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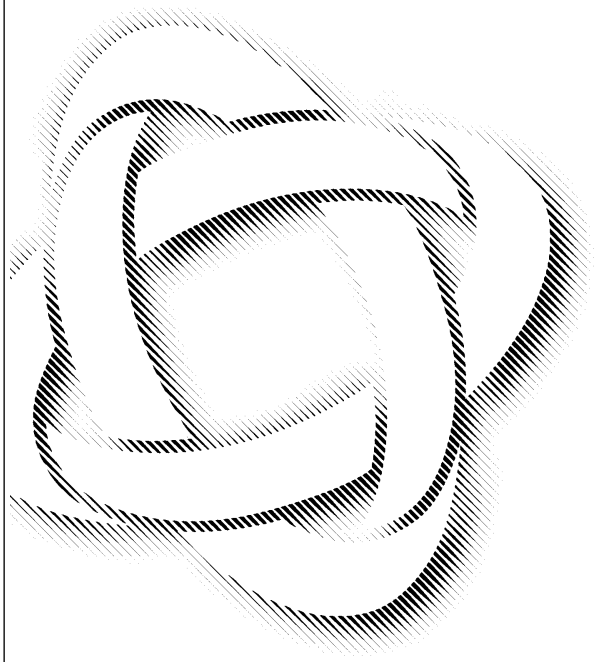
OECD

International Standard Problem (ISP) No. 43
Rapid Boron-Dilution Transient Tests for Code Verification



Comparison Report

OECD Nuclear Energy Agency
Le Seine Saint-Germain - 12, boulevard des Îles
F-92130 Issy-les-Moulineaux, France
Tél. +33 (0)1 45 24 82 00 - Fax +33 (0)1 45 24 11 10
Internet: http://www.nea.fr

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- to provide authoritative assessments and to forge common understandings on key issues, as input to government decisions on nuclear energy policy and to broader OECD policy analyses in areas such as energy and sustainable development.

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OECD/CSNI ISP Nr. 43

Rapid Boron-dilution Transient Tests for

Code Verification

NEA/CSNI/R(2000)22

November 4, 2000

Authors: Mirela Gavrilas, University of Maryland USA (mirela@eng.umd.edu)
Ken Kiger, University of Maryland USA (kkiger@eng.umd.edu)

Contributors: Bret Boman and Jim Smotrel, Framatech USA (bboman@framatech.com)
Chris Boyd US Nuclear Regulatory Commission USA CXB5@nrc.gov)
François de Crécy and Menant Bernard, CEA-Grenoble France (DECRECY@DTP.CEA.fr)
Chris Fry, AEA Technologies UK (chris.fry@aeat.co.uk)
Bengt Hemstorm, Vattenfall Sweden (Bengt.Hemstrom@utveckling.vattenfall.se)
Filippo Gavelli, University of Maryland USA (gavelli@eng.umd.edu)
Aaron Kneer and Manfred Schall, Battelle Germany (akn@battelle.de)
Tadashi Morii, NUPEC Japan (morii@rs01.spnet.nupec.or.jp)
Petr Muhlbauer, Czech Republic Nuclear Research Institute (muh@nri.cz)
Vesselin Palazov, University of Maryland USA (vpalazov@eng.umd.edu)
Martina Scheurer, GRS Germany (BAM@grs.de)
Timo Toppila and Peter Gango, Fortrum Engineering Finland (timo.toppila@ivo.fi)
Brian Woods, University of Maryland USA (bwoods@wam.umd.edu)

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Additional copies of this report or CD can be obtained from:
Jacques Royen
Nuclear Safety Division
OECD Nuclear Energy Agency
Le Seine - Saint Germain
12 Boulevard des Iles
F-92130 Issy-les-Moulineaux
France
E-mail: jacques.royen@oecd.org

Executive Summary

International Standard Problem No. 43 (ISP 43) addresses the nuclear industries present capabilities of simulating fluid dynamics aspects of a subset of rapid boron dilution transients. Specifically, the exercise focuses on the sequence involving the transport of a boron-dilute slug through the actuation of a pump. The slug is formed on the primary side of the steam generator as a consequence of in interfacing system leak from the secondary unborated coolant.

Experimental data was collected using the University of Maryland 2x4 Thermalhydraulic Loop (UM 2x4 Loop) and the Boron-mixing Visualization Facility. Two blind test series were proposed during the first workshop (October 1998) and refined using participant input. The first series, test series A, deals with the injection of a front, i.e., a single interface between borated and dilute fluids. The second blind series, test series B, is the more realistic injection of a slug, i.e., a dilute fluid volume preceded and followed by the borated coolant of the primary system.

Data are collected in the UM 2x4 Loop and refined details are obtained from the Visualization Facility, which represents a replica of the Loop's vessel downcomer. In the Loop experimental program, the dilute volume is simulated by cold water and the borated primary coolant is simulated by hot water. The Visualization Facility uses dye to mark the diluted front or slug. The measured boundary conditions for both test series include the initial temperature of the primary system, the front/slug injection flowrate and temperature, and the pressure drop across the core. Temperature data is collected at 185 thermocouple positions in the downcomer and 38 positions in the lower plenum. The advancement of the front/slug through the system is monitored at discrete horizontal levels that contain the thermocouples. The performance of codes is measured relative to a set of figures of merit. During the first workshop, the principal figure of merit was established to be the average temperature of the 24 channel-centered thermocouples at the downcomer outlet. The frequency of data acquisition for code predictions was set to 2 Hz, which corresponds to the acquisition frequency of the two experimental setups. The figures of merits were expanded at the second workshop (February 2000) after experimental and computational data was collected. The revised list of figures of merit included the level average temperatures before the downcomer expansion and just above the injection cold leg. No turbulence measurements were provided. Quantitative measures of azimuthal distribution were also added to the figures of merit list: standard deviations, minima and maxima at the aforementioned levels. Furthermore, since discrepancies in flow pattern are noticeable among the tests of series A, the flow patterns obtained experimentally and from computations at 4 distinct times during the transients, were also extracted. Data were reduced into a standard format that facilitates comparisons.

Ten organizations from eight countries participated in the exercise. All used computational fluid dynamics (CFD) codes to obtain predictions. Most participants used commercial software (Fluent, CFX) while some used independently developed codes (TRIO-U, PLASHY). The number of nodes used to discretize the simulation volume ranged over two orders of magnitude. The turbulence models ranged from no turbulence to renormalization group (RNG) k-epsilon. The spatial and temporal discretizations also

varied substantially. Overall, code predictions show good agreement with experimental data for first order figures of merit. Contrary to previous observations, flow patterns showed high sensitivity to buoyancy effects and the level to which temperature dependent properties and buoyancy-related turbulence effects were included in code models affected the predictions of higher order figures of merit. One more important factor needs to be considered in this discussion, namely the local refinement in regions where the flow is subject to large gradients or where flow patterns are rapidly changing. The importance of detail modeling is also evident from the comparisons of ISP 43. Specifically, where discrepancies are noted between computations and experimental data, the level 8 and level 10 predictions already reflect the disagreement. These levels are immediately adjacent to the injection site, where flow gradients are largest and flow pattern features actually form. The issue of local node refinement cannot be isolated from general mesh convergence and turbulence models, so it must also need to be investigated through parametric studies.

The most general finding of ISP 43 is that there is no reason to preclude the use of CFD codes from investigating prototype PWR boron-dilution transients and, more broadly, transients that involve single phase mixing. The good agreement between experiments and many of the computational predictions shows that computational fluid dynamics methods have reached the maturity necessary to obtain realistic predictions for averaged values. It is also evident that computational power and the expertise of modelers are at a stage at which it has become feasible to carry out some of the complex computations that describe the behavior of nuclear systems.

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1 Motivation and Background

Rapid boron-dilution (RBD) transients have been the subject of extensive investigation for more than a decade. Among the 13 groups of reactivity transients classified by the IAEA, nine are boron-dilution related. B-10, a large cross section neutron absorber, is a normal means of reactivity control in pressurized water reactors (PWRs) and in ex-reactor fuel storage locations (e.g., the refueling cavity). Furthermore, emergency safety systems are designed to decrease core reactivity under accident conditions by injecting borated water from emergency supplies (accumulators, refueling water storage tanks, etc.). The boration of water is accomplished by the addition of soluble boric acid (H_3BO_3).

RBD transients involve the sudden deboration of water at a location that is subject to a consequent reactivity excursion. Most studied are refueling cavities and reactor cores. For refueling cavities, NEA (August 1988) and INPO (August 1989) have reported precursor events. The refueling cavity RBD precursors are only listed for completeness, but are beyond the scope of this report.

UM focuses on RBD transients that can trigger core reactivity excursions. The sequences of events that potentially lead to such an excursion are discussed by Gavrilas et al. (1997) and summarized in Figure 1-1. The current test program involves the formation of a slug through ingress of deborated water into a stagnant section of the primary system, specifically accumulation in a steam generator (the sequence on the right-hand side of Figure 1-1). Five precursor occurrences that fall along this sequence are listed by Jacobsen (1989 and 1992). Another occurrence of deborated water accumulation in the primary system was documented in France's Blayais PWR. (INPO, 1990)

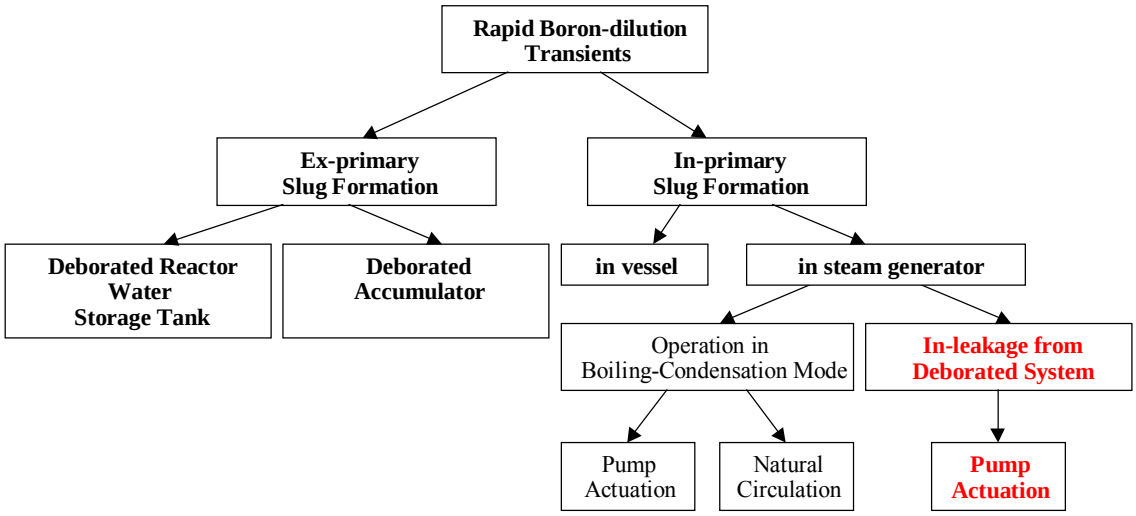

Figure 1-1. RBD transient event initiation and progression

The resolution of actual consequences of an RBD transient requires two separate steps: 1) determining the temporal and spatial concentration of boron at the core entrance, and 2)

carrying out coupled thermalhydraulics-neutronics calculations for the core region. The first step thus provides the initial and boundary conditions for the second step.

The UM program, and several others, are seeking to elucidate step 1. Work is progressing in three areas: scaling, experimental, and computational. Scaling has been approached by both experimental and computational groups. Significant experimental programs have been undertaken by BoraBora—France, Vattenfall—Sweden, Pactel—Finland, UPTF—Germany and UM 2x4 Loop—U.S.A. Computational efforts have paralleled experimental work in all these countries and have also been performed by institutions in England and Japan. In 1997, the Committee on the Safety of Nuclear Institutions within the Organization for Economic Cooperation and Development (OECD/CSNI) approved an experimental test program at the UM 2x4 Loop as international standard problem number 43 (ISP Nr. 43). ISP Nr. 43 verifies the ability of computational fluid dynamics (CFD) codes to properly predict the mixing experienced by a deborated (clean) slug from its initial stagnant position along its way to the core inlet.

1.1 RBD Test Program Objectives

The test series devised for ISP Nr. 43 has to simultaneously satisfy both experimental and computational experts. While the needs of the two groups can be rather distinct, the tests must preserve the principal physical characteristics of RBD transients to have benchmark value, and have to provide clean initial/boundary conditions and accurate data to permit the proper evaluation of code results.

From the point of view of verifying code predictions, the experiment has to contain the major geometric/operational features that would be encountered in the prototype. As can be seen in Figure 1-2, an expansion is designed into the downcomer to test a code's ability to deal with geometric discontinuities introduced by, for example, the presence of thermal shields. The modularity designed into the facility is conducive not only to reinstrumentation for different test programs but also to flow path selection for different test series within a program.

Code predictions and experimental data are only compared for the downcomer region. The lower plenum is included in the simulation boundary because of the physical significance of the actual boron concentration at core inlet. To get a reasonable flow pattern estimate in the lower plenum, a portion of the core must also be simulated. Specifically, one has to include core pressure drops in the model to make it possible for the code to simulate potential back-flow cells in the downcomer.

Four test series will be run in the course of ISP Nr. 43. The first is very simple and approaches a special effect type exercise, while the last involves all integral test facility features of the UM 2x4 Loop. In test series A, the "clean" water is injected from an external tank, which effectively simulates the injection of a front rather than a slug. The test has the advantage of eliminating back-end distortions from data interpretation—see Figure 1-3. All cold legs, except the one used for front injection (CL A1—see Figure 2-2), are isolated from the vessel. This limits the path of the fluid from the tank, through the cold leg and downcomer, up the core and out through hot leg A (HL A). The front is injected using the CL A1 primary coolant pump. In test series B, the slug is injected into the bottom of steam generator A from an external tank. The primary system is then

isolated, and the slug is set in motion by pump A1. The other cold legs remain isolated. The slug follows a closed path through CL A1, the downcomer, the lower plenum, the core, and returns to its initial position through HL A. Test series C and D remain to be performed. These two series increase test realism by permitting bypass flow to occur. In test series C, CL A2 will be allowed to participate. A fraction of the flow that enters through CL A1 will continue downwards through the downcomer along the path of test series B, while a lesser fraction will return directly to the steam generator (SG) through CL A2. In test series D, all cold legs will participate, and bypass will thus be possible in all non-injection cold legs.

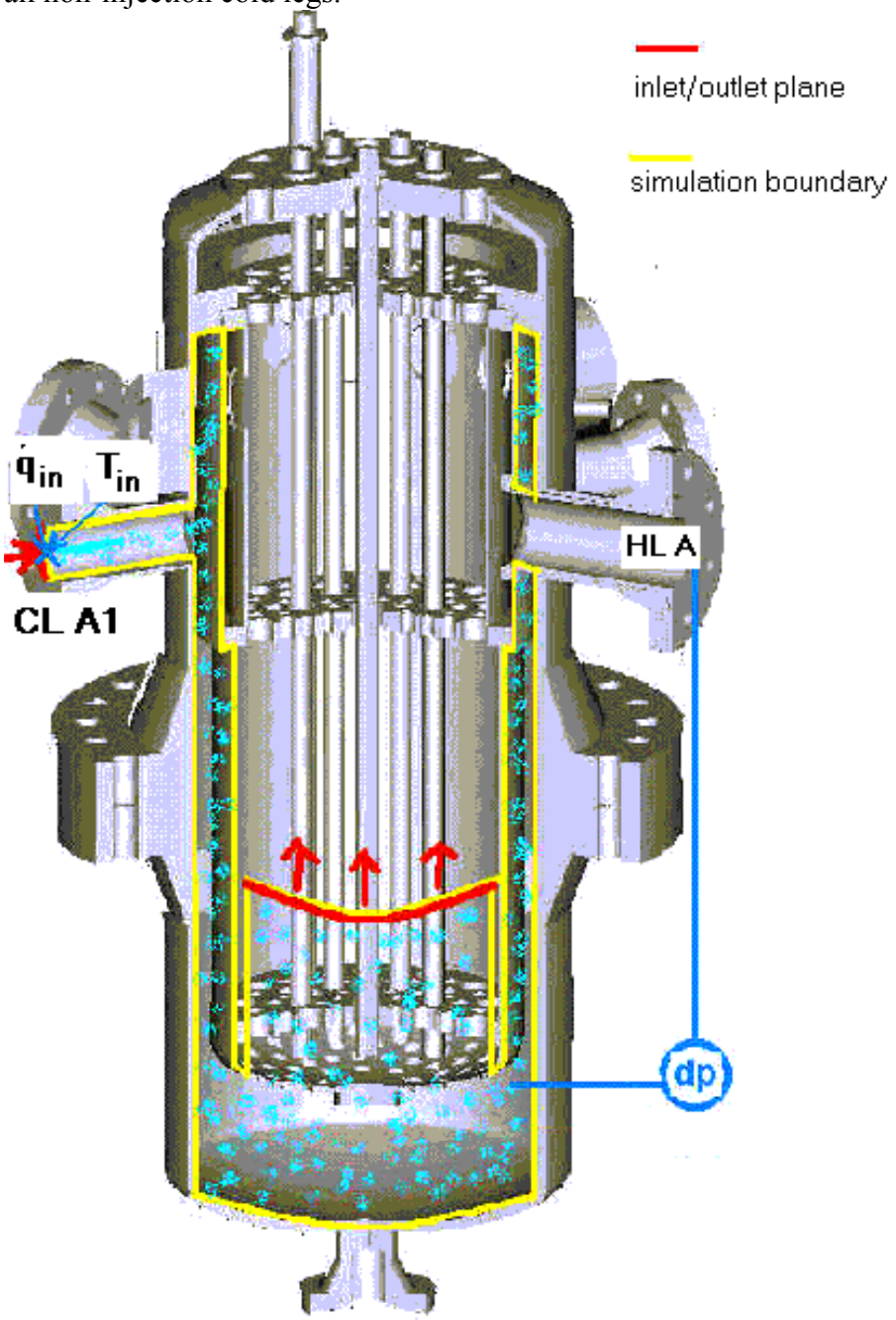

Figure 1-2. The recommended simulation boundary for ISP Nr. 43

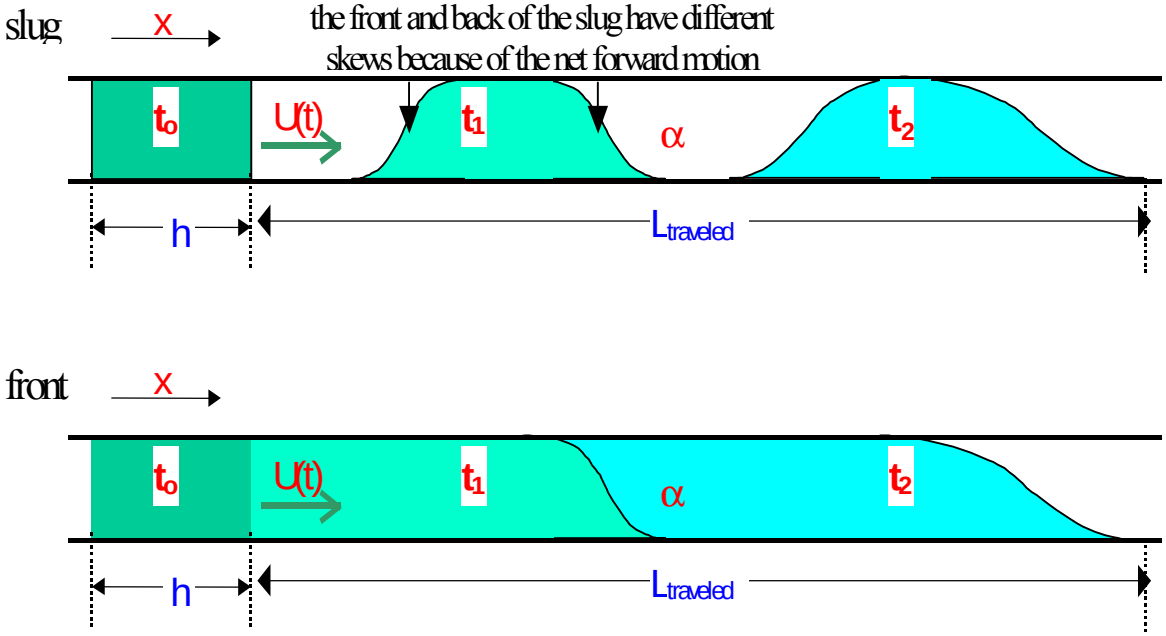

Figure 1-3. Illustration of slug/front deformation as it travels through a 1D channel.

2 Facility and Instrument Documentation

Data was acquired from the UM 2x4 Loop as well as a specially designed sister visualization facility. Both facilities, their measurement techniques, instrumentation and data reduction procedures are described in this section and the next.

2.1 Facilities

Two experimental facilities were used for ISP 43: the UM 2x4 Thermalhydraulic Facility, and its sister LIF Visulization Facility.

2.1.1 Loop Facility Description

The University of Maryland, College Park 2x4 Thermal-Hydraulic Loop Facility is a scaled down model of the Three Mile Island Unit 2 Babcock & Wilcox (B&W) pressurized water reactor (PWR). The main components of the model reactor coolant system (RCS) include a reactor vessel, two hot legs, two once-through steam generators (SGs), four cold legs, four reactor coolant pumps (RCPs), and one pressurizer. It is made of stainless steel, for a maximum pressure of 2.1 MPa (300 psi), which corresponds to a scaling pressure ratio of 1:7. The volumetric ratio between the model and the prototype is 1:508 and the height ratio is 1:4.

Important features of the facility are flexibility through its modular design, expandability with regard to instrumentation addition and replacement, and the possibility for direct flow observation through view ports. Figure 2-1 shows a 3D view of all major components except the pressurizer, which is irrelevant to the boron mixing investigation.

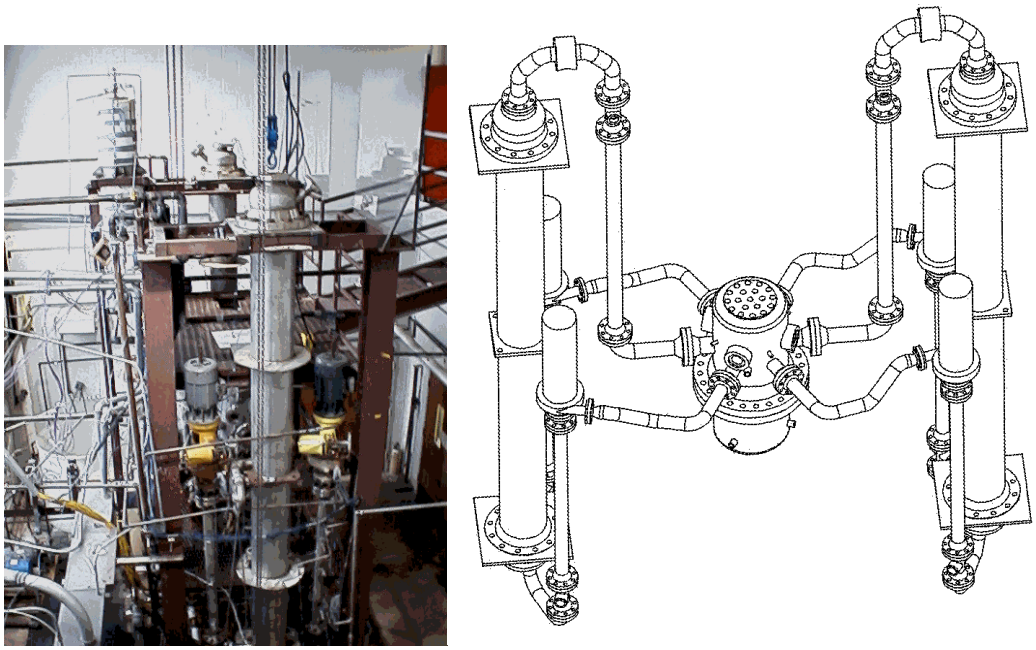

Figure 2-1. Photograph and schematic of the UM 2x4 B&W Loop Facility

A top view of the facility is shown in Figure 2-2 below. As shown, there are two main circulating loops and each loop includes one hot leg and two cold legs with one RCP in each cold leg. As illustrated in this figure, the facility components are distinguished according to the quadrant where they are located in the figure. The quadrants on the right hand side are labeled with the letter A and the quadrants on the left hand side are labeled with the letter B. In addition, a digit suffix makes the quadrant identification label unique with the suffix 1 for the quadrants in the lower part of Figure 2-2 and the suffix 2 for the quadrants in the upper part of the figure. Thus, the hot legs and SGs are labeled with A and B respectively and the cold legs and RCPs are labeled with A1, A2, B1, and B2 accordingly.

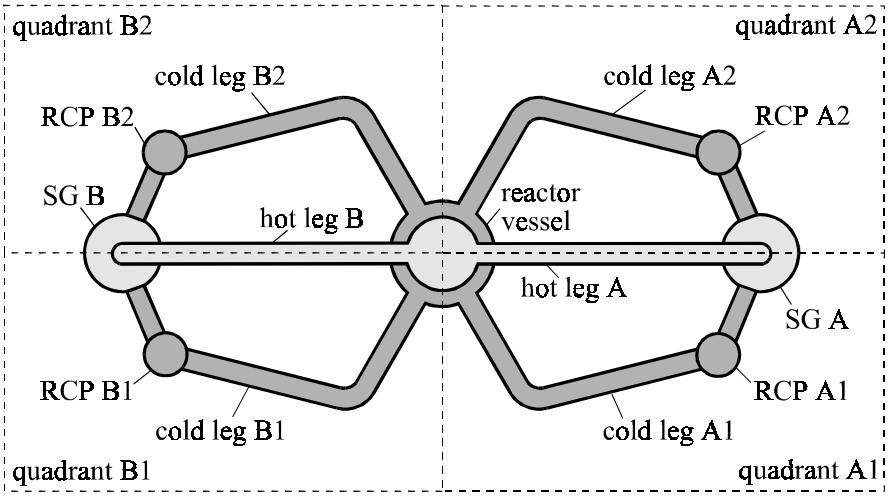

Figure 2-2. Identification scheme for the main RCS components

The main RCS model components are described in the following text along with modifications made for the purpose of the present investigation. Table 2-1 below gives the volumetric characteristics of the 2x4 Loop main system components in comparison with the prototype.

Table 2-1: Volumetric characteristics of the 2x4 loop facility

System Components	2x4 loop facility		TMI-2 Prototype		Volume fraction ratio (Model to Prototype)
	Volume (l)	Fraction	Volume (l)	Fraction	
Cold legs	77	0.129	41,000	0.136	1: 1.054
Downcomer	55	0.092	28,300	0.094	1: 1.022
Lower plenum	33	0.056	17,600	0.058	1: 1.036
Core	55	0.093	22,100	0.073	1: 0.785
Upper plenum	50	0.084	30,900	0.102	1: 1.214
Upper head	35	0.059	15,600	0.052	1: 0.881
Hot legs	57	0.096	27,000	0.089	1: 0.927
SGs	233	0.392	119,600	0.396	1: 1.010
Whole system volume ratio	***595***	***1***	***302,100***	***1***	***1: 508***

2.1.1.1 Reactor Vessel

The reactor vessel is made of stainless steel. It is 1.2764 m (50.25 in) in height and has an outside diameter of 0.5080 m (20 in). The inside diameter of the reactor vessel is 0.4826 m (19 in), for a wall thickness of 0.0127 m (0.5 in). The annular region between the vessel wall and the core barrel wall comprises the downcomer.

The core barrel is made of 304 stainless steel with a wall thickness of 0.0048 m (3/16 in). The outer diameter of the core barrel in its upper section is 0.4191 m (16.5 in) and the core barrel outer diameter in its lower section is 0.3810 m (15 in). Thus, the downcomer gap is equal to 0.0508 m (2 in) in its lower portion of the downcomer. In the upper portion, the downcomer gap is 0.0318 m (1.25 in). The wider area in the downcomer corresponds to the smaller diameter of the core barrel and is designed to increase the fractional volume of the downcomer in order to meet the prototypical value.

All vent valves (eight of them) originally installed in the core barrel above the hot leg penetrations were removed and the openings sealed for the purposes of the current investigation.

Welded to the reactor vessel at the same axial elevation are two neck flanges for the hot legs and four neck flanges for the cold legs. All flanges are made of stainless steel. Figure 2-3 below shows a scaled view of the reactor vessel.

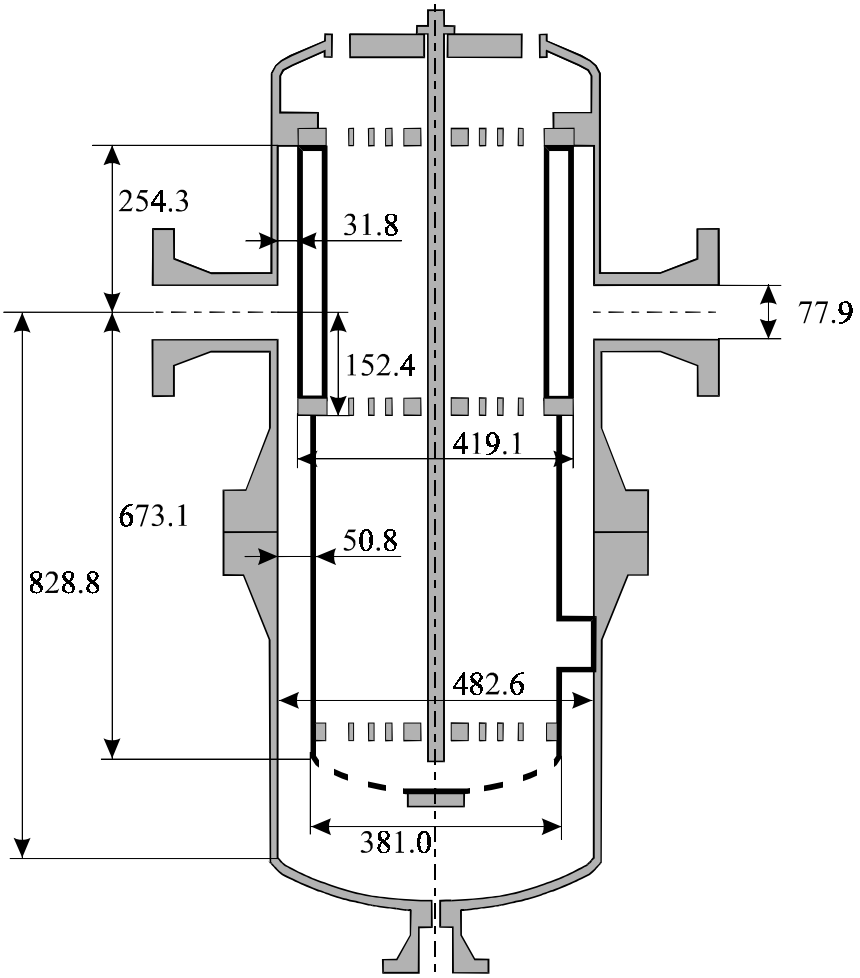

Figure 2-3. Vertical cross of reactor vessel section through the cold legs (dimensions in millimeters)

As seen from Figure 2-3, the fluid from the downcomer enters the lower reactor plenum. Through the perforated elliptic bottom of core barrel, the fluid can further penetrate into the core region from the reactor lower plenum. The reactor core structure itself was not simulated.

The mixing of the slug volume along its path towards the core is studied by distributed measurement of the fluid temperature in the downcomer volume. It is clear however that the slug temperature field, besides by mixing with the surrounding fluid of distinctive temperature, is also affected by heat transfer at the surrounding wall surfaces. Thus, direct heat exchange with the facility metal walls can also affect the slug temperature field. In turn, the walls are surrounded and exchange heat with the ambient air in the case of an external wall, such as the reactor vessel wall, or with fluid of different temperature in the case of an internal wall, such as the core barrel wall. In the latter case, heat is transported through the core barrel wall between the downcomer fluid flowing downwards and the fluid in the core region flowing upwards. Thermal insulation was used to minimize heat exchange through the facility walls.

The internal vessel wall surface and both surfaces of the core barrel, Figure 2-4, were coated with an insulating layer 0.8 mm thick. The cumulative effect of coating the barrel and vessel results in a 5 % gap reduction on the upper portion and 3 % on the lower portion of the downcomer, which fall within expected tolerances for the vessel. The coating material consisted of an epoxy (brand name Novolaq) mixed with evacuated ceramic micro-spheres in a volumetric ratio of 2:1. The thermal conductivity of the coating at room temperature was measured to be 0.90 W/(mK). This is more than one order of magnitude less than the conductivity of 304 stainless steal at room temperature, which is equal to 14.9 W/(mK). It was estimated that the coating reduced the effect of the wall heat transfer on the temperature of the fluid entering into the lower plenum from the downcomer to less than 10 %.

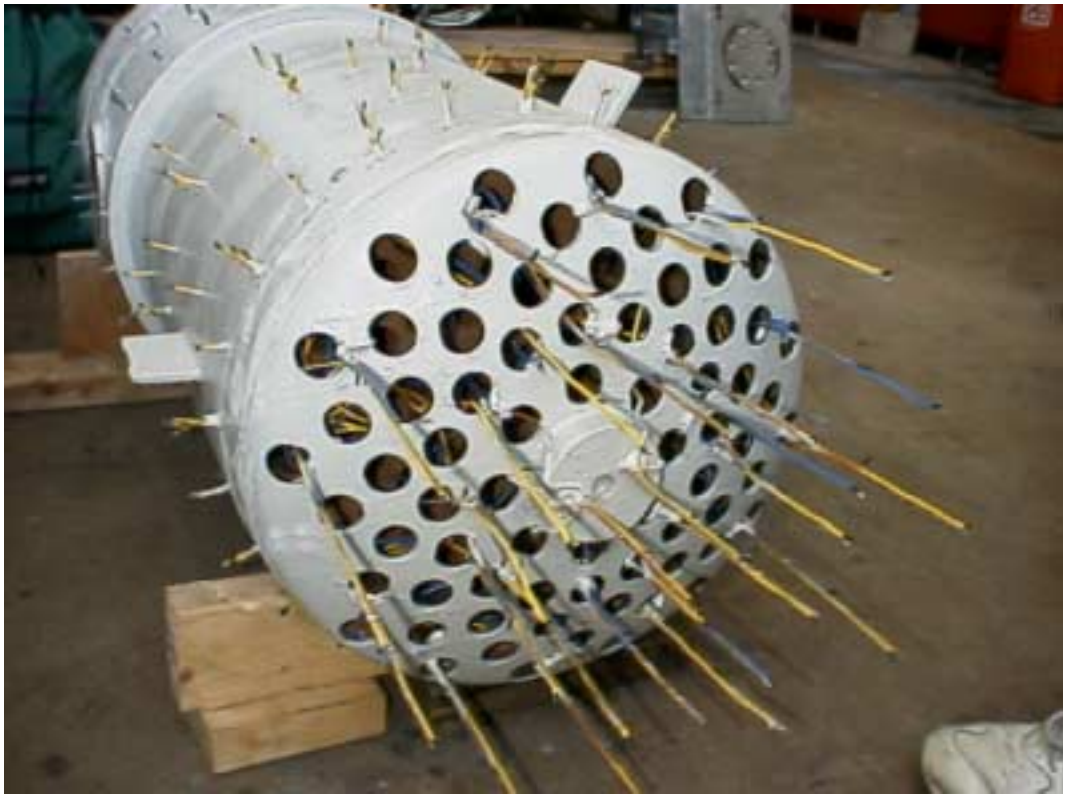

Figure 2-4. Photograph of the core barrel with the applied insulating coating

2.1.1.2 Hot Legs

The hot legs, shown in Figure 2-5 are made of 0.089 m (3.5 in) nominal diameter 304 stainless steel schedule 40S piping. The corresponding hot leg inside diameter is equal to 0.090 m (3.55 in). The hot legs have two view ports: one view port in the vertical section and one view port in the candy cane section. The design of the view ports is such as to minimize any dead water regions or flow disturbance. Both view ports for each hot leg are shown in Figure 2-1. One important feature of the system is the geometry of the hot leg portion, which is connected to the SG. The shape of this portion is like an inverted U and it is called a candy cane. It includes the highest elevation along the flow path between the core and the SG as seen from Figure 2-1.

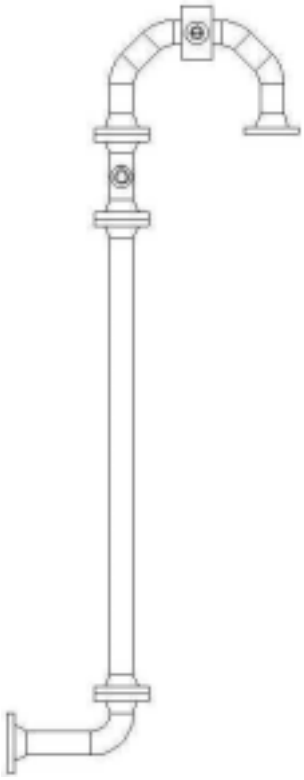

Figure 2-5. Hot leg schematic

2.1.1.3 Cold Legs

The cold legs, shown in Figure 2-6, are made of 0.0762 m (3.0 in) nominal diameter 304 stainless steel schedule 40S piping. The corresponding cold leg inside diameter is equal to 0.0779 m (3.068 in). One view port is located in the vertical section of each cold leg near the bottom of the SGs as shown in Figure 2-1.

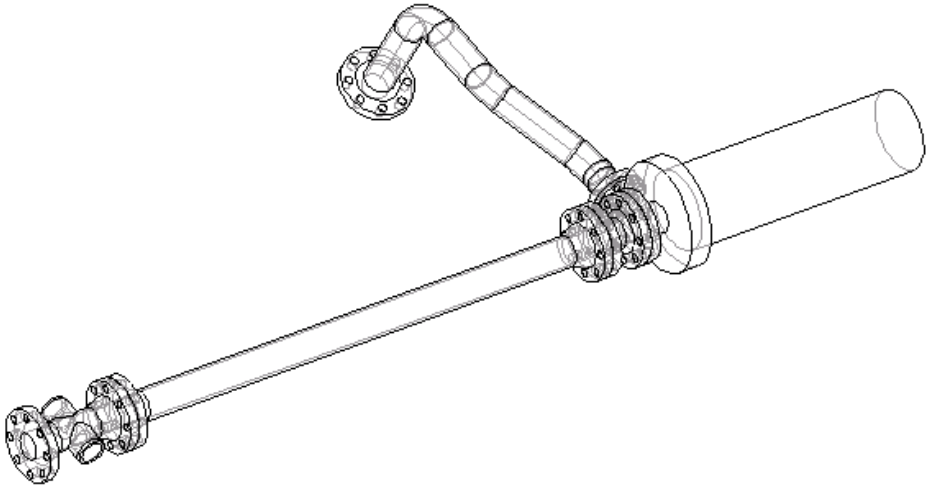

Figure 2-6. Cold leg and reactor coolant pump schematic

The liquid level in the cold leg riser, above that water from the vertical riser starts spilling over through the pump propeller into the horizontal section of the cold leg attached to the pump discharge is called loop elevation. Because of the lowered loop configuration, the loop seal elevation corresponds approximately to the middle height of the SG. Thus, the W-shaped volume including the portion of the SG primary volume below the loop seal elevation and the two attached cold leg risers is equal to approximately 82 liters, which represents 13.78% of the primary volume. This volume is available for slug accumulation prior to an RBD transient.

In the present study, pump A1 is activated to transport the slug towards the downcomer. The other three RCPs are always idle. Thus, water entering into the downcomer from clod leg A1 can either flow through the downcomer into the reactor core or bypass the downcomer and enter into the three cold legs with idle RCPs. When desired, the bypass flow through cold leg A2 and cold leg B2 can be individually blocked through the insertion of aluminum blanks between the flanges that attach the cold legs to the reactor vessel. The bypass flow through cold leg B1 can be blocked via a gate valve that is installed at the flange connecting the cold leg to the reactor vessel. Cold leg A1 is always open for flow.

In order to provide well-defined boundary conditions for numerical simulations and comparison with the loop data, cold leg A1 is constructed with a flow straightener, which consists of a honeycomb structure that occupies the entire flow area of the cold leg. Figure 2-7 shows a schematic of the flow straightener. The honeycomb is made of straws 15 cm long and 6 mm in diameter, and a thin mesh screen at the straw outlet side. The screen has 8 threads per cm and an open area of 41%. It is located about 18 cm upstream from the cold leg entrance into the downcomer and 5 cm downstream from the honeycomb end. The honeycomb was found effective in straightening the flow through the elimination of azimuthal velocity component. In addition, the axial velocity profile at the honeycomb outlet was found to be relatively flat upon the activation of the RCP using laser Doppler anemometry in the loop's sister boron-mixing optical vessel (B-MOV) visualization facility.

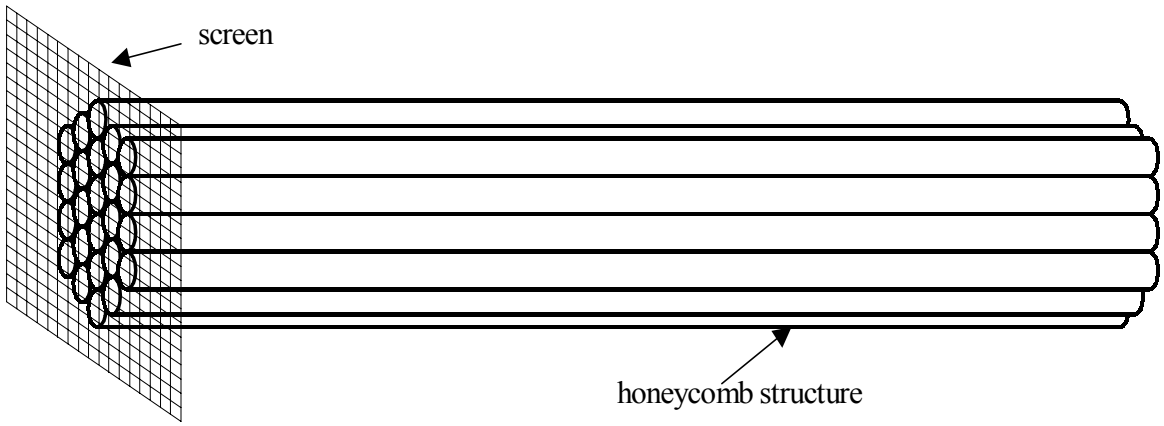

Figure 2-7. Flow straightener inserted in injection cold leg.

2.1.1.4 Steam Generators

The components of the two steam generators, Figure 2-8, are made of stainless steel. Each contains 28 straight stainless steel tubes located in an outer shell tube. The tubes are 3.9052 m (12 ft 9-3/4 in) long and have an inside diameter of 0.02997 m (1.18 in) and an outside diameter of 0.03175 m (1.25 in). The outer shell of the steam generator is of 0.3075 m (12 in) schedule 20 stainless steel pipe with an outside diameter of 0.32385 m (12.75 in) and a wall thickness of 0.00635 m (0.25 in). The primary coolant enters from the top and flows inside the straight tubes whereas the secondary water occupies the volume between the primary tubes and the outer shell tube. No secondary cooling was used for the current investigation and the steam generators secondary volume was dry.

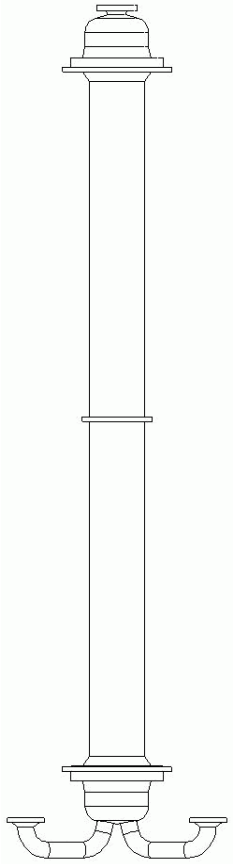

Figure 2-8. Steam generator schematic

2.1.1.5 Reactor Coolant Pumps

A centrifugal pump is installed at the top of each of the four cold leg risers as can be seen from Figure 2-1 and Figure 2-6. Each RCP is individually activated and an emergency trip can be used to shut down all active pumps. The steady-state pump speed can be set manually at any level of up to 1500 rpm to provide the desired pump volumetric flow rate up to about 10.3 l/s. As already mentioned, only RCP A1 was activated in the present study in order to transport the slug while the other pumps were kept idle. In addition, RCP B1 was used to circulate the primary system volume during the initial heat-up of the coolant to the desired temperature. The impellers of the idle three RCPs provide a

hydraulic resistance, which is important for realistic simulation of the core bypass flow through the corresponding cold legs during an RBD transient.

2.1.1.6 Power System

The UM 2x4 Loop facility is equipped with a power system capable of providing up to 115 kW of heat power. For this purpose, 19 cartridge heaters can be installed in the reactor vessel. The heaters are of two different types to allow for operation with an uncovered upper portion of the core. There are 9 low-power heaters, each of 3.0 kW capacity, designed to operate in both steam and water environment. There are also 10 high-power heaters, each of 8.8 kW capacity, which can operate properly only immersed in water. Both types are resistance heaters operating on delta connected three phase AC at 480 volts.

The high-power heaters are 0.0254 m (1 in) in diameter and 1.1430 m (44 in) in length. They have Incaloy sheathed cartridges with a heated lower section of 0.3556 m (14 in) and an unheated upper section of 0.6096 m (24 in). A nominal pipe thread male fitting at the top of each heater allows it to be directly attached to the pressure vessel upper head.

The low-power heaters are 0.0254 m (1 in) in diameter and 1.2954 (51 in) in length. They also have Incaloy sheathed cartridges with a heated lower section of 0.6096 (24 in) and an unheated upper section of 0.6604 (26 in).

Since both the high- and the low-power heaters begin at the lower core barrel plate, the heated section of the low-power 3.0 kW heaters extends 0.254 m (10 in) above that of the higher power 8.8 kW heaters. The longer length of the low-power heaters requires that each one be raised up from a flush attachment to the vessel upper head by using a 0.1524 m (6 in) piece of stainless steel pipe.

Each heater has an internal thermocouple (type K) and the temperatures from those thermocouples are displayed on the control monitor to verify proper functioning by the operator. The heating power is varied using silicon-controlled rectifiers under the control of the DAS (HP-3497). An automatic shutdown feature of the DAS cuts off the power supply if any of the heater thermocouples exceeds a preset threshold value (usually 400 ^{o}C).

The UM 2x4 Loop as redesigned for the boron-mixing tests was capable of providing 61.6 kW of power using 7 high-power cartridge heaters for maximum heat output. The other 12 heaters, including all low-power heaters, were removed to allow for thermocouple penetration into the downcomer. The heaters were divided into four banks for the purpose of power control with each bank being controlled by a silicon-controlled rectifier. The heaters in each bank were connected in series to the corresponding silicon controlled rectifier, which operates on a 4-20 mA current input signal provided by a voltage supplied by the DAS (HP-3497). In order to ensure operator control of the power input to the system, a calibration was performed over a range of input powers.

2.1.2 Visualization Facility Description

The visualization facility was constructed as a scaled replica of the UM 2x4 Loop facility as a special effect facility. The entire reactor vessel and most of the attached pipes are made of transparent plexiglas, as shown in Figure 2-9a. This allows the use of flow

visualization techniques, such as Particle Image Velocimetry (PIV) and Laser Induced Fluorescence (LIF), to perform high-resolution measurements of the flow field and mixing phenomena. These methods offer several advantages over the traditional measurement techniques (e.g., thermocouples, conductivity probes), since they are non-intrusive and can achieve a much higher spatial and temporal resolution. The facility is built to replicate the dimensions of the flow path (from the pump to the core inlet) of the 2x4 loop system (the relevant dimensions are listed in Table 2-2). As shown in Figure 2-9b, only the components necessary to model the slug flow path are reproduced: the pump suction volume (or loop seal volume), the injection cold leg with its reactor coolant pump, and the reactor vessel. Additional components include a controlled-resistance bypass flow leg, which simulates flow through the adjacent cold leg as required for the test C case, and a return flow path for the liquid leaving the reactor vessel (subsequently referred to as a return pipe).

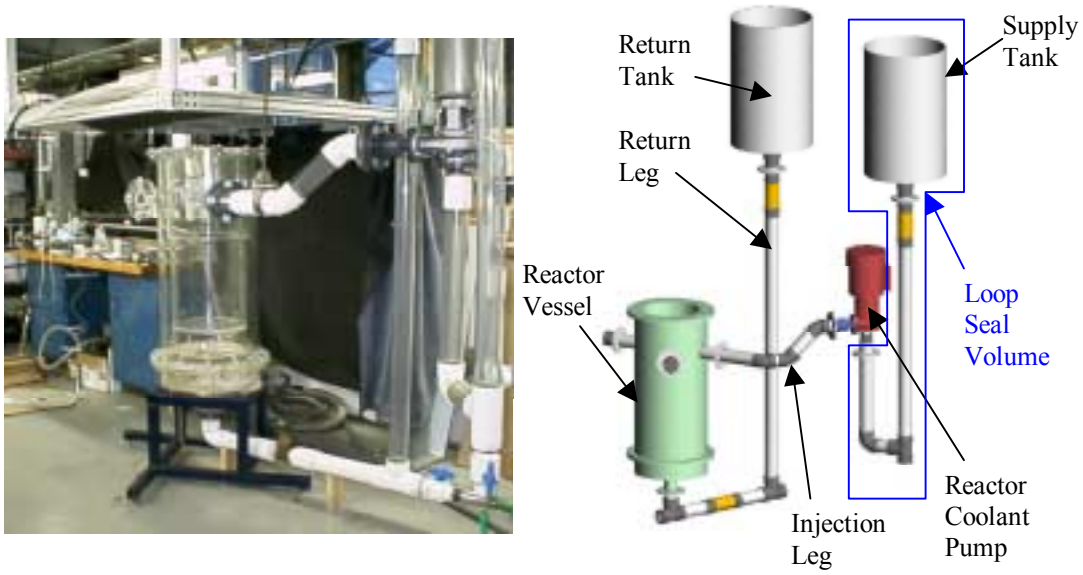

Figure 2-9. (a) photograph and (b) 3-D drawing of the BMOV

Table 2-2: Dimensions of the BMOV facility

Component	**Dimensions (cm)**
Vessel inner diameter	48.30
Downcomer gap thickness (above expansion)	3.18
Downcomer gap thickness (below expansion)	5.08
Cold leg diameter	7.79
Downcomer length (above CL centerline)	25.40
Downcomer length (below CL centerline)	71.12
Distance of gap expansion from CL centerline	15.24

Some modifications to the reactor vessel were also necessary in order to allow for the placement of the optical equipment.Figure 2-10 shows a comparison between the vessels of the BMOV and integral facilities. It can be observed that in the BMOV the 'core' region is not part of the flow path; instead, it is simply an air-filled volume open from above. Consequently, the flow of liquid entering the bottom of the core barrel has to be diverted and, as shown in the cross-sectional view, it leaves through a pipe from the bottom of the reactor vessel. The flow then proceeds along the controlled-resistance return leg and is collected in the return tank, shown in Figure 2-9b. The controlled-resistance leg allows adjustment of the pressure drop along the flow path to match the resistance of those components that are in the core of the integral facility. Also, in order to reproduce the obstruction of the downcomer flow path caused by the hot leg sleeves in the integral facility, two cylindrical inserts are placed in the BMOV downcomer gap.

The reactor coolant pump, which is responsible for the initiation of flow during the experiments, consists of a 3-hp centrifugal pump actuated by a controller coupled with a pulse width modulated inverter. This provides control capabilities over both the steady-state and transient pump characteristics, and is necessary to reproduce the boundary conditions observed in the integral facility.

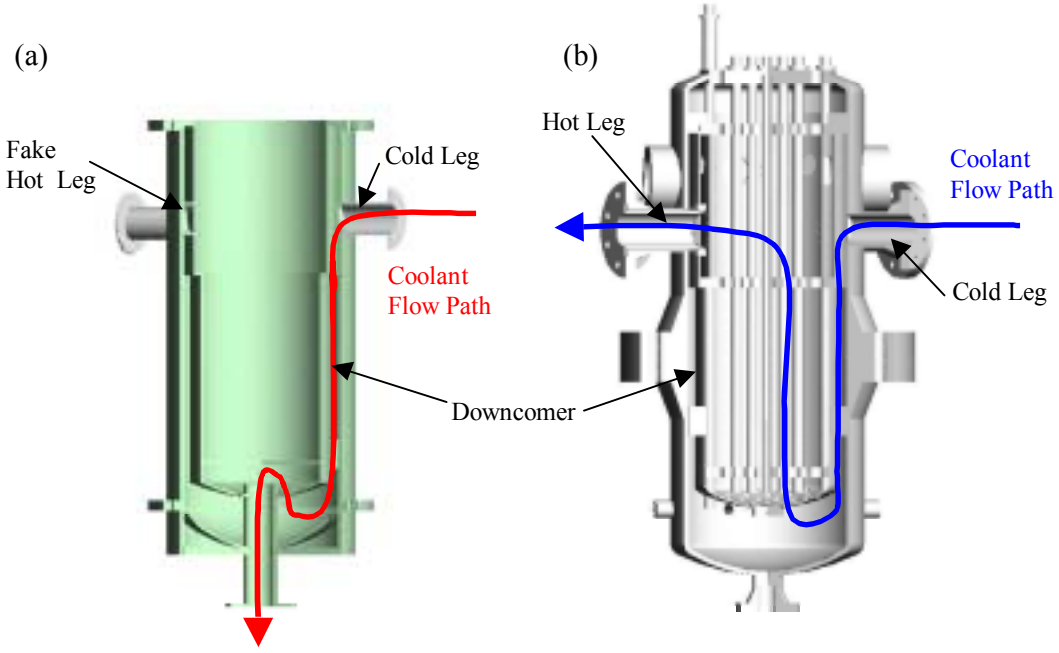

Figure 2-10. Cross-sectional view of the (a) BMOV and (b) integral vessels

The passage of the slug through the pump impeller volume was shown to have a relevant effect on the turbulent mixing of the slug along the discharge pipe (Gavelli, 1997). Preliminary experiments on the BMOV facility also indicate that the flow leaves the pump with a noticeable azimuthal velocity component. Due to the difficulty in trying to quantify this swirling effect, both the 2x4 loop and the BMOV are constructed with a honeycomb structure inside the injection cold leg, with the purpose of straightening the flow and reducing the pump-induced turbulence. The honeycomb is made of 15 cm long, 6 mm diameter straws and a thin mesh screen, placed about 17.8 cm before the

downcomer entrance, as shown in Figure 2-11. The radial streamwise velocity profile is shown in Figure 2-12 at various times during the development of the flow.

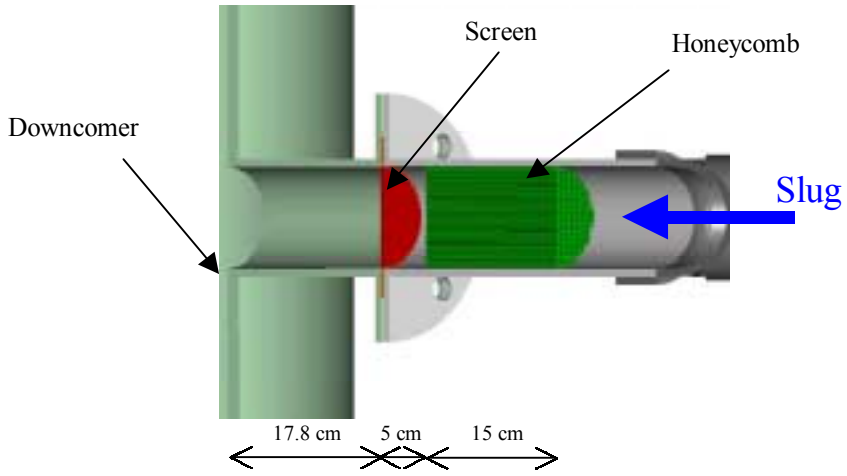

Figure 2-11. Honeycomb and screen position within cold leg inlet pipe

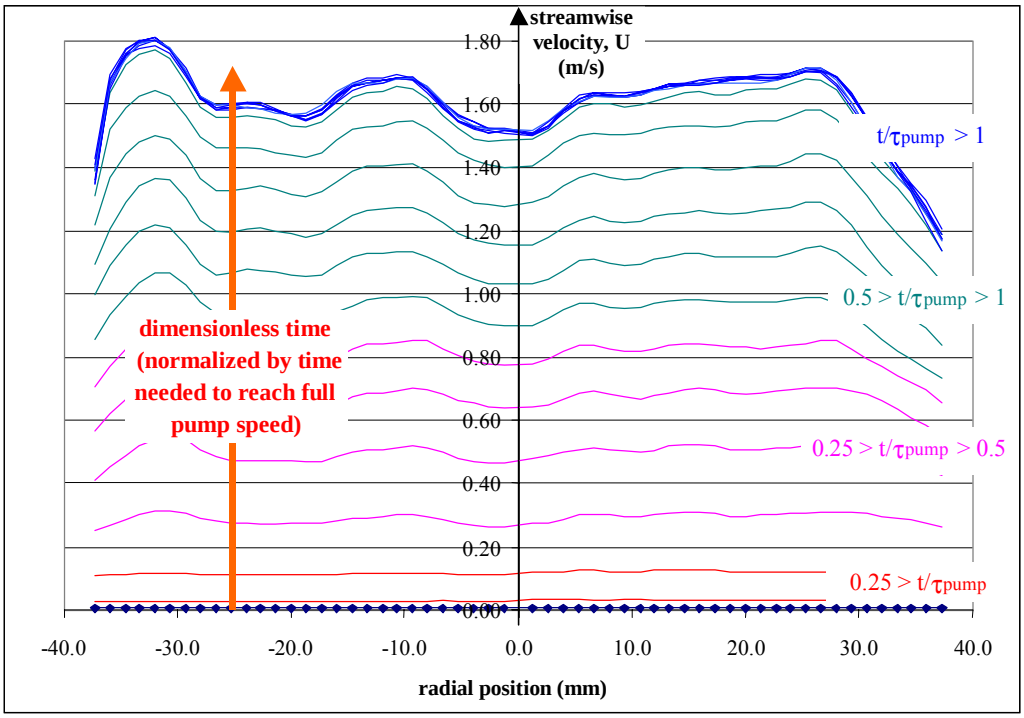

Figure 2-12. Mean streamwise velocity at the inlet of the simulation boundary for various flow rates

2.2 Instrumentation

2.2.1 Loop Instrumentation and Data Acquisition

The phenomenon of fluid mixing is simulated in the test facility through mixing of water volumes of different temperatures. The degree of fluid mixing is reflected by the fluid temperature, which is measured by thermocouples (TCs) mounted steadily in the vessel

downcomer, lower plenum, and cold legs. In addition, differential pressures and volumetric flow rates are also measured.

2.2.1.1 Control System

The HP-3497 DAS has provisions for a total of six DC output signals to be used for automatic system control. The DAS can control three systems: pressurizer heaters, makeup water supply and core power heaters. For the current test series, the DAS system controls only the core power heaters. The average phased resistance of each core heater has been determined. These resistance values are combined with measured phase voltages to provide a calibration curve to be used by the DAS control system. A desired power is supplied by the control room via the DAS computer. The calibration curve determines the necessary DC output voltage to be fed to the SCR control banks of the core heaters. Each of the core heaters has an installed K-type thermocouple. If this thermocouple surpasses a preset temperature, power will be deactivated. (Gavrilas et al., 1996, p. 103-104)

2.2.1.2 Power Measurement

The UMCP facility is capable of providing 115 kW of power using nineteen cartridge heaters. Two types of heaters are used to allow for the uncovering of a portion of the core without severe consequences. There are nine 3 kW heaters designed to operate in either a gas or a liquid. There are ten 8.8 kW heaters that must be immersed in liquid in order to operate. Both types are 3 phase, 480 volts AC, delta connected, resistance heaters. Heater power is controlled using silicon controlled rectifiers (SCR) under the control of the DAS (HP-3497).

The 8.8 kW heaters are 2.54 cm (1 inch diameter), 114.3 cm (44 inches) long, Incoloy sheathed cartridges with a heated length of 35.56 cm (14 inches) below and unheated length of 60.96 cm (24 inches). An internal type K thermocouple in each heater is used to determine heater temperature so that burnout can be avoided. The heaters must be covered by water during operation. A nominal pipe thread (NPT) male fitting at the top of the heater allows it to be directly attached to the pressure vessel's upper head.

The 3 kW heaters are 2.54 cm (1 inch) diameter, 129.54 (51 inches) long, Incoloy sheathed cartridges with a heated length of 60.96 (24 inches) below and unheated length of 66.04 (26 inches). An internal type J thermocouple in each heater is used to determine heater temperature so that burnout can be avoided. The longer length of these heaters requires that the heater be raised up from a flush attachment to the upper head by using a 15.24 cm (6 inch) piece of stainless steel pipe. Both the high and the low power heaters begin at the lower core barrel plate. Therefore, the heated section of the 3 kW heaters extends 25.4 cm (10 inches) above that of the higher power heaters.

The UMCP facility redesigned for the boron-mixing tests is capable of providing 61.6 kW of power using seven cartridge heaters. Twelve heaters have been removed to allow for thermocouple penetration into the downcomer. Each of the seven in the boron-mixing tests is an 8.8 kW heater. Using the high-power heaters allows for the greatest power input range (0-61.6 kW).

The heaters have been divided into four banks for the purpose of power control. Each bank is controlled by a silicon controlled rectifier (SCR). The heaters in each bank are

connected in series to the SCR. There are five banks available, however, only four are being used for this series of tests.

The power is generated by applying 3 phase AC voltage to the heaters. The maximum voltage is 480 volts per phase. The voltage necessary to energize the heaters is provided by four power controllers. Each controller is an SCR which operates on a 4-20 mA current input signal provided by a voltage supplied by the DAS (HP-3497). Based upon the input current, the power demand, the SCR supplies part or all of the AC voltage cycle. At lower power, the SCR provides a small portion of the sinusoidal cycle and thus the RMS voltage is in greater error than at higher power. The improved accuracy at high power comes from the fact that, as more of the input AC cycle is used, the output cycle better approximates a sine curve.

To determine the power, the resistance of each leg of the heater is measured. Power is then based on the AC voltage applied to each phase of the heater by the SCR. The AC voltage is supplied by the SCR and is converted to an equivalent DC voltage with AC-DC converter chips. The AC-DC converter chips are connected to each phase of the SCR. Therefore, a more accurate measure of the AC voltage is available. The function of the AC-DC converter chips is to measure the true RMS voltage of each phase. There are two SCRs that are connected. Each chip has been calibrated and the signal from it is stored during the tests. The average voltage per bank (average voltage of 3 phases) is evaluated and used for calculating the heater power. Heater power is calculated by:

$$P = \frac{3V^2}{R} \qquad \text{Equation 2-1}$$

where V is the average phase voltage across the heaters and R is the load resistance. The load resistance is determined by:

$$R_L = \frac{3}{2} R_M \qquad \text{Equation 2-2}$$

where R_L is the load resistance and R_M is the average of the three phase measured resistances.

In order to ensure operator control of the power input to the system, a calibration has been performed over a range of input powers. The control signal from the DAS to the SCRs has been fit over a range of power inputs. (Gavrilas et al., 1996, p.104-106)

2.2.1.3 Temperature Measurement

The TCs used in the present study are made by Omega Engineering, Inc. and are of types K and T. The thermocouple (TC) characteristics are presented in Table 2-3.

Previous experiments at UM and elsewhere have shown that the slug mixing occurs predominantly in the downcomer. To trace the temperature field there, altogether 286 TCs are mounted in the downcomer and the lower plenum of the reactor vessel on 11 horizontal planes labeled Level 1 through Level 11. Level 1 denotes the lowest plane and Level 11 denotes the uppermost plane. The vertical location of all levels is measured from the axis of the cold leg nozzles and is given with positive numbers for levels below

the cold leg nozzle axis and with positive numbers for levels above the reference point as shown in Figure 2-13 below.

Table 2-3: Thermocouple characteristics

ANSI Code	Alloy Combination		Range (°C)	Error Limits (whichever is greater)	
	+ Lead	- Lead		Above 0 °C	Below 0 °C
K	Chromega© (Ni-Cr)	Alomega© (Ni-Al)	-200 to 1,250	2.2 °C or 0.75%	2.2 °C or 2.0%
T	Copper	Constantan (Cu-Ni)	-200 to 350	1.0 °C or 0.75%	1.0 °C or 1.5%

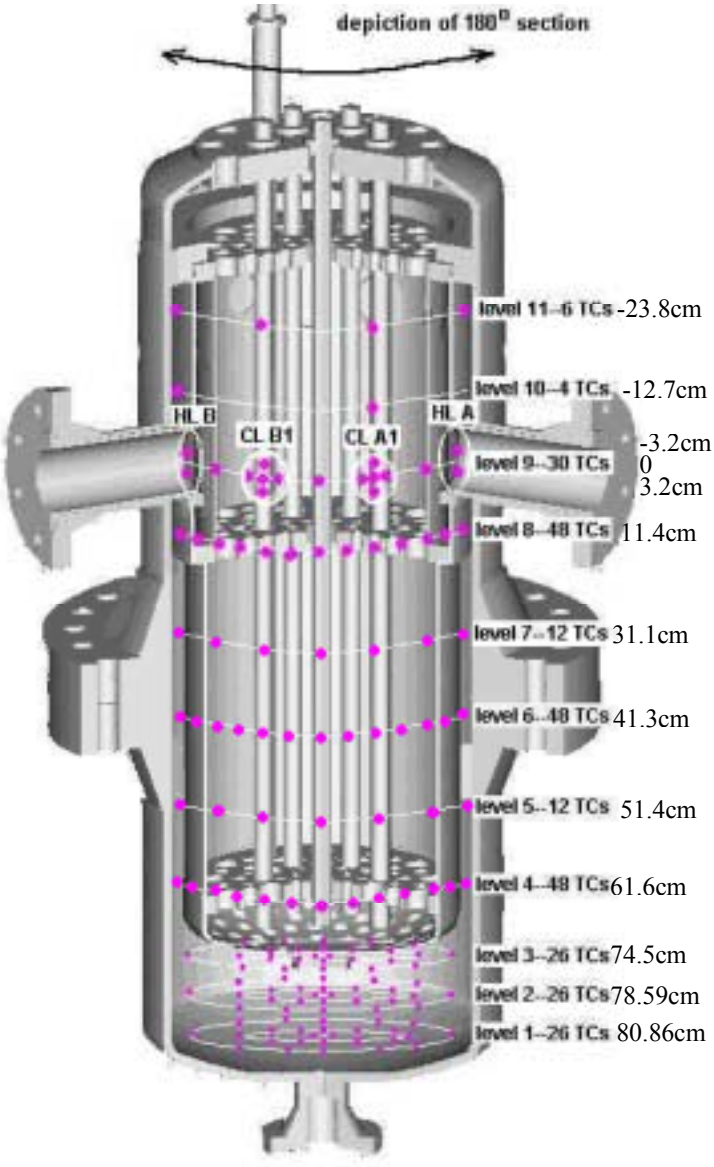

Figure 2-13. Thermocouple levels in the reactor downcomer and lower plenum

Levels 1, 2, and 3 are located within the lower reactor plenum and each level contains 26 TCs. This makes 78 TCs for the whole volume of the lower plenum. For each level, the TCs are uniformly spaced along three concentric circles. There are 2 TCs on the innermost circle of 0.02 m radius, 12 TCs on the middle circle of 0.0825 m radius, and 12 TCs on the outer circle of 0.165 m radius. The center point of the circles is located on the axis of the rector vessel. Level 1 is located 0.8721 m below the cold leg nozzle axis and Level 2 is placed 0.8086 m below the reference point. The TCs for Level 3 are 0.745 m below the cold leg nozzle axis with the exception of the two TCs on the innermost circle that are located 0.7859 m below the reference point. There is no azimuthal angle displacement between the TC locations for all three levels and a top view of the TC positions is shown in Figure 2-14 below.

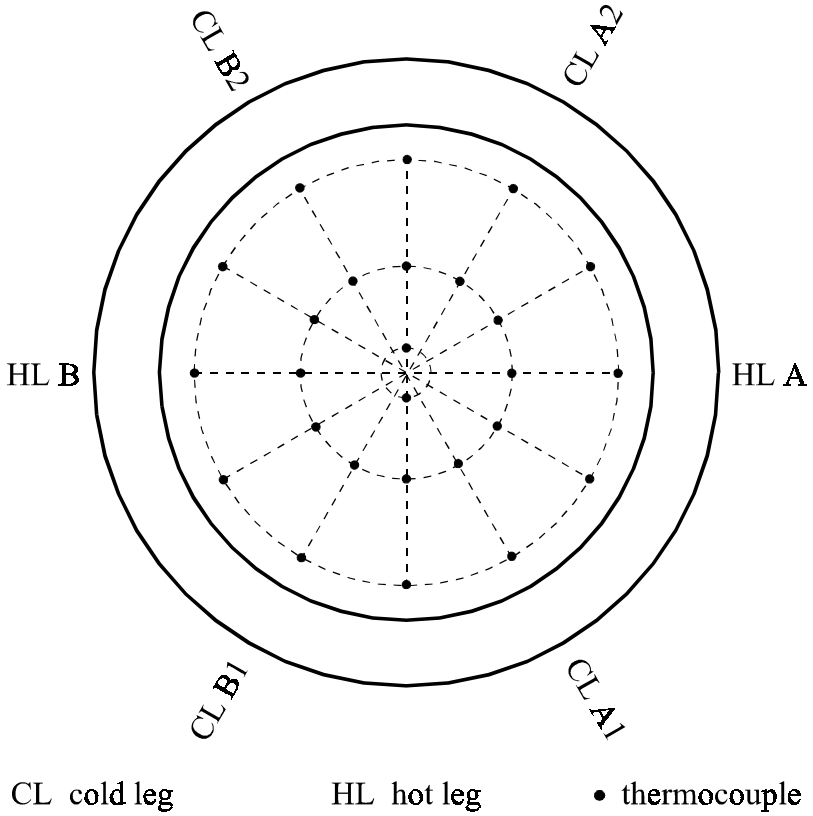

Figure 2-14. Thermocouple positioning in the lower plenum (Levels 1, 2, and 3)

Levels 4, 5, 6, and 7 are located in the lower portion of the downcomer, which has a larger gap flow area. The TCs on Level 4 are located 0.616 m below the cold leg nozzle axis. This level is at the downcomer outlet and therefore is heavily instrumented. The TCs are located at an azimuthal angle increment of 15^{o} at the middle of the annulus gap. At alternating azimuthal TC locations, the central TC is augmented by two more TCs located at different radial positions. The additional TCs are used to examine the radial variation of the slug temperature in the downcomer. The outer TC is located at a distance of 0.006 m from the vessel wall and the inner TC is at the same distance from the barrel wall. Thus, there are 12 inner TC, 24 TCs central TCs, and 12 outer TCs, which make 48 TCs altogether on this level. The TCs arrangement for Level 4 is illustrated in Figure 2-15.

Level 5 is located 0.514 m below the cold leg nozzle axis and contains 12 TCs located at the middle of the downcomer gap. The TCs are equally spaced along the downcomer perimeter. The arrangement for Level 5 is illustrated in Figure 2-15.

Level 6 is located 0.413 m below the cold leg nozzle axis and contains 48 TCs arranged as on Level 4. Level 7 is positioned 0.311 m below the cold leg nozzle axis and contains 12 TCs arranged as on Level 5. It is important to notice that Level 6 is located 7 expansion step heights downstream of the elevation of the expansion step and Level 7 is located 5 expansion step heights downstream the expansion step. This corresponds to the expected position for flow reattachment at 5 to 7 step heights downstream of the backward facing step (Heenan and Morrison, 1998). Figure 2-15 below illustrates the TC arrangement for Levels 6 and 7.

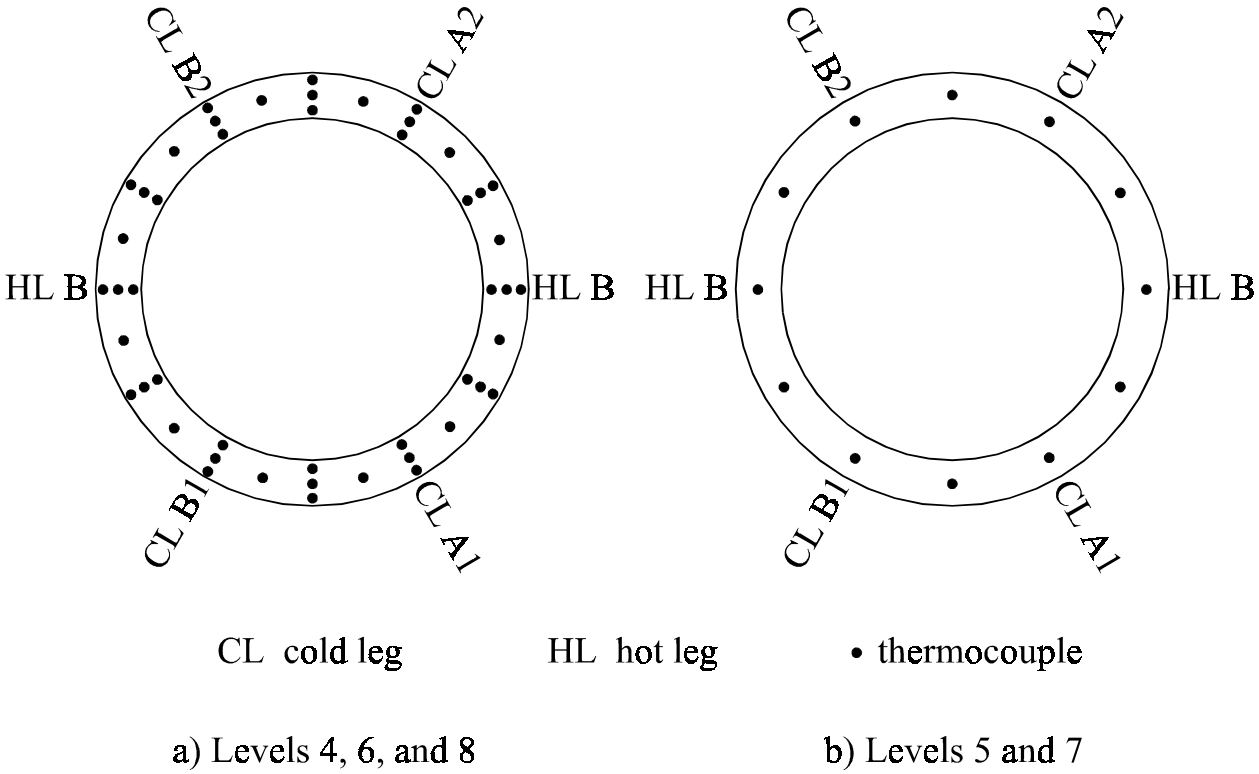

Figure 2-15. Thermocouple positions in the downcomer (Levels 4, 5, 6, 7, and 8)

All other levels are located within the upper part of the reactor downcomer, which has a smaller gap flow area. Level 8 is located 0.114 m below the cold leg nozzle axis and has 48 TCs arranged as on Level 4 as shown in Figure 2-15.

Level 9 is at the height of the cold and hot leg nozzles and it contains 30 TCs. There are 5 TCs positioned at the interface of each cold leg nozzle with the downcomer outer wall. One TC is at the axis of the cold leg nozzle and the other 4 are positioned at a distance of 0.032 m from that axis along the cold leg nozzle vertical and horizontal diameter. In addition, 6 TCs on Level 9 are positioned in the downcomer between the adjacent leg nozzles at the middle of the gap. The last 4 TCs measure the temperature in the upper

plenum at the inlet points to both hot leg nozzles. There are 2 TCs located at the inlet to each hot leg nozzle. Both TCs are positioned at a distance of 0.032 m from the hot leg axis along the vertical hot leg nozzle diameter. The distance between each of these TCs and the reactor vessel vertical axis is 0.241 m. The arrangement of Level 9 TCs is illustrated in Figure 2-16 below.

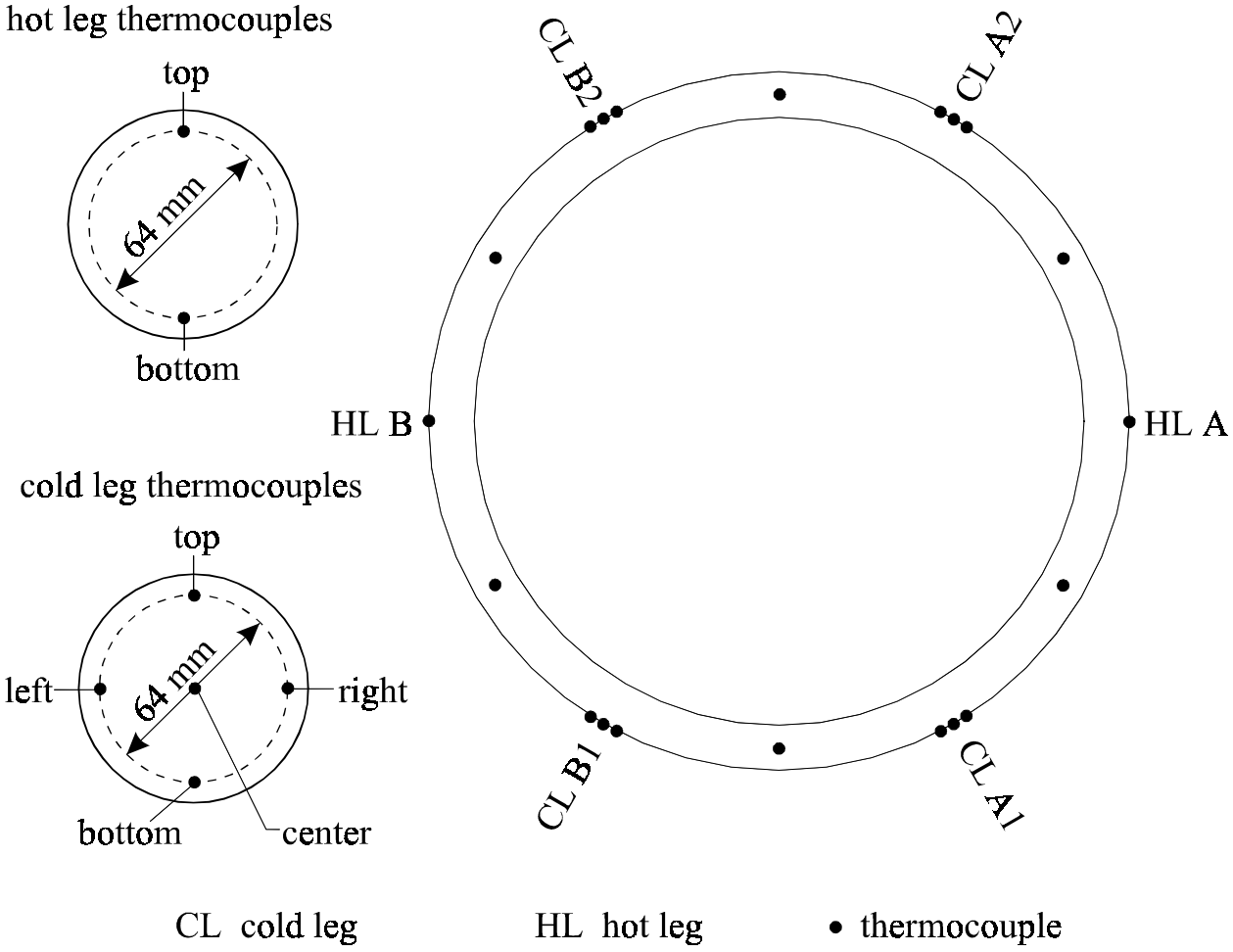

Figure 2-16. Thermocouple positions in the downcomer nozzle area (Level 9)

Levels 10 and 11 are located in the portion of the downcomer above the leg nozzles and they contain relatively few TCs. Level 10 is located 0.127 m above the leg nozzle axes and has 4 TCs. They are positioned at the middle of the downcomer gap at an azimuthal angle interval of 90^{o}. Level 11 is located 0.238 m above the cold leg nozzle axes and contains 6 TCs, which are also positioned at the middle of the downcomer gap. These TCs are positioned at an azimuthal angle interval of 60^{o}. Figure 2-17 below illustrates the positions of Level 10 and 11 TCs. Table 2-4 below summarizes the TC instrumentation for all levels in the 2x4 loop vessel.

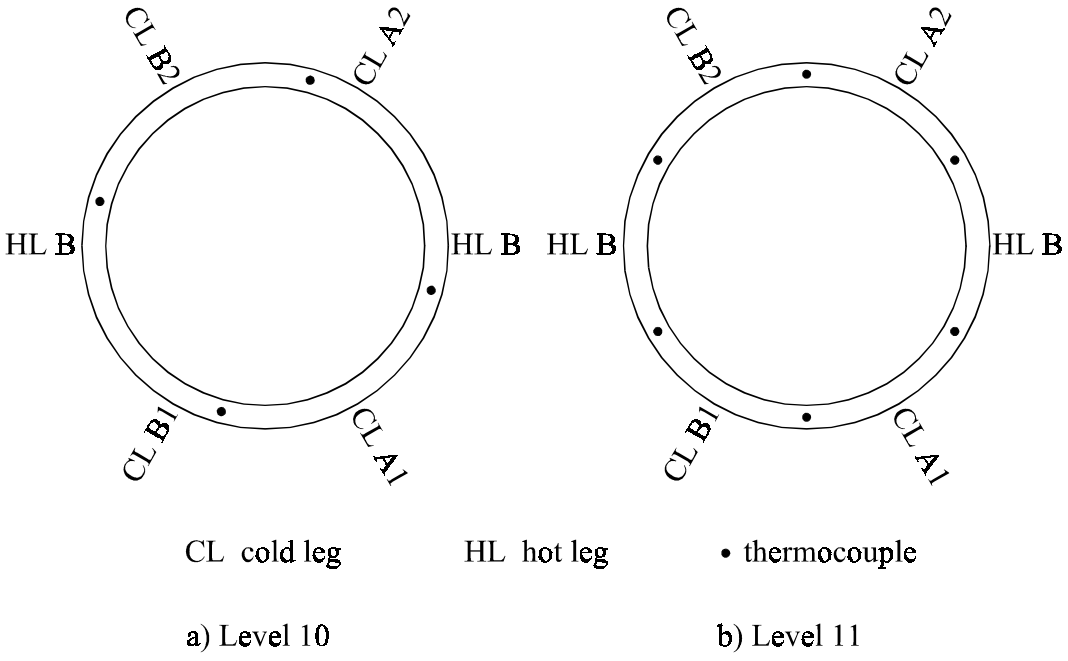

Figure 2-17. Thermocouples in the downcomer above nozzle area (Levels 10 and 11)

Table 2-4: Thermocouple instrumentation in the 2x4 loop vessel

Vessel Region	Level	Elevation (m)	TC Number	TC Type
Downcomer above nozzles	11	-0.2380	6	T
	10	-0.1270	4	T
Nozzle area	9	-0.0320 0 0.0320	6 18 6	K(20)/T(10)
Above step	8	0.1140	48	T
Downcomer below step	7	0.3110	12	K
	6	0.4130	48	K
	5	0.5140	12	K
	4	0.6160	48	K
Lower plenum	3	0.7450 0.7859	24 2	K(3)/T(23)
	2	0.8086	26	K(25)/T (1)
	1	0.8721	26	K

2.2.1.4 Flow Measurement

Two ultrasonic flowmeters—a TransPort™ Model PT868 device and a TransPort™ Model PT868-R both made by Panametrics, Inc—are used to measure the flow through the cold legs. This flowmeter uses the transit time flow measurement technique. In this method, two transducers are mounted to the exterior of the pipe at a fixed distance apart. Each transducer sends out a series of acoustic pulses that are received by the other transducer. The time interval from transmission to reception is measured in both directions. If the liquid is stagnant, then the upstream transit time is equal to the

downstream transit time. When the liquid is flowing, the downstream transit time is less than the upstream transit time. This method requires acoustically conductive single-phase fluids, which may contain traces of a second phase. Such fluids include most clean liquids and liquids with a small percentage of entrained gas (e.g., air) bubbles.

The flowmeters are powered by a dedicated wall outlet connection. The instruments can provide a standard 4-20 mA output signal or they can provide an outlet signal via an RS-232 cable to a dedicated laptop computer. Since the UMCP facility DAS can only record DC voltages, if the 4-20 mA signal is used, a 500 Ohm precision resistor is installed and the voltage drop across this resistor is measured and recorded by the DAS.

One flowmeter is dedicated to cold leg A1, through which the slug is transported into the downcomer. The second flowmeter is used to measure the bypass flow rate through any one of the other three cold legs if desirable.

The flowmeters are appropriate for measuring velocities from 0.03 m/s to 12.2 m/s. For a 3 inch Schedule 40S pipe used for the cold leg, this velocity range corresponds to a volumetric flow range of 0.14 l/s to 58.2 l/s. The observed flow rate stayed within this range, once the RCP had run for a few seconds. For clamp-on ultrasonic transducers (transducer number 30) mounted with a slide track fixture on the external pipe wall, the accuracy is given in Table 2-5 below. As seen from the table, for typical flow conditions encountered in the cold leg A1 of the UM 2x4 Loop facility during the RBD mixing experiments, the flowmeter accuracy was within 5%. It is important to mention that the specifications given require straight runs of 10 diameters upstream and 5 diameters downstream from the flowmeter itself. For this reason, the flowmeter transducers were mounted in the cold leg risers at a position dividing the straight vertical portion of the risers into two sections with a length ratio of 2:1. For cold leg A1 with upward flow in the riser, the flowmeter was closer to the pump suction. For the other cold legs, the flowmeter was closer to the bottom end of the riser due to the downward direction of the bypass flow.

Table 2-5: TransPort™ PT868/PT868-R flowmeter characteristics

Pipe Diameter	Typical Accuracy for Velocity Range		Repeatability
	0.03 m/s – 0.3 m/s	0.3 m/s – 12.2 m/s	
≤ 150 mm (6 in)	±0.05 m/s	2-5%	±(0.2–0.5%)
> 150 mm (6 in)	±0.01 m/s	2%	

2.2.1.5 Differential Pressure Measurement

Differential pressure (DP) across different points in the reactor vessel was measured with DP cell transmitters model 823DP-I made by the Foxboro Company. The transmitters included two different sensor types: low range and medium range sensors. The transmitter is an electronic instrument that measures continuously differential pressure and transmits this pressure as a proportional analog signal (in the mA range). The transmitter can be used for measuring DPs associated with flow, liquid level, or other type of applications. Depending on the jumper position of the transmitter, the range limits of the devices are given in Table 2-6 below.

Table 2-6: Measurement limits for Foxboro 823DP-I DP cell transmitters

Sensor	DP Range Limits		Repeatability
	KPa	mm H_2O (at 20 ^oC)	
Low range	0 – 7.2	762	±(0.2–0.5%)
Medium range	0 – 36	3,810	

The maximum inherent error due to the built-in resistor across the output-test terminals of the transmitter is ±0.1% of span. Care should be exercised that environmental influences on the transmitter and that of the calibrating equipment are minimized.

To mount the DP cells, six taps at different locations were used with four taps connected to the downcomer directly through the vessel wall, one tap connected to cold leg A1 and one tap connected to hot leg A.

The downcomer taps are located at two different elevations. Two upper taps are at the plane that contains the leg nozzle axes. Two lower taps are at a horizontal plane located 0.759 m below the leg nozzle axes, which corresponds to the lower plenum region. The cold leg tap is connected to the bottom of the horizontal portion of cold leg A1 close to the cold leg nozzle. The distance from the cold leg inlet to the downcomer and the tap port is 0.394 m. Thus, the honeycomb structure in the cold leg is located downstream from the cold leg tap. The hot leg tap is connected to the bottom of the horizontal portion of hot leg A close to the hot leg nozzle. The distance between the tap port and the reactor vessel inner wall is 0.346 m. The azimuthal positioning of the upper and lower downcomer taps as well as the connection scheme for all DP cells are shown in Figure 2-18 below.

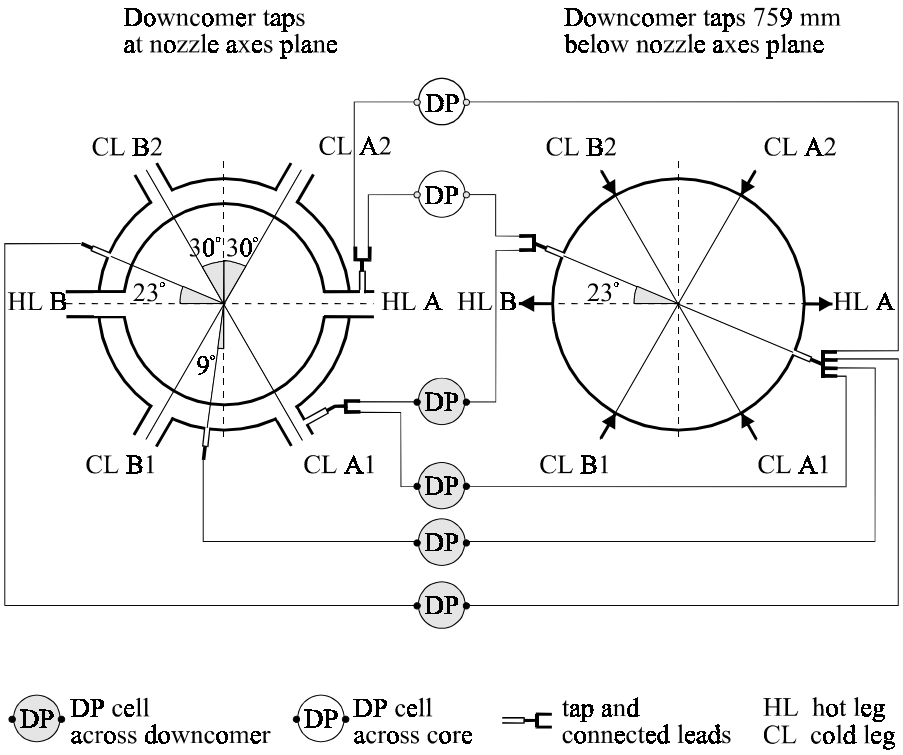

Figure 2-18. DP taps positioning and DP cells connection scheme

In addition, two ITT differential pressure transducers are employed in the slug injection series. These instruments provide water level information for the slug injection tank and the high-pressure injection (HPI) tank. A dedicated 30 DCV power supply provides excitation voltage to these DP transducers. These instruments are designed to provide a standard 4-20 mA output signal. However, a 500 Ohm precision resistor is installed in the same manner as with the flow measurement.

2.2.1.6 Data Acquisition System

The data acquisition system (DAS) for the UM 2x4 Loop employs two Hewlett Packard (HP) data acquisition units, HP-3497 and HP-3852. A personal computer with a Pentium 133 MHz processor communicates with both units and stores measured data from thermocouples, differential-pressure cells and flowmeters. A Hewlett Packard Interface Bus measurement coprocessor acts as the interface between the computer and the data acquisition units. This is a self-contained unit with a speed of 8 MHz. The user interface is done with HP Visual Engineering Environment (HPVee) software. The DAS also has provisions for control output signals, e.g., to control the core heating power.

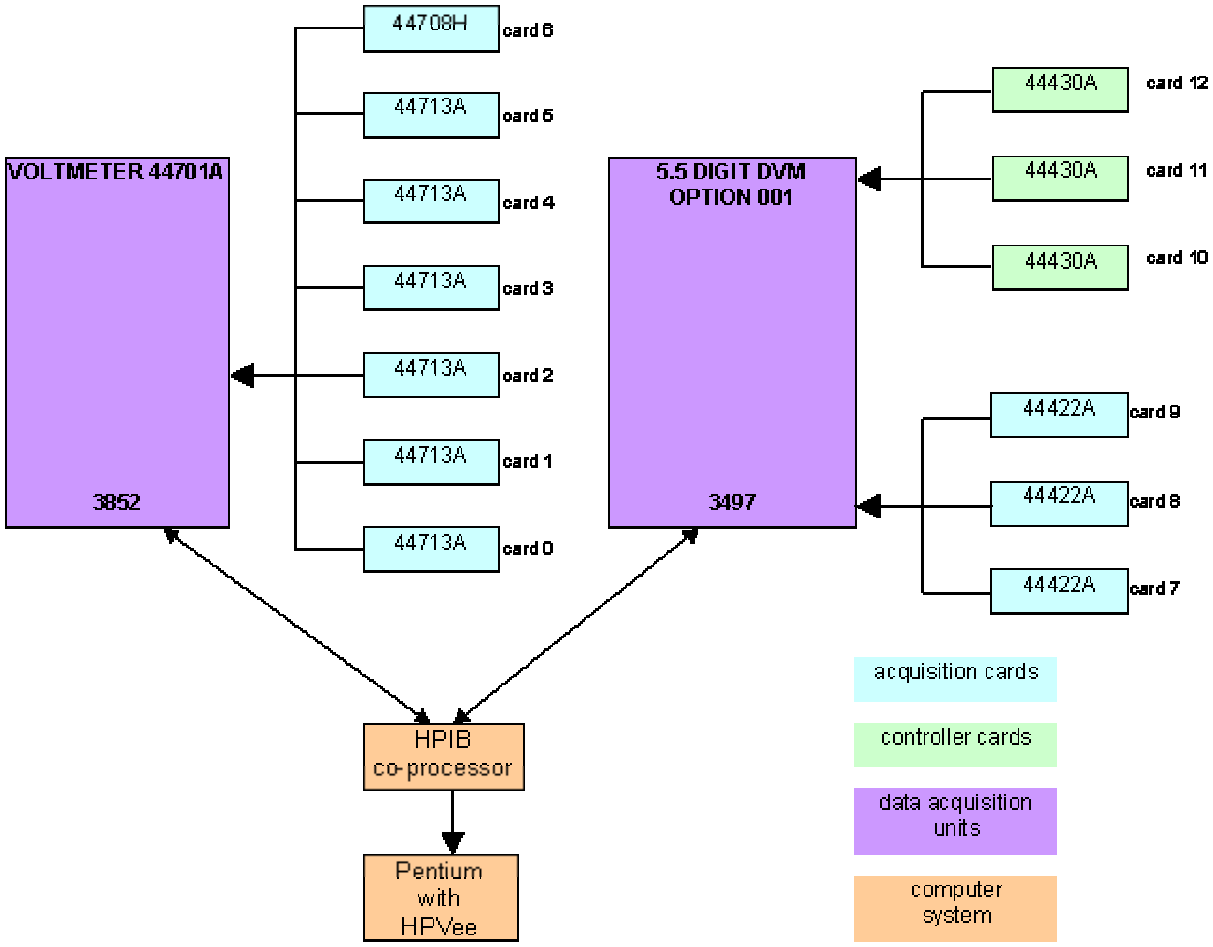

Figure 2-19. Diagram of DAS

The HP-3497 data acquisition unit is slower than the HP-3852 unit. HP-3497 allows for six output signals through six dual current controller cards of the type HP-44430A. For the present test program, only one output signal for the core heating power was used. The HP-3497 unit can be also used to measure direct current voltages from the system sensors such as DP cells and pressure transducers. For this purpose, it uses three HP-44422A acquisition cards each of 20 direct current channels.

The HP-3852 data acquisition unit uses an HP-44701A integrating voltmeter, which is equipped with six HP-44713A acquisition cards each of 24 direct current channels and one HP-44708H acquisition card with 20 input channels for higher voltages and currents. Thus, the unit can be used to multiplex through a maximum of 164 channels. The HP-3852 data acquisition unit has its own processor, which makes the unit faster than HP-3497, as already mentioned. HP-3852 was used to collect the temperature measurements from the TCs of both type K and T.

To increase the speed of data acquisition, both data acquisition units record the measured signals as direct current voltage signals. After each test run, a post-processing program converts the measured signals into the corresponding physical quantities. In this mode of operation, the HP-3852 unit at full load processes one set of TC readings for 0.404 s, which is on the order of the response time for the thermocouples used in the present study. The processing time consists of 0.024 s for measurement setup and additional 0.380 s for measurement and signal transfer. The HP-3852 can be also programmed to take temperature measurements directly, which, as already mentioned, is more time consuming.. As a whole, the DAS at its maximum capacity load of 172 channels worked with a data acquisition frequency of approximately 2 Hz.

2.2.2 Visualization Measurement Techniques and Calibration

Laser Induced Fluorescence (LIF) is a common technique used in experimental fluid mechanics to measure the concentration of a scalar species within a fluid, primarily applied to study the fundamental behavior of turbulent scalar transport in jets and mixing layers. The fundamental principle of quantitative LIF is that the fluorescent intensity given off by an illuminated volume of dyed fluid will be proportional to the number of dye molecules contained within that volume. When absorbing radiation of proper wavelength, some molecular species respond by emitting light through a very rapid process of electronic excitation and decay known as fluorescence (which usually takes less than 10^{-9} s). The fluorescence occurs when a molecule in an excited electronic state undergoes a nonradiative transition to an intermediate state before making the radiative transition to its ground state. This results in an emission spectrum that is shifted with respect to the spectrum of absorption, which is a fundamental characteristic of fluorescence. With the selection of dyes that exhibit a large separation between their absorption and fluorescence spectra and the use of the proper filters, the two radiations (incident and emitted) can be separated. Furthermore, for a fixed value of the incident radiation, it can be seen that the observed fluorescence intensity will be proportional to the number of molecules present within the illuminated region. In the BMOV facility, a 5-W multiline Argon-ion laser (which has emission peaks of 488 and 514.5 nm) is used as the excitation source, and Rhodamine-6G ($C_{28}H_{31}N_2O_3Cl$) is the fluorescent dye used to simulate the concentration of the boric acid. Rhodamine-6G was selected because its

absorption spectrum overlaps the emission of the Argon-ion laser while its emission spectrum has a peak at 560 nm, as listed inTable 2-7. Although the physical basis of the measurement is relatively simple, the difficulty in obtaining quantitative results is usually in ensuring that the illuminating intensity is constant (i.e. there is no significant absorption of the incident light as it propagates through the dyed volume). This is typically accomplished by controlling both the maximum concentration of the dye and the path length over which the illuminating beam has to travel before reaching the observation volume.

Table 2-7: Emission and absorption spectra for aqueous solution of Rhodamine-6G

	Wavelength		
	Lower	Upper	Peak
Emission	540	660	560
Absorption	460	560	530

LIF measurements are based on the fact that, under conditions of linearity, the fluorescent intensity of a volume of fluid, excited by a laser light, is proportional to the concentration of dye in that same volume. Thus, the average dye concentration in a liquid volume can be determined by measuring its light emission and comparing it with a proper calibration. Before discussing how this proportionality can be ensured, the setup of the optical equipment must be described.

When applied to the Boron dilution event in the downcomer of the PWR, a method needed to be developed to illuminate and view the downcomer volume with a high spatial resolution, while maintaining adequate temporal resolution and minimizing the illumination beam path within the dye. Since the downcomer is largely a thin annular volume, it made the most sense to have the illumination source projected radially outward from the centerline, and then scanned azimuthally with a sufficient rotation speed to satisfy the temporal resolution requirements.

The placement of the optical components is shown in Figure 2-20. The assembly is designed to direct the laser beam through the downcomer gap from inside the core region. In passing through the liquid in the gap, the laser excites the dissolved dye, inducing the desired fluorescence. The light emitted is then measured by a photomultiplier tube (PMT), which is focused on the excited volume composed of the entire beam path which resides in the liquid. Thus, the measurements represent the average dye concentration that is distributed over the length of the illuminated volume. The measurements constitute primarily a radial average, but at the top and bottom regions of the downcomer the beam will be angled approximately 25º with respect to the horizontal. This small distortion can be corrected through the proper transformations. In order to study the mixing occurring throughout the downcomer, the laser beam is swept over the annular volume in a raster-scan fashion: vertical sweeps are obtained by reflecting the beam off an octagonal rotating mirror, while an axial rotation about the z-axis is achieved by mounting the entire optical assembly on a motor-driven bearing. The optical carriage assembly rotates at 120 rpm and the octagonal mirror at approximately 6000 rpm. As a result, the

downcomer is scanned at a frequency of 2 Hz, with about 400 vertical sweeps per revolution.

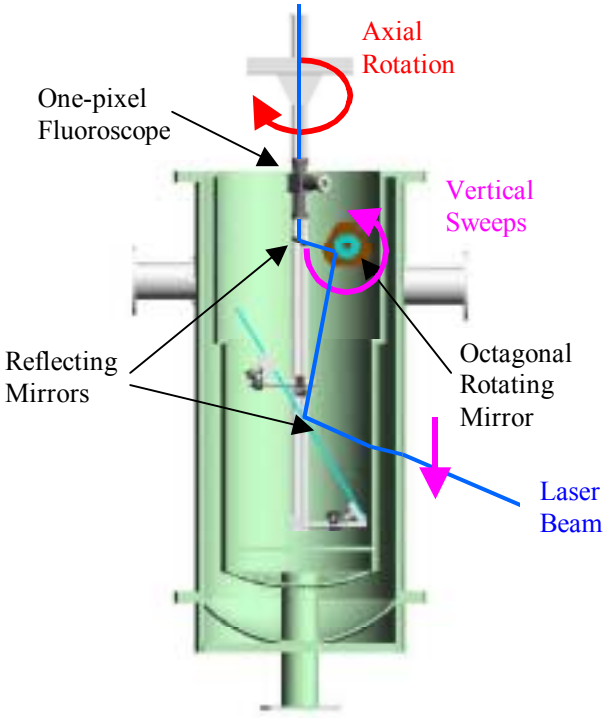

Figure 2-20. Optical instrumentation setup for LIF in BMOV facility

Figure 2-21 shows the coordinate system which will be utilized for the concentration measurements. To measure the fluorescence generated by the different regions of the downcomer, the PMT must be constantly aligned with the laser beam path. This is obtained through use of the 'one-pixel fluoroscope' shown in Figure 2-22. A short-pass filter ($\lambda < 600$ nm) is placed along the path of the laser, to allow only radiation in the absorption spectrum of Rhodamine-6G to reach the downcomer. A long-pass filter ($\lambda > 560$ nm) is placed along the optical path from the downcomer to the PMT; its purpose is to block out any light that may be elastically scattered by reflection from downcomer walls or suspended particles within the flow, so that only the fluorescence intensity of the dye is measured. The alignment of the PMT with the laser beam is maintained by the 45°-inclined half-silvered mirror, which allows about 50% of the incident radiation to pass through, while reflecting the other half, as indicated in Figure 2-22.

The PMT outputs an electrical current that is proportional to the intensity of the radiation reaching its sensor, which is subsequently converted to a voltage and amplified prior to sampling. The voltage is recorded by a 12-bit A/D card, which samples the data at a rate of 500 kHz. Combined with the raster scanning of the downcomer by the laser beam, the digitizing rate allows an angular sampling resolution of 0.24° (vertically) x 0.9° (azimuthally), which translates to a spatial resolution of about 0.3 cm x 0.3 cm within the optically accessible region.

As mentioned earlier, the dye concentration can be measured from the fluorescence intensity if the two are directly proportional to each other. This condition, however, is not trivially satisfied. Care must be exercised to ensure that the concentration of the dye is sufficient to produce measurable intensity, yet dilute enough to prevent nonlinear fluorescence effects. One of the most important considerations is the absorption of the laser light by the dye molecules as the illumination beam travels through the liquid volume. Since the fluorescent emission is directly proportional to the incident light intensity, the attenuation of the incident light inside the control volume causes a nonlinear response in fluorescence intensity. This effect can be negligible for low dye concentrations or small liquid regions, but it becomes more and more significant as either one increases.

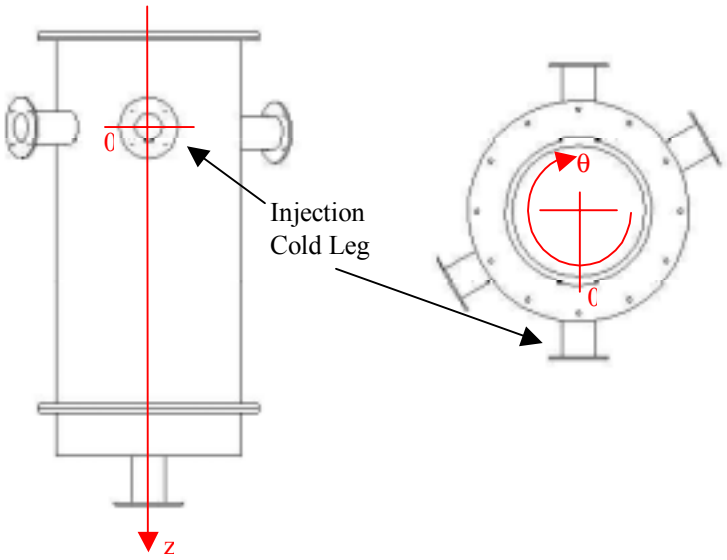

Figure 2-21. Coordinate system for concentration measurements

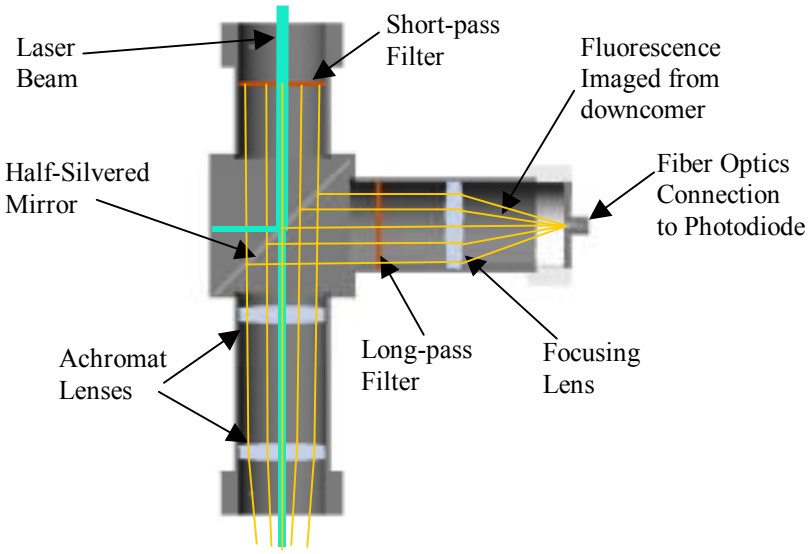

Figure 2-22. Schematic of the 'One-pixel fluoroscope'

To ensure a linear relationship between dye concentration and luminous emission, a set of calibration tests are performed. The optical equipment is aligned so that the laser beam sweeps a vertical section of the downcomer, passing through the centerline of the injection cold leg (no axial rotation of the assembly). The entire volume is filled with a well-mixed solution of known concentration, and a set of fluorescence measurements along the calibration section are sampled. Seven different concentrations are used, and the results are compared in Figure 2-23a.

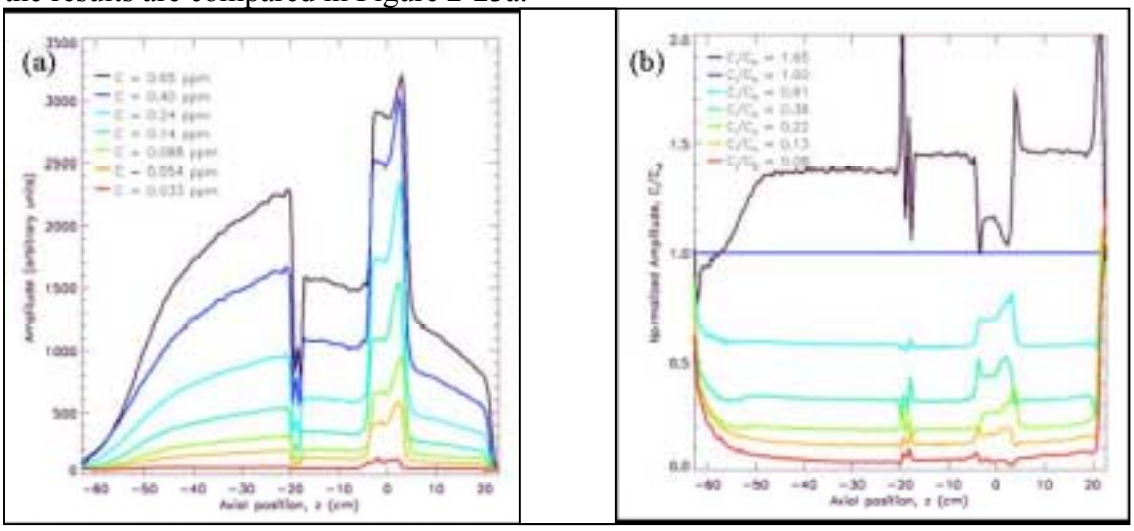

Figure 2-23. (a) Raw calibration curves for different dye concentrations, and (b) curves normalized by 0.40 ppm

The horizontal axis represents the axial position along the downcomer with respect to the cold leg centerline, the top of the downcomer being at the right end of the plot. The fluorescence intensity captured by the photodiode varies largely with the position of the beam as it crosses the downcomer gap. This is due to several factors: the change in gap width of the downcomer at z = -19 cm, a change in the illumination volume due to the change in angle of incidence as the downcomer is scanned, and a change of the laser beam intensity due to reflection and refraction as it enters the gap at different angles. The highest fluorescence is measured when the laser penetrates the injection cold leg, as the length of its path in the liquid is much longer than at any other location. A sudden drop in the signal is observed between -17 and -19 cm, which results from strong scattering of the beam by the seams in the plexiglas between the top and bottom half of the core barrel.

Figure 2-23b shows the same calibration curves, this time normalized with respect to the value C_0 = 0.40 ppm. With exception of the ratio C/C_0 = 1.65, the normalized curves are nearly constant over a large portion of the downcomer. The main deviations are observed over the injection cold leg region and towards the lower part of the downcomer. In the cold leg, this is due to the long path of the laser in the dye solution, which causes excessive attenuation of the beam. In the lower part of the downcomer, the problem is likely a result of partial clipping of the laser beam on the rotating mirror corner, causing a sharp decrease in intensity in this region. As the signal becomes small, the relative error is increased and small changes in the offset values can lead to unreliable measurements. Since the time of the calibration shown in Figure 2-23b, the optical alignment procedure

had been substantially improved, which subsequently allowed the system to accurately measure down to an axial position of z = -63 cm.

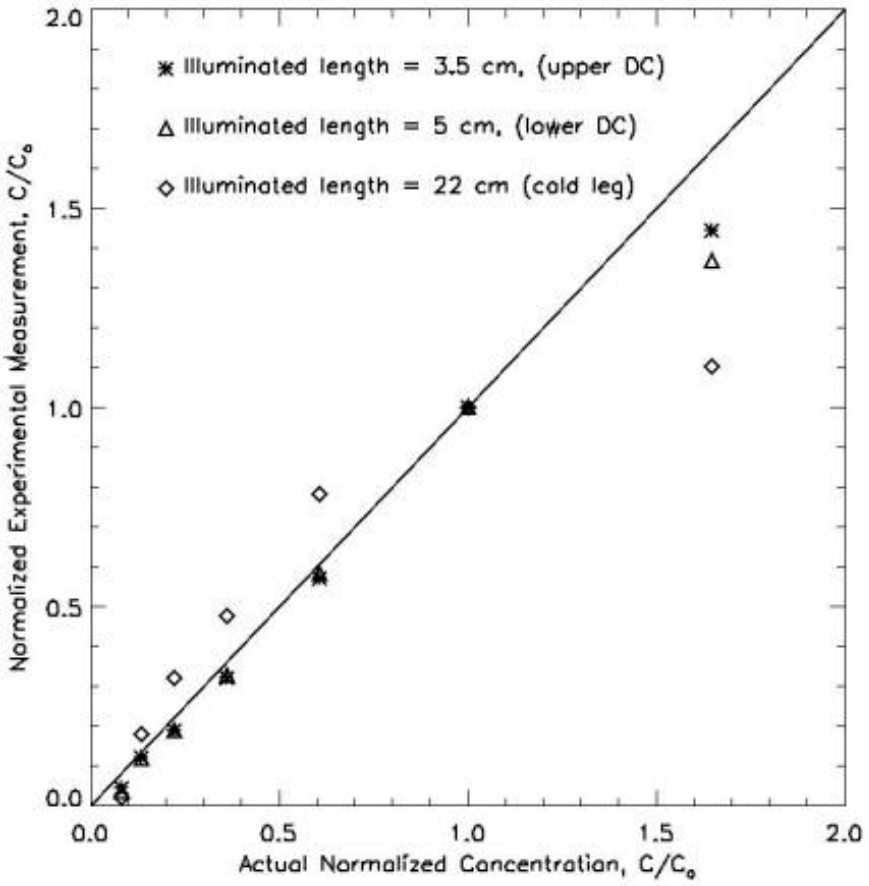

Figure 2-24. Verification of quantitative measure of normalized concentration from several regions of the downcomer. With the exception of the cold leg, the deviation is less than 5%.

Figure 2-24 shows that the LIF-measured concentration ratios correspond to the respective actual ones to within a few percents, both in the upper and lower portions of the downcomer. The same figure also shows the nonlinear response that is obtained, even at lower concentrations, when the laser beam travels inside the cold leg. From these measurements it is concluded that, if a maximum concentration not in excess of 0.40 ppm is used, the response can be considered linear over the region $-55 < z < 20$ cm (excluding the cold leg inlets), and the values will be within 5% of the concentration (based on full scale). As mentioned above, the region of valid data collection was later extended to include the lower region of the downcomer from $-63 < z < -55$ not reflected in Figure 2-23b. In the data collected for these experiments, the nominal concentration of the dye was set to 0.1 ppm.

An additional laser and photodiode was used to measure the mean concentration inlet conditions approximately 10 cm upstream of the cold leg/downcomer junction. For this measurement a 50 mW laser beam from a separate Ar+ laser was directed through the diameter of the inlet pipe. As for the primary LIF measurements, a half-silvered mirror

and long-pass filter was used to eliminate contamination by scattered light and ensure a complete observation of the illuminated volume.

Finally, two differential pressure transducers (Validyne model P55D-4-N-1-30-S-5-A, ±0.25% full scale, calibrated for a range of 0 to 89 cm of H_20) were used to monitor the fluid levels within the supply and return tanks. Due to a slight variability of the tank cross-section, both transducers were calibrated *in situ* in terms of volume occupied within the tank. The tank was filled in 1 liter increments up to the 200 liter capacity of the tank. The resulting uncertainty is approximately ±1 liter over the range used within the experiments.

In addition to the quantitative LIF measurements, the visualization facility was also used to make steady-state velocity measurements within select regions of the downcomer. The measurements were completed using a two-component Dantec laser Doppler anemometer, which was based on their MultiPDA (57N80) processor system with the sizing module turned off. The system was configured to operate in backscatter mode in order to eliminate the difficulties of aligning a separate receiver, and low f-number optics were used to minimize the probe volume dimensions. This corresponded to a lens with a 310 mm focal length and a clear aperture of over 50 mm (beam separation was 40 mm), giving an effective probe volume with a diameter of approximately 0.1 mm and a length of nearly 2 mm. The filter bandwidth used to process the Doppler signals was varied during the profiles in order to optimize the instrument resolution when passing through areas of significantly different mean velocity. The transmitter was aligned perpendicular to the outer vessel wall, which allowed for the measurements of the velocity components in the azimuthal (θ) and axial (z) directions.

A viewing prism was also constructed and attached to the outer wall of the downcomer to correct the optical distortions caused by the cylindrical vessel. Without the prism, the beams in the horizontal plane would be focused to a different spatial location than the beams contained in the radial plane. The prism consisted of a small tank approximately 60 cm in length and 8 cm wide, which was cut such that the open side would seal tightly against the vessel. The tank was then attached to the vessel and filled with water to generate an effective planar surface through which to transmit the beams. With the prism in place, the distortion in the effective probe volume locations was calculated to be less than 1 mm, which is half the value of the long axis of the probe volume. Data points were validated using both the signal to noise ratio and the coincidence between the v_z and v_θ channels, thus preventing measurements of seed particles that may have only been detected by one set of the laser beams.

The seed tracer particles were silver-coated, hollow glass spheres approximately 10 μm in diameter with a specific gravity of 1.4. Their small size and low specific gravity ensure that they will adequately follow the fluctuations of the flow.

The data measurements were acquired on a grid spaced 2 mm in the radial direction and 25 mm in the axial direction. Each data point consisted of a range of 2,000 to 10,000 individual data samples, depending on the local convection velocity (the larger the speed, the greater the number of samples). Typical uncertainties in the velocity mean values are less than 1%, with the exception of the near wall data, which is contaminated by poor

signal quality and spurious reflections from the walls. Uncertainty in the higher order moments is estimated to be less than 10%.

3 Testing Procedure

3.1.1 Loop Testing Procedures

The experimental program carried out consisted of four test series: A, B, C, and D, designed with an increasing degree of complexity. The experimental procedures for all test series are described here.

3.1.1.1 Test Series A

Test Series A was designed to study the mixing of a single front as it enters the downcomer through cold leg A1 from an external source and leaves the system through an opening at hot leg A. A single mixing front condition is achieved when the injected front volume is large enough. To provide for such a volume, an external tank of 400 l capacity was connected to cold leg A1 through a two-inch PVC pipe. The pipe connection point to the cold leg was in the cold leg riser close to the bottom knee of the leg. The tank was placed above the reactor vessel but the tank water level was below the highest point in the reactor system represented by the hot leg candy cane section. For this reason, a two-inch check valve was installed in the connecting pipe to prevent backflow from the primary system into the slug tank. During the experiment, the tank water was sucked into the reactor system by the reactor coolant pump in cold leg A1. An aluminum diaphragm was inserted into the cold leg between the tank injection port and SG A in order to prevent flow circulation through SG A during the test. The water was taken out of the reactor system through a vent valve, which was installed on the top of steam generator A. The vent was two inches in diameter and was controlled by means of a two-inch gate valve. This outlet was connected to an overflow tank through a two-inch hose attached to the vent.

Test Series A flow configuration is characterized by a single inlet path and a single outlet path for the downcomer flow. There was a single inlet into the downcomer through cold leg A1 and a single outlet from the downcomer through the reactor core then hot leg A. To provide for such flow conditions, the four-loop integral facility configuration was effectively reduced to a single-loop configuration. For this purpose, cold legs A2 and B2 were isolated by inserting aluminum diaphragms between the flanges, which connect the cold legs to the reactor vessel. Cold leg B1 was isolated by closing a gate valve installed at the cold leg flange. Figure 3-2 shows the participating components and flow paths.

The test A procedure is as follows:

a. Fill the loop with tap water. Use air vents to remove trapped air from the top of the downcomer.

b. Fill the slug injection tank with tap water.

c. With the valve to cold leg B1 open and the B1 RCP running (for mixing purposes), use the system heaters to heat the system water.

d. When the system reaches about 75°C, turn off the heaters and RCP B1, and close the valve to cold leg B1.

e. Wait a few minutes for the system to come to rest.

f. Open the vent valve for SG A and start RCP A1. Continue until the slug tank is nearly empty

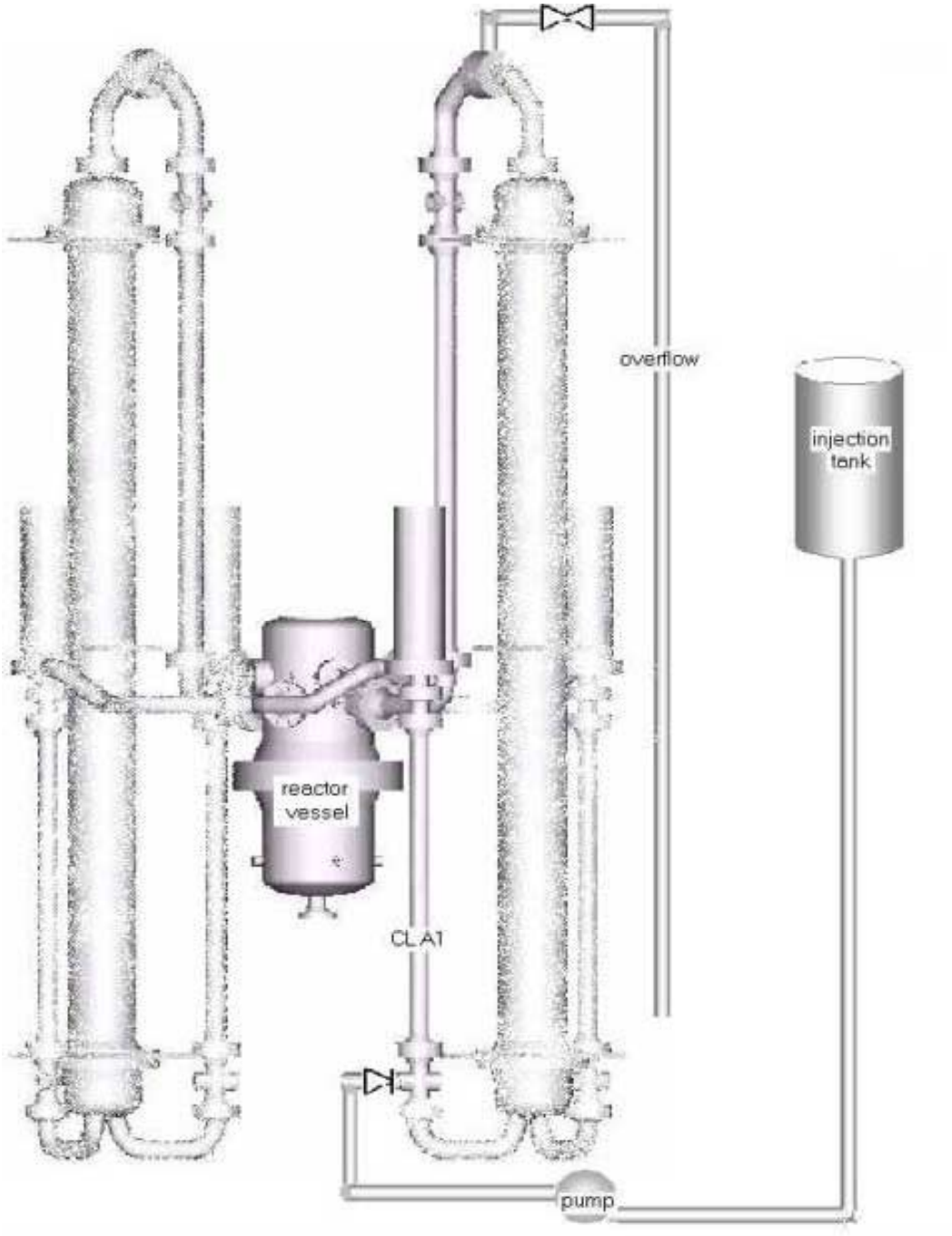

Figure 3-1. Configuration for Test A (faded components are inactive in this test)

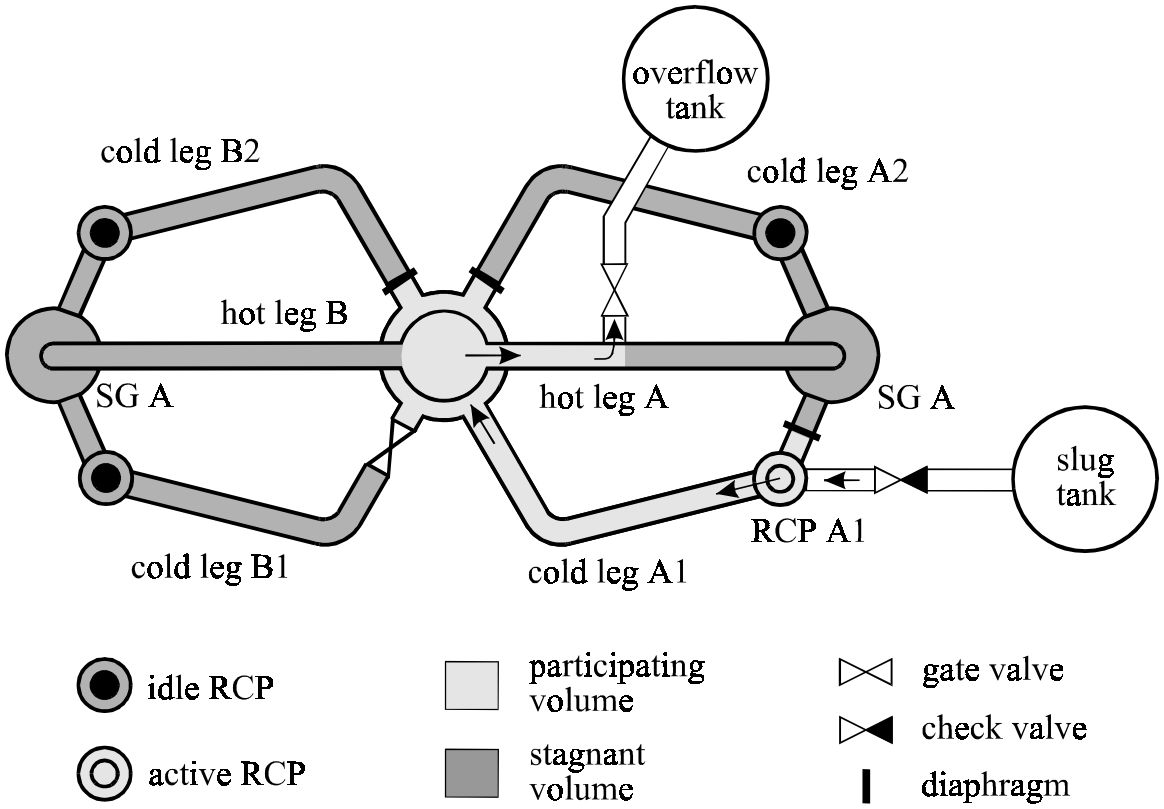

Figure 3-2. Participating components and flow paths in Test Series A

3.1.1.2 Test Series B

Test Series B, like the first test series, involved a single reactor loop with a downcomer flow configuration (Figure 3-3), which is characterized by a single inlet path and a single outlet path for the downcomer flow. However, it brings the experiment close to the reality in the sense that the slug is of a limited volume and resides inside the reactor system prior to its transportation phase. The flow paths were the same as in Test Series A with the difference that a closed circulation loop through SG A was established. For this purpose, the vent from SG A was closed and the aluminum diaphragm in cold leg A1 was removed. Figure 3-4 below shows the participating components and flow paths in Test Series B.

The test B procedure is as follows:

a. Fill the loop with tap water. Use air vents to remove trapped air.
b. Fill the slug injection tank with tap water.
c. Use the system heaters to heat the system while RCP A1 circulates water through HL A and CL A1.
d. When the system reaches about 75°C, turn off the heaters and RCP A1.
e. Wait a few minutes for the system to come to rest.
f. With the HL A vent open, use the slug-line pump to inject the slug at the injection point. Using the water level in the slug tank as a guide, continue until about 55.3 l have been injected. This is enough to bring the beginning of the slug to the pump impeller.

g. Close the valve to the slug line.
h. Close the SG A vent.
i. Set up the DAS to record data, then turn on RCP A1. Run it for about 200 seconds, and then turn it off.

This procedure was also followed for test series C and D.

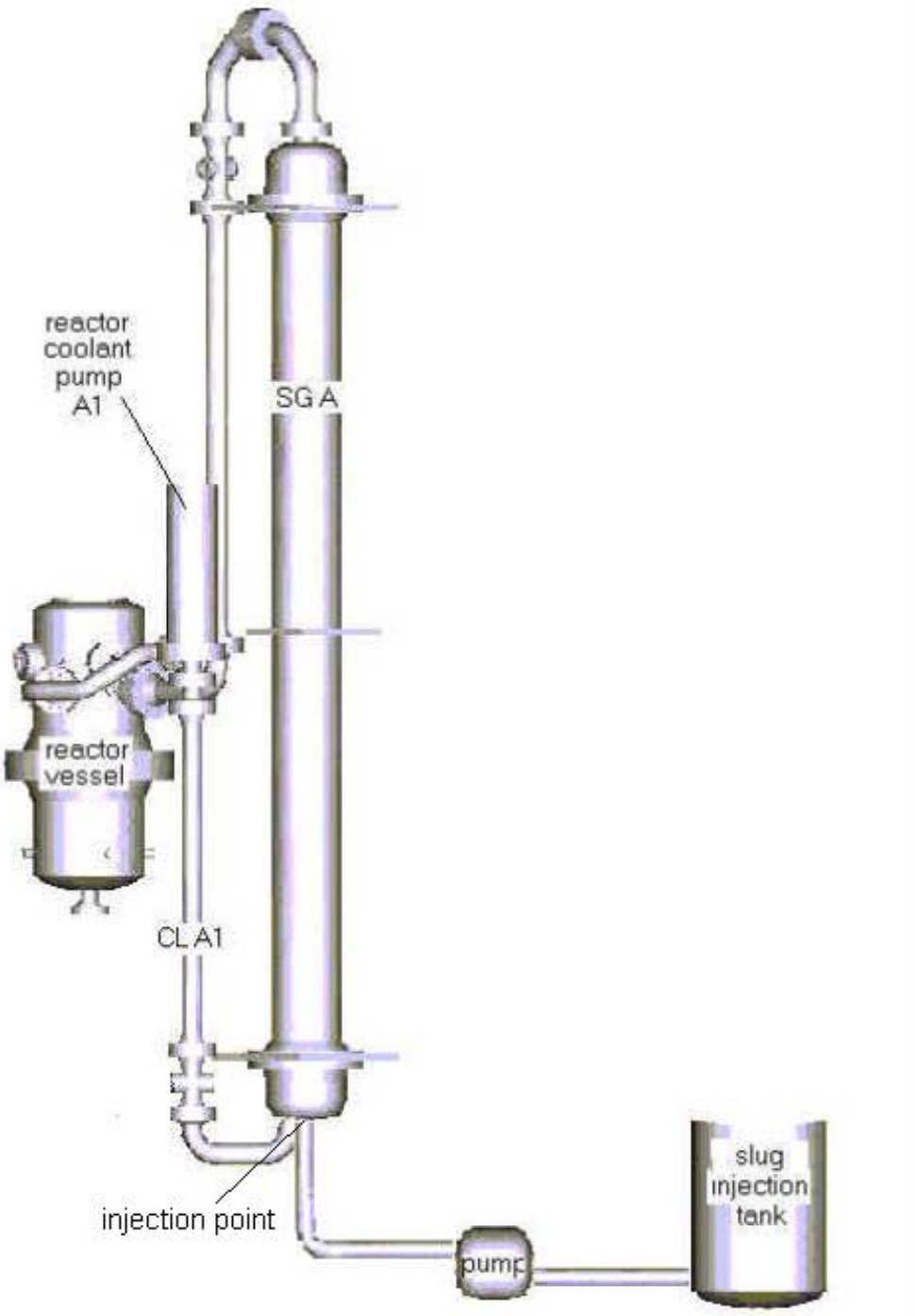

Figure 3-3. Configuration of participating components for Test B

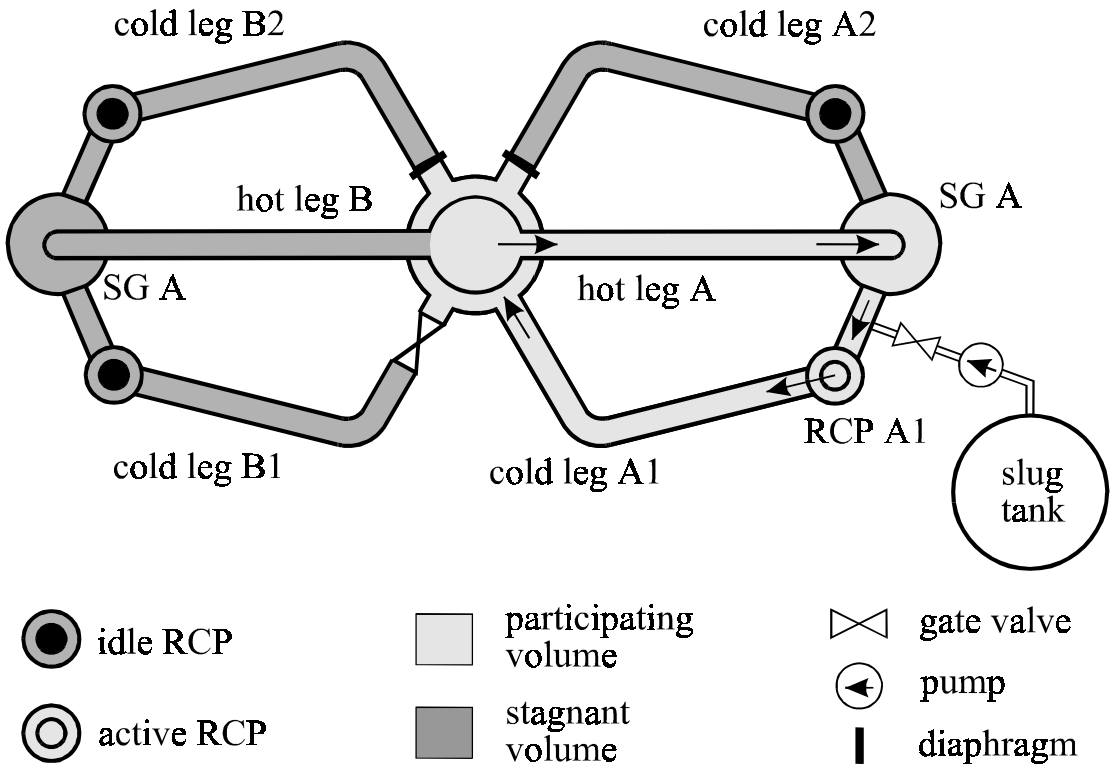

Figure 3-4. Participating components and flow paths in Test Series B

Since the flow path in Test Series B was a closed loop, the test runs involved two mixing fronts associated with the front and rear end of the slug volume. Respectively, an oscillatory temperature pattern in the reactor downcomer was observed. The duration of the runs spanned over two to three temperature cycles.

3.1.1.3 Test Series C

Test Series C added another step of complexity with respect to the downcomer flow pattern in the sense that the downcomer flow configuration involved a single flow inlet and multiple flow outlets. In addition to the main downcomer outlet path through the core, a second outlet was provided through cold leg A2. For this purpose, the aluminum diaphragm in cold leg A2 was removed and a core bypass flow path through the cold leg was established. As in Test Series A and B, loop B was isolated by the aluminum diaphragm in cold leg B2 and the gate valve in cold leg B1. Figure 3-5 below shows the participating components and flow paths for the Test Series C. The test procedure was identical to that applied in Test Series B.

3.1.1.4 Test Series D

Test Series D was performed with the participation of all facility loops. For this purpose, in addition to the system modification in Test Series C, the aluminum blank in cold leg B2 was removed and the gate valve in cold leg B1 was opened. Thus, the second main loop involving hot leg B and cold legs B1 and B2 was engaged. Cold legs A2, B1, and B2 provided bypass flow paths for the downcomer. Like in Test Series C, Test Series D

involved a downcomer flow configuration with a single inlet and multiple flow outlets. The test procedure was identical to that applied in Test Series B and C. Figure 3-6 below shows the participating components and flow paths for the Test Series D.

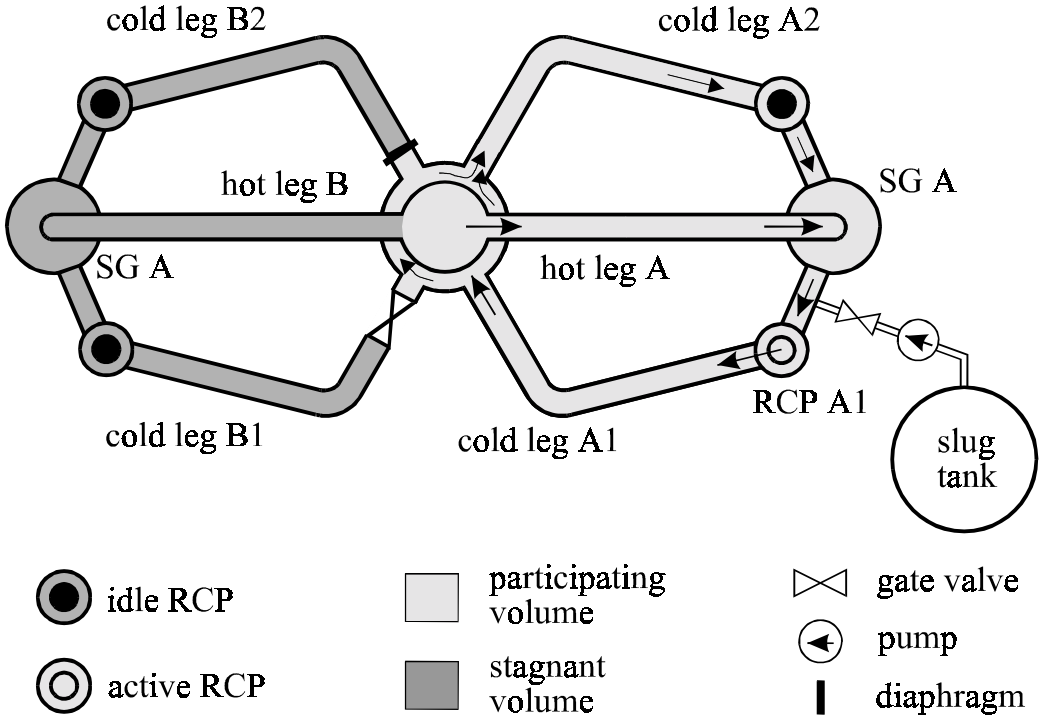

Figure 3-5. Flow paths and participating components in Test Series C

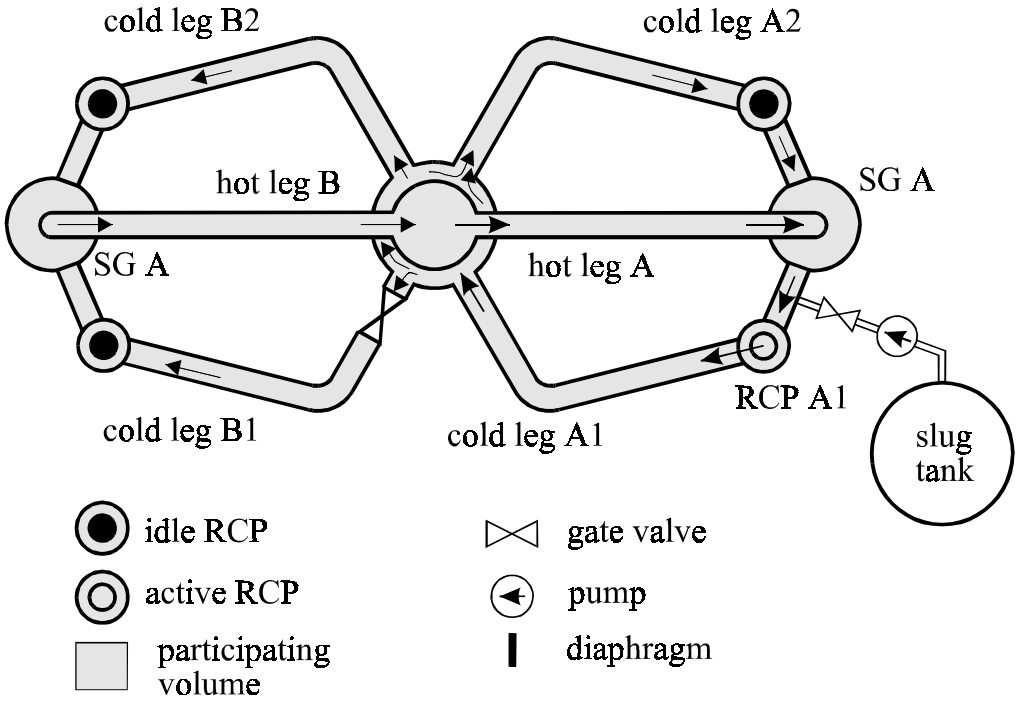

Figure 3-6. Flow paths and participating components in Test Series D

3.1.2 Visualization Testing Procedures

The injected volume transients for the tests are shown in Figure 3-7. For both the front and slug mixing cases, the nominal pump behavior was kept the same with a steady state flow rate of approximately 8 liters/sec. The start-up transient for the pump consists of a gradual ramp over a span of approximately 12.5 seconds, which was selected to match the preliminary tests simultaneously performed in the 2x4 loop facility.

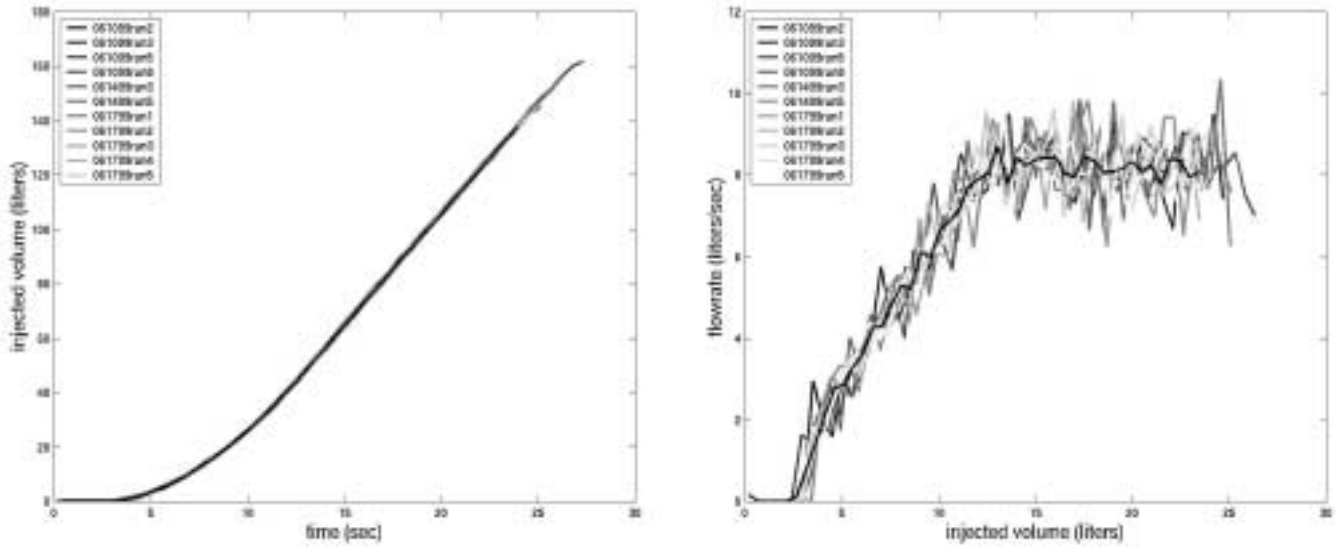

Figure 3-7. (a) Injected volume as a function of time for 12 separate front injection tests, (b) flow rate vs. time obtained from the derivative of the injected volume

Repeatable inlet concentration boundary conditions are generated using a small drain valve at the bottom of the lowered loop upstream of the pump (see

Figure 3-8). For both the front and the slug, the leading interface is very sharp and repeatable. The trailing interface for the slug event was generated by placing a thin (0.1 mm) polyethylene sheet over the free surface of the fresh water in the supply tank, and then filling the tank up with dyed water reserved from the filling of the vessel. In addition, a recirculation pipe is placed in the inlet to the recovery tank, which returns the outflow to the supply tank. Thus, once the test is initiated and the supply tank is slowly drained, the plastic sheet is drawn closer and closer to the exit. Upon reaching the exit, a small fixed razor perforates the sheet and allows the dyed water to follow behind the fresh water. Although there is a slight amount of variability as to when the knife cuts the sheet (which results in a slightly greater variability the volume of the injected slug), the procedure produces a consistent slug with a sharp interface. Also note that with the lack of a full steam generator and core volume, the total system volume of the BMOV is approximately ½ of the 2x4 loop. The main effect of this difference will be a reduced system cycle time with respect to the dilution oscillations as shown for the 2x4 loop in Figure 3-5. Although the volume along the slug path is matched between the two facilities, it was not possible to match the total system volume in a realistic manner.

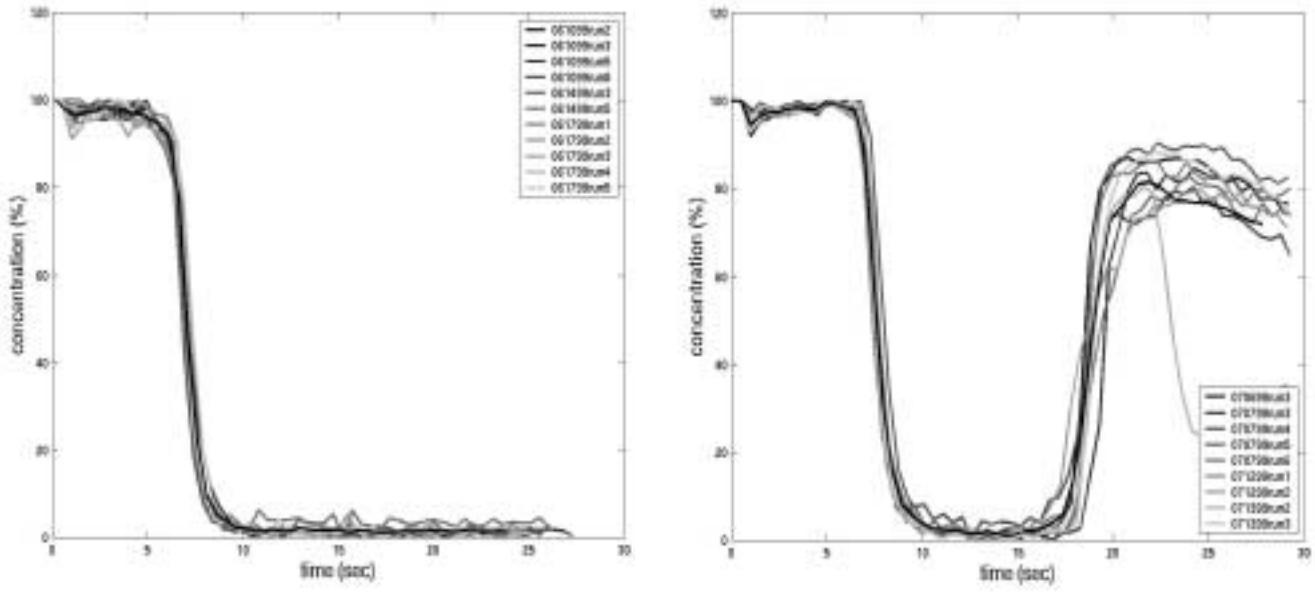

Figure 3-8. Mean concentration histories measured approximately 10 cm upstream of the downcomer. (a) front injection, (b) slug injection

A detailed list of the set-up and testing procedure for both the front (Test A) and the slug (Test B) experiments is enumerated below.

1. Front injection test procedure
    a. Fill system and add dye to known concentration of 0.10 ppm.
    b. Insert recirculation pipe to allow pumping of fluid from the exit line back into the inlet tank, and circulate with the main pump to ensure dye uniformity and remove trapped air bubbles.
    c. Optimize optical alignment of the photomultiplier tube (downcomer measurement) and photodiode (inlet concentration) for uniform signal.
    d. Shut off the main pump, and continue to circulate with small bypass pump. (flow path is from downcomer exit to bypass cold leg A2)
    e. Block exit pipe into recovery tank, remove the recirculation pipe, and place exit line overflow standpipe over exit pipe. Open the main exit tank valve, and allow stand pipe to equilibrate with system level.
    f. Close exit pipe valve.
    g. Drain inlet tank to a level approximately 6’ above the lower loop seal .
    h. Slowly fill the inlet tank with clean, fresh water to height of the standpipe in the exit tank.
    i. Shut off bypass circulation. Open exit pipe valve.
    j. After tank is filled, slowly bleed the tank with stopcock at bottom of lower loop seal until the interface between the dyed and fresh water is centered over the valve. (approx. 90 sec.)
    k. Rotate the optical carriage assembly to 120 rpm. (approx. 90 sec.)
    l. Initiate injection test.

2. Slug injection test procedure
    a. Fill and add dye to known concentration of 0.10 ppm
    b. Insert recirculation pipe to allow pumping of fluid from the exit line back into the inlet tank, and circulate with the main pump to ensure dye uniformity and removal trapped air bubbles.
    c. Optimize optical alignment of the photomultiplier tube (downcomer measurement) and photodiode (inlet concentration) for uniform signal.
    d. Shut off main pump, and continue to circulate with small bypass pump. (flow path is from downcomer exit to bypass cold leg A2)
    e. Close valve on exit pipe into recovery tank.
    f. Drain inlet tank to a level approximately 6' above the lower loop seal.
    g. Slowly fill the inlet tank until the tank contains 80 liters of clean, fresh water.
    h. Insert the perforation device in the exit of the inlet tank.
    i. Place 0.004" polyethylene sheet on the surface of the fresh water and drape over the upper edges of the tank.
    j. Fill the inlet tank with dyed water in the exit tank.
    k. Shut off bypass circulation.
    l. After tank is filled, slowly bleed the tank with stopcock at bottom of lower loop seal until the interface between the dyed and fresh water is centered over the valve. (approx. 90 sec.)
    m. Rotate the optical carriage assembly to 120 rpm. (approx. 90 sec.)
    n. Initiate injection test.

3.2 Data Reduction and Processing

The data reductions for loop and visualization facilities are described in the subsequent sections. The goal of the reduction was to obtain thermocouple/concentration readings at the locations of thermocouples installed in the loop. Both the loop and visualization facilities scanned through the entire region of interest within less than 0.5 s. The participants were required to submit temperature computational results at the locations of loop thermocouples at time intervals of 0.5 s.

3.2.1 Loop Data Reduction

The reduction of loop data is coupled to the data acquisition software. Specifically, measured thermocouple voltages are directly processed by HPVee as shown in section 3.2.1.1. The reduction of flowmeter and DP data involves the conversion of voltages into l/s of H_2O respectively as described in sections 3.2.1.2 and 3.2.1.3. The chart of

Figure 3-9 summarizes the entire data processing procedure. To be able to adequately compare data from the loop and visualization facility to participant submissions, the visualization facility data and those of participants were also manipulated through the steps highlighted on the chart.

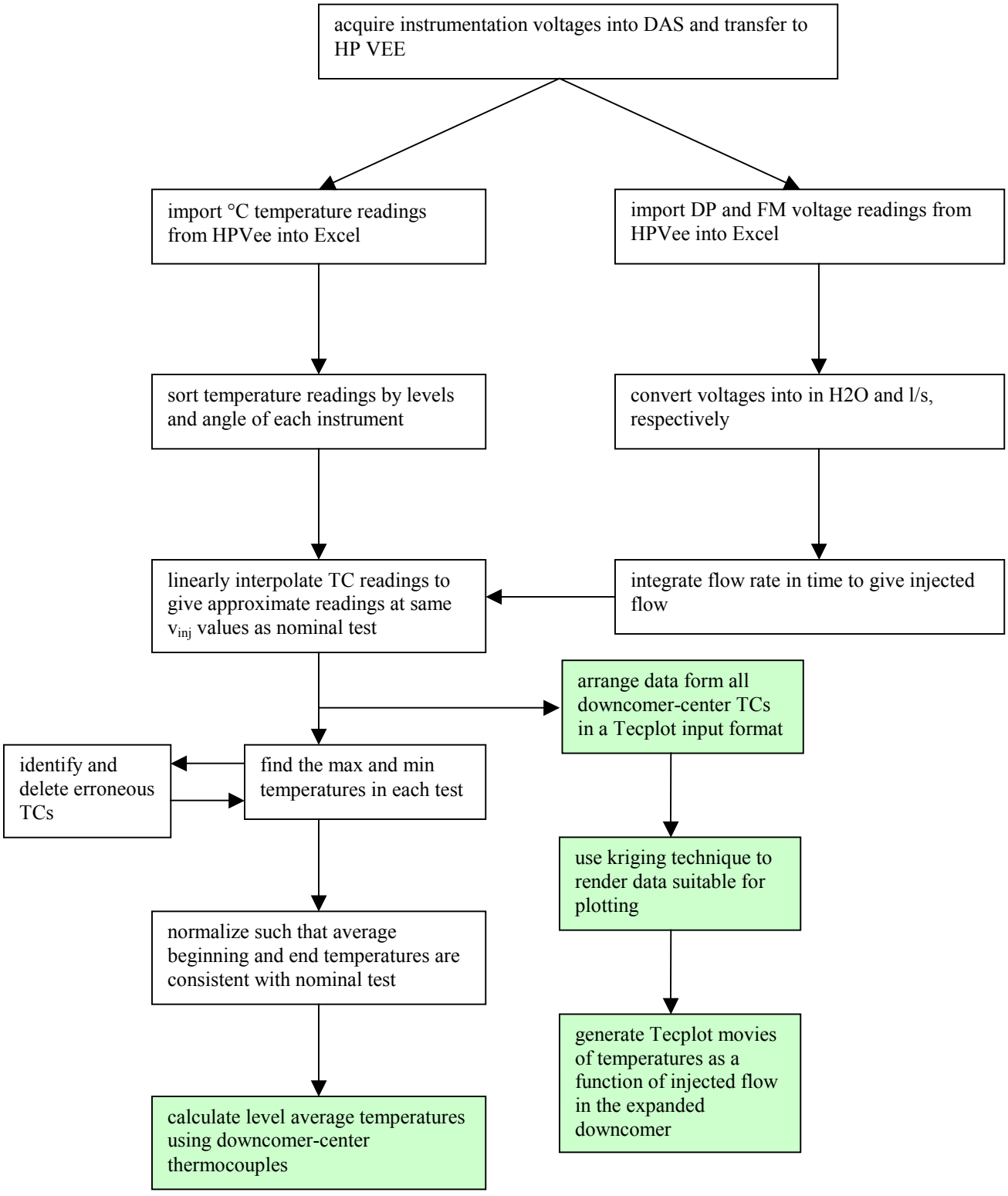

Figure 3-9. Data processing for UM Loop; highlighted boxes show steps applied to visualization facility data and participant data to render them all in format conducive for comparison

3.2.1.1 Data Reduction for Thermocouples

The UM Loop facility is instrumented with 286 thermocouples, of which 164 can be continuously measured and stored using the HP-3852. Two types of thermocouples are used: type T and type K. They provide temperatures of the fluid in the primary and the secondary systems as well as the heater temperatures.

The recording of the temperature data takes into account the processing speed of the DAS. The voltage produced at the tip of the thermocouples is proportional to the temperature at the location of contact between two dissimilar metals. The measured voltage (in mV) is passed to the DAS computer and stored by the HPVee program.

The voltages fed into the HPVee program represent the potential difference between the two ends of the thermocouple. To account for the positive temperature of the base of the thermocouple, the DAS generates a reference temperature. This reference temperature is converted to a voltage and added to the measured voltage, achieving an adjusted voltage that corresponds to the true measured temperature. The HPVee program converts the voltages into temperatures using Equation 3-1 (NIST), and the constants are given in Table 3-1. The output of temperatures is in Excel format.

$$T=P_0 + P_1*V + P_2*V^2 + P_3*V^3 + P_4*V^4 + P_5*V^5 + P_6*V^6 + P_7*V^7 + P_8*V^8 + P_9*V^9$$

Equation 3-1

Table 3-1: Thermocouple constants for calculating temperature from voltage

Constant	Type K	Type T
R_0	-8.167743593 E-7	5.257929840 E-7
R_1	3.963927586 E-5	3.860071243 E-5
R_2	1.066719241 E-8	4.186486602 E-8
P_0	-5.115307103 E-2	1.238117795 E-1
P_1	2.485028007 E4	2.686117637 E4
P_2	-3.826622822 E5	-8.964942880 E5
P_3	9.966105673 E7	-4.648926088 E7
P_4	-1.082062357 E10	1.244114245 E10
P_5	6.039285524 E11	2.275304922 E12
P_6	-1.910899962 E13	-6.399496867 E14
P_7	3.478234730 E14	5.435757807 E16
P_8	-3.399102821 E15	2.0123615370 E18
P_9	1.382851398 E16	2.830121167 E19

(taken from Gavrilas et al., 1996, p.53)

To arrive at comparable data for each trial, thermocouple readings were both interpolated and normalized. Using Microsoft Excel, the data for each trial was linearly interpolated in flow rate using Equation 3-2. This yielded a temperature reading for each TC in each trial that corresponded to the same set of injected flows and the same times. Then, each trial within each test was normalized to cover the same range of temperatures using Equation 3-3.

$$T_{\text{int}} = \frac{\left(flow_{\text{int}} - flow_{before}\right) * \left(T_{after} - T_{before}\right)}{\left(flow_{after} - flow_{before}\right)} + T_{before}$$ Equation 3-2

$$T_{normalized} = \frac{\left(T_{raw} - T\min_{raw}\right) * \left(T\max_{desired} - T\min_{desired}\right)}{\left(T\max_{raw} - T\min_{raw}\right)} + T\min_{raw}$$ Equation 3-3

3.2.1.2 Data Reduction for Ultrasonic Flow Anemometers

Flow rate was integrated in time, yielding injected flow. This injected flow, which is a function of time, is the most accurate way to define the state of the system. The scaling approach developed by Gavrilas and Palazov (1997) shows that test-to-test comparison is best carried out using the injected flow time scale.

3.2.1.3 Data Reduction for Pressure Transducers

In order to calibrate the ITT DP transducers, one must first vent both sides of the cell to ensure that there is no air trapped in either line. Then take measurements at many points along the full range of the water level that is to be measured. With this data, fit a linear regression model. This model is used within the HPVee program to convert the voltages from DP Cells to water level in the tanks. As with the temperature readings, this conversion from voltage to water level is conducted after the test is completed.

3.2.2 Visualization Facility Data Reduction

3.2.2.1 Data Reduction for Laser Induced Fluorescence (LIF) Data

During each test, five different ASCII data files were recorded which contain the raw data of the experiment. These files are detailed in Table 3-2. The signals from the pressure transducers are converted into fluid level measurements from their calibration coefficients determined prior to the tests. The signal is further conditioned by averaging the data over 0.5 second intervals to remove fluctuations caused by waves on the free surface and noise contamination. The pump speed data were examined for consistency, but no quantitative results were developed from them.

The concentration data recorded by the photodiode upstream of the downcomer inlet (led.dat) was normalized using:

$$C(t) = 100\frac{V(t) - O}{V(0) - O}$$ Equation 3-4

where O is the offset voltage and *V(0)* is the initial voltage when the probe volume is occupied by dyed fluid with a maximum concentration.

In order to reduce the photomultiplier tube (PMT) data representing the concentration within the downcomer, the raw data vector first had to be parsed into temporal sequence of arrays representing azimuthal and axial evolution of the flow. In order to facilitate this reconstruction, a series of LED's were placed on the optical carriage such that they would be observed at the beginning of each vertical scan. This provided a synchronization pulse that could be used to unambiguously identify the starting point of each segment. A similar reference light source was placed at a fixed azimuthal location to permit the determination of one complete revolution.

Table 3-2: Data files recorded during each visualization test

Name	Acquisition Rate (Hz)	Description
pmt.dat	500,000	Raw data output from photomultiplier tube for concentration measurement in downcomer
led.dat	5,000	Intensity of fluoresced light measured across the diameter of the cold leg inlet 10 cm upstream of the downcomer junction
pumpspd.dat	5,000	Output from the pump controller. Voltage is proportional to the impeller speed.
supplytank.dat	5,000	Voltage signal from differential pressure transducer connected to supply tank.
returntank.dat	5,000	Voltage signal from differential pressure transducer connected to the return tank.

Once the data was ordered into the proper set of arrays, it must be normalized in order to provide a quantitative result. Slight aberrations in the optical alignment (i.e. the beam not being centered with the axis of rotation, and vibration induced by the drive teeth of the optical carriage motor) created a small amount of azimuthal variation in the intensity of the illuminating laser beam. As a result, the normalization procedure must also account for the azimuthal as well as the axial changes, namely:

$$C(n,z,\theta) = 100\frac{V(n,z,\theta)-O}{V(1,z,\theta)-O} \qquad \text{Equation 3-5}$$

where n is the number of azimuthal revolutions completed, z is the azimuthal coordinate, and θ is the azimuthal coordinate.

Once the raw data has been reduced into the quantitative data, the tests can be examined individually or used to generate an ensemble average of the temporal evolution of the injection event (Figure 3-10). Such averages have been generated to allow comparison to the computational results. Initially, 8 separate tests have been used to generate the ensemble average, although 12 data sets for test A and 9 data sets for test B are shown in the figures. This discrepancy results from additional tests that were processed after the comparisons to the code results were completed. The azimuthal starting location for the data sampling was not controlled, and as a result, each test has a temporal variability of around ±0.25 seconds when comparing with other runs. Each sequence may be advanced or delayed by one revolution to compensate for these timing errors when generating the ensemble average data.

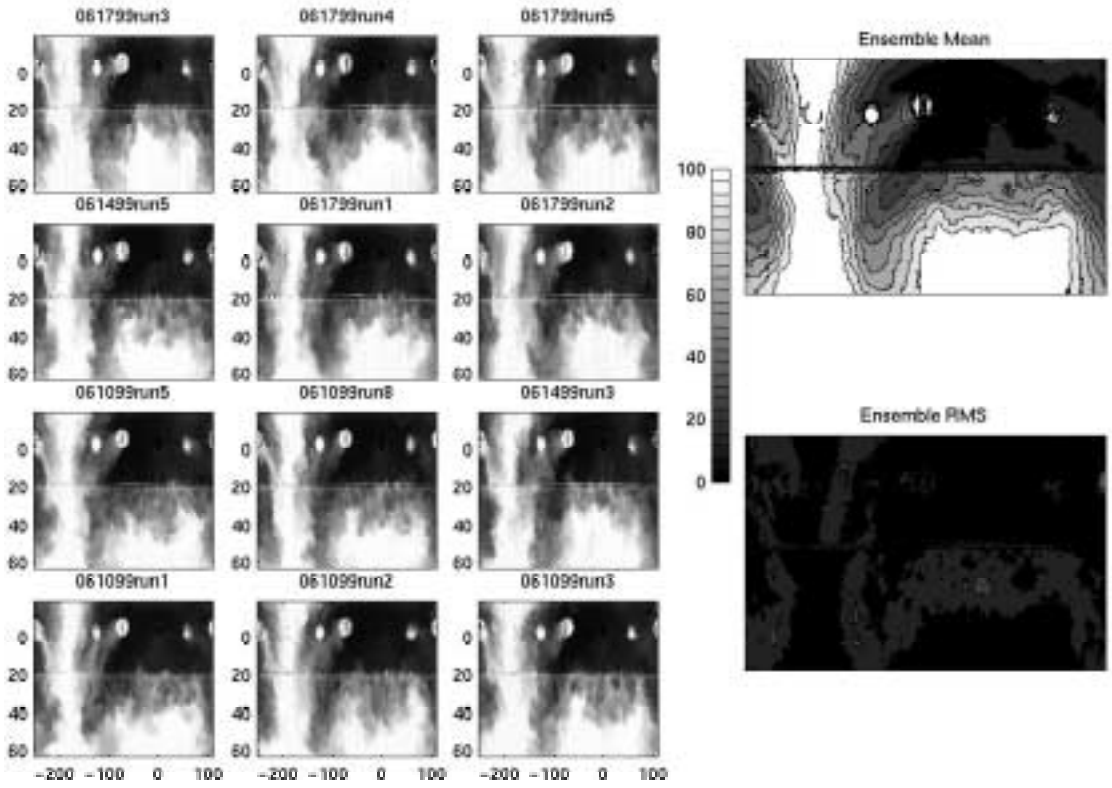

Figure 3-10. Generation of ensemble average and ensemble standard deviation of the instantaneous spatial concentration fields

When comparing the visualization data to the computational results or the loop data for test A, it has been noticed that there are some discrepancies in both the average injection rate as well as the initial location of the injection interface (see Figure 3-11). The injection rate of the simulation and the loop were conducted at approximately 7 liters/sec, while the visualization studies had a flow rate of 8 liters/second. This difference is compensated by making comparisons based upon the total injected volume after the interface has entered the downcomer, and not on similar injection times. Once the correction is completed, the inlet concentration histories will allow for a more reasonable comparison between the experiments and the simulations. A tabulated version of the exact revolutions data used for each corresponding time step is listed in Table 3-3. The injected flowrate for the Test B conditions was closer to the 8 liters/sec used in the visualization facility, and so no volume correction was used.

3.2.2.2 Data Reduction for Laser Doppler Anemometer Data

In addition to the quantitative fluorescent measurements, the visualization facility was also used to map the steady-state velocity field within select regions of the downcomer. The experiment was set-up with a viewing prism as described in section 2.2.2, and the pump was operated under steady conditions with a flowrate of approximately 8 liters/sec. The data was sampled on a grid with a spacing of 2 mm in the radial direction and 25 mm in the axial direction, resulting in 253 individual sampling locations. At each grid point, approximately 2000 to 10,000 velocity samples were acquired, and the mean and standard deviations were calculated using a transit-time corrected weighted average in

order to correct for the inherent velocity bias found in turbulent LDA measurements (McGlaughlin & Tiederman, 1972; Buchhave *et. al*, 1979).

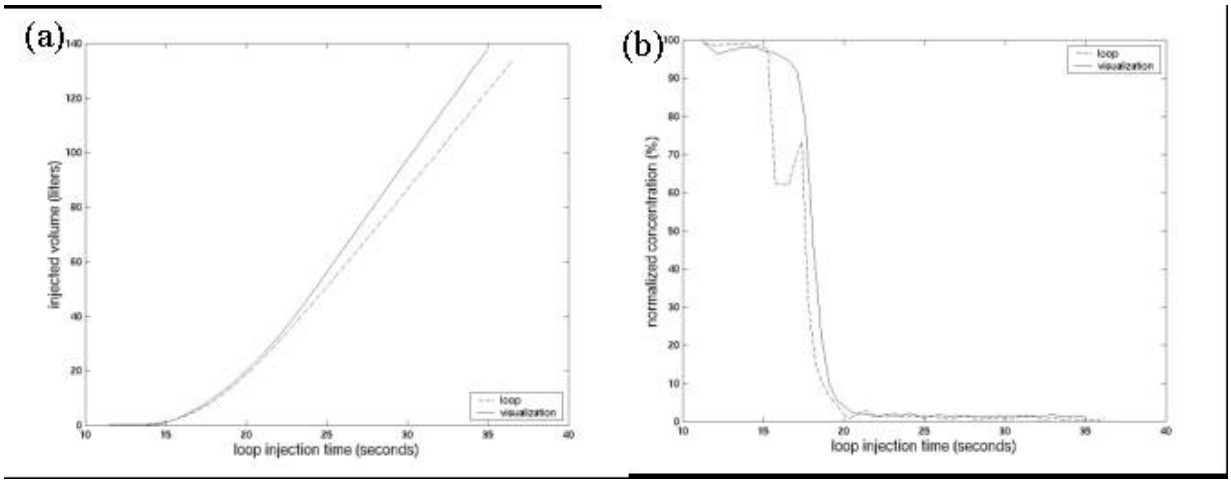

Figure 3-11. Comparison of uncorrected loop and visualization transients between (a) injected volume, and (b) inlet concentration

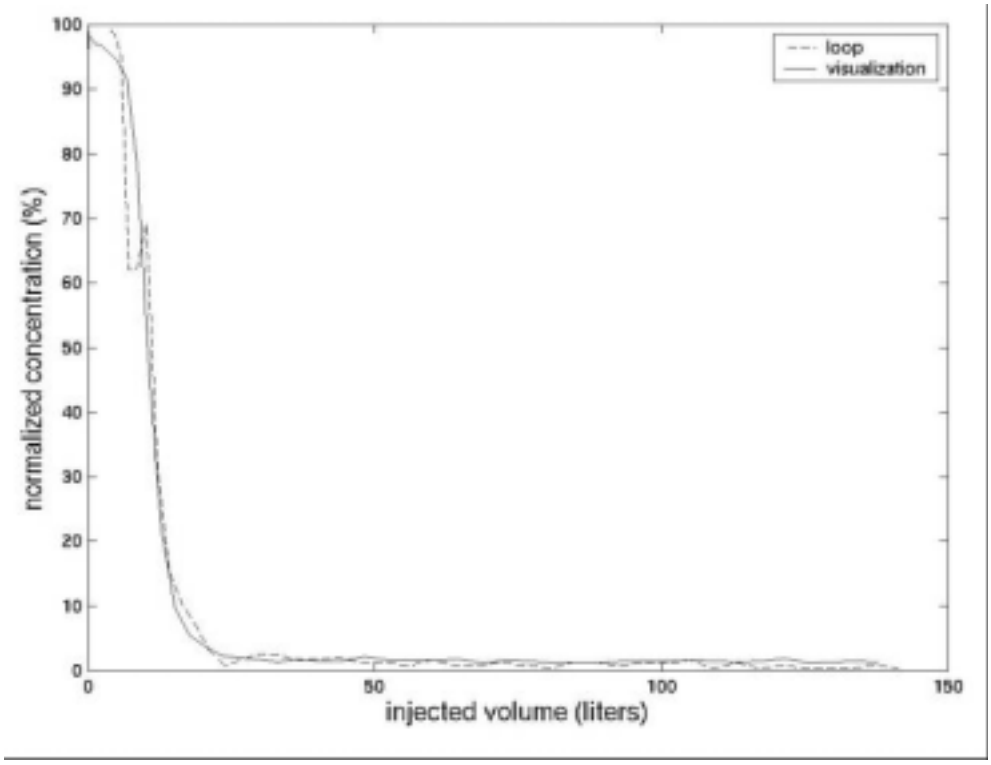

Figure 3-12. Inlet concentration history of the visualization and loop, plotted as a function of injected volume. Visualization data has been shifted by -3.5 liters to compensate for different initial positions of the interface.

Table 3-3: Volume injected mapping to determine the nearest corresponding revolution from the visualization data

ISP TIME (sec)	INJECTED VOL (liters)	Nearest Visualization Revolution	Corrected Revolution Number
11.0	0.03	1	11
11.5	0.04	1	11
12.0	0.05	1	11
12.5	0.05	1	11
13.0	0.10	2	11
13.5	0.19	7	11
14.0	0.41	8	11
14.5	0.77	8	11
15.0	1.29	9	12
15.5	2.02	10	12
16.0	2.96	10	13
16.5	4.14	11	14
17.0	5.57	12	14
17.5	7.24	13	15
18.0	9.13	14	16
18.5	11.23	15	17
19.0	13.57	16	18
19.5	16.10	17	19
20.0	18.82	18	20
20.5	21.62	19	21
21.0	24.55	20	22
21.5	27.63	21	22
22.0	30.83	22	23
22.5	33.97	23	24
23.0	37.31	24	25
23.5	40.62	25	26
24.0	43.99	26	27
24.5	47.45	27	28
25.0	50.91	28	28
25.5	54.36	28	29
26.0	57.89	29	30
26.5	61.42	30	31
27.0	65.03	31	32
27.5	68.59	32	33
28.0	72.19	33	34
28.5	75.79	34	35
29.0	79.39	35	35
29.5	82.96	35	36
30.0	86.62	36	37
30.5	90.22	37	38
31.0	93.85	38	39
31.5	97.45	39	40
32.0	101.08	40	41
32.5	104.77	41	42
33.0	108.34	42	43
33.5	111.96	43	43
34.0	115.59	43	44
34.5	119.21	44	45
35.0	122.86	45	46
35.5	126.49	46	47
36.0	130.08	47	48
36.5	133.70	48	49

4 Participant Input Models

The following table lists specification and code parameters deemed important for reproducibility and evaluation of code predictions.

Table 4-1: Participant code specifications and input parameters

Parameter	Relevance
CFD code:	general information
Version:	
Type of node FEM FV FD	numerical diffusion, flow pattern, accuracy
Type of mesh	
Total number of cells:	
downcomer radial narrow/wide	
downcomer axial narrow/wide	
downcomer azimuthal narrow wide	
lower plenum vertical levels	
lower plenum rings	

Parameter (continued)	Relevance (continued)
Time step	accuracy, convergence, numerical diffusion
Temporal discretization (order and method)	
Spatial discretization (order and method)p-v coupling	
temperature dependent density (how)	buoyancy effect, mixing, flow pattern
temperature dependent viscosity	
temperature dependent thermal conductivity	
temperature dependent specific heat	
turbulence model and constants if different from standard:	mixing, flow pattern
Wall treatment	
Mass conservation:	general check
Outlet locations (fn z)	flow pattern
Boundary condition at the outlet	
Modeling of core support plate	
Total pressure drop from bottom of the vessel to the outlet at steady state	

In addition to general information for computation reproduction, there are specific input options that affect overall convergence, numerical diffusion, mixing, buoyancy effects and flow pattern establishment.

4.1 General code information

Table 4-2 shows the codes used by the 10 participants; note that CEA has 3 entries corresponding to the 3 models run using different turbulence parameters. Four participants used Fluent and three used CFX; both are finite volume codes. Trio U and Flotran are also finite element codes. Thus 80% of participants chose finite volume codes, which are traditionally most prevalent for computational fluid dynamics. Of the remaining two, one of the codes employs the finite difference method and the other is a finite element code

Table 4-2: Codes, versions and nodalization mode

Organization	CFD code	Version	Type of node
AEA Technology	CFX-4	4.2	Finite Volume
Battelle Ingenieurtechnik GmbH	Comet	version 1.040	Finite Volume
CEA keps	Trio_U	V1,1,3	Finite Volume
CEA nut0 (sequential)	Trio_U	V1,1,3	Finite Volume
CEA par (parallel)	Trio_U	V1,1,3	Finite Volume
Fortum Engineering Ltd	Fluent	5.0	Finite Volume
Framatome Technologies Inc.	ANSYS/FLOTRAN	5.5.3	Finite Element
GRSmbH, Germany	CFX-TASCflow	Version2.9	Finite Volume
Nuclear Research Institute Rez plc	FLUENT 5	5.0.2	Finite Volume
US Nuclear Regulatory Commission	FLUENT V5	5.2	Finite Volume

Organization (continued)	CFD code (continued)	Version (continued)	Type of node (continued)
NUPEC(Nuclear Power Engineering Corporation)	PLASHY code (Parallel Large Scale Analysis System for HYdrodynamics)	1	Finite Difference
Vattenfall Utveckling AB	Fluent	5.1.1	Finite Volume

4.2 Spatial and temporal discretization

The equation discretization method and step size impact numerical diffusion and accuracy. Table 4-3 lists the discretization methods employed by participants. Most participants selected higher order discretization methods for both energy and momentum equations. Expeditious hybrid schemes such as QUICK and SIMPLE were most common in participant models. The majority of participants selected the more efficient and stable implicit temporal discretization for this relatively slowly progressing transient; only CEA and NUPEC used explicit schemes. The computational steps ranged from 0.01-0.1 s for implicit schemes and were occasionally as low as 10^{-5} for explicit schemes.

Table 4-3: Spatial and temporal discretization method

Organization	Type of mesh	Spatial discretization (order and method)p-v coupling	Temporal discretization (order and method)	Time step
AEA Technology	Body fitted multi-block	QUICK 3rd order backward scheme, SIMPLEC p-v coupling	fully implicit 1st order backward Euler	0.05s
Battelle Ingenieurtechnik GmbH	unstructured	1st order upwind, simple	Euler, implicit	0.1 s
CEA keps	Stuctured, X,Y;Z	2 : Quick for momentum and energy, p-v coupling	1 : euler explicit	dt = 0,000578 s at nominal flow (23,257s)
CEA nut0 (sequential)	Stuctured, X,Y;Z	2 : Quick for momentum and energy, p-v coupling	1 : euler explicit	dt = 0,000955 s at nominal flow (23,644s)
CEA par (parallel)	Stuctured, X,Y;Z	2 : Quick for momentum and energy, p-v coupling	1 : euler explicit	dt = 0,000955 s at nominal flow (23,644s)
Fortum Engineering Ltd	Unstructured hybrid mesh: tetrahedral and hexahedral cells	2nd order upwind scheme	2nd order implicit scheme	0.05-0.10 s
Framatome Technologies Inc.	Hexagonal (Brick) Elements	Linear elements, Segregated sequential algorithm (finite-element analog of SIMPLER)	Implicit, Second Order	0.05 sec
GRSmbH, Germany	block-structured hexahedral	2. order mass-weighted skew-upwind differences	1. order implicit Euler	0.1 to 0.5

Organization (continued)	Type of mesh (continued)	Spatial discretization (order and method) p-v coupling (continued)	Temporal discretization (order and method) (continued)	Time step (continued)
Nuclear Research Institute Rez plc	mixed, unstructured	diffusion - central differences, convection - 1st order upwind, SIMPLE	1st order implicit	0.025 - 0.1
US Nuclear Regulatory Commission	Hexagonal	2nd order Momentum and Energy (Simple)	2nd order Implicit	0.05s
NUPEC(Nuclear Power Engineering Corporation)	3D Cylindrical	QUICK for spatial discretization, SMAC method for p-v coupling	First order Euler explicit	variable (from 7.7*10-5 to 5.6*10-3 sec for Test-A and from 7.7*10-5 to 4.0*10-3 sec for Test-B)
Vattenfall Utveckling AB	Unstructured (hexas in downcomer, tetras in lower plenum and core.)	second order upwind, SIMPLEC	2-nd order implicit	0.01 sec

Table 4-4 shows the meshes selected by participants. This information must be considered together with solution method and discretization schemes to assess the extent of numerical diffusion. Overall, the simulation volume ranged from 75,976 to 750,000 cells with most models containing between a quarter and a half million cells. Note that regions of refined meshing should be identified to get a more informed view of mesh adequacy for the particular flow pattern.

Table 4-4: Mesh description of participants input models

Organization	Total number of cells	downcomer radial narrow/wide	downcomer axial narrow/wide	downcomer azimuthal narrow wide	lower plenum vertical levels	lower plenum rings
AEA Technology	454,720	10/16	42/54	144/144	15	32
Battelle Ingenieurtechnik GmbH	75,976	narrow: 5, wide: 9	narrow: 28, wide: 50	72	10	9
CEA keps	600,000	constant, ,005 m	most of the time constant, ,0,05 m; etired up to ,015 m when possible	no azimuthal values : X,Y,Z coordinates	levels of uniform height of ,005 m	no rings : X,Y,Z coordinates
CEA nut0 (sequential)	750,000	constant, ,005 m	constant, ,005 m	no azimuthal values : X,Y,Z coordinates	levels of uniform height of ,005 m	no rings : X,Y,Z coordinates
CEA par (parallel)	750,000	constant, ,005 m	constant, ,005 m	no azimuthal values : X,Y,Z coordinates	levels of uniform height of ,005 m	no rings : X,Y,Z coordinates
Fortum Engineering Ltd	175,361	7/11	26/28	62	15	38

Organization (continued)	Total number of cells (continued)	downcomer radial narrow/wide (continued)	downcomer axial narrow/wide (continued)	downcomer azimuthal narrow wide (continued)	lower plenum vertical levels (continued)	lower plenum rings (continued)
Framatome Technologies Inc.	210,456 elements	7 elements narrow DC, 10 elements wide DC	Typically 0.50 in (1.27 cm) axial spacing with finer spacing at transitions	120 elements (every 3-degrees)	Approx. 18 vertical levels	Approx. 25 radial rings
GRSmbH, Germany	470,000	DC radial narrow KV = 6 / wide KV = 6	DC axial narrow KV = 10 / wide KV = 53	DC azimuthal KV = 160	LP vertical KV = 20	LP radial KV = 36 / azimuthal KV = 160
Nuclear Research Institute Rez plc	272,261	10/16	~ 50/100, partially unstructured (nozzles region)	90/90	15	~50, partially unstructured
US Nuclear Regulatory Commission	434,589	8 to 12 / 13 (upper region grid adaption results in range of values)	50 to 100 / 55	180 to 240 / 180	19	30
NUPEC(Nuclear Power Engineering Corporation)	273,945	10/15	8/36	74	21	64
Vattenfall Utveckling AB	133,136	9 / 15	31 / 27	120 / 120	15	15

4.3 Buoyancy effect modeling

Buoyancy mainly affects flow pattern and thus it can play a significant role in the validity of a simulation. Furthermore, if buoyant effects are substantial, the turbulence generated must be modeled to get an accurate estimate of mixing. The participant models ranged substantially in the inclusion of temperature dependent properties. While most participants employed forms of temperature dependent densities and viscosities, fewer considered the effect of temperature on conductivity and specific heat to be relevant.

Table 4-5: Temperature dependent parameters used in participant models

Organization	temperature dependent density (how)	temperature dependent viscosity	temperature dependent thermal conductivity	temperature dependent specific heat
AEA Technology	No but Boussinesq buoyancy approximation included	Yes	No	No
Battelle Ingenieurtechnik GmbH	Boussinesc approximation, BETA = 2.07E-4 1/K	Mu = 1.002E-2 Pas	k = 5.996E-1 W/mK (const.)	c = 4.182E+3 J/kgK (const.)

Organization (continued)	temperature dependent density (how) (continued)	temperature dependent viscosity (continued)	temperature dependent thermal conductivity (continued)	temperature dependent specific heat (continued)
CEA keps	yes using Boussinesq approximation, Reference temperature 59 and beta function of T according to the real density at T; reference density at 59	dynamic viscosity mu function of T	constant, value at 59	constant, value at 59
CEA nut0 (sequential)	yes using Boussinesq approximation, Reference temperature 59 and beta function of T according to the real density at T; reference density at 59	dynamic viscosity mu function of T	constant, value at 59	constant, value at 59
CEA par (parallel)	yes using Boussinesq approximation, Reference temperature 59 and beta fonction of T according to the real density at T; reference density at 59	dynamic viscosity mu function of T	constant, value at 59	constant, value at 59
Fortum Engineering Ltd	Yes	Yes	No	Yes
Framatome Technologies Inc.	YES - Variable density via quadratic equation fit	YES - Variable viscosity via exponential equation fit	YES - Variable conductivity via exponential equation fit	NO
GRSmbH, Germany	const. density	const. viscosity	const. thermal conductivity	const. specific heat
Nuclear Research Institute Rez plc	no	no	no	no
US Nuclear Regulatory Commission	Table, Code uses Interpolation at each time step	Table, Code uses Interpolation at each time step	Table, Code uses Interpolation at each time step	Constant
NUPEC(Nuclear Power Engineering Corporation)	Yes (1000.8+2.59*10-2*T-6.05*10-3*T2+1.60*10-5*T3)	Yes (fitted by the 4'th order polynominal)	No, constant value	No, constant value
Vattenfall Utveckling AB	piecewise linear, 4 points	piecewise linear, 5 points	piecewise linear, 5 points	piecewise linear, 5 points

4.4 Turbulence modeling and wall treatment

The consequences of a rapid boron dilution transient depend not only on the initial slug volume but also on the mixing experienced by the slug as it progresses to the core inlet. This mixing is turbulence dominated, and thus the turbulence modeling is an essential component of input model preparation. If computational methods and mesh refinement are adequate, turbulence modeling must be employed to reproduce the physical mixing associated with rapid boron-dilution transients. As can be seen in Table 4-6, all but one participant used turbulence modeling. One other participant carried out a sensitivity study on the effect of turbulence by running a model with a 600,000 cells using k-ε, and than increasing the cells to 125 % but omitting turbulence. Only two participants deemed the increased computational complexity associated with the RNG turbulence model necessary.

Table 4-6: Turbulence and wall modeling parameters

Organization	Turbulence model and constants if different from standard	Wall treatment
AEA Technology	k-epsilon	Smooth, adiabatic with standard logarithmic wall functions
Battelle Ingenieurtechnik GmbH	k-eps standard model	log - law
CEA keps	standard K-Epsilon	standard wall laws, without any mesh refinement near the wall
CEA nut0 (sequential)	Turbulent diffusivity = 0	No wall laws
CEA par (parallel)	Turbulent diffusivity = 0	No wall laws
Fortum Engineering Ltd	Standard k-eps model	Logarithmic wall functions
Framatome Technologies Inc.	K-epsilon	Log law of the wall
GRSmbH, Germany	k-e turbulence model	log law
Nuclear Research Institute Rez plc	k - epsilon	standard wall function
US Nuclear Regulatory Commission	RNG k-epsilon	non-equilibrium wall functions
NUPEC (Nuclear Power Engineering Corporation)	No use of any special turbulence model	No slip and adiabatic condition
Vattenfall Utveckling AB	RNG-k-epsilon	adiabatic, roughness=0, non-equilibrium wall function

4.5 Outlet modeling

The simulation outlet boundary is positioned one-third to half-way up into the core region. The reason for it is the flow feedback to the lower plenum and the downcomer can affect the flow pattern. The parameters of Table 4-7 describe the outlet boundary of each simulation. In addition to the physical position of the outlet and the boundary condition, the modeling of the support plate and the pressure loss experienced by the fluid can potentially affect the

feedback into the lower plenum and downcomer. Although participants' input model outlets range significantly, a comparison of effect is not possible from the ISP 43 data since too many parameters are dissimilar.

Table 4-7: Outlet boundary input parameters

Organization	Outlet locations (fn z)	Boundary condition at the outlet	Modeling of core support plate	Total pressure drop from bottom of the vessel to the outlet at steady state
AEA Technology	Ring around inside of core barrel, 0.156m above centre of cold legs	Neumann boundary conditions	Porous medium with flow resistance	100 Pa
Battelle Ingenieurtechnik GmbH	z = 0,167 m	zero gradient	actual simulation via nonmatch	6847 Pa
CEA keps	Z = -,62865	Uniforme pressure	No modeling : continuous medium as possible using coarse meshes	Computations stopped before steady-state is reached; buoyancy effects included in pressure pressure not stored and difficult to understand
CEA nut0 (sequential)	Z = -,62865	Uniforme pressure	No modeling : continuous medium as possible using coarse meshes	Computations stopped before steady-state is reached; buoyancy effects included in pressure pressure not stored and difficult to understand
CEA par (parallel)	Z = -,62865	Uniforme pressure	No modeling : continuous medium as possible using coarse meshes	Computations stopped before steady-state is reached; buoyancy effects included in pressure pressure not stored and difficult to understand
Fortum Engineering Ltd	Model included short parts of the hot leg pipes	Reference pressure P=0 Pa	Detailed model using tetrahedral mesh	8 kPa
Framatome Technologies Inc.	At extended core outlet (Z = -20.25 inches above nozzles)	Constant pressure	5 Rings of distributed resistance elements	1.7 inches H2O
GRSmbH, Germany	hot leg A intersection with DC wall	const. pressure	porous media	1500 Pa
Nuclear Research Institute Rez plc	0.5731 m under leg level	pressure	none	268.52 Pa
US Nuclear Regulatory Commission	z = -.448m (44.8 cm below cold legs)	constant P	Porous Media	150 Pa at centerline
NUPEC(Nuclear Power Engineering Corporation)	level where downcomer gap changes from narrow to wide (0.7504m from bottom of the vessel)	free outflow	The plate was not modeled but the equivalent flow resistance was applied.	1000(Pa) for Test-A and 1200(Pa) for Test-B
Vattenfall Utveckling AB	z=+0.216	static pressure = 0	uniformly distributed resistance	180 Pa

5 Data and Figures of Merit Comparison

The initial figure of merit selected at the first ISP 43 workshop was the average temperature at level 4, i.e., at the exit of the downcomer. During the second workshop, participants selected an additional set of indicators to aid in the overall evaluation of code performance.

Specifically, the level average temperature was supplemented with the standard deviation at that level, and the minimum and maximum, which are indicative of the azimuthal mixing of the front/slug. Furthermore, the same first order (level average temperature) information was to be evaluated just below and above the slug entrance, i.e., at levels 8 and 10. The azimuthal distribution figures of merit are also evaluated at these levels. The flow pattern in the expanded downcomer is also shown at several representative times for both the tests and participant submissions.

5.1 Test A

The precision of an azimuthal average and standard deviation obtained by sampling only the 24 channel-centered thermocouples at a particular level was verified in the visualization facility. The Figure 5-1 plots show a comparison of the average and standard deviations obtained using the full azimuthal resolution of the LIF technique (360 points) as compared to the 8, 12, or 24 points used in the loop level averages. Typically the mean values were close, although the level 10 data show some clear differences with the full resolution results. The more important level 4 data gives very good agreement, indicating that 24 azimuthally spaced points seems to be sufficient to capture the first and second moments of the concentration distribution.

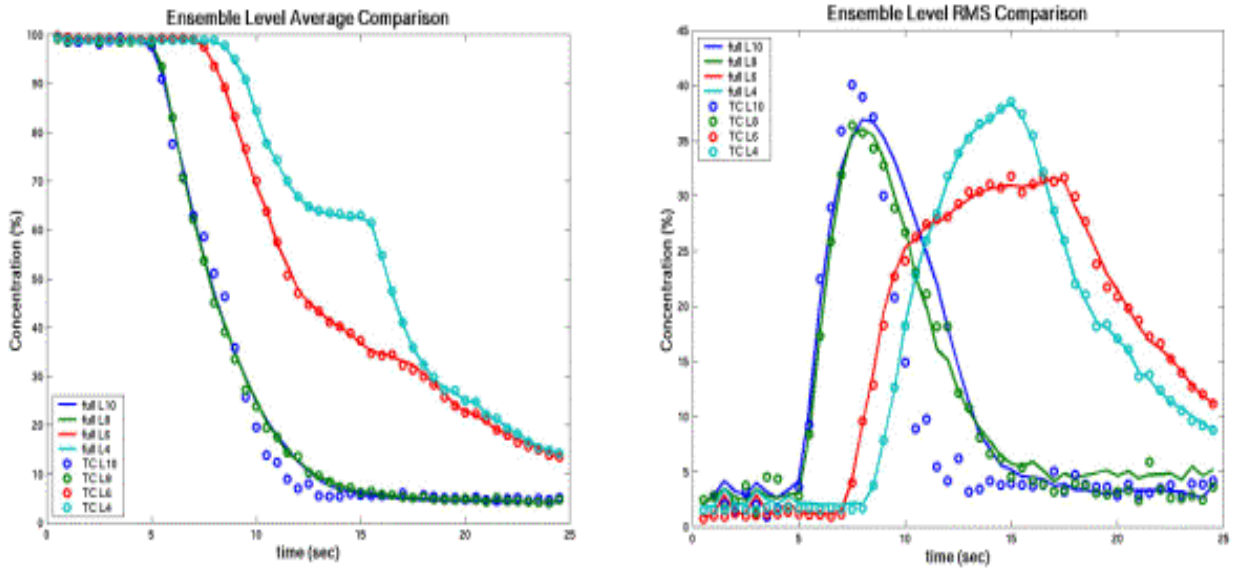

Figure 5-1. Comparison of continuous azimuthal sampling to 24 discrete locations sampling for levels 4, 8 and 10 during test A

It should be pointed out, however, that the sampled points used in this comparison still represent radially averaged values, whereas the loop thermocouple data is only acquired at a single radial position; the measurement loci difference is illustrated in Figure 5-2.

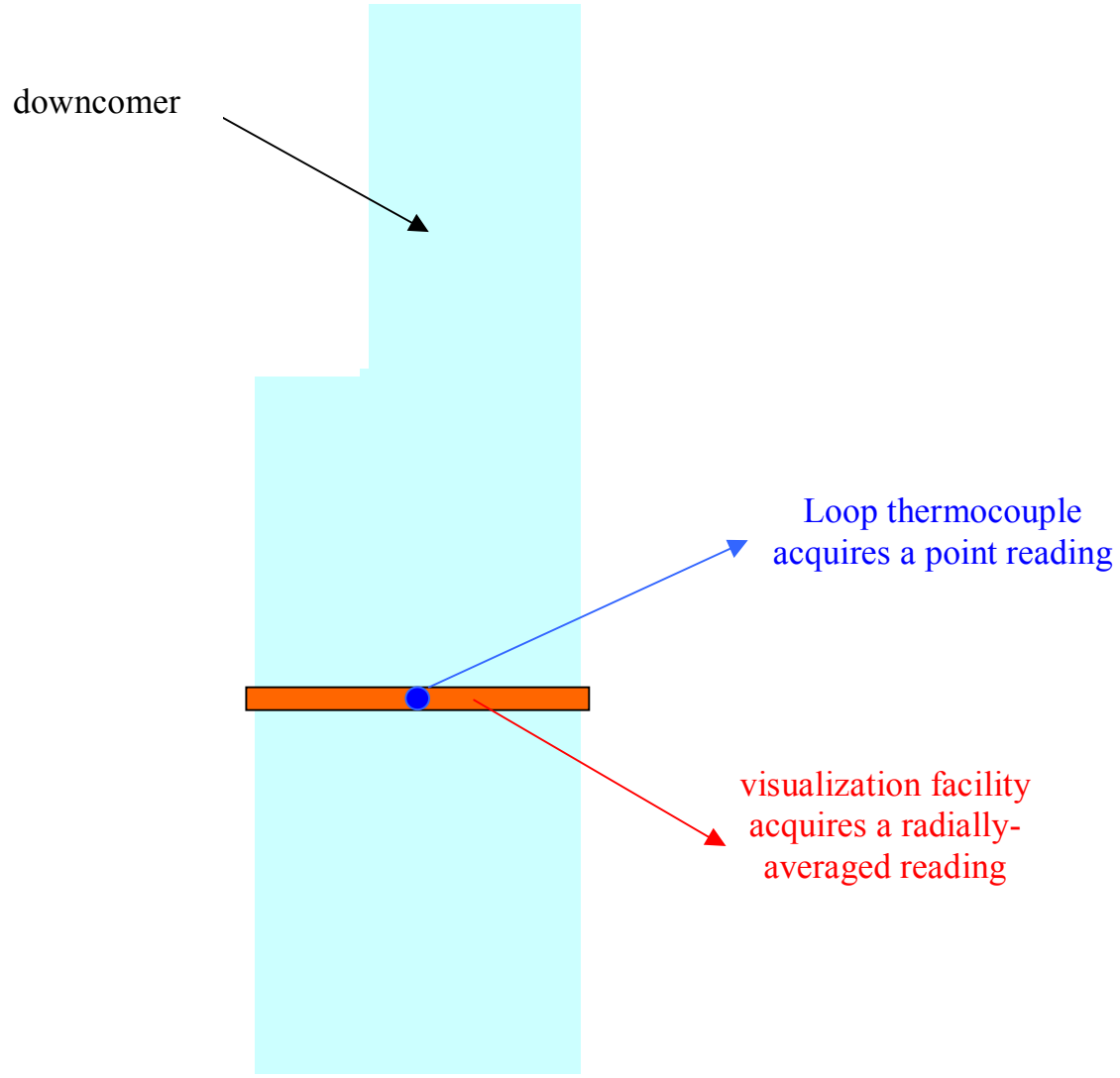

Figure 5-2. Measurement loci of the loop and visualization facility

5.1.1 Initial/Boundary Conditions and Ensemble Data for Test A

Initial and boundary conditions supplied to participants were taken from the second test of series A. The initial primary coolant temperature was specified to be uniform at 74 °C. The boundary conditions consisted of the inlet flow rate and front temperature given in Figure 5-3 and the core pressure drop given in Figure 5-4.

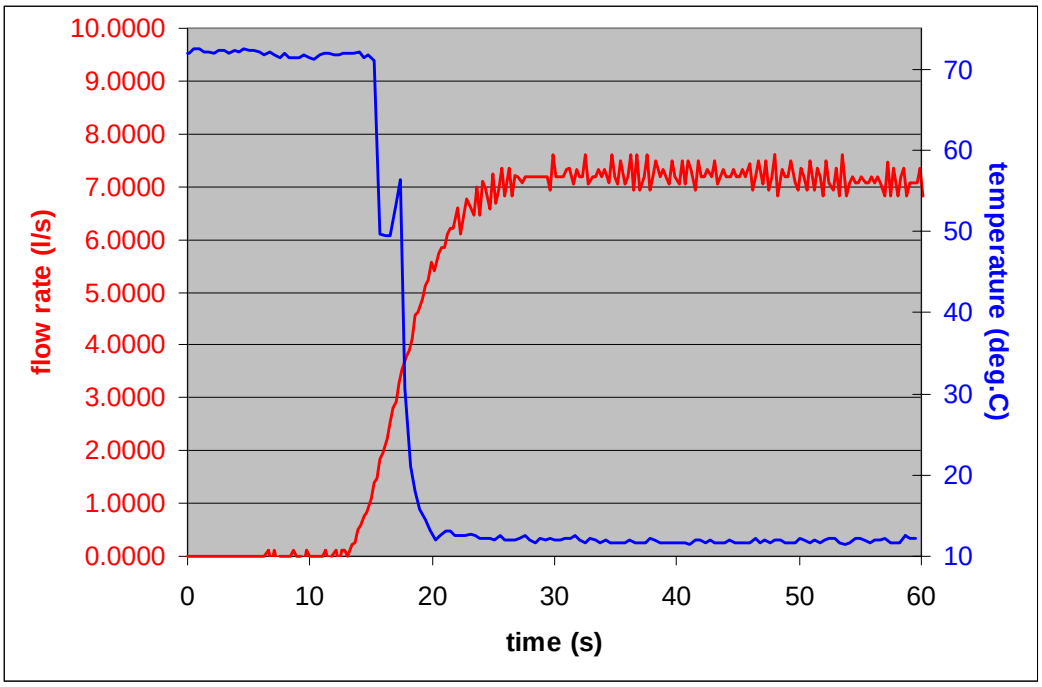

Figure 5-3. Flow and temperature boundary conditions for test A

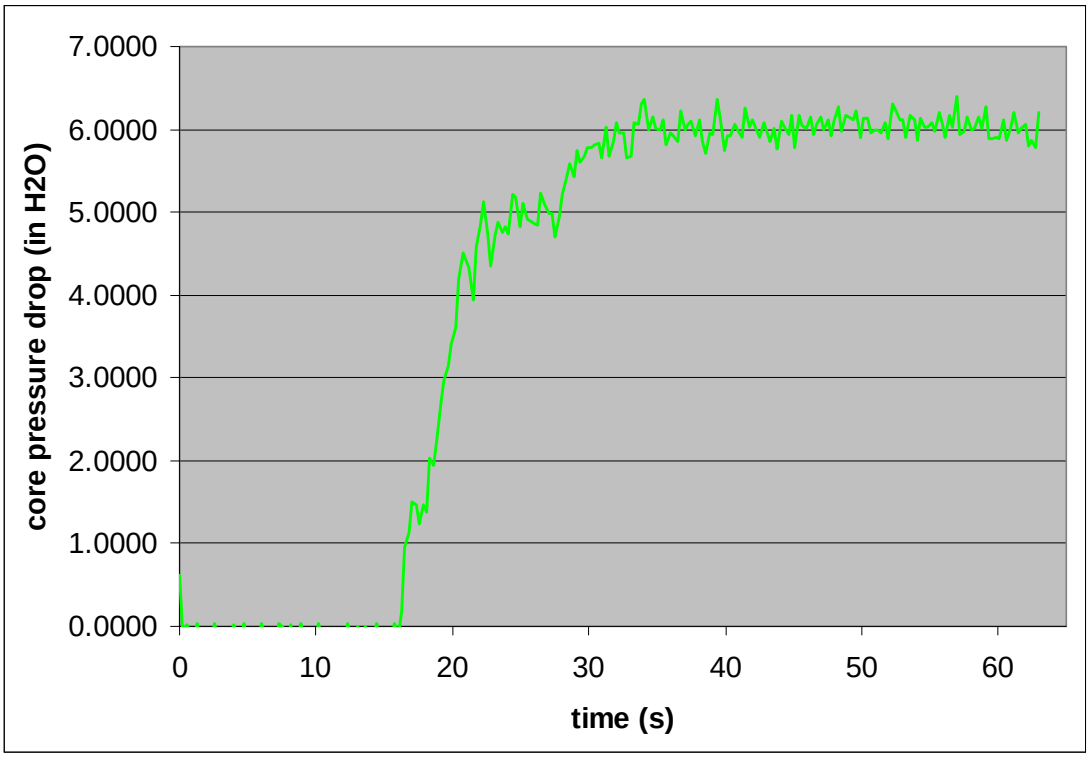

Figure 5-4. Core pressure drop boundary conditions for test A

5.1.1.1 Level 4

The level 4 azimuthally averaged temperature history is the principal figure of merit for ISP 43. This figure is augmented by indicators of azimuthal mixing: standard deviation, minimum, and maximum among thermocouples positioned at the 24 azimuthal locations

Figure 5-5 plots the azimuthally averaged temperature histories at level 4. Experimental and computational data are shown. The solid black line and the black error bars represent the loop data for the 16 redundant tests. The nominal test, i.e., the test for which boundary conditions where supplied to participants, falls within the standard deviation and is represented by a thin black line. The ensemble average and standard deviation of the 8 redundant visualization test is represented by the red line and the red error bars. The loop and visualization facility temperature histories are within each other's standard deviation. Participant submissions are indicated by the other lines on the plot. While computations appear to be generally in very good agreement, a general trend of slight undermixing is noticeable in about half of the simulations.

Figure 5-6 shows the history of the standard deviation among the 24 thermocouples of level 4. This is a measure of the azimuthal mixing the front has experienced by the time it reaches the downcomer outlet. Ensemble loop and visualization facility data are again within each other's standard deviation. Participant predictions are distributed around the experimental data with some showing more azimuthal mixing than measured experimentally, and other showing less. It is interesting to note that at about 30 seconds all simulations show a more uniform azimuthal distribution than the experiments.

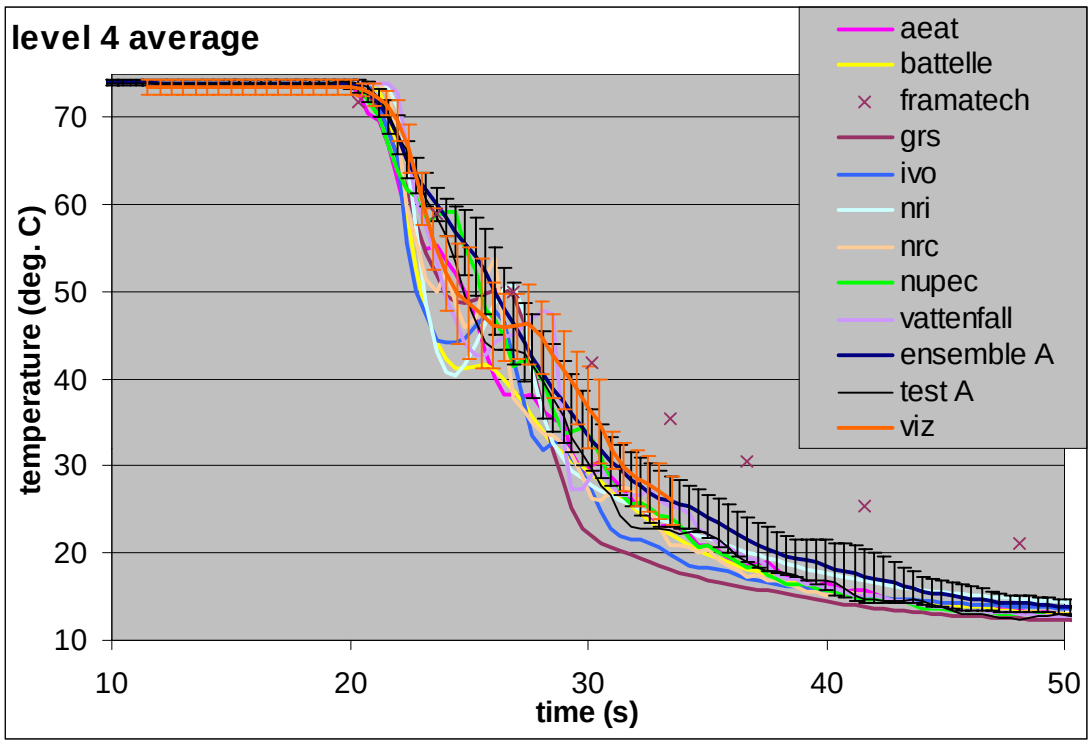

Figure 5-5. Level 4 azimuthally averaged temperature histories for Test A

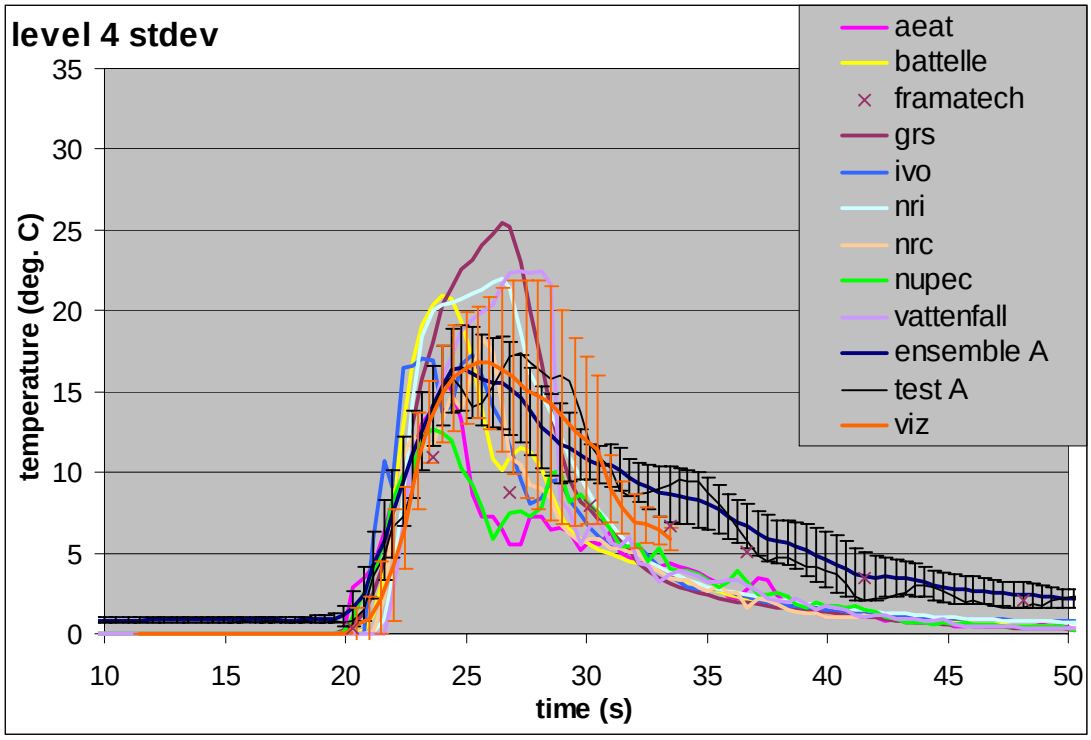

Figure 5-6. History of the standard deviation of the 24 channel-center thermocouples at level 4 for Test A

The minima and maxima, Figure 5-7 and Figure 5-8, are further indicators of azimuthal mixing. The general agreement between experiments and predictions is very good for minima. The minimum histories that fall below the experimental data confirm a trend of under mixing in a couple of predictions. The general agreement is not equally good for the maxima. Note that the maximum is representative of the primary coolant in the boron dilution transient. This means that the experiments show the front to be more segregated that do some calculations, since it takes longer for the primary coolant to be mixed into the diluted slug in both the loop and the visualization facility.

5.1.1.2 Level 8

Level 8 thermocouple readings were added to the list of figures of merit during the second workshop. Data from this level indicates flow pattern development as shown in subsequent sections and in section 5.2.2.

Level 8 average temperature histories are shown in Figure 5-9. Loop and visualization facility data fall within each others standard deviations, but are more distinct than level 4 averages. Almost all participant submissions are within the visualization facility standard deviations, but lie distinctly below the loop with the exception of the IVO submission. As will be discussed in section 5.2.2, the level 8 behavior is a primary indicator of distinctions in flow pattern.

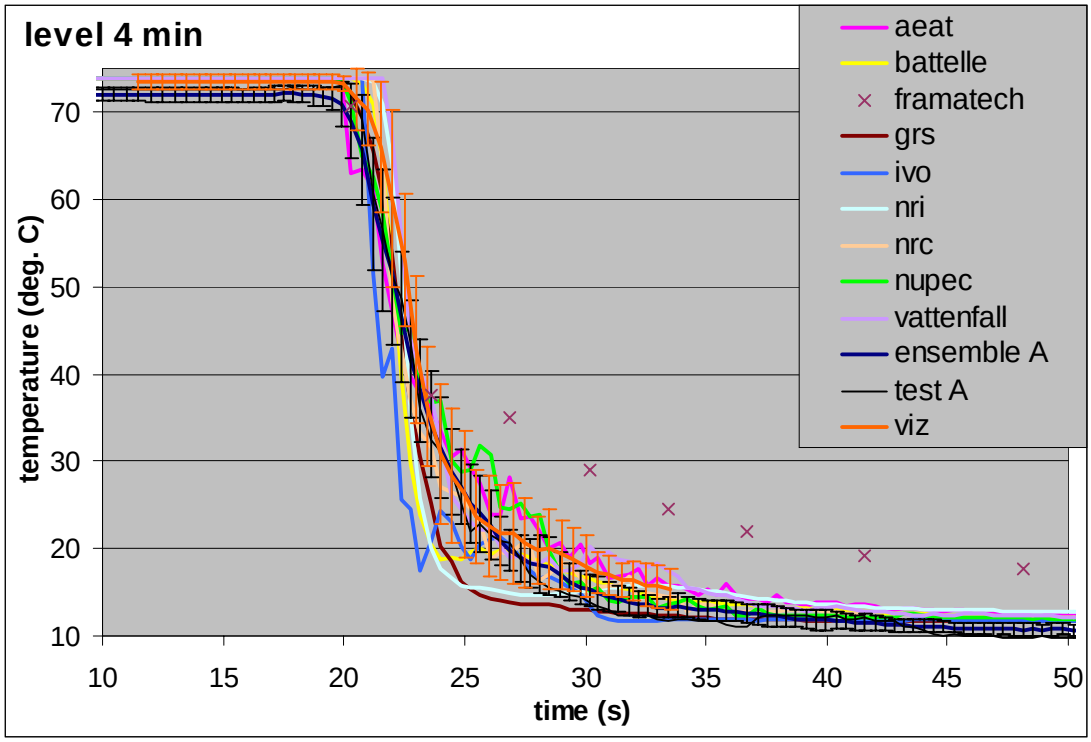

Figure 5-7. History of the minimum among the 24 channel-center thermocouples at level 4 for Test A

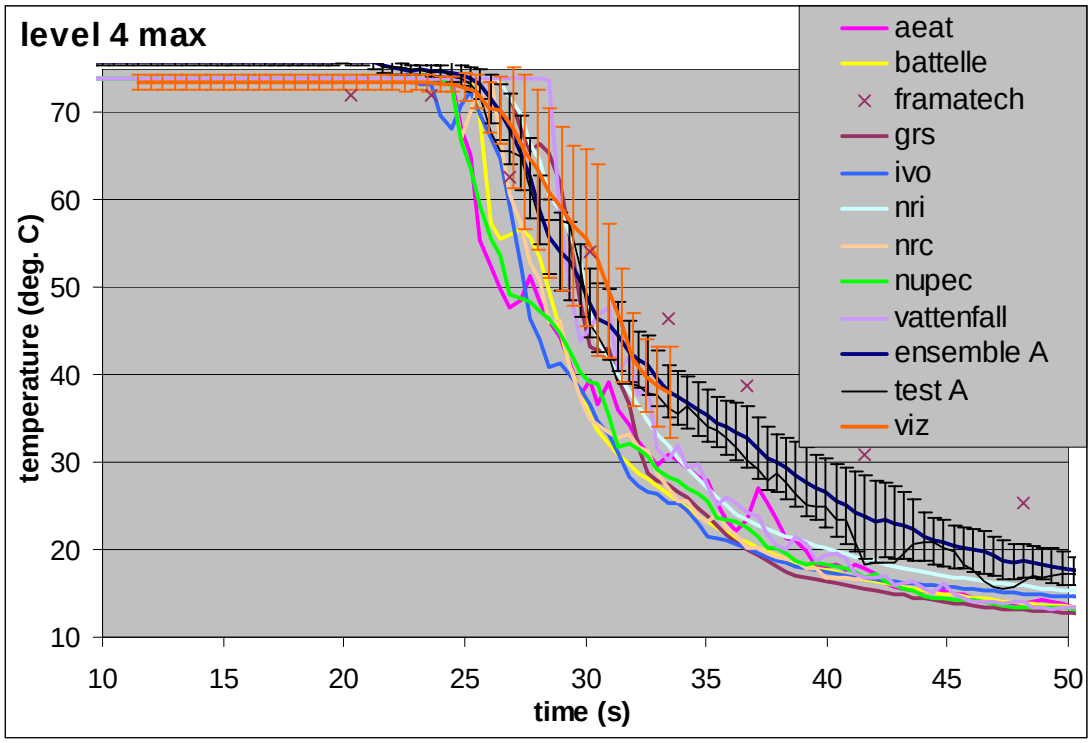

Figure 5-8. History of the maximum among the 24 channel-center thermocouples at level 4 for Test A

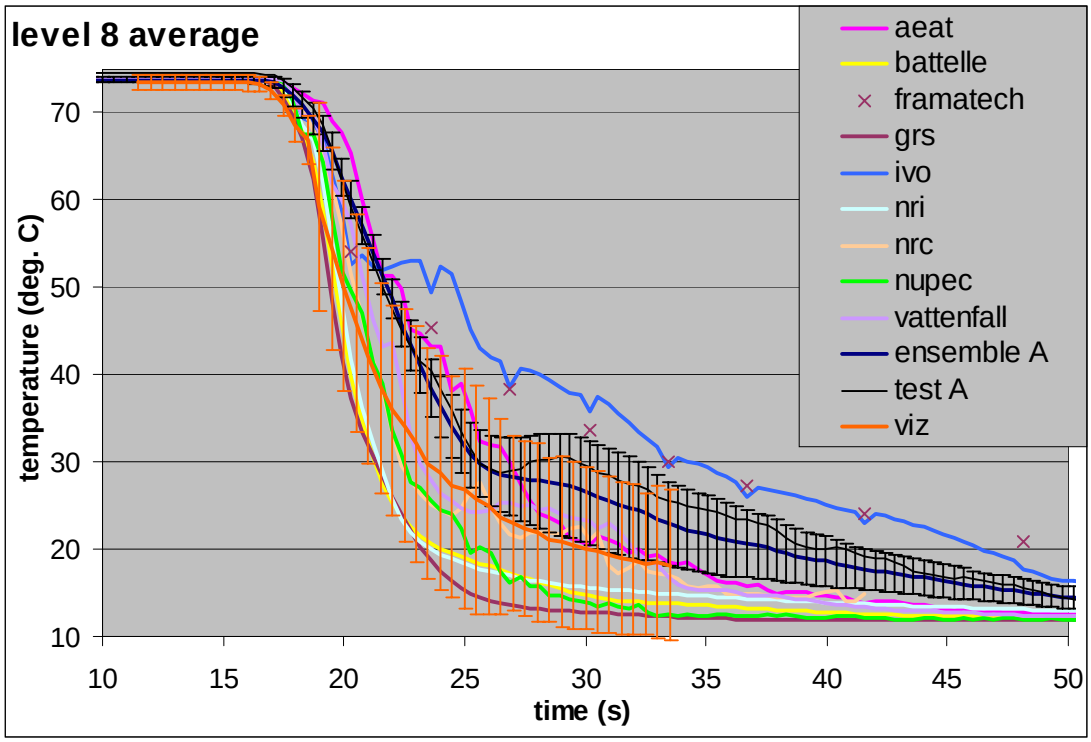

Figure 5-9. Level 8 average temperatures among the 24 channel-center thermocouples for Test A

Figure 5-10 through Figure 5-12 show the standard deviation minima and maxima histories at level 8. The figures indicate that the front remains more segregated and the primary fluid is slower to get entrained into the front (see especially Figure 5-12) in the loop and IVO data, but is more uniformly mixed azimuthally in the visualization facility and the balance of participant submissions.

5.1.1.3 Level 10

Level 10 is relatively poorly instrumented in the loop. The average temperature and standard deviation histories are plotted, however, to complete the quantitative analysis of flow pattern features. The average temperature histories of Figure 5-13 show that the front affects level 10 about 3 seconds later in the loop than in the visualization facility or participant submissions. Furthermore, the loop and IVO histories show that throughout the transient, level 10 is slower to become mixed. The standard deviation histories depicted in Figure 5-14 also show substantial differences between most of the simulations and the loop and visualization facility data. Experimental data show that the front penetrates upwards, a relatively high degree of segregation between cold and warm fluids persists throughout the transient. Computational data, with the exception of IVO, NRI and Battelle, indicate that level 10 becomes uniformly mixed within about 30 seconds of the start of the simulation.

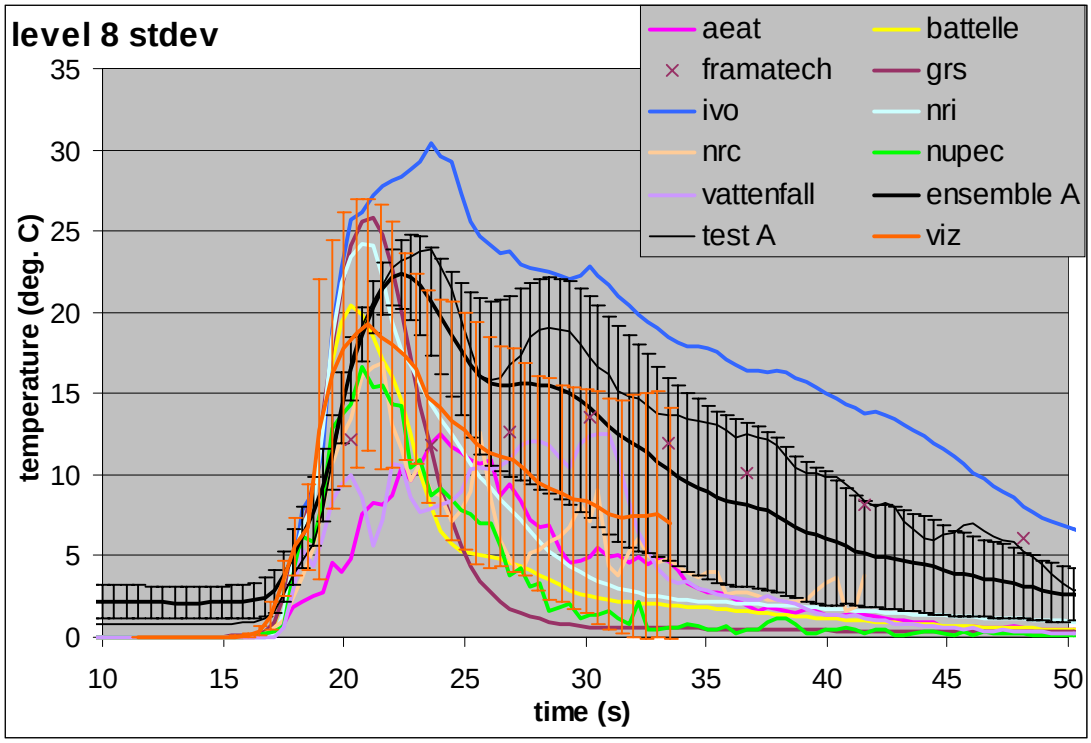

Figure 5-10. Level 8 standard deviations among the 24 channel-center thermocouples for Test A

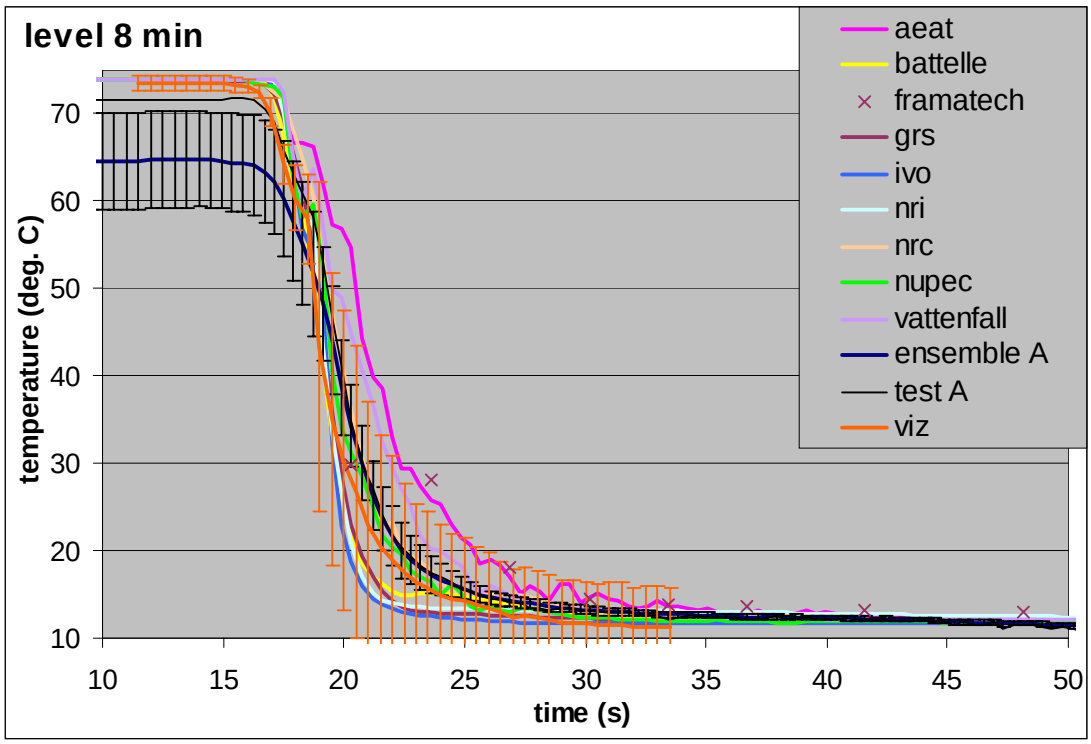

Figure 5-11. Level 8 minima among the 24 channel-center thermocouples for Test A

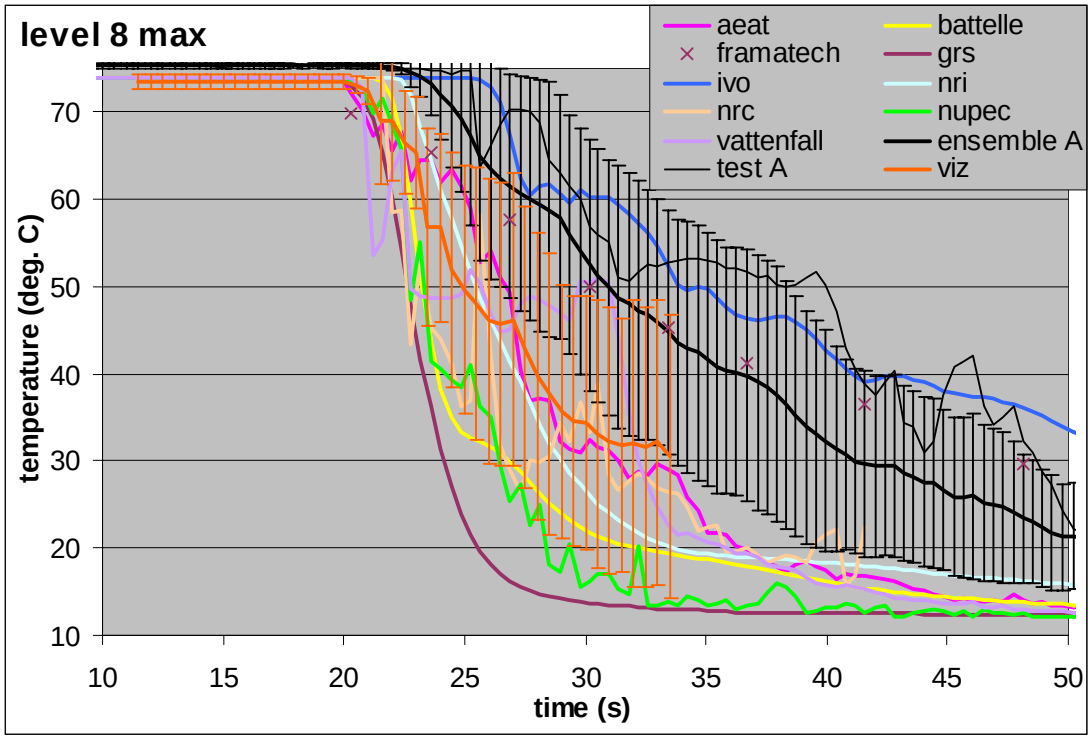

Figure 5-12. Level 8 maxima among the 24 channel-center thermocouples for Test A

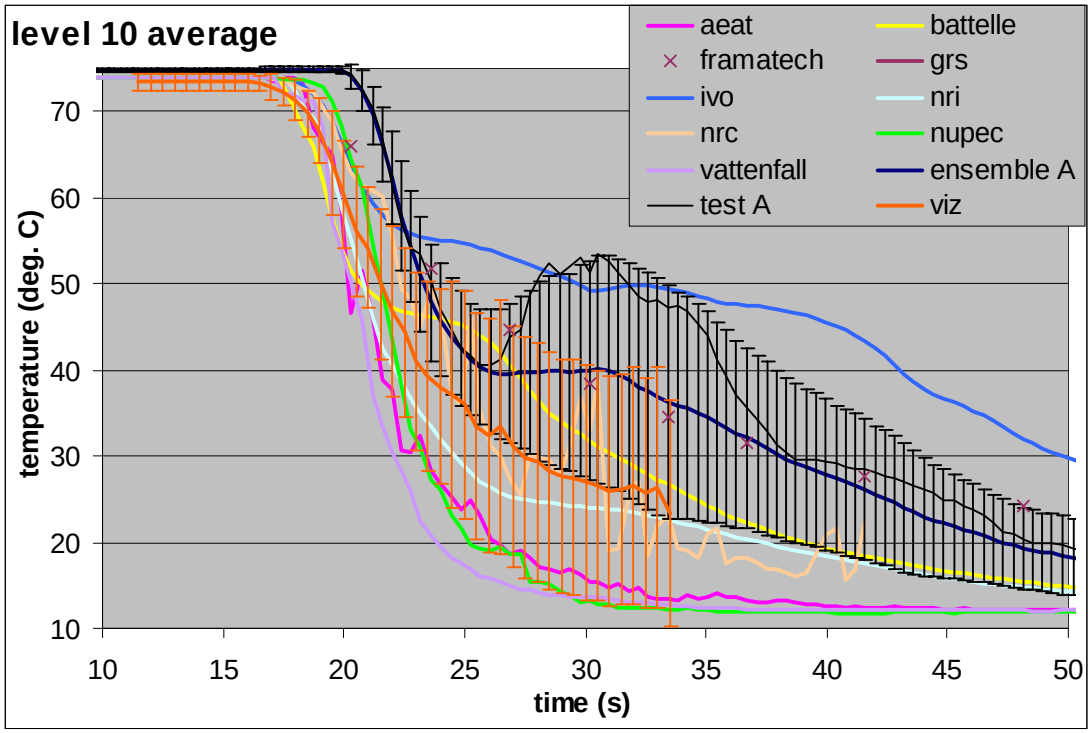

Figure 5-13. Level 10 average temperatures among the 24 channel-center thermocouples for Test A

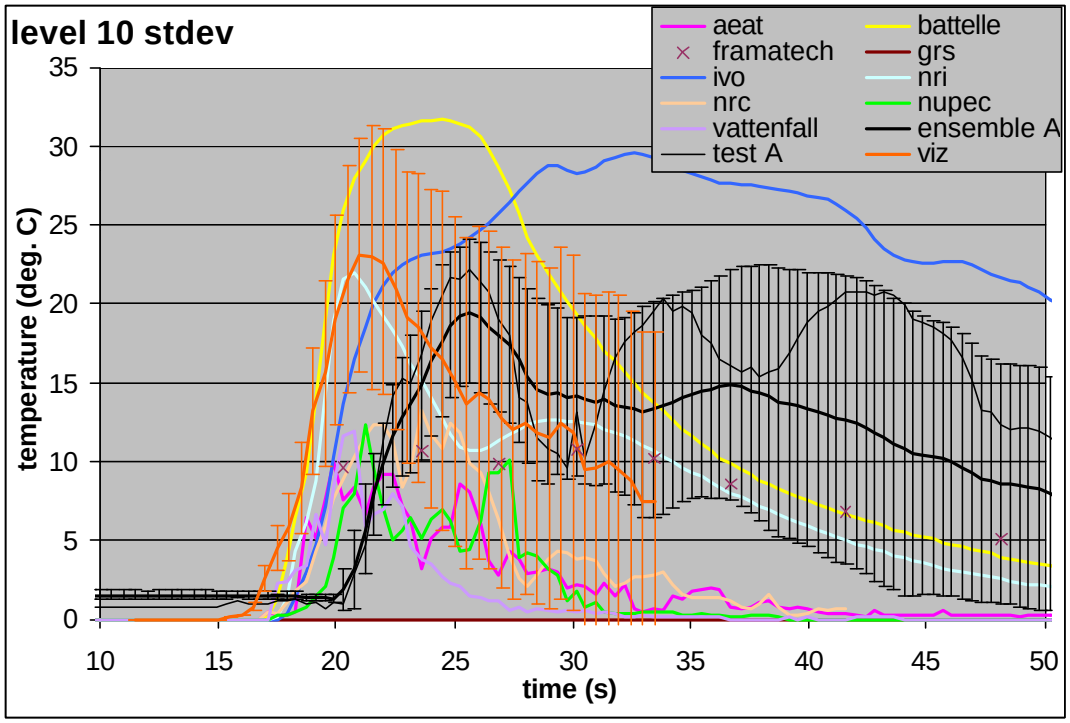

Figure 5-14. Level 10 standard deviations among the 24 channel-center thermocouples for Test A

5.1.2 Azimuthal Behavior for Test A Levels 4, 8 and 10

The progression of the front through the system can be tracked by plotting the temporal evolution of the front at a particular level. Figure 5-15 shows this information as obtained from loop data.

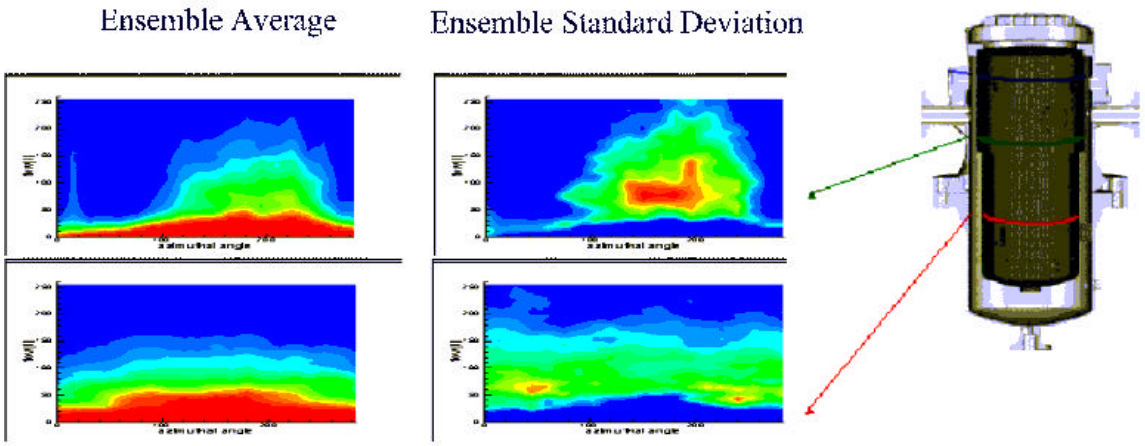

Figure 5-15. Test A ensemble averages and ensemble standard deviation obtained in the loop for Levels 8 (top pair), and 4 (bottom pair). The horizontal axis represents the azimuthal position, the vertical axis represents volume injected, and the color indicates concentration (red = warm primary or “borated”, dark blue = cold front or “dilute”)

Figure 5-16 shows the temporal evolution of the azimuthally resolved ensemble averages at three different levels of the downcomer as measured in the visualization facility. These levels correspond to three of the specific locations (level 4, 8, and 10) in which detailed instrumentation was installed within the integral 2x4 loop facility. The plots show time along the vertical axis, and the azimuthal position around the downcomer (positive angles are clockwise when viewing the downcomer from above). The red end of the spectrum indicates the maximum scalar concentration of the simulated Boron, while the dark blue indicates a near zero or "dilute" volume of fluid.

Level 10 (topmost level, blue line) gives the average concentration evolution in the upper downcomer, in a region between the injection inlet and the upper DC boundary. This level sees the earliest evolution of the front passage, with the interface passing through level 10 first at an azimuthal location of 0°, at a time of approximately 7 seconds. This corresponds to the radial expansion of the front around the injection point. The relatively weak ensemble standard deviation for this level also shows the strong repeatability of the flow evolution in this part of the downcomer, along with a relatively sharp interface that is characterized by relatively little mixing.

Level 8 (middle level, green line) shows the concentration evolution within a region just above the DC gap expansion. The trace is very similar to the Level 8 evolution, with the exception of a little more irregularity in the region opposite the injection leg (-180 degrees), where the front interfaces meet at a stagnation plane before they are forced to enter the lower plenum.

Level 4 shows the greatest amount of mixing and variability, concentrated in a recirculation zone centered below the injection leg (starting first in the region close to 0 degrees and spreading out towards +/- 100 degrees as time increases). The large ensemble standard deviation in this region indicates a variability of the large-scale structures along the interface. In addition, the fact that the azimuthal profile remains relatively unchanged from 12 to 17 seconds gives rise to a consistent "flat spot" that can be characteristically observed in the level 4 average profiles shown in figure 5-1. A discussion of these features and their cause will be discussed in the flow pattern section the report (section 5.2.2).

5.1.2.1 Level 4

A quantitative way of examining the flow pattern is by plotting the azimuthal profile at several times through out the transients. The times selected for test A are 24, 28, 32 and 36 seconds. In Figure 5-17, the origin corresponds to the center of the injection cold leg, CL A1, and the angle increases counterclockwise when viewed from the top. The data of Figure 5-17 is the ensemble average of the 16 redundant A tests in the loop; standard deviations marked by error bars. The plot shows that the front penetrates downwards under the cold leg and that the region opposite the injection site is the last to be mixed. The significant standard deviation around the injection site at 24 s shows that the front is spreading to varying degrees as it travels through the downcomer.

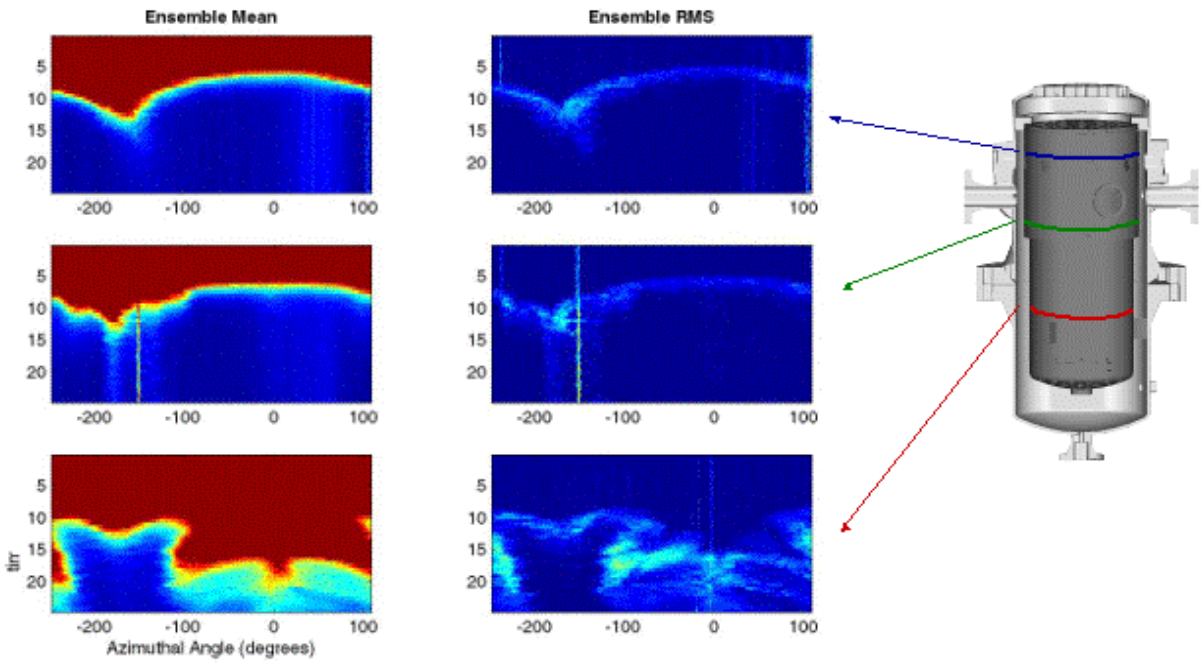

Figure 5-16. Test A ensemble averages and ensemble standard deviation obtained in the visualization facility for Levels 10 (top pair), 8 (middle pair), and 4 (bottom pair). The horizontal axis represents the azimuthal position, the vertical axis represents time, and the color indicates concentration (red = 100% or "borated", dark blue = 0% or "dilute"). Note inverted time axis relative to Figure 5-15.

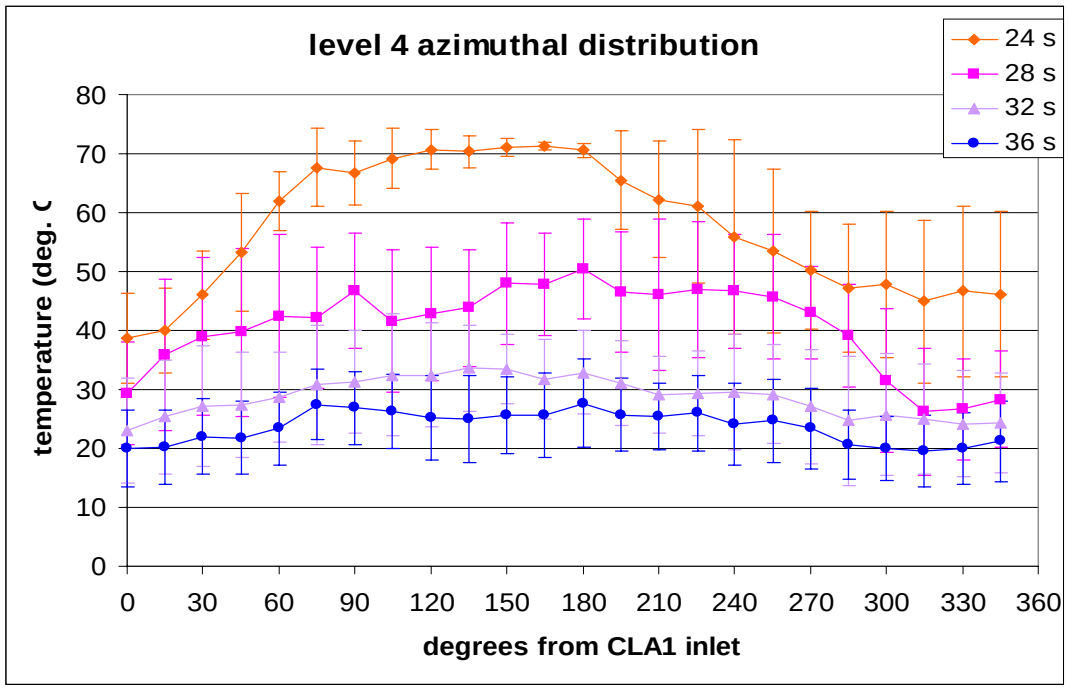

Figure 5-17. Temporal progression of the azimuthal distribution at level 4 in the loop for Test A

Figure 5-18 through Figure 5-21 compare the loop and Visualization facility data to participant submissions. The visualization data differ from the loop data, and indicate a different flow pattern. In the visualization facility, the front reaches level 4 predominantly to the left and the right of the injection cold leg, and less mixing is observed under the injection site and on the side opposite to CL A1. At 28 seconds, the front is predominantly flowing on the side opposite the injection cold leg. Participant submissions at both 24 and 28 s appear closer to the visualization facility experiments. At 32 and 36 data, all experimental and computational data converge. The flow pattern is discussed in further details in section 5.2.2.

5.1.2.2 Level 8

The azimuthal temperature evolution at level 8 in the loop is plotted in 4 s increments in Figure 5-22. Since 0 degree corresponds to the injection site, it can be noted that the front flows primarily vertically under CL A1.

Figure 5-23 through Figure 5-26 compare loop data to visualization facility and participant submissions. While in the first part of the transient experimental data and computations are in good agreement, differences become apparent as the transient progresses. Specifically, at 28 and 32 s only the loop and IVO data show that the primary coolant on the side opposite the injection is relatively unaffected, and that the front entrains primarily fluid under the injection site. This observation is consistent with flow pattern examinations, which are presented in section 5.2.2.

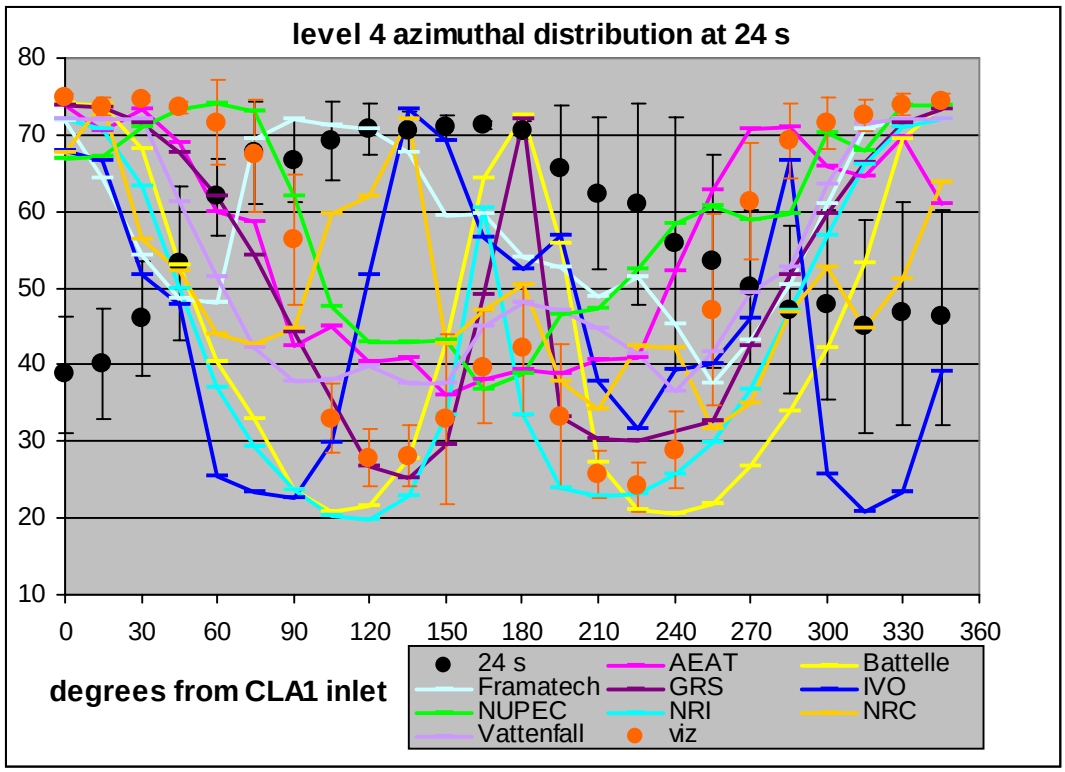

Figure 5-18. Azimuthal distribution at level 4 at 24 s for Test A

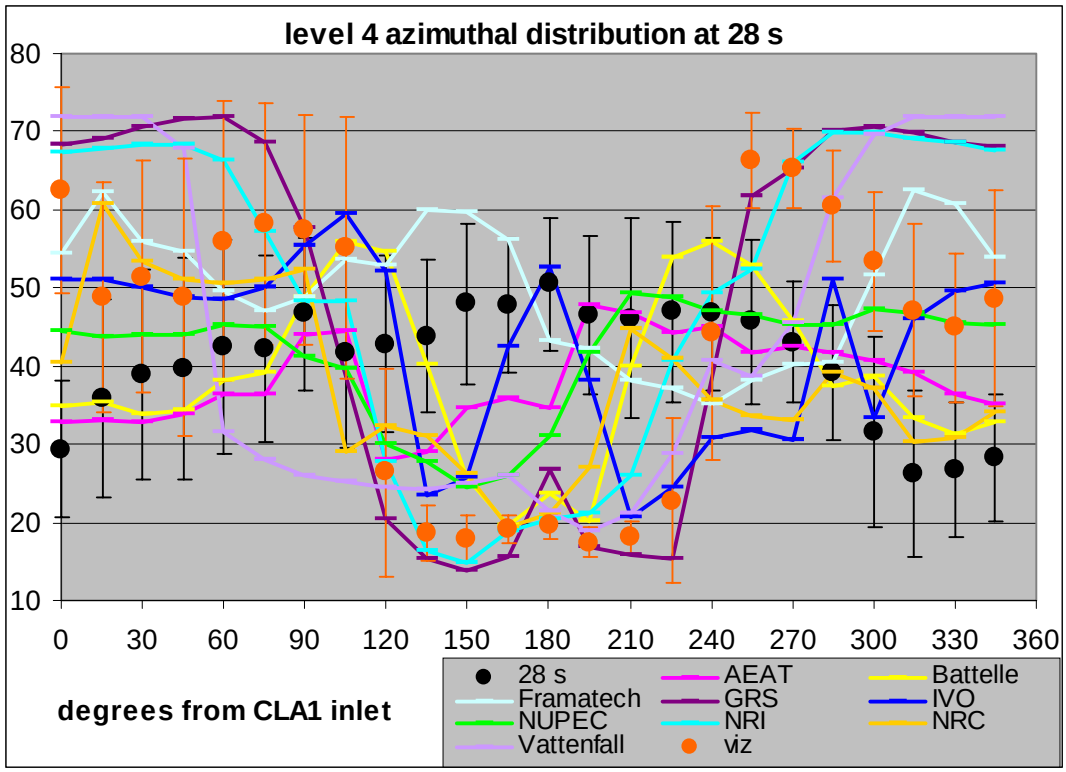

Figure 5-19. Azimuthal distribution at level 4 at 28 s for Test A

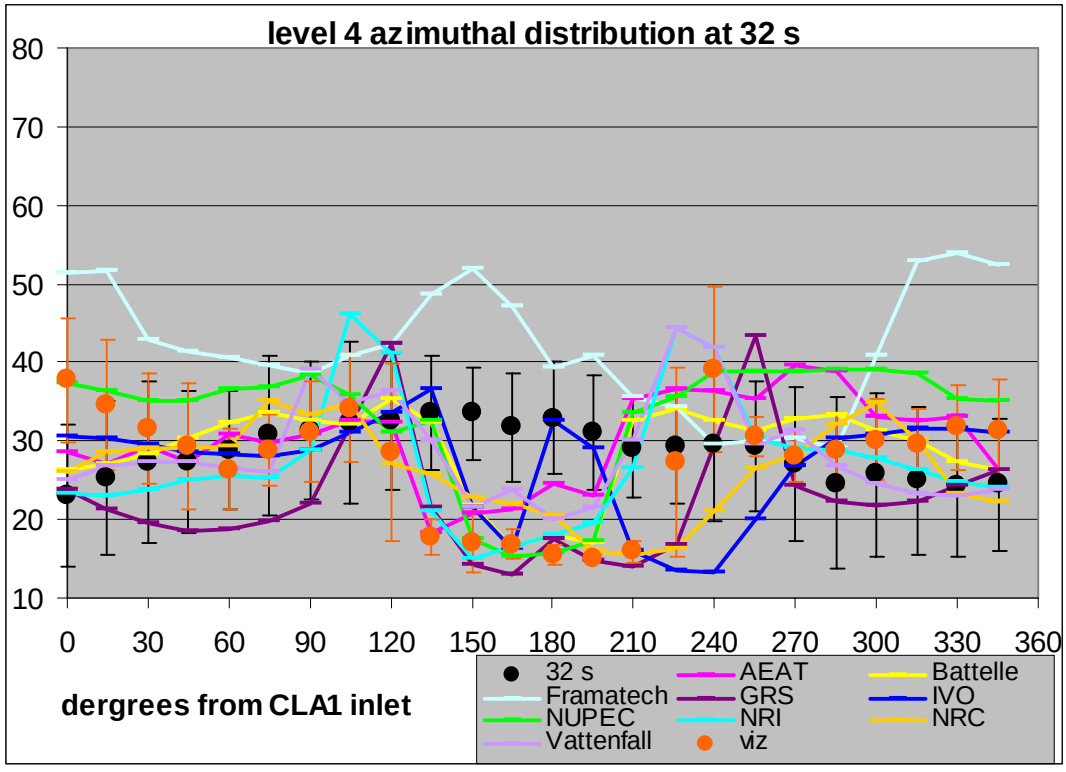

Figure 5-20. Azimuthal distribution at level 4 at 32 s for Test A

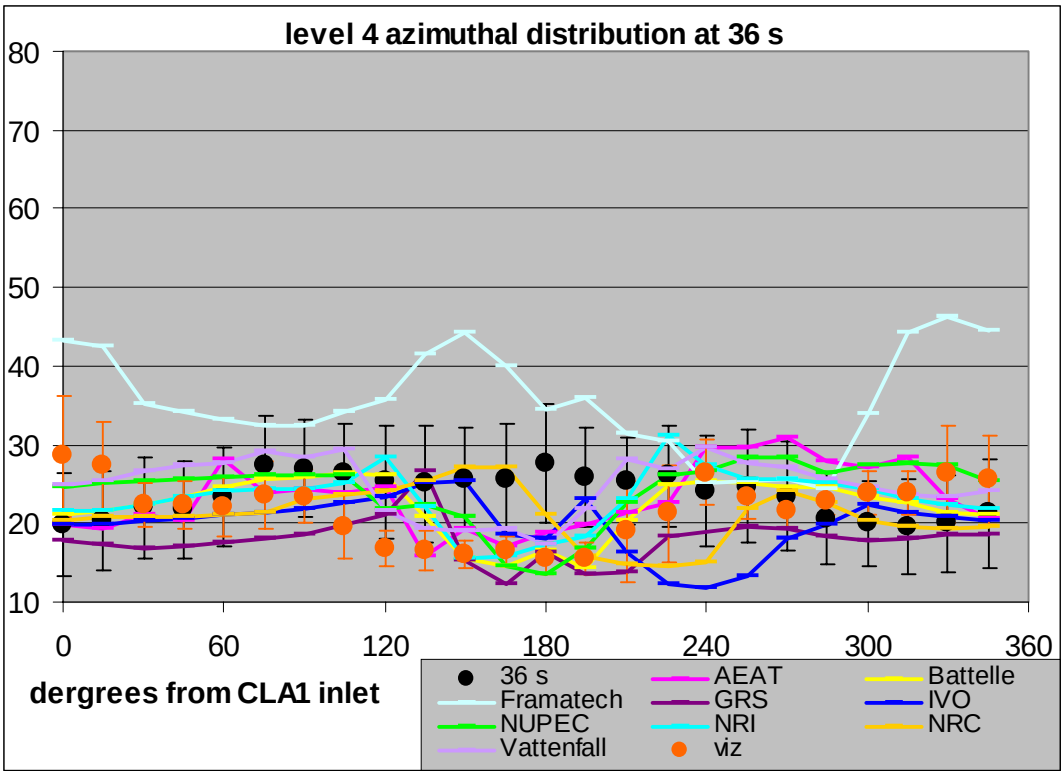

Figure 5-21. Azimuthal distribution at level 4 at 36 s for Test A

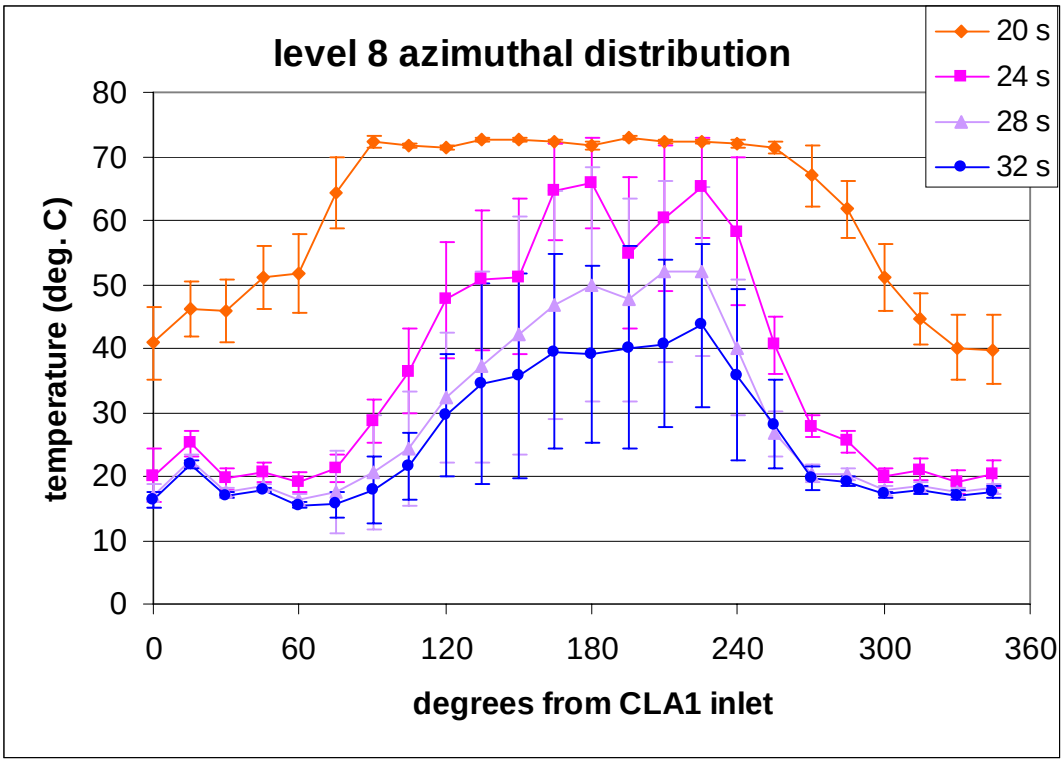

Figure 5-22. Azimuthal distribution at level 8 in the loop at 20, 24, 28 and 32 s for Test A

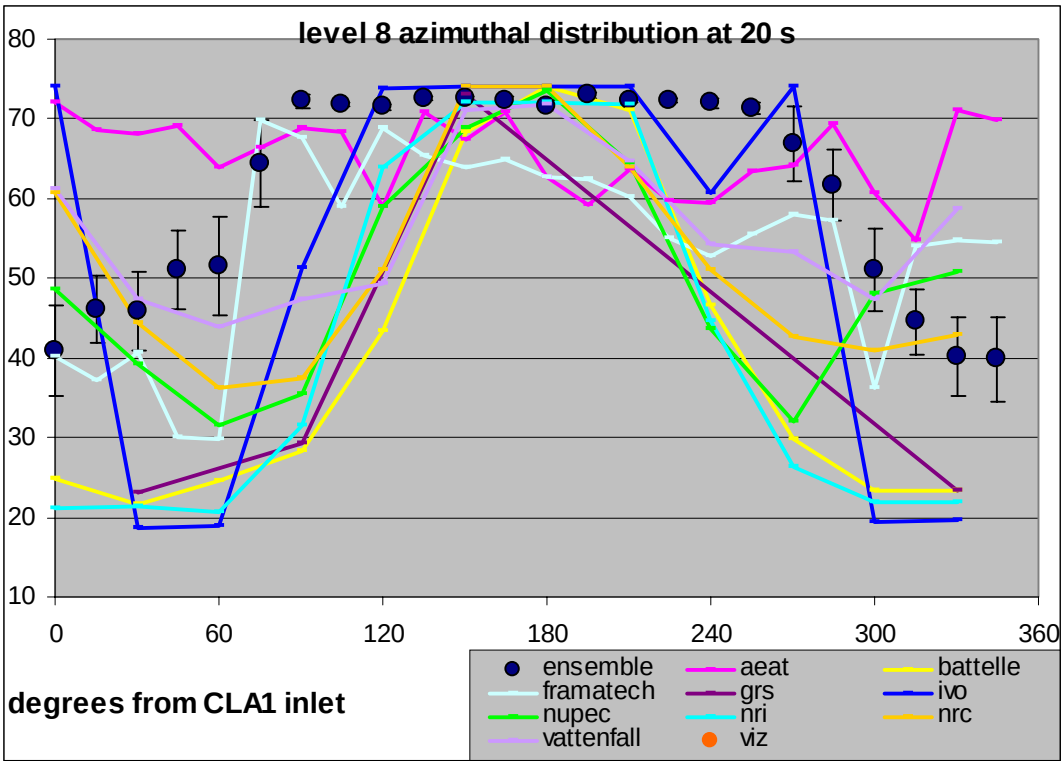

Figure 5-23. Azimuthal distribution at level 8 at 20 s for Test A

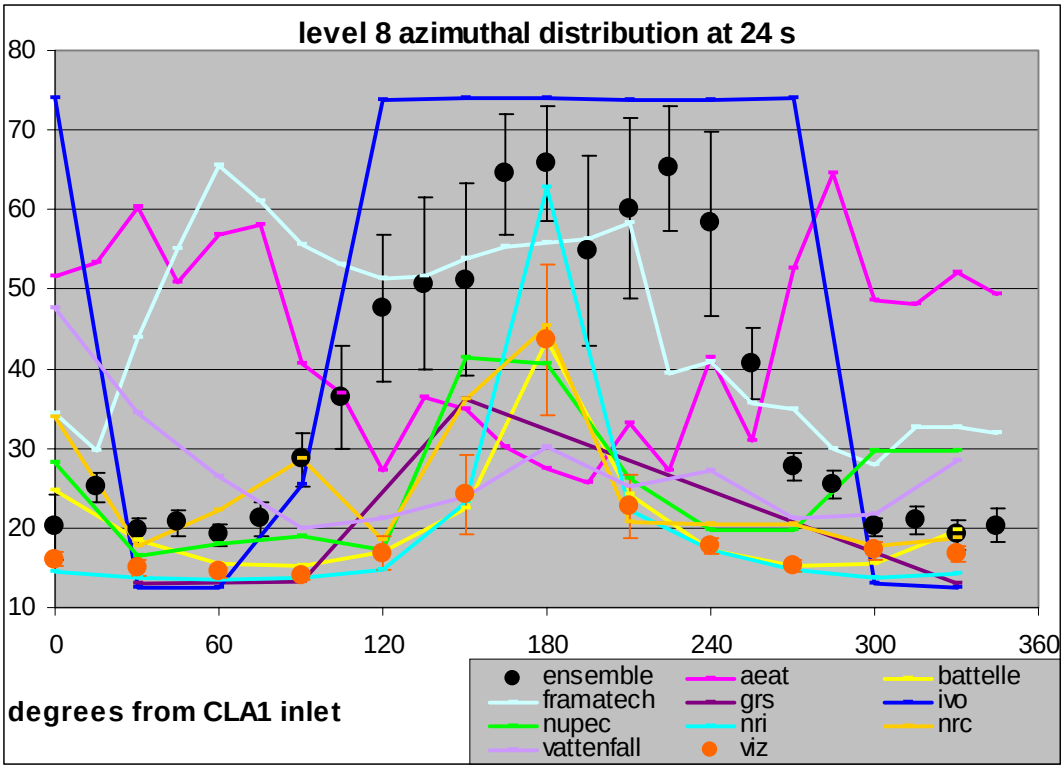

Figure 5-24. Azimuthal distribution at level 8 at 24 s for Test A

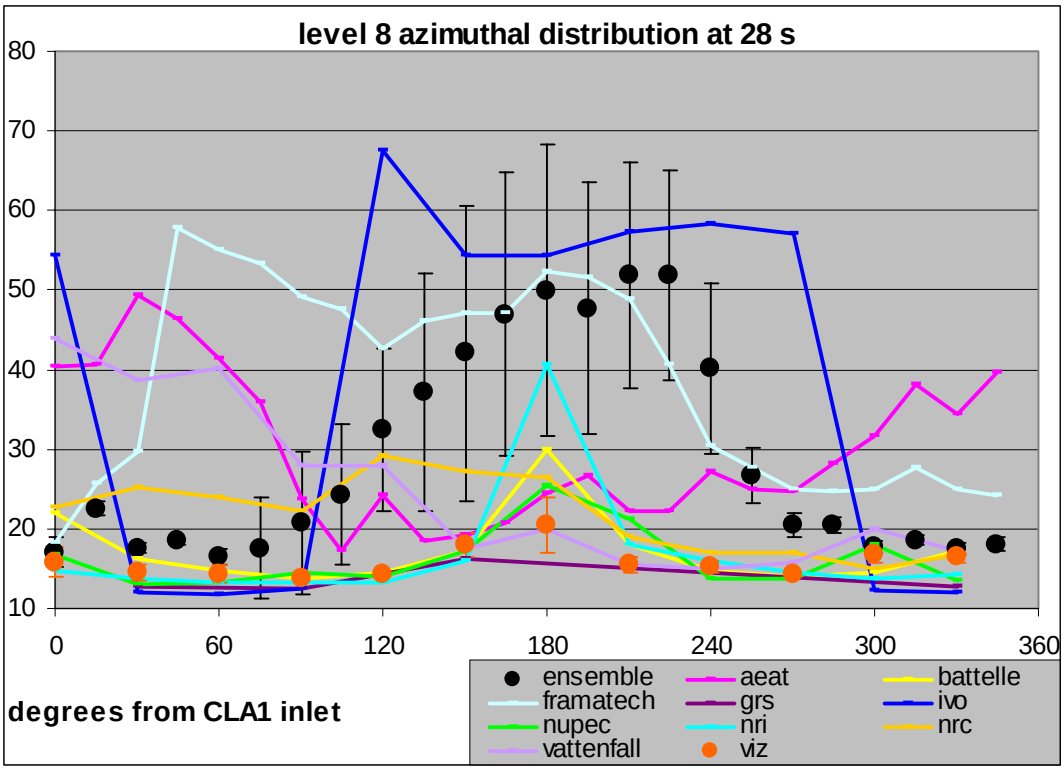

Figure 5-25. Azimuthal distribution at level 8 at 28 s for Test A

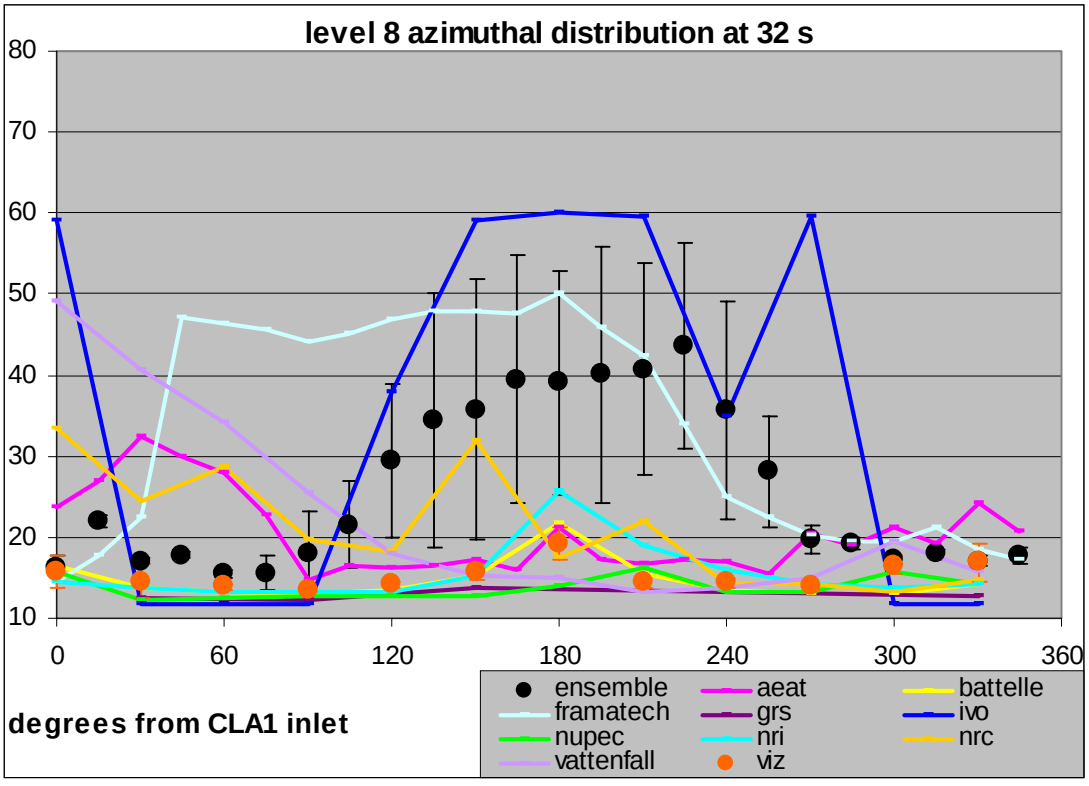

Figure 5-26. Azimuthal distribution at level 8 at 32 s for Test A

5.2 Test B

As for test A, the visualization facility confirmed the adequacy of thermocouple sampling in the loop. The azimuthally averaged data (Figure 5-4) leads one to similar conclusions to those provided by the front case. Namely, the high-resolution levels (24 sampling points) appear to provide adequate sampling to provide a converged mean and standard deviation provided there are not any significant radial variations in the concentration data.

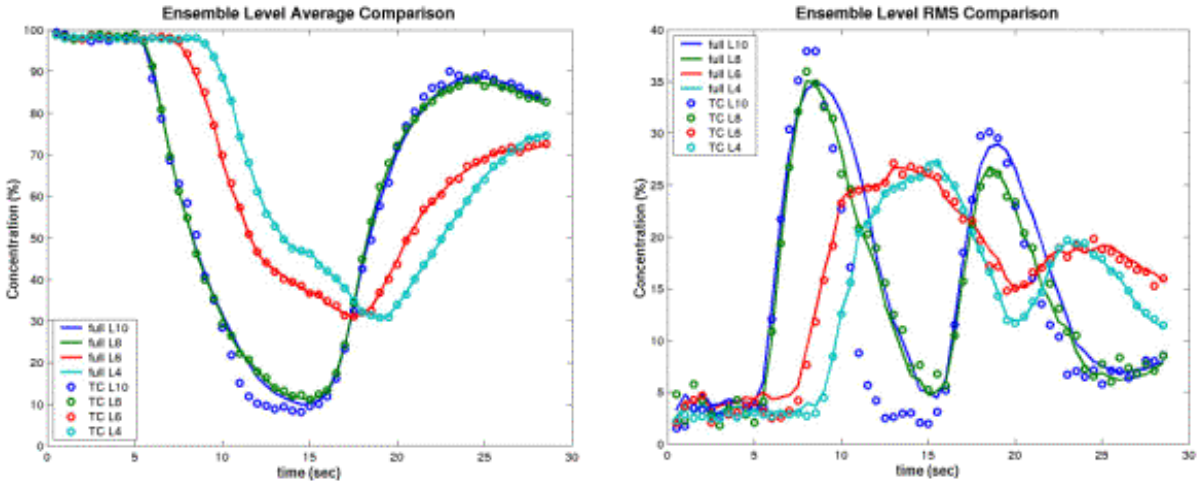

Figure 5-27. Level average and standard deviation comparisons of concentration vs. time for Test B

5.2.1 Initial and Boundary Conditions and Ensemble Data for Test B

The initial and boundary conditions for test B were derived from the second test in the series. The temperature and flow given to participants is shown in Figure 5-28.

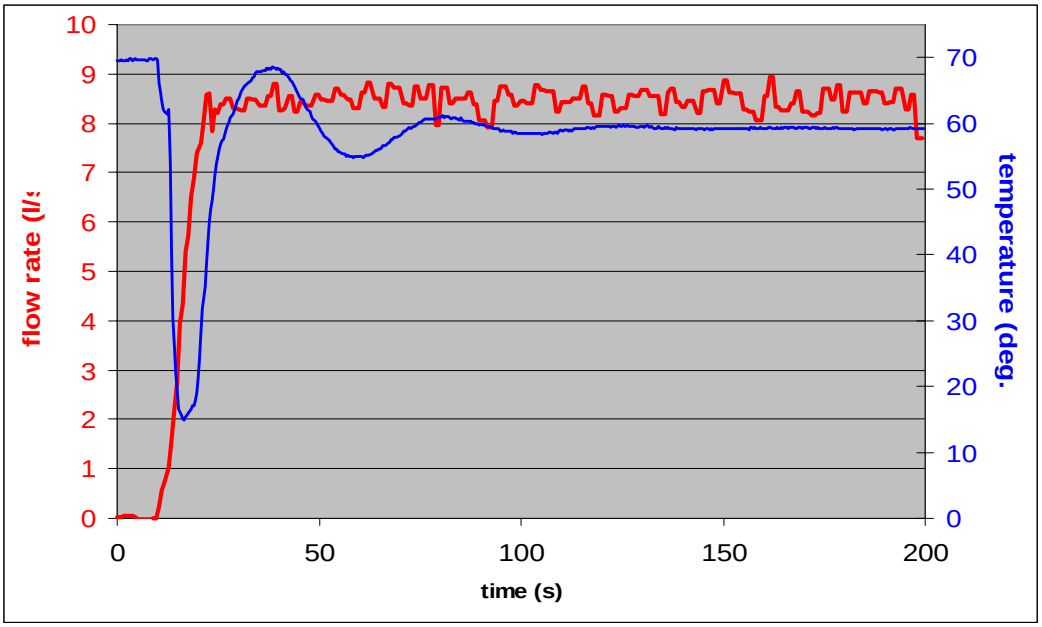

Figure 5-28. Flow and temperature boundary conditions for test B

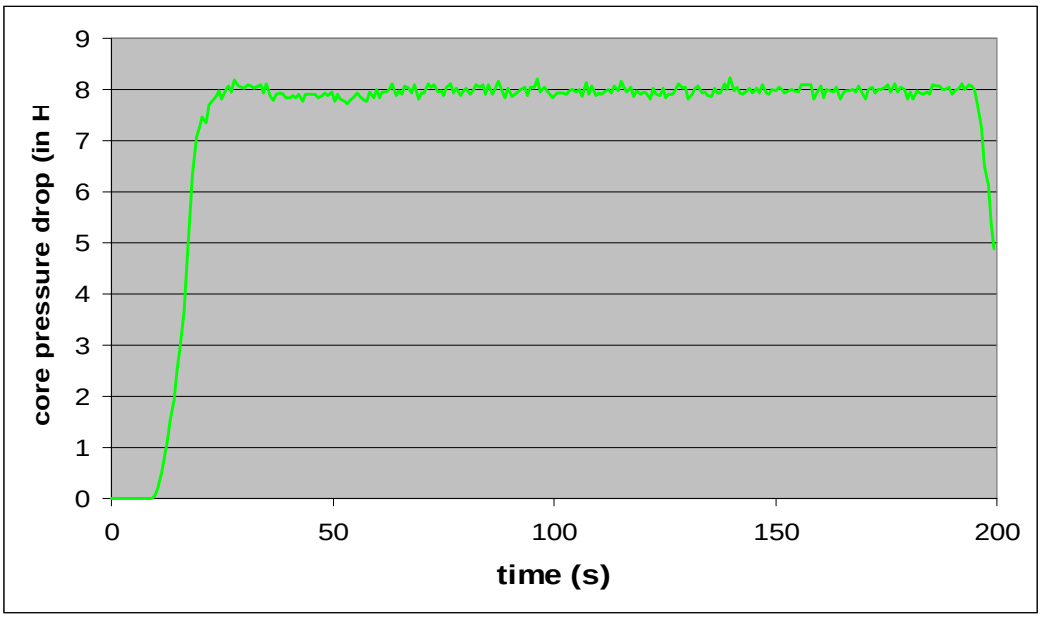

Figure 5-29. Core pressure drop boundary condition for test B

As in test A, the averages of the channel center thermocouples on levels 4 and 8 are the principal figures of merit. The data are supplemented with standard deviation, minimum and maximum histories to evaluate the azimuthal mixing. Because test series B injects a slug, which is a realistic representation of the injected volume in the boron-dilution transient, the average readings and mixing parameters at level 3 are also compared. This is the core inlet plane, and the quantities examined would provide the boundary and initial conditions for the coupled neutronic thermal-hydraulic computations necessary to evaluate the consequences of a boron dilution scenario.

5.2.1.1 Level 4

Participant submissions are in good agreement with the loop data, as can be observed in Figure 5-30. Furthermore, several participant submissions fall within the narrow standard deviation of the 6 redundant test B loop runs. Note that the slug injected in the loop is 56 l, while that injected in the visualization facility is 80l, which makes the comparison between the two sets of experimental data difficult. A further data reduction step that extracts the slug center is potentially possible, but it has to be applied individually at each level. This reduction step has not been carried out because the loop and visualization facility slugs differ in one other aspect. Specifically, the end of the slug is separated through a membrane in the visualization facility, which limits all diffusion at that end between the primary and slug coolants. Figure 5-30 illustrates this aspect by the steeper ascension of the trailing end of the slug, relative to loop, of computational temperature histories.

Figure 5-31 shows the standard deviations among the 24 channel center thermocouples. There are two local maxima in the history corresponding to the front and trailing ends of the slug. Participant simulations are again in good overall agreement with loop data. The minima of Figure 5-32 and the maxima of Figure 5-33 confirm that the simulations properly capture the azimuthal mixing at level 4.

5.2.1.2 Level 8

The level 8 average temperatures measured by the 24 channel center thermocouples are depicted in Figure 5-34. The loop standard deviation from the 6 redundant tests is very low as a consequence of the good repeatability of this test. As seen in Figure 5-35, most participant submission azimuthal mixing predictions are in very good agreement with loop data, but some simulations appear to excessively segregate the slug and primary fluids. It must also be noted that the standard deviation at level 8 only exhibits one maximum. This is indicative of the fact that the flow becomes well mixed azimuthally after the front end of the slug passes. Figure 5-36, the minimum temperature history, and Figure 5-37, the maximum temperature history, demonstrate that investigating standard deviation alone is insufficient. Specifically, the maxima of Figure 5-37 show that code predictions overestimate the extent to which warm primary coolant is entrained into the cold slug. This suggests that further attention has to be paid to mesh refinement near the injection site where the main flow features develop.

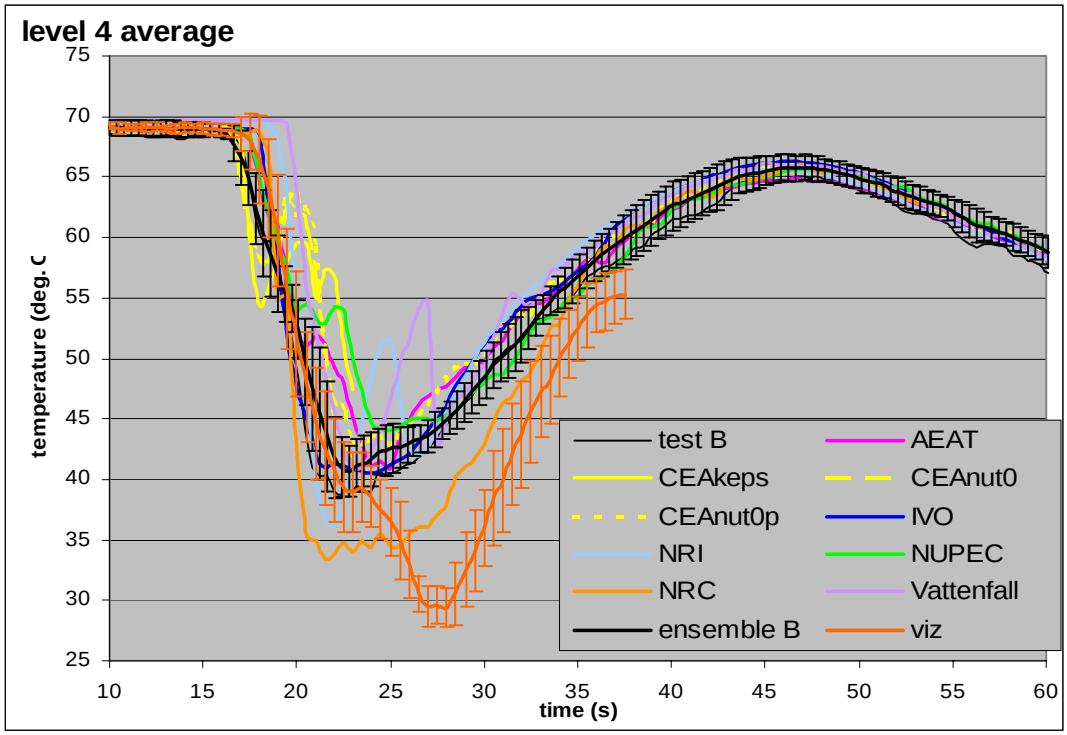

Figure 5-30. Level 4 average of the 24 channel-center thermocouples for Test B

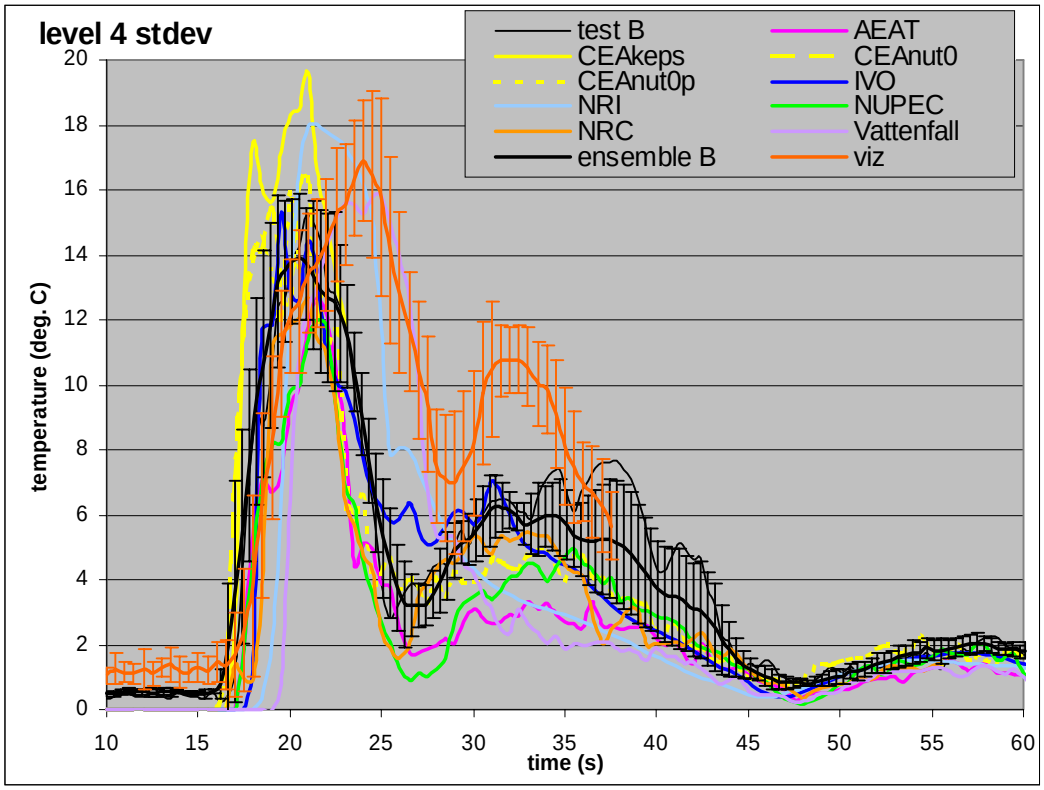

Figure 5-31. Level 4 standard deviations among the 24 channel-center thermocouples for Test B

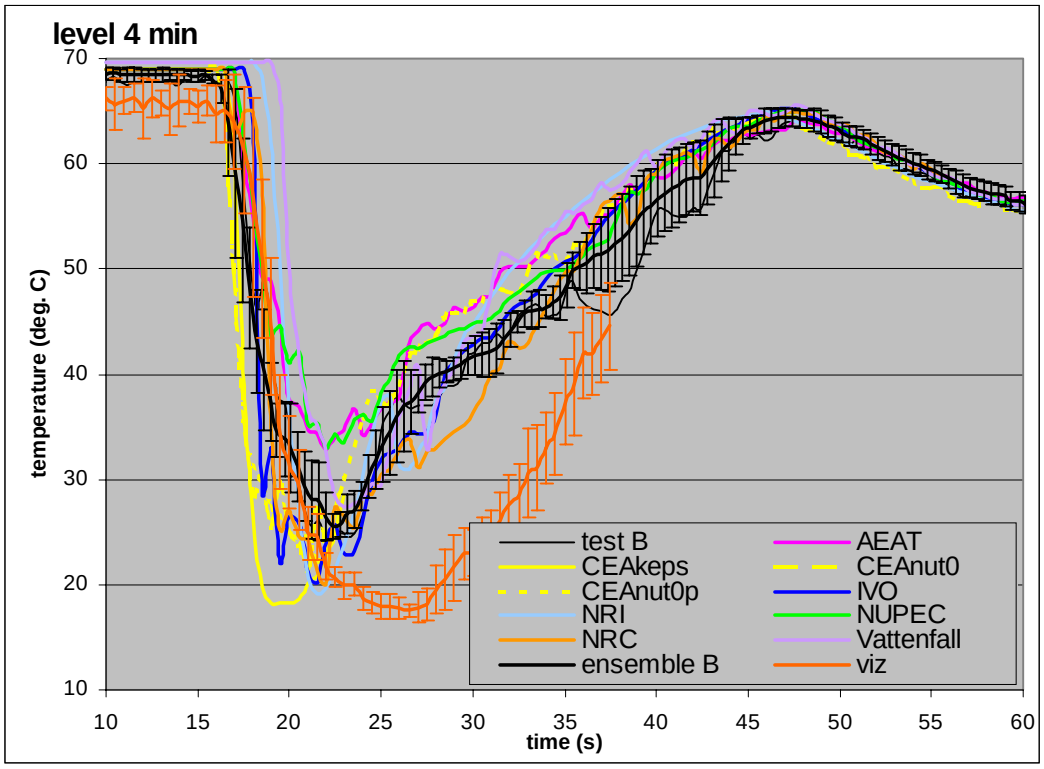

Figure 5-32. Level 4 minima among the 24 channel-center thermocouples for Test B

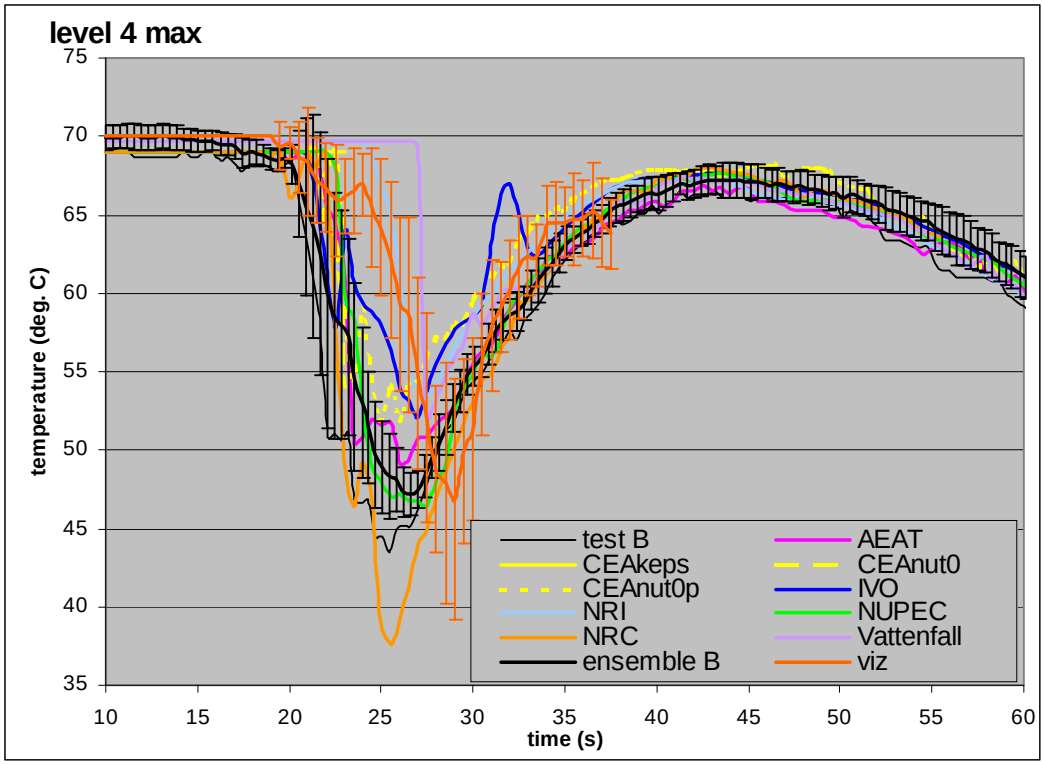

Figure 5-33. Level 4 maxima among the 24 channel-center thermocouples for Test B

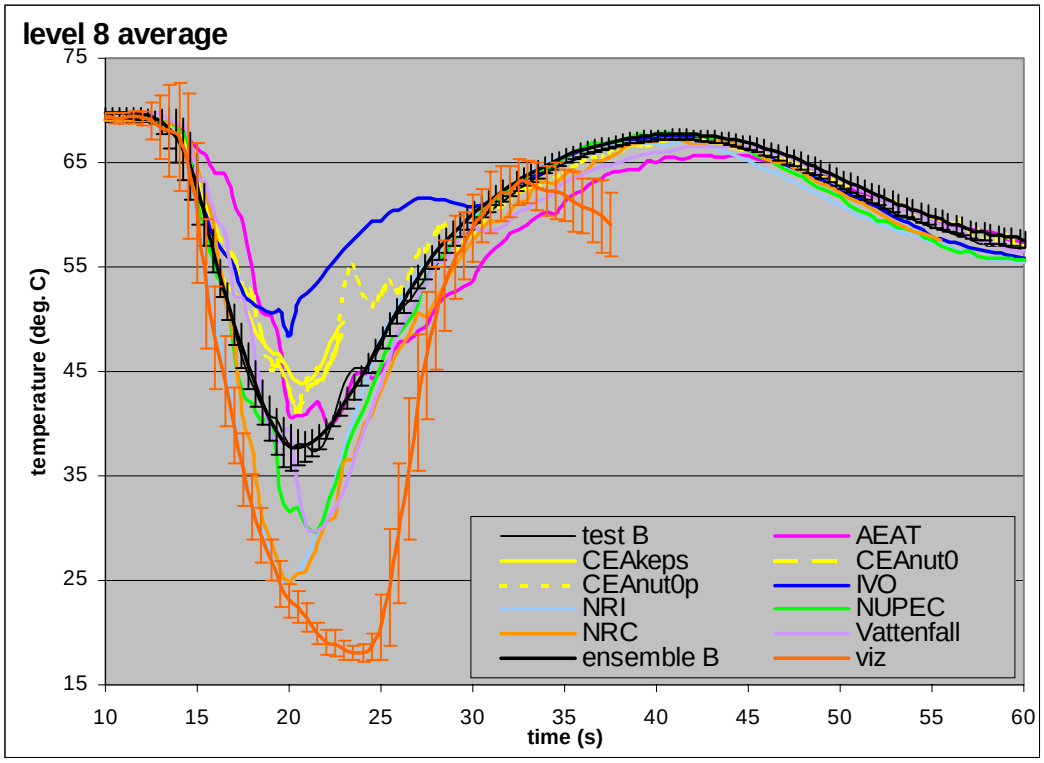

Figure 5-34. Level 8 averages of the 24 channel-center thermocouples for Test B

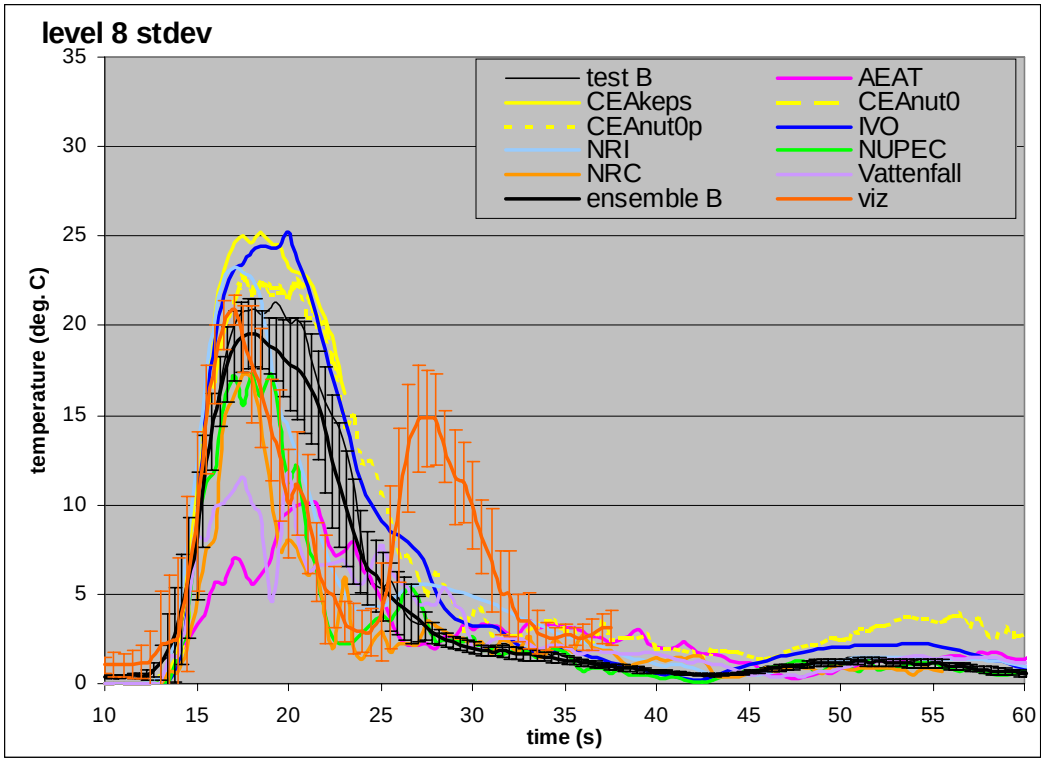

Figure 5-35. Level 8 standard deviations among the 24 channel-center thermocouples for Test B

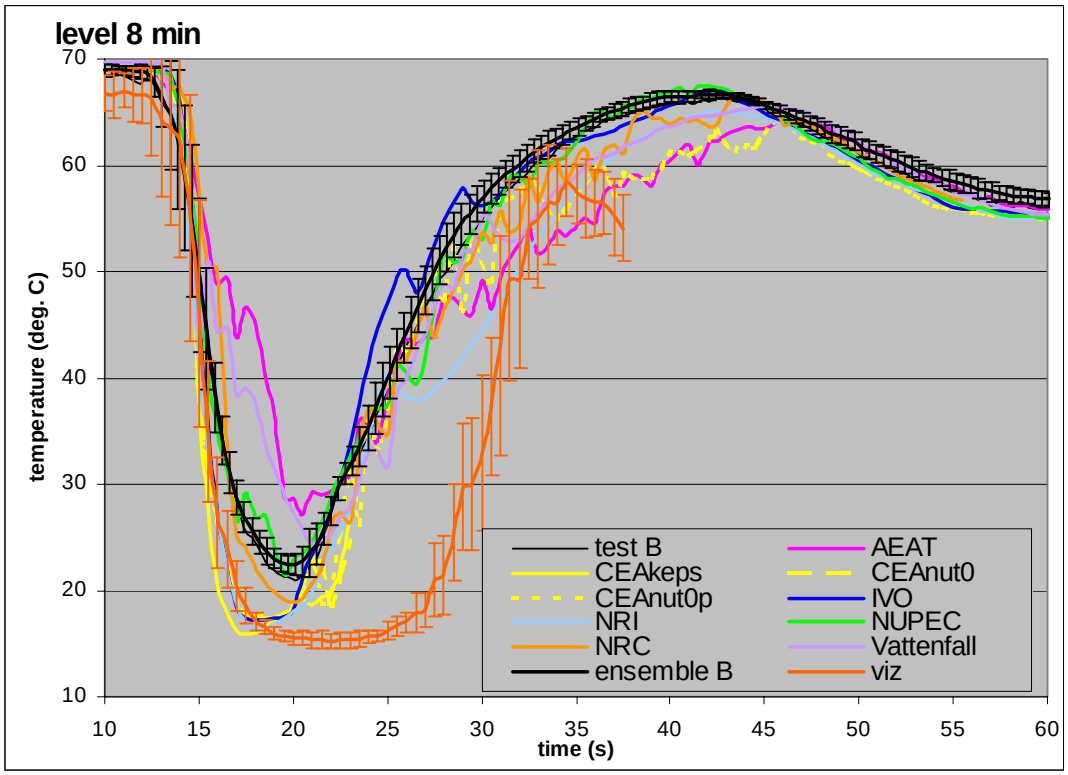

Figure 5-36. Level 8 minima among the 24 channel-center thermocouples for Test B

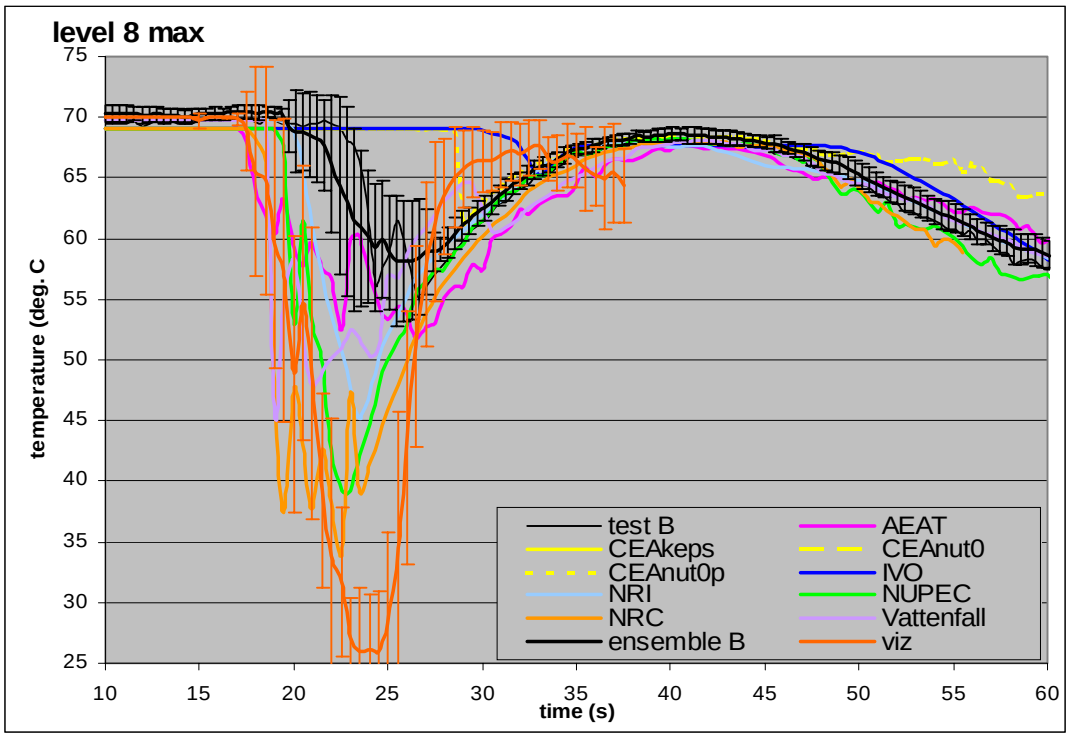

Figure 5-37. Level 8 maxima among the 24 channel-center thermocouples for Test B

5.2.1.3 Level 10

The level 10 figures of merit show that only a few predictions capture the predominantly downward flow of the injected slug. As seen in the level average temperature histories of Figure 5-38 CEA and IVO are in good agreement with experimental data, but the other simulations show substantial cooling at level 10. The finding is supported by the standard deviations, minima, and maxima of Figure 5-39 through Figure 5-41, in which most code predictions rapidly transfer a large portion of the slug upwards and quickly entrain the warm primary coolant.

5.2.1.4 Level 3

CFD codes will be used to estimate the amount of unborated fluid that reaches the core entrance in rapid boron dilution investigations. Both the spatial and temporal distributions of boron in the coolant are boundary and initial conditions needed for coupled neutronics thermal-hydraulics computations. These parameters are represented by the same figures of merit as investigated at levels 4 and 10. The average temperature histories at the core inlet, actually below the core support plate, are depicted in Figure 5-42. Figure 5-43 through Figure 5-45 show the standard deviation, minimum and maximum histories at the same level. The level average simulation predictions are in excellent agreement with experimental loop data. However, some simulations show the primary coolant to remain more segregated spatially from the slug than the experiment. A few appear to somewhat overmix the two fluids. It is also interesting to note that the two maxima in Figure 5-43 show that the standard deviations are noticeable for both the front and end of the slug. Computations accurately capture this feature of the transient.

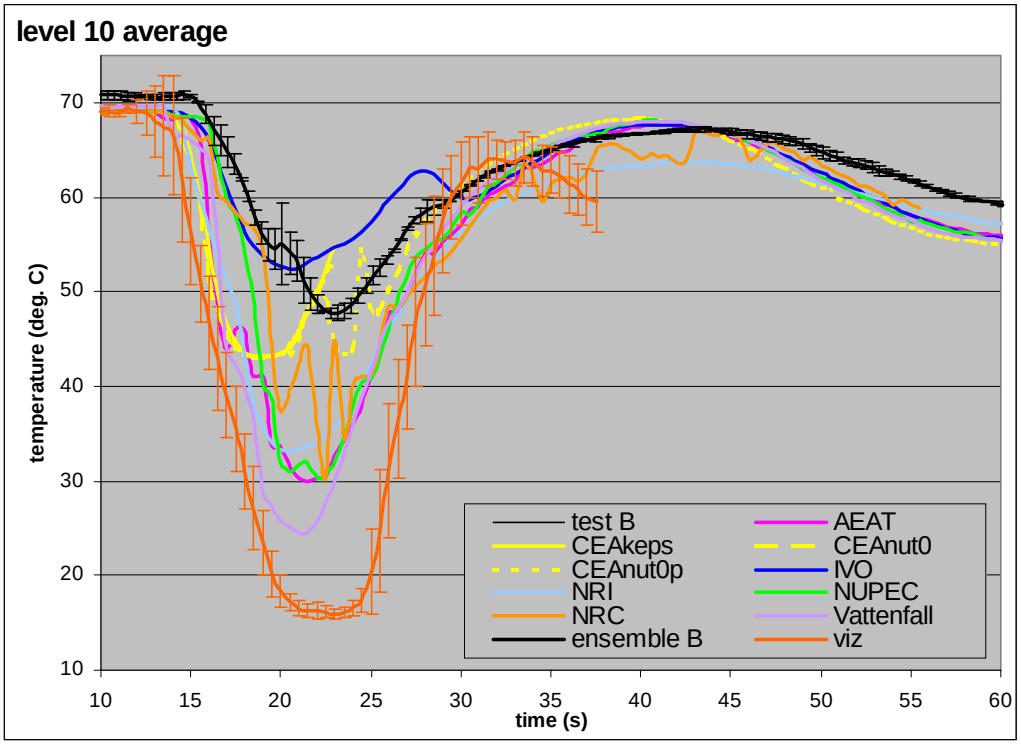

Figure 5-38. Level 10 averages of the 24 channel-center thermocouples for Test B

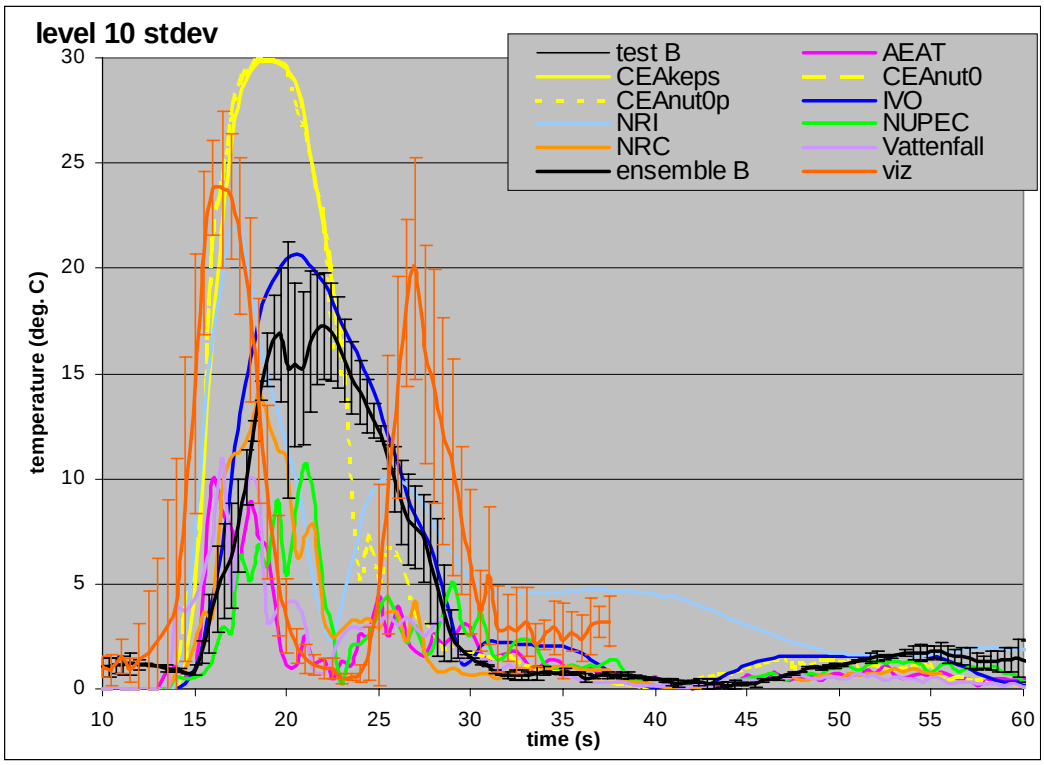

Figure 5-39. Level 10 standard deviations among the 24 channel-center thermocouples for Test B

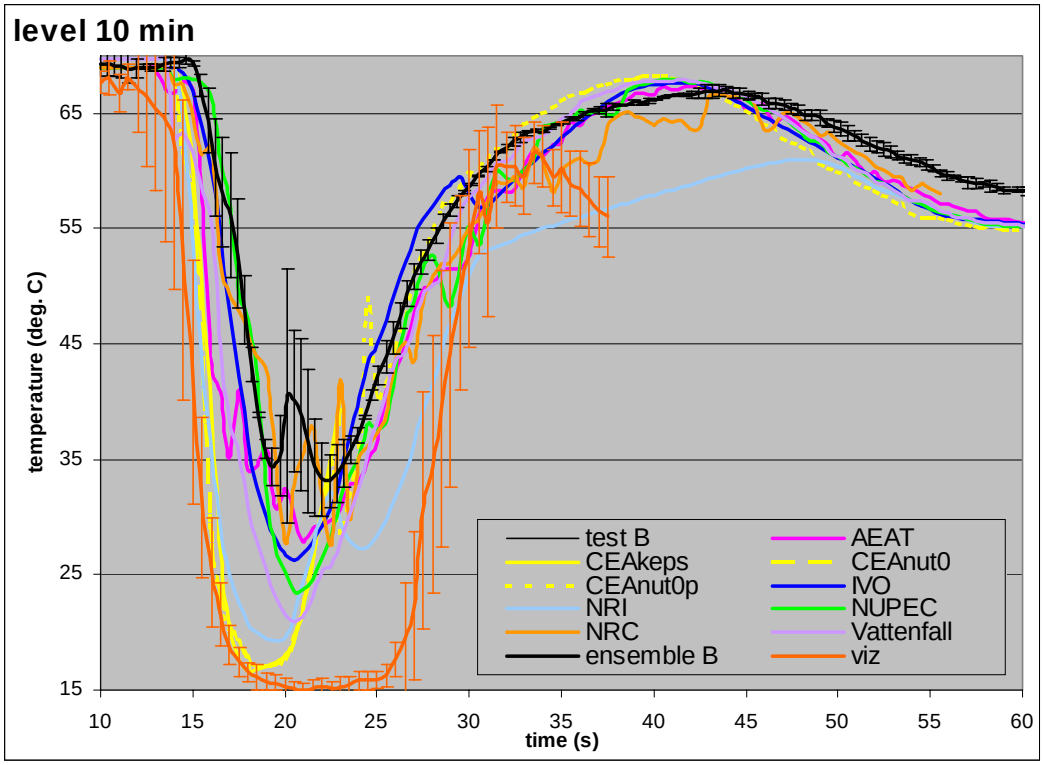

Figure 5-40. Level 10 minima of the 24 channel-center thermocouples for Test B

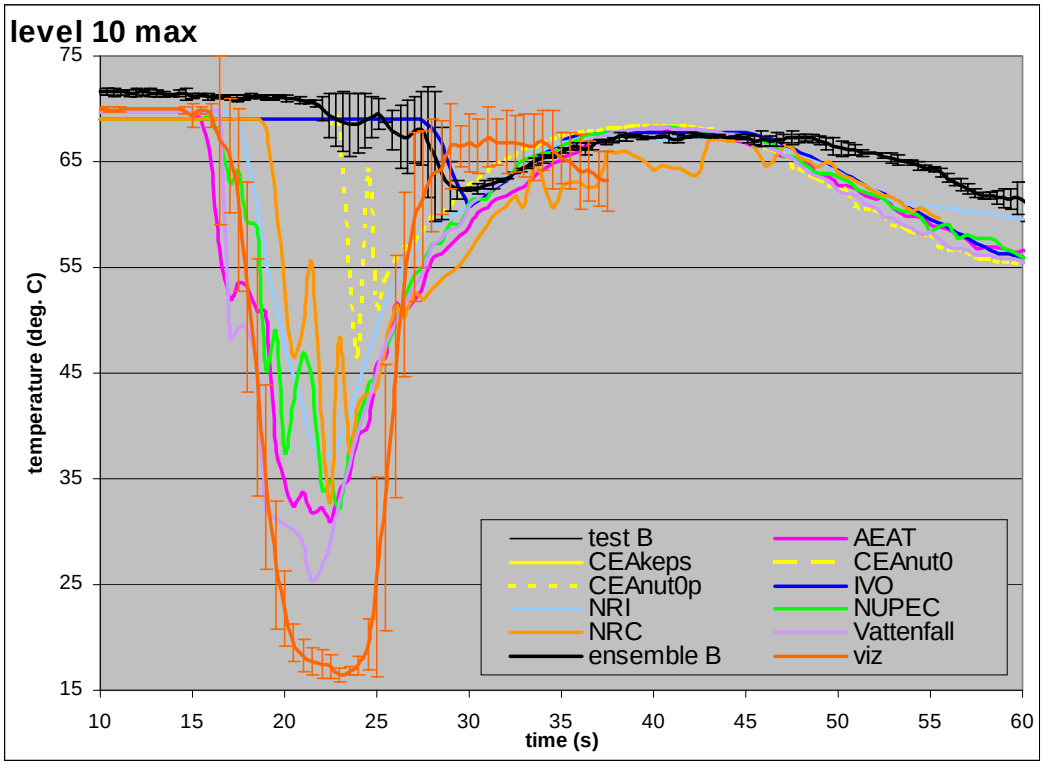

Figure 5-41. Level 10 maxima of the 24 channel-center thermocouples for Test B

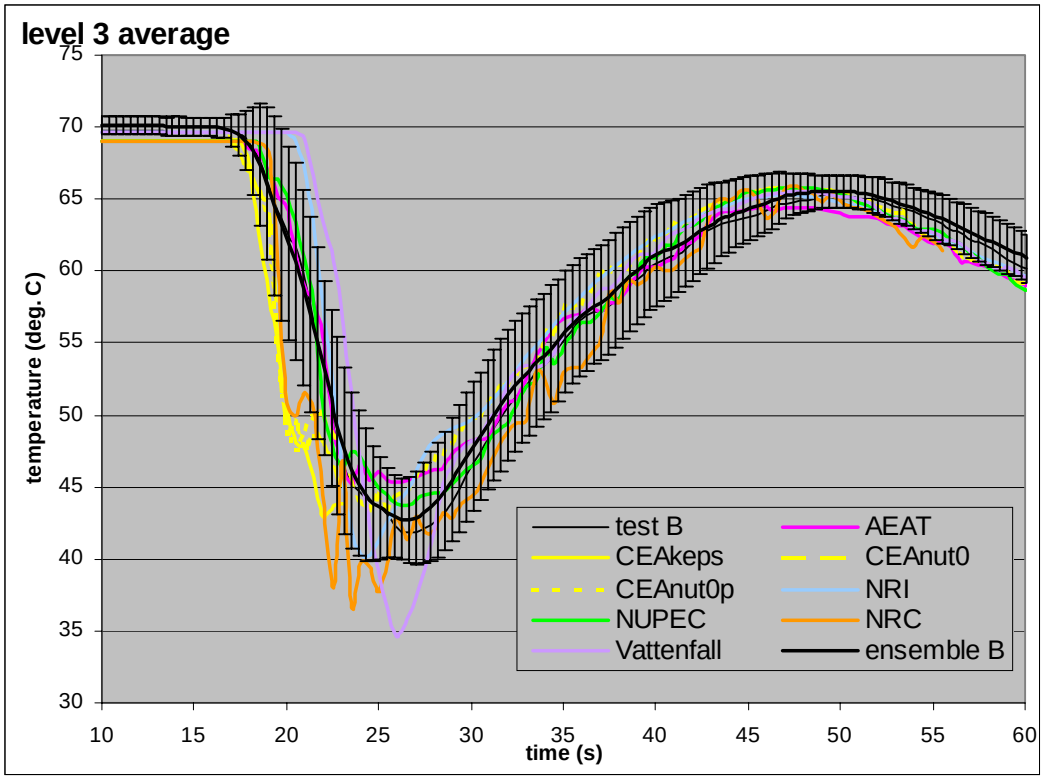

Figure 5-42. Level 3 averages of the 24 channel-center thermocouples for Test B

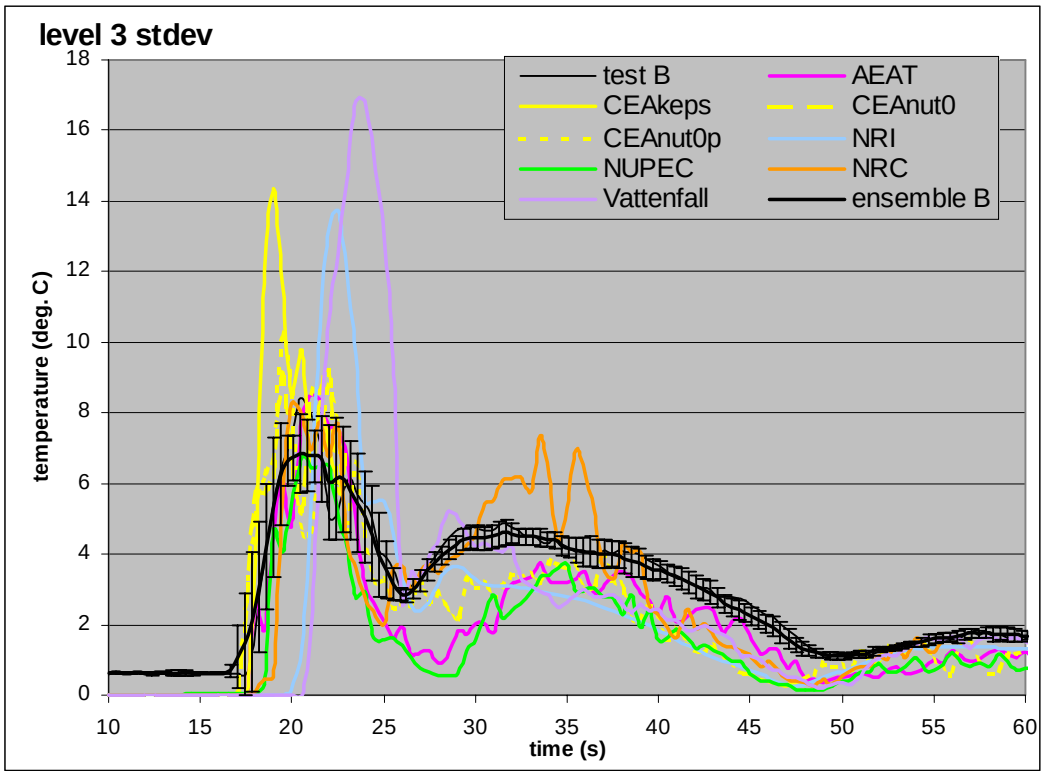

Figure 5-43. Level 3 standard deviations among the 24 channel-center thermocouples for Test B

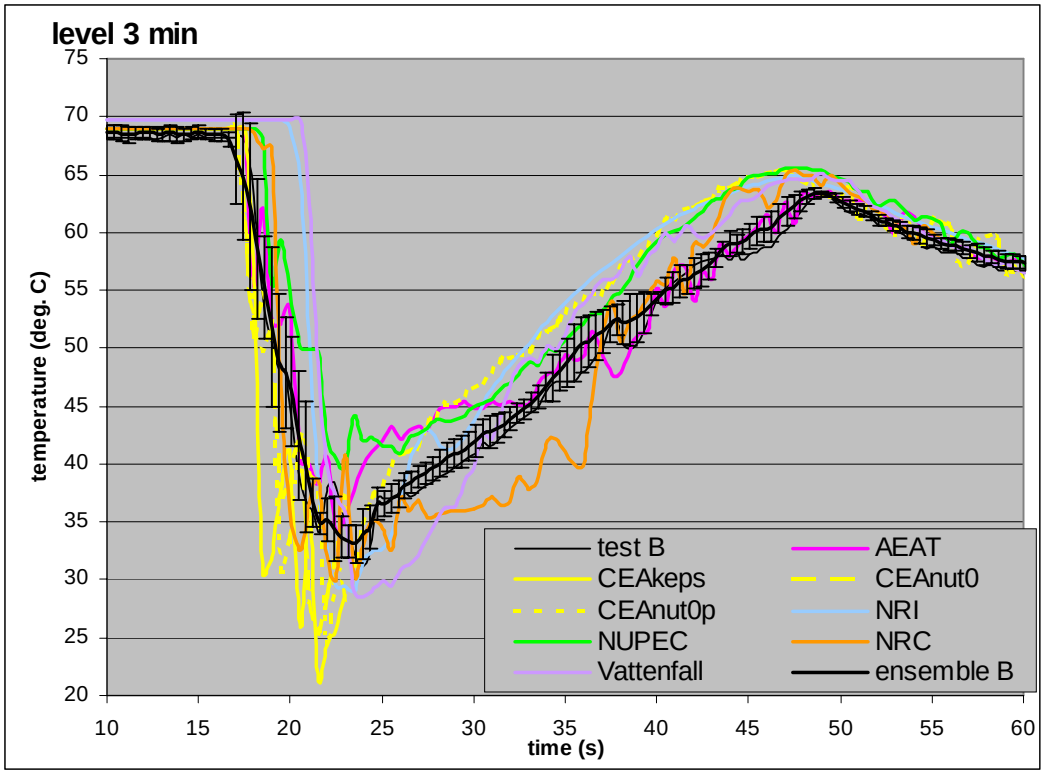

Figure 5-44. Level 3 minima of the 24 channel-center thermocouples for Test B

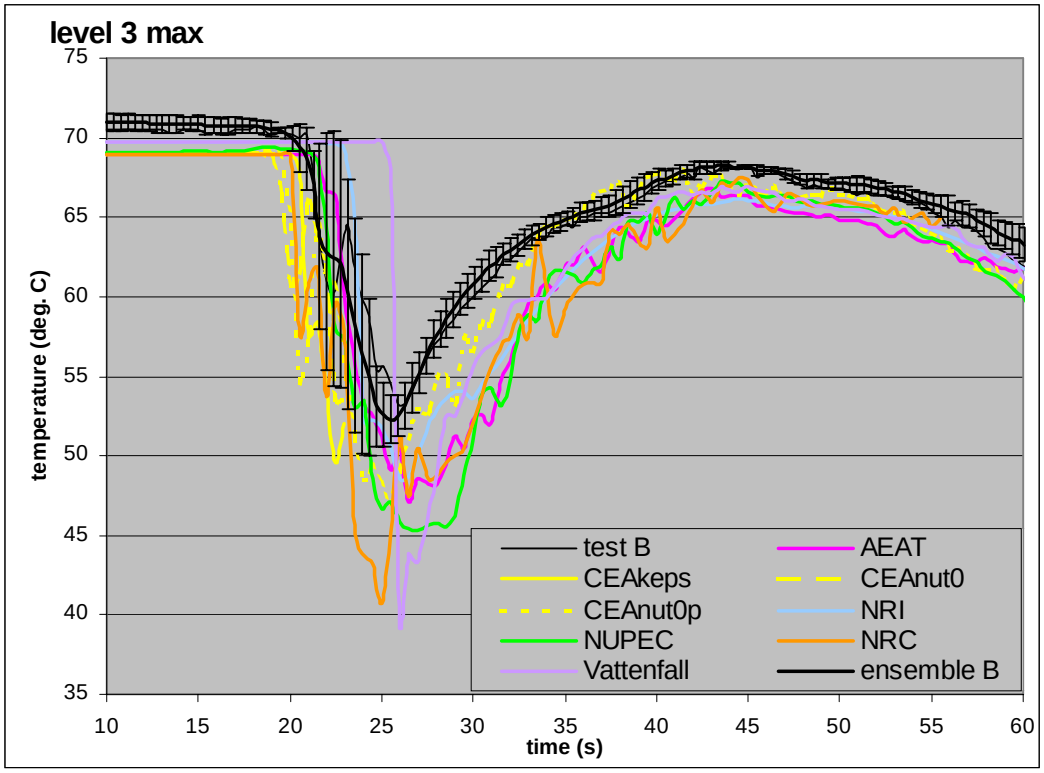

Figure 5-45. Level 3 maxima of the 24 channel-center thermocouples for Test B

5.2.2 Azimuthal Behavior for Test B Levels 4, 8 and 10

The pattern similarity between loop and visualization facility data, detailed in section 6.2, allows the discussion of azimuthal behavior to be made by illustrating visualization facility data. The ensemble averaged mean and standard deviation of the slug concentration is shown in figure 5-3. The plots show time along the vertical axis, and the azimuthal position around the downcomer (positive angles are clockwise when viewing the downcomer from above). The red end of the spectrum indicates the maximum scalar concentration of the simulated Boron, while the dark blue indicates a near zero or "dilute" volume of fluid.

The azimuthally resolved slug level averages shown below give a similar shape to the front evolution shown in the section 5.1.2. The main difference is that a trailing interface can now be observed to pass through a given level at a later time, restoring the concentration to near its original value. Qualitatively, the evolution of the trailing interface typically looks quite similar to the leading interface, but perhaps shows a slightly greater standard deviation value, which is consistent with the greater variability that was observed in the timing of the trailing interface. The total amount of mixed volume within the downcomer, however, will be greater than the front case, owing to the fact that there is a greater interfacial area available for mixing (i.e., both the leading and trailing interface).

6 Flow Pattern

The movies of temperatures in the expanded downcomer generated from loop, visualization facility and participant submissions show that there is variability in flow pattern. The variability is also noticeable in the results presented in section 5. An observation of the general flow pattern is beneficial and instructive to:

- understanding the general behavior of the mixing one expects to encounter in such complex geometries,
- comparing similarities and differences between the various experiments and simulations,
- facilitating future discussions of the flow features to which the simulations may be particularly sensitive.

In order to present a general discussion of the observed features, a representative temporal sequence of images generated by the 2x4 loop, the visualization LIF studies, and participant submissions are shown in the following sections.

6.1 Test A

The azimuthal temperatures plotted at levels 4 and 8 indicate that a further investigation into flow pattern is desirable. The following sections present this investigation for both experimental facilities and participant submissions.

6.1.1 Loop flow pattern

Two-dimensional downcomer temperature field visualizations were produced from the downcomer TC measurements and presented as colored rectangular maps. The map area represents the unfolded downcomer in its entire axial height, which includes TC levels 4 through 11. Only data from the TCs located at the downcomer gap midpoint were used for visualization. The openings of all cold leg nozzles are indicated as white circles as are the hot

leg penetrations. The red color corresponds to the maximum normalized temperature of one, indicating unmixed system coolant, and black corresponds to the lowest normalized temperature of zero, indicating unmixed front fluid. The azimuthal unfolding of the downcomer is performed in a way as if the cold leg is located in front of the figure so that the front enters the downcomer along the direction from the viewer's eyes towards the map.

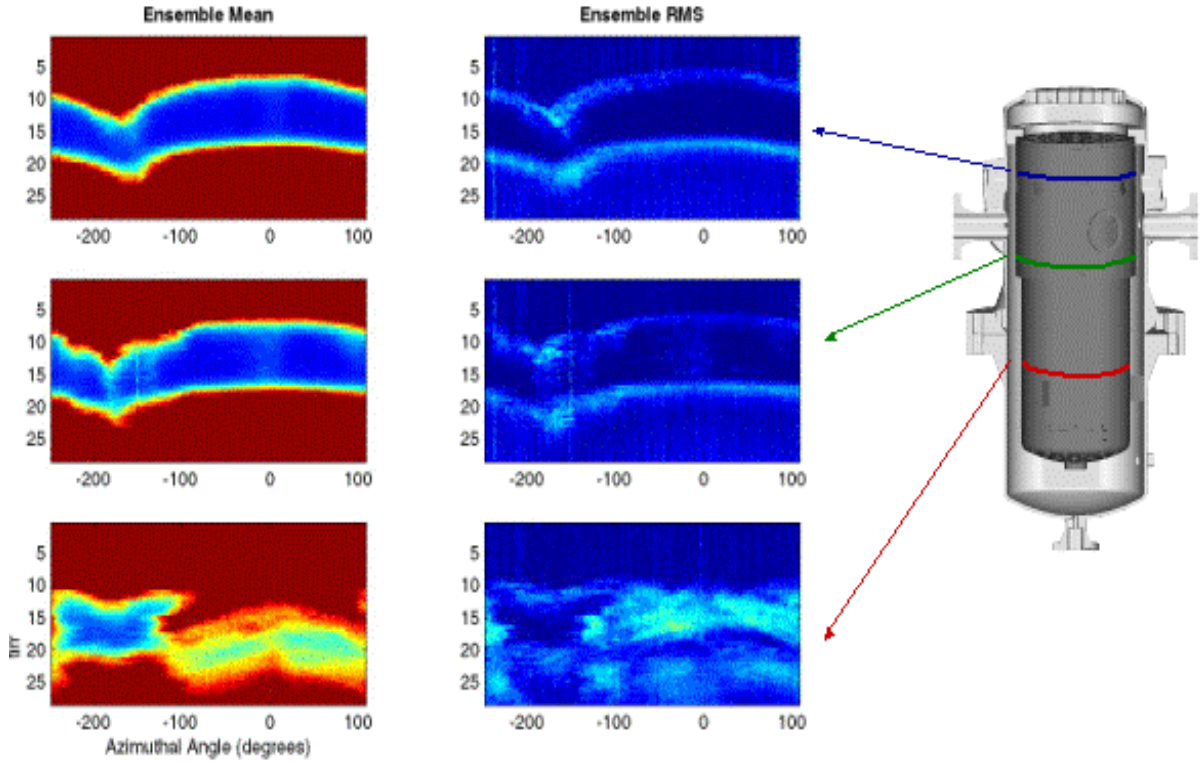

Figure 6-1. Test B ensemble averages for Levels 10 (top pair), 8 (middle pair), and 4 (bottom pair). The horizontal axis represents the azimuthal position, the vertical axis represents time, and the color indicates concentration (red = 100% or "borated", dark blue = 0% or "dilute").

Figure 6-2 a. shows 4 snapshots, arranged horizontally and ranging from left to right, of the flow pattern in the loop downcomer at 24, 28, 32 and 36 seconds for the nominal A test, i.e., the test for which initial and boundary conditions were provided to participants. After its practically uniform radial spreading upon the barrel wall, the front fluid follows predominant flow paths for subsequent advancement and occupation of the downcomer volume. Initially, a predominant favorable path is established going from the injection point diagonally down- and leftwards. This is explained by the presence of the hot leg A that forms a local flow blockage to the right from the injection point beneath hot leg B, being the predominant entrance position, and beneath hot leg A as the front encompasses and streams downwards with its advancement into the downcomer.

The ensemble averages of the 16 redundant A tests at the same time points are shown on Figure 6-2 b. Figure 6-2 c. shows the standard deviations among the 16 redundant tests at the same time points. Since the standard deviations appear substantial at 28 and 32 s, individual snapshots of each test are also plotted.

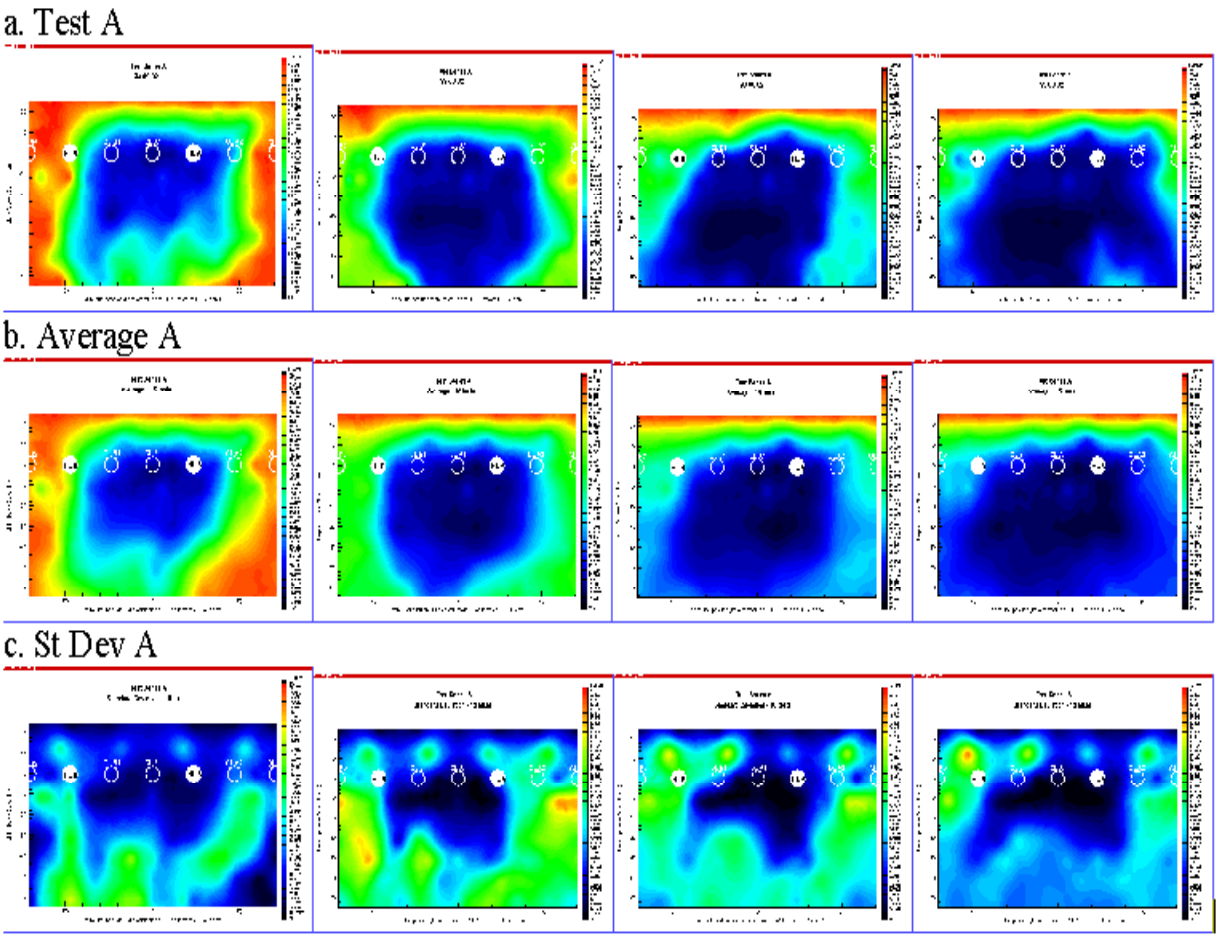

Figure 6-2. Flow patterns at 24, 28, 32 and 36 seconds as obtained from: a. the nominal test A, and b. ensemble of the 16 redundant tests; c. standard deviation in the ensemble of the 16 redundant tests

Individual snapshots shown in Figure 6-3 through Figure 6-6 for 24 s through 36s, are placed as shown in Table 6-1. A close investigation of the snapshots at 28, 32 and 36 s shows that the tests fall into two categories. The first category comprises tests 93 60 01, 93 60 02, 93 60 03, 93 60 05, 93 60 06, 93 60 08, 93 60 09, 93 60 13, and 93 60 16, which exhibit the same behavior of the nominal test A. However, 93 60 07, 93 60 10, 93 60 14, 93 60 17, 93 60 18, 93 60 19, and 93 60 20 differ from the first group. Specifically, a weaker flow tongue finds its way from the injection point diagonally right- and downward. This forms a Λ-shaped structure with a stronger left branch. The area between the two flow tongues, located beneath the cold leg nozzle, represents a slow moving recirculation zone, which persists throughout the time period depicted in the snapshots.

Table 6-1. Matrix of tests depicted in Figure 6-3 through Figure 6-6

93 60 01	93 60 02	93 60 03	93 60 05
93 60 06	93 60 07	93 60 08	93 60 09
93 60 10	93 60 13	93 60 14	93 60 16
93 60 17	93 60 18	93 60 19	93 60 20

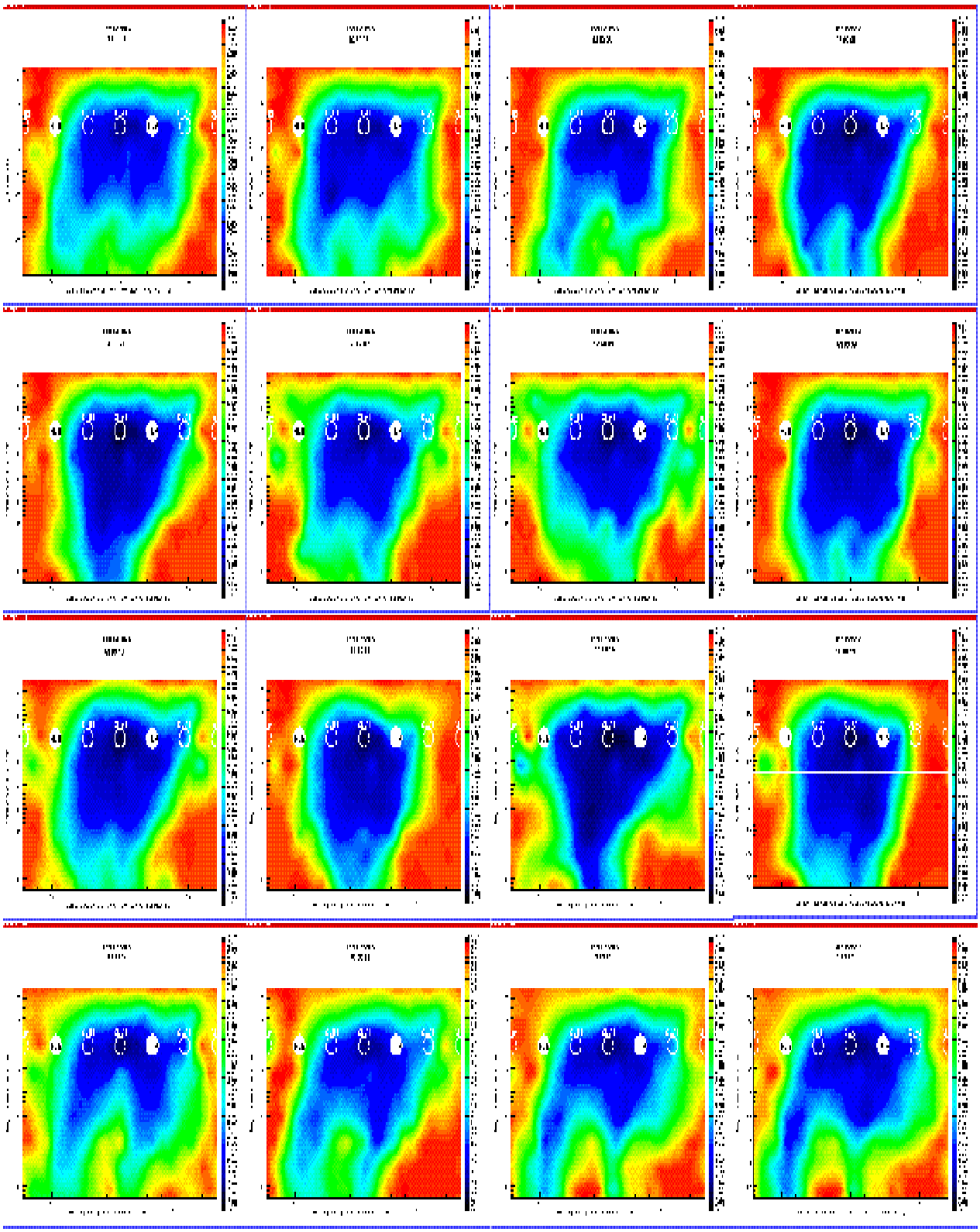

Figure 6-3. Snapshots of the 16 redundant tests of series A at 24 s (42 liters)

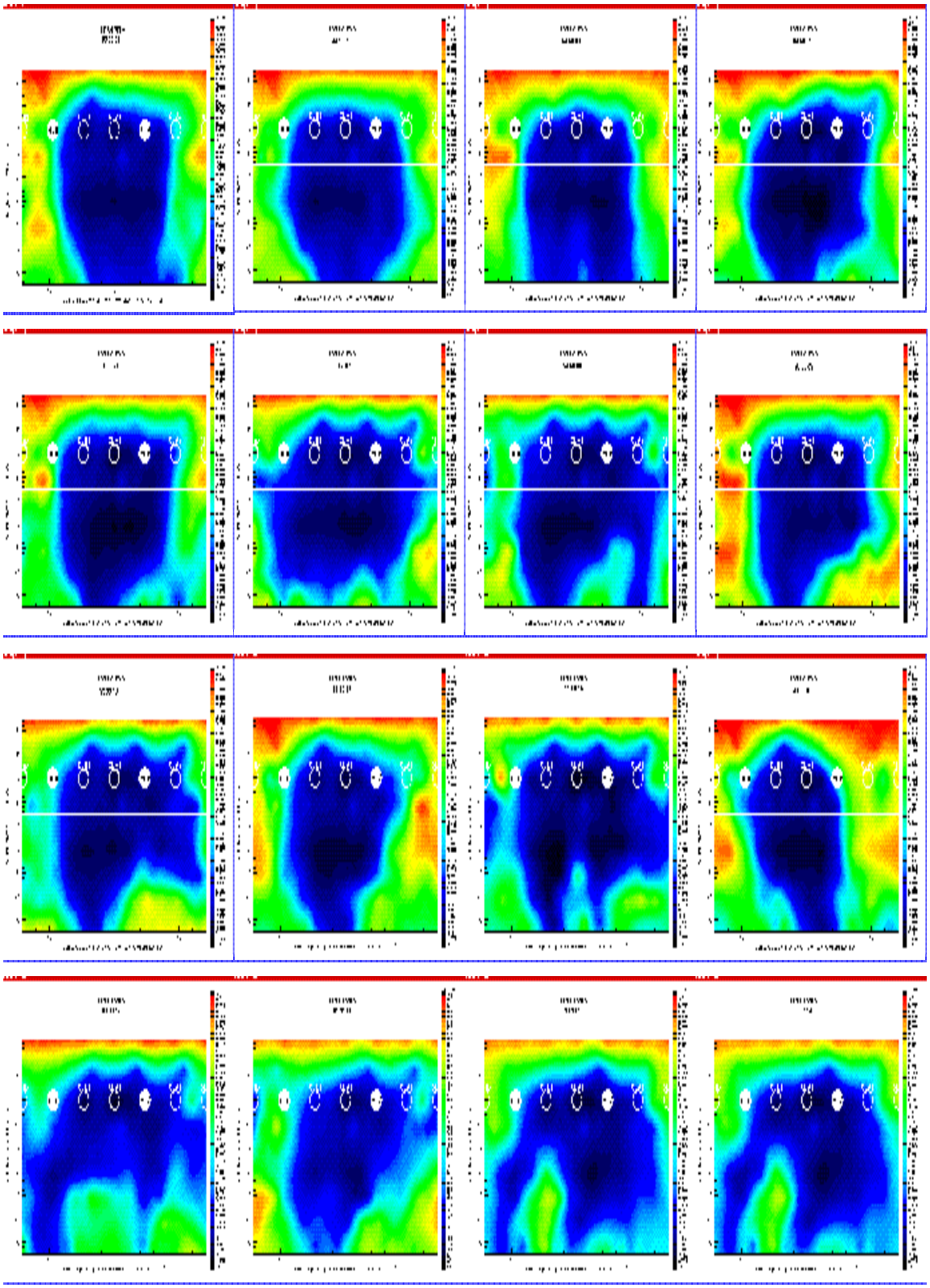

Figure 6-4. Snapshots of the 16 redundant tests of series A at 28 s (72 liters)

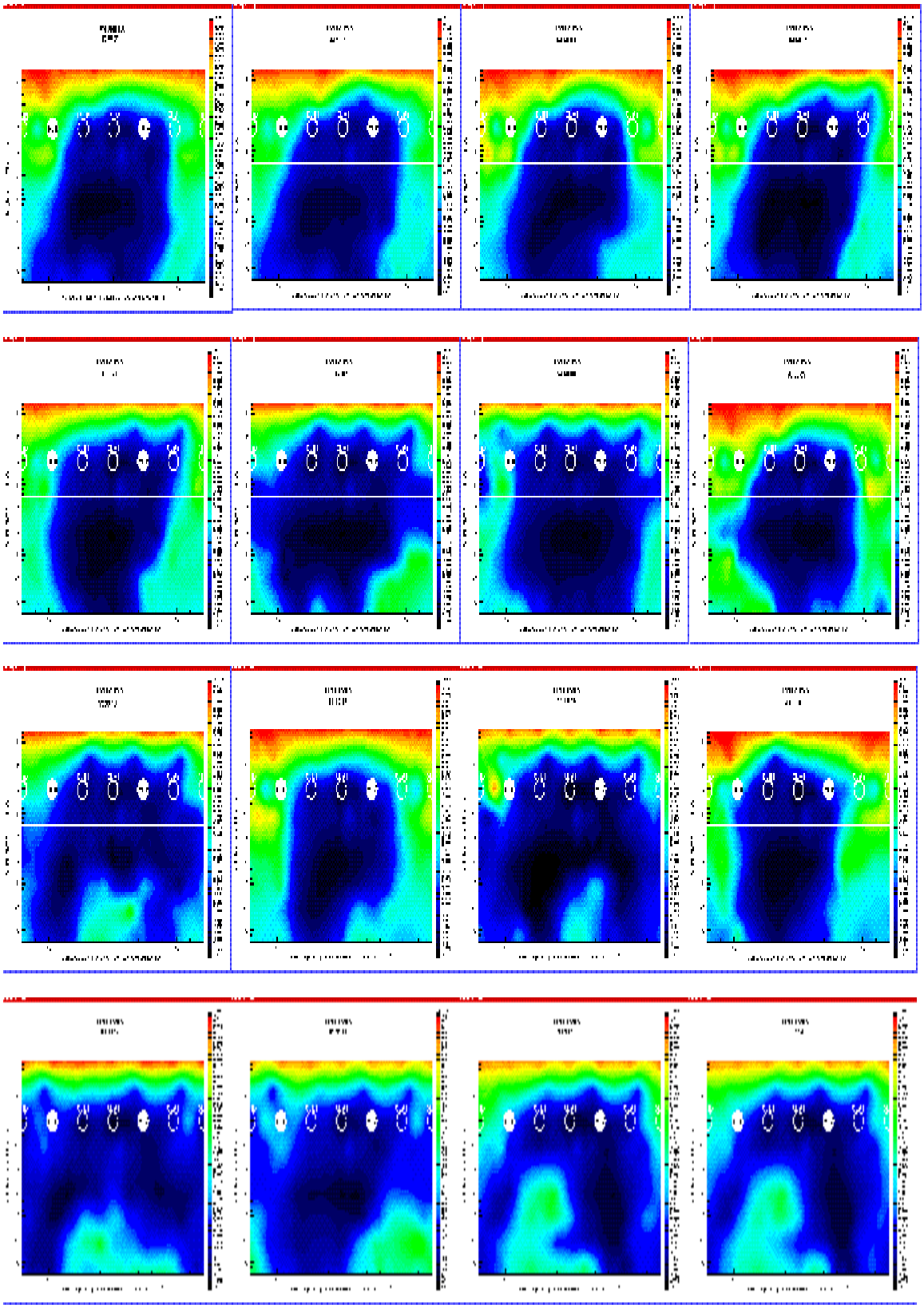

Figure 6-5. Snapshots of the 16 redundant tests of series A at 32 s (100 liters)

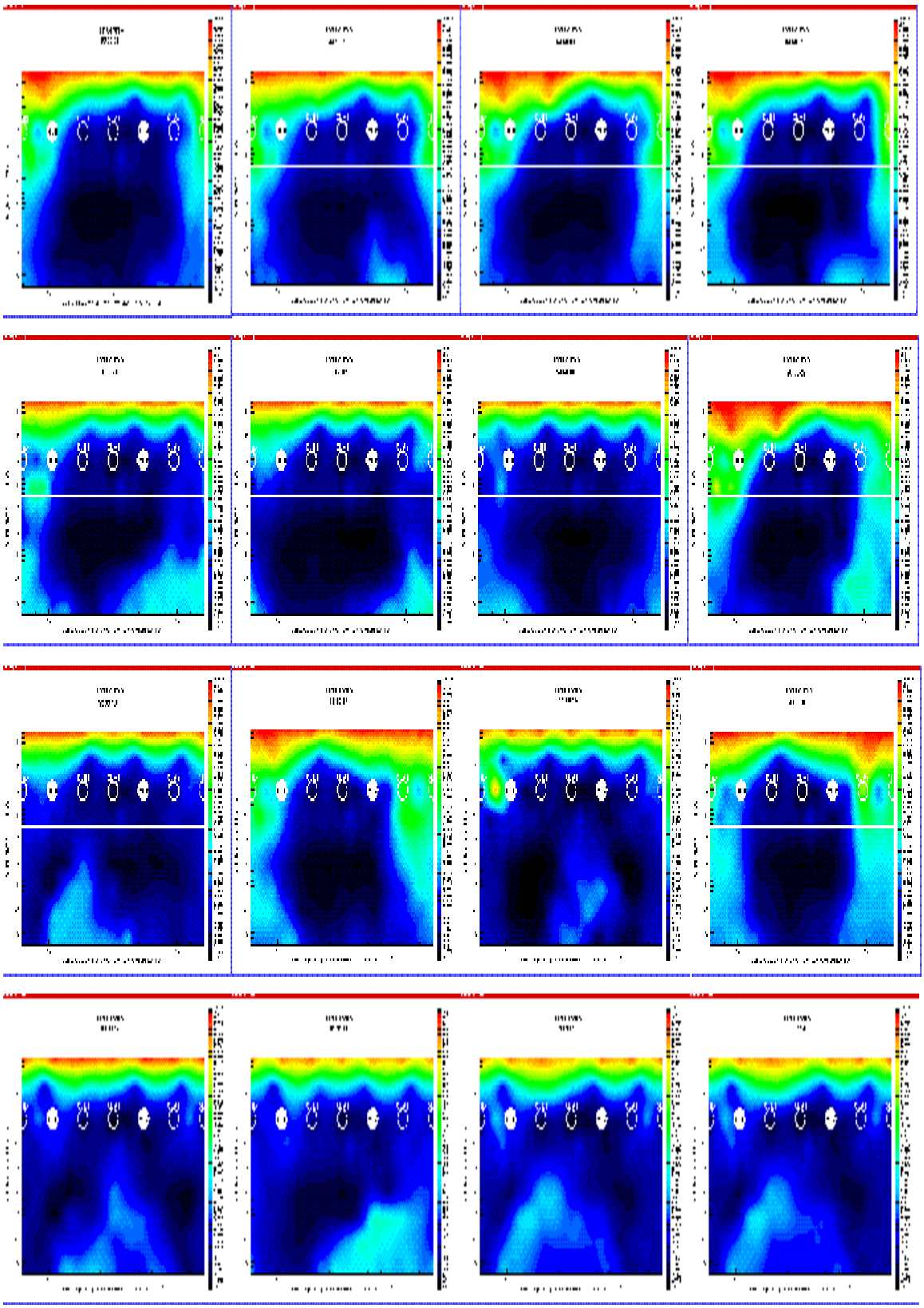

Figure 6-6. Snapshots of the 16 redundant tests of series A at 36 s (128 liters)

Although the non-linearity of the flow caused by the multidimensional domain and the turbulent flow regime does not preclude variations in flow pattern (see also visualization facility data discussion), the distinction between the two groups identified above is attributable to slight differences in buoyancy effect among the tests. The differences are due to the temperature differences of the primary coolant and front caused by fluctuations in initial heat up as well as changes in city water temperature. To quantify buoyancy differences, the Froude (Fr) number was calculated from:

$$Fr = \frac{\text{flow rate}}{\text{downcomer area}\sqrt{\text{length} * \text{gravity} * \text{bulk density} * (\text{jet density} - \text{bulk density})}}$$

Equation 6

where: flowrate—is as measured during the test in kg/s,
downcomer area—is the horizontal cross section at level 8 in m^2,
length—is the vertical distance between the center of the injection cold leg and level 8 in m,
gravity—is in m/s^2,
bulk density—is the azimuthally averaged density at level 8 in kg/m^3, and
jet density—is the inlet density measured by the thermocouples in CL A1 in kg/m^3.

Level 8 was selected to represent the bulk temperature because differences are already apparent at this point. The density was obtained from all channel center thermocouples to eliminate any arbitrariness in the calculation of the Fr number. The Fr number histories of the redundant tests of series A are plotted in Figure 6-7. The plots clearly show two families of curves. In the first, the Fr number levels off at about 50 l and remains flat under a value of 6. These tests exhibit a predominant single branch of downwards flow. In the second family, Fr numbers continue to ascend past 50 l and reach values of 9 to 11. These tests all exhibit the stagnation region under the injection cold leg. The only test that does not distinctly fall within one of these families is 93 60 09; that test reaches a Fr of 7 at 100 l injected and appears typical of the first family.

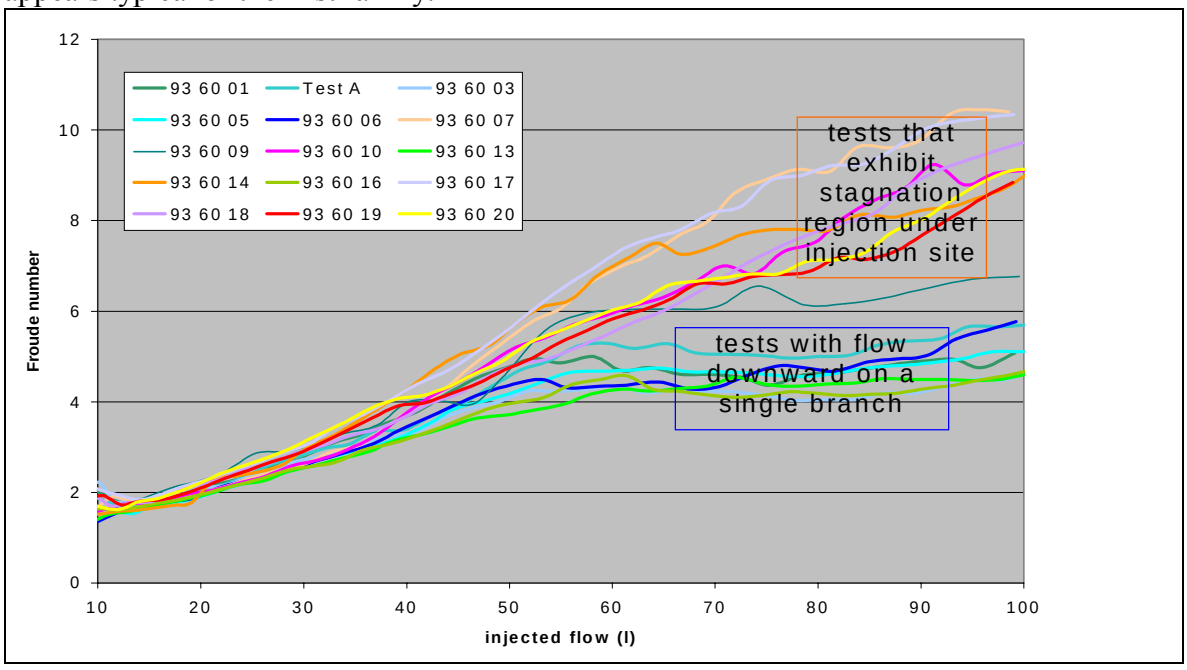

Figure 6-7. Froude number histories for the redundant tests of series A

6.1.2 Visualization facility flow pattern

A sequence of quantitative images from the visualization facility is shown in Figure 6-3. Each of these images corresponds to a reduced data field that is approximately 400x500 elements (horizontal x vertical), which has not been smoothed or filtered in any way after the normalization. Within each of these figures, the horizontal axis corresponds to the azimuthal position (0 being the position of the injection cold leg, positive increasing angles correspond to clockwise direction when vessel is viewed from above) and the vertical axis is the axial location (z = 0 being the inlet level). The high-resolution of the images clearly depict the scale and shape of the radially-averaged turbulent mixing interface between the dyed and dilute streams, as well as the geometrical features within the downcomer itself.

As the leading edge of the front is injected into the downcomer (Figure 6-3a), the interface at first expands radially outward from around the cold leg inlet. A circular recirculation zone or vortex ring is centered about the axis of the injection leg. Occasionally these rings can be seen owing to the mixing layer that forms in the mid-plane of the downcomer, causing waves and striations of non-uniform concentration to appear around the cold leg injection point.

The cylindrical symmetry about the inlet leg is soon broken by the curvature of the downcomer, the upper boundary, and the gap expansion. The front then expands azimuthally around the downcomer (Figure 6-3b), until it nears the region 180 degrees opposite the inlet leg, where a stagnation plane is formed (Figure 6-3c). Note that the strong asymmetry observed in the 2x4 loop measurements is not as prevalent in the visualization studies. Although there appears to be a slightly advanced development in the plume extending towards Hot Leg B ($\theta = 110°$), it appears to be only a minor deviation from the azimuthally symmetric pattern. There are several possible reasons that could contribute to this difference in flow pattern between the 2x4 loop and the visualization facility:

1. The visualization measurement represents a radial average, while the 2x4 loop data are from single points in the center of the downcomer.
2. The 2x4 loop injected front is negatively buoyant due to the temperature difference between the mixed and unmixed fluid, while the visualization front is neutrally buoyant.
3. The hot legs in the visualization facility are slightly misplaced (shifted azimuthally by 10°) in comparison to the corresponding locations on the 2x4 loop.

While the differences are likely due to a combination of these three factors, the first two are the most significant.

After the plumes start to reach the stagnation plane opposite the injection leg, the flow is then directed downward toward the lower plenum. Wakes from the hot-leg plenum are clearly visible, as is the entrainment that occurs past the other stagnant cold leg volumes Figure 6-3c).

One interesting feature of the flow is the recirculating region that occurs immediately *below* the injection leg. This region maintains a volume of relatively unmixed high concentration fluid in lower downcomer until the dilute fluid reaches the lower plenum opposite the injection leg (Figure 6-3d). After entering the lower plenum, some of the fluid enters the core, while the balance is eventually brought into the recirculation region from below (Figure

6-3e, 6-3f). During the time that the front is propagating in the lower plenum, the concentration distribution within the downcomer is relatively unchanged, which results in the characteristic "flat spot" observed in the level average concentration profiles (Figure 5-1, at a time of 13 to 17 seconds).

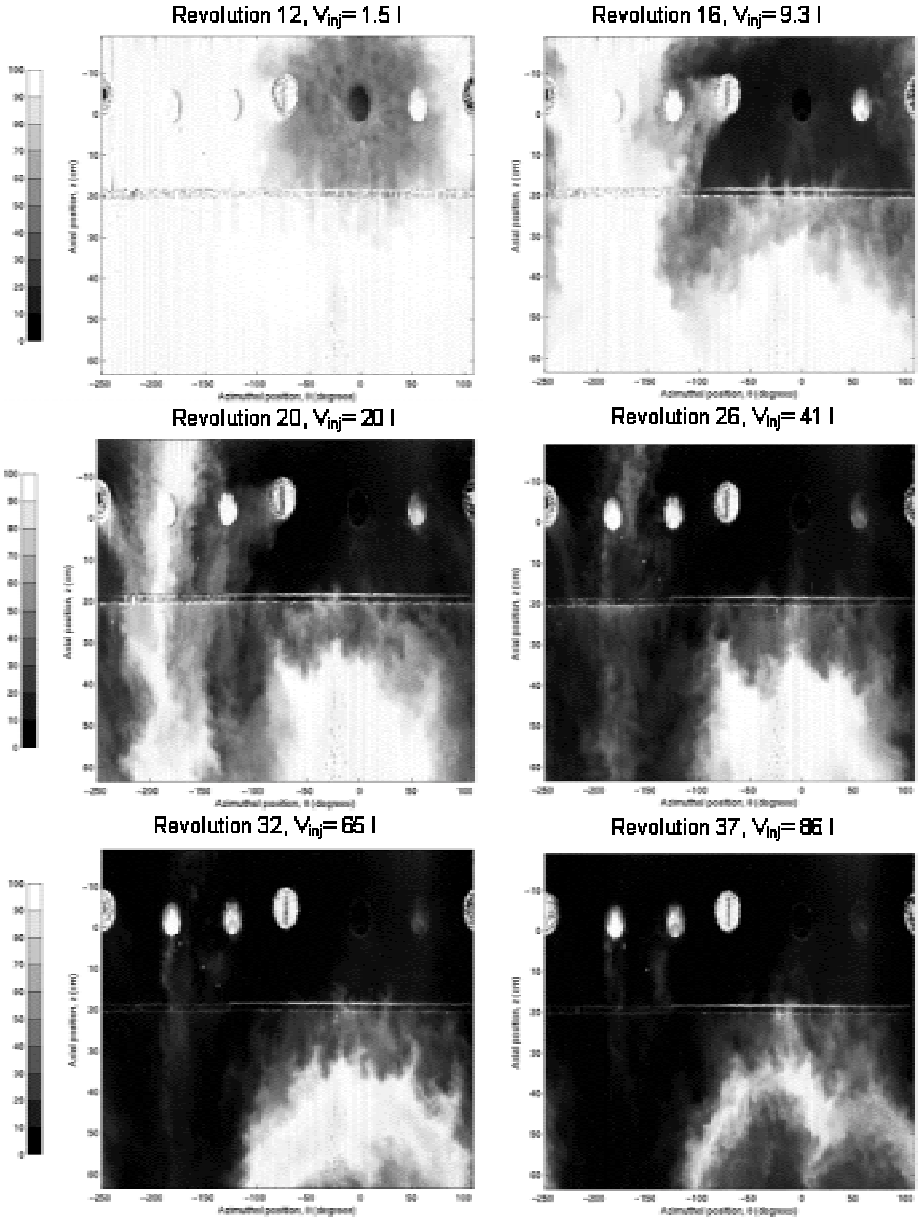

Figure 6-8. Temporal sequence of a single front injection test (061499_run3). Vinj is the injected volume corresponding to the equivalent loop tests as listed in Table 3-3.

Even though great pains were taken to ensure repeatable testing conditions, there were several notable variations in the flow pattern observed for the same nominal test. These differences occurred at the interface between the recirculation region within the lower downcomer beneath the injection leg and the streaming front as it was moving azimuthally

around the downcomer. Representative images illustrating these differences from several different cases acquired at the same injected volume are shown in Figure 6-4.

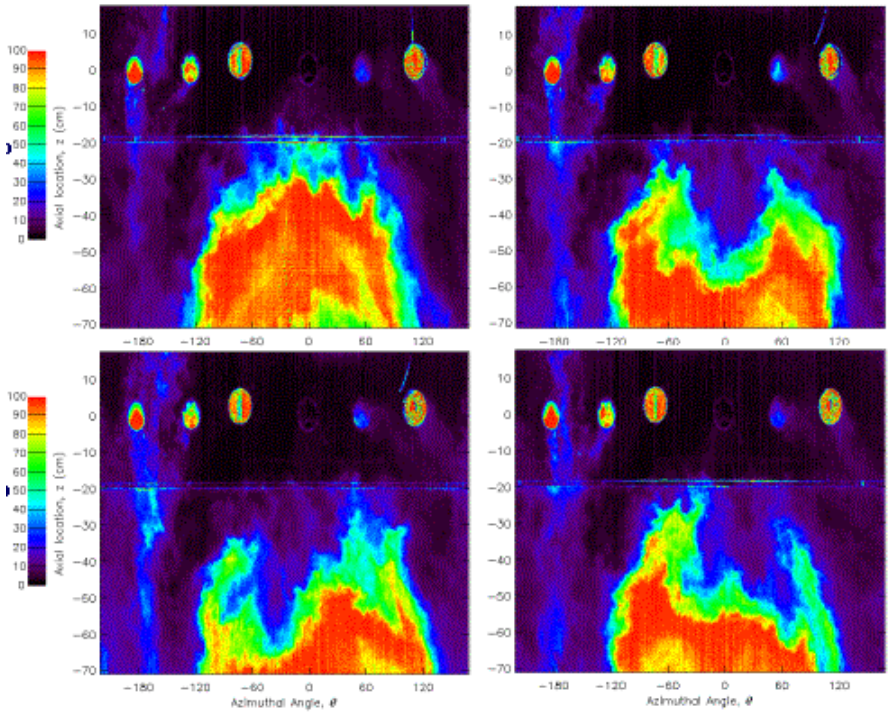

Figure 6-9. Variation in mixing pattern observed within nominally identical initial conditions

The images of Figure 6-9 are sampled from four different tests at the same injection time. The other half of the cases exhibited "tongues" of dilute fluid that would drop down into the middle of the recirculation region (Figure 6-9b), or to the left (Figure 6-9c) or right (Figure 6-9d) of the cold leg plane. These plumes likely originate from some type of instability that occurs along the stagnation point between the recirculation zone and the fluid streaming downward from the upper downcomer. Further evidence of this will be presented throughout the discussion.

In addition to the radial-averaged concentration field, the azimuthal and axial velocity field was measured in two separate radial planes within the downcomer using a two-component LDV system. In order to obtain the data with sufficient grid resolution within the time constraints of the project, the velocity fields were sampled under steady state conditions (the pump was operated at the nominal flow rate of 8 liters/sec and with sufficient settling time to ensure steady conditions within the entire flow volume).

The two-component system was used in backscatter mode to simplify alignment, with the transceiver positioned orthogonal to the outer barrel wall. This enabled the measurement of the azimuthal and axial velocity components. Owing to the use of backscatter collection, the probe volume consisted of an ellipsoidal region that was approximately 2 mm long and 0.08 mm in diameter. For this reason, data within a couple mm of the wall is less reliable than the flow in general, and should be treated with caution. 15 micron, silver-coated, hollow glass beads (specific gravity of 1.4) were used as tracer particles for the study. The measurements were sampled on a grid with a spacing of 2 mm in the radial direction and 25 mm in the axial

direction. The measurement region extended over a region of approximately 250 mm above and below the gap expansion in the downcomer. With the exception of the near-wall points and regions of nearly stagnant flow, 10,000 individual samples were acquired for each grid point, which were then used to calculate the mean, standard deviation and Reynolds Stress for each point.

The first samples were obtained in a radial plane located 30 degrees clockwise (viewed from above) from the injection leg (Figure 6-10). The most readily visible feature in this plane is the strong jet that is impacting on the inner core barrel and streaming radially away from the inlet. At the level of the inlet (z = 0), the azimuthal velocity on the inner barrel shows average magnitudes that are close to 2 m/s (the average pipe inlet velocity is 1.75 m/s). Near the outer barrel wall, the velocity is reversed, with peak velocities on the order of 0.5 m/s.

In the axial direction, the inner jet shows regions of growing upward velocity above the plane of the inlet, and downward velocity components below. As with the azimuthal velocity, the axial velocity also shows reversed directions for the outer wall region. These features are consistent with a trapped recirculating vortex ring that is caused by the strong flow separation at the sharp edge of the inlet leg. The recirculation in this region forms a strong shear layer, whose large-scale structures are highly strained by the radial expansion of the rings as they propagate away from the cold leg inlet, and will also result in one of the strongest mixing regions that the interface will likely pass through. The free shear layer formed between the wall jet and the vortex ring can occasionally be visualized in the LIF images as rings of intermediate concentration propagating outward from the inlet (Figure 6-11). Apart from the vortex rings that appear as a natural feature of turbulent shear layers, the strain field between successive vortex rings is known to amplify the formation of streamwise vortex structures. When this natural instability is combined with the added mean shear of the radial expansion, one would expect to see strong streamwise features forming as well. Evidence of these radial streak features is clearly visible in LIF images (Figure 6-11).

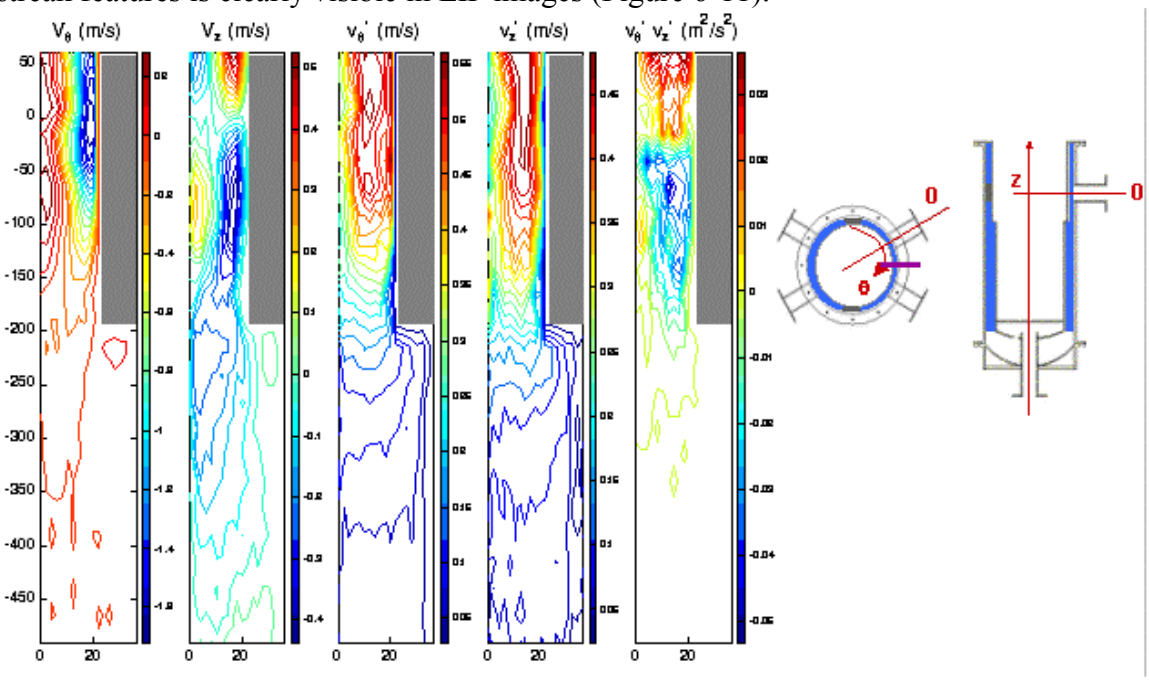

Figure 6-10. Steady-state downcomer radial and axial velocities contours at q = 30°

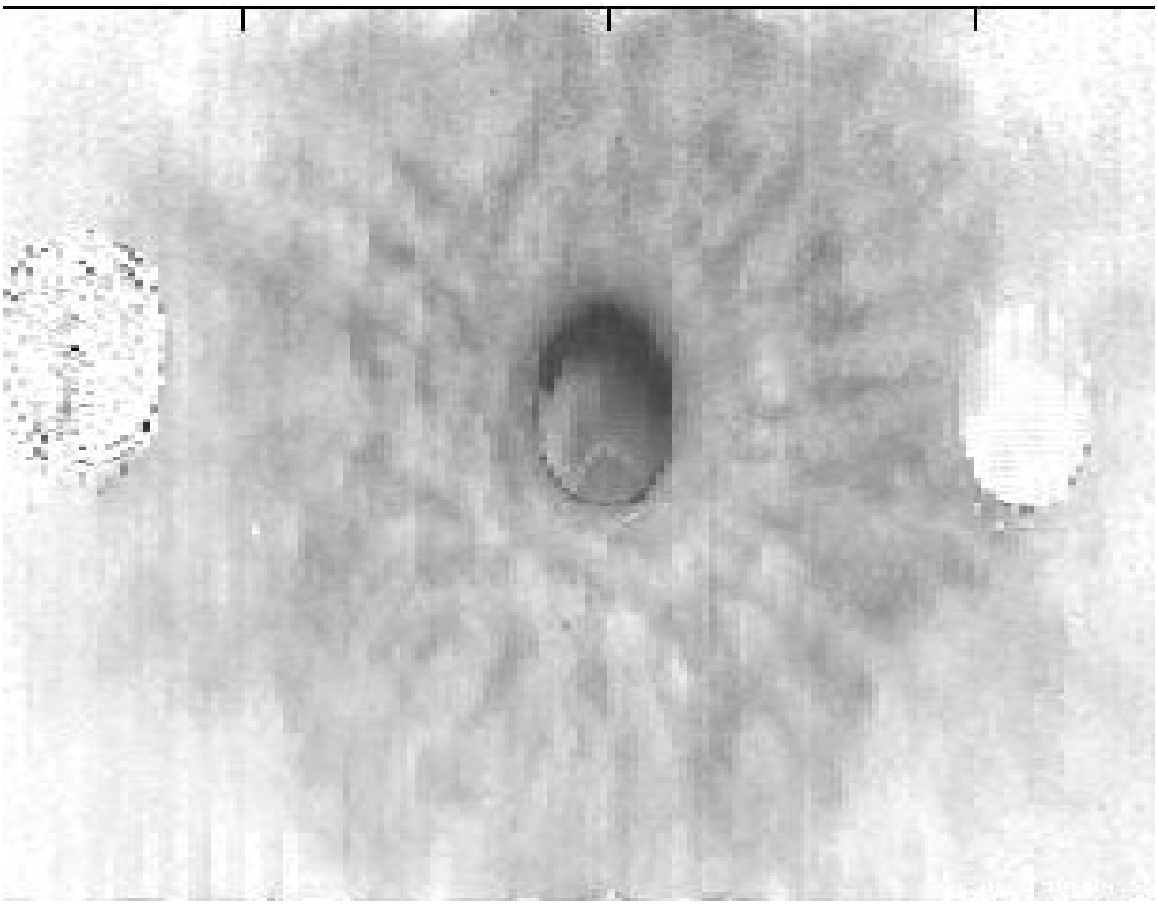

Figure 6-11. Vortex rings and radial non-uniformities caused by the separated jet and resulting mixing layer at the injection leg downcomer junction

In the lower downcomer, the azimuthal velocity is only several cm/sec, while the axial velocity shows some downward motion on the order of 10 to 30 cm/sec. This area corresponds to the middle of the recirculation region in the lower DC beneath the inlet leg. There is also a slight upward motion beneath the gap expansion, which results from the separation past the sharp lip.

The standard deviation of the mean velocities and the Reynolds stress give their greatest values in the region between the wall jet and the recirculation ring around the inlet region. The $v_z v_\theta$ Reynolds stress indicate that the coherent structures of the turbulent mixing layer are largely responsible for the transport of momentum across the gap with.

At 150 degrees around from the inlet, the flow is still clearly streaming azimuthally around in the upper DC, and a little bit weaker in the lower DC (Figure 6-12). The wake generated by the hot leg blind (located azimuthally at approximately 110 degrees) is clearly visible around z = -50 mm. The axial flow at this plane is predominantly a downward streaming motion, with similar magnitudes in both the upper and lower DC. The turbulent fluctuations in this plane are dominated by the near wake flow of the hot leg, which shows the typical signatures that one would expect from such a flow.

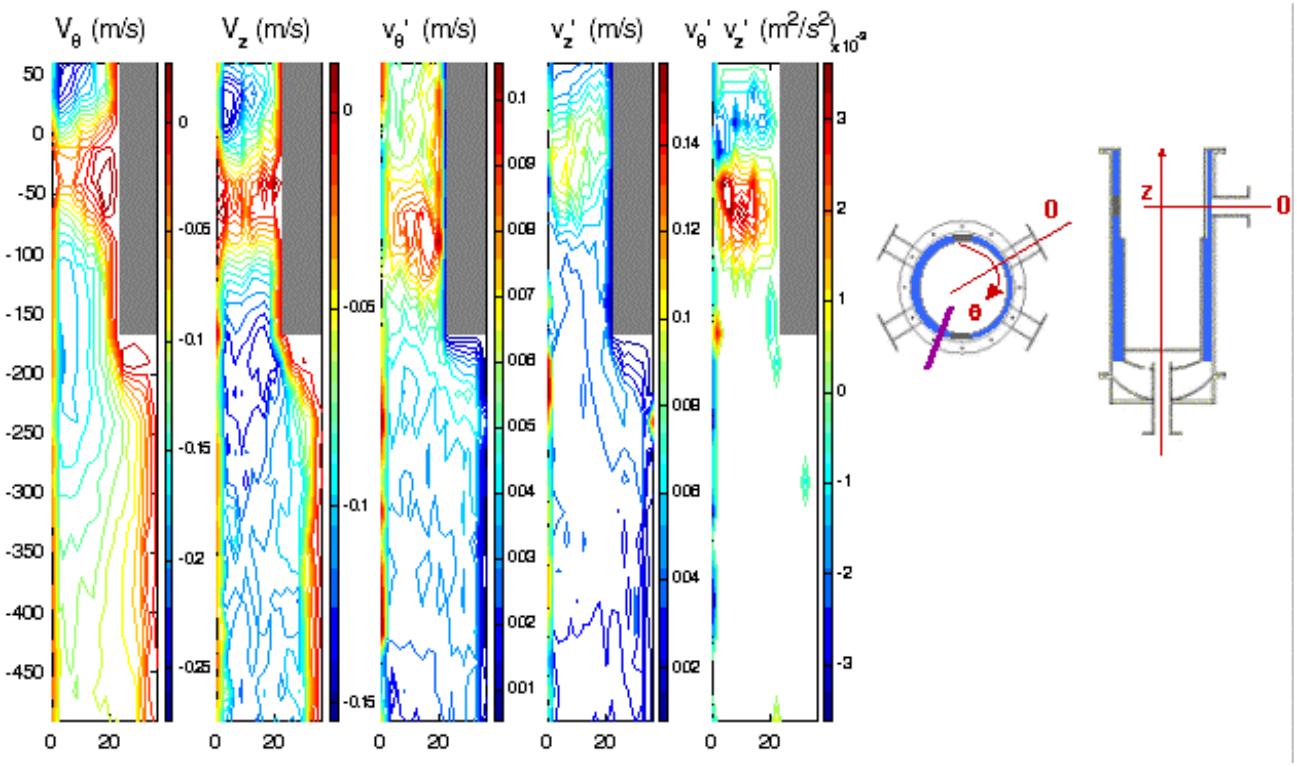

Figure 6-12. Steady-state downcomer radial and axial velocities contours at q = 150°

6.1.3 Participant submission flow pattern

Table 6-2 is the matrix of participant submission snapshots in Figure 6-13 through Figure 6-16. It is noticeable in Figure 6-13 that most code predictions establish the stagnation region early in the transient. Only IVO's prediction shows a predominant flow downwards. Battelle, GRS, NUPEC and Vattenfall exhibit clear stagnation regions at this early point. The stagnation region persists throughout the period captured by the snapshots of Figure 6-14 through Figure 6-16 in all submissions, with the exception of IVO, which preserves the predominantly leftward tongue flow. The differences are consistent with the extent to which participants selected to model buoyancy effects, i.e., with IVO's extensive inclusion of buoyancy dependent properties relative to those of other participants. Specifically, IVO's simulation captures the features of the low Froude number flow, while the other submissions fall within the high Fr family.

Table 6-2. Matrix of code submission snapshots depicted in Figure 6-13 through Figure 6-16

AEAT	Battelle
GRS	IVO
NRC	NRI
Nupec	Vattenfall

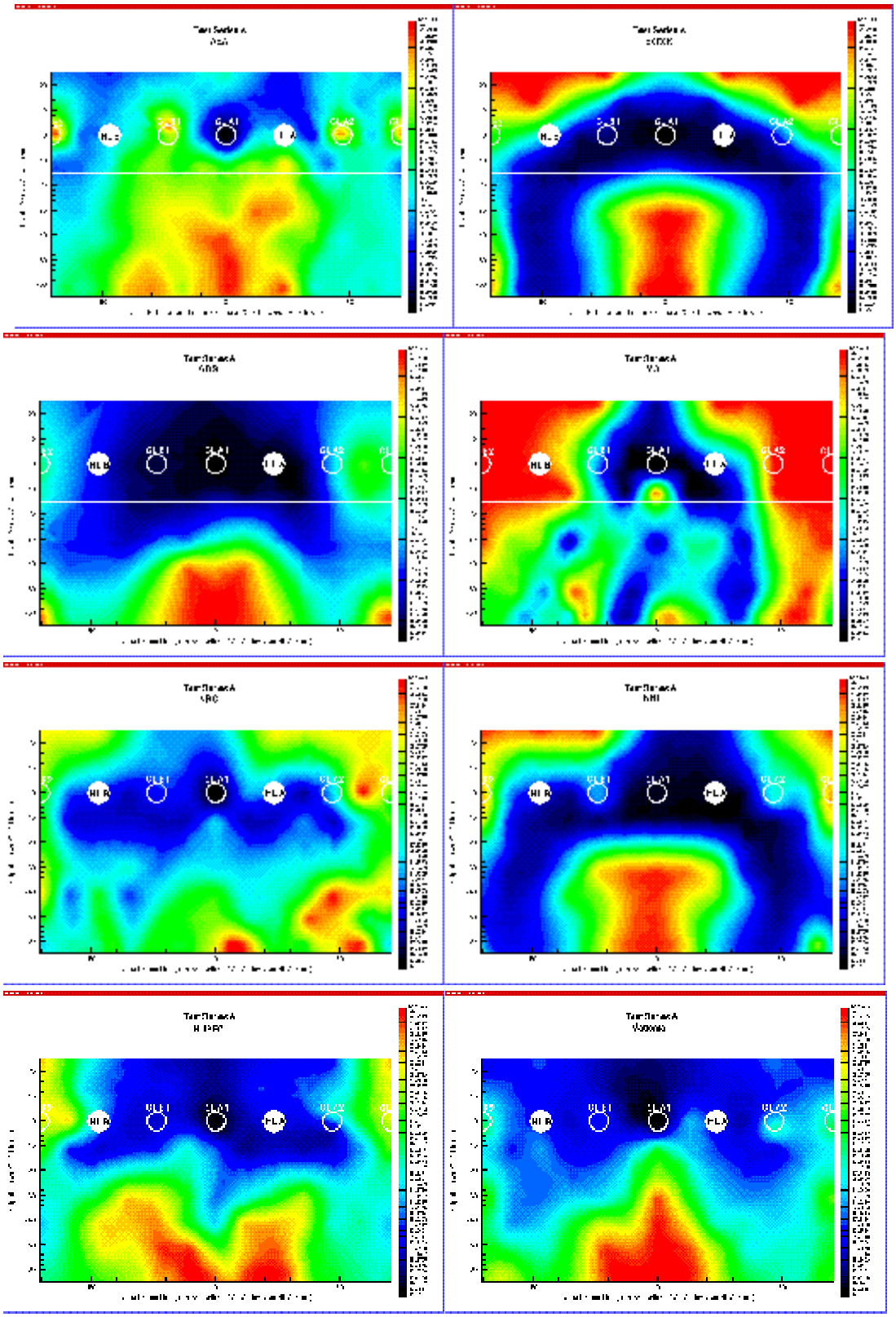

Figure 6-13. Snapshots of the 8 participant submissions for test A at 24 s (42 liters)

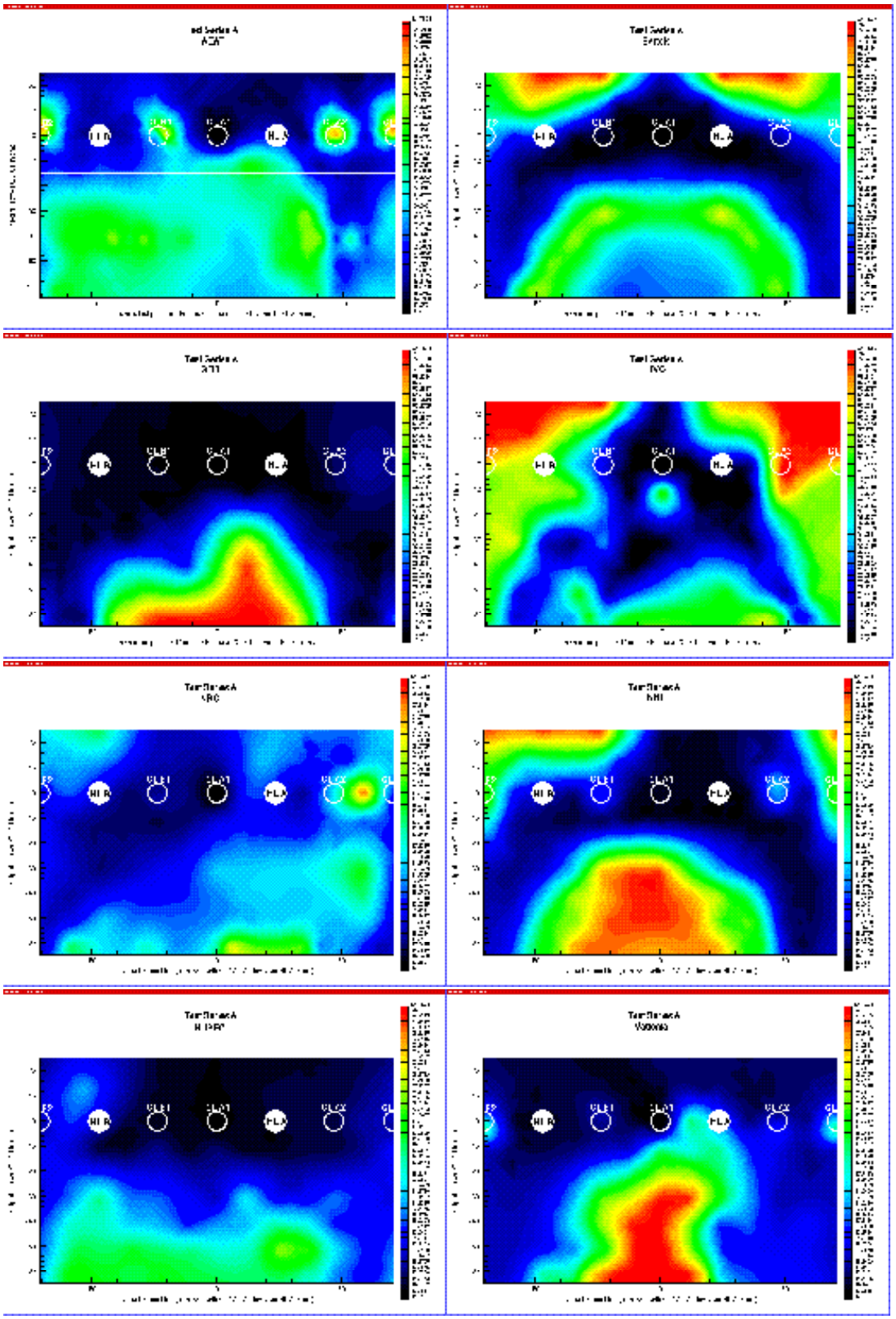

Figure 6-14. Snapshots of the 8 participant submissions for test A at 28 s (72 liters)

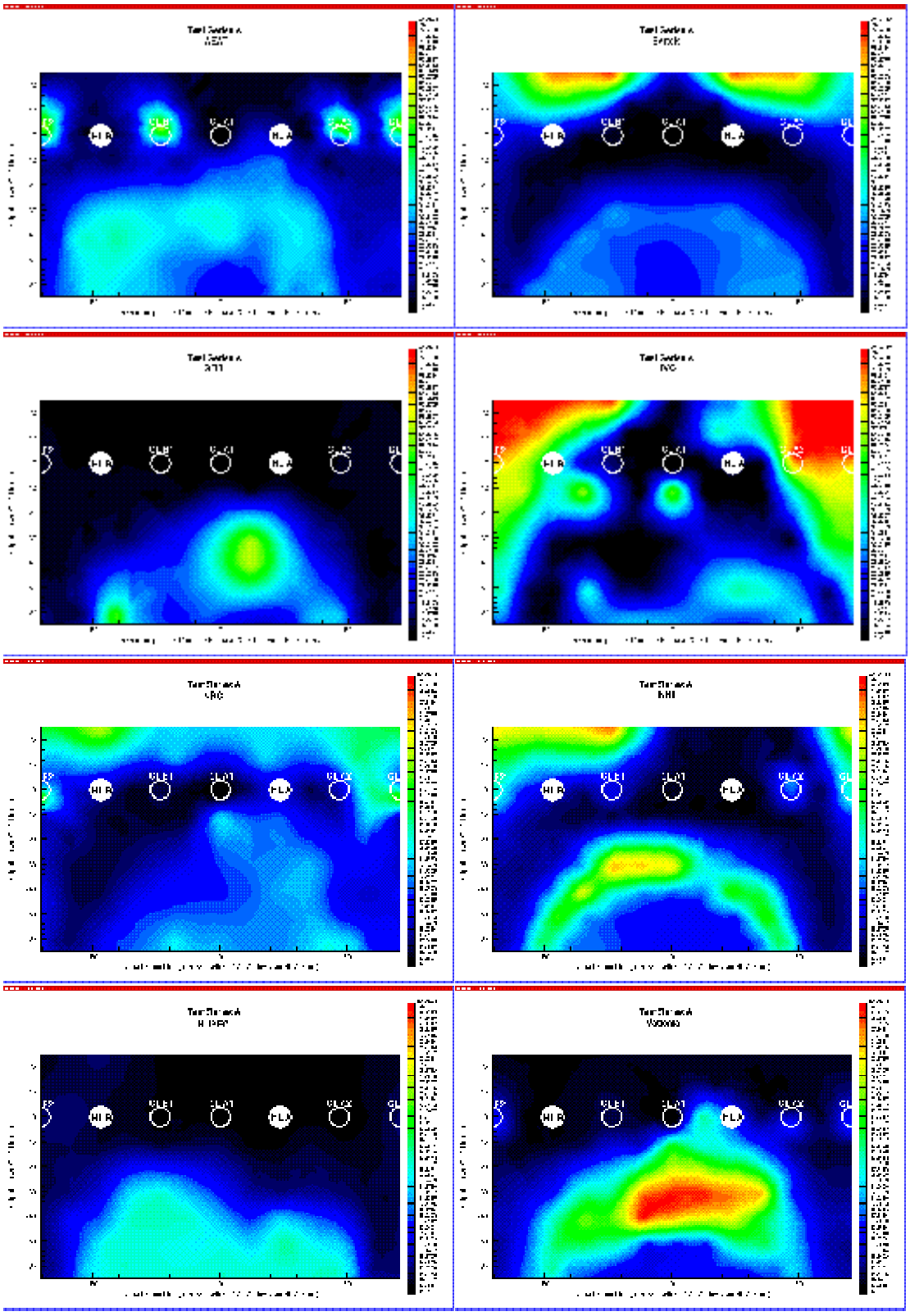

Figure 6-15. Snapshots of the 8 participant submissions for test A at 32 s (100 liters)

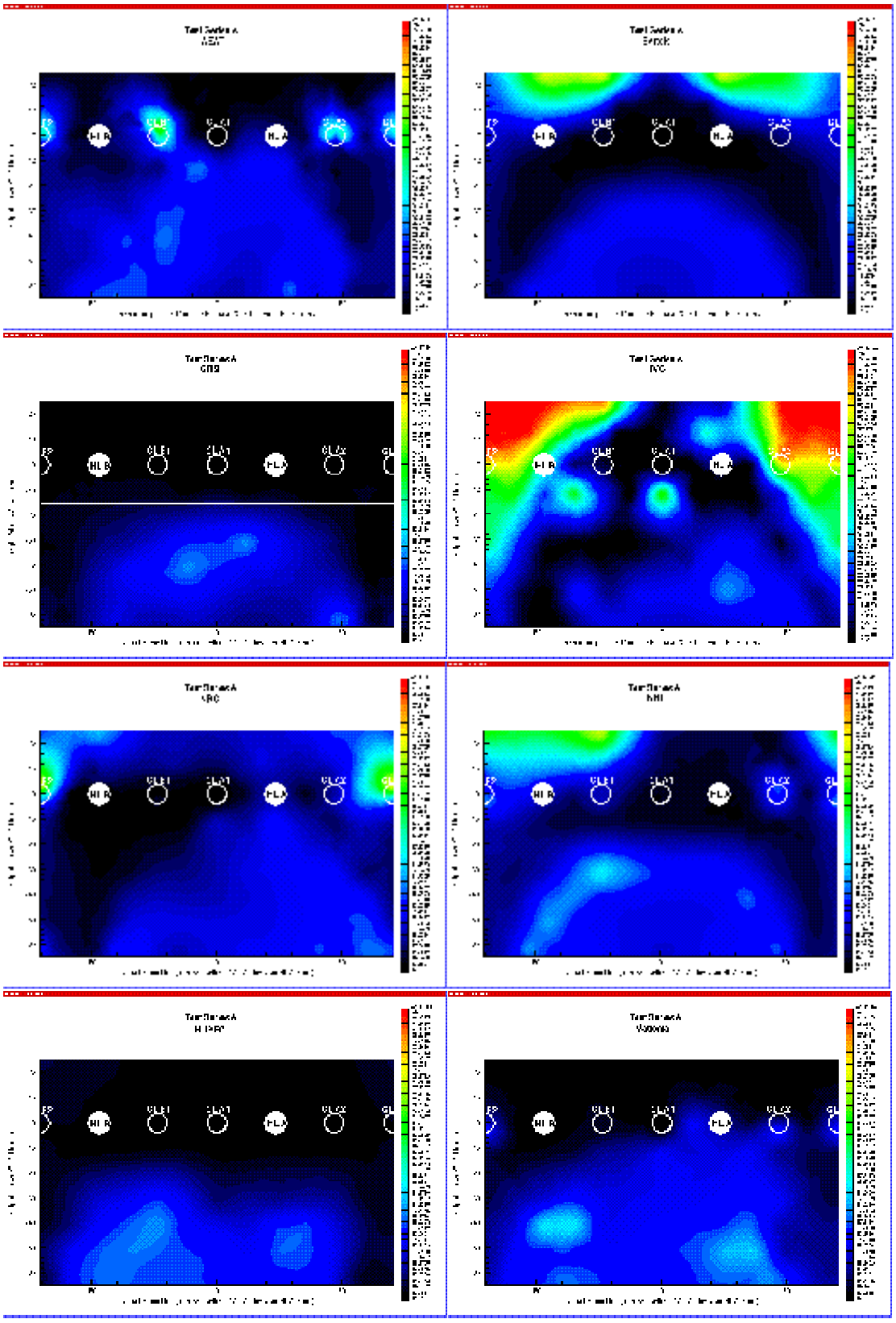

Figure 6-16. Snapshots of the 8 participant submissions for test A at 36 s (128 liters)

6.2 Test B

The tests of series B have a very short period of time at the beginning of the transient when buoyancy density differences are significant. This is because a slug is injected, and thus after the front of the slug passes, the density difference actually reverses as the tail end flows through the downcomer. The Fr number for the 6 redundant tests of series B is shown in Figure 6-17. It is important to note that the visualization facility slug is 40 % larger than that injected in loop experiments and used in simulations, so a direct quantitative comparison cannot be made. Qualitatively, however, the next sections show that the flow pattern is largely consistent among experiments and simulations in this test series.

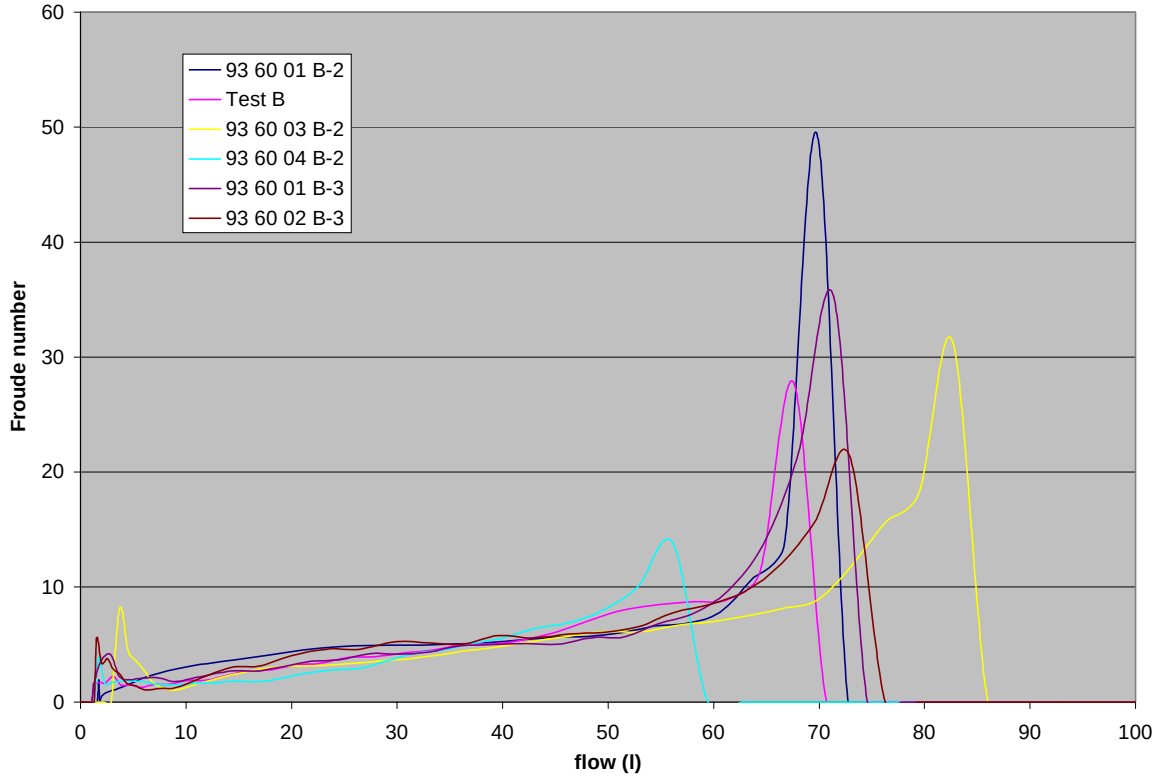

Figure 6-17. Fr number histories of the 6 redundant tests of series B

6.2.1 Loop downcomer flow pattern for test B

Because buoyancy plays a minor role in this test series, the results are highly reproducible. A single point, at 48 liters injected, can be used to compare experimental and computational results. As can be seen in Figure 6-18, the nominal test B, i.e., that for which boundary and initial conditions were supplied to participants, is very similar to the average of the ensemble of the 6 redundant tests. Note also that the standard deviation of the ensemble tests is very small, confirming great reproducibility.

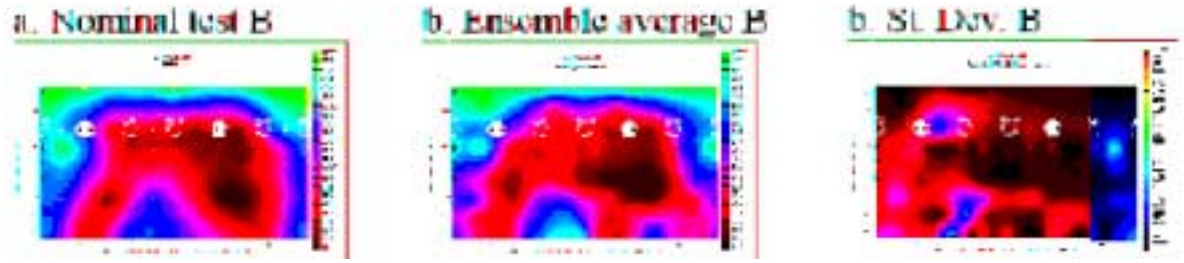

Figure 6-18. Flow patterns at 48 liters injected as obtained from: a. the nominal test B, and b. ensemble of the 6 redundant tests; c. standard deviation in the ensemble of the 6 redundant tests

The patterns of the 6 tests depicted in Figure 6-19 show that all B tests exhibit the stagnation region underneath the injection cold leg. As expected, in these tests where the Fr number is high throughout, the flow entering the downcomer spreads azimuthally and than flows downwards forming the Λ structure.

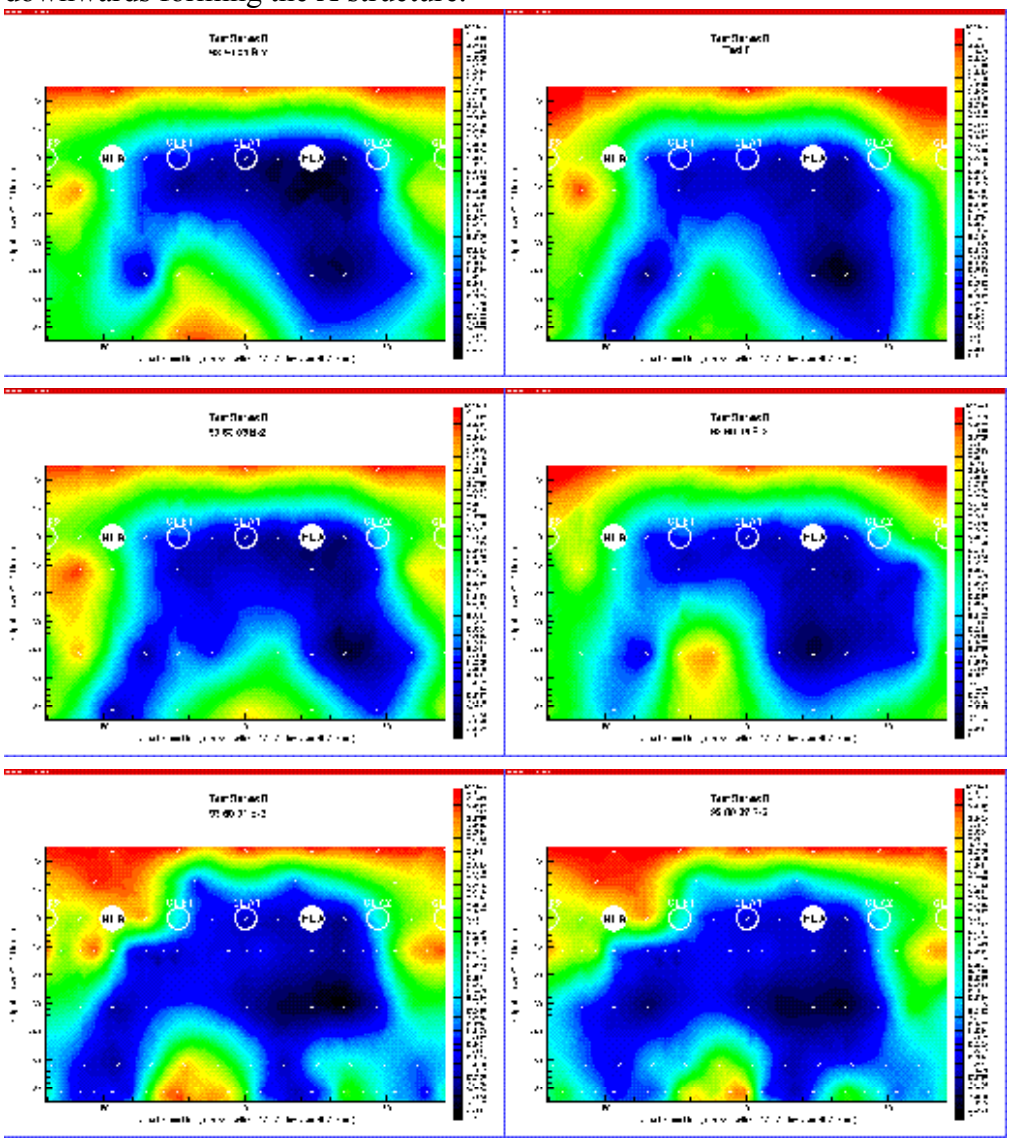

Figure 6-19. Snapshots of the 6 redundant tests of series B at 48 liters

6.2.2 Visualization facility downcomer flow pattern for test B

In the neutrally buoyant case of the visualization facility, the transient mixing process for the slug case is initially identical to that of the front. As the trailing interface is injected, however, the dilute "boron-free" water is flushed from the system in the same way it was filled. The timing is such that the low-speed recirculation region immediately below the injection leg is the last region to be flushed clear of the diluted slug. Note also that the slug has a volume of 80 liters, which is approximately the same as that of the downcomer and the lower plenum. As mentioned earlier, the water is recirculated for the slug test so that the fluid entering on the “tail” side of the slug has been slightly diluted by that portion of the slug, which already exited the lower plenum.

6.2.3 Participant submissions downcomer flow pattern for test B

Table 6-3 shows the matrix of snapshots depicted in Figure 6-21. AEAT, NRC, NRI, NUPEC and Vattenfall show downcomer flow pattern consistent with those observed in the loop and visualization facility. IVO’s flow exhibits only a slight stagnation region, while all of CEA’s simulations show a predominant downward flow.

Table 6-3. Matrix of code submission snapshots depicted in Figure 6-21

AEAT	CEA keps	CEA nut0
CEA nut0par	IVO	NRC
NRI	Nupec	Vattenfall

6.3 Flow Pattern Observed Under Injection Cold Leg

One of the interesting features observed in the visualization of the flow pattern is the structure of the impinging jet, and its intersection with the slow-moving recirculation zone in the lower downcomer. Accurate representation of this feature, and its rate of mixing, will likely have an impact on the structure of the rest of the flow field. Although some information has already been provided with the steady-state velocity fields presented in section 6-1, additional qualitative visualizations have been performed to supplement this data.

Data was acquired in this case using a high-resolution (1008x1016 pixels) 8-bit CCD camera to image a fixed radial plane centered on the cold leg inlet, sampled at a rate of 10 frames per second. The field of view of the camera was selected to image the downcomer gap from just below the cold leg, to a region approximately 15 cm below the gap expansion. No corrections were made for the optical distortion caused by viewing the plane through the cylindrical wall of the downcomer. Although the images were normalized to provide a semi-quantitative representation of the data, the noise of the camera at these particularly low light levels was sufficient to render the data suitable mainly for qualitative visualization. The sequence of images showing a front injection event (test A) is depicted in Figure 6-12.

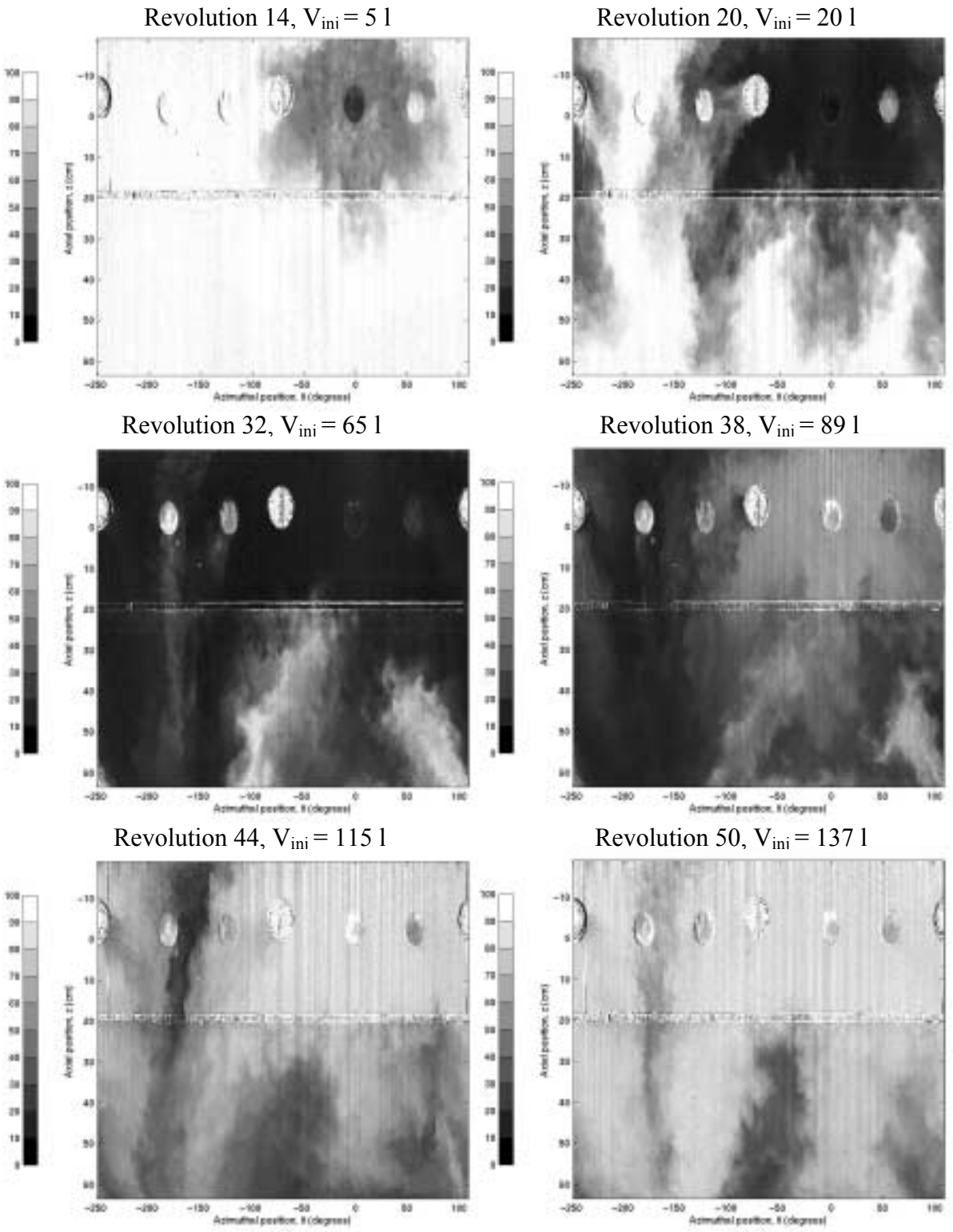

Figure 6-20. Temporal sequence of a single slug injection test (061499_run3). V_{inj} is the injected volume corresponding to the equivalent loop tests as listed in Table 3-3.

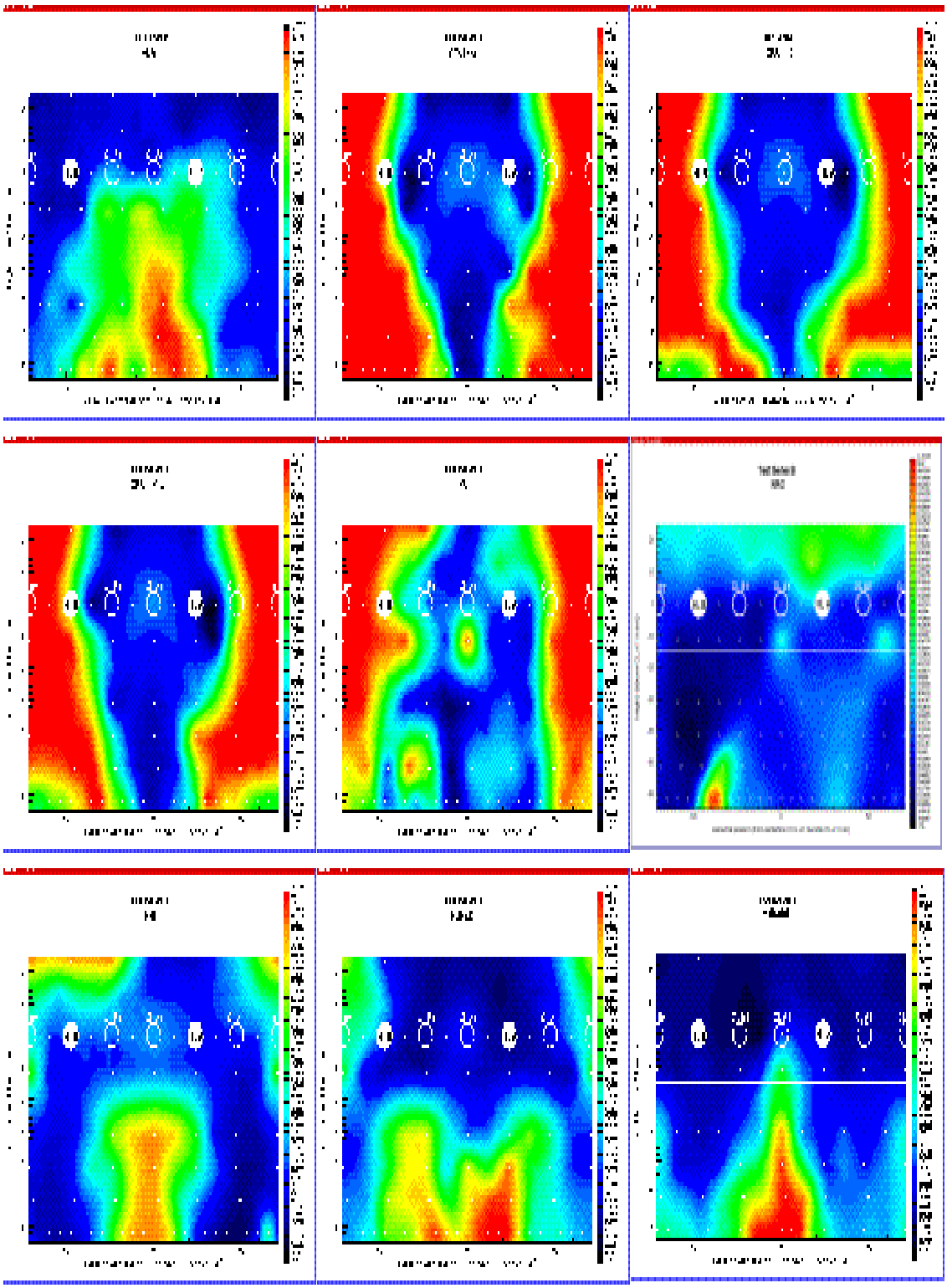

Figure 6-21. Snapshots of the 9 participant submissions of test B at 48 liters

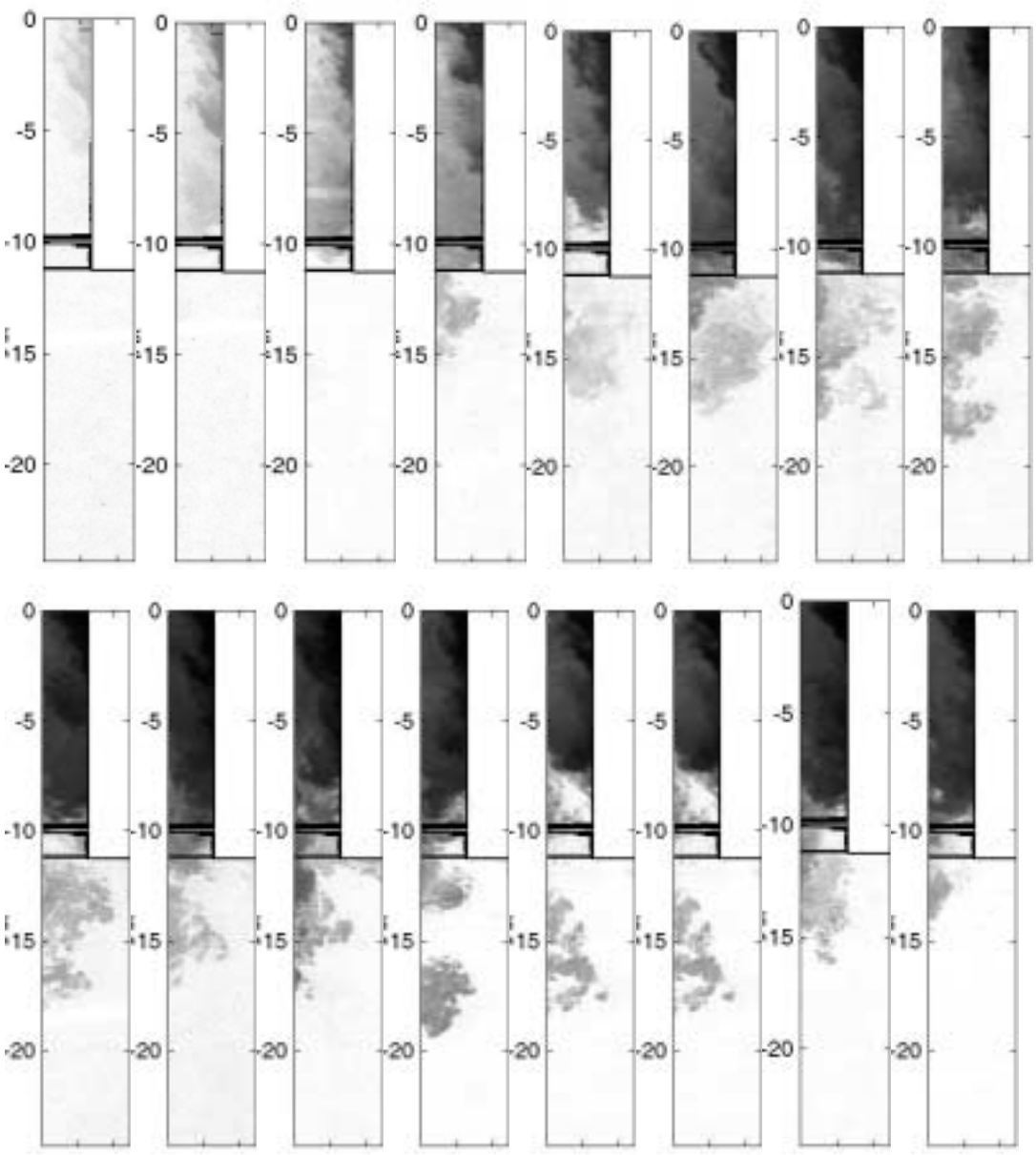

Figure 6-12. Sequence of images depicting the temporal evolution of the concentration field in the radial plane aligned with the downcomer. Numbers indicate approximate distances in centimeters. Black color indicated zero concentration (dilute), while white indicated 100% concentration (borated). The image sequence starts when the front first exits the cold leg and subsequent images are separated by 1 second.

As the front first enters, the impinging jet can be clearly seen on the outer core barrel wall. Fairly strong radial gradients initially exist during the first several seconds before the mixing layer has had a chance to transport and mix the incoming dilute fluid with the borated fluid trapped in the recirculating water moving towards the cold leg inlet. The ring structures themselves are clearly visible as dark lumps spaced periodically along the downcomer.

As the impinging jet moves toward the gap widening, it is seen to separate from the outer barrel wall and reattach on the inner pressure vessel wall. From this point, the jet tip appears to slowly roll up into a larger structure, which maintains its position just below the gap widening. The mixing zone within this area appears to surge up and down several times throughout the duration of the injection event, and other structures appear, grow, and decay as if they were moving perpendicular to the illuminated plane. This would be consistent with the "nominal" cases observed where small mixing features are observed to propagate along the interface between the dilute plume and borated recirculation region that exists in the lower downcomer. The interesting aspect of this feature is that it's behavior is in stark contrast to that of the prototypical backwards-facing step flow, where the fluid exiting the narrower gap separates at the corner, and then reattaches to the same wall some 5 to 8 step heights downstream. The important thing to remember, however, is that this geometry is only superficially similar to a prototypical backwards-facing step within this local region, and is in reality a composition of several complex features which all are strongly coupled with one another to form the overall flow pattern.

7 Conclusions

It is important to note that ISP 43 is only the second standard international computational exercise to employ CFD codes for nuclear industry applications. The rapid boron dilution scenario targeted by ISP 43 also involves the largest simulation volume of a standard exercise using CFD codes. Thus the conclusions are twofold: first regarding the applicability of CFD codes to problems specific to the nuclear industry, and second regarding the performance of codes in simulating the integral facility behavior of a rapid boron dilution transient.

The test series for rapid boron dilution run in the UM 2x4 Loop were designed to a large extent to provide adequate insight into codes' ability to capture phenomena important in this transient. Thus, the two closed test series included in this report are the injection of a front and the single inlet/single outlet injection of a slug. Both scenarios are sufficiently simple to permit the examination of phenomena important to this transient, but sufficiently complex to draw conclusions regarding the performance of codes in simulating the realistic transient. The front injection, test series A, was not initially drafted to provide insight into the actual boron dilution scenario. However, the 16 redundant tests of this series showed that buoyancy has an impact on the transient and that the judicious inclusion of temperature dependent properties is essential. This conclusion is very important in the context of the real boron dilution transient, for which temperature differences between the slug and the primary coolant into which it is injected can be substantial. An examination of downcomer Fr number must be made before running plant simulations, even at the very high Re numbers expected in the prototype pump startup.

The second test series, B, involved the injection of a slug. Six redundant tests were documented. This is a realistic scenario for the downcomer volume, which was the focus of this ISP. Like in the prototype, the slug has a steep front and a more shallow tail. Because of the B&W lowered loop configuration of the UM 2x4 Loop, the slug size is substantially larger than that expected to accumulate in U-tube steam generators. Thus, the temporal and spatial distribution of boron scaled up from the UM 2x4 Loop experiments would not be prototypical of most PWRs. Even with a smaller slug, mixing cannot be directly extrapolated

to the prototype. Specifically, while it is expected that most of the prototype slug mixing will occur in the downcomer, both the flow pattern and the entrainment of primary coolant into the slug are affected by plant-specific features. This makes the use of computational tools essential in assessing plant-specific boron dilution scenarios, and was an essential motivation for this exercise.

The acquisition of data from several redundant tests for both the loop and visualization facility, is also a unique feature of ISP 43. The data was processed and reduced to yield ensemble averages and standard deviations that confirm repeatability and provide a true experimental error band for the comparison of experimental and computational results. The experimental error bands proved to be narrow for the figures of merit of the exercise. The figures of merit being level average behavior and azimuthal mixing are primarily first order, since they target basic conservation of mass, momentum and energy. Not surprisingly, codes performed well overall with respect to the average mixing at the first level below the injection site (level 8) and at the downcomer outlet (level 4) for both tests A and B.

Discrepancies were however evident in the more qualitative but essential comparison of experimental and computational downcomer flow patterns. The evaluation of test A flow patterns was challenging because the loop tests fell into two families: one that exhibited a stagnation region under the injection site as did the visualization facility data and most of the simulations, and one in which flow was predominant along a single tongue extending downward in the direction of hot leg B. During the second workshop, participants suspected the differences to be either due to buoyancy effects or the modeling of the simulation domain outlet, i.e., the flow pressure drop beyond the downcomer. Further investigation of the Fr number showed that slight variations (less than 5 °C) in the initial heat up of the primary volume coupled with natural fluctuations of city water temperature, which thus changed the initial front temperature, impact the effect of buoyancy in the different tests. Thus, the extent to which participants accounted for temperature depended properties and whether or not they included the effect of buoyancy on the generation and dissipation of turbulent kinetic energy does affect the predicted flow pattern.

It is important to note that, even in the absence of buoyancy effects, a complex highly non-linear flow such as that in the downcomer of an integral test facility will exhibit some variation. This is evident in the neutrally buoyant visualization facility tests, in which several of the flow patterns show a tongue of fluid penetrating into the stagnation region that forms under the injection cold leg.

Because the test B experiments are subject to strong buoyancy effects only while the front of the slug enters the downcomer, a stagnation region consistently develops under the injection site in all experiments and most code predictions. It is important to note that temperature differences between the slug and primary coolant are largest while the pump is ramping up and in the very first seconds of steady state injection, thus while inertial forces are lowest. The B test code predictions are overall in very good agreement with experimental data. This good agreement extends beyond the downcomer to the plane below the core support plate. At this level, both experiments and code predictions show the presence of still dilute coolant for this large slug. Note that the consequences of any reactivity insertion caused by the penetration of dilute fluid into the core must be assessed through coupled thermalhydraulic-neutronic computations, which are beyond the scope of ISP 43.

The goal of ISP 43 was to examine CFD codes' ability to properly predict mixing of fluids in a complex geometry under transient conditions. Broadly, there are two factors that affect code-predicted mixing: mesh resolution and turbulence modeling. This makes it difficult to evaluate the individual impact of these factors without rigorous parametric studies. Given modern solution algorithms, an adequately resolved mesh can reduce numerical diffusion to negligible levels in transients where mixing is turbulence dominated. The discretizations and mesh refinements selected by some participants clearly show that mesh convergence had been achieved. The under-mixing in several participant submissions evidences this. In the case of a resolved mesh the selection of an appropriate turbulence model is essential to the proper prediction of mixing. One more important factor needs to be considered in this discussion, namely the local refinement in regions where the flow is subject to large gradients or where flow patterns are rapidly changing. The importance of detail modeling is also evident from the comparisons of ISP 43. Specifically, where discrepancies are noted between computations and experimental data, the level 8 and level 10 predictions already reflect the disagreement. These levels are immediately adjacent to the injection site, where flow gradients are largest and flow pattern features actually form. The issue of local node refinement cannot be isolated from general mesh convergence and turbulence models, so it must also be investigated through parametric studies.

Based on the findings of ISP 43, there is no reason to preclude the use of CFD codes to from investigating prototype PWR boron-dilution transients and, more broadly, transients that involve single phase mixing. Parametric studies that lead to input/model improvements are desirable for buoyancy effects. The good agreement between experiments and many of the computational predictions shows that computational fluid dynamics methods have reached the maturity necessary to obtain realistic predictions. It is also evident that computational power and the expertise of modelers have reached a stage at which it has become feasible to carry out some of the complex computations that describe the behavior of nuclear systems.

8 References

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9 Appendix A—Instrumentation Specifications

9.1 DAS Specifications

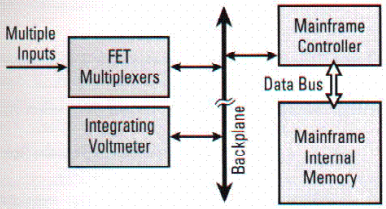
SYSTEM SPEED CHARACTERISTICS

Measurement and Reading Transfer Time

Measurement and transfer rates to close channels, trigger, measure, and transfer readings.

Integrating Voltmeter Using FET Multiplexers
(Fixed range, auto-zero off for DC volts, offset compensated Ω off for resistance)

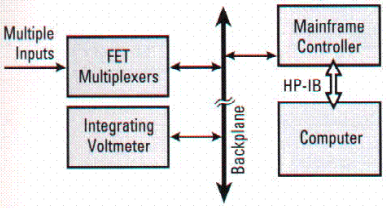
Readings to Mainframe Internal Memory:



Measurement and Transfer Rate
(readings/sec), 60/50 Hz

HP 44709A/44710A/ 44711A/B44712A/44713A/B		Integration Time in # of Power Line Cycles (NPLC) 1.0	0.1	0.005	0.0005
DC Volt Format	Packed	54/46	330/310	880/880	1060/1060
	64-bit Real	54/45	320/285	680/680	770/770
Resistance: (2-w & 4-w Ω) Format:	Packed	24/20	95/89	138/138	144/144
	64-bit Real	24/20	92/86	132/132	138/138

Readings to HP Series 300 Computers over HP-IB:



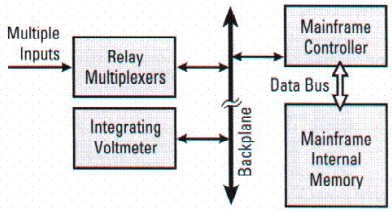
Measurement and Transfer Rate
(readings/sec), 60/50 Hz

HP 44709A/44710A 44711A/B44712A/44713A/B		Integration Time in # of Power Line Cycles (NPLC) 1.0	0.1	0.005	0.0005
DC Volt Format	Packed	52/44	290/265	600/600	690/690
	64-bit Real	50/43	250/230	430/430	470/470
	ASCII Real	47/40	180/170	265/265	275/275
Resistance: (2-w & 4-w Ω) Format:	Packed	23/20	88/83	125/125	130/130
	64-bit Real	23/20	83/80	118/118	122/122
	ASCII Real	22/19	73/70	102/102	103/103

For accurate resistance measurements using FET multiplexers, 4-wire Ω is recommended.

Integrating Voltmeter Using Relay Multiplexers
(fixed range, auto-zero off for DC volts, offset compensated Ω off for resistance)

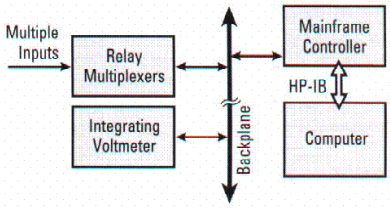
Readings to Mainframe Internal Memory:



Measurement and Transfer Rate
(readings/sec), 60/50 Hz

HP 44705A/44705F/ 44706A/44708A/44708F		Integration Time in # of Power Line Cycles (NPLC) 1.0	0.1	0.005	0.0005
DC Volt Format	Packed	51/44	230/216	387/387	417/417
	64-bit Real	51/43	230/214	387/387	417/417
Resistance (2-w & 4-w Ω) Format	Packed	23/20	80/76	108/108	114/114
	64-bit Real	23/20	80/76	108/108	114/114
HP 44705H/44708H only					
DC Volt Format	Packed	47/40	168/158	228/228	240/240
	64-bit Real	47/40	168/158	228/228	240/240
Resistance: Format:	Packed	22/19	70/67	90/90	94/94
	64-bit Real	22/19	70/67	90/90	94/94

Readings to HP Series 300 Computer over HP-IB:



Measurement and Transfer Rate
(readings/sec), 60/50 Hz

HP 44705A/44705F/ 44706A/44708A/44708F		Integration Time in # of Power Line Cycles (NPLC) 1.0	0.1	0.005	0.0005
DC Volt Format	Packed	49/41	220/200	358/358	388/388
	64-bit Real	48/40	190/177	300/300	310/310
	ASCII Real	43/37	150/142	205/205	210/210
Resistance (2-w & 4-w Ω) Format	Packed	22/19	78/72	103/103	107/107
	64-bit Real	22/19	77/70	100/100	105/105
	ASCII Real	21/18	68/64	87/87	91/91

These specifications give you total system accuracy including all errors contributed by the voltmeters, system back-plane, ribbon cables, and function modules. Cross talk between channels is not included here, but is specified under the multiplexer descriptions.

Specified over time since last calibration, and operating temperature, with a one-hour warm-up.

DC Voltage ± (% of reading + volts)

Integrating Voltmeter with Relay Multiplexers

90 Days, 18 to 28 °C, Auto-zero On.

	Integration Time in Number of Power Line Cycles (NPLC)			
	1	0.1	0.005	0.0005
Range				
30 mV	0.02%+8 µV	0.02%+10 µV	0.02%+22 µV	0.02%+60 µV
300 mV	0.008%+8 µV	0.008%+12 µV	0.008%+40 µV	0.008%+400 µV
3 V	0.008%+10 µV	0.008%+40 µV	0.008%+400 µV	0.008%+4 mV
30 V	0.008%+300 µV	0.008%+700 µV	0.008%+4 mV	0.008%+40 mV
300 V	0.008%+700 µV	0.008%+4 mV	0.008%+40 mV	0.008%+400 mV

1 Year: Add 0.01% of reading to 90-day specifications.

Temperature Coefficient:
Add as an additional accuracy error using ± (% of reading + volts) per °C change outside 18 to 28 °C, as long as the operating temperature is maintained between 0 to 18 or 28 to 55 °C.

For 30 mV range, add 0.002% + 30 nV
For 300 mV and 3 V ranges, add 0.0006% + 300 nV
For 30 V and 300 V ranges, add 0.0006% + 30 µ

Auto-zero Off:
Add as an additional accuracy error if auto-zero is turned off. Assumes stable environment, ± 1 °C, for 24 hours.

For 30 mV, 300 mV, and 3 V ranges, add 10 µV
For 30 V range, add 100 µV
For 300 V range, add 1 mV

Integrating Voltmeter with FET Multiplexers

90 Days, 18 to 28 °C, Auto-zero On.

	Integration Time in Number of Power Line Cycles (NPLC)			
	1	0.1	0.005	0.0005
Range				
30 mV	0.02%+32 µV	0.02%+50 µV	0.02%+240 µV	0.02%+300 µV
300 mV	0.008%+32 µV	0.008%+50 µV	0.008%+320 µV	0.008%+1 mV
3 V	0.008%+34 µV	0.008%+80 µV	0.008%+700 µV	0.008%+4 mV
30 V	0.068%+330 µV	0.068%+700 µV	0.068%+4 mV	0.068%+40 mV
300 V	0.068%+700 µV	0.068%+4 mV	0.068%+40 mV	0.066%+400 mV

1 Year: Add 0.01% of reading to 90-day specifications.

Temperature Coefficient:
Add as an additional accuracy error for operating temperature, T, between 0 to 18 or 28 to 55 °C.

For 30 mV range,
0 to 18 °C, add (0.002% + 30 nV)*(18 - T);
28 to 40 °C, add (0.002% + 2.63 µV)*(T - 28);
40 to 55 °C, add (0.002% + 9.28 µV)*(T - 40) + 31.56 µV.

For 300 mV and 3 V ranges,
0 to 18 °C, add (0.0006% + 300 nV)*(18 - T)
28 to 40 °C, add (0.0006% + 2.9 µV)*(T - 28);
40 to 55 °C, add (0.0006% + 9.55 µV)*(T - 40) + 34.8 µV.

For 30 V and 300 V ranges,
0 to 18 °C, add (0.0006% + 30 µV)*(18 - T);
28 to 40 °C, add (0.0006% + 32.6 µV)*(T - 28);
40 to 55 °C, add (0.0006% + 39.25 µV)*(T - 40) + 391.2 µV .

Auto-zero Off:
Add as an additional accuracy error if auto-zero is turned off. Assumes stable environment, ± 1 °C, for 24 hours.

For 30 mV, 300 mV, and 3 V ranges, add 10 µV
For 30 V range, add 100 µV
For 300 V range, add 1 mV

High Speed Voltmeter HP 44702 A/B with High-Speed FET Multiplexers HP 44711A or HP 44713A

Specified with auto-zeroing performed within one minute of measurement

90 Days, 18 to 28 °C.

Range	Linearity	Single Reading Noise and Offset	Averaged Reading Noise and Offset	Averages
40 mV	0.05%	+ 88 µV	+ 59 µV	100
320 mV	0.05%	+234 µV	+ 156 µV	10
2.56 V	0.05%	+ 1.88 mV	+ 1.25 mV	10
10.24 V	0.05%	+ 7.5 mV	+ 5 mV	10

1 Year: Add 0.05% of reading to 90-day specifications.

Temperature Coefficient:
Add as an additional accuracy error per °C change outside 18 to 28 °C, but within 0 to 55 °C.

For 40 mV range,
0 to 18 °C, add (0.004% + 0.448 µV)*(18 - T);
28 to 40 °C, add (0.004% + 3.1 µV)*(T - 28);
40 to 55 °C, add (0.004% + 9.74 µV)*(T - 40) + 37.2 µV.

For 320 mV range,
0 to 18 °C, add (0.002% + 3.91 µV)*(18 - T);
28 to 40 °C, add (0.002% + 6.51 µV)*(T - 28);
40 to 55 °C, add (0.002% + 13.16µV)*(T - 40) + 78.12 µV.

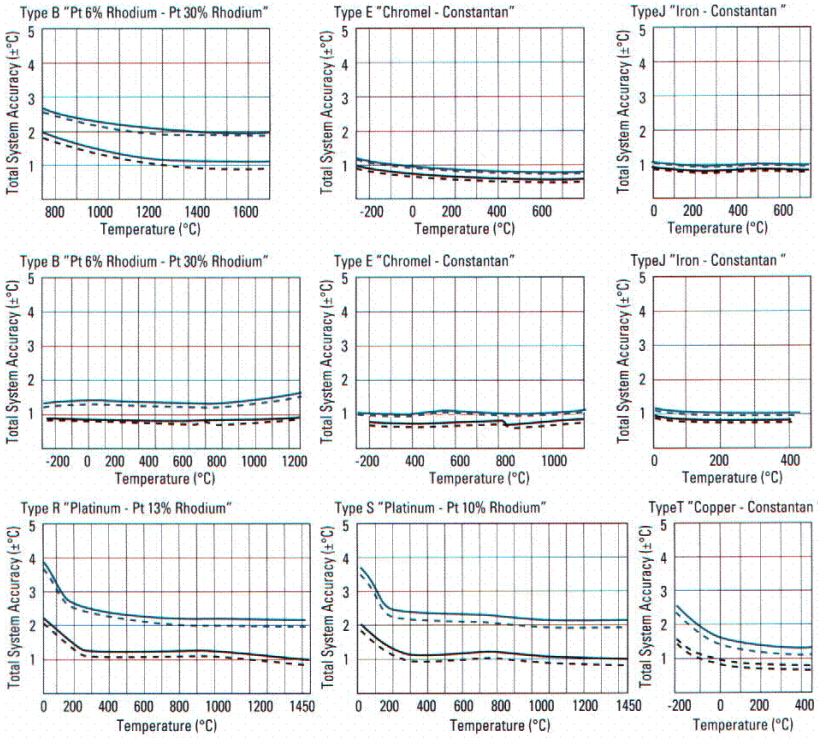
For 2.56 V range,
0 to 18 °C, add (0.002% + 31.3 µV)*(18 - T);
28 to 40 °C, add (0.002% + 33.9 µV)*(T - 28);
40 to 55 °C, add (0.002% + 40.55 µV)*(T - 40) + 406.8 µV.

For 10.24 V range,
0 to 18 °C, add (0.002% + 125 µV)*(18 - T);
28 to 40 °C, add (0.002% + 127.6 µV)*(T - 28);
40 to 55 °C, add (0.002% + 134.25 µV)*(T - 40) + 1.53 mV.

Key:
Thermocouples

Integrating DVM with:
HP 44708A Relay Multiplexer
—— NPLC = 0.1
- - - - - NPLC = 1.0

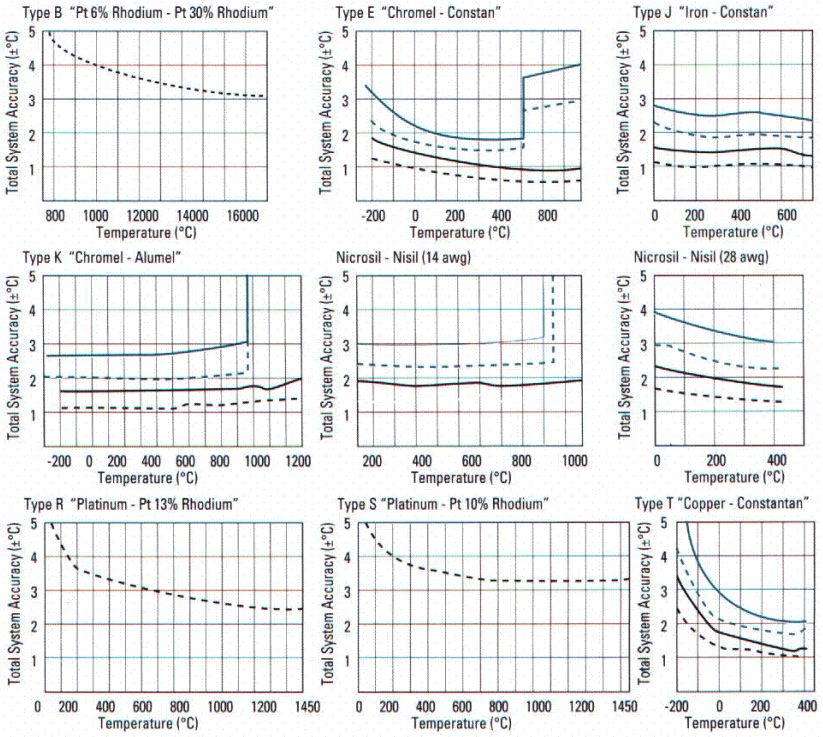
HP 44708H High Voltage Multiplexer
—— NPLC = 0.1
- - - - - NPLC = 1.0



Key:
Thermocouples

Integrating DVM with:
HP 44710A FET Multiplexer
—— NPLC = 0.1
- - - - NPLC = 1.0

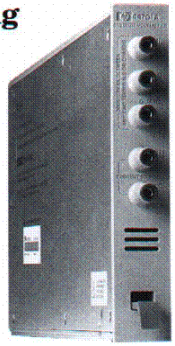
High Speed DVM (HP 44702A/B) with:
HP 44713A FET Multiplexer
—— single reading
- - - - 100 averaged readings



Temperature
± °C, 90 days, 18 to 28 °C operating temperature (auto-zero on for integrating voltmeter and autozeroing within one minute for high-speed voltmeter)

5 1/2- to 3 1/2-Digit Integrating Voltmeter

HP 44701A



Directly Measures:

- DC Voltage
- Resistance
- AC Voltage

Benefits

- **Accurately measure small signal changes in noisy environments:**
  - –Integrating A/D rejects normal mode noise at multiples of the power line frequency.
  - –Guarded input maximizes common-mode rejection.
- **Choose the resolution, accuracy, and noise rejection needed, while maximizing measurement speed:**
  - –Integration selection (number of power line cycles) is key to optimizing these performance parameters.
  - –This voltmeter provides the fastest DC reading rates available with power line-related noise rejection.
- **Optimize resistance measurements to the accuracy you need:**
  - –Use two-wire Ω for measurements where lead resistance is not critical.
  - –Use four-wire Ω where inaccuracies due to measurement leads cannot be tolerated (most accurate measurement technique for RTDs).
  - –Use offset-compensated Ω to correctly measure resistance in the presence of series voltages (often caused by thermocouple effects).

DC Voltage

Accuracy:

± (% of reading + volts), rear terminal input, one-hour warm-up, specified over time since last calibration, and operating temperature.

90 Days, 18 to 28 °C, Auto-zero On.

	Integration Time in Number of Power Line Cycles (NPLC)			
Range	**1**	**0.1**	**0.005**	**0.0005**
30 mV	0.02%+6 µV	0.02%+8 µV	0.02%+20 µV	0.02%+60 µV
300 mV	0.008%+6 µV	0.008%+10 µV	0.008%+40 µV	0.008%+400 µV
3 V	0.008%+8 µV	0.008%+40 µV	0.008%+400 µV	0.008%+4 mV
30 V	0.008%+300 µV	0.008%+700 µV	0.008%+4 mV	0.008%+40 mV
300 V	0.008%+700 µV	0.008%+4 mV	0.008%+40 mV	0.008%+400 mV

1 Year: Add 0.01% of reading to 90-day specifications.

Temperature Coefficient:

Add as an additional accuracy error using ± (% of reading + volts) per °C change outside 18 to 28 °C, as long as the operating temperature is maintained between 0 to 18 or 28 to 55 °C.

For 30 mV range, add 0.002% + 30 nV

For 300 mV and 3 V ranges, add 0.0006% + 300 nV

For 30 V and 300 V ranges, add 0.0006% + 30 µV

Auto-zero Off:

Add as an additional accuracy error if auto-zero is turned off. Assumes stable environment, ± 1 ° C, for 24 hours.

For 30 mV, 300 mV, and 3 V ranges, add 10 µV

For 30 V range, add 100 µV

For 300 V range, add 1 mV

Resolution:

	Integration Time in Number of Power Line Cycles (NPLC)			
Range:	**1**	**0.1**	**0.005**	**0.0005**
30 mV	10 nV	100 nV	1 µV	10 µV
300 mV	100 nV	1 µV	10 µV	100 µV
3 V	1 µV	10 µV	100 µV	1 mV
30 V	10 µV	100 µV	1 mV	10 mV
300 V	100 µV	1 mV	10 mV	100 mV

Over-ranging: 1% of full scale

Reading Rate/Noise Rejection:

	Integration Time in Number of Power Line Cycles (NPLC)			
	1	**0.1**	**0.005**	**0.0005**
Integration Time 60 Hz (50 Hz)	16.7 (20.0) msec	1.67 (2.0) msec	100 (100) µsec	10 (10) µsec
Number of Converted Digits	6 1/2	5 1/2	4 1/2	3 1/2
Reading Rate (readings/sec) with auto-zero, auto-range off 60 Hz (50 Hz)	57 (48)	415 (360)	1350 (1350)	1600 (1600)
Min Noise Rejection (dB) Normal Mode Rejection at 50 or 60 Hz ± 0.09%	60	0	0	0
DC Common Mode Rejection with 1 kΩ in low lead	120	120	120	120
Effective Common Mode Rejection, at 50 or 60 Hz ±0.09% with 1 kΩ in low lead	150	90	90	90

DC Voltage Example:

Suppose that you want to measure an 8-volt signal 100 times per second. What is your resolution and accuracy?

Answer: Use the reading rate table to find that you would set the VM to the 0.1 NPLC integration time which gives you 5 1/2 digits at up to 415 Hz.Use the resolution table to find that you would get 100 µV resolution on the 30 volt range at 0.1 NPLC. Use the accuracy table to find that you would have an error of 1.3 mV (.008% * 8 V + 700 µV) or .02%.

Resistance

Accuracy:

± (% of reading + Ω), 4- or 2-wire Ω, offset compensation on or off, rear terminal inputs, one-hour warm-up, specified over time since last calibration, and operating temperature. (Current source compliance voltage is at least 6 V).

90 Days, 18 to 28 °C.

	Integration Time in Number of Power Line Cycles (NPLC)			
Range	**1**	**0.1**	**0.005**	**0.0005**
(1 mA current source)				
30 Ω	0.02%+6 mΩ	0.02%+20 mΩ	0.02%+40 mΩ	0.02%+75 mΩ
300 Ω	0.015%+6 mΩ	0.015%+20 mΩ	0.015%+60 mΩ	0.015%+400 mΩ
(100 µA current source)				
3 kΩ	0.015%+60 mΩ	0.015%+200 mΩ	0.015%+650 mΩ	0.015%+4 Ω
30 kΩ	0.015%+00 mΩ	0.015%+400 mΩ	0.015%+5 Ω	0.015%+80 Ω
(10 µA current source)				
300 kΩ	0.015%+1 Ω	0.015%+4 Ω	0015%+50 Ω	0.015%+800 Ω
(1 A current source)				
3 mΩ	0.1%+17 Ω	0.1%+70 Ω	0.1%+500 Ω	01%+6 kΩ

1 Year: Add 0.01% of reading to 90-day specifications.

Temperature Coefficient:

Add as an additional accuracy error using ± (% of reading + Ω) per °C change outside 18 to 28 °C, as long as the operating temperature is maintained between 0 to 18 or 28 to 55 °C.

For 30 Ω, 300 Ω, and 3 kΩ ranges,
add 0.0006% + 500 µΩ

For 30 kΩ range,
add 0.0006% + 5 mΩ

For 300 kΩ range,
add 0.001% + 50 mΩ

For 3 MΩ range,
add 0.001% + 500 mΩ

Reading Rate:

	Integration Time in Number of Power Line Cycles (NPLC)			
	1	**0.1**	**0.005**	**0.0005**
Reading Rate (readings/sec)				
with auto-zero, auto-range off	25	100	155	160
60 Hz (50 Hz)	(20)	(95)	(155)	(160)

AC Voltage

Accuracy:

± (% of reading + volts), 1 NPLC integration time, one-hour warm-up, specified over time since last calibration, and operating temperature. AC measurements are made with an average detector calibrated in RMS, and are intended to measure sine waves between 45 to 500 Hz (AC-coupled). The voltmeter accuracy is *specified only when the input voltage is greater than 10% of full scale.*

Accuracy:

90 Days, 18 to 28 °C.

	90 day	1 year
Range		
200 mV	0.5% + 600 µV	0.75% + 900 µV
2 V	0.5% + 6 mV	0.75% + 9 mV
20 V	0.5% + 60 mV	0.75% + 90 mV
200 V	0.5% + 600 mV	0.75% + 900 mV

Temperature Coefficient:

Add as an additional accuracy error using ± (% of reading + volts) per °C change outside 18 to 28 °C, as long as the operating temperature is maintained between 0 to 18 or 28 to 55 °C.

For 200 mV range,
add 0.01% + 7 µV

For 2 V range,
add 0.01% + 70 µV

For 20 V range,
add 0.01% + 700 µV

For 200 V range,
add 0.01% + 7 mV

Reading Rate:

1.5 sec/reading; changing to the AC Volts function requires approximately 4 seconds.

Input Characteristics

Max Input Voltage:

354 V peak or 250 V DC between any two points (terminals or chassis)

Warning:

This voltage is higher than the rating for multiplexers or high-speed voltmeters that can share the analog back-plane.

Input Impedance:

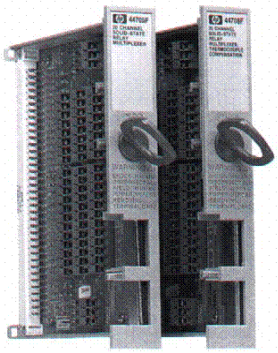
	Terminals		
	High to Low	**Low to Guard**	**Guard to Chassis**
Resistance (Ω)			
30 mV to 3V ranges	$>10^9$	$>10^8$	$>10^8$
30 V, 300 V ranges	$>10^7 \pm 5\%$	$>10^8$	$>10^8$
Max Capacitance (pF)			
at 1 MHz, all ranges	120	2700	2500

Max Bias Current:

Currents sourced by high or low into rear input terminals or backplane
± 1 nA DC

Solid State Relay Multiplexers:

HP 44705F/44708F



Directly Multiplexes:

- Voltage
- 4-wire Ω Resistance (HP 44705F only)
- Thermocouples (HP 44708F only)

Benefits

- **Solid state switching is free from wearout normally associated with electromechanical relays:**
  - –Solid State Relay multiplexers do not rely on a mechanical system to actuate the switching. Switching is performed by optically-coupled Field Effect Transistors.
  - –The switching element does not degrade when used within its maximum ratings. The Solid State Relay is free from the damaging arc associated with electromechanical relays.
- **Optimize thermocouple measurement accuracy with the HP 44708F:**
  - –Thermocouple types can be mixed on the HP 44708F multiplexer to optimize accuracy over the temperature ranges needed.
  - –Thermocouple compensation is performed automatically by the HP 3852A without the need for external wiring.
- **Perform precision measurements of real world electrical signals:**
  - –Three-wire switching of High, Low, and Guard is provided to minimize the effects of Common Mode Voltage.
  - –Errors due to injected currents and thermal offsets are minimized with the Solid State Relay Multiplexer.
  - –Break-before-make switching prevents inadvertent connection of separate channels during scanning.
  - –Tree switching isolates the unused multiplexers from the backplane of the HP 3852A.
  - –Internally, the HP 44705F Solid State Relay card is divided into two groups to minimize crosstalk and facilitate 4-wire resistance measurements.
  - –The Solid State Relay becomes a high impedance when powered down thereby isolating each channel in the event of power loss.

Input Characteristics

Max Switch Rate:
450 channels/second

Max Input Voltage between any two points:
100 VDC, 70 VAC_{rms} (100 V Peak)

Safety Note: *The maximum voltage allowed on the internal analog buses of the HP 3852A and HP 3853A is determined by the lowest voltage plug-in accessory. Refer to page 21 for ratings of the other accessories present. The HP 44705/08F limits the maximum voltage allowed on the internal analog bus to 100 VDC, 70 VACrms (100 V Peak).*

Note: *The maximum voltage restriction is specified between any two points. This includes high, low guard, and chassis of any channel to any other channel and chassis. For example, if + 50 dc/peak (35 VACrms) were applied to channel 0, the maximum negative voltage on any other channel would be - 50 Vdc/peak (35 VACrms)*

Max Input Current: 20 mA non-inductive per channel

Max Input Power: 1 VA_{rms} per channel

Closed-channel Resistance:
< 700 Ω in each high, low, and guard path.
Application Note:
The closed-channel resistance adds directly to Ω measurements made in 2-wire mode. The 4-wire-Ω method is recommended for Ω measurements on the HP 44705F

Max Offset Voltage: (measured high to low) ± 5 uV

Max Bias Current:
(source by high, low, or guard into input terminals or backplane): ± 1.2 nA DC

Input Resistance:
(high to low, low to guard, guard to chassis)
Ambient Temperature < 28 °C: 10^9 Ω
Ambient Temperature > 28 °C: 2 x 10^8 Ω

Common Mode Rejection (1 kΩ unbalance)

	DC	60 Hz
1 accessory	110 dB nominal	75 dB nominal
7 accessories	100 dB nominal	65 dB nominal

Input Capacitance:

High to Low:	65 pF nominal
High to Guard:	75 pF nominal
High to Chassis:	200 pF nominal
Low to Guard:	90 pF nominal
Low to Chassis:	190 pF nominal
Guard to Chassis:	350 pF nominal

Bandwidth:
50 Ω source, 1 MΩ termination
1% Flatness: 50 kHz nominal
3 dB Bandwidth: 500 kHz nominal

Cross Talk:
channel-to-channel, 100 kHz, 50 Ω source, 1 MΩ termination 30 dB nominal

Reference Junction Compensation Accuracy:
(HP 44708F only): 0.1 °C (ambient range of 18 to 28 °C)

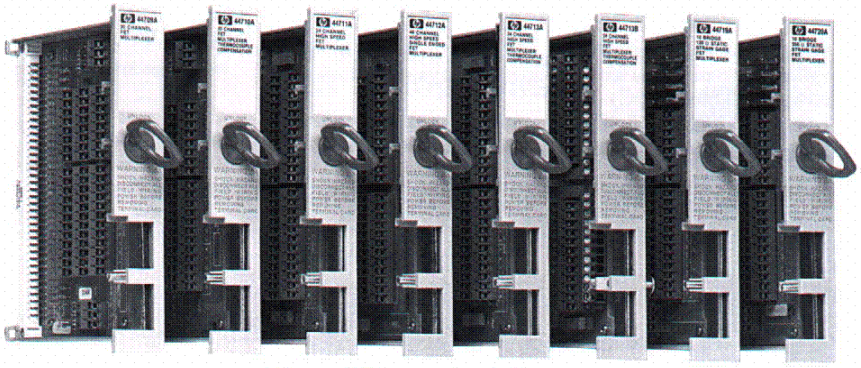
Max Temperature Difference Across Isothermal Block: (HP 44708F only) 0.2 °C

Max Wire Size: 16 AWG

Note: *Nominal values are non-warranted characteristics which are representative of this product.*

FET Multiplexers:

HP 44709A/44710A/44711A/B /44712A/44713A/B/44719A/ 44720A



Directly Multiplexes:

- Voltage
- Resistance
- Thermocouples
- Strain Gages

Benefits

- **Maximize your measurement throughput:**
  - –A throughput rate of 100,000 readings/sec is realized using High-Speed FET Multiplexers (HP 44711A/B/44712A/44713A/B) directly controlled through a dedicated ribbon cable by the High-Speed Voltmeters.
  - –Up to six (eight in an extender) High-Speed FET Multiplexers can be controlled through this ribbon cable.
  - –The 24-channel multiplexers switch high and low only. Each floating input is balanced (that is, equal impedance between high-to-chassis and low-to-chassis) to provide good common mode noise rejection.
  - –For lower costs per channel, single-ended multiplexing of 48 channels (HP 44712A) is also available (has no common mode noise rejection, however).
- **Increase system reliability:**
  - –FETs have no mechanical limitations such as wear out due to switching. —Similar to their relay counterparts, the HP 44709A/ 44710A/44719A/44720A FET multiplexers have high, low, and guard connections for better common mode rejection than the high-speed FET multiplexers.

Input Characteristics

Max Switch Rate:

Ribbon Cable Control
(HP 44711A/B/44712A/ 44713A/B):
100,000 channels/sec

Back-plane Control (all FET multiplexers):
5,500 channels/sec (using SCAN command and external scan trigger)

Max Input Voltage:
All inputs (rear and back-plane) are protected to 16 V peak above chassis. Input impedances, however, decrease above 12 V due to internal protection circuitry. The analog back-plane can be disconnected from the FET multiplexers, allowing the maximum back-plane voltage to be 42 V peak.

Max Input Current: 1 mA non-inductive per channel

Input Characteristics

Input Impedance:
HP44711A/44713A (HP44711B/HP44713B)

		Terminals	
		High to Low	High to Low to Chassis
Power On Resistance (Ω)		$> 10^8$ ($>10^8$)	$> 10^8$ ($> 10^8$)
Power Off Resistance (Ω)	Vin ≤ 10V	> 1000 (> 200)	> 1000 (> 200)
	Vin > 10V	> 200 (> 200)	> 200 (> 200)
Max Capacitance (pF) @1 MHz		< 200 (< 200)	< 200 (< 250)

The input impedance of the HP44712A is the same as the HP 44711A and HP 44713A specifications for high-to-low terminals. Because the HP 44712A is a single-ended 48-channel multiplexer, the resistance from low to chassis is 100 Ω ± 5%.

Closed Channel Path Resistance:
3.1 kΩ for either high or low inputs considered separately
2.1 kΩ for the guard input (HP44709A/44710A)

<800 Ω for channels 00-11 on the HP44711B/44713B
<1.3 kΩ for channels 12-23 on the HP44711B/44713B

Bandwidth:
50 Ω source, 1 mΩ termination

1.0% Flatness: 20 kHz
- 3 dB Bandwidth: 200 kHz

For the HP 44711B/44713B
1.0% Flatness: 40 kHz
- 3 dB Bandwidth: 40 kHz

Cross-Talk:
Channel-to-channel, 50Ω source, 1MΩ termination

- 50 dB @ 10 kHz
- 35 dB @ 100 kHz

For the HP 44711B/44713B

- 55 dB @ 10 kHz
- 45 dB @ 100 kHz

Max Offset Voltage:
Offset voltage between high and low,
15 μV (0 to 28 °C)
185 μV (28 to 55 °C)

9.2 Thermocouple Data

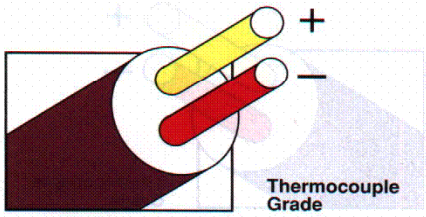
Thermoelectric Voltage in Millivolts

°F	0	−1	−2	−3	−4	−5	−6	−7	−8	−9	−10	°F
−450	−6.456	−6.456	−6.457	−6.457	−6.458							−450
−440	−6.446	−6.448	−6.449	−6.450	−6.451	−6.452	−6.453	−6.454	−6.454	−6.455	−6.456	−440
−430	−6.431	−6.433	−6.435	−6.436	−6.438	−6.440	−6.441	−6.443	−6.444	−6.445	−6.446	−430
−420	−6.409	−6.411	−6.414	−6.416	−6.419	−6.421	−6.423	−6.425	−6.427	−6.429	−6.431	−420
−410	−6.380	−6.383	−6.386	−6.389	−6.392	−6.395	−6.398	−6.401	−6.404	−6.406	−6.409	−410
−400	−6.344	−6.348	−6.352	−6.355	−6.359	−6.363	−6.366	−6.370	−6.373	−6.377	−6.380	−400
−390	−6.301	−6.306	−6.310	−6.315	−6.319	−6.323	−6.328	−6.332	−6.336	−6.340	−6.344	−390
−380	−6.251	−6.257	−6.262	−6.267	−6.272	−6.277	−6.282	−6.287	−6.292	−6.296	−6.301	−380
−370	−6.195	−6.201	−6.207	−6.213	−6.218	−6.224	−6.230	−6.235	−6.241	−6.246	−6.251	−370
−360	−6.133	−6.139	−6.146	−6.152	−6.158	−6.165	−6.171	−6.177	−6.183	−6.189	−6.195	−360
−350	−6.064	−6.071	−6.078	−6.085	−6.092	−6.099	−6.106	−6.113	−6.119	−6.126	−6.133	−350
−340	−5.989	−5.997	−6.004	−6.012	−6.020	−6.027	−6.035	−6.042	−6.049	−6.057	−6.064	−340
−330	−5.908	−5.917	−5.925	−5.933	−5.941	−5.949	−5.957	−5.965	−5.973	−5.981	−5.989	−330
−320	−5.822	−5.831	−5.840	−5.848	−5.857	−5.866	−5.874	−5.883	−5.891	−5.900	−5.908	−320
−310	−5.730	−5.739	−5.749	−5.758	−5.767	−5.776	−5.786	−5.795	−5.804	−5.813	−5.822	−310
−300	−5.632	−5.642	−5.652	−5.662	−5.672	−5.682	−5.691	−5.701	−5.711	−5.720	−5.730	−300
−290	−5.529	−5.540	−5.550	−5.561	−5.571	−5.581	−5.592	−5.602	−5.612	−5.622	−5.632	−290
−280	−5.421	−5.432	−5.443	−5.454	−5.465	−5.476	−5.487	−5.497	−5.508	−5.519	−5.529	−280
−270	−5.308	−5.320	−5.331	−5.343	−5.354	−5.365	−5.377	−5.388	−5.399	−5.410	−5.421	−270
−260	−5.190	−5.202	−5.214	−5.226	−5.238	−5.250	−5.261	−5.273	−5.285	−5.296	−5.308	−260
−250	−5.067	−5.079	−5.092	−5.104	−5.117	−5.129	−5.141	−5.153	−5.166	−5.178	−5.190	−250
−240	−4.939	−4.952	−4.965	−4.978	−4.991	−5.003	−5.016	−5.029	−5.042	−5.054	−5.067	−240
−230	−4.806	−4.820	−4.833	−4.847	−4.860	−4.873	−4.886	−4.900	−4.913	−4.926	−4.939	−230
−220	−4.669	−4.683	−4.697	−4.711	−4.724	−4.738	−4.752	−4.766	−4.779	−4.793	−4.806	−220
−210	−4.527	−4.542	−4.556	−4.570	−4.584	−4.599	−4.613	−4.627	−4.641	−4.655	−4.669	−210
−200	−4.381	−4.396	−4.411	−4.425	−4.440	−4.455	−4.469	−4.484	−4.498	−4.513	−4.527	−200
−190	−4.231	−4.246	−4.261	−4.276	−4.291	−4.306	−4.321	−4.336	−4.351	−4.366	−4.381	−190
−180	−4.076	−4.091	−4.107	−4.123	−4.138	−4.154	−4.169	−4.185	−4.200	−4.215	−4.231	−180
−170	−3.917	−3.933	−3.949	−3.965	−3.981	−3.997	−4.013	−4.029	−4.044	−4.060	−4.076	−170
−160	−3.754	−3.771	−3.787	−3.803	−3.820	−3.836	−3.852	−3.869	−3.885	−3.901	−3.917	−160
−150	−3.587	−3.604	−3.621	−3.638	−3.655	−3.671	−3.688	−3.705	−3.721	−3.738	−3.754	−150
−140	−3.417	−3.434	−3.451	−3.468	−3.486	−3.503	−3.520	−3.537	−3.554	−3.571	−3.587	−140
−130	−3.243	−3.260	−3.278	−3.295	−3.313	−3.330	−3.348	−3.365	−3.382	−3.400	−3.417	−130
−120	−3.065	−3.083	−3.101	−3.119	−3.136	−3.154	−3.172	−3.190	−3.207	−3.225	−3.243	−120
−110	−2.884	−2.902	−2.920	−2.938	−2.957	−2.975	−2.993	−3.011	−3.029	−3.047	−3.065	−110
−100	−2.699	−2.718	−2.736	−2.755	−2.773	−2.792	−2.810	−2.829	−2.847	−2.865	−2.884	−100
−90	−2.511	−2.530	−2.549	−2.568	−2.587	−2.605	−2.624	−2.643	−2.662	−2.680	−2.699	−90
−80	−2.320	−2.339	−2.359	−2.378	−2.397	−2.416	−2.435	−2.454	−2.473	−2.492	−2.511	−80
−70	−2.126	−2.146	−2.165	−2.185	−2.204	−2.223	−2.243	−2.262	−2.282	−2.301	−2.320	−70
−60	−1.929	−1.949	−1.969	−1.988	−2.008	−2.028	−2.048	−2.067	−2.087	−2.106	−2.126	−60
−50	−1.729	−1.749	−1.770	−1.790	−1.810	−1.830	−1.850	−1.869	−1.889	−1.909	−1.929	−50
−40	−1.527	−1.547	−1.568	−1.588	−1.608	−1.628	−1.649	−1.669	−1.689	−1.709	−1.729	−40
−30	−1.322	−1.343	−1.363	−1.384	−1.404	−1.425	−1.445	−1.466	−1.486	−1.507	−1.527	−30
−20	−1.114	−1.135	−1.156	−1.177	−1.198	−1.218	−1.239	−1.260	−1.281	−1.301	−1.322	−20
−10	−0.905	−0.926	−0.947	−0.968	−0.989	−1.010	−1.031	−1.052	−1.073	−1.094	−1.114	−10
0	−0.692	−0.714	−0.735	−0.756	−0.778	−0.799	−0.820	−0.841	−0.862	−0.883	−0.905	0
0	−0.692	−0.671	−0.650	−0.628	−0.607	−0.586	−0.564	−0.543	−0.521	−0.500	−0.478	0
10	−0.478	−0.457	−0.435	−0.413	−0.392	−0.370	−0.349	−0.327	−0.305	−0.284	−0.262	10
20	−0.262	−0.240	−0.218	−0.197	−0.175	−0.153	−0.131	−0.109	−0.088	−0.066	−0.044	20
30	−0.044	−0.022	0.000	0.022	0.044	0.066	0.088	0.110	0.132	0.154	0.176	30
40	0.176	0.198	0.220	0.242	0.264	0.286	0.308	0.330	0.353	0.375	0.397	40
50	0.397	0.419	0.441	0.463	0.486	0.508	0.530	0.552	0.575	0.597	0.619	50
60	0.619	0.642	0.664	0.686	0.709	0.731	0.753	0.776	0.798	0.821	0.843	60
70	0.843	0.865	0.888	0.910	0.933	0.955	0.978	1.000	1.023	1.045	1.068	70
80	1.068	1.090	1.113	1.136	1.158	1.181	1.203	1.226	1.249	1.271	1.294	80
90	1.294	1.316	1.339	1.362	1.384	1.407	1.430	1.453	1.475	1.498	1.521	90
100	1.521	1.543	1.566	1.589	1.612	1.635	1.657	1.680	1.703	1.726	1.749	100
110	1.749	1.771	1.794	1.817	1.840	1.863	1.886	1.909	1.931	1.954	1.977	110
120	1.977	2.000	2.023	2.046	2.069	2.092	2.115	2.138	2.161	2.184	2.207	120
130	2.207	2.230	2.253	2.276	2.298	2.321	2.344	2.367	2.390	2.413	2.436	130
140	2.436	2.459	2.483	2.506	2.529	2.552	2.575	2.598	2.621	2.644	2.667	140
150	2.667	2.690	2.713	2.736	2.759	2.782	2.805	2.828	2.851	2.874	2.897	150
160	2.897	2.920	2.944	2.967	2.990	3.013	3.036	3.059	3.082	3.105	3.128	160
170	3.128	3.151	3.174	3.197	3.220	3.244	3.267	3.290	3.313	3.336	3.359	170
180	3.359	3.382	3.405	3.428	3.451	3.474	3.497	3.520	3.544	3.567	3.590	180
190	3.590	3.613	3.636	3.659	3.682	3.705	3.728	3.751	3.774	3.797	3.820	190
200	3.820	3.843	3.866	3.889	3.912	3.935	3.958	3.981	4.004	4.027	4.050	200
210	4.050	4.073	4.096	4.119	4.142	4.165	4.188	4.211	4.234	4.257	4.280	210
220	4.280	4.303	4.326	4.349	4.372	4.395	4.417	4.440	4.463	4.486	4.509	220
230	4.509	4.532	4.555	4.578	4.601	4.623	4.646	4.669	4.692	4.715	4.738	230
240	4.738	4.760	4.783	4.806	4.829	4.852	4.874	4.897	4.920	4.943	4.965	240
250	4.965	4.988	5.011	5.034	5.056	5.079	5.102	5.124	5.147	5.170	5.192	250
260	5.192	5.215	5.238	5.260	5.283	5.306	5.328	5.351	5.374	5.396	5.419	260
270	5.419	5.441	5.464	5.487	5.509	5.532	5.554	5.577	5.599	5.622	5.644	270
280	5.644	5.667	5.690	5.712	5.735	5.757	5.779	5.802	5.824	5.847	5.869	280
290	5.869	5.892	5.914	5.937	5.959	5.982	6.004	6.026	6.049	6.071	6.094	290
300	6.094	6.116	6.138	6.161	6.183	6.205	6.228	6.250	6.272	6.295	6.317	300
310	6.317	6.339	6.362	6.384	6.406	6.429	6.451	6.473	6.496	6.518	6.540	310
320	6.540	6.562	6.585	6.607	6.629	6.652	6.674	6.696	6.718	6.741	6.763	320
330	6.763	6.785	6.807	6.829	6.852	6.874	6.896	6.918	6.941	6.963	6.985	330
340	6.985	7.007	7.029	7.052	7.074	7.096	7.118	7.140	7.163	7.185	7.207	340
350	7.207	7.229	7.251	7.273	7.296	7.318	7.340	7.362	7.384	7.407	7.429	350
360	7.429	7.451	7.473	7.495	7.517	7.540	7.562	7.584	7.606	7.628	7.650	360
370	7.650	7.673	7.695	7.717	7.739	7.761	7.783	7.806	7.828	7.850	7.872	370
380	7.872	7.894	7.917	7.939	7.961	7.983	8.005	8.027	8.050	8.072	8.094	380
390	8.094	8.116	8.138	8.161	8.183	8.205	8.227	8.250	8.272	8.294	8.316	390
400	8.316	8.338	8.361	8.383	8.405	8.427	8.450	8.472	8.494	8.516	8.539	400
410	8.539	8.561	8.583	8.605	8.628	8.650	8.672	8.694	8.717	8.739	8.761	410
420	8.761	8.784	8.806	8.828	8.851	8.873	8.895	8.918	8.940	8.962	8.985	420
430	8.985	9.007	9.029	9.052	9.074	9.096	9.119	9.141	9.163	9.186	9.208	430
440	9.208	9.231	9.253	9.275	9.298	9.320	9.343	9.365	9.388	9.410	9.432	440
450	9.432	9.455	9.477	9.500	9.522	9.545	9.567	9.590	9.612	9.635	9.657	450
460	9.657	9.680	9.702	9.725	9.747	9.770	9.792	9.815	9.837	9.860	9.882	460
470	9.882	9.905	9.927	9.950	9.973	9.995	10.018	10.040	10.063	10.086	10.108	470
480	10.108	10.131	10.153	10.176	10.199	10.221	10.244	10.267	10.289	10.312	10.334	480
490	10.334	10.357	10.380	10.402	10.425	10.448	10.471	10.493	10.516	10.539	10.561	490
°F	0	1	2	3	4	5	6	7	8	9	10	°F

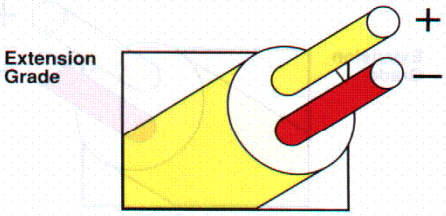
Revised Thermocouple Reference Tables

TYPE K

Reference Tables N.I.S.T. Monograph 175 Revised to ITS-90



Nickel-Chromium vs. Nickel-Aluminum



MAXIMUM TEMPERATURE RANGE

Thermocouple Grade
– 328 to 2282°F
– 200 to 1250°C

Extension Grade
32 to 392°F
0 to 200°C

LIMITS OF ERROR
(whichever is Greater)
Standard: 2.2°C or 0.75% Above 0°C
2.2°C or 2.0% Below 0°C
Special: 1.1°C or 0.4%

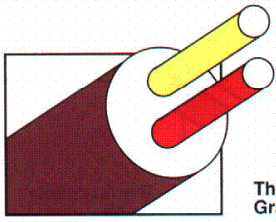
COMMENTS, BARE WIRE ENVIRONMENT:
Clean Oxidizing and Inert; Limited Use in Vacuum or Reducing; Wide Temperature Range; Most Popular Calibration

TEMPERATURE IN DEGREES °F
REFERENCE JUNCTION AT 32°F

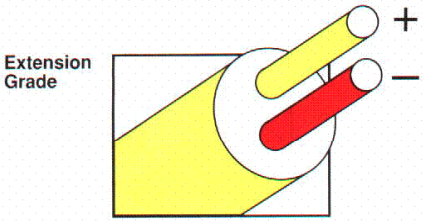
Revised Thermocouple Reference Tables

TYPE K

Reference Tables
N.I.S.T. Monograph 175
Revised to ITS-90



Nickel-Chromium vs. Nickel-Aluminum



MAXIMUM TEMPERATURE RANGE

Thermocouple Grade
– 328 to 2282°F
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Extension Grade
32 to 392°F
0 to 200°C

LIMITS OF ERROR
(whichever is Greater)
Standard: 2.2°C or 0.75% Above 0°C
2.2°C or 2.0% Below 0°C
Special: 1.1°C or 0.4%

COMMENTS, BARE WIRE ENVIRONMENT:
Clean Oxidizing and Inert; Limited Use in Vacuum or Reducing; Wide Temperature Range; Most Popular Calibration

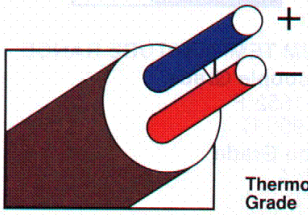
TEMPERATURE IN DEGREES °F
REFERENCE JUNCTION AT 32°F

Thermoelectric Voltage in Millivolts

°F	0	1	2	3	4	5	6	7	8	9	10	°F
500	10.561	10.584	10.607	10.629	10.652	10.675	10.698	10.720	10.743	10.766	10.789	500
510	10.789	10.811	10.834	10.857	10.880	10.903	10.925	10.948	10.971	10.994	11.017	510
520	11.017	11.039	11.062	11.085	11.108	11.131	11.154	11.176	11.199	11.222	11.245	520
530	11.245	11.268	11.291	11.313	11.336	11.359	11.382	11.405	11.428	11.451	11.474	530
540	11.474	11.497	11.519	11.542	11.565	11.588	11.611	11.634	11.657	11.680	11.703	540
550	11.703	11.726	11.749	11.772	11.795	11.818	11.841	11.864	11.887	11.910	11.933	550
560	11.933	11.956	11.978	12.001	12.024	12.047	12.070	12.093	12.116	12.140	12.163	560
570	12.163	12.186	12.209	12.232	12.255	12.278	12.301	12.324	12.347	12.370	12.393	570
580	12.393	12.416	12.439	12.462	12.485	12.508	12.531	12.554	12.577	12.600	12.624	580
590	12.624	12.647	12.670	12.693	12.716	12.739	12.762	12.785	12.808	12.831	12.855	590
600	12.855	12.878	12.901	12.924	12.947	12.970	12.993	13.016	13.040	13.063	13.086	600
610	13.086	13.109	13.132	13.155	13.179	13.202	13.225	13.248	13.271	13.294	13.318	610
620	13.318	13.341	13.364	13.387	13.410	13.433	13.457	13.480	13.503	13.526	13.549	620
630	13.549	13.573	13.596	13.619	13.642	13.665	13.689	13.712	13.735	13.758	13.782	630
640	13.782	13.805	13.828	13.851	13.874	13.898	13.921	13.944	13.967	13.991	14.014	640
650	14.014	14.037	14.060	14.084	14.107	14.130	14.154	14.177	14.200	14.223	14.247	650
660	14.247	14.270	14.293	14.316	14.340	14.363	14.386	14.410	14.433	14.456	14.479	660
670	14.479	14.503	14.526	14.549	14.573	14.596	14.619	14.643	14.666	14.689	14.713	670
680	14.713	14.736	14.759	14.783	14.806	14.829	14.853	14.876	14.899	14.923	14.946	680
690	14.946	14.969	14.993	15.016	15.039	15.063	15.086	15.109	15.133	15.156	15.179	690
700	15.179	15.203	15.226	15.250	15.273	15.296	15.320	15.343	15.366	15.390	15.413	700
710	15.413	15.437	15.460	15.483	15.507	15.530	15.554	15.577	15.600	15.624	15.647	710
720	15.647	15.671	15.694	15.717	15.741	15.764	15.788	15.811	15.834	15.858	15.881	720
730	15.881	15.905	15.928	15.952	15.975	15.998	16.022	16.045	16.069	16.092	16.116	730
740	16.116	16.139	16.163	16.186	16.209	16.233	16.256	16.280	16.303	16.327	16.350	740
750	16.350	16.374	16.397	16.421	16.444	16.468	16.491	16.514	16.538	16.561	16.585	750
760	16.585	16.608	16.632	16.655	16.679	16.702	16.726	16.749	16.773	16.796	16.820	760
770	16.820	16.843	16.867	16.890	16.914	16.937	16.961	16.984	17.008	17.031	17.055	770
780	17.055	17.078	17.102	17.125	17.149	17.173	17.196	17.220	17.243	17.267	17.290	780
790	17.290	17.314	17.337	17.361	17.384	17.408	17.431	17.455	17.478	17.502	17.526	790
800	17.526	17.549	17.573	17.596	17.620	17.643	17.667	17.690	17.714	17.738	17.761	800
810	17.761	17.785	17.808	17.832	17.855	17.879	17.902	17.926	17.950	17.973	17.997	810
820	17.997	18.020	18.044	18.068	18.091	18.115	18.138	18.162	18.185	18.209	18.233	820
830	18.233	18.256	18.280	18.303	18.327	18.351	18.374	18.398	18.421	18.445	18.469	830
840	18.469	18.492	18.516	18.539	18.563	18.587	18.610	18.634	18.657	18.681	18.705	840
850	18.705	18.728	18.752	18.776	18.799	18.823	18.846	18.870	18.894	18.917	18.941	850
860	18.941	18.965	18.988	19.012	19.035	19.059	19.083	19.106	19.130	19.154	19.177	860
870	19.177	19.201	19.224	19.248	19.272	19.295	19.319	19.343	19.366	19.390	19.414	870
880	19.414	19.437	19.461	19.485	19.508	19.532	19.556	19.579	19.603	19.626	19.650	880
890	19.650	19.674	19.697	19.721	19.745	19.768	19.792	19.816	19.839	19.863	19.887	890
900	19.887	19.910	19.934	19.958	19.981	20.005	20.029	20.052	20.076	20.100	20.123	900
910	20.123	20.147	20.171	20.194	20.218	20.242	20.265	20.289	20.313	20.336	20.360	910
920	20.360	20.384	20.407	20.431	20.455	20.479	20.502	20.526	20.550	20.573	20.597	920
930	20.597	20.621	20.644	20.668	20.692	20.715	20.739	20.763	20.786	20.810	20.834	930
940	20.834	20.857	20.881	20.905	20.929	20.952	20.976	21.000	21.023	21.047	21.071	940
950	21.071	21.094	21.118	21.142	21.165	21.189	21.213	21.236	21.260	21.284	21.308	950
960	21.308	21.331	21.355	21.379	21.402	21.426	21.450	21.473	21.497	21.521	21.544	960
970	21.544	21.568	21.592	21.616	21.639	21.663	21.687	21.710	21.734	21.758	21.781	970
980	21.781	21.805	21.829	21.852	21.876	21.900	21.924	21.947	21.971	21.995	22.018	980
990	22.018	22.042	22.066	22.089	22.113	22.137	22.160	22.184	22.208	22.232	22.255	990
1000	22.255	22.279	22.303	22.326	22.350	22.374	22.397	22.421	22.445	22.468	22.492	1000
1010	22.492	22.516	22.540	22.563	22.587	22.611	22.634	22.658	22.682	22.705	22.729	1010
1020	22.729	22.753	22.776	22.800	22.824	22.847	22.871	22.895	22.919	22.942	22.966	1020
1030	22.966	22.990	23.013	23.037	23.061	23.084	23.108	23.132	23.155	23.179	23.203	1030
1040	23.203	23.226	23.250	23.274	23.297	23.321	23.345	23.368	23.392	23.416	23.439	1040
1050	23.439	23.463	23.487	23.510	23.534	23.558	23.581	23.605	23.629	23.652	23.676	1050
1060	23.676	23.700	23.723	23.747	23.771	23.794	23.818	23.842	23.865	23.889	23.913	1060
1070	23.913	23.936	23.960	23.984	24.007	24.031	24.055	24.078	24.102	24.126	24.149	1070
1080	24.149	24.173	24.197	24.220	24.244	24.267	24.291	24.315	24.338	24.362	24.386	1080
1090	24.386	24.409	24.433	24.457	24.480	24.504	24.527	24.551	24.575	24.598	24.622	1090
1100	24.622	24.646	24.669	24.693	24.717	24.740	24.764	24.787	24.811	24.835	24.858	1100
1110	24.858	24.882	24.905	24.929	24.953	24.976	25.000	25.024	25.047	25.071	25.094	1110
1120	25.094	25.118	25.142	25.165	25.189	25.212	25.236	25.260	25.283	25.307	25.330	1120
1130	25.330	25.354	25.377	25.401	25.425	25.448	25.472	25.495	25.519	25.543	25.566	1130
1140	25.566	25.590	25.613	25.637	25.660	25.684	25.708	25.731	25.755	25.778	25.802	1140
1150	25.802	25.825	25.849	25.873	25.896	25.920	25.943	25.967	25.990	26.014	26.037	1150
1160	26.037	26.061	26.084	26.108	26.132	26.155	26.179	26.202	26.226	26.249	26.273	1160
1170	26.273	26.296	26.320	26.343	26.367	26.390	26.414	26.437	26.461	26.484	26.508	1170
1180	26.508	26.532	26.555	26.579	26.602	26.626	26.649	26.673	26.696	26.720	26.743	1180
1190	26.743	26.767	26.790	26.814	26.837	26.861	26.884	26.907	26.931	26.954	26.978	1190
1200	26.978	27.001	27.025	27.048	27.072	27.095	27.119	27.142	27.166	27.189	27.213	1200
1210	27.213	27.236	27.259	27.283	27.306	27.330	27.353	27.377	27.400	27.424	27.447	1210
1220	27.447	27.471	27.494	27.517	27.541	27.564	27.588	27.611	27.635	27.658	27.681	1220
1230	27.681	27.705	27.728	27.752	27.775	27.798	27.822	27.845	27.869	27.892	27.915	1230
1240	27.915	27.939	27.962	27.986	28.009	28.032	28.056	28.079	28.103	28.126	28.149	1240
1250	28.149	28.173	28.196	28.219	28.243	28.266	28.289	28.313	28.336	28.360	28.383	1250
1260	28.383	28.406	28.430	28.453	28.476	28.500	28.523	28.546	28.570	28.593	28.616	1260
1270	28.616	28.640	28.663	28.686	28.710	28.733	28.756	28.780	28.803	28.826	28.849	1270
1280	28.849	28.873	28.896	28.919	28.943	28.966	28.989	29.013	29.036	29.059	29.082	1280
1290	29.082	29.106	29.129	29.152	29.176	29.199	29.222	29.245	29.269	29.292	29.315	1290
1300	29.315	29.338	29.362	29.385	29.408	29.431	29.455	29.478	29.501	29.524	29.548	1300
1310	29.548	29.571	29.594	29.617	29.640	29.664	29.687	29.710	29.733	29.757	29.780	1310
1320	29.780	29.803	29.826	29.849	29.873	29.896	29.919	29.942	29.965	29.989	30.012	1320
1330	30.012	30.035	30.058	30.081	30.104	30.128	30.151	30.174	30.197	30.220	30.243	1330
1340	30.243	30.267	30.290	30.313	30.336	30.359	30.382	30.405	30.429	30.452	30.475	1340
1350	30.475	30.498	30.521	30.544	30.567	30.590	30.613	30.637	30.660	30.683	30.706	1350
1360	30.706	30.729	30.752	30.775	30.798	30.821	30.844	30.868	30.891	30.914	30.937	1360
1370	30.937	30.960	30.983	31.006	31.029	31.052	31.075	31.098	31.121	31.144	31.167	1370
1380	31.167	31.190	31.213	31.236	31.260	31.283	31.306	31.329	31.352	31.375	31.398	1380
1390	31.398	31.421	31.444	31.467	31.490	31.513	31.536	31.559	31.582	31.605	31.628	1390
1400	31.628	31.651	31.674	31.697	31.720	31.743	31.766	31.789	31.812	31.834	31.857	1400
1410	31.857	31.880	31.903	31.926	31.949	31.972	31.995	32.018	32.041	32.064	32.087	1410
1420	32.087	32.110	32.133	32.156	32.179	32.202	32.224	32.247	32.270	32.293	32.316	1420
1430	32.316	32.339	32.362	32.385	32.408	32.431	32.453	32.476	32.499	32.522	32.545	1430
1440	32.545	32.568	32.591	32.614	32.636	32.659	32.682	32.705	32.728	32.751	32.774	1440
1450	32.774	32.796	32.819	32.842	32.865	32.888	32.911	32.933	32.956	32.979	33.002	1450
1460	33.002	33.025	33.047	33.070	33.093	33.116	33.139	33.161	33.184	33.207	33.230	1460
1470	33.230	33.253	33.275	33.298	33.321	33.344	33.366	33.389	33.412	33.435	33.458	1470
1480	33.458	33.480	33.503	33.526	33.548	33.571	33.594	33.617	33.639	33.662	33.685	1480
1490	33.685	33.708	33.730	33.753	33.776	33.798	33.821	33.844	33.867	33.889	33.912	1490
°F	0	1	2	3	4	5	6	7	8	9	10	°F

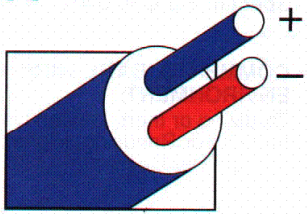
TYPE T

Reference Tables
N.I.S.T.
Monograph 175
Revised to
ITS-90



Thermocouple Grade

Copper vs. Copper-Nickel



Extension Grade

Thermoelectric Voltage in Millivolts

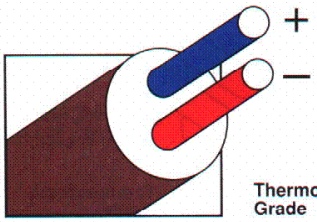
°F	0	−1	−2	−3	−4	−5	−6	−7	−8	−9	−10	°F
−450	−6.254	−6.255	−6.256	−6.257	−6.258							−450
−440	−6.240	−6.242	−6.243	−6.245	−6.247	−6.248	−6.250	−6.251	−6.252	−6.253	−6.254	−440
−430	−6.217	−6.220	−6.222	−6.225	−6.227	−6.230	−6.232	−6.234	−6.236	−6.238	−6.240	−430
−420	−6.187	−6.191	−6.194	−6.197	−6.200	−6.203	−6.206	−6.209	−6.212	−6.215	−6.217	−420
−410	−6.150	−6.154	−6.158	−6.162	−6.166	−6.170	−6.173	−6.177	−6.180	−6.184	−6.187	−410
−400	−6.105	−6.110	−6.115	−6.119	−6.124	−6.128	−6.133	−6.137	−6.141	−6.146	−6.150	−400
−390	−6.053	−6.059	−6.064	−6.069	−6.075	−6.080	−6.085	−6.090	−6.095	−6.100	−6.105	−390
−380	−5.994	−6.001	−6.007	−6.013	−6.019	−6.025	−6.030	−6.036	−6.042	−6.047	−6.053	−380
−370	−5.930	−5.937	−5.943	−5.950	−5.956	−5.963	−5.969	−5.976	−5.982	−5.988	−5.994	−370
−360	−5.860	−5.867	−5.874	−5.881	−5.888	−5.896	−5.902	−5.909	−5.916	−5.923	−5.930	−360
−350	−5.785	−5.792	−5.800	−5.808	−5.815	−5.823	−5.830	−5.838	−5.845	−5.853	−5.860	−350
−340	−5.705	−5.713	−5.721	−5.729	−5.737	−5.745	−5.753	−5.761	−5.769	−5.777	−5.785	−340
−330	−5.620	−5.629	−5.638	−5.646	−5.655	−5.663	−5.672	−5.680	−5.688	−5.697	−5.705	−330
−320	−5.532	−5.541	−5.550	−5.559	−5.568	−5.577	−5.585	−5.594	−5.603	−5.612	−5.620	−320
−310	−5.439	−5.448	−5.458	−5.467	−5.476	−5.486	−5.495	−5.504	−5.513	−5.523	−5.532	−310
−300	−5.341	−5.351	−5.361	−5.371	−5.381	−5.391	−5.400	−5.410	−5.420	−5.429	−5.439	−300
−290	−5.240	−5.250	−5.261	−5.271	−5.281	−5.291	−5.301	−5.312	−5.322	−5.332	−5.341	−290
−280	−5.135	−5.145	−5.156	−5.167	−5.177	−5.188	−5.198	−5.209	−5.219	−5.230	−5.240	−280
−270	−5.025	−5.036	−5.048	−5.059	−5.070	−5.081	−5.091	−5.102	−5.113	−5.124	−5.135	−270
−260	−4.912	−4.923	−4.935	−4.946	−4.958	−4.969	−4.980	−4.992	−5.003	−5.014	−5.025	−260
−250	−4.794	−4.806	−4.818	−4.830	−4.842	−4.854	−4.865	−4.877	−4.889	−4.900	−4.912	−250
−240	−4.673	−4.685	−4.698	−4.710	−4.722	−4.734	−4.746	−4.759	−4.771	−4.783	−4.794	−240
−230	−4.548	−4.561	−4.573	−4.586	−4.599	−4.611	−4.624	−4.636	−4.648	−4.661	−4.673	−230
−220	−4.419	−4.432	−4.445	−4.458	−4.471	−4.484	−4.497	−4.510	−4.523	−4.535	−4.548	−220
−210	−4.286	−4.300	−4.313	−4.326	−4.340	−4.353	−4.366	−4.380	−4.393	−4.406	−4.419	−210
−200	−4.149	−4.163	−4.177	−4.191	−4.205	−4.218	−4.232	−4.246	−4.259	−4.273	−4.286	−200
−190	−4.009	−4.023	−4.037	−4.052	−4.066	−4.080	−4.094	−4.108	−4.122	−4.136	−4.149	−190
−180	−3.865	−3.879	−3.894	−3.908	−3.923	−3.937	−3.952	−3.966	−3.980	−3.995	−4.009	−180
−170	−3.717	−3.732	−3.747	−3.762	−3.777	−3.791	−3.806	−3.821	−3.836	−3.850	−3.865	−170
−160	−3.565	−3.581	−3.596	−3.611	−3.626	−3.642	−3.657	−3.672	−3.687	−3.702	−3.717	−160
−150	−3.410	−3.426	−3.441	−3.457	−3.473	−3.488	−3.504	−3.519	−3.535	−3.550	−3.565	−150
−140	−3.251	−3.267	−3.283	−3.299	−3.315	−3.331	−3.347	−3.363	−3.379	−3.394	−3.410	−140
−130	−3.089	−3.105	−3.122	−3.138	−3.154	−3.171	−3.187	−3.203	−3.219	−3.235	−3.251	−130
−120	−2.923	−2.940	−2.956	−2.973	−2.990	−3.006	−3.023	−3.040	−3.056	−3.072	−3.089	−120
−110	−2.754	−2.771	−2.788	−2.805	−2.822	−2.839	−2.856	−2.873	−2.889	−2.906	−2.923	−110
−100	−2.581	−2.598	−2.616	−2.633	−2.651	−2.668	−2.685	−2.702	−2.719	−2.737	−2.754	−100
−90	−2.405	−2.423	−2.440	−2.458	−2.476	−2.493	−2.511	−2.529	−2.546	−2.564	−2.581	−90
−80	−2.225	−2.244	−2.262	−2.280	−2.298	−2.316	−2.334	−2.351	−2.369	−2.387	−2.405	−80
−70	−2.043	−2.061	−2.079	−2.098	−2.116	−2.134	−2.153	−2.171	−2.189	−2.207	−2.225	−70
−60	−1.857	−1.875	−1.894	−1.913	−1.931	−1.950	−1.969	−1.987	−2.006	−2.024	−2.043	−60
−50	−1.667	−1.686	−1.705	−1.724	−1.743	−1.762	−1.781	−1.800	−1.819	−1.838	−1.857	−50
−40	−1.475	−1.494	−1.514	−1.533	−1.552	−1.572	−1.591	−1.610	−1.629	−1.648	−1.667	−40
−30	−1.279	−1.299	−1.319	−1.338	−1.358	−1.378	−1.397	−1.417	−1.436	−1.456	−1.475	−30
−20	−1.081	−1.101	−1.121	−1.141	−1.161	−1.181	−1.200	−1.220	−1.240	−1.260	−1.279	−20
−10	−0.879	−0.900	−0.920	−0.940	−0.960	−0.980	−1.001	−1.021	−1.041	−1.061	−1.081	−10
0	−0.675	−0.695	−0.716	−0.736	−0.757	−0.777	−0.798	−0.818	−0.839	−0.859	−0.879	0
°F	0	−1	−2	−3	−4	−5	−6	−7	−8	−9	−10	°F

°F	0	1	2	3	4	5	6	7	8	9	10	°F
					Thermoelectric Voltage in Millivolts							
0	−0.675	−0.654	−0.633	−0.613	−0.592	−0.571	−0.550	−0.530	−0.509	−0.488	−0.467	0
10	−0.467	−0.446	−0.425	−0.404	−0.383	−0.362	−0.341	−0.320	−0.299	−0.278	−0.256	10
20	−0.256	−0.235	−0.214	−0.193	−0.171	−0.150	−0.129	−0.107	−0.086	−0.064	−0.043	20
30	−0.043	−0.022	0.000	0.022	0.043	0.065	0.086	0.108	0.130	0.151	0.173	30
40	0.173	0.195	0.216	0.238	0.260	0.282	0.303	0.325	0.347	0.369	0.391	40
50	0.391	0.413	0.435	0.457	0.479	0.501	0.523	0.545	0.567	0.589	0.611	50
60	0.611	0.634	0.656	0.678	0.700	0.723	0.745	0.767	0.790	0.812	0.834	60
70	0.834	0.857	0.879	0.902	0.924	0.947	0.969	0.992	1.015	1.037	1.060	70
80	1.060	1.083	1.105	1.128	1.151	1.174	1.196	1.219	1.242	1.265	1.288	80
90	1.288	1.311	1.334	1.357	1.380	1.403	1.426	1.449	1.472	1.496	1.519	90
100	1.519	1.542	1.565	1.588	1.612	1.635	1.658	1.682	1.705	1.729	1.752	100
110	1.752	1.776	1.799	1.823	1.846	1.870	1.893	1.917	1.941	1.964	1.988	110
120	1.988	2.012	2.036	2.060	2.083	2.107	2.131	2.155	2.179	2.203	2.227	120
130	2.227	2.251	2.275	2.299	2.323	2.347	2.371	2.395	2.420	2.444	2.468	130
140	2.468	2.492	2.517	2.541	2.565	2.590	2.614	2.639	2.663	2.687	2.712	140
150	2.712	2.737	2.761	2.786	2.810	2.835	2.860	2.884	2.909	2.934	2.958	150
160	2.958	2.983	3.008	3.033	3.058	3.082	3.107	3.132	3.157	3.182	3.207	160
170	3.207	3.232	3.257	3.282	3.307	3.333	3.358	3.383	3.408	3.433	3.459	170
180	3.459	3.484	3.509	3.534	3.560	3.585	3.610	3.636	3.661	3.687	3.712	180
190	3.712	3.738	3.763	3.789	3.814	3.840	3.866	3.891	3.917	3.943	3.968	190
200	3.968	3.994	4.020	4.046	4.071	4.097	4.123	4.149	4.175	4.201	4.227	200
210	4.227	4.253	4.279	4.305	4.331	4.357	4.383	4.409	4.435	4.461	4.487	210
220	4.487	4.513	4.540	4.566	4.592	4.618	4.645	4.671	4.697	4.724	4.750	220
230	4.750	4.776	4.803	4.829	4.856	4.882	4.909	4.935	4.962	4.988	5.015	230
240	5.015	5.042	5.068	5.095	5.122	5.148	5.175	5.202	5.228	5.255	5.282	240
250	5.282	5.309	5.336	5.363	5.389	5.416	5.443	5.470	5.497	5.524	5.551	250
260	5.551	5.578	5.605	5.632	5.660	5.687	5.714	5.741	5.768	5.795	5.823	260
270	5.823	5.850	5.877	5.904	5.932	5.959	5.986	6.014	6.041	6.068	6.096	270
280	6.096	6.123	6.151	6.178	6.206	6.233	6.261	6.288	6.316	6.343	6.371	280
290	6.371	6.399	6.426	6.454	6.482	6.510	6.537	6.565	6.593	6.621	6.648	290
300	6.648	6.676	6.704	6.732	6.760	6.788	6.816	6.844	6.872	6.900	6.928	300
310	6.928	6.956	6.984	7.012	7.040	7.068	7.096	7.124	7.152	7.181	7.209	310
320	7.209	7.237	7.265	7.294	7.322	7.350	7.378	7.407	7.435	7.463	7.492	320
330	7.492	7.520	7.549	7.577	7.606	7.634	7.663	7.691	7.720	7.748	7.777	330
340	7.777	7.805	7.834	7.863	7.891	7.920	7.949	7.977	8.006	8.035	8.064	340
350	8.064	8.092	8.121	8.150	8.179	8.208	8.237	8.266	8.294	8.323	8.352	350
360	8.352	8.381	8.410	8.439	8.468	8.497	8.526	8.555	8.585	8.614	8.643	360
370	8.643	8.672	8.701	8.730	8.759	8.789	8.818	8.847	8.876	8.906	8.935	370
380	8.935	8.964	8.994	9.023	9.052	9.082	9.111	9.141	9.170	9.200	9.229	380
390	9.229	9.259	9.288	9.318	9.347	9.377	9.406	9.436	9.466	9.495	9.525	390
400	9.525	9.555	9.584	9.614	9.644	9.673	9.703	9.733	9.763	9.793	9.822	400
410	9.822	9.852	9.882	9.912	9.942	9.972	10.002	10.032	10.062	10.092	10.122	410
420	10.122	10.152	10.182	10.212	10.242	10.272	10.302	10.332	10.362	10.392	10.423	420
430	10.423	10.453	10.483	10.513	10.543	10.574	10.604	10.634	10.664	10.695	10.725	430
440	10.725	10.755	10.786	10.816	10.847	10.877	10.907	10.938	10.968	10.999	11.029	440
450	11.029	11.060	11.090	11.121	11.151	11.182	11.213	11.243	11.274	11.304	11.335	450
460	11.335	11.366	11.396	11.427	11.458	11.489	11.519	11.550	11.581	11.612	11.643	460
470	11.643	11.673	11.704	11.735	11.766	11.797	11.828	11.859	11.890	11.920	11.951	470
480	11.951	11.982	12.013	12.044	12.075	12.106	12.138	12.169	12.200	12.231	12.262	480
490	12.262	12.293	12.324	12.355	12.386	12.418	12.449	12.480	12.511	12.543	12.574	490
500	12.574	12.605	12.636	12.668	12.699	12.730	12.762	12.793	12.824	12.856	12.887	500
510	12.887	12.919	12.950	12.982	13.013	13.045	13.076	13.108	13.139	13.171	13.202	510
520	13.202	13.234	13.265	13.297	13.328	13.360	13.392	13.423	13.455	13.487	13.518	520
530	13.518	13.550	13.582	13.614	13.645	13.677	13.709	13.741	13.772	13.804	13.836	530
540	13.836	13.868	13.900	13.932	13.964	13.995	14.027	14.059	14.091	14.123	14.155	540
550	14.155	14.187	14.219	14.251	14.283	14.315	14.347	14.379	14.411	14.444	14.476	550
560	14.476	14.508	14.540	14.572	14.604	14.636	14.669	14.701	14.733	14.765	14.797	560
570	14.797	14.830	14.862	14.894	14.926	14.959	14.991	15.023	15.056	15.088	15.121	570
580	15.121	15.153	15.185	15.218	15.250	15.283	15.315	15.347	15.380	15.412	15.445	580
590	15.445	15.477	15.510	15.543	15.575	15.608	15.640	15.673	15.705	15.738	15.771	590
600	15.771	15.803	15.836	15.869	15.901	15.934	15.967	15.999	16.032	16.065	16.098	600
610	16.098	16.130	16.163	16.196	16.229	16.262	16.295	16.327	16.360	16.393	16.426	610
620	16.426	16.459	16.492	16.525	16.558	16.591	16.624	16.657	16.690	16.723	16.756	620
630	16.756	16.789	16.822	16.855	16.888	16.921	16.954	16.987	17.020	17.053	17.086	630
640	17.086	17.120	17.153	17.186	17.219	17.252	17.286	17.319	17.352	17.385	17.418	640
650	17.418	17.452	17.485	17.518	17.552	17.585	17.618	17.652	17.685	17.718	17.752	650
660	17.752	17.785	17.819	17.852	17.886	17.919	17.952	17.986	18.019	18.053	18.086	660
670	18.086	18.120	18.153	18.187	18.221	18.254	18.288	18.321	18.355	18.389	18.422	670
680	18.422	18.456	18.490	18.523	18.557	18.591	18.624	18.658	18.692	18.725	18.759	680
690	18.759	18.793	18.827	18.861	18.894	18.928	18.962	18.996	19.030	19.064	19.097	690
700	19.097	19.131	19.165	19.199	19.233	19.267	19.301	19.335	19.369	19.403	19.437	700
710	19.437	19.471	19.505	19.539	19.573	19.607	19.641	19.675	19.709	19.743	19.777	710
720	19.777	19.811	19.845	19.879	19.913	19.947	19.982	20.016	20.050	20.084	20.118	720
730	20.118	20.152	20.187	20.221	20.255	20.289	20.323	20.358	20.392	20.426	20.460	730
740	20.460	20.495	20.529	20.563	20.597	20.632	20.666	20.700	20.735	20.769	20.803	740
750	20.803	20.838	20.872									750
°F	0	1	2	3	4	5	6	7	8	9	10	°F

Revised Thermocouple Reference Tables

TYPE T

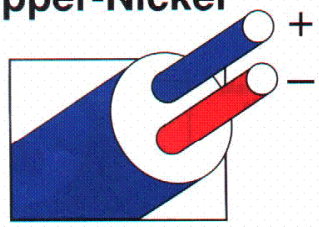
Reference Tables
N.I.S.T.
Monograph 175
Revised to
ITS-90



Thermocouple Grade

Copper vs. Copper-Nickel

Extension Grade



MAXIMUM TEMPERATURE RANGE

Thermocouple Grade
– 328 to 662°F
– 200 to 350°C

Extension Grade
– 76 to 212°F
– 60 to 100°C

LIMITS OF ERROR
(whichever is Greater)
Standard: 1.0°C or 0.75% Above 0°C
1.0°C or 1.5% Below 0°C
Special: 0.5°C or 0.4%

COMMENTS, BARE WIRE ENVIRONMENT:
Mild Oxidizing, Reducing Vacuum or Insert; Good Where Moisture is Present; Low Temperature and Cryogenic Applications

TEMPERATURE IN DEGREES °F
REFERENCE JUNCTION AT 32°F

9.3 Differential Pressure Data

SPECIFICATION SHEET

Barton™ FCX Differential Pressure & Flow Transmitters

Service: Liquid, gas, or vapor

Output:

Model FHCG:	4 to 20 mAdc, 2 wire, linear with D.P.
Model FHFG:	4 to 20 mAdc, 2 wire, linear with flow (square root of DP)
Model FKCG:	4 to 20 mAdc, 2 wire, with FSK digital signal superimposed, linear or square root of D.P.

Ranges:

0)	0-4" w.c.	SWP 450 PSI
1)	0-24" w.c.	SWP 450 PSI
2)	0-125" w.c.	SWP 1500, 2300, or 6000 PSI
3)	0-250" w.c.	SWP 1500, 2300, or 6000 PSI
4)	0-520" w.c.	SWP 1500, 2300, or 6000 PSI
5)	0-70 PSID	SWP 1500, 2300, or 6000 PSI
6)	0-280 PSID	SWP 6000 PSI
7)	0-430 PSID	SWP 2300 PSI

Span Control:

Model FHCG and FHFG:	10:1 turndown
Model FKCG:	100:1 turndown (range [0] 10:1, range [1] 60:1)

Zero Control:

Model FHCG and FHFG:	-100% to +90%
Model FKCG:	-100% to 99%

NOTE: the total calibrated span and zero adjustment can not exceed the upper range limit

Temperature Limits:

Electronics Unit

-40° to +185°F (-40° to +85°C)
-5° to +175°F (-20° to +80°C) for LCD Indicator
-40° to +140°F (-40° to +60°C) for lightning arrestor
NOTE: for units located in hazardous areas, the ambient temperature must be within the limits specified by the appropriate standard.

Process:

-40° to +250°F (-40° to +120°C) silicone filled units
-5° to +250°F (-20° to +120°C) Fluorolube† filled units

Storage:

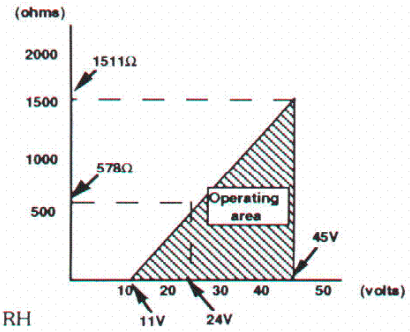
-40° to +195°F (-40° to +90°C)

Overpressure Limit: Up to the SWP

Static Pressure Limit: Up to the SWP

Power Supply: 11 to 45 Vdc at transmitter terminals
11 to 27 Vdc for units with lightning arrester

Load Limitations:



Humidity Limit: 0 - 100% RH

Update Time: Approx. 150 msec

Volumetric Displacement:
Ranges 0 to 4: 0.001 cu. in.
Range 5: 0.003 cu. in.
Ranges 6 and 7: 0.008 cu. in.

Dampening:
Model FHCG and FHFG: 5 step switch selectable time constant: 0, 0.3, 1.2, 4.8, or 19.2 seconds
Model FKCG: Adjustable via HHC from 0 to 38.4 seconds

PERFORMANCE SPECIFICATIONS

LINEAR OUTPUT MODE (Model FHCG and FKCG)

Accuracy: (Includes linearity, hysteresis, and repeatability)

±0.10% of calibration span, up to 10:1 turndown
For greater than 10:1 turndown:
±0.05 + 0.005 x turndown (%)

Linearity:

±0.05% of calibrated span

Temperature Effect:

Cell Range	Zero Shift (% of URL)	Span Shift (% of Calibrated Span)
2 to 7 0 to 1	±0.25%/100°F ±0.5%/100°F	±0.25%/100°F ±0.3%/100°F

Static Pressure Effect:

SWP	Zero Shift (% of URL)	Span Shift (% of Calibrated Span)
1500, 2300 or 6000 PSI 450 PSI (4" w.c) 450 PSI(24" w.c.)	±0.07%/1000 PSI ±0.2%/150 PSI ±0.2%/450 PSI	-0.14%/1000 PSI -0.2%/450 PSI -0.2%/450 PSI

Overpressure Effect:

SWP	Zero Shift (% of URL)
1500 PSI 2300 PSI 6000 PSI 450 PSI (4" w.c.) 450 PSI (24" w.c.)	±0.3%/1500 PSI ±0.3%/2300 PSI ±0.5%/6000 PSI ±0.3%/150 PSI ±0.3%/450 PSI

SQUARE ROOT OUTPUT MODE (Model FHFG and FKCG)

Accuracy:

	Turndown	
Output	Up to 10:1	Greater than 10:1
50 to 100% 20 to 50% 10 to 20%	±0.1% ±0.25% ±0.5%	±(0.05 + 0.005 x turndown) (%) ±2.5 x (0.05 + 0.005 x turndown) (%) ±5 x (0.005 x turndown) (%)

Temperature Effect:

Cell Ranges	Shift at 20% Output (% of URL)
2 to 7 0 to 1	±0.7%/100°F ±1.5%/100°F

Static Pressure Effect:

SWP	Shift at 20% Ouput (% of URL)
1500, 2300, or 6000 450 PSI (4" w.c.) 450 PSI (24" w.c.)	±0.17%/1000 PSI ±0.5%/150 PSI ±0.5%/450 PSI

Overrange Effect:

SWP	Shift at 20% Ouput (% of URL)
1500, 2300 PSI 6000 PSI 450 PSI (4" w.c.) 450 PSI (24" w.c.)	±0.75%@SWP ±1.25%@SWP ±0.75%/150 PSI ±0.75%@SWP

Low Flow Cutoff:

Model FHFG: 7% of Flow
Model FKCG: Adjustable via HHC from 7 to 20% of Flow

PERFORMANCE SPECIFICATIONS

ALL UNITS

Stability: ±0.1% URL/6 months

Supply Voltage Effect: ±0.005% of calibration span/1 Volt change

RFI Effect: Built in RFI filters, negligible effect from 20 to 1000 MHz at 10V/m (Classification: 2 - abc span per SAMA PMC 33.1)

Mounting Position Effect: Zero shift less than 0.5" w.c./10° tilt (no effect on span)

Step Response:

Cell Range	Time Constant
Range 0	1.25 sec.
Range 1	0.85 sec.
Range 2	0.45 sec.
Ranges 3 to 7	0.2 sec.

PHYSICAL SPECIFICATIONS

Process Connections: 1/4-18 NPT on 2 1/8" centers (std)
1/2-14 NPT on 2", 2 1/8", or 2 1/4" centers with flange adapters (optional)

Conduit Connection: Two 1/2-14 NPT on terminal box

Process Wetted Materials:

Material Code	Process Cover	Diaphragm	Wetted Sensor Body	O-Ring
E	Carbon Steel	Hastelloy C††	316 SST	Viton†††
W	316 SST	Hastelloy C	316 SST	Viton
H	316 SST	Hastelloy C	Hastelloy C	Viton
M	316 SST	Monel††††	Monel	Viton
T	316 SST	Tantalum	Tantalum	Viton
B	Hastelloy C	Hastelloy C	Hastelloy C	Teflon†††
L	Monel	Monel	Monel	Teflon
U	Tantalum	Tantalum	Tantalum	Teflon

Fill Fluid: Silicone Oil (std), Fluorolube (optional)

Bolts and Nuts: Cr-Mo alloy (std)
304 SST (optional, reduces the SWP to 1500 PSI)
17-4 PH SST (optional, for 6000 PSI SWP)

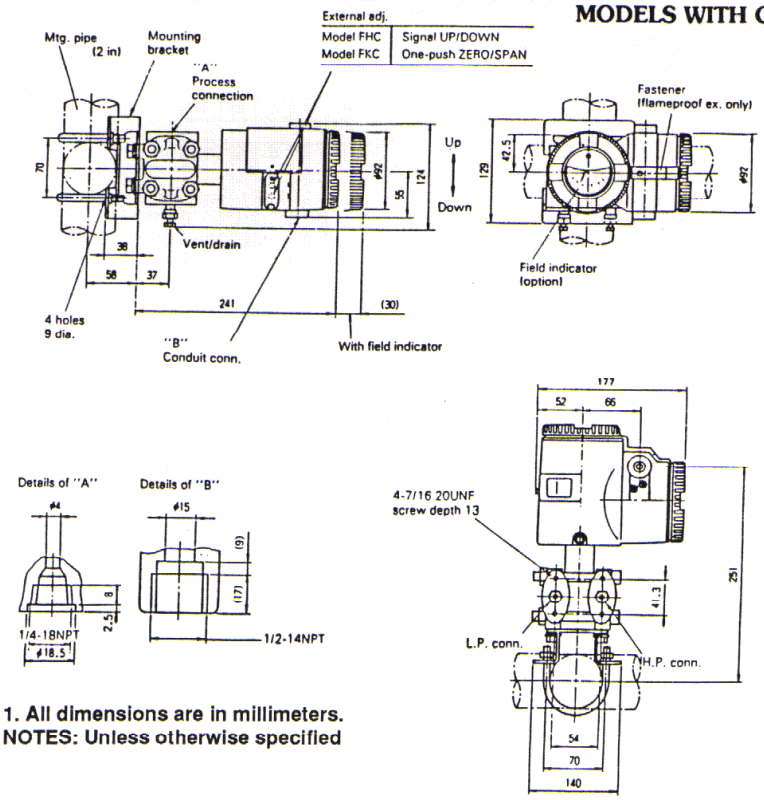
Electronics Housing: Low copper aluminum alloy, anodized and finished with epoxy/polyurethane double coating process (std)
304 SST (optional)

Mounting Bracket: Carbon Steel, epoxy coated (std)
304 SST (optional)

Environmental Protection: NEMA 4X and IEC IP-67

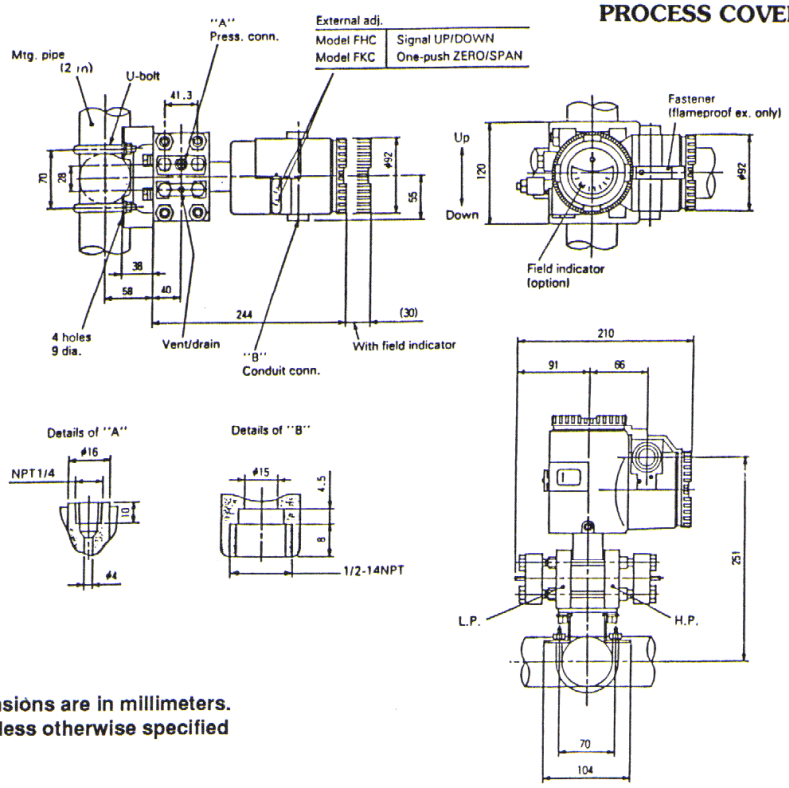
OUTLINE DIMENSION DRAWINGS

MODELS WITH CS OR SS PROCESS COVERS



1. All dimensions are in millimeters.
NOTES: Unless otherwise specified

MODELS WITH SPECIAL MATERIAL PROCESS COVERS



1. All dimensions are in millimeters.
NOTES: Unless otherwise specified

9.4 Flowmeter Data

Overall

Flow Accuracy (% of reading):	***Transit-Time Mode:*** **Pipe Diameter > 150 mm (6")** Velocity > 0.3 m/s (>1 ft/s): 2 % typical (1% with calibration) Velocity ≤ 0.3 m/s (≤ 1 ft/s): ± 0.01 m/s (± 0.03 ft/s) typical **Pipe Diameter ≤ 150 mm (6")** Velocity > 0.3 m/s (> 1 ft/s): 2-5% typical Velocity < 0.3 m/s (< 1 ft/s): ± 0.05 m/s typical (± 0.15 ft/s) ***TransFlection Mode:*** Velocity > 0.3 m/s (>1 ft/s), ±5% typical or ±2 % calibrated accuracy. *In normal single-phase situations.
Range:	-12.2 to 12.2 m/s (-40 to 40 ft/s).
Rangeability:	400:1.
Repeatability:	***Transit-Time Mode:*** ±0.2% to 0.5% clamp-on transducers. ***TransFlection Mode:*** ±0.5 % (camp-on transducers).

Energy Accuracy (% of reading):	The accuracy of the energy measurement is a combination of the accuracy of the flow and temperature measurement. ***Transit-Time Mode:*** Accuracy of 1 % is typical for calibrated systems. ***TransFlection Mode:*** Accuracy of 2 % is typical for calibrated systems.
Note:	*Above specifications require straight runs of 10 diameters upstream and 5 diameters downstream.*
Low Voltage Directive Compliance	This unit complies with European Standard EN61010. Installation Category II, Pollution Degree II.

Electrical

Meter

Operating Power: 6 W, maximum.

Fuses: One 250 mA, 32 V.
Two 1 A, 125 V, Slo-Blo.

Internal Batteries

Size: 4 C-size NiCad high-energy rechargeable batteries.

Battery Life: ***Transit-Time Mode:***
8-10 hours of continuous operation is typical.

TransFlection Mode:
3-4 hours of continuous operation typical.

Note: *The battery life will be reduced if you use the 4-20 mA output and/or loop powered temperature inputs, back light, or the printer output.*

Recharge Time: 16-20 hours using the external power supply/charger.

Power Supply/Charger

Input: 100/120 VAC or 200/260 VAC, 50/60 Hz ±10 %, 5 W maximum.

Output: 12 VDC unregulated.

Note: *The PT868-R may also be powered/charged by any regulated DC source that provides spike-free voltage of 10 to 28 VDC.*

Size/Weight

Size: 12.7 mm × 22.9 mm × 5.8 cm .
(5 × 9 × 2.3 inches).

Weight: 1.0 kg (2.2 lbs).

Environmental

Operating Temperature:	-10 to 50°C (14 to 122°F).
Storage Temperature:	-10 to 50°C (14 to 122°F).

Note: *To ensure maximum battery life, the storage life should exceed 35°C (95°F) for long periods.*

Operating Modes

Flow Measurement:	Transit-Time or TransFlection Mode with clamp-on or wetted transducers.
Energy:	Two loop-powered temperature transmitter inputs to calculate energy flow.

Input/Output

Keypad:	30-key tactile feedback membrane keypad.
Display:	64 × 128 pixel LCD graphic display with back light.
Printer/ Terminal:	One RS232 port for printer, terminal, or PC.
Analog Output:	One 4-20 mA or 0-20 mA current output (550 Ω maximum load).
Analog Input:	Two 4-20 mA analog inputs with switchable 16 V supply for loop-powered temperature transmitters.
Acoustic:	One pair of LEMO coaxial transducer connectors. Cable length 8 m (25 ft) standard. Up to 305 m (1000 ft) optional.

Operational Specifications

Site Parameter Programming:	Menu-driven operator interface using a keypad and "soft" functions keys.
	On-line help functions including pipe tables.
	Storage for saving parameters for up to 20 sites.
Data Logging:	Memory capacity to log over 43,000 flow data points.
	Keypad programmable for log units, update times and start and stop times.
Display Functions:	Graphic displays shows flow in numeric or graphical format.
	Also displays logged data.
Printer Output:	Supports several thermal or impact printers.
	Output data in numeric or graphical ("strip chart") format.

Transducer

Clamp-On Transducer

Standard:	Panametrics' clamp-on and wetted transducers
Temperature Range:	-40 to 100°C (-40 to 212°F) standard. -200 to 260°C (-328 to 500°F) optional.
Frequency:	1 MHz standard. 500 kHz, 2MHz, 4 MHz optional.
	Note: *Transducers special applications are available. Flowcells are also available. Consult the factory for details.*
Optional Materials:	Stainless steel, high-temperature plastics, Hastelloy, Monel, Titanium, etc.
Mounting:	Chain, strap or magnetic slide-track mounting fixtures.

Temperature Transducer

Type:	Loop-powered 3-wire platinum RTD's; clamp-on and wetted (thermowell) types are available.
Accuracy:	0.1°C (0.2°F), wetted RTD's (matched pairs)
Range:	-20 to 260°C (-4 to 500°F)

Pipe Size and Material

Clamp-On Transducers

Materials:	All metals, most plastics; consult Panametrics for concrete, wood, and composite materials for highly corroded, or lined pipes.
Pipes Sizes:	***Transit-Time Mode:*** 12.7 mm to 5 m (0.5 to 200") outside diameter (OD).
	TransFlection Mode: 5 cm to 5 m (2 to 200") outside diameter (OD).
Pipe Wall Thickness:	Up to 76.2 mm (3").

Wetted Transducers

Materials:	All metals, most plastics; consult Panametrics for concrete, glass, and cement.
Pipe Sizes:	***Transit-Time Mode:*** 1 mm to 5 m (0.04 to 200") inside diameter (ID).
	TransFlection Mode: 5 cm to 5 m (2 to 200") inside diameter (ID).

Available Options

Thickness Gage

Standard Transducer:	Panametrics dual element transducer
Pipe Wall Thickness Range:	1.3 to 76.2 mm (0.05 to 3.0 inches)
Pipe Materials:	Most standard metal and plastic pipe materials
Accuracy:	±1% typical or ±0.05 mm (±0.002 inches)
Display Resolution:	0.01 mm (0.001 inches)
Thermal Exposure:	Continuous operation to 37°C (100°F). Intermittent operation to 260°C (500°F) for 10 seconds followed by air cooling for 2 minutes.
Energy Equipment	Dual RTD transmitter; two 4 to 20-mA transmitter with input for 3-wire RTD (100 ohm pt) and terminals for 4 to 20-mA output; and 6 ft. cable.
Printer Option	Thermal printer with rechargeable battery, 6 ft. cable and 120-VAC or 240-VAC charger.
PC Interface Software	TransPort Data Manager (TDM) software links PT868-R with computer or PC. Includes 3.5-in. and 5.25-in. diskettes, interconnection cable (please specify type), and manual.

10 Appendix B—Participant Model Information and Documentation

10.1 Presentation of the contribution of CEA/DRN/DTP/SMTH to ISP43

Bernard MENANT
Commissariat à l'Energie Atomique Grenoble
DRN/DTP/SMTH
LAboratoire de Thermohydraulique Avancée
17 avenue des Martyrs
F 38054 GRENOBLE cedex 9

This work is supported by CEA/IPSN/DES/SECCA.

10.1.1 Introduction

The TRIO** thermal hydraulic programs developed in CEA are of general purpose.

The first contributions of CEA Grenoble to heterogeneous dilution problems were based on TRIO_VF computations. More recently TRIO_U, which is the CEA/DRN thermal-hydraulic reference software, became available for these applications.

The applications of TRIO-VF were limited to the reactor vessel. This limitation is a consequence of the structured volume approach in I,J,K numerotation.

In TRIO_U, the numerotation by element, compatible with unstructured mesh approaches was chosen. In consequence, more complex geometries can be modeled using either structured finite volumes (VDF), or unstructured finite volumes (VEF). In 1998, a computation of the transit of a cold plug through a complete 3 loop REP was successfully attempted as a demonstration of the feasibility of such approaches using VDF 3D transient modeling.

One interesting step in this approach is to validate our modeling for the reactor vessel. For this reason we have chosen to work on case A or B of ISP 43. Case A is relative to the response to an inlet temperature step during pump start-up transient. Case B, relative to the transit of a cold plug, is closer to the practical case of the transit of a clear water plug. For this reason, we focused our efforts on case B.

10.1.2 Summary description of the modeling

10.1.2.1 Generalities

The first attempt to use VEF tetrahedral meshes has shown that the computational time for a sufficient description of ISP43 case B transient will be too important. For this reason we have decided to use VDF. Furthermore, this approach is supported by the previous work using TRIO_VF and TRIO_U.

Due to the flow transient, the complexity of the geometry, and the importance of differential gravity effects, classical turbulence models are not well qualified for ISP 43 applications.

Nevertheless, two approaches of instabilities and turbulence effects were attempted. The first one is a classical K-Epsilon model, and the second one is a model using 0 turbulent

diffusivities in which the explicitly modeled instabilities are supposed to account for these effects.

The aim of our contribution is to evaluate the validity of these approaches, and to support more general reflections about heterogeneous dilution.

Heat transfer to and through the solid boundaries is difficult to calculate, especially because it is impossible to appreciate precisely the effects of the thermal coating used, in the case of ISP43, on the walls. For these reasons, and in agreement with the reduced thermal losses stated in the experience, the heat transfer through and inside the walls was neglected.

10.1.2.2 Mesh

Correct application of K_Epsilon modeling requires adapted mesh refinement near the walls. As such refinement was not compatible with reasonable meshes, we have chosen to work on nearly uniform meshes: in the case of $\nu_t = 0$ computation, the mesh is constituted of about 750 000 cubes of .005 m of side; in the case of K-Epsilon modeling, the mesh is constituted of about 600 000 parallelepipedic meshes (most of the meshes are identical to the meshes for $\nu_t = 0$ case, but some meshes located in the downcomer have been stretched in the axial direction up to an aspect ratio of 3 :1)

The choice of these meshes is not supported by any convergence study. Comparisons with experiments would show the validity of these approaches.

The K_Epsilon computation was run on one processor of an HP J2240 work station; The $\nu_t = 0$ computation was run on another processor of this work station, and also on 36 processors of a CRAY T3E (parallel processing).

Meshes are fully described in files which constitute the geometry inputs of TRIO_U. These big files may be transmitted on DAT if requested.

Half of he computed area and its partition for the parallel computation are illustrated on the figure next page.

10.1.2.3 Special models

Turbulence: classical K-Epsilon and wall laws if any.

No heat transfer at the walls assumed.

10.1.2.4 Solution procedure

The spatial discretisation scheme is of the QUICK-FRAM type for momentum balances and QUICK-SHARP for energy balances.

The time discretisation is of the EXPLICIT-EULER type.

The resolution of the pressure system is of the preconditioned alternate gradient type. The criteria for convergence was chosen in order to get excellent mass-balances (for the two sequential computations the maximum value of velocity divergence over one computational mesh remains lower than 1.E-11 m3s-1 and the maximum difference between inlet and outlet flow remains lower than 1.E-9 m3s-1; for the parallel computation these maximal values are

respectively 1.E-7 m3s-1 and 1.E-5 m3s-1). In both cases the inlet flow is exactly the flow specified in the tables available on the net.

- Full input deck listings are given in attachment for the three computations.

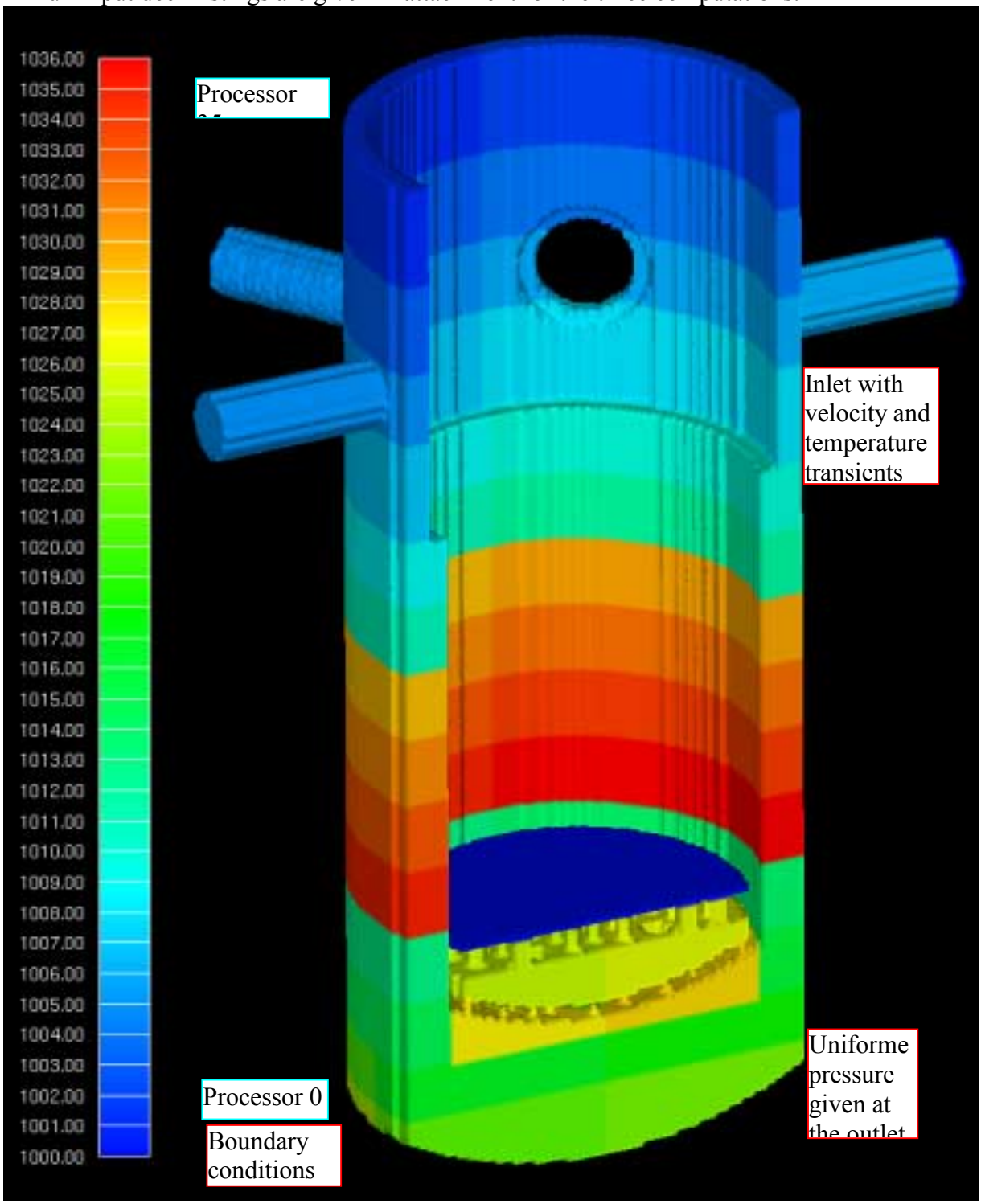


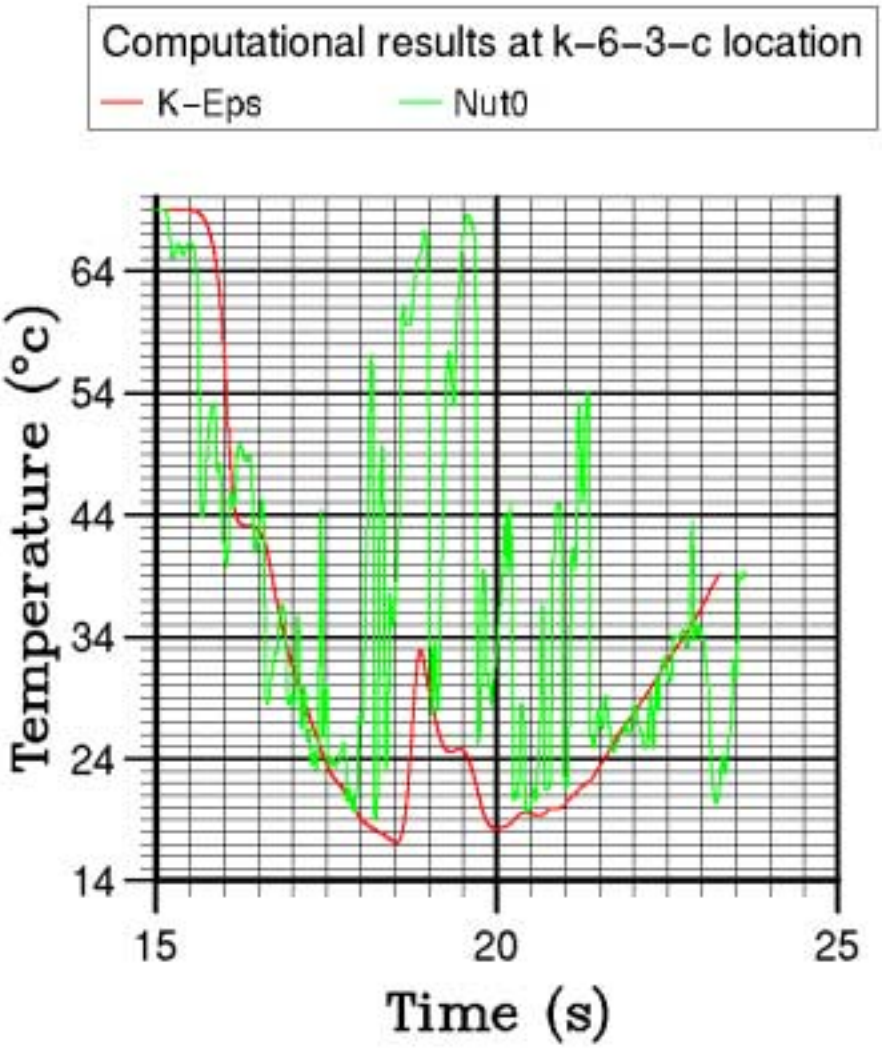
Figure 10-1. Illustration of the modeled fluid region

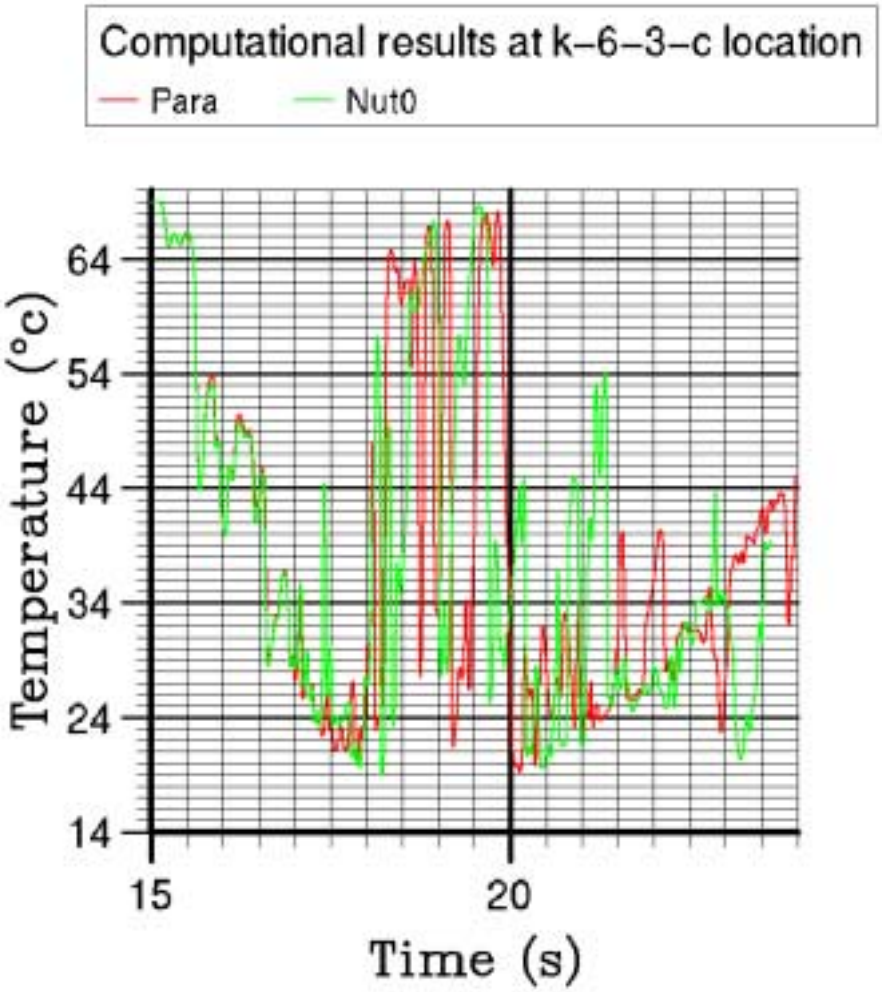
10.1.3 Presentation of the results

10.1.3.1 Data acquisition

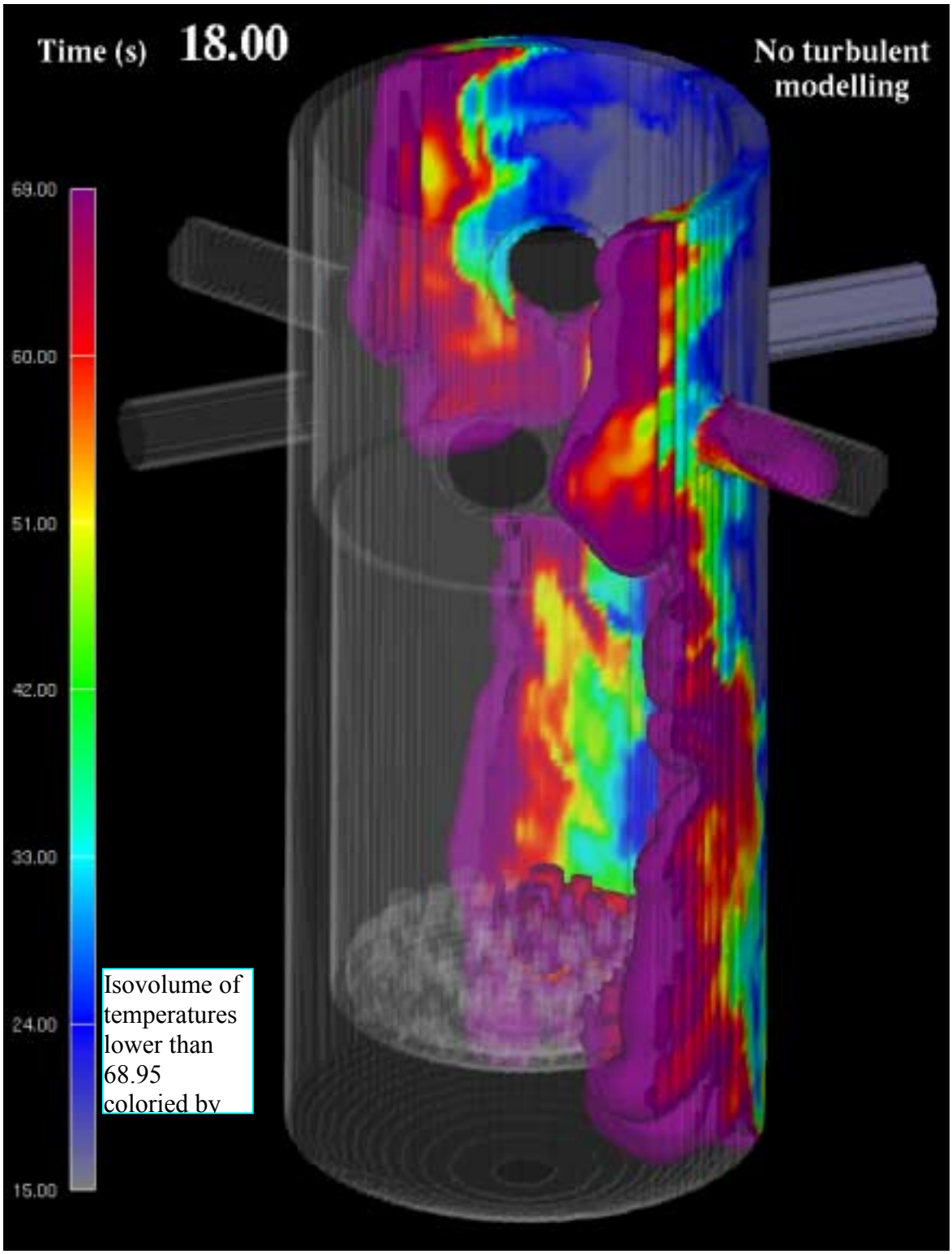
All along the transients 3 types of data were acquired:

➔ Time evolution of temperatures and of the 3 velocity components for each computational time step, for the 185 TC locations specified to acquire, were stored for the 3 computations (note that the time step due mainly to Courant stability condition is about one millisecond after the pump start-up). Illustrations of acquired temperature evolutions are given on the 2 following figures.

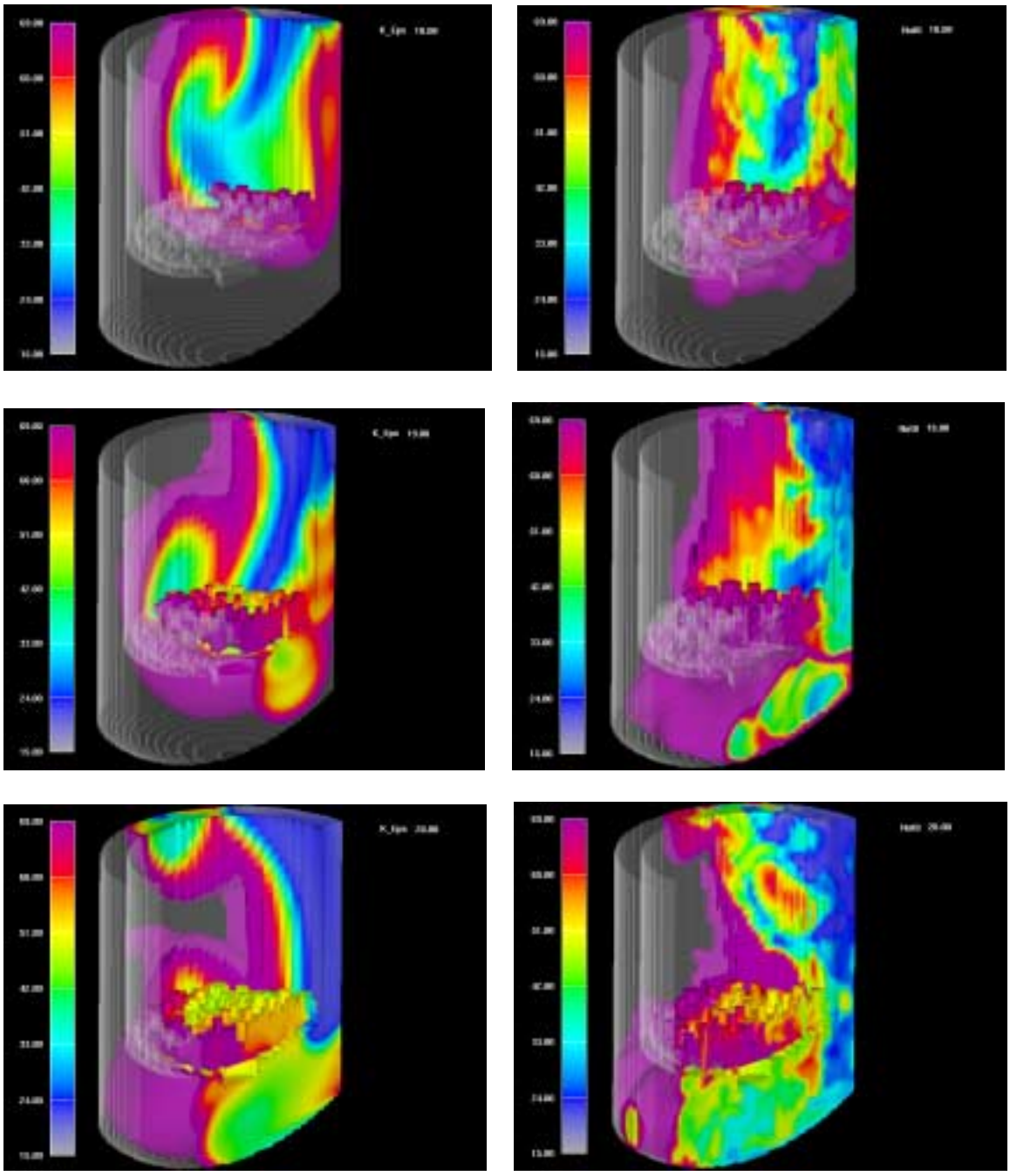




➔ Snapshots of complete temperature fields were acquired for the two sequential computations every .04 physical seconds. This is useful for fine visual analysis of the flow behavior we computed. For this analysis we use 3D detailed visualizations (see next figure below) and animations of these visualizations (see the 3 mpeg movie joined). For instance this may help to understand the global effects of turbulent modeling (see next page).



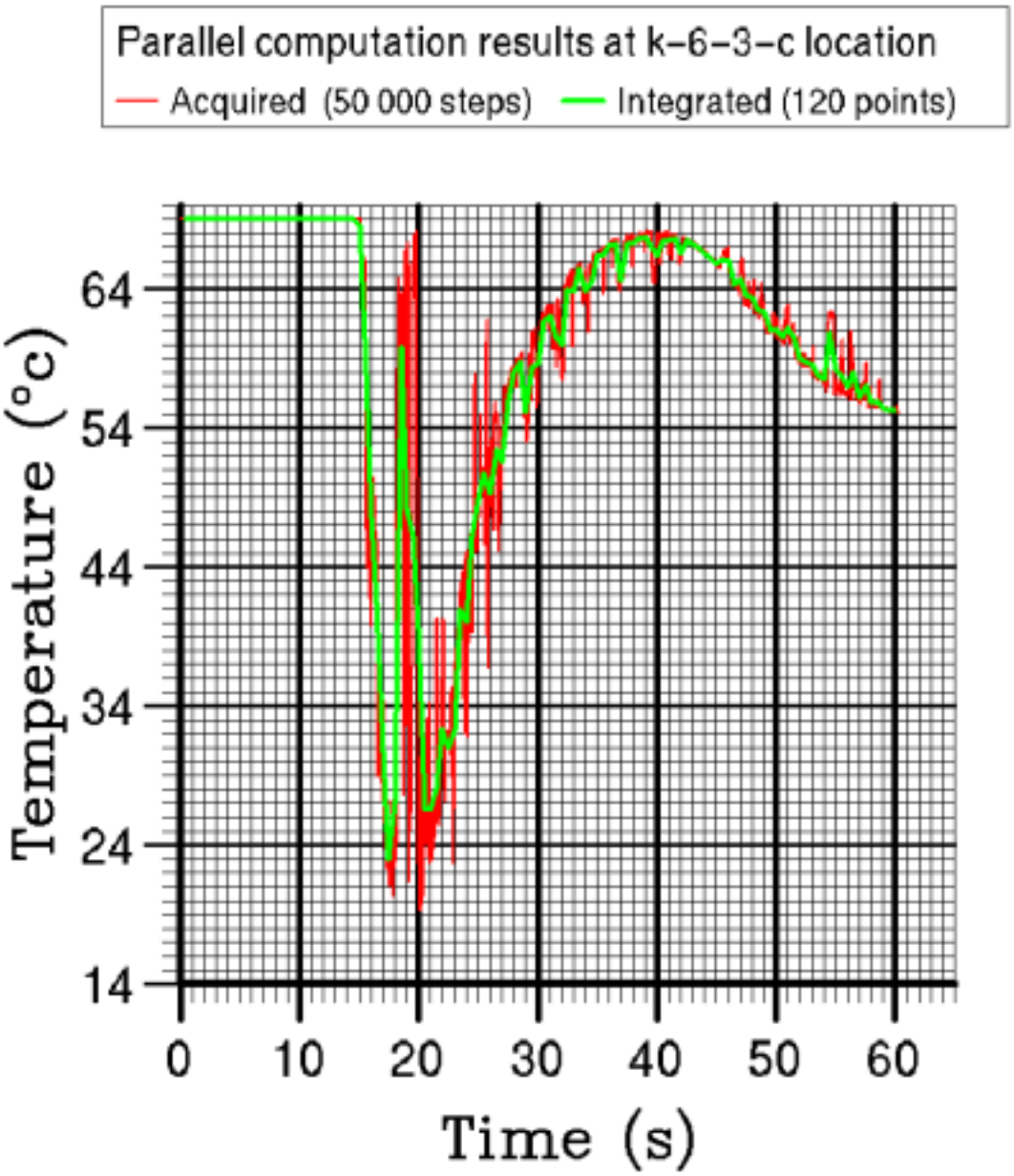
Visual comparison between K-Eps and Nut0 modelings.



➔ Dumps of all the variables necessary to restart the computation were performed every .125 physical seconds for sequential computations and every .5 seconds for parallel computation.

10.1.3.2 Data transmitted to UMD

The temperature time evolutions we acquired were integrated over .5 seconds and stored every .5 seconds at the middle time of the integration area in order to get results comparable to other results of this ISP. The integrated results were introduced in the templates prepared by UMD which are joined for the 3 computations. The effect of averaging is illustrated on the next figure.



10.1.4 Further work.

Our slow computations have been interrupted.

The physical time reached for sequential computations is about 23 seconds, and it is about 60 seconds for the parallel computation.

We hope this is sufficient for interesting analysis and comparisons with experimental results and other computational results.

More analysis, and the redaction of a final report on this task are planned afterwards according to the discussions of these comparisons during the next workshop.

10.2 Description of the Computation Model made in Fortum Engineering Ltd (referred to as IVO throughout the report)

Timo Toppila

Fortum Engineering Ltd
Timo.Toppila@fortum.com

10.2.1 Introduction

This paper describes a computational fluid dynamics (CFD) model of the 2x4 Thermal-hydraulics loop facility of the University of Maryland made in Fortum Engineering Ltd for the ISP-43. The boundary conditions used in the simulation of the test cases A and B are also shortly described.

10.2.2 Computation model

10.2.2.1 Mesh

The computation mesh was developed according to next principles:

Detailed geometry description: all that may affect to the flow field is modeled.

Although the flow field and mixing in the downcomer is the main goal, the model should include the core volume and part of the hot legs to correctly take into account inertia effects. That will also be useful if the same model is used for calculations including open loops and bypass flow.

Minimum number of computational cells that together with second order discretization schemes gives reasonable accurate results.

Near wall mesh that gives $30 < y^+ < 300$ for the first cell: no accurate wall flow modeling but logarithmic wall functions together with an appropriate turbulence model.

The computation mesh was made using the commercial preprocessing tool Geomesh. The total number of hexahedral and tetrahedral cells is 175 361. The computation mesh is illustrated in Figure 10-2 through Figure 10-6.

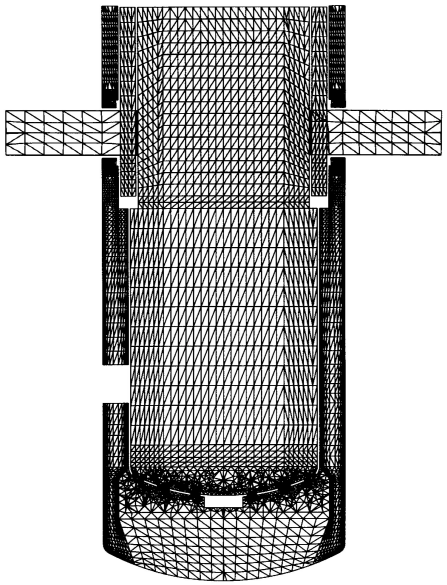


Figure 10-2. Computation mesh, cross section through the hot legs

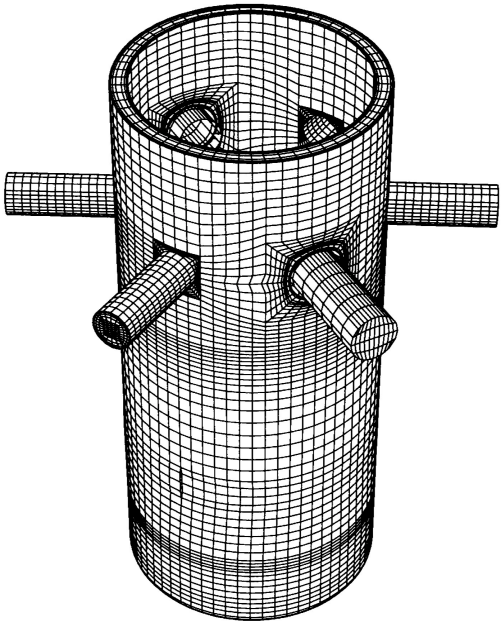


Figure 10-3. Computation mesh, outer wall of the reactor vessel

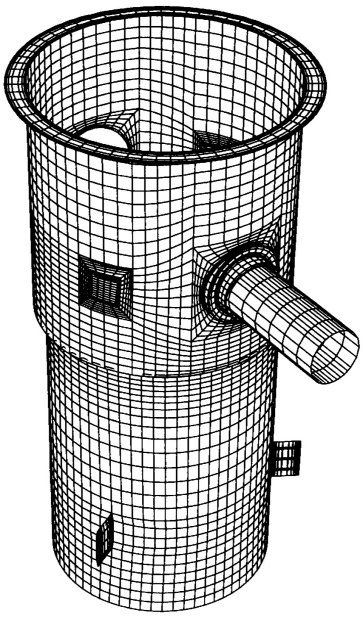


Figure 10-4. Computation mesh, core barrel

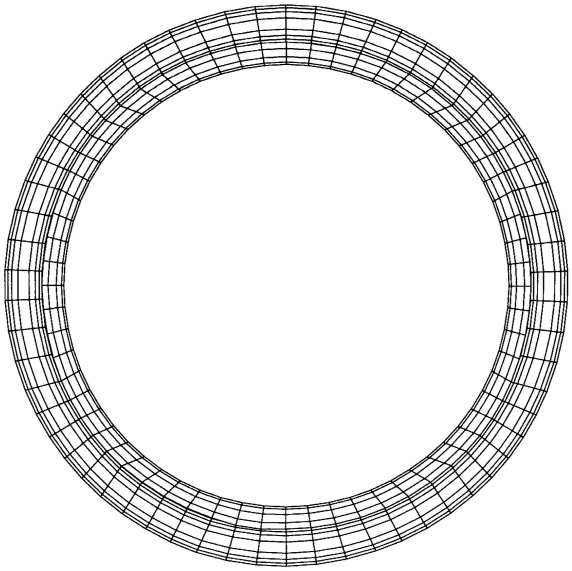


Figure 10-5. Downcomer, horizontal cross-section, lower part of the downcomer

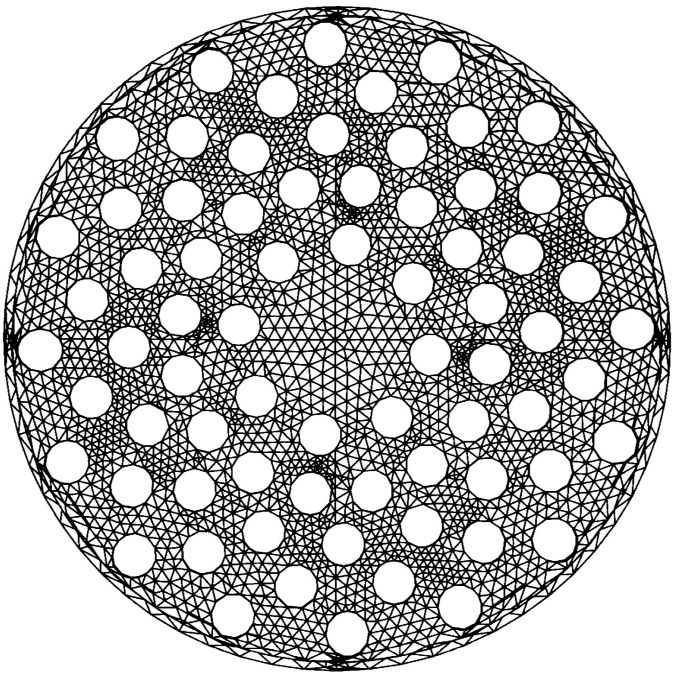


Figure 10-6. Bottom plate, tetrahedral wall grid

10.2.2.2 Numerical models

The Reynolds averaged Navier-Stokes equations together with the heat transfer equation and Standard k-ε turbulence model equations were solved using commercial CFD code Fluent 5.0. The most important numerical settings were:

- Solver: so called segregated solver with SIMPLE pressure-velocity coupling
- Discretizations: Control-volume based discretization. Standard discretization scheme for pressure equation, 2^{nd} order upwind scheme for spatial discretization and 2^{nd} order implicit scheme for time discretization.
- Time step size 0.05 sec for the first seconds of the transient, then 0.1 sec.

The transient took about 3 weeks of CPU time to compute using Silicon Graphics Octane workstation (250 MHz CPU, 1GB memory).

10.2.2.3 Boundary conditions and material properties

The flow velocity components and temperature at the inlet were given as a function of time using piecewise linear functions. The boundary conditions were based on the measurements during the transient. The temperature and velocity boundary conditions at inlet are presented in Figure 10-7 and Figure 10-8.

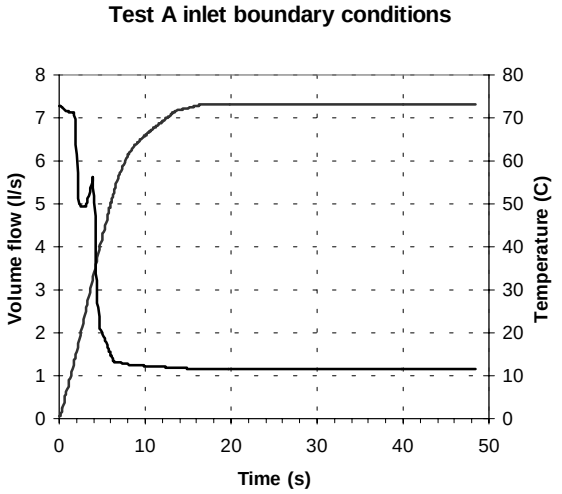


Figure 10-7. Inlet boundary conditions for Test A

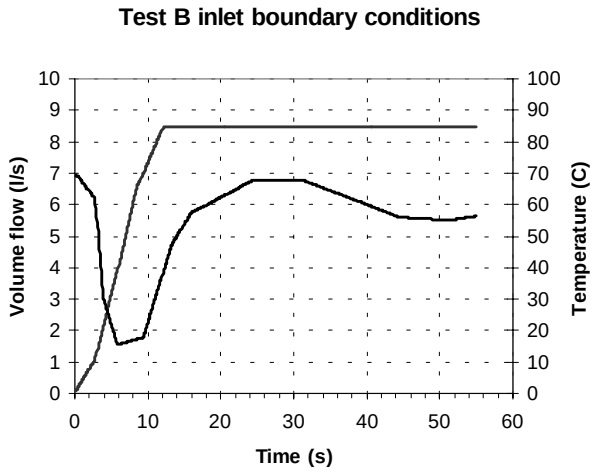


Figure 10-8. Inlet boundary conditions for Test B

The reference pressure at the outlet was set to P=0.0 Pa.

All walls were set adiabatic and the standard logarithmic wall functions were used.

The numerical calculation was started when the flow rate starts to rise from zero. That means that there is an 8.5 second time-difference between experiment and calculation in test A and 10.0 seconds difference in test B.

The viscosity, density and specific heat were set as a function of temperature using piecewise linear function. A temperature dependent density is presented in Figure 10-9. A constant value was used for the thermal conductivity.

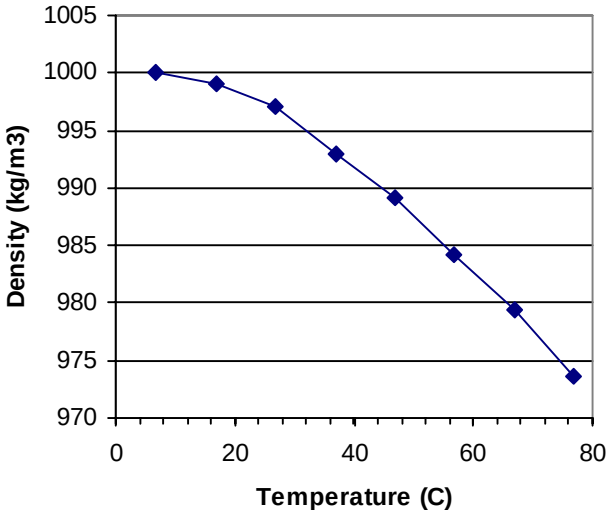


Figure 10-9. Water density

10.3 ISP 43 Final Report: GRS Participant Discussion

M. Scheuerer

Gesellschaft für Anlagen- und Reaktorsicherheit GmbH,

Forschungsgelände ,

D-85748 Garching

10.3.1 Description of the CFD-method

GRS has performed calculations for test case A with the CFD-software developed by AEA-Technology CFX-TASCflow. CFX-TASCflow solves the three-dimensional Reynolds-averaged conservation equations for mass, momentum and energy (Navier-Stokes-equations). The turbulent momentum and energy transfer terms which appear in the mean flow equations are calculated with the k-ε turbulence model (Launder and Spalding, 1974). The numerical solution method is a conservative, element-based finite-volume method with co-located variable storage. The numerical grids are non-orthogonal, hexahedral and block-structured.

CFX-TASCflow offers a choice of various discretization schemes for the convective fluxes appearing in the model transport equations. These are the Upwind Differencing Scheme (UDS), the Mass-Weighted Skew-Upwind Differencing (MWS) and the Linear-Profile Skew-Upwind Differencing (LPS) methods developed by Raithby (1976). The approximation of the convective fluxes can be improved by using the Physical Advection Correction (PAC) scheme. The former two methods have first order truncation errors. The LPS-method combined with PAC is second order accurate. In the present work the latter scheme is used. Diffusive fluxes are approximated using trilinear form-functions. Time derivatives are discretized with a first-order backward Euler-method.

Picard iteration is used to resolve the nonlinearities in the governing equations. For each iteration the pressure and velocity fields are solved as a coupled block system. An algebraic multi-grid method, based on incomplete Gauss-elimination (Raw, 1996) is used for the solution of the difference equations.

In the calculations described in this paper, which should be regarded as a first test of the three-dimensional prediction procedure, several simplifying assumptions have been made. These are:

- The fluid properties are constant.
- Buoyancy (gravity) effects are neglected.
- The outlet static pressure does not vary with time.

The above assumptions have been made to achieve good accuracy and good robustness. They are no limitations of the underlying calculation procedure.

10.3.2 Boundary and Initial Conditions

The geometry of the numerical model of the pressure-vessel, the cold legs, the hot leg outlet and the downcomer is shown in Figure 10-10. The internal diameter of the test vessel is 48,3 cm. The internal diameter of the main cooling line is 7,6 cm. Centred inside the pressure vessel is the core, approximated by a porous region. Figure 10-11 shows the numerical grid with the cold legs, the downcomer with an increase of its diameter in the lower part, the downcomer walls, the bottom and the core of the RPV. It consists of 467040 flux elements.

The static pressure loss of 6 inches H_2O across the core was obtained by a porosity factor of 0.7. The unborated, cold water is injected at the cross sectional area located at the first flange of cold leg A1. The primary system is initially well mixed at a temperature To = 74° C. The injected water has an initial temperature of Tmax = 72° C. After approximately 5 s its minimum temperature of Tmin = 12° C is reached. The maximum mass flow rate reaches m = 7.2 kg/s after 27 s problem. The inlet velocities, calculated from the specified mass flow rates, are assumed to be constant across the inlet faces. Turbulence intensities at the inlet are set to 7 % and the turbulence length scales to 0.005 m. The static pressure at the outlet cross section, at hot leg A, is set to a constant value. There are no heat losses at the outer walls.

Initially the relative pressure and velocity fields are set equal to zero. The properties of the fluid are set at a reference temperature of 287K, the density is ρ_{fluid} = 999.2 kg/m^3, the dynamic viscosity has a value of μ_{fluid} = 0.001 Pa s, the heat capacity at constant pressure is C_{fluid} = 4207 J/kg K and the conductivity is λ_{fluid} = 0.02 W/m K.

10.3.3 Results and Discussion

In the following discussion the nomenclature for the locations of temperatures adhere to the thermocouple locations prescribed for the ISP43 experiment. Figure 10-12 gives an overview on the location of measurement levels from the bottom to the top of the downcomer and lower plenum. Figure 10-13 and

Figure 10-14 show the azimuthal distribution of the thermocouples in cross sections of level 8 and level 7. On each level thermocouple one is located at the 3 o'clock position corresponding to the centerline of cold leg A1, numbering proceeds from there in counter-clockwise direction.

The three-dimensional effects of the asymmetric ECC-injection are shown in Figure 10-15 through Figure 10-17 of the temperature distributions in the downcomer at transient times of 20, 40, and 62 s. Initially the system is filled with stagnant water at a temperature of 74° C (347 K). Figure 10-15 shows the temperature distribution at time = 20 s. The cold water flows downward and in circumferential direction. Higher temperatures appear at the cross section where the downcomer radius increases. These are caused by local recirculation due to the geometry discontinuity. After 40 s, in Figure 10-16, the cold water has reached the lower plenum of the reactor where strong

recirculation zones evolve. The flow in the core is strongly three-dimensional and has a complex structure. At the end of the transient, at time = 62 s, shown in Figure 10-17, the core is almost completely cooled down. The mixing of hot and cold water is very good.

The designated figure of merit for the comparison of experimental and numerical results is the average fluid temperature at the center of level 4 in the downcomer for the transient period from 0 to 62 s. In Figure 10-18 the experimental results are shown with its corresponding maximum and minimum values. The averaged calculated temperatures are within the experimental data range following mostly the lower limit of the transient. The time history of the local temperatures at the center of the downcomer on level 4 at the 3, 6, 9 and 12 o'clock position are shown in Figure 10-19 through Figure 10-22. The graphs with the individual temperatures show the three-dimensionality of the flow. Because of the complex flow the temperature plots at the four positions are not quite symmetrical. During the experiment the fastest cool-down occurs at the 3 o'clock position (Figure 10-22) while calculated temperatures drop fastest at the 9 o'clock position, opposite to the inlet location, see Figure 10-21.

The time history of the average fluid temperatures located at the center of the downcomer at level 7 and 9 is plotted in Figure 10-23 and Figure 10-24 together with the averaged experimental value and its maximum and minimum value. Level 7 is located below the step change in diameter of the downcomer and level 9 corresponds to the center of injection plane. On both levels the calculated temperature gradients are within the experimental range. The temperature drop corresponds to the temperature gradient of the injected plug. The temperature distribution at the entrance plane (level 9) in Figure 10-24 shows that initial temperatures for the calculations are chosen close to minimum values of the experiment. Therefore, numerical results remain at the lower temperature limit compared to the experimental data at all other locations.

The calculations were performed on a DEC Alpha Server 8200 with 1GB RAM. The simulation requires 512 MB storage and an average calculation time of 1.85 x 10-2 CPU s /(real time s x grid point). An average time step size of 0.25 s is used, requiring ca. 5 iterations for convergence. The convergence criterion is set at 0.001 for the normalized maximum residuals of the mass, momentum and energy equations.

10.3.4 Conclusions and Outlook

The rapid boron dilution transient test case A were calculated using the CFX-TASCflow software. The presented results show good agreement with the experimental data. However, the calculations should be further validated. The calculations should be repeated using higher order difference schemes and the different solutions should be compared in order to quantify the numerical errors. Then the spatial grids and time steps need to be adjusted to minimize the solution error. Finally, model uncertainties should be investigated, e.g. turbulence model, neglect of buoyancy effects, porous media assumptions. These additional investigations will help to understand and interpret the results better.

10.3.5 References

Launder, B. E., Spalding, D. B., 1974, The Numerical Computation of Turbulent Flows. Comp. Meth. Appl. Mech. Eng., Vol. 3, pp. 269 - 289.

Raithby, G. D., 1976, Skew-Upstream Differencing Schemes for Nearly-Steady Problems Involving Fluid Flow, Computer Methods in Applied Mechanics and Engineering, Vol. 9, pp. 153 - 164.

Raw, M. J., 1996, Robustness of Coupled Algebraic Multigrid for the Navier-Stokes Equations, AIAA-Paper 96-0297.

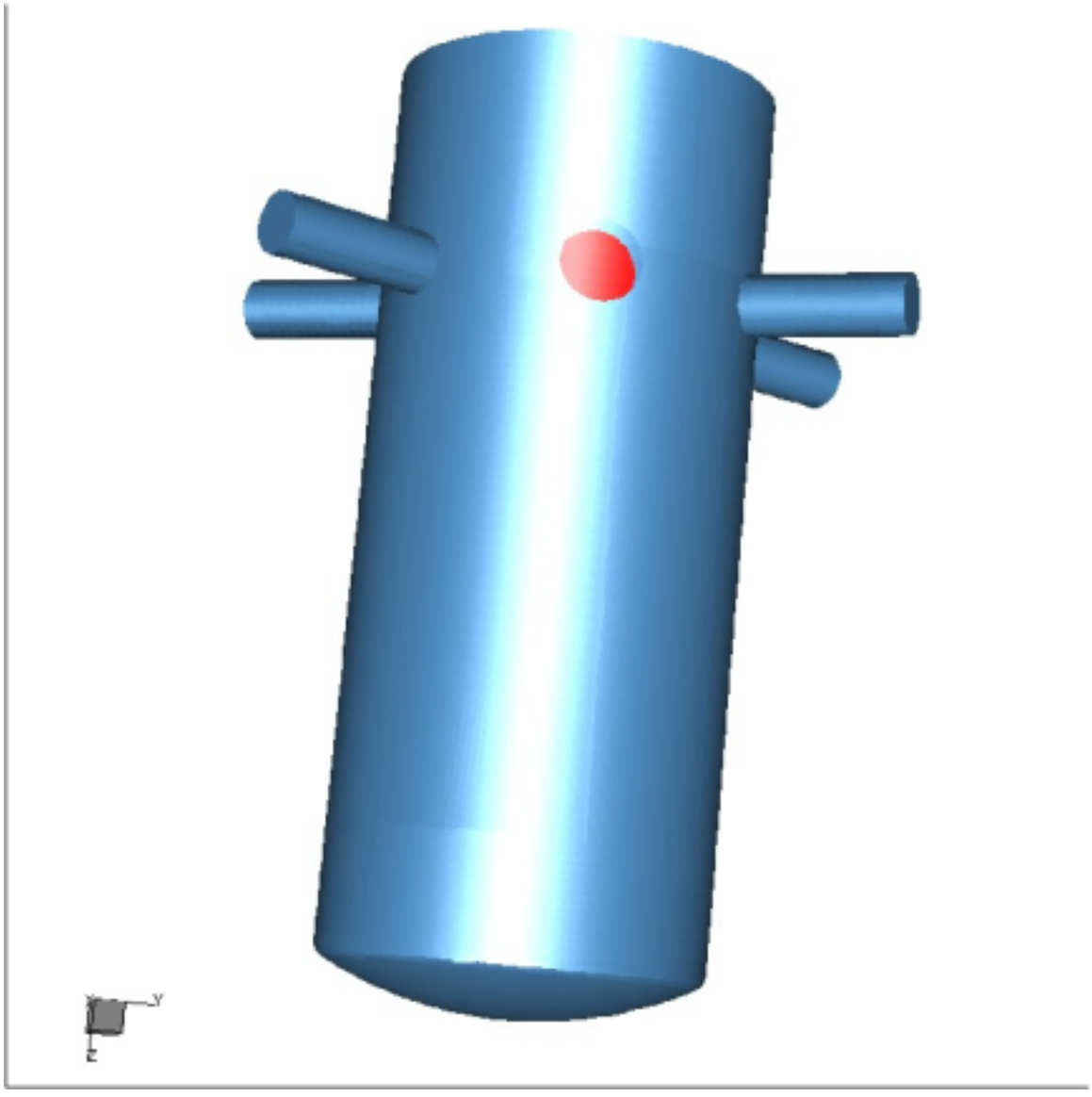


Figure 10-10. Geometry of the numerical model of the reactor vessel

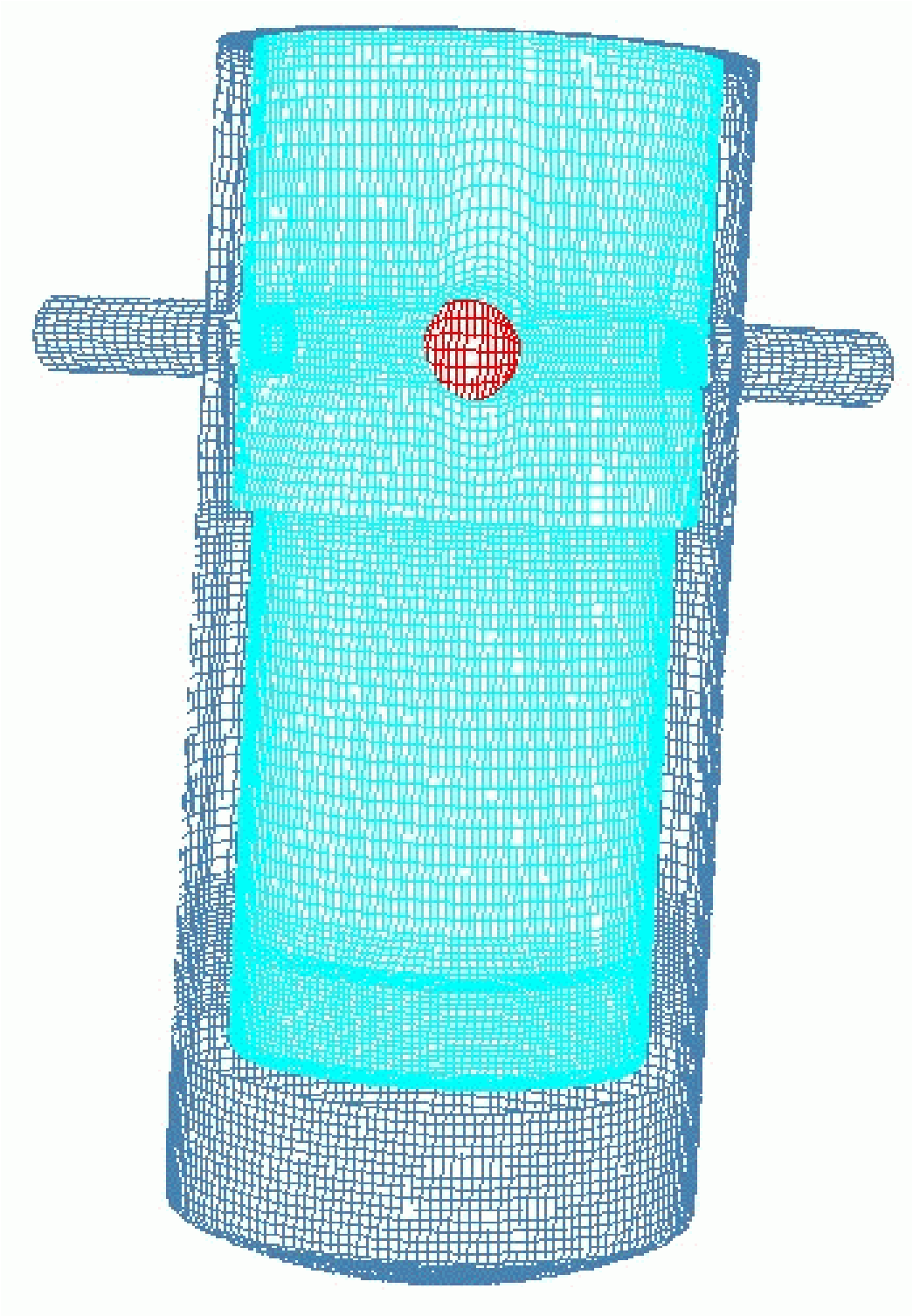


Figure 10-11. Numerical grid

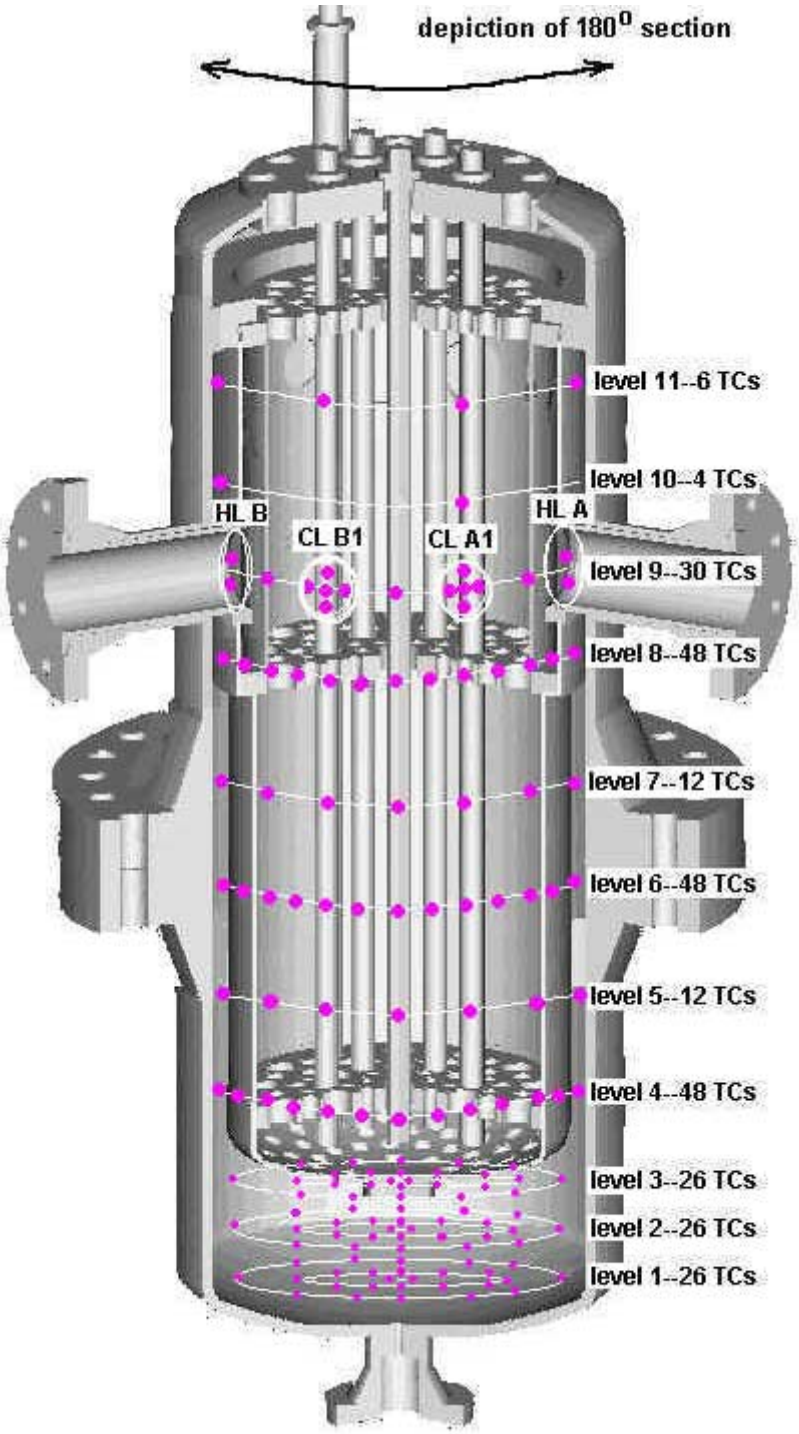


Figure 10-12. Thermocouple level location

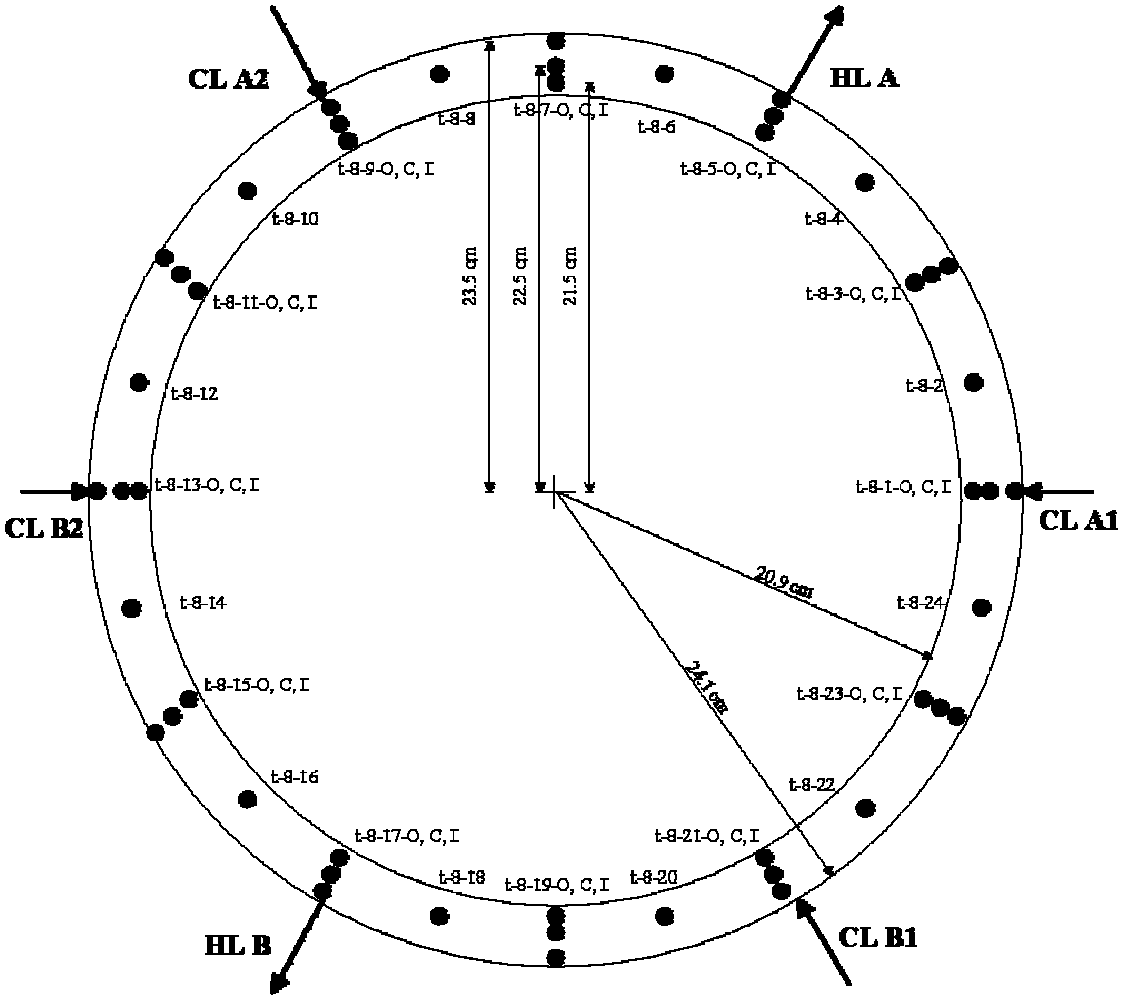


Figure 10-13. Azimuthal thermocouple location on level 8

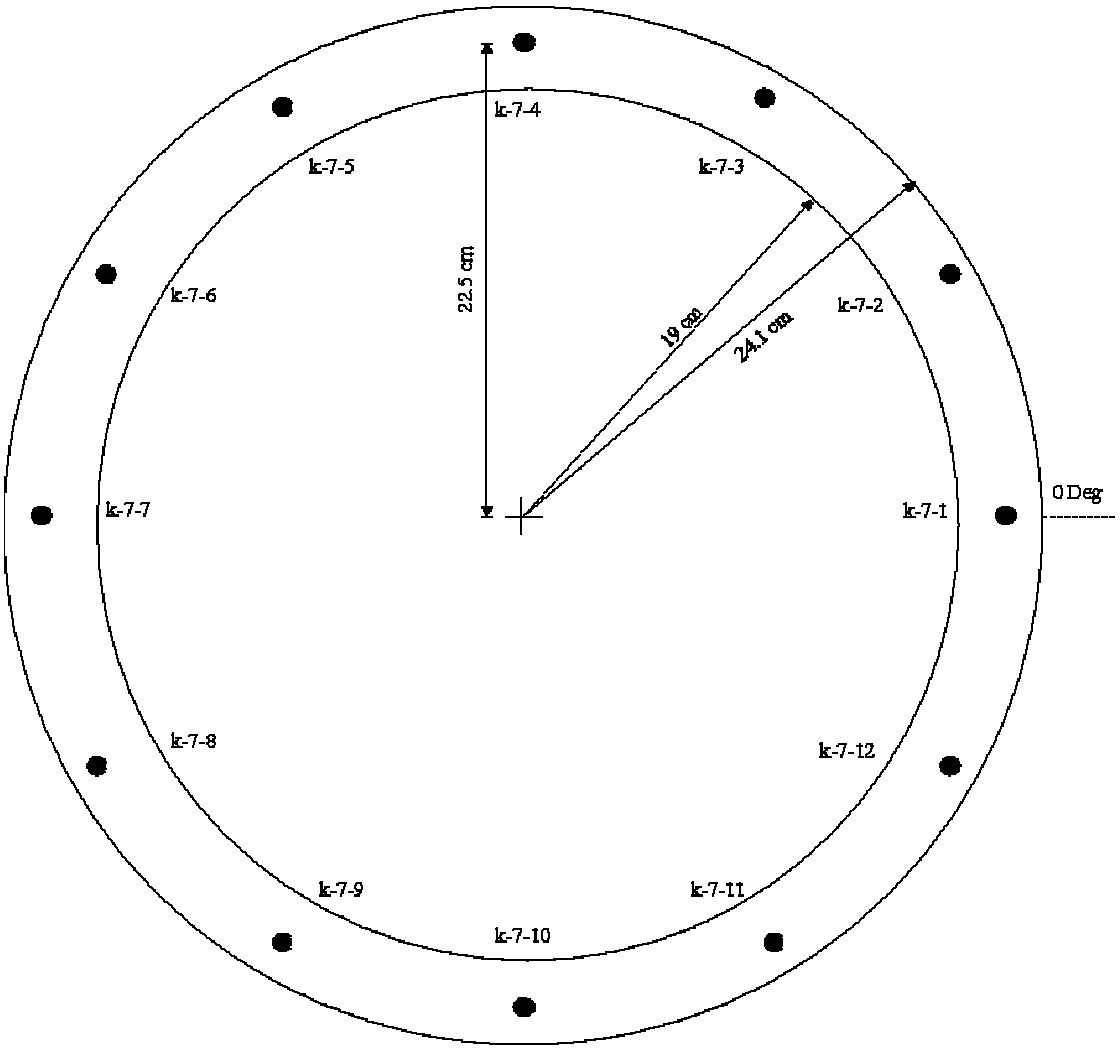


Figure 10-14. Azimuthal thermocouple location on level 7

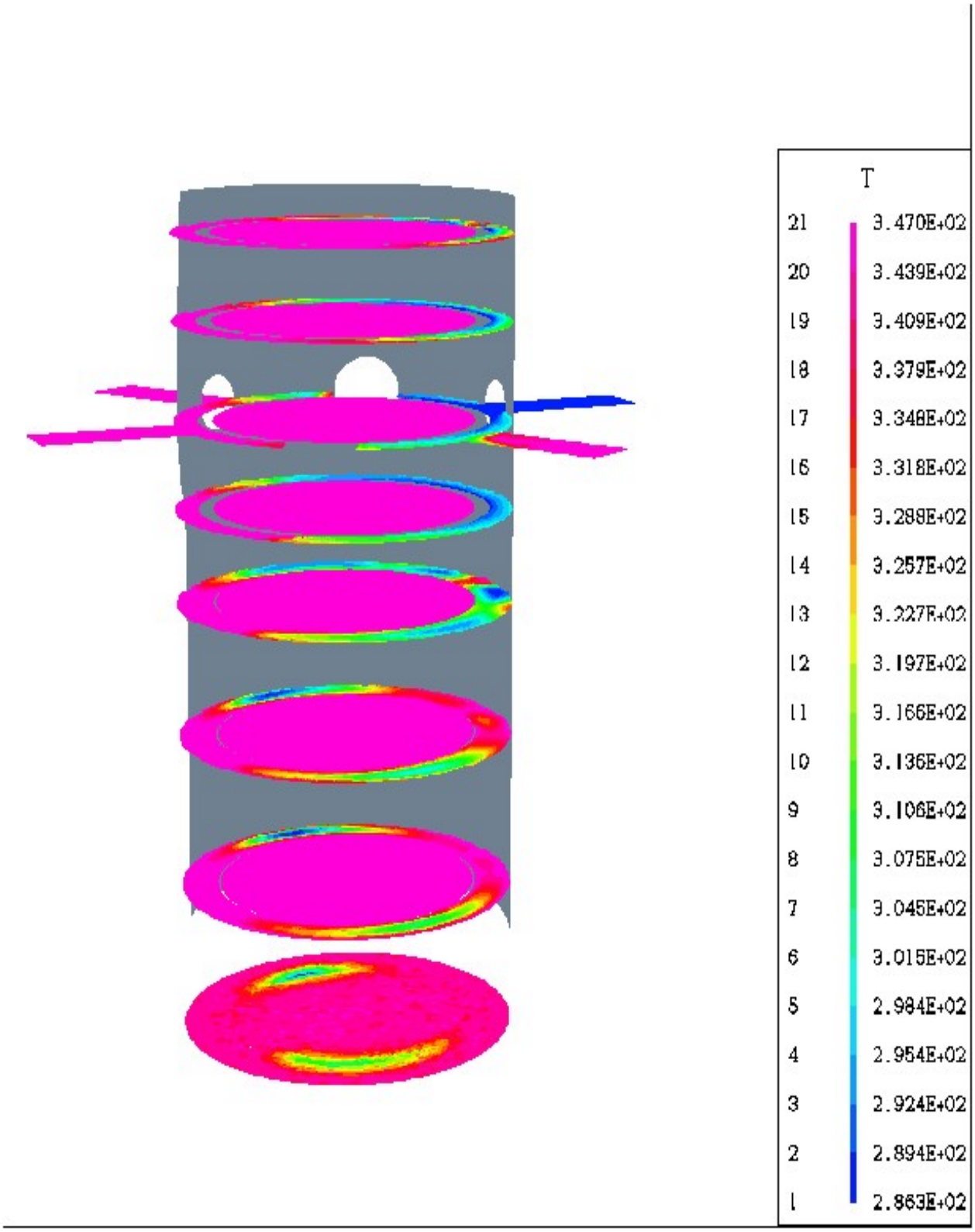


Figure 10-15. Temperature distribution, time = 20s

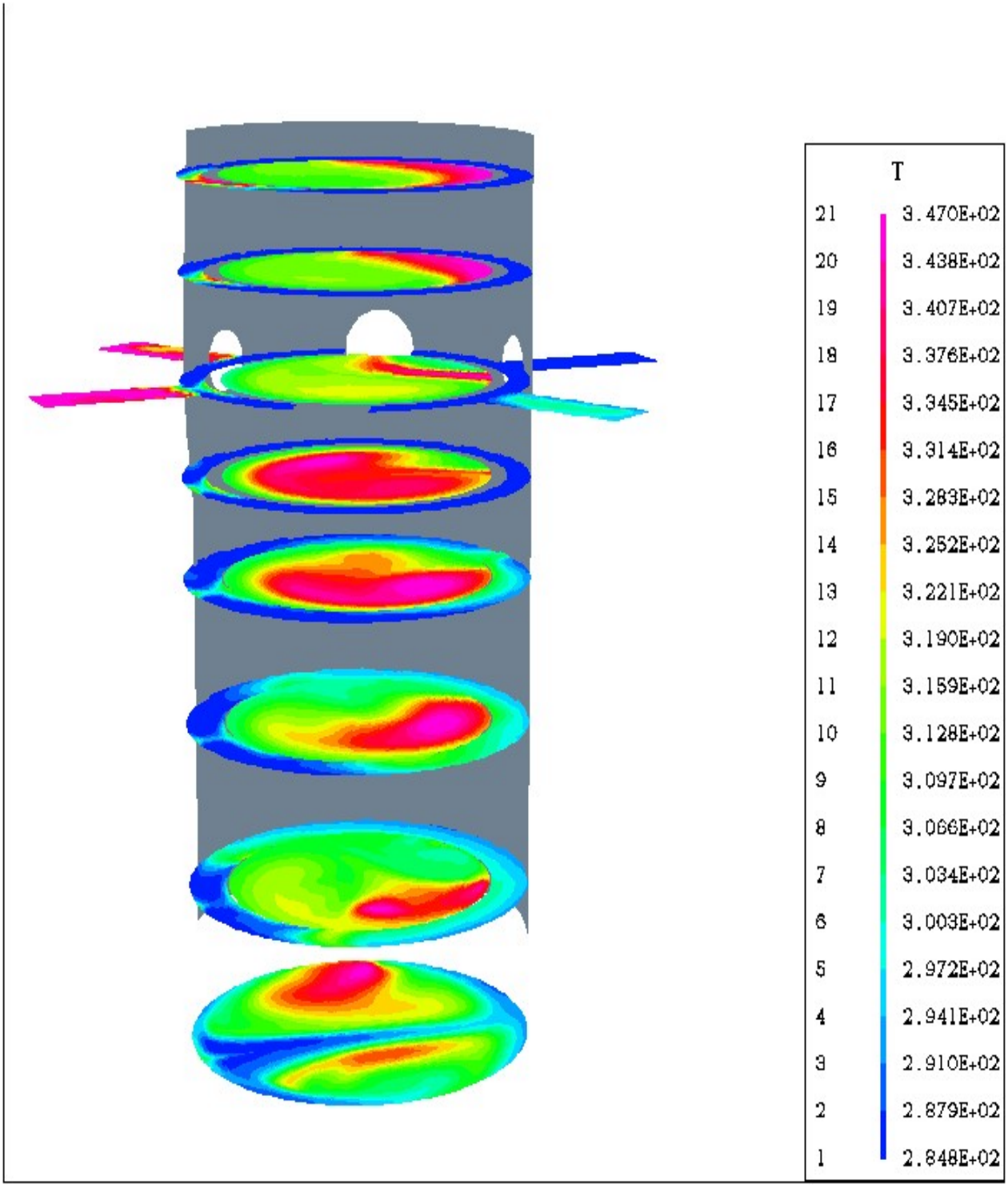


Figure 10-16. Temperature distribution, time = 40s

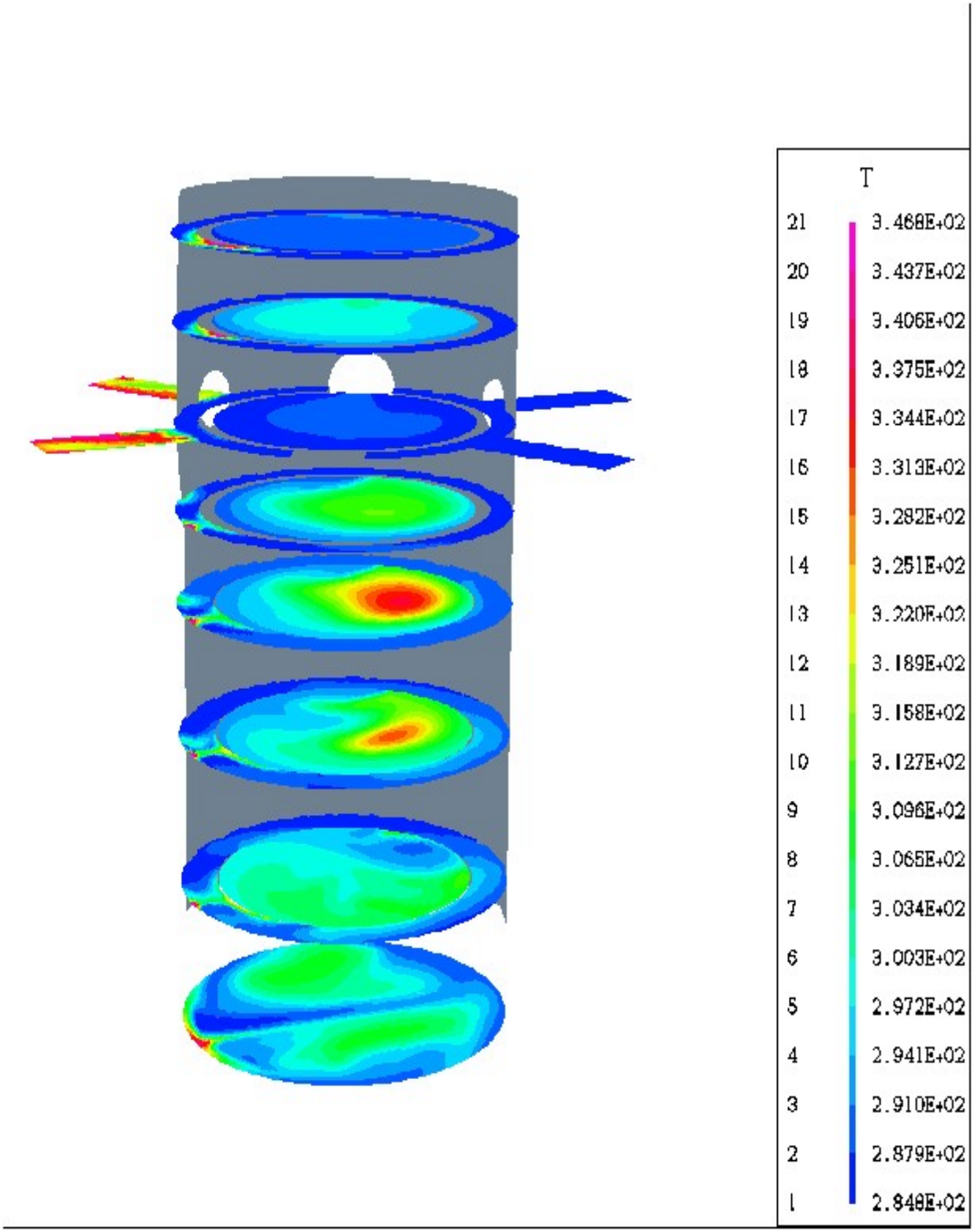


Figure 10-17. Temperature distribution, time = 62s

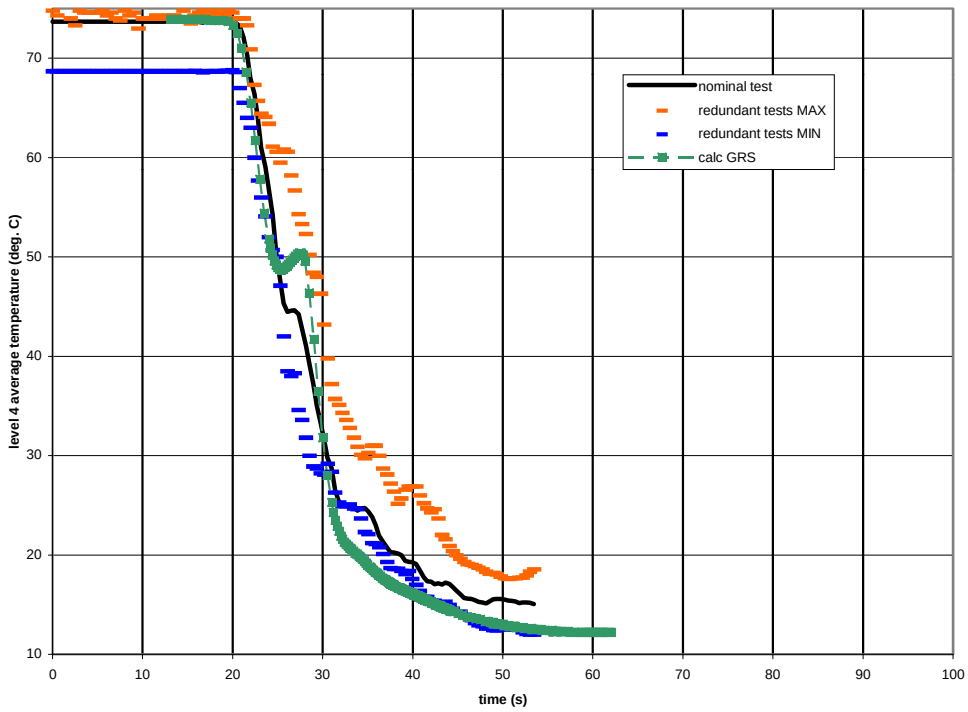


Figure 10-18. Average fluid temperature at level 4

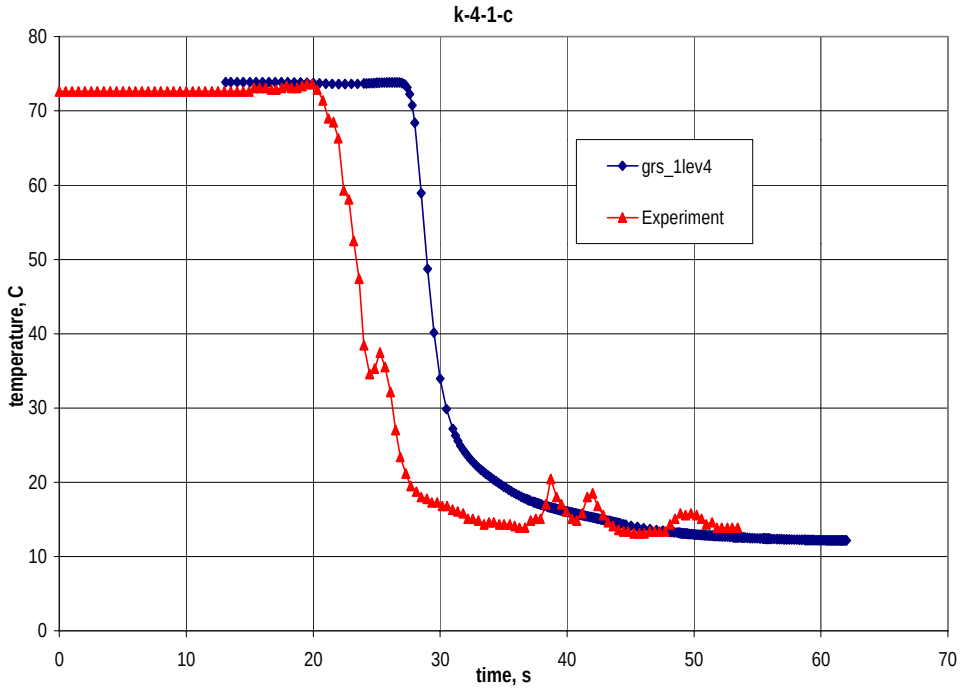


Figure 10-19. Local fluid temperature at 3 o'clock position on level 4

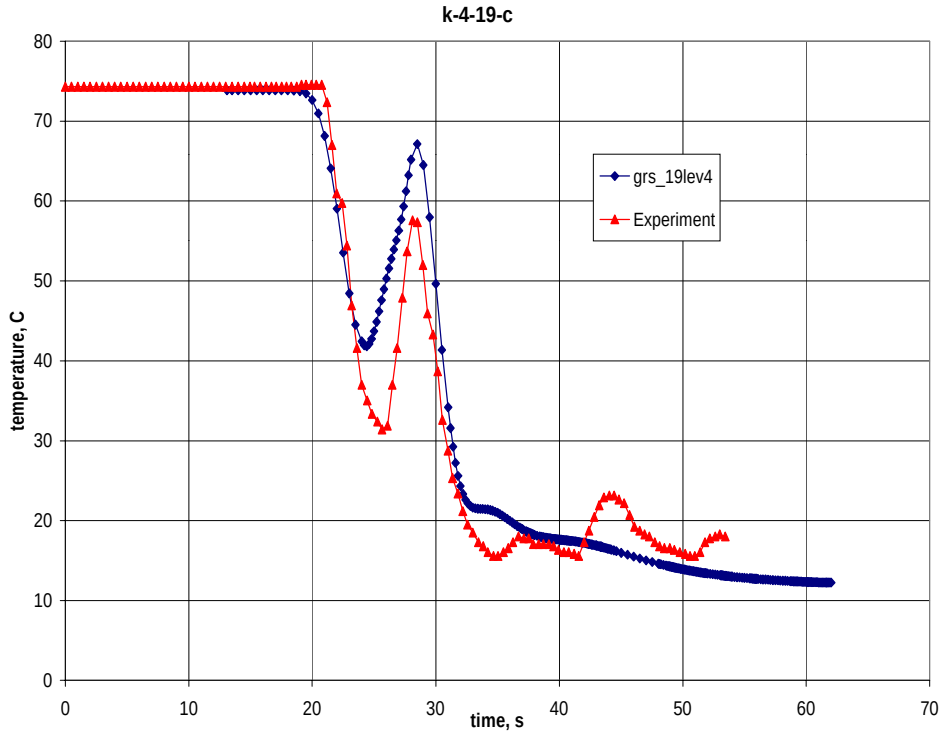


Figure 10-20. Local fluid temperature at 6 o'clock position on level 4

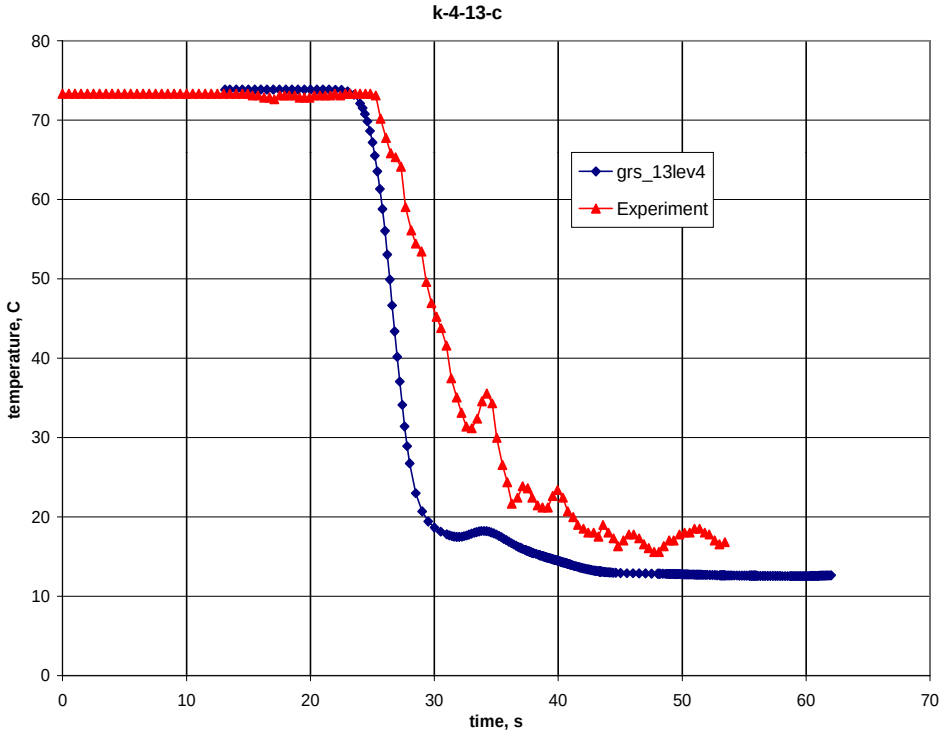


Figure 10-21. Local fluid temperature at 9 o'clock position on level 4

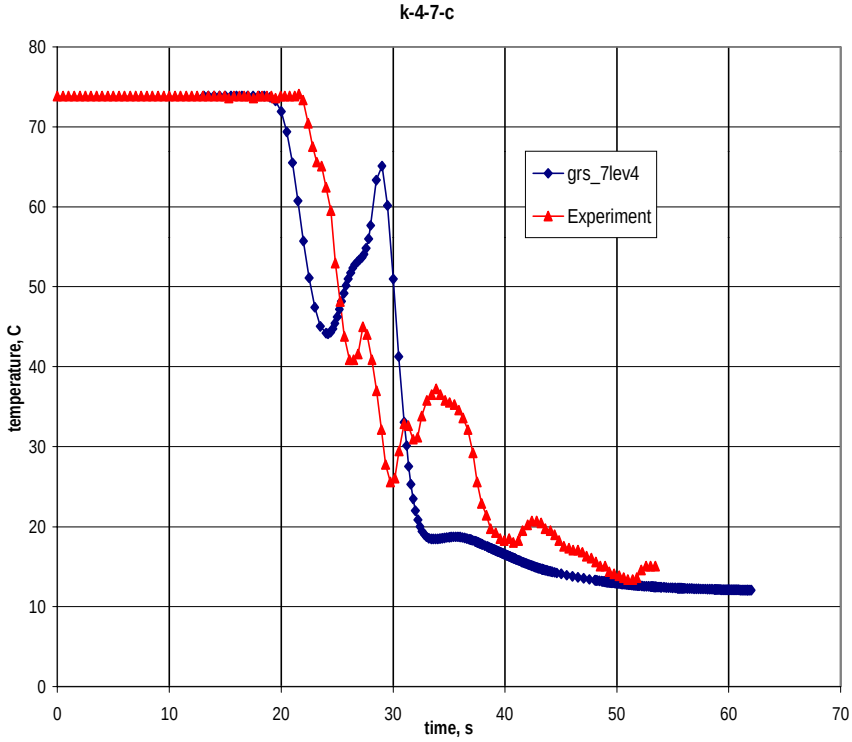


Figure 10-22. Local fluid temperature at 12 o'clock position on level 4

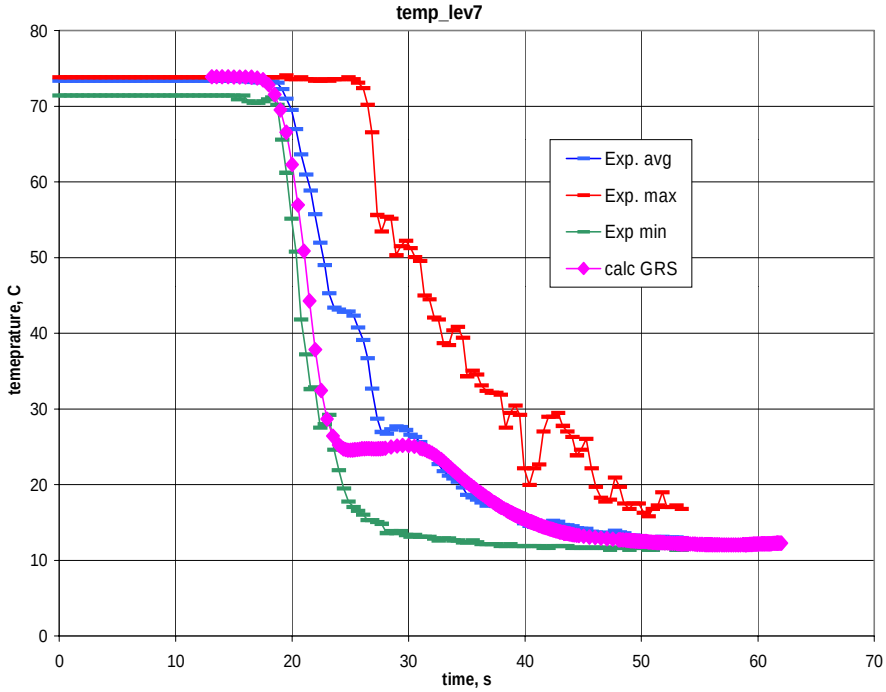


Figure 10-23. Average fluid temperature at level 7

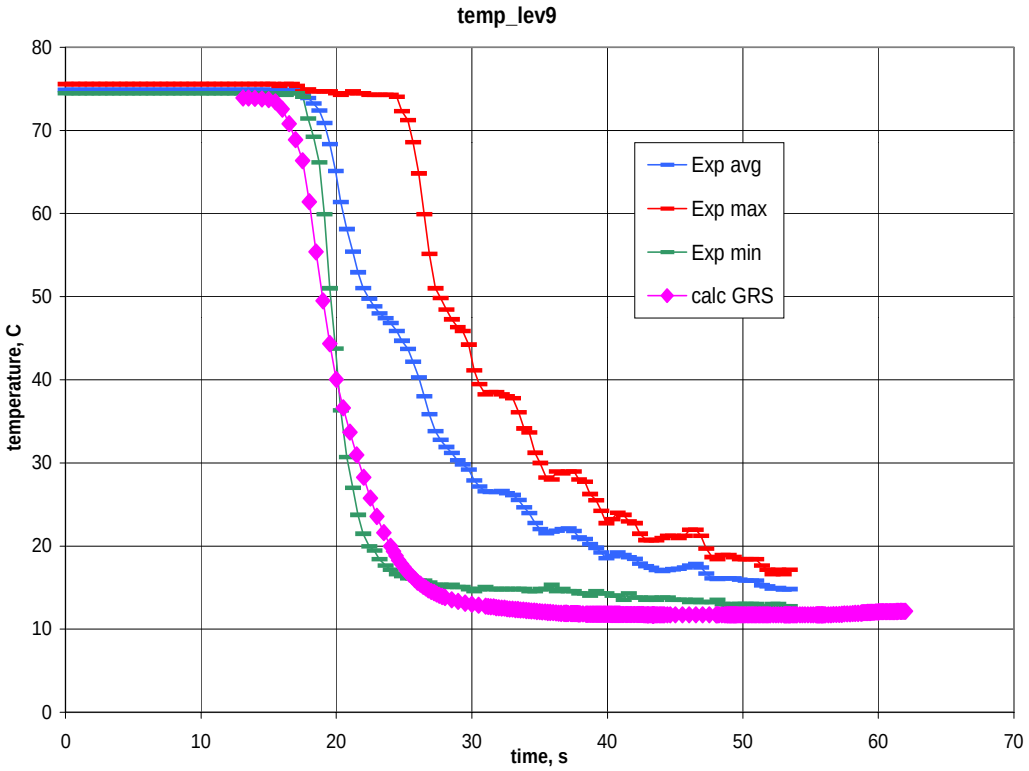


Figure 10-24. Average fluid temperature at level 9

10.4 NRI Simulation of the ISP-43 Experiments

Petr Műhlbauer

Nuclear Research Institute Řež plc, 250 68 Řež, Czech Republic
Muh@nri.cz

10.4.1 Introduction

Numerical simulations of the ISP-43 experiments in the NRI were performed within an effort to evaluate the possible application of up-to-date multi-dimensional thermal hydraulic codes to analysis of problems of boron dilution in the VVER NPPs. The commercial CFD computer code FLUENT 5 was selected as the first tested code. In the following chapters, a short description of NRI approach to the pretest simulations is given.

10.4.2 Computational Model

Since it became very early clear that modeling of the whole experimental facility would be very expensive as to the hardware and CPU time requirements (and, in fact, not necessary), the modeled geometry was limited to the recommended simulation boundary. Owing to limited computational resources at the time of calculations (512 Mb of operational memory, only one license for the selected solver FLUENT 5) it was decided for the pretest calculations to simplify the geometry and physical phenomena taken into consideration in the following way:

- The three flaps near the downcomer outlet are not modeled.
- The spherical bottom of the vessel is modeled as a cylindrical one.
- The perforated bottom of the core barrel and the lower plate are not modeled.
- The heating rods are not modeled.
- Buoyancy effects are not taken into account
- Physical characteristics of water are taken as independent of temperature.

A scheme of the geometry and the number of computational cells in the individual parts of the computational region is shown in Figure 10-25 and Table 10-1. In the nozzle region, a very complicated flow should be expected, so quite small tetrahedral elements are used there in order to reduce the numerical diffusion. In the rest of the downcomer, brick elements are used to decrease the total number of computational cells. Brick elements are used also in the lower plenum and in the outlet part of the model

Time dependent boundary conditions were modeled as piecewise-linear functions of time. Uniform velocity inlet and pressure outlet boundary conditions options of the FLUENT 5 code were used. Since the pressure difference between the lower plenum and hot leg was supplied to the participants, the following procedure was used in order to obtain a corresponding pressure difference in the geometrical model: A steady state calculation for the final stage of the Test A was performed with outflow (zero streamwise

gradients of all quantities except of pressure) boundary condition and a reference pressure set in the lower plenum. Then the resulting pressure difference between the lower plenum and outlet of 268.52 Pa was determined and compared with the measured pressure difference of 1514.5 Pa. The supplied time courses of the experimental pressure difference for both tests were then multiplied by the ratio 268.52/1514.5 = 0.1773.

As for the model of turbulence and the numerical methods, it was decided to use the well-known k – ε model of turbulence with standard wall functions, and first-order accurate implicit segregated solver, first order upwind differencing, and SIMPLE algorithm for the pressure–velocity coupling. All calculations were performed in single precision on HP9000 K260 with 4 processors and 512 MB of RAM.

During the calculations of both tests, there was a backflow through a part of the outlet plane that should be eliminated in the post-test calculations.

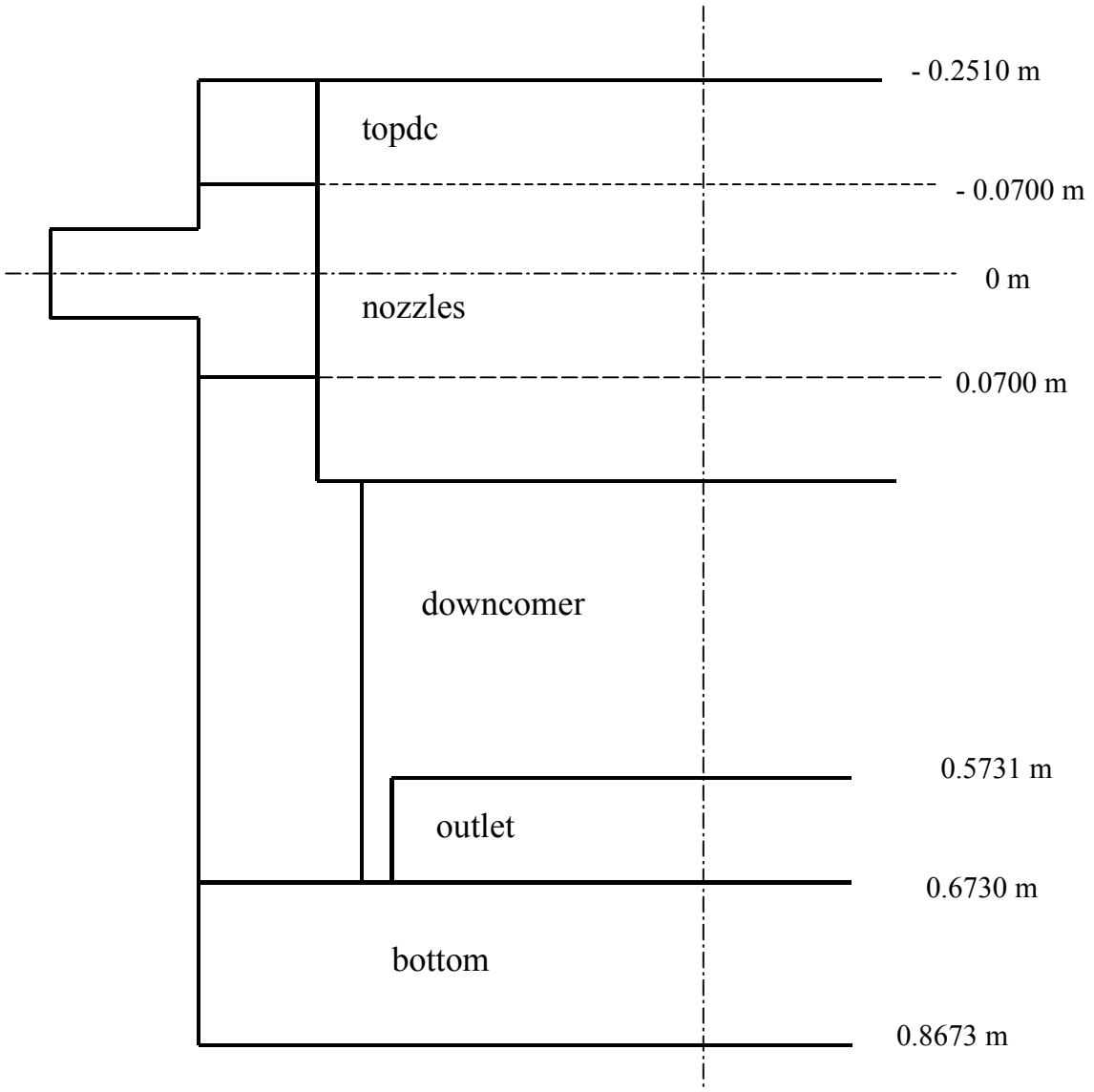


Figure 10-25. Scheme of the solution domain (not to scale)

Table 10-1: Types and numbers of cells in solution domain

Region	Number of cells	Type of control volumes
Topdc	13 500	Hexahedral
Nozzles	137 929	Hexahedral in pipes, tetrahedral
Downcomer	81 000	Hexahedral
Bottom	33 960	Hexahedral
Outlet	5 872	Hexahedral

Total number of computational cells: 272 261.

10.4.3 Principal result

During the first workshop, level 4 average temperature was selected as the primary figure of merit. This quantity for both tests is shown in

Figure 10-26. Large changes of the temperature between the 20 and 30 s of the experiment do not correspond to the experiments and their reason must be found in the stage of post-test calculations.

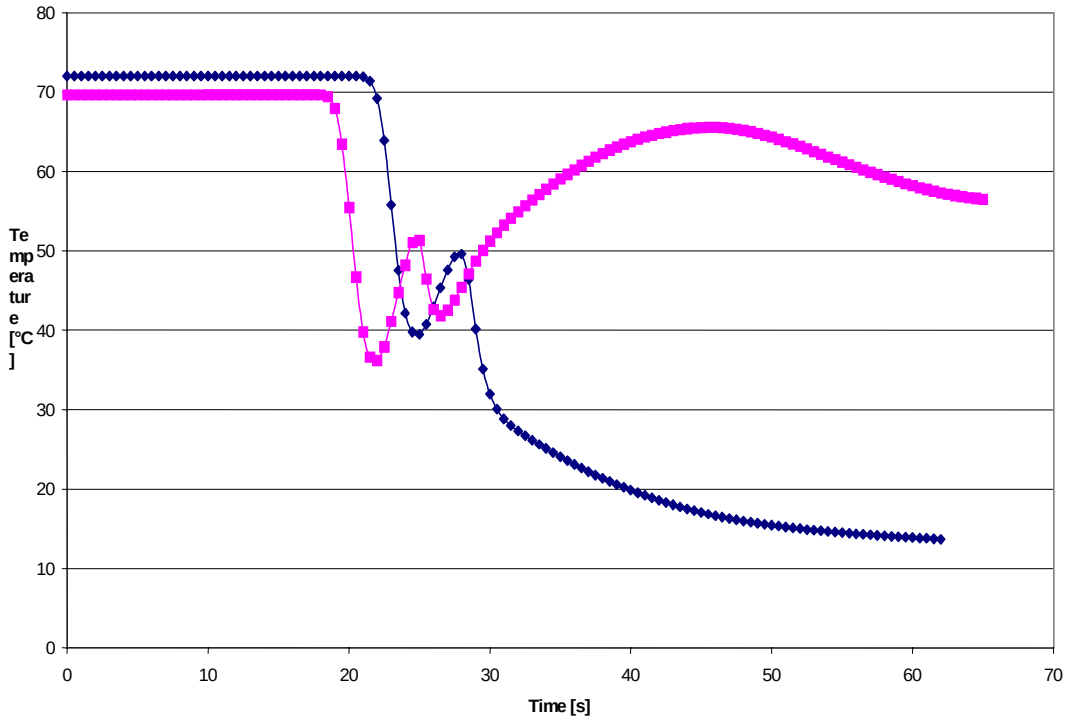


Figure 10-26. Level 4 average temperatures for Test A (blue) and Test B (pink)

A quantitative way of examining the flow pattern is by plotting the azimuthal profile at several times through out the transients. The times selected for test A are 24, 28, 32 and 36 seconds. In Figure 5-17, the origin corresponds to the center of the injection cold leg, CL A1, and the angle increases counterclockwise when viewed from the top. The data of Figure 5-17 is the ensemble average of the 16 redundant A tests in the loop; standard deviations marked by error bars. The plot shows that the front penetrates downwards under the cold leg and that the region opposite the injection site is the last to be mixed. The significant standard deviation around the injection site at 24 s shows that the front is spreading to varying degrees as it travels through the downcomer.

10.5 NUPEC Rapid Boron Dilution Calculations using thePLASHY/IMPACT Code

T. Morii[1], H. Terasaka[2], E. Hirano[3]

[1] Advanced Simulation Systems Department, Nuclear Power Engineering Corporation

Fujita Kanko Bldg., 6F, 3-17-1, Toranomon, Minato-ku, Tokyo 105-0001, Japan
Phone: +81-3-3435-3403, Fax: +81-3-3435-3413, e-mail: ms-naito@nupec.or.jp
[2] Toshiba Corporation
4-1, Ukishima-cho, Kawasaki-ku, Kawasaki, Kanagawa, Japan
[3] Toshiba Advanced Systems Corporation
1-2-4, Isago, Kawasaki-ku, Kawasaki, Kanagawa, Japan

10.5.1 Introduction

NUPEC has developed a general-purpose three-dimensional thermal-hydraulic code, PLASHY, to solve large scale complicated fluid flow problems(1). PLASHY, which stands for Parallel Large Scale Analysis System for HYdrodynamics, consists of two independent modules, PLASHY-CRT and PLASHY-BFC. Both modules solve a set of single-phase fluid thermal-hydraulic equations with or without turbulence transport equations, heat conduction equation, and mass transfer equation in Cartesian/Cylindrical coordinate system and Boundary Fitted Coordinate system, respectively. They can run on a parallel computer, IBM SP2, by employing the zone decoupling method.

NUPEC continues the effort to assess the PLASHY code, and thus the benchmark analysis of RBD transient was carried out. Because of the measured data for the ISP43 were closed, several sensitivity studies were required to select the computational grid system, inlet/outlet boundary conditions, turbulent model and other modeling options. After the sensitivity studies, about 300,000 cells in total, QUICK scheme for the momentum equations, the first order upwind scheme for the energy equation, etc. were selected. The turbulent model was neglected in the calculations because the occurrences of laminar to turbulent transition were expected in the transient. PLASHY has the k-e turbulent model, however the model of the PLASHY code did not work well for the turbulent transition.

According to the procedure mentioned above, three-dimensional downcomer mixing behaviors were calculated on the parallel computer SP2 by using the 12 of 76 CPU units. To reduce the computing time, PLASHY-CRT was employed instead of PLASHY-BFC. The curved wall of the lower plenum, the cold leg, and so on were modeled precisely by a porous body method in the cylindrical coordinate system.

10.5.2 Outline of PLASHY-CRT

PLASHY-CRT is a three dimensional single-phase flow analysis code. It is one of the base modules of IMPACT(1), and used as the independent flow analysis code or as a

cooperate module of a boiling transition analysis code, a fluid-structure interaction analysis code and a severe accident analysis code. It employs a domain decoupling method for parallel computation. The parallel processing efficiency is over 60% and the speed-up ratio is about 40 in the 64-CPU calculations with over 1,000,000 cells in total. Outline of PLASHY-CRT is as follows:

(a) Coordinate	3D Cartesian/Cylindrical
(b) Fluid	Single-phase incompressible
(c) Basic equations	Mass and momentum conservation and Energy conservation equation
(d) Auxiliary equations	Heat conduction equation and mass transfer equation
(e) Turbulence model	k-e two-equation model or Large eddy simulation (LES)
(f) Numerical method	Finite differential method
(g) Solution scheme	SMAC method
(h) Difference scheme in time	Euler Explicit or RRK(2) or Adams-Bashforth method
(i) Difference scheme in space	1st-order upwind or QUICK or 3rd-order upwind or 2nd-order central or 4th-order central difference scheme
(j) Matrix solver	ICCG method
(k) porous body	Available
(l) Parallelization	Domain decoupling method

10.5.3 Survey Studies

Because of the blind benchmark, survey study was necessary for selecting inlet/outlet boundary conditions, convection term differencing scheme, turbulence model, and computational grid. The brief explanations are as follows.

10.5.3.1 Inlet/outlet condition

The values of the inlet velocity and temperature at the point A1 of the cold leg, shown in Figure 10-27, were obtained form the digitized flow rate data in the MS Excel file provided and set as time-dependent table-type data. The radial and azimuthal distributions were neglected, and thus flat and uniform distributions were assumed. Elevation of the outlet boundary was selected at the middle part of the core to reduce the computational grid numbers. The free outflow boundary condition was adopted.

10.5.3.2 Resistance plate

Two multi-hole plates are installed on the bottom of the core (see Figure 10-27). These might cause a significant pressure loss. These were modeled as a local resistance thin plate in the calculations. Total pressure drop from bottom of the vessel to the outlet at steady state was set at 1000(Pa) for Test-A and 1200(Pa) for Test-B. The value of the resistance was estimated form the parameter survey study. Effects of flaps were also considered.

10.5.3.3 Downcomer-to-core heat transfer

In the early stages, when cold water came into the downcomer region, water in the core was still hot. Therefore, heat transfer from the hot water in the core region to the cold water in the downcomer was expected. To evaluate effects of the heat transfer, survey calculations with the coarser mesh (about 30,000) were carried out. However, very small effects were found for the temperature changes in the downcomer region, and therefore it was neglected

10.5.3.4 Turbulence model

The value of the averaged Reynolds number at the downcomer region was expected to change from 0 to over 10,000 during the transient. The standard k-e model was employed at first with the coarser mesh (about 30,000), however the result was rather poor. Therefore, we tried to use no turbulent model on the assumption that the numerical diffusion generated from the differencing scheme applied to the convection term of the momentum equation could provide an "equivalent" turbulent mixing (diffusion). Although there was no physical basis for this assumption, turbulence was often accounted for well in this way. (e.g. Kawamura and Kuwabara 1984)

10.5.3.5 Convection term differencing scheme

The method of differentiating the convection term of the momentum equation is a very important issue because the amount of the numerical diffusion depends on the differencing scheme. The calculated results by using the first upwind, the second upwind Computational grid

In order to evaluate effects of mesh size, calculation with finer grid (about 300,000), was performed. Although the small differences between the two were observed, the calculation results were qualitatively the same. From these results, the fine grid system was employed for the final calculation.

10.5.4 Benchmark analysis

10.5.4.1 Model configuration

The cold leg, reactor vessel and part of the hot leg were modeled in the cylindrical coordinate system. Figure 10-29 shows the computational grid. The total number of cells of the fine grid was 273,945. The curved walls of the cold/hot leg and the lower plenum were precisely modeled by using the porous body approximation, as shown in Figure 10-30.

10.5.4.2 Material property

For accurate calculation, water density and viscosity were considered as variables of temperature. The explicit forms of them are as follows:

$$\text{Density} = 1000.8 + 2.591\times10^{-2}\,T - 6.046\times10^{-3}\,T^2 + 1.595\times10^{-5}\,T^3 \quad [kg/m^3],$$

$$\text{Viscosity} = 1.787\times10^{-3} - 5.4851\times10^{-5}\,T + 9.598\times10^{-7}\,T^2 - 8.696\times10^{-9}\,T^3 + 3.059\times10^{-11}\,T^4 \quad [Pa.s],$$

where T[°C.] denotes water temperature. Specific heat and thermal conductivity were simply set as,

Specific heat = 4174.0 [J/kg],
Thermal conductivity = 0.6114 [W/m.K],

(QUICK) and the third upwind scheme with the coarser mesh (about 30,000) were

compared and shown in the following Figure 10-28.

First, the result of the third upwind scheme was different from those of the other two schemes and seemed strange. This was perhaps due to numerical instability that the scheme had. Second, the first upwind was stable but had too large a numerical scheme to get the real flow field. Consequently, we selected the QUICK scheme.

10.5.4.3 Test A results

At about 13 seconds, the inlet flow rate increased and reached approximately 7 liters/min (the corresponding velocity is approximately 1.535 m/s) at about 30 seconds. On the other hand, the temperature, approximately 73 °C., decreased steeply at about 15 seconds and reached the lowest value, approximately 12 °C., about 20 seconds.

The calculated transient behavior in the vessel is shown in Figure 10-31. At 20 seconds, the cold water reached the downcomer region and impinged to the shroud wall. Some of the cold water flowed downward and rest took a roundabout way to the opposite side. At 32 seconds, the inlet flow rate became the maximum value, 7 liters/min, and the cold water filled the downcomer region. However, some part of the region, under the clod leg, was still warm because of upward flow from the lower plenum.

Figure 10-32 and

Figure 10-33 show the temperature change at several TCs locations. The temperatures of almost every point decreased steeply at around 20 seconds. This means the front of the cold water reached these TCs at that time. The difference between the coarse (about 30,000) and the fine results (about 300,000) is small.

10.5.4.4 Test B results

Test B was almost the same transient test as Test A, except the cold water came from the Steam Generator (SG) instead of the external tank. Therefore, the same grid system was employed. The cold water was swept from the bottom of the SG by hot water. As a result, the temperature decreased and then increased again. Figure 10-34 and Figure 10-35 show the transient behavior of Test B. Although the flow pattern change is almost the same as Test A, the temperature in the vessel is quite different because of the above reason.

10.5.5 Reference

(1) Ujita, H. *et al*., "Development of severe accident analysis code 'SAMPSON' for IMPACT project", *J. Nucl. Sci. Technol.*, Vol. 36, No. 11, pp.1076- (1999).
(3) A. Wambecq, "Rational Runge-Kutta method for solving systems of ordinary differential equations", Computing, 20, pp.333-342 (1978).

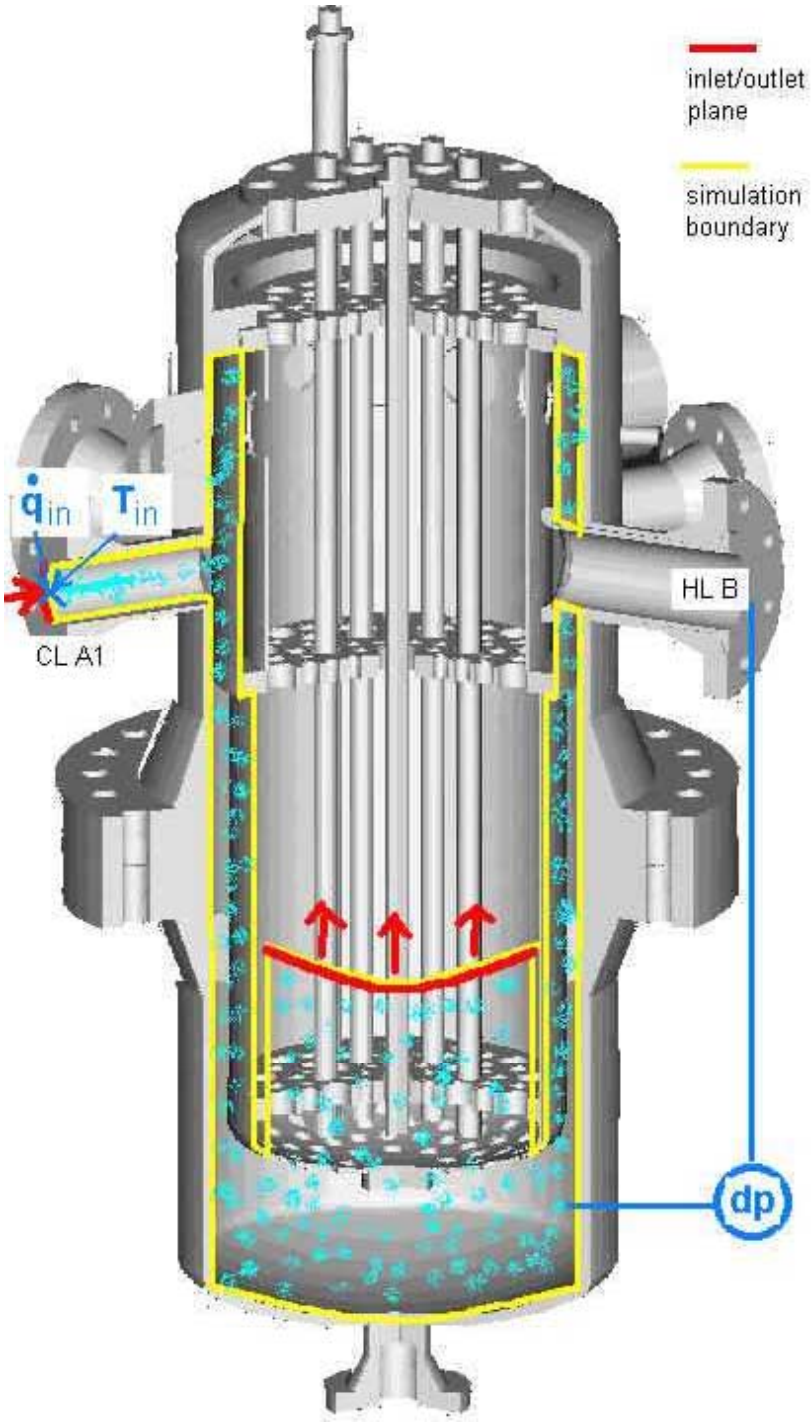


Figure 10-27. Schematic of PWR test reactor vessel

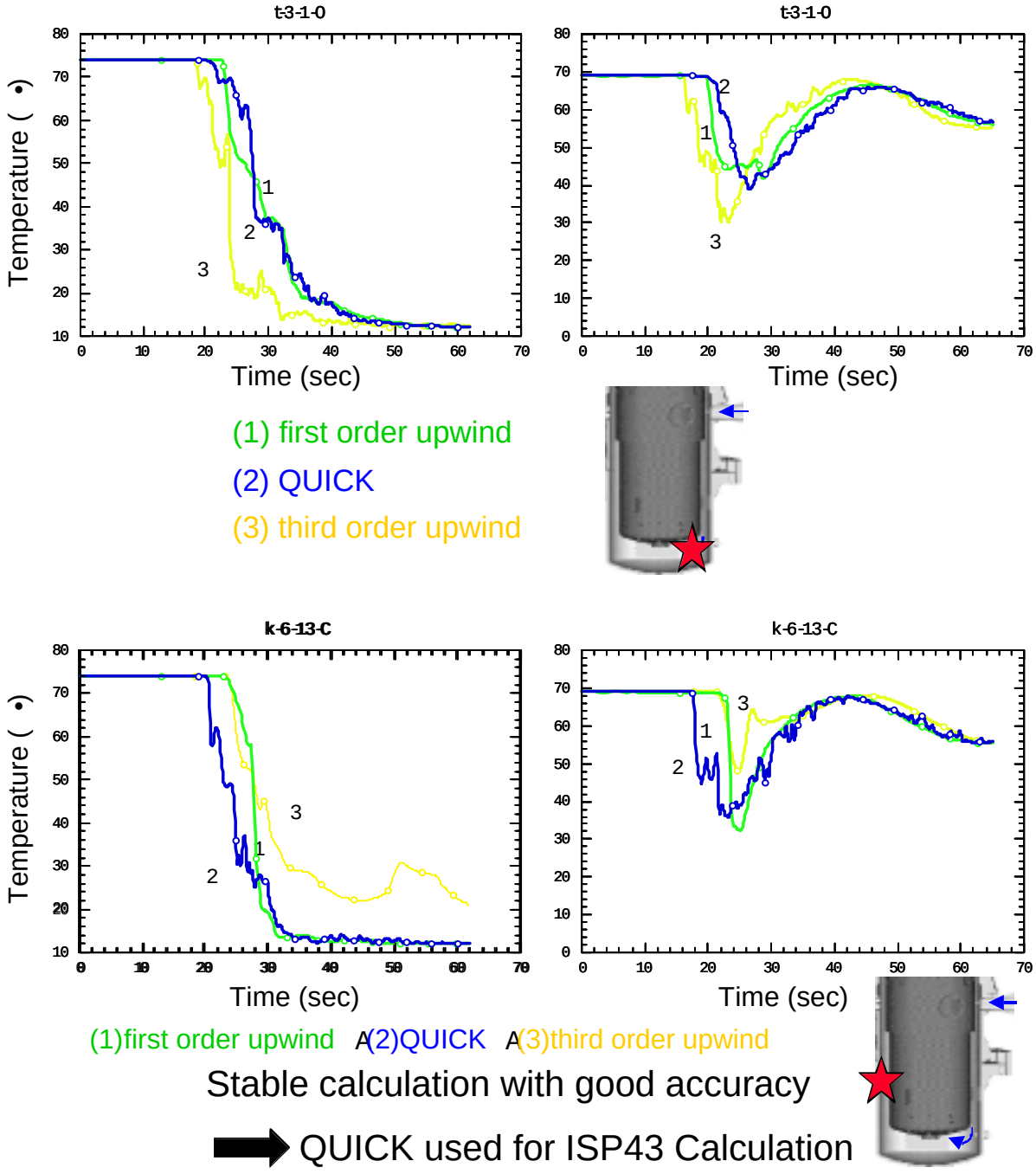


Figure 10-28. Survey of convection term differencing methods

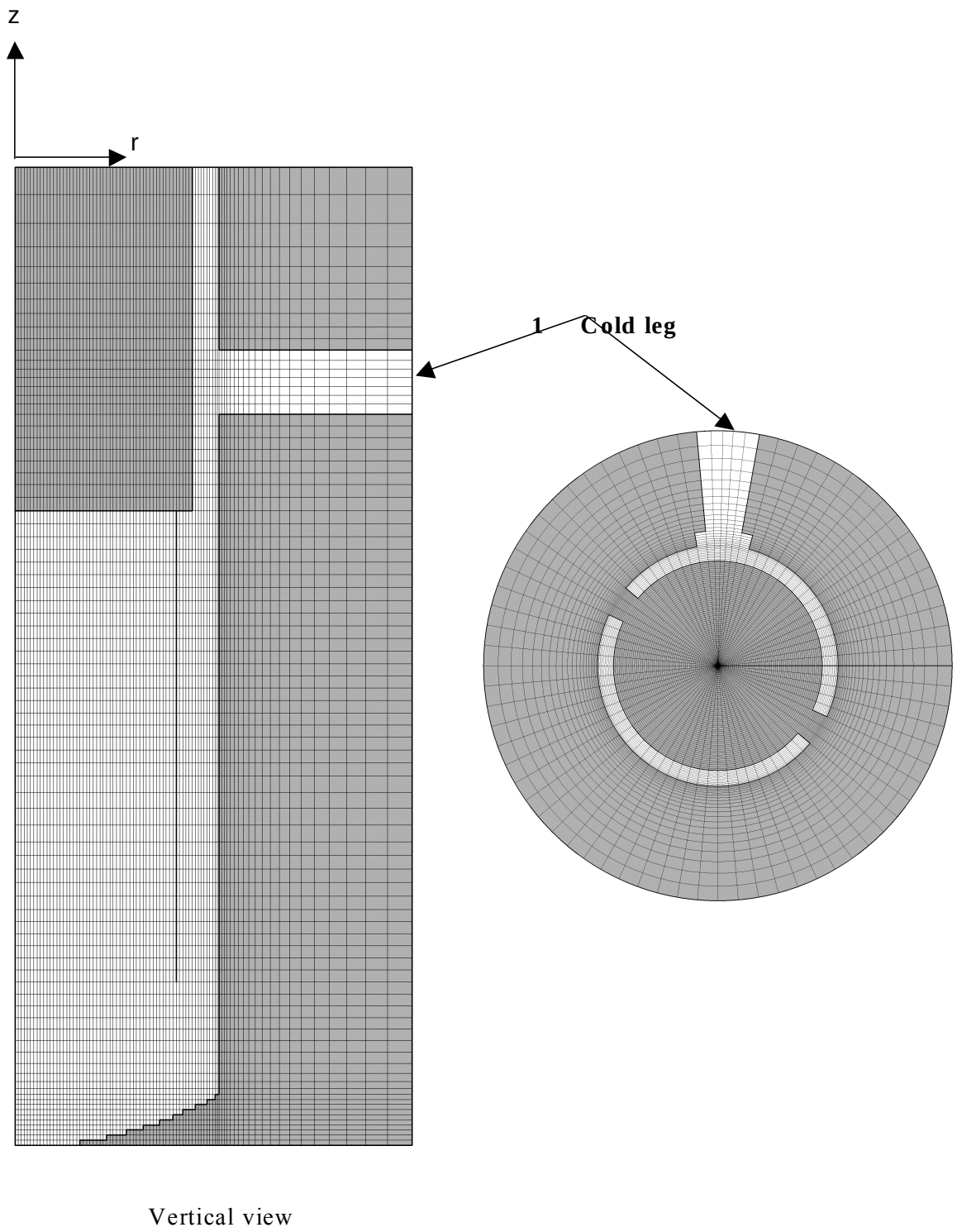


Figure 10-29. Computational grid for benchmark analysis

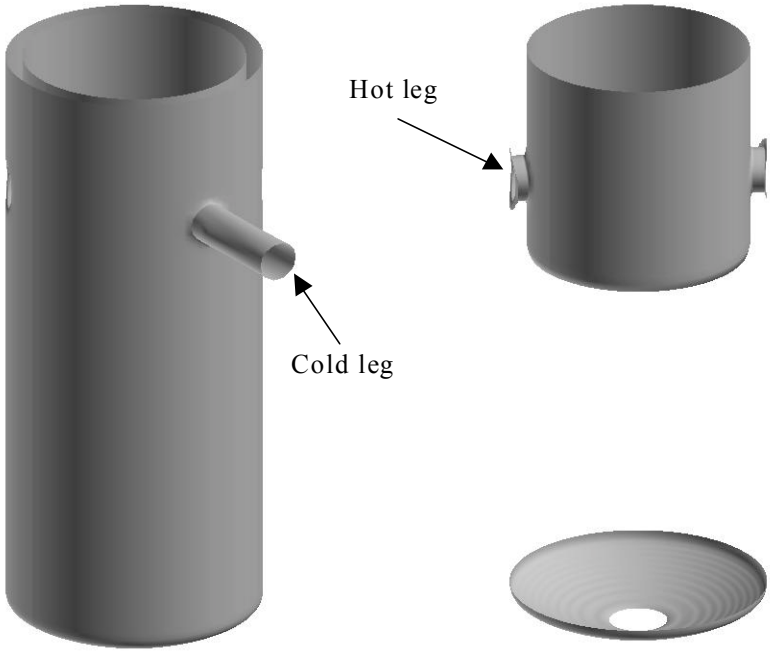


Figure 10-30. Geometrical model of the test vessel by porous body approximation

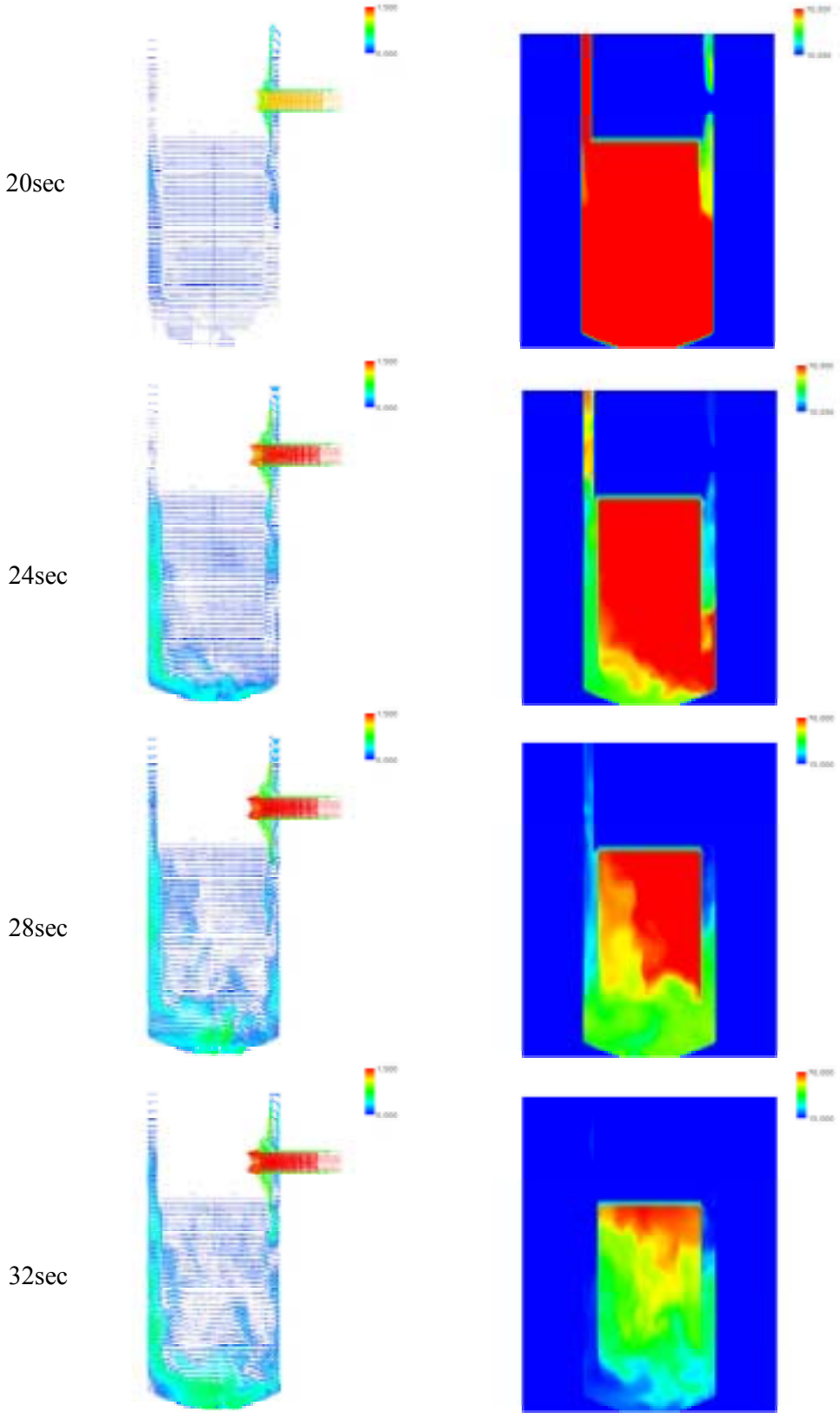


Figure 10-31. Series of velocity vectors and temperature contour in the vessel (Test A)

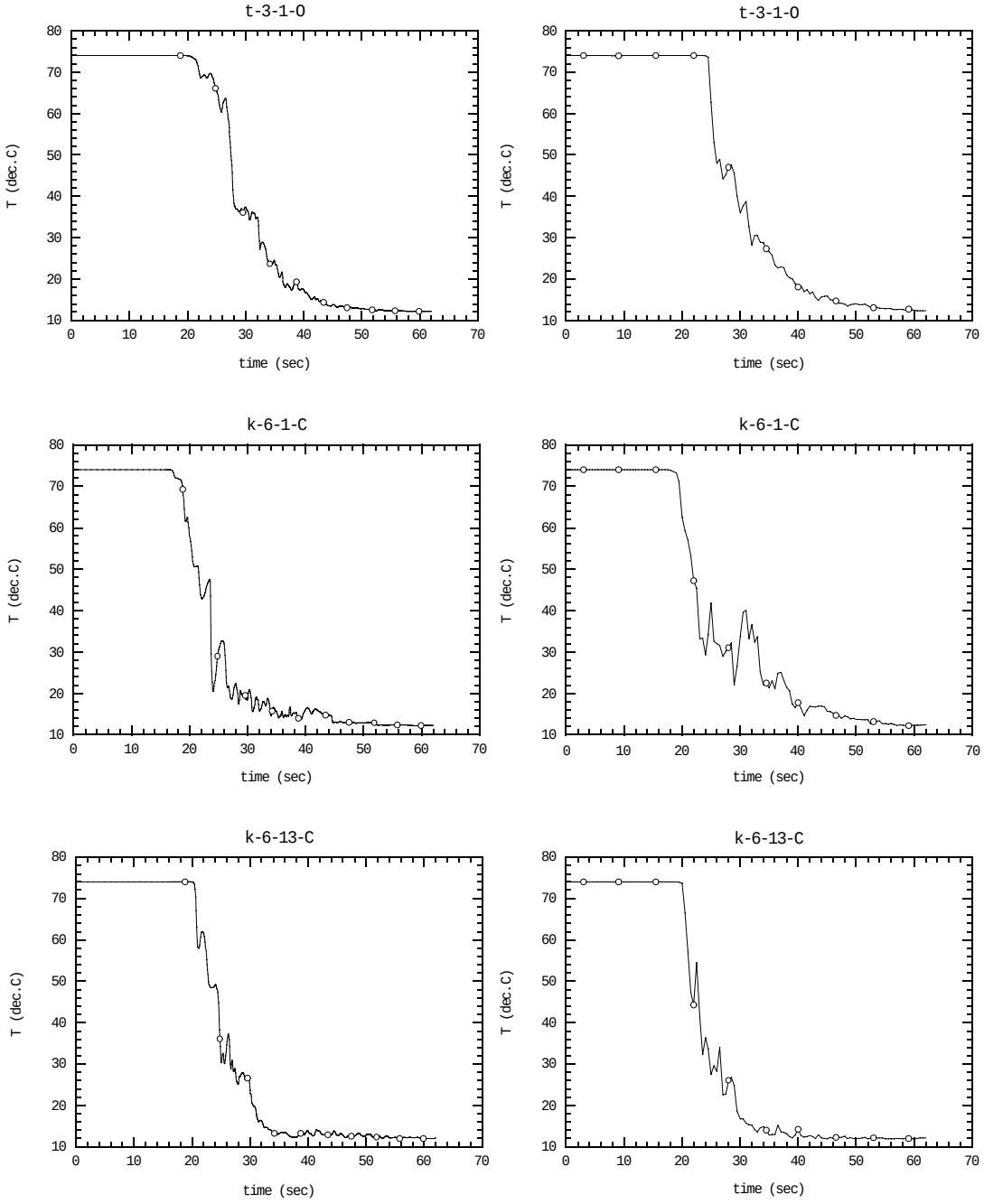


Figure 10-32. Temperature change during the transient, levels 3 and 6 (Test-A)

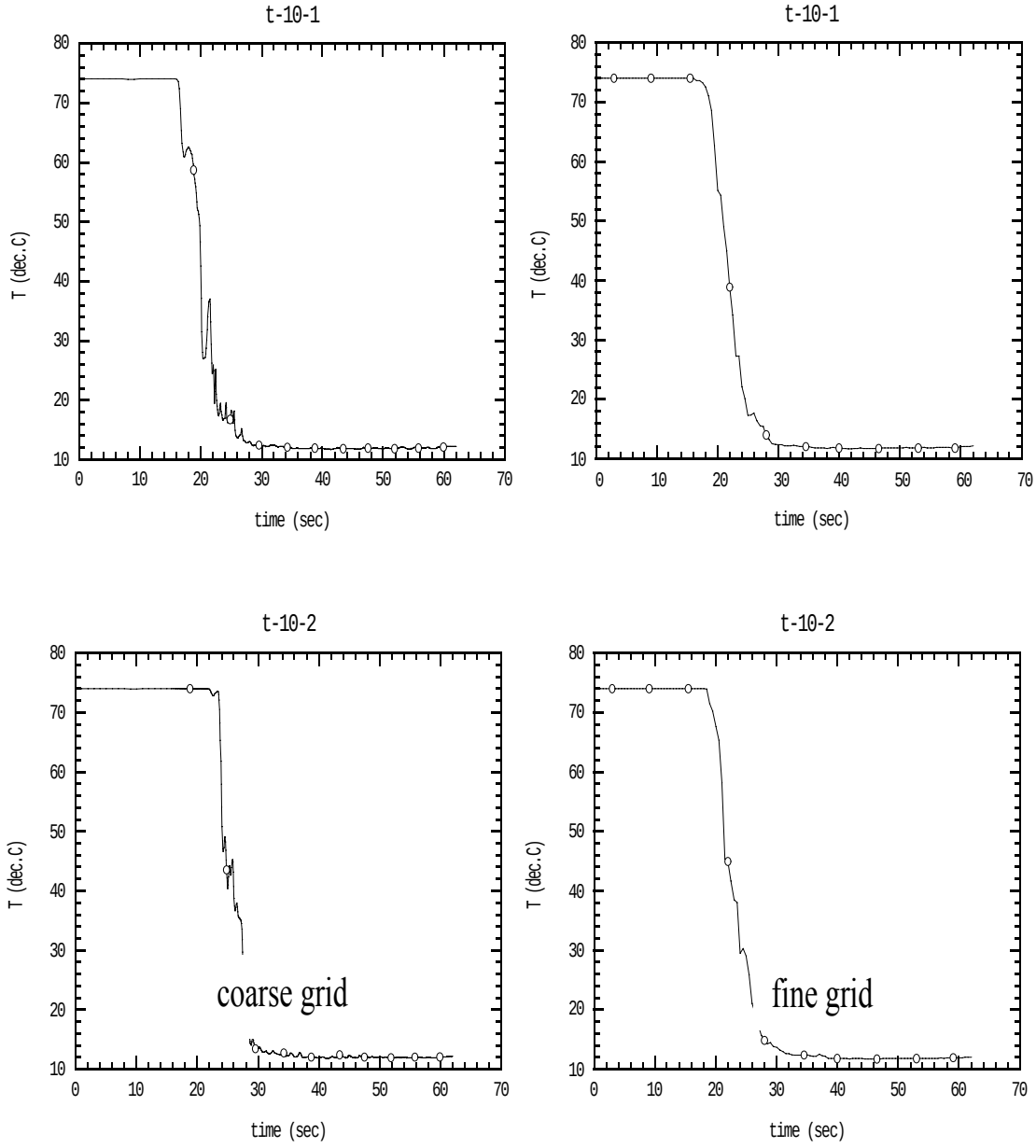


Figure 10-33. Temperature change during the transient, level 10 (Test-A)

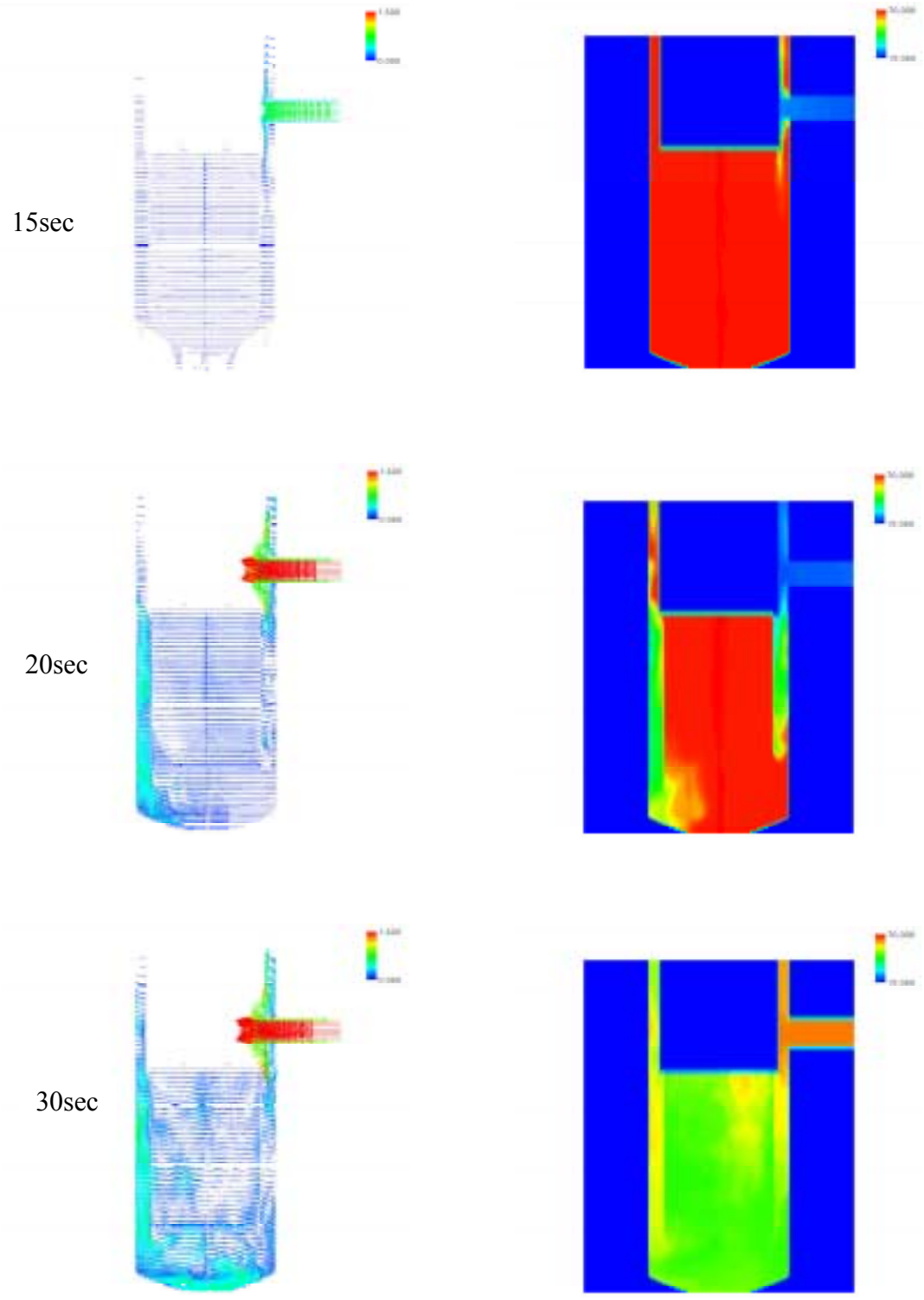


Figure 10-34. Series of velocity vectors and temperature contour in the vessel, 15-30 seconds (Test B)

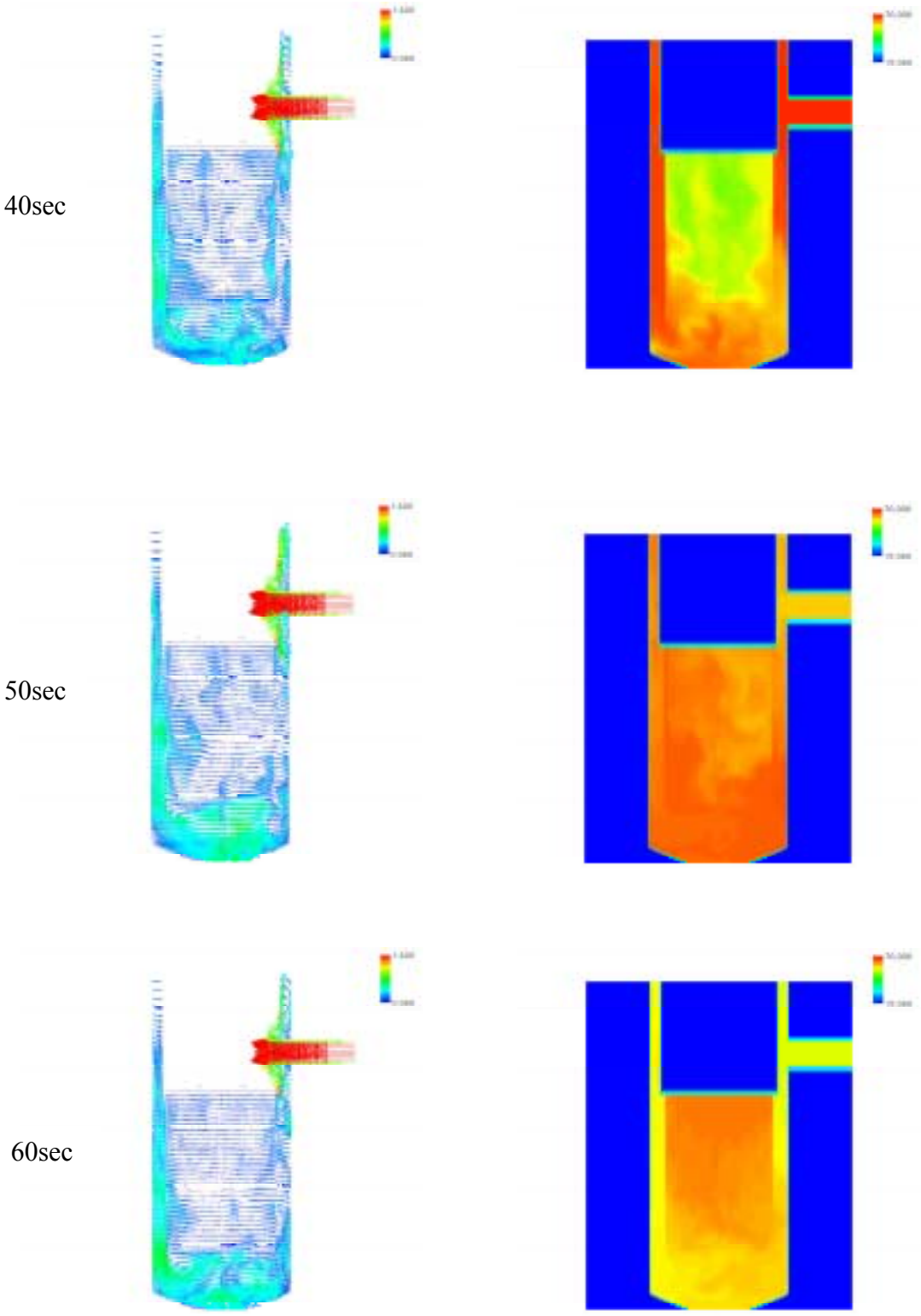


Figure 10-35. Series of velocity vectors and temperature contours in the vessel, 40-60 seconds (Test B)

10.6 Vattenfall Utveckling AB

This appendix is a short summary of the report: Andreasson P. & Hemström B. "Simulation of rapid boron-dilution transient (OECD/CSNI ISP Nr. 43)". Report nr. US 00:10.

When using CFD for complex processes computational resources are limited. A computational effort of around one cpu-month for one case using one processor was decided to be endurable for these simulations. One has to find the optimal balance between spatial and temporal resolution, model and numerical complexity and extent of the computational domain.

The following discussion gives motivations for some of our model choices.

10.6.1 Computational domain

The computational domain includes the entrance pipe downstream from where the measured inlet profiles are given. The outlet boundary is positioned 0.44 m above the core entrance. This placing of the outlet is believed to be sufficiently far downstream not to significantly affect the flow in the downcomer.

10.6.2 Grid

A total of about 133 000 cells (70% hexahedrals, all in the downcomer, and 30% tetrahedrals) was considered to be optimal. The cold leg (inlet) and the downcomer are prioritised regions in the measurements. The spatial resolution is therefore finest in these parts. However, a finer resolution in all parts of the reactor vessel would have been desirable. Small flow structures in the downcomer (near the entrance and the annular void widening) will have a poor resolution with the grid used. Also finer details of the flow in the lower plenum are likely to be lost. Fully grid independent solutions are therefore not to be expected.

10.6.3 Time-step

Ideally the CFL (Courant-Friedrichs-Lewy) number should be small in all regions, in the order of or less than one if possible. Since velocity is highest and the grid finest near the entrance of the cold leg into the reactor vessel, this is the critical region. The time-step corresponding to a CFL number of 1.0 is around 0.001 sec. However, such a fine temporal resolution was not possible to use with the chosen grid and computational effort. Instead a time-step of 0.01 sec was used.

To investigate the influence of the choice of time-step a simulation with a time-step of 0.02 sec was conducted for the first 40 sec of case A. In Figure 10-36 the simulations with the two different time-steps are compared for a level of $z = 0.616$ m and tangential angles 0º, 120º, and 180 º (monitor points k-4-1-C, k-4-9-C, and k-4-13-C respectively).

As seen in Figure 10-36 there is a difference between the results for the two different time-steps, although the overall trends are similar. There are differences in details in all parts of the reactor vessel, quantitatively as in Figure 10-36, or less. Another important observation was that for $\Delta t = 0.02$ sec the temporal spectrum of the temperature variation (and thereby also the dominant frequency) is exactly the same as for $\Delta t = 0.01$ sec. It is

not surprising that instabilities display different features for different time-steps. A small difference in the perturbation (such as imposed by a different time-step) grows to display large differences in the variation from the mean temperature. However, the fact that the statistical quantities of the variation are equal implies that the mechanism causing these variations is time-step independent. It cannot be excluded, however, that there are other features (other than the variation around the mean value) which display a time-step dependence. The somewhat delayed temperature drop at time 30 - 31 s at monitor point k-4-1-C seems to imply this.

10.6.4 Numerical schemes

Second order schemes are used. The mixing of a temperature slug is very sensitive to the diffusional strength of the calculation. It is therefore important to avoid excessive numerical diffusion.

10.6.5 Turbulence models

It is hardly motivated to use higher order turbulence models. It is better to spend computational efforts on spatial and temporal resolution. What is "industrial standard" (i.e. a two-equation turbulence model (here the RNG k-ε model) and Reynolds extended analogy for heat) is therefore used.

For wall boundaries the momentum transfer and near-wall turbulent quantities were modelled by so called wall functions. For momentum, k and ε the nonequilibrium wall function by Kim & Choudhury (1995) was used. For equilibrium conditions at high Reynolds number conditions in the wall-adjacent cells this wall function conforms to the standard "logarithmic law" for hydrodynamically smooth conditions. However, low-Reynolds number flow conditions and nonequilibrium conditions (production of k does not equal destruction ε) can be anticipated in many regions. The model by Kim & Choudhury (1995) attempts to compensate for these conditions by relating the momentum transfer to k (uses $k^{1/2}$ as velocity scale instead of friction velocity as in the standard log-law) and solve for conservation of k also in the wall-adjacent cells. The production of k and ε are prescribed (varies with k and wall distance).

10.6.6 Core inlet plates and core

The holes in the core entrance plates are not modelled individually. The pressure drops are modelled using a uniformly distributed resistance. This approximation is believed not to significantly effect the flow field in the downcomer.

The resistance in the core region is modelled using a distributed resistance.

10.6.6.1 Buoyancy influence

Buoyant influence was, at the time of model set-up, believed to be negligible. It has, however, later been shown that this is not the case. A simulation for Case A with buoyancy forces modelled has later been performed. Figure 10-37 shows the temperature field at level 4 after 24 seconds for this simulation. At this time only part of level 4 are affected by the cold water plug. Figure 10-38 shows the temperature field at t=24 seconds when the buoyancy force is not modelled, i.e. as in the transmitted simulation. The

temperature fields differ, although the coldest temperatures are found at approximately 120 degrees from the inlet for both cases. As can be seen in Figure 10-39, which shows temperatures as a function of azimuthal angle at the same level and time, this is also the case for the concentration measurements in the visualisation loop at University of Maryland.

10.6.6.2 Heat transfer to the walls

Heat transfer to walls is believed to be negligible.

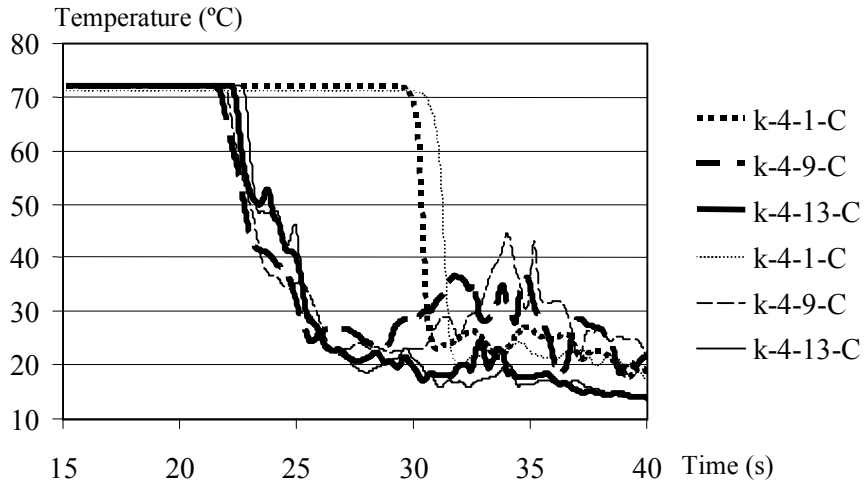


Figure 10-36. Comparison of predictions with two different time-steps (thicker curves are for Dt = 0.01 s, finer curves are for Dt = 0.02 s)

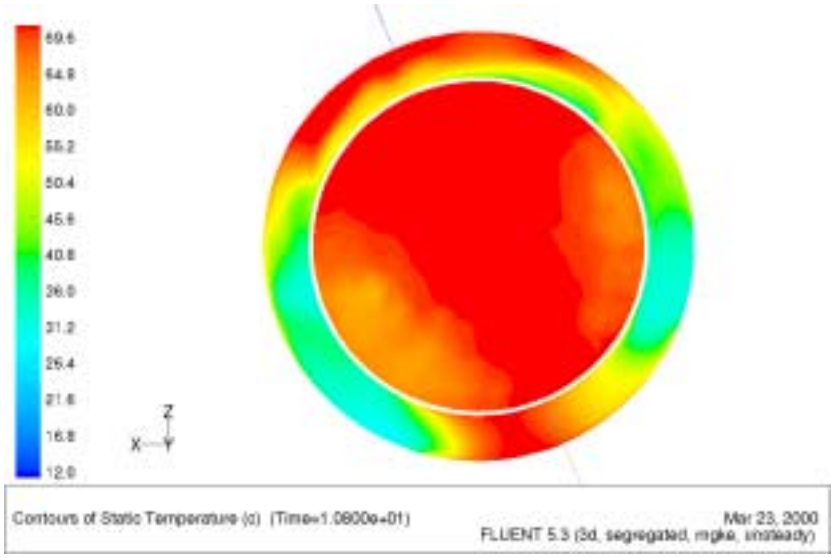


Figure 10-37. Case A. Buoyancy forces modeled. Contour plot at level 4, seen from above, at t=24 sec. The inlet is at 11:15.

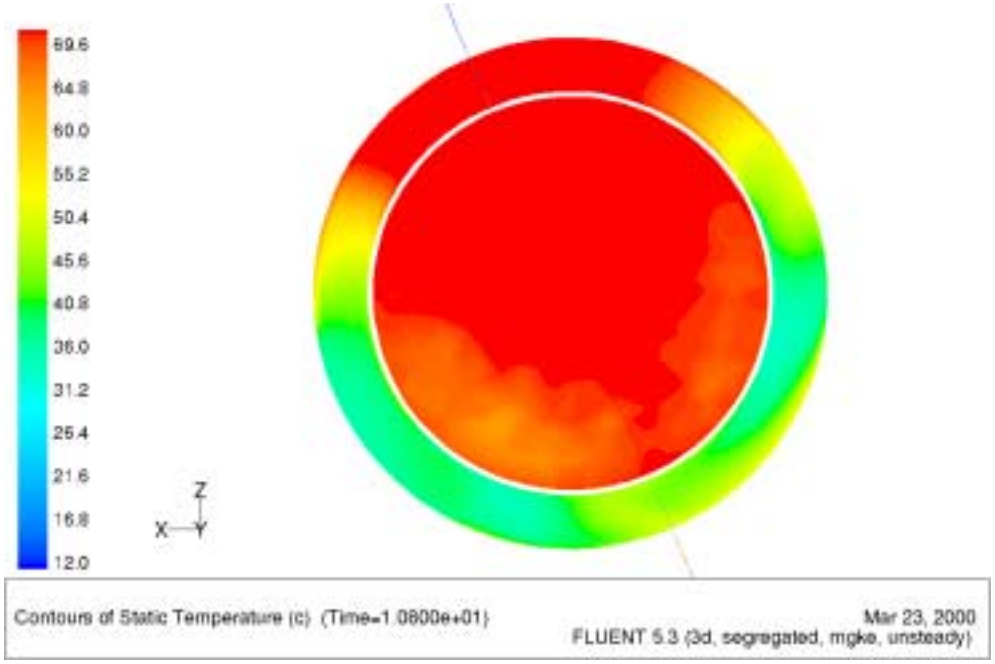


Figure 10-38. Case A. Buoyancy forces not modeled (transmitted simulation). Contour plot at level 4, seen from above, at t=24 sec. The inlet is at 11:15.

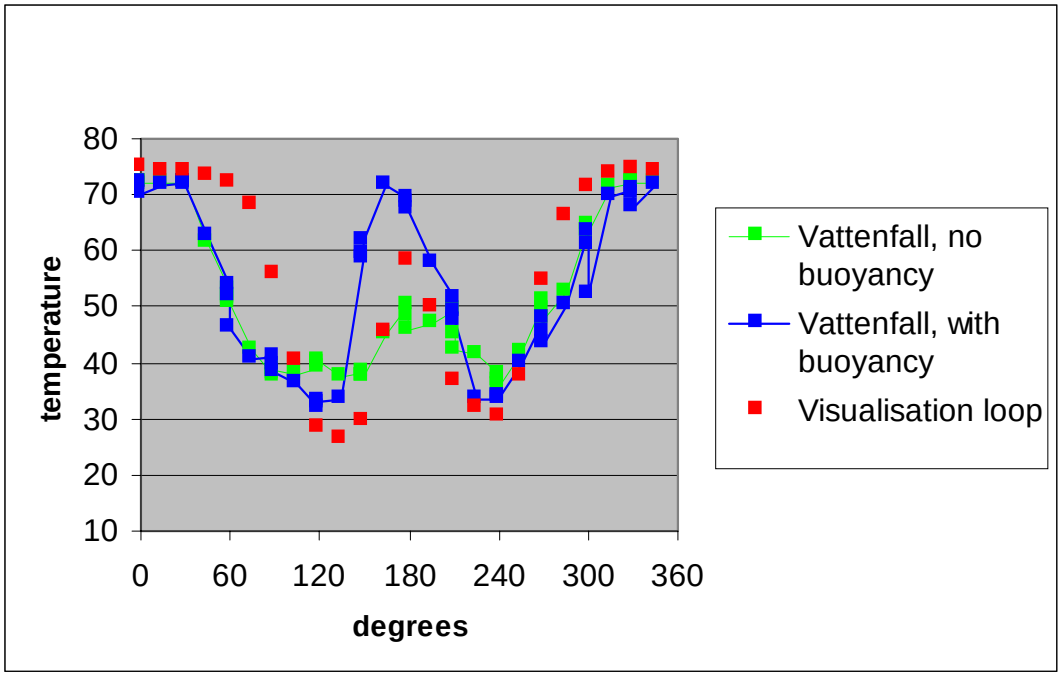


Figure 10-39. Case A: Calculated and measured temperatures at level 4 at t=24 sec as a function of angle