproducing the overall thermal-

hydraulic phenomena for the DVI line break scenario, only 86 key parameters were selected and considered to be sufficient to characterize the ISP-50 scenario.

In the 2nd workshop, multi-dimensional behavior in the reactor pressure vessel was discussed. Hence, the operating agency provided additional data, including the detailed

temperature distribution in the core region. In order to perform a more improved comparison of calculations with the data, the requested parameter sets were expanded from 86 to 145 parameters. The organizations who showed their willingness to perform 3-D modeling for the core region could submit their calculation results.

Table 2. List of Participants

Country	Organization	Participants	Code
China	CIAE	Chen Yuzhou; chenyz@ciae.ac.cn	RELAP5/MOD3.3
Czech Republic	NRI	Radim Meca; mec@ujv.cz	ATHLET
Finland	VTT	Pasi Inkinen; Pasi.Inkinen@vtt.fi Ismo Karppinen; Ismo.karppinen@vtt.fi	APROS 5.09
	FORTUM ¹⁾	Ahonen Aino; Aino.Ahonen@fortum.com	APROS v.5.08
Germany	GRS	Henrique Austregesilo; Henrique.Austregesilo@grs.de	ATHLET Mod 2.2 Cycle A
Hungary	KFKI/AEKI ²⁾	Antal Takacs; takacs@aeki.kfki.hu	CATHARE2V1.5Bmod3.1
Italy	U. of Pisa	Marco Cherubini; m.cherubini@ing.unipi.it	RELAP5/MOD3.3
Japan	JAEA ³⁾	Akira Satou; Satou.akira@jaea.go.jp	TRACE 5.0
	JNES ³⁾	Hideaki Utsuno; Utsuno-hideaki@jnes.go.jp	TRACE
Russia	EDO Hidropress	I. A. Cheremisov, V. V. Schekoldin (blind) M.S. Khvostov, V. V. Schekoldin (open) Schekoldin_vv@grpress.podolsk.ru V. I. Shchekoldin V.V. Yudahin S.L. Borisov	KORSAR/GP (GP1) KORSAR/GP (GP1) KORSAR/GP (GP2) KORSAR/GP (GP3) TECH-M-97 (GP4)
Sweden	KTH	Erdenechimeg Sudvantsetseg, Fabio Veronese and Tomasz Kozlowski tomasz@safety.sci.kth.se	TRACE 5.0 patch 01
Switzerland	PSI ²⁾	Annalisa Manera; Annalisa.manera@psi.ch Medhat Sharabi; Medhat.sharabi@psi.ch	RELAP5/MOD3.3
UK	HSE ³⁾	John Jones; john.jones@hse.gsi.gov.uk	NA
USA	NRC	Harrington Ronald; Ronald.Harrington@nrc.gov Scott Krepel; Scott.krepel@nrc.gov	TRACE 5.200
Korea	KAERI	K. D. Kim; kdkim@kaeri.re.kr	MARS-KS
	KINS	S. H. Ahn; K175ash@kins.re.kr	MARS-KS
	KNF (KEPCO NF)	T. S. Choi; tschoi@knfc.co.kr	RELAP5/MOD3.3
	KEPRI (KEPCO RI)	S. J. Ha; hsj@kepri.re.kr S.Y. Kim; seyunkim@kepri.re.kr	MARS-KS
	KOPEC (KEPCO E&C)	C. W. Kim; cwkim@kopec.co.kr H. R. Choi; hrrchoi@kopec.co.kr Y.M. Kim; kimym@kopec.co.kr	RELAP5-ME RELAP5/MOD3.3

¹⁾ contributed to the “blind” calculation only

²⁾ joined the “open” calculation

³⁾ participated as an observer

3. FACILITY DESCRIPTION

3.1 ATLAS Facility

The ATLAS is a large-scale thermal-hydraulic integral effect test facility with a reference plant of APR1400 and it has a scaling ratio of 1/2 in height and 1/288 in volume with respect to APR1400 and a summary of the scaling ratios of the major parameters is shown in Table 3. The three-level scaling methodology consisting of integral scaling, boundary flow scaling, and local phenomena scaling was applied to the design of ATLAS [5]. The ATLAS can simulate a wide variety of accident and transient conditions including large- and small-break LOCAs. The ATLAS has been actively utilized to establish an integral effect data base which can be used to resolve safety issues, to investigate new safety concepts, and to validate and to improve the safety analysis codes. Detailed information on the ATLAS program and major design characteristics can be found in reference [6].

3.2 Test Loop Configuration

In the ISP-50 test, one among the four DVI nozzles directly attached at the reactor pressure vessel was assumed to be broken abruptly. The break area was controlled to discharge the scaled break flow rate, assuming that a 50% DVI nozzle of the APR1400 was broken. The broken nozzle is located at 1.05m higher than the elevation of the cold leg. As for the safety injection, a single failure assumption was applied so that one SIP (Safety Injection Pump) and three SITs (Safety Injection Tank) were available to deliver the safety injection water into the upper downcomer region. The loop configuration used in the

ISP-50 test is shown in Figure 1. More information is available from reference [7].

Table 3. Summary of Scaling Ratios of the ATLAS

Parameters	Scaling law	ATLAS design
Length	l_{OR}	1/2
Diameter	d_{OR}	1/12
Area	d_{OR}^2	1/144
Volume	$l_{OR} d_{OR}^2$	1/288
Velocity	$l_{OR}^{1/2}$	$1/\sqrt{2}$
Time	$l_{OR}^{1/2}$	$1/\sqrt{2}$
Flow rate	$l_{OR}^{1/2} d_{OR}^2$	1/203.6
Core ΔT	ΔT_{OR}	1
Core power	$l_{OR}^{1/2} d_{OR}^2$	1/203.6
Heat flux	$1/l_{OR}^{1/2}$	$\sqrt{2}$
Power/volume	$1/l_{OR}^{1/2}$	$\sqrt{2}$
Pressure drop	l_{OR}	1/2
Pump head	l_{OR}	1/2
Core rod diameter	1	1
SG U-tube diameter	$l_{OR}^{1/2}$	$1/\sqrt{2}$
No. of core rods	d_{OR}^2	1/144
No. of SG U-tubes	-	1/72

Fig. 1. Loop Configuration for the DVI Line Break Test

Table 4. Grouping of the Submitted Participants

Group ID	Participants index	Code used	Remarks
A	KAERI (Korea), KEPRI (Korea), KTH (Sweden), NRC (USA)	MARS or TRACE	4 orga'ns
B	CIAE (China), KNF (Korea), KOPEC (Korea), PSI (Switzerland), UNIPI (Italy)	RELAP series	5 orga'ns
C	AEKI (Hungary), GP1, GP2, GP3 (Russia)	CATHARE, KORSAR/GP	4 orga'ns
D	GRS (Germany), NRI (Czech Republic), VTT (Finland)	ATHLET, APROS	3 orga'ns

Table 5. Summary of Nodalization Schemes in Open Calculation

	Group A				Group B					Group C				Group D		
	KAERI	KEPRI	KTH	NRC	CIAE	KNF	KOPEC	PSI	Univ. of Pisa	AEKI	EDO Gid 1 (GP1)	EDO Gid 2 (GP2)	EDO Gid 3 (GP3)	GRS	NRI	VTT
Code	MARS-KS	MARS-KS	TRACE 5.0 p.1	TRACE 5.0 p.2	RELAP5/M3.3	RELAP5/M3.3	RELAP5-ME	RELAP5/M3.3	RELAP5/M3.3	CATHARE2V1.5B mod3.1	KORSAR/GP	KORSAR/GP	KORSAR/GP	ATHLET M2.2	ATHLET	APROS 5.09
Node information																
No. of Volume	267	275	863	94	NA	256	321	309	823	532	357	633	351	297	145	592
No. of Junction	360	368	97	114	NA	349	415	305	1029	47	357	633	351	379	378	749
No. of Heat Structure	433	433	4	44	NA	433	435	80	780	24	70	21	59	382	155	1866
Downcomer ¹⁾ axi x rad x azi	2-D 10x6	2-D 10x6	2-D	2-D 19x1 x8	2-D 10x1 x6	2-D 10x1 x6	2-D 10x1 x6	2-D 10x1 x6	2-D 23x1 x4	1-D	2-D 17x1 x4	2-D 16x1 x1	2-D 22x1 x4	2-D 11x1x4	2-D 14x1 x6	2-D 24x1 x6
RPV ¹⁾ axi x rad x azi	1-D	1-D	3-D 19 x3x6	3-D 19x4 x8		1-D	1-D	1-D	1-D	1-D	1-D 12x1 x1	1-D 12x1 x1	1-D 12x1 x1	1-D	1-D	1-D 24x1 x1
Others										RPV 4 parallel channels				RPV 3 parallel channels		

Note ¹⁾ Number of detailed nodes was inferred from the participants' reports in some cases

4. COMPARISON RESULTS

The ISP-50 participants in the open calculation were grouped into 4 sub-groups by taking into account the similarity of the code used as shown in Table 4. The PSI of Switzerland who joined the open calculation was included in Group B because they used the RELAP5/MOD3.3 code. KOPEC which performed two calculations in the previous blind phase submitted one calculation with RELAP5-ME code in the open phase. Gidropress which used two codes – KORSAR/GP and TECH-M-97- in the blind phase submitted only one calculation with TECH-M-97 code in the open phase.

4.1 Nodalization Scheme

A summary of nodalization schemes of the submitted calculations is listed in Table 5. Most calculations were performed by one dimensional modeling, but multi-dimensional modeling on the downcomer and the reactor pressure vessel was done by some participants. Most participants applied two-dimensional modeling to the downcomer region. When multiple channels were used to take into account the effects of cross flow between two adjacent channels, this modeling can be treated as two-dimensional. The number of azimuthal sections showed a variation from 4 to 8 depending on calculations. As for the reactor pressure vessel, KTH and NRC applied a 3-D

Fig. 2. Comparison of the Number of Nodes

vessel component in order to predict the 3-D behavior of the peak cladding temperature.

The number of nodalizations is summarized in Table 5 where a wide range of variation can be found. A comparison of the number of volumes, nodes and heat structures is shown in Figure 2. KTH used the greatest number of volumes, 863 volumes, to model the ATLAS facility with the TRACE code. Whereas, NRC who used the same TRACE code used only 94 volumes. It is because the number of volumes used to model the core with the VESSEL component was not taken into account in the table. UNIP used 823 volumes with RELAP5/MOD3.3 code. VTT used 592 volumes with the APROS code. On average, the number of volumes used by the other participants ranges around 100 and 300. The number of heat structures also showed a great variation. KTH used the minimum number of heat structures but VTT used the maximum of 1866. Details of nodalization of the submitted calculations can be found in the participants' report of volume 3 of the final integration report [4].

4.2 Inventory Distribution

The primary and the secondary side inventories are considered as one of the most influential factors of the code models to affect a transient calculation. These inventories of the code models should be as close as those of the test facility to minimize the transient distortion. A component-wise inventory is also as important as the total inventory. Inventory distributions of the participants' code models are compared with the geometric data of the ATLAS and the calculated percentile error (ϵ) distribution was sum-

marized in Table 6. Detailed geometric information of the ATLAS facility can be found in the latest facility description report [8]. The primary system was divided into several major components and their internal volumes were compared with the measured ones. As for the secondary system, the steam generator itself and the steam pipe lines to the turbine isolation valve were separated.

In group A, for instance, KTH showed a +40% error in modeling the core region but each RCP's volume was modeled with a small volume by -60%. In general, the percentage errors of KTH and NRC, who used the TRACE code, were very similar. On the other hand, participants in group B showed very similar errors and an excellent agreement with the data, but KOPEC modeled the cold leg with larger volume than the data by 60%. In group C, the AEKI's CATHARE model showed larger volumes especially in the downcomer and the pressurizer. The other GP models were all similar with each other. Participants in group D showed excellent agreement in volume distribution.

Compared with the primary inventory, the secondary inventory showed much larger errors. In general, the steam generator was modeled with a small volume and the steam line was also modeled with a small volume compared with the data. Comparison of the total volumes of the primary and the secondary system is shown in Figure 3.

Subsequent to the qualitative comparison, nodalization quantification was performed according to the method used in the BEMUSE Phase II [9]. The present quantification is not a rigorous one because only the primary and the secondary inventories were used as quantities. As the first step, the acceptable errors (AE) for the quantification

Table 6. Summary of Percentile Errors of the Inventory Distributions of the Code Models

	Group A				Group B					Group C				Group D		
	KAERI	KEPRI	KTH	NRC	CIAE	KNF	KOPEC	PSI	UNIP1	AEKI	GP1	GP2	GP3	GRS	NRI	VTT
Core	2.20%	-2.24%	39.84%	11.33%	-5.55%	-2.37%	-2.37%	-2.34%	-0.44%	-8.33%	2.06%	-0.99%	4.61%	-1.22%	0.52%	-1.30%
Down-comer	-7.88%	-3.69%	3.91%	-7.29%	-2.29%	-6.70%	-0.56%	-0.56%	-7.09%	30.50%	-5.42%	-9.44%	-8.16%	-6.70%	-6.65%	-0.56%
Pres-surizer	0.53%	0.51%	0.74%	1.03%	0.51%	0.51%	-0.33%	0.37%	0.51%	37.50%	1.03%	2.06%	0.55%	0.55%	0.22%	-5.88%
PZR surge-line	-14.68%	-14.89%	-10.64%	11.91%	-14.89%	-14.89%	-14.89%	-14.89%	-14.89%	-36.17%	-4.26%	-	-2.13%	-12.77%	-14.89%	-2.13%
Hot leg (1 of 2)	-6.45%	-6.49%	3.44%	3.74%	-6.49%	-6.49%	-6.49%	-6.49%	-6.49%	4.96%	-2.29%	-11.45%	-11.45%	-3.44%	-6.49%	-24.05%
SG (1 of 2)	-0.48%	-0.49%	-33.46%	-33.50%	-1.57%	-0.49%	1.47%	-0.52%	1.47%	-21.72%	-0.75%	0.55%	-14.22%	1.86%	-0.49%	7.63%
Cold leg (1 of 4)	-0.78%	-0.87%	7.83%	8.09%	-0.78%	-0.87%	58.26%	-0.87%	-0.87%	18.52%	39.13%	44.35%	6.09%	28.70%	-0.87%	-17.39%
Int. leg (1 of 4)	13.85%	-1.24%	5.59%	5.65%	-12.80%	-1.24%	-1.24%	-1.24%	-1.24%	6.46%	6.21%	40.99%	-21.12%	11.18%	-1.24%	6.83%
RCP (1 of 4)	28.68%	28.30%	-56.60%	-55.85%	28.30%	28.30%	28.30%	28.30%	28.30%	-	-	-	-	-	28.30%	13.21%
Primary sum	-0.81%	-0.95%	-2.85%	-10.62%	-2.44%	-1.31%	-0.04%	-0.40%	0.6%	-0.04%	-0.24%	0.21%	-6.42%	-0.41%	-0.69%	0.69%
SG (1 of 2)	-12.18%	-12.18%	-27.61%	-44.85%	-12.18%	-12.18%	-12.18%	-12.23%	-12.15%	0.68%	-25.98%	-12.25%	-12.06%	-12.29%	-12.18%	-6.85%
Steam line (1 of 2)	-20.94%	-21.00%	-100.0%	-15.43%	-20.88%	663.46%	-21.00%	-25.75%	-21.00%	-52.32%	-24.59%	-51.28%	-75.17%	-20.88%	663.34%	-44.90%
Secondary sum	-12.72%	-12.72%	-31.97%	-43.06%	-12.71%	33.66%	-12.71%	-12.98%	-12.74%	-2.54%	-25.90%	-16.12%	-16.65%	-12.81%	28.85%	-9.16%

Note : percentile error (ϵ) = (model – data)/data

Fig. 3. Comparison of the Participants' Inventory Distribution

process were determined. 2% and 5% were used for AEs for the primary and the secondary inventories, respectively. In fact, the AEs affect the final quantification output, the global acceptability factor, Q_A . The effects of the AE, especially of the secondary inventory, were investigated

and compared in Figure 4. The percentile error, E was defined as the ratio

$$E = \frac{(\text{exp value} \pm \text{exp error}) - \text{calc value}}{|\text{exp value} \pm \text{exp error}|} \quad (1)$$

The percent error, E becomes zero if the $|\text{exp value} \pm \text{exp error} - \text{calc. value}|$ is lower than the experimental error. Secondly, weighing factors for taking into consideration the importance of the parameters with respect to the present SBLOCA transient were determined. Taking into account the phenomena of the SBLOCA, the relative importance of the secondary inventory was assumed to be half that of the primary inventory. Thus, the weighting factors, ω_{Ai} , of 1.0 and 0.5 were used for the primary and the secondary inventory, respectively. Then, the single acceptability factor, Q_{Ai} was obtained by the following formula:

$$Q_{Ai} = \left(\frac{E}{AE} \right)_i \cdot \omega_{Ai} \quad (2)$$

where normalized weighting factors were used. Finally,

 Fig. 4. Comparison of Q_A for Nodalization Quantification

the global acceptability factor, Q_A can be obtained by summing the whole single acceptability factors

$$Q_A = \sum_i Q_{Ai} \quad (3)$$

In the literature, $Q_A < 1.0$ is required as an acceptable criterion. Around 50% calculations fulfilled the global acceptability with the AE of 5%. If the acceptable error level increases, more calculations fall into the acceptable region. In fact, Q_A is affected by two factors, AE and ω_{Ai} , and a proper choice of those factors is important for a meaningful quantification process. In the present quantification, two factors were determined by considering the relative importance of each inventory during the typical SBLOCA scenario though they look more or less subjective.

4.3 Initial and Boundary Conditions

The initial steady state and the boundary conditions of the code models should be close to the experimental data as much as possible for correct prediction of the transient behavior. The calculated initial and boundary conditions of the selected major parameters in the open calculation are listed in Table 7. Better agreement with the data was achieved in the open calculation compared with in the blind calculation.

Figure 5 shows the initial core power. Depending on whether the primary heat loss was taken into account in the code model, the difference in the calculated core power was obtained. For instance, KEPRI excluded the additional power for compensating the primary heat loss in the model, resulting in around 1.56 MW. It is interesting that NRC and KNF changed their modeling strategy in the open

calculations. NRC included the additional core power for the primary heat loss in the blind calculations but excluded it in the open calculations. KNF took the opposite strategy between two calculations. How the heat loss effects can be treated in the code model is still under debate. However, most participants were in favor of inclusion of the additional core power for heat loss compensation in their model.

Comparison of the initial primary pressure is shown in Figure 6. In the open calculation, the PT-LP-01 was used as a representative primary pressure instead of PT-UH-01 in the blind calculation. Therefore, pressure from PT-LP-01 has a higher value than that for PT-UH-01. However, a few organizations produced lower primary pressures than those in the blind case. Calculated primary pressures showed a variation from 15.39 MPa (KTH) to 15.76 MPa (AEKI).

The submitted core inlet temperatures were close to the measured data and the minimum was 561.9 K by UNIP and the maximum was 566.7 K by AEKI. NRI and VTT presented better values than the blind case. As for the core exit temperature, most calculations were in very good agreement with the data. In particular, the improvement in the KOPEC's calculation was remarkable.

It is worth comparing the downcomer-to-upper head and the downcomer-to-hot leg bypass flow rate as their effects on the core water level are significant. In the actual test, two bypass flow rates were estimated to be very close to zero. In particular, the downcomer-to-upper head flow rate was inferred to be negative based on experimental results. A detailed comparison of the temperature distribution inside the upper head and the upper downcomer region was performed to investigate the flow direction. Many organizations including KEPRI, KNF, KOPEC, PSI,

Table 7. Comparison of Initial Conditions in Open Calculations

	Experiment	Group A				Group B					Group C				Group D		
		KAERI	KEPRI	KTH	NRC	CIAE	KNF	KOPEC	PSI	Univ. of Pisa	AEKI	EDO Gid 1 (GP1)	EDO Gid 2 (GP2)	EDO Gid 3 (GP3)	GRS	NRI	VTT
Primary system																	
Core power, MW	1.635	1.635	1.566	1.636	1.553	1.613	1.636	1.633	1.638	1.636	1.636	1.636	1.635	1.636	1.636	1.636	1.64
Pressure, MPa	15.67	15.67	15.59	15.39	15.63	15.15	15.66	15.66	15.53	15.67	15.76	15.67	15.67	15.52	15.63	15.60	15.6
Core inlet temp., K	562.7	563.1	563.8	562.9	562.7	562.5	564.6	563.0	562.3	561.9	566.7	563.8	565.0	564.8	565.0	562.9	562.3
Core exit temp., K	597.7	598.2	598.5	598.3	598.5	597.3	598.2	596.4	597.4	596.6	597.7	599.0	598.8	597.8	598.4	597.2	595.5
Bypass DC-UH, kg/s	~0.0	0.0158	-0.008	0.0	0.0	0.0	-0.0185	-0.0089	-0.0336	-0.1073	0.0027	0.1105	0.0	0.0	-0.033	0.567	-0.03
Bypass DC-HL, kg/s	~0.0	0.0178	0.0	0.0	0.0	0.0	0.0322	0.0011	0.0	0.0	NA	0.3478	0.0	0.0	7.5e-6	0.48	0.08
CL flow rate, kg/s	2.2 ±10%	1.9988	2.0068	1.9568	1.8469	2.017	2.0657	2.1098	2.0032	2.0306	2.2657	2.0412	2.0590	2.0433	2.11	2.18	2.1
PZR level, m	3.36	3.587	4.112	3.23	3.42	3.22	3.323	3.365	3.252	3.309	3.242	3.234	3.360	3.745	3.307	3.32	3.3
RCP speed, rpm	15±5	22.2	223.9	21.5	200.5	24.0	263.9	30.0	23.3	11.6	0.0	0.0	0.0	0.0	10.7	18.9	19.2
Secondary system																	
Pressure, MPa	7.83	7.775	7.831	7.830	7.830	7.832	7.832	7.787	7.861	7.831	7.831	7.830	7.728	7.862	7.83	7.83	7.83
Steam temp., K	568.5	566.1	566.6	566.7	566.7	566.6	568.5	566.2	566.9	566.7	566.7	566.5	565.9	566.8	566.7	566.2	566.4
Avg. FW temp., K	508.2		505.4	508.0	508.4		-	505.4	-	-	508.0	-	-	-	508.2	507.2	508.2
FW flow (ECO), kg/s	0.43	0.455	0.3998	0.473	0.432	0.431	0.433	0.4639	0.4206	0.4326	0.4600	0.4382	0.4059	0.4566	0.432	0.431	0.42
FW flow (DC), kg/s	~0.0	0.0	0.0444	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
SG level, m	1.97~2.03		4.08	3.44	1.83		-	5.91	-	-	2.61	-	-	-	2.07	4.76	2.70
Heat removal, kW	753.67	815.8	781.17	815.46	777.06	784.17	810.82	816.97	750.92	772.94	813.18	791.96	796.80	817.54	786	730	775
ECC																	
SIT pressure, MPa	4.19	4.19	4.23	4.19	4.20	4.21	4.21	4.23	4.17	4.19	4.19	4.17	4.20	4.20	4.19	4.23	4.23
SIP Temp., K	321.3	323.3	320.9	325.1	323.3	323.3	323.3	323.2	320.2	323.0	323.2	322.9	323.1	323.2	323.2	323.2	321.3
SIT Temp., K	323.5	323.4	324.3	323.4	323.4	323.3	323.5	320.9	323.2	323.2	323.4	323.5	323.1	323.2	323.6	323.2	324.1
SIT level, %	~95		95	95	95	-	-	~95	-	-	~95	-			-	9	95
Containment																	
Pressure, MPa	0.10	0.1013	0.1013	0.1029	0.1088	0.1013	0.1028	0.1029	0.1444	0.1013	0.1	0.1013	0.1000	0.0	0.1032	0.10	0.100

Fig. 5. Comparison of the Initial Core Power

Fig. 6. Comparison of the Initial Primary Pressure

Fig. 7. Comparison of the Initial Steam Generator (SG-1) Pressure

Fig. 8. Comparison of the Initial Heat Removal Rate by Steam Generator 1 (SG-1)

UNIFI, GRS, VTT predicted a negative downcomer-to-upper head flow rate. NRI's calculation showed a little higher downcomer-to-upper head flow rate than that in the case of the open calculation. On the other hand, the predicted downcomer-to-hot leg bypass flow rate was always positive which was consistent with the experimental observation. Most calculations in the open phase agreed well with the data. However, GP1 predicted an increased bypass flow rate in the open phase compared with that in the blind phase.

Regarding the cold leg flow rate, most calculations were in good agreement with the data. KTH and NRC predicted decreased cold leg flow rates compared with those in the blind phase. AEKI showed the maximum flow rate among the calculations.

The secondary pressures are compared in Figure 7. There was no significant difference between the blind and the open calculations. Overall, KAERI's prediction was a little lower than the data. A better agreement can be observed in the predictions by KNF and GP2. The feed water flow rates through the economizer and the downcomer were in good agreement with the data. In particular, the NRI's prediction was much improved compared with the blind case. Incorrect predictions of the downcomer feed water flow rate in the blind phase were improved. Figure 8 compares the heat removal rate by the steam generator (SG-1). Most calculations predicted higher heat removal rates except for PSI and NRI. The initial pressure of the SIT-1 and the coolant temperature of the SIP-1 were well predicted in most calculations. The water temperature of the SIT-1 and the containment pressure were well predicted by all the models.

Similar to the inventory quantification method described in the previous section, quantification of the prediction accuracy of the steady state calculations were performed

Fig. 9. Accuracy Quantification Results of Steady State Calculations

by defining the following acceptable factor, Q_B ,

(4)

where $(E/AE)_i$ is a ratio of a calculated error and an acceptable error and ω_{Bi} is a weighting factor of each parameter. Almost all the parameters defined in Table 7 were incorporated to calculate Q_B , but the average feedwater temperature and the SG water level were excluded because data from a few participants was not available. In general, $Q_B < 1.0$ is recommended as an acceptable criterion. The final calculation result is shown in Figure 9. Most calculations were within the acceptable range, but a few calculations were far beyond the acceptable criterion. It was due to overestimation of the bypass flow rates of the

downcomer-to-upper head and the downcomer-to-hot leg. Great deviation of the bypass flow rate from the data can be seen in Table 7. Thus, a sensitivity study was performed by excluding the two bypass flow rates in the calculation of Q_B and its results were plotted together in Figure 9. When the bypass flow rates were not taken into account, decreased Q_B values were obtained. The higher value than $Q_B=1.0$ by CIAE was found to be due to lower primary pressure. In fact, the Q_B value depends on selection of the weighting factors, but the relative prediction accuracy among the code models can be compared with each other quantitatively and it gives useful insight into the code models of the participants.

4.4 Sequence of Events

Table 8 summarizes the sequence of events calculated by the participants in the open calculation. In order to make the comparison with the data convenient, the submitted

calculation times and experimental times were adjusted for the break time to be 0.0 s. A detailed sequence of events in open calculations was compared with the previous blind calculation as well as the experimental values to investigate how much improvement was obtained. Table 9 shows the comparison of the calculated sequence of events of Group A. Note that only the timing of the sequence of events is compared and agreement in timing of a certain event does not always imply quantitative agreement in the physical phenomena. There was great difficulty in predicting the correct timing and location of the loop seal clearing in most calculations.

5. TRANSIENT ACCURACY QUANTIFICATION

5.1 FFTBM Methodology

In order to give clearer quantification of the prediction

Table 8. Summary of Calculated Sequence of Events in Open Calculation

	Exp. (shifted time, sec)	Group A				Group B					Group C				Group D		
		KAERI	KEPRI	KTH	NRC	CIAE	KNF	KOPEC	PSI	Univ. of Pisa	AEKI	EDO Gid 1 (GP1)	EDO Gid 2 (GP2)	EDO Gid 3 (GP3)	GRS	NRI	VTI
Break	0.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
1st MSSV open	24.	28.0	29.0	49.2	37.0	33.1	6.0	21.0	28.0	28.1	64.0	32.0	34.0	17.0	23.4	33.0	33.0
LPP trip	25.	25.0	26.0	37.1	34.0	25.1	28.0	29.0	25.0	26.4	29.1	26.0	27.0	29.0	23.0	28.5	28.0
RCP trip	25.	25.0	26.4	37.1	34.0	37.1	0.0	29.0	52.0	0.0	30.14	0.0	0.0	0.0	23.0	28.9	28.35
MSIV closure	25.	32.1	26.1	37.2	33.3	24.1	29.1	28.8	25.0	230.0	30.1	26.5	NM	NM ⁴	23.0	28.6	28.0
MFW isolation	32.	32.1	33.5	44.2	41.1	29.1	35.0	35.0	31.0	33.4	37.1	33.1	34.1	36.1	30.0	35.5	35.0
Core decay	33.	29.0	26.5	32.1	34.0	29.1	29.0	35.0	26.0	38.1	30.1	26.4	27.3	29.4	28.5	33.0	34.0
SIP activation	54.	86.0	54.3	65.2	62.1	49.0	57.0	58.0	54.0	54.7	57.6	54.3	55.3	57.3	52.0	57.3	56.3
SIT activation	468.	452	453.4	426.4	416.8	433.0	475.0	399.0	469.0	469.0	460.9	477.0	508.3	464.0	494.0	500.2	485.0
Loop seal clear	CL1A	190.	170	172	X	188	145	180.0	1710.0	183.0	185.0	1400	X	X	X	X(281) ³⁾	165
	CL1B	190.	170	172	X	188	145	180.0	X	183.0	X	1400	420	X	X	217	X(400) ³⁾
	CL2A	X¹⁾	X	172	204	X	1472	181.0	142.0	X ²⁾	184.0	160	390	280	X	192	X
	CL2B	1236	170	172	X	188	1472	X	142.0	168.0	184.0	160	X	280	X	X	182
Stop	2933	1999	2000	3300	1999	1500	2000	2000	3000	2500	3000	2933	3000	3000	2807	2933	2000

Note

¹⁾ X: not occurred

²⁾ Loop seal clearing occurred at 168 s but, after about 25 s it returned to water plugging

³⁾ Loop seal clearing was reported in the participant's report, but it did not occur according to the submitted data

⁴⁾ NM: not modeled

performance, a methodology proposed by Prof. F. D'Auria at the University of Pisa (DCMN), FFTBM (Fast Fourier Transform Based Method) was adopted in the present ISP-50 exercise [10, 11, 12]. It is an integral method using the Fast Fourier Transform (FFT) in order to represent the code discrepancies in the frequency domain. This method has been successfully applied to the past international standard problems (ISPs) or standard problem exercises (SPEs) organized by CSNI or IAEA in order to quantify the prediction accuracy of the codes used in the program. The FFTBM methodology is briefly summarized here [11]. Suppose that there are N consecutive sampled values, the error signal in the discrete time domain can be expressed:

$$\Delta F(t_k) = F_{\text{cal}}(t_k) - F_{\text{exp}}(t_k), \quad t_k = k\tau, \quad k=0, 1, 2, \dots, N-1, \quad (5)$$

where $F_{\text{cal}}(t_k)$ and $F_{\text{exp}}(t_k)$ are calculated and experimental signals sampled at evenly spaced intervals in time, respectively. The number of discrete signals should be a power with a base equal to 2, that is, $N=2^{m+1}$ to apply FFT and the sampling theorem must be fulfilled. By applying

FFT on the discrete experimental signal and the error signal, we can obtain the discrete Fourier transform of the N points F_k in the frequency domain.

$$\tilde{F}_{\text{exp}}(f_n) = \tau \sum_{k=0}^{N-1} F_{\text{exp},k} e^{2\pi i k n / N}, \quad (6)$$

$$\Delta \tilde{F}(f_n) = \tau \sum_{k=0}^{N-1} \Delta F_k e^{2\pi i k n / N}, \quad (7)$$

where $f_n = n/N\tau$.

The accuracy quantification for an individual parameter is based on amplitude of discrete experimental and error signals obtained by FFT at frequencies, f_n , where ($n=0, 1, \dots, 2m$) and m is the exponent ranging from $m=8$ to $m=11$. According to the sampling theorem, the sampling frequency is calculated by

$$\frac{1}{\tau} = f_s = 2f_{\text{max}} = \frac{N}{T_d} = \frac{2^{m+1}}{T_d}, \quad (8)$$

Table 9. Detailed Comparison of Calculated Sequence of Events of Group A

		Exp. (shifted time, sec)	Group A															
			KAERI				KEPRI				KTH				NRC			
			Blind		Open		Blind		Open		Blind		Open		Blind		Open	
			cal.	diff.	cal.	diff.	cal.	diff.	cal.	diff.	cal.	diff.	cal.	diff.	cal.	diff.	cal.	diff.
Break		0.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1st MSSV open		24.	34.1	+10.1	28.0	+4.0	X	bad	29.0	+5.0	X	bad	49.2	+25.2	37.7	+13.3	37.0	+13.0
LPP trip		25.	29.0	+4.0	25.0	0.0	23.0	-2.0	26.0	+1.0	23.5	-1.5	37.1	+12.1	31.0	+6.0	34.0	+9.0
RCP trip		25.	0.0	-	25.0	0.0	13.9	-11.1	26.4	+1.4	24.0	-1.0	37.1	+12.1	31.5	+6.5	34.0	+9.0
MSIV closure		25.	32.1	+7.1	32.1	+7.1	25.5	+0.5	26.1	+1.1	23.6	-1.4	37.2	+12.2	28.4	+3.4	33.3	+8.3
MFW isolation		32.	38.1	+6.1	32.1	+0.1	31.7	+0.3	33.5	+1.5	30.0	-2.0	44.2	+12.2	38.7	+6.7	41.1	+9.1
Core decay		33.	30.1	-2.9	29.0	-4.0	25.54	-7.46	26.5	-6.5	30.0	-0.9	32.1	-0.9	31.5	-1.5	34.0	+1.0
SIP activation		54.	57.1	+3.1	86.0	+32.0	52.7	-1.3	54.3	+0.3	50.0	-4.0	65.2	+11.2	60.1	+6.1	62.1	+8.1
SIT activation		468.	435.	-33.0	452	-16.0	433.1	-34.9	453.4	-14.6	224.0	-244.0	426.4	-41.6	387.8	-80.2	416.8	-51.2
Loop seal clear	CL1A	190.	108.	-82.0	170	-20.0	325.8	+135.8	172	-18	83	-107	X	bad	170	-20	188	-2.0
	CL1B	190.	107.	-83.0	170	-20.0	323.2	+133.8	172	-18	113	-77	X	bad	169	-21	188	-2.0
	CL2A	X¹⁾	105.	bad	X	good	139.1	bad	172	bad	83	-107	204	bad	170	bad	X	good
	CL2B	1236	105	-113.1	170	-106.6	141.6	-109.4	172	-106.4	83	-107	X	bad	170	-106.6	188	-104.8
Stop		2933	1806	-	1999	-	2000	-	2000	-	2932	-	3300	-	3000	-	1999	-

Note

¹⁾ X: not occurred

where $f_{\max}$ is the maximum frequency component of the signal. These spectra of amplitude together with frequencies are used for calculation of average amplitude (AA) and the weighted frequency (WF) that characterize code accuracy. The AA is defined as the sum of error function amplitudes normalized to the sum of experimental signal amplitude as follows:

$$AA = \frac{\sum_{n=0}^{2^m} |\Delta \tilde{F}(f_n)|}{\sum_{n=0}^{2^m} |\tilde{F}_{\text{exp}}(f_n)|} \quad (9)$$

and the WF is defined as the sum of frequencies multiplied by the error function amplitudes, normalized to the sum of the error function amplitude

$$WF = \frac{\sum_{n=0}^{2^m} |\Delta \tilde{F}(f_n)| \cdot f_n}{\sum_{n=0}^{2^m} |\Delta \tilde{F}(f_n)|} \quad (10)$$

A cut-off frequency (f_{cut}) is introduced to cut off spurious contribution to the accuracy quantification. The overall accuracy of the code calculation can be obtained by defining average performance indices, the total weighted AA and the total WF as follows:

$$AA_{\text{tot}} = \sum_{i=1}^{N_{\text{var}}} (AA)_i \cdot (w_f)_i \quad (11)$$

$$WF_{\text{tot}} = \sum_{i=1}^{N_{\text{var}}} (WF)_i \cdot (w_f)_i \quad (12)$$

$$\sum_{i=1}^{N_{\text{var}}} (w_f)_i = 1 \quad (13)$$

where, N_{var} is the number of the variable analyzed, and $(AA)_i$, $(WF)_i$, and $(w_f)_i$ are AA, WF and weighting factors for i -th analyzed variable, respectively. The weighting factor can be further sub-divided into three components by considering experimental accuracy $(w_{\text{exp}})_i$, safety relevance $(w_{\text{saf}})_i$, and primary pressure nodalization $(w_{\text{norm}})_i$. Thus, the weighting factor for the i -th variable is therefore defined as:

$$(w_f)_i = \frac{(w_{\text{exp}})_i (w_{\text{saf}})_i (w_{\text{norm}})_i}{\sum_{i=1}^{N_{\text{var}}} (w_{\text{exp}})_i (w_{\text{saf}})_i (w_{\text{norm}})_i} \quad (14)$$

where $(w_{\text{exp}})_i$ is the contribution related to the experimental accuracy, $(w_{\text{saf}})_i$ is the contribution related to safety and $(w_{\text{norm}})_i$ the contribution of primary pressure normalization.

5.2 Parameter Selection

The full FFTBM method requires 20-25 parameters selected representing relevant thermal-hydraulic aspects. In order to apply the FFTBM to the ISP-50 calculation, major parameters should be selected among the submitted parameters. By personal communication with Prof. D'Auria's group in the blind phase, 22 parameters among the submitted 86 parameters were selected to characterize all the relevant phenomena that were measured during the experiment. Similar parameters which would affect the analysis results and the parameters which have much measurement uncertainties were avoided in this selection process. In the subsequent open phase, the same parameters used in the blind phase were used except for the cladding temperature in the middle region. The cladding temperature at the 7th elevation was replaced with that at the 10th elevation as the maximum PCT was observed at the 10th elevation in the ISP-50 test. As reference data, the cross sectional maximum temperatures at the 2nd, 10th, and 12th elevations were used for comparison with the calculations. The final selected parameters are listed in Table 10.

5.3 Weighting Factors

Weighting factors are used to consider the different importance from the viewpoint of safety analysis and to calculate overall accuracy of the calculation, i.e., the total average amplitude (AA_{tot}). The weighting factors are determined by engineering judgment. It is widely known and accepted that the weighting factors used in Table 1 of reference [11] can be used in the analysis of LBLOCA as well as SBLOCA. Thus, in the present analysis, the same weighting factors were used and listed in Table 10.

5.4 Time Interval and Cut-off Frequency

In order to determine the time interval, the transient behavior of the DVI line break scenario should be identified from the viewpoint of phenomenology. According to the Phenomena Identification Ranking Table (PIRT) performed for the DVI line break, the transient behavior can be categorized into 4 phases: the pre-trip phase, the post-trip phase, the refill phase, and the long term cooling phase [13].

Based on the PIRT results and observed phenomena in the ISP-50 test, three time intervals have been selected to perform the FFTBM as shown in Table 11. Submitted calculations showed some differences in the time when the core power started to decay, even though the core power began to decay at 33 s. Thus, the shortest time of 24 s was selected as the first time of interval relevant to the pre-trip phase among the calculated times when the core power started to decay. This time frame focuses on the prediction accuracy comparison during the initial blowdown period. In this time frame, all the FFTBM assessments were carried out at the constant power condition. Despite a very short time window of 24 s, we sampled 512 data points for the FFT calculation according

Table 10. A list of Parameters and Weighting Factors for FFTBM Analysis

Parameters	Instrument name	Weighting factor			
		w_{exp}	w_{saf}	w_{norm}	w_f
Core power	$\sum$ HP-CO-0i-P	0.8	0.8	0.5	0.32
Pressurizer pressure	PT-PZR-01	1.0	1.0	1.0	1.00
SG1 steam dome pressure	PT-SGSD1-01	1.0	0.6	1.1	0.66
SIT-01 pressure	PT-SIT1-02	1.0	0.6	1.1	0.66
Core inlet temperature	TF-LP-2G18	0.8	0.8	2.4	1.536
Core exit temperature	averaged	0.8	0.8	2.4	1.536
Clad temp. at region 2	max. at reg. 2	0.9	1.0	1.2	1.08
Clad temp. at region 10	max. at reg. 10	0.9	1.0	1.2	1.08
Clad temp. at region 12	max. at reg. 12	0.9	1.0	1.2	1.08
Hot leg 1 flow rate	QV-HL1-01A+B	0.5	0.8	0.5	0.20
Hot leg 2 flow rate	QV-HL2-01A+B	0.5	0.8	0.5	0.20
Active SIT-01 flow rate	QV-SIT1-01	0.5	0.8	0.5	0.20
Active SIP-02 flow rate	QV-HPSI1-03	0.5	0.8	0.5	0.20
Total break flow rate	calculated	0.5	0.8	0.5	0.20
Accumulated break mass	Integral of total break flow rate	0.8	0.9	0.9	0.648
Downcomer level	LT-RPV-04A	0.8	0.9	0.6	0.432
Active core region level	LT-RPV-01	0.8	0.9	0.6	0.432
Pressurizer level	LT-PZR-01	0.8	0.9	0.6	0.432
Collapsed water level IL1A	LT-IL1A-03	0.8	0.9	0.6	0.432
Collapsed water level IL1B	LT-IL1B-03	0.8	0.9	0.6	0.432
Collapsed water level IL2A	LT-IL2A-03	0.8	0.9	0.6	0.432
Collapsed water level IL1B	LT-IL2B-03	0.8	0.9	0.6	0.432

Table 11. Selected Time of Interval for the Present FFTBM Analysis

Time of interval	Phase relevant to PIRT	Phenomena observed	Number of data	Max. frequency $f_{max}=0.5f_s$ $f_{max}=0.5f_s$ (Hz)
0~24 s	Pre-trip	Before the core power decay Core power decay at 33 s in the test	512	10.66
0~300 s	Post-trip	Before the SIT injection SIP injection at 54 s in the test SIT injection at 468 s in the test 1 st loop seal clearing at 190 s in the test	1024	1.71
0~2000 s	Refill and long term cooling	All the interesting phenomena are included in this time frame	4096	1.02

to the suggestion in reference [11], resulting in a maximum frequency of up to 10.66 Hz. The sampling process was done by a linear interpolation of the calculation and the experimental data.

The second interval time was selected as the time up to which the SITs were activated. This time of sequences also showed more or less small variations in the submitted results. So, the smallest value among those submitted calculations was selected as the second time interval. In this time frame, all the important thermal-hydraulic phenomena are expected to occur, including interaction of the break flow with the ECC flow by SIP and SITs. Also, the loop seal clearing was expected to happen. A total of 1024 data points in the second interval time was sampled by a linear interpolation of the calculation and the experimental data in order to take into account slightly higher frequencies than the cut-off frequency.

The third interval time was selected to cover the entire phenomena relevant to the DVI line break scenario. The most meaningful phenomena took place less than 2000 s even though the test was carried out for up to 2932 s. So, the 2000 s was selected as the third time frame of the present FFTBM assessment. This period corresponds to the refill and long term cooling phases defined at the PIRT activity. In this third interval time, a total of 4096 data points were sampled in order to include a high frequency contribution of up to 1.0 Hz.

It seems that the effects of the cut-off frequency on the total average amplitude are not so significant. The high frequency errors are more acceptable than the errors caused by low frequency components. Therefore, the cut-off frequency was decided to be close to the maximum frequency, 1.0 Hz. The sensitivity study on the impact of the cut-off frequency on the AA was carried out, but it was confirmed that its impact was small if we took 1.0 Hz as a cut-off frequency.

5.5 Accuracy Improvement Index

In order to quantify improvement of the prediction accuracy during the exercise phase from blind to open, an improvement factor was defined based on AA_{tot} as the following:

$$I = (AA_{tot,open} - AA_{tot,blind}) / AA_{tot,blind} \quad (15)$$

The negative value of I indicates an improvement in prediction accuracy based on FFTBM and the positive I means a worse prediction accuracy.

5.6 FFTBM Results

Prediction accuracy was evaluated at three time frames, taking into account the different transient phases. The calculated AA and WF for each selected parameter of typical calculation is shown in Table 12. The total AA and WF of each calculation is summarized in Table 13.

The calculated AA_{tot} results at three time frames are plotted in Figure 10. As the time frame becomes longer, AA_{tot} becomes larger. Yet, most calculations showed a very good prediction accuracy. In the third time interval, the largest AA_{tot} (0.379) was obtained by GP2, but the difference from the other calculations was very small to be neglected. On the other hand, the smallest AA_{tot} (0.201) was obtained by CIAE. It is interesting that CIAE showed the best prediction accuracy among the participants even though their prediction of the initial steady state conditions was beyond the acceptable limit of $Q_B=1$. As described in the previous section, a higher value of Q_B by CIAE was caused by relatively lower primary pressure than the data. Therefore, such lower initial primary pressure was not a significant factor to impact the transient behavior, especially in the SBLOCA scenario where the primary pressure decreased fast on break. In the FFTBM it is widely accepted that only AA_{tot} can have a physical meaning as an index for accuracy quantification and WF_{tot} can be neglected.

In order to investigate an improvement in the open calculation, the 'I' factors in three time frames were compared as shown in Table 14. In the first time frame (0 s to 24 s), the calculated AA_{tot} showed more or less the similar values as the blind cases. However, the KOPEC's calculation showed a significant improvement among the other calculations. In the open phase, all the calculations showed excellent prediction accuracy where AA_{tot} values were less than 0.1. Great improvement was achieved in the second time frame by most participants. Most calculations have AA_{tot} values near 0.2. The CIAE's calculation showed a 20.5% worse prediction than the blind case because a little worse prediction of the pressurizer pressure was obtained. Though the 'I' value of CIAE seems to be great, but the obtained AA_{tot} value of 0.135 still represents an excellent prediction. In the third time frame, it is noteworthy that KOPEC showed an improvement of 44.6%. GP1, GRS, NRI, and VTT showed an improvement around 25%. Meanwhile, KEPRI, NRC, CIAE, and UNIPi showed worse calculation results compared with the blind calculations. In the case of KEPRI, the open calculation resulted in higher PCTs and more oscillating SIT flow rates than those in the blind phase. The prediction of the loop seal clearing phenomena was also more or less worsened, causing 5.6% deterioration in the AA_{tot} value. The NRC's calculation showed improved predictions of most parameters in the open phase. However, more oscillating predictions of the hot leg and the SIT flow rates in later phase of the transient than the blind calculation counterbalanced the improvement, resulting in 8.8% deterioration in the AA_{tot} value. CIAE presented the best prediction accuracy in the blind and the open calculations. The 2.6% decrease in the AA_{tot} value is not a big deal. Finally, the UNIPi's calculation showed 4.1% worse than the blind calculation. A bad result in predicting the hot leg flow rates caused this decrease. Average improvement for each time interval was 19%, 16%, and 12%, respectively.

Table 12. Total Prediction Accuracy by KAERI in the Open Calculation

Number	Parameter	Time of interval					
		0 ~ 24 s		0 ~ 300 s		0 ~ 1800* s	
		N=512		N=1024		N=4096	
		AA	WF	AA	WF	AA	WF
1	Core power	0.002	0.158	0.004	0.192	0.007	0.201
2	Pressurizer pressure	0.157	0.168	0.153	0.036	0.131	0.035
3	SG1 steam dome pressure	0.008	0.031	0.063	0.114	0.107	0.097
4	SIT-01 pressure	excl.	excl.	excl.	excl.	0.090	0.075
5	Core inlet temperature	0.002	0.174	0.016	0.065	0.023	0.093
6	Core exit temperature	0.004	0.192	0.007	0.077	0.017	0.097
7	Clad temp. at region 2	0.007	0.203	0.011	0.071	0.016	0.133
8	Clad temp. at region 10	0.007	0.143	0.018	0.098	0.023	0.128
9	Clad temp. at region 12	0.005	0.222	0.015	0.185	0.022	0.109
10	Hot leg 1 flow rate	0.357	0.099	1.374	0.155	2.997	0.257
11	Hot leg 2 flow rate	1.600	0.111	1.486	0.159	3.537	0.262
12	Active SIT-01 flow rate	excl.	excl.	excl.	excl.	1.585	0.168
13	Active SIP-02 flow rate	excl.	excl.	0.426	0.114	0.329	0.108
14	Total break flow rate	0.544	0.193	0.593	0.186	0.709	0.204
15	Accumulated break mass	0.264	0.149	0.035	0.079	0.023	0.099
16	Downcomer level	0.014	0.137	0.179	0.107	0.426	0.101
17	Active core region level	0.252	0.173	1.028	0.083	0.776	0.061
18	Pressurizer level	0.395	0.096	0.284	0.075	0.272	0.074
19	Collapsed water level IL1A	0.150	0.116	0.266	0.104	0.376	0.100
20	Collapsed water level IL1B	0.068	0.211	0.357	0.086	1.138	0.117
21	Collapsed water level IL2A	0.140	0.145	0.460	0.083	0.870	0.100
22	Collapsed water level IL2B	0.167	0.084	1.131	0.104	1.000	0.133
	Total (AA _{tot} , WF _{tot})	0.110	0.160	0.210	0.096	0.322	0.108

*excl : excluded in this time of interval

*Maximum calculation is limited to 1800 s

A detailed investigation of the distribution of AA for each calculation revealed that the parameters predicted poorly are the hot leg flow rate, SIT flow rate and the collapsed water level in the intermediate legs. Though a little improvement was obtained in the open phase, these parameters are still dominant factors to degrade the total prediction accuracy. Relatively, the critical flow was well predicted. It seems that most participants used their own expertise to obtain the same break flow rate as the data. It was also found that prediction of the behavior of the

collapsed water levels was much improved. This improvement can also be found in the comparison table of the sequence of events summarized from Table 9.

6. DISCUSSION ON KEY PHENOMENA

Detailed analysis on the key thermal-hydraulic phenomena was performed to achieve a valuable insight into the deficiencies of the system codes and the user effects.

Table 13. Summary of the Results of FFTBM to ISP-50 Open Calculation

Group	Participant/Code		Time of interval					
			0 ~ 24 s		0 ~ 300 s		0 ~ 2000 s	
			N=512		N=1024		N=4096	
			AA _{tot}	WF _{tot}	AA _{tot}	WF _{tot}	AA _{tot}	WF _{tot}
A	KAERI	MARS-KS	0.110	0.160	0.210	0.096	0.322 ¹⁾	0.108
	KEPRI	MARS-KS	0.123	0.141	0.213	0.096	0.359	0.108
	KTH	TRACE 5.0 p. 02	0.137	0.134	0.241	0.068	0.353	0.087
	NRC	TRACE 5.0 p. 02	0.076	0.143	0.162	0.106	0.348	0.104
B	CIAE	R5/M3.3	0.092	0.149	0.135	0.084	0.201 ²⁾	0.085
	KNF	R5/M3.3	0.097	0.140	0.159	0.087	0.302	0.096
	KOPEC	RELAP-ME	0.096	0.169	0.229	0.103	0.372	0.071
	PSI	R5/M3.3	0.091	0.166	0.160	0.098	0.262	0.110
	UNIPI	R5/M3.3	0.067	0.173	0.187	0.094	0.278	0.108
C	AEKI	CATHARE2V1.5Bmod3.1	0.099	0.122	0.243	0.100	0.265	0.101
	GP1	KORSAR	0.078	0.130	0.192	0.093	0.324	0.106
	GP2	KORSAR	0.115	0.136	0.251	0.104	0.379	0.092
	GP3	KORSAR	0.107	0.158	0.171	0.086	0.352	0.100
D	GRS	ATHLET M2.2	0.109	0.127	0.206	0.094	0.310	0.107
	NRI	ATHLET	0.127	0.159	0.216	0.104	0.316	0.077
	VTT	APROS	0.090	0.160	0.211	0.099	0.298	0.106

¹⁾ Maximum calculation time is limited to 1800 s

²⁾ Maximum calculation time is limited to 1460 s

Fig. 10. Comparison of the Open Prediction Accuracy of the Participants Based on FFTBM

Only a part of the analysis is briefly described in this paper. A full description of the analysis can be found in the final integration report [4].

Fig. 11. Comparison of Improvement of Prediction Accuracy

6.1 Two-Phase Break Flow

The break flow rate is the most influencing factor governing the transient behavior. It was confirmed experimentally that choking occurred during the discharge of the single-phase liquid, two-phase mixture, and the single-

Table 14. Improvement of AA_{tot} between the Blind and Open Calculations

Grp.	Partic'nt	Time of interval								
		0 ~ 24 s			0 ~ 300 s			0 ~ 2000 s		
		N=512			N=1024			N=4096		
		blind	open	I(%) ¹⁾	blind	open	I(%) ¹⁾	blind	open	I(%) ¹⁾
A	KAERI	0.1	0.110	10.0	0.25	0.210	-16.0	0.333	0.322	-3.3
	KEPRI	0.134	0.123	-8.2	0.271	0.213	-21.4	0.34	0.359	5.6
	KTH	0.147	0.137	-6.8	0.298	0.241	-19.1	0.417	0.353	-15.3
	NRC	0.121	0.076	-37.2	0.218	0.162	-25.7	0.32	0.348	8.8
B	CIAE	0.093	0.092	-1.1	0.112	0.135	20.5	0.196	0.201	2.6
	KNF	0.122	0.097	-20.5	0.158	0.159	0.6	0.331	0.302	-8.8
	KOPEC	0.403	0.096	-76.2	0.385	0.229	-40.5	0.672	0.372	-44.6
	PSI	-	0.091	-	-	0.160	-	-	0.262	-
	UNIP	0.118	0.067	-43.2	0.22	0.187	-15.0	0.267	0.278	4.1
C	AEKI	-	0.099	-	-	0.243	-	-	0.265	-
	GP1	0.08	0.078	-2.5	0.383	0.192	-49.9	0.444	0.324	-27.0
	GP2	-	0.115	-	-	0.251	-	-	0.379	-
	GP3	-	0.107	-	-	0.171	-	-	0.352	-
	GP4	0.155	-	-	0.317	-	-	0.546	-	-
D	FORTUM	0.086	-	-	0.249	-	-	0.397	-	-
	GRS	0.102	0.109	6.9	0.222	0.206	-7.2	0.411	0.310	-24.6
	NRI	0.124	0.127	2.4	0.213	0.216	1.4	0.405	0.316	-22.0
	VTT	0.113	0.090	-20.4	0.251	0.211	-15.9	0.384	0.298	-22.4

¹⁾ Improvement, I is defined by (open-blind)/blind in percentile

phase steam throughout the test. Such three phases of the break flow can also affect the multi-dimensional phenomena in the downcomer region.

The break flow rate decreased rapidly after the break opening, reached a plateau with a short duration, and then decreased again in the experiment as shown in Figure 12. A hybrid break flow rate has been obtained by combining the RCS inventory-based data with the load cell-based data at a time of 364 s in order to provide reliable data for the break flow. Most calculations showed the trends of subcooled liquid choking, saturated two-phase choking, and single-phase steam choking. The accumulated total break flow is shown in Figure 13. The predictions by KAERI and KEPRI, UNIP, KOPEC, GP2, and VTT were excellent. However, CIAE, KNF and PSI showed a slightly lower prediction than the data, whereas KTH, NRC, AEKI, GP1, GP3, and GRS showed much a lower prediction than the data. In particular, a significantly lower prediction than the data was obtained by NRI.

Fig. 12. Measured Total Break Flow Rate Comparison

Fig. 13. Comparison of Accumulated Break Flow

Table 15 shows the brief summary of the break flow rate and the accumulated mass. The peak flow rate, the mean flow rate at the plateau, and the transition time from the two-phase to single-phase flow, and the accumulated masses at the transition time and at 1,600 s were compared with the experimental data. Comparison results showed that KAERI of Group A, KOPEC and UNIPi of Group B, GP2 of Group C, and VTT of Group D predicted both the break flow rate and the accumulated mass very accurately. Each code has different critical flow models. The reported critical flow models are listed in Table 15, including the discharge coefficient used to fit their simulation results to the experimental data. Also their prediction results were classified into “agreed,” “underestimated,” “slightly underestimated,” and “highly underestimated” as there

Table 15 Summary of the Break Flow Rate and Accumulated Mass

	Exp. (shifted time, sec)	Group A				Group B					Group C				Group D		
		KAERI	KEPRI	KTH	NRC	CIAE	KNF	KOPEC	PSI	Univ. of Pisa	AEKI	EDO Gid 1 (GP1)	EDO Gid 2 (GP2)	EDO Gid 3 (GP3)	GRS	NRI	VTT
Peak flow rate (kg/s)	5.79	7.05	7.23	4.86	6.03	7.00	7.12	6.77	7.64	5.61	6.80	5.34	5.22	7.13	7.98	7.21	7.04
Mean flow rate at the plateau (kg/s)	4.12	3.60	3.89	2.57	2.59	4.22	3.65	4.63	3.67	3.94	3.75	2.96	3.76	3.04	2.93	2.09	3.96
Transition end time (second)	195	206	197	240	209	185	193	160	192	198	165	210	232	194	231	NA	194
Mass at transition time (kg)	825.4	819.2	836.3	680.1	670.6	816.2	796.2	793.2	789	811.4	679	702	884	699.6	768.9	NA	826.2
Mass at 1,600 s (kg)	1393.8	1403.1	1331.7	1094.2	1160.3	NA	1316.5	1401.4	1280	1400.1	1194.2	1315.7	1410	1266.1	1237.2	798.8	1423.9
Critical flow model used	-	R-T ¹⁾	H-F ²⁾ Cd:0.85	Note ⁴⁾	Note ⁴⁾	H-F Cd:0.83	H-F Cd:0.85	H-F ³⁾ Cd:1.0	H-F ²⁾ Cd:0.82	H-F ³⁾ Cd:1.0	Note ⁵⁾	Modified CATH ARE model	Modified CATH ARE model	Modified CATH ARE model	CDR1 D with Cd:1.0	CDR1D with Cd:1.0	Moody model Cd:0.95
Simulation capability ⁶⁾	-	G	SU	U	U	U	SU	G	U	G	U	SU	G	U	U	HU	G

Note

¹⁾ Ransom-Trapp model (subcooled Cd= 0.9, two-phase Cd=1.2, superheated Cd=0.95)

²⁾ Henry-Fauske model

³⁾ Henry-Fauske model, piping from the break nozzle to the break valve was modeled

⁴⁾ Burnell model (subcooled), Ransom-Trapp model (two-phase), isentropic expansion (single-phase vapor)

⁵⁾ Gros d' Aillon correlation

⁶⁾ G: Good Prediction, U: Underestimation, SU: Slight Underestimation, HU: High Underestimation

Fig. 14. Maximum Envelope of the Measured PCTs of all Instrumented Heaters

isn't any "overestimated" results in Table 15. Through the (long) break nozzle with $L/D = 12$, fluid should have become near to be saturated at the tip of the nozzle even for the subcooled liquid at the nozzle inlet, which allowed a good critical flow rate calculation by the employed critical flow models. The Ransom-Trapp model, modified the CATHARE model, and the Moody model with a discharge coefficient of 0.95 were properly used to agree with the experimental data reasonably well by KAERI, EDO Gid2(GP2), and VTT, respectively. In case of GP2, the hydraulic resistance of the break nozzle was increased during the open calculation to correct the overestimation during the blind calculation. Also the Henry-Fauske model with a default discharge coefficient of 1.0 was properly used to agree with the experimental data reasonably well by both KOPEC and UNIPI. They simulated all the break lines from the break nozzle to the containment simulator. However, KEPRI, CIAE, KNF, and PSI used discharge coefficients of 0.82 ~ 0.85 and they underestimated the break flow rates considerably even though they used the same Henry-Fauske model. Also the other critical flow models used by KTH, NRC, AEKI, GP1, GP3, and NRI simulated the mean flow rates at the plateau lower than the experimental data.

6.2 Multi-Dimensional Heater Wall Surface Temperatures

The maximum envelope of the measured heater wall temperatures is shown in Figure 14 and it was found that the maximum PCT was 587.7 K in the peripheral region of the core (group 3). The heater rods in the quadrant where the broken DVI nozzle is located showed a higher temperature excursion than those in the other quadrants

as shown in Figure 15. Since a radial non-uniformity in the heater wall temperatures in the core was observed in the experiment, the 3-dimensional core modeling was used only by NRC with TRACE 5.0 Patch 2 among the participants. NRC modeled the core region with four Rings in a radial direction and the detailed information can be found in the final integration report [4]. The operating agency also performed an additional 3-dimensional simulation with MARS-3D as a counterpart calculation. In order to model the core region, the "MULTID" and "VESSEL" components were used in the MARS-3D and TRACE, respectively.

The observed heater wall surface temperature excursion was not reproduced in the MARS-3D calculation because the "MULTID" model was not so much accurate as the real geometry. On the other hand, the TRACE calculation by NRC predicted a temporary temperature excursion in the heater groups 2 and 3, which was the similar results found in the experiment. However, this multi-dimensional effect in the prediction of the surface temperature of the heater rods was somewhat different from that of the experiment. The TRACE calculation showed a temperature excursion in almost all azimuthal angles of the heater groups 2 and 3 as shown in Figure 16.

More investigation on multi-dimensional behavior in the core was done with the 3-D models by NRC and the operating agency. The main cause of the heater wall temperatures observed in the peripheral region of the core rather than in the center region might be due to non-uniform mass flux distribution in the core region. If the mass flux in the center region is higher than that in the side region, a temperature excursion can be observed in the side region first. Unfortunately, there is no local data

Fig. 15. Measured Heater wall Surface Temperatures at the 19th Elevation, $z=1517\text{ mm}$

Fig. 16. TRACE Prediction of the Heater wall Surface Temperature at the 20th Elevation, $z=1819\text{ mm}$

Fig. 17. TRACE Prediction of Total Mass Flux at the Top of the Heated Section, $z=1905\text{mm}$ Just after Break

about the mass flux distribution in the core to support this reason. However, as the NRC's 3-D calculation succeeded in capturing the temperature excursion in the side region, the NRC's computational results were further investigated by the help of NRC.

In the NRC's calculation, some asymmetries were obtained at the beginning of the problem, most notably in Ring 4. NRC concluded that this may be attributed to the inherent instability of the model. They also obtained that once the transient initiated, the flow in Ring 4 became negative. This was an interesting result and may have an impact on the results—other data from the calculation suggested that the water in the Ring 4 area completely vaporized first, followed by Ring 3, Ring 2, and then Ring 1.

A cross sectional mass flux distribution by the TRACE code at the time of the temperature excursion is shown in Figure 17. Compared with the initial distribution, a very low mass flux, very close to zero was obtained over the whole cross section when the maximum heater wall temperature was obtained at 383.5 s. The side core region showed a smaller mass flux than the center region, resulting in temperature excursion.

6.3 Multi-Dimensional Coolant Mixing in the Annular Downcomer

Multi-dimensional phenomena such as the Emergency Core Cooling (ECC) water mixing in the upper downcomer observed in the test were highlighted in terms of code prediction capability in the subsequent open phase. It was found that the code's prediction capability of the 3-D downcomer mixing phenomena was not satisfactory in most calculations even in the open phase as shown in Figure 18. During the ISP-50 test, cold ECC water was introduced by a SIP and three SITs at different times. The SIP injected ECC water into the downcomer annulus through the DVI nozzle opposite to the broken DVI nozzle and three SITs injected ECC water through the intact three DVI nozzles. At the time of SIP injection, the downcomer annulus was full of hot water and it was observed that the cold ECC water was well mixed with the hot inventory. However, this vigorous and instant mixing was not predicted appropriately by codes. In most calculations, the fluid temperature of the intact loop side annulus was much lower than that of the broken side annulus. That is, azimuthal temperature stratification was predicted even

Fig. 18. A Water Temperature Distribution in the Unfolded Downcomer Region:
(a) Experimental Data (b) Code Calculation by KAERI with MARS-1D

in lower downcomer regions. This incorrect prediction seems to be due to limitation of the one-dimensional code. It is suggested that the momentum flux in lateral direction needs to be improved for realistic simulation of the downcomer fluid mixing. Compared with other calculations, the NRC's calculation utilizing 3-dimensional modeling of the reactor pressure vessel showed a better predictability for the ECC mixing in the downcomer.

6.4 Non-Uniform Loop Seal Clearing

Reproduction of the asymmetric loop seal clearing behavior seemed to cause great difficulties for most participants. Acceptable reproduction of the loop seal clearing was not made in most calculations, particularly with respect to occurrence order and timing in four intermediate loops. Only three among sixteen calculations succeeded in predicting the same locations of the loop seal clearing to the test data. The location of the loop seal clearing and the number of cleared loop seals do not seem to be important from a viewpoint of safety. However, the timing of the 1st loop seal clearing is considered to be important as the loop seal clearing affects overall transient behavior.

7. CONCLUSION AND RECOMMENDATIONS

The ISP-50 is the first-ever international cooperative program focusing on the DVI line break LOCA as well as the direct vessel injection of ECC water whose configuration is different from those of many conventional PWRs. An integral effect data for a 50% DVI line break obtained from the ATLAS was used as a reference and nineteen organizations from 11 countries participated in the consecutive blind and open phase. Eight leading system-scale safety analysis codes with different code models were used in the ISP-50 and their prediction performances were evaluated against the data. The present ISP-50 gave a wide and very valuable outlook of the actual status of code performance in that various codes were tested against the same test data.

Great user effects were also found in this ISP-50 exercise especially in the blind phase. The user effects, in general, arise due to many reasons such as the ill-preparation of input caused by simple mistake, misunderstanding of the given boundary and initial condition(s), misunderstanding how to properly use the computer code, misunderstanding of the phenomena that appeared during the test scenario,

and misunderstanding of the models incorporated in the computer codes. Several computer codes with various nodalization methods were also used. Therefore, it was surely hard to define them quantitatively in the present phase, but great user effects resulting from the combination of the possible reasons were again found, confirming that user effect is still one of the major issues in connection with the system thermal-hydraulic code application. Careful modeling is recommended when the code input is prepared to analyze phenomena without relevant experimental data.

Following the BEMUSE Phase II procedure for evaluating the nodalization quality, the primary and the secondary inventories of the code models were compared with the measured geometric data as the inventories significantly affect the transient behavior. Compared with the primary inventory, the secondary inventory showed much larger errors. About 50% calculations fulfilled the global acceptability $Q_A < 1.0$ with an Acceptable Error (AE) of 5%.

In addition to the qualitative comparison of the selected major parameters and thermal-hydraulic phenomena, quantitative comparisons were performed using the Fast Fourier Transform Based Method (FFTBM) to compare the overall accuracy of the submitted calculations. Open calculations showed better prediction accuracy than the blind calculations in terms of average amplitude (AA) value. Average improvement for each time interval was 19%, 16%, and 12%, respectively. It has also been confirmed that the FFTBM is a useful method to quantify code prediction accuracy. Among the selected key parameters, the hot leg flow rate and the SIT flow rate were the most dominant parameters degrading the total prediction accuracy. Besides, as most participants experienced a difficulty in predicting the occurrence order and the timing of the loop seal clearing, the water level in the intermediate legs was not properly predicted. On the contrary, the prediction accuracy of the break flow rate was relatively good. It was due to the efforts of the participants to capture the measured flow rate and the primary pressure. As all the code groups showed the similar prediction capability, no concrete conclusions could be made in this ISP-50 exercise on the relative accuracy of a specific code or a code group.

NOMENCLATURE

AA	: Average Amplitude
AE	: Acceptable Errors
CEA	: Commissariat à l'Énergie Atomique
CIAE	: China Institute of Atomic Energy (China)
CSNI	: Committee on Safety of Nuclear Installations (OECD/NEA)
FFTBM	: Fast Fourier Transform Based Method
FORTUM	: Fortum Nuclear Services Ltd. (Finland)
Gidropress	: OKB Hidropress (Russia)
GRS	: Gesellschaft für Anlagen- und Reaktorsicherheit mbH (Germany)
HSE	: Health and Safety Executive (UK)

IAEA	: Japan Atomic Energy Agency
JNES	: Japan Nuclear Energy Safety Organization
KFKI/AEKI	: Atomic Energy Research Institute (Hungary)
KTH	: Royal Institute of Technology (Sweden)
NEA	: Nuclear Energy Agency (OECD)
NRC	: Nuclear Regulatory Commission (USA)
NRI	: Nuclear Research Institute (Czech Republic)
PRG	: Program Review Group
PIRT	: Phenomena Identification Ranking Tabulation
PSI	: Paul Scherrer Institute (Switzerland)
UNIFI	: University of Pisa (Italy)
VTT	: Technical Research Center (Finland)
WF	: Weighted Frequency
WGAMA	: Working Group on Analysis and Management of Accident (OECD)

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REFERENCES

- [1] W. P. Baek, C.-H. Song, B. J. Yun, T. S. Kwon, S. K. Moon and S. J. Lee, "KAERI Integral Effect Test Program and the ATLAS Design," *Nuclear Technology*, **152**, 183 (2005).
- [2] W. P. Baek and Y. S. Kim, "Accident Simulation ATLAS for APWRs," *Nuclear Engineering International*, **53**, 21 (2008).
- [3] EPRI, "EPRI Utility Requirement Documents for the Advanced Light Water Reactor (Chapter 5)," (1995).
- [4] K. Y. Choi, W. P. Baek, S. Cho, H.S. Park, K.H. Kang, Y.S. Kim and H. T. Kim, "OECD/NEA/CSNI International Standard Problem No. 50, Final Integration Report," Volume 1 ~3, NEA/CSNI/R(2012)6.
- [5] M. Ishii and I. Kataoka, "Similarity Analysis and Scaling Criteria for LWRs Under Single Phase and Two-Phase Natural Circulation," NUREG/CR-3267, ANL-83-32, Argonne National Laboratory (1983).
- [6] K.Y. Choi, Y. S. Kim, C.-H. Song, and W. P. Baek, "Major Achievements and Prospect of the ATLAS Integral Effect Tests," *Science and Technology of Nuclear Installations*, Volume 2012, Article ID 375070, doi:10.1155/2012/375070, (2012).
- [7] K. Y. Choi, H. S. Park, S. Cho, K. H. Kang, N. H. Choi, W. P. Baek, and Y. S. Kim, "Effects of Break Size on Direct Vessel Injection Line Break Accidents of the ATLAS," *Nuclear Technology*, **175**, 604, (2011).
- [8] K. H. Kang, S. K. Moon, H. S. Park, S. Cho, K.Y. Choi, B. J. Yun, T. S. Kwon, S. J. Yi, C. K. Park, B. D. Kim, Y. S. Kim, C.-H. Song, and W. P. Baek, "Detailed Description Report of ATLAS Facility and Instrumentation," KAERI/TR-4316/2011 (2011).
- [9] OECD/NEA, "Re-Analysis of the ISP-13 Exercise, Post Test Analysis of the LOFT L2-5 Test Calculation," BEMUSE

- PHASE II Report, NEA/CSNI/R(2006)2 (2005).
- [10] F. D'Auria, M. Leonardi, R. Pochard, "Methodology for the evaluation of thermal hydraulic codes accuracy," *Proc. Int. Conf. on New trends in Nuclear System Thermohydraulics*, Pisa, 467–477 (1994).
 - [11] A. Prosek, F. D'Auria, and B. Mavko, "Review of Quantitative Accuracy Assessments with Fast Fourier Transform Based Method (FFTBM)," *Nuclear Engineering and Design*, **217**, 179, (2002).
 - [12] R. F. Kunz, G. F. Kasmala, J. H. Mahaffy, C. J. Murray, "On the automated assessment of nuclear reactor systems code accuracy," *Nuclear Engineering and Design*, **211**, Issues 2-3, 245, (2002).
 - [13] B.D. Chung et al., "Phenomena Identification and Ranking Tabulation for APR1400 Direct Vessel Injection Line Break," *The 10th International Topical Meeting on Nuclear Reactor Thermal Hydraulics (NURETH-10)*, Seoul, Korea, October 5-9, (2003).