International Benchmark on Pressurised Water Reactor Sub-channel and Bundle Tests

Volume II: Benchmark results of phase I – Void distribution
International Benchmark on Pressurised Water Reactor Sub-channel and Bundle Tests

Volume II: Benchmark Results of Phase I: Void Distribution

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Foreword

The need to refine models for best-estimate calculations, based on good-quality experimental data, has been expressed in many recent meetings in the field of nuclear applications. The needs arising in this respect should not be limited to the currently available macroscopic methods but should be extended to next-generation analysis techniques that focus on more microscopic processes. One of the most valuable databases identified for the thermal-hydraulics modelling was developed by the Nuclear Power Engineering Corporation (NUPEC), Japan, which includes sub-channel void fraction and departure from nucleate boiling (DNB) measurements in a representative Pressurised Water Reactor (PWR) fuel assembly. Part of this database has been made available for this international benchmark activity entitled “NUPEC PWR Sub-channel and Bundle Tests (PSBT) benchmark”. This international project has been officially approved by the Japanese Ministry of Economy, Trade, and Industry (METI), the US Nuclear Regulatory Commission (NRC) and endorsed by the NEA.

The JNES has made available the PWR NUPEC database for the purposes of the PSBT international benchmark and has asked PSU to organise and conduct this benchmark activity. The PSBT benchmark was announced at the sixth and last workshop for the NEA/NRC Benchmark based on NUPEC BWR Full-size Fine-mesh Bundle Tests (BFBT-6), which was held on 27-28 April 2009 in University Park/State College, PA, US. The presentation of the new benchmark included the benchmark database, specification and schedule. Three PSBT workshops have taken place since then. The first workshop (PSBT-1) was hosted by the San Piero a Grado Nuclear Research Group, University of Pisa, Italy in April 2010. The second workshop (PSBT-2) was hosted by the Royal Institute of Technology (Kungliga Tekniska högskolan, KTH), Sweden in April 2011. The third and last workshop (PSBT-3) was held in conjunction with the 14th International Topical Meeting on Nuclear Reactor Thermal Hydraulics (NURETH-14), Toronto, Canada on 25 September 2011.

Volume I of the NEA/NRC PSBT Benchmark: Experimental Database and Final Problem Specifications was distributed to the benchmark participants and the NEA in January 2010. The PSBT was designed to provide a data set for evaluation of the abilities of existing sub-channel, system, and Computational Fluid Dynamics (CFD) thermal-hydraulics codes to predict void distribution and Departure from Nucleate Boiling (DNB) in PWRs under steady-state and transient conditions. The benchmark consists of seven exercises divided into two phases, a void distribution benchmark and a DNB benchmark. A specification was created to distribute experimental information to the participants. In addition, two studies were performed to determine the reliability of the experimental data.

Volume II of the NEA/NRC PSBT Benchmark: Benchmark Results for the Void Distribution Phase summarises the results of Phase I, which focused on an assessment and validation of void generation and distribution models in CFD codes; sub-channel thermal-hydraulic codes and system thermal-hydraulic codes.

Volume III of the NEA/NRC PSBT Benchmark: Benchmark Results for the Departure from Nucleate Boiling Phase summarises the results of Phase II, which was designed to assess and validate the models for DNB prediction under steady-state and transient PWR conditions.
Acknowledgements

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Table of contents

Executive summary ....................................................................................................................... 14

Chapter 1 Introduction .................................................................................................................. 15
  1.1 Introduction ..................................................................................................................................... 15
  1.2 Benchmark Objective ...................................................................................................................... 15
  1.3 Definition of Benchmark Phases ................................................................................................... 15
  1.4 Benchmark Team and Sponsorship .............................................................................................. 16
  1.5 Report Outline ................................................................................................................................. 18

Chapter 2 Void Distribution Benchmark ...................................................................................... 19
  2.1 General .............................................................................................................................................. 19
  2.2 Test Facility ....................................................................................................................................... 19
  2.3 Experimental Data Analysis ........................................................................................................... 33

Chapter 3 Comparative Analyses of Submitted Final Results for Void Distribution ...................... 42
  3.1 General .............................................................................................................................................. 42
  3.2 Exercise 1 – Steady-state Single Sub-channel ............................................................................. 42
  3.3 Exercise 2 – Steady-state Rod Bundle .......................................................................................... 48
  3.4 Exercise 3 – Transient Rod Bundle ................................................................................................ 55
  3.5 Exercise 4 – Pressure Drop ............................................................................................................. 59

Chapter 4 Conclusion .................................................................................................................... 61

Bibliography .................................................................................................................................. 62

Appendix I: Phase I Exercise 1 Results ......................................................................................... 63

Appendix II: Phase I Exercise 2 Results ....................................................................................... 105

Appendix III: Phase I Exercise 3 Results ....................................................................................... 131

Appendix IV: Phase I Exercise 4 Results ....................................................................................... 167

Appendix V: Participants’ Questionnaires ....................................................................................... 169
List of Figures

Figure 1.4-1 PSBT Benchmark Team ................................................................. 16
Figure 2.2-1 NUPEC Test Facility ................................................................. 19
Figure 2.2.1-1 Test Section for Central Sub-channel Void Distribution Measurement ........ 21
Figure 2.2.1-2 Cross-sectional View of Sub-channel Test Assembly ...................... 21
Figure 2.2.2-1 Test Section for Rod Bundle Void Distribution Measurement .......... 23
Figure 2.2.2-2 Radial Power Distribution A .................................................... 24
Figure 2.2.2-3 Radial Power Distribution B .................................................... 25
Figure 2.2.2.1-1 View of Simple Spacer Grid .................................................... 26
Figure 2.2.2.1-2 View of Non-Mixing Vane Spacer Grid ..................................... 27
Figure 2.2.2.1-3 View of Mixing Vane Spacer Grid ............................................ 27
Figure 2.2.2.2-1 Cross-sectional View of Heater Rod ....................................... 28
Figure 2.2.3-1 Void Fraction Measurement Procedure ....................................... 30
Figure 2.2.3-2 Relation Between Chordal and CT Averaged Densities (for S1) ....... 32
Figure 2.3.1-1 Deviation of Measured Void Fraction from Recalculated Void Fraction .... 34
Figure 2.3.2-1 Deviation of Measured Quality from Recalculated Quality for Test Series 1 and 2 ...... 35
Figure 2.3.2-2 Deviation of Measured Quality from Recalculated Quality for Test Series 5 ...... 36
Figure 2.3.2-3 Deviation of Measured Quality from Recalculated Quality for Test Series 6 ...... 36
Figure 2.3.2-4 Deviation of Measured Quality from Recalculated Quality for Test Series 7 ...... 37
Figure 2.3.2-5 Deviation of Measured Quality from Recalculated Quality for Test Series 8 ...... 37
Figure 2.3.3-1 Illustrations of Chordal Measurements Taken at High Void Fractions ....... 38
Figure 2.3.3-2 Illustration of Chordal Measurements Taken at Low Void Fractions .......... 38
Figure 2.3.3-3 Illustration of Mask “Shift” Effect ................................................. 39
Figure 2.3.4-1 Temperature Shift for Test Case 5T (TI) ....................................... 39
Figure 2.3.4-2 Shift in Void Fraction for Test Case 5T (TI) .................................... 40
Figure 2.3.4-3 Temperature Shift for Test Cases 6T (TI) and 7T (TI) ..................... 40
Figure 2.3.4-4 Temperature Shift for Test Cases 11T (TI) and 12T (TI) .................. 41
Figure 3.2.4-1 Void Fraction Error by Test Series ............................................ 46
Figure 3.2.4-2 Void Fraction Standard Deviation by Test Series ......................... 47
Figure 3.3.4-1 Test Series 5 Void Fraction Error ............................................. 51
Figure 3.3.4-2 Test Series 5 Void Fraction Standard Deviation .......................... 52
Figure 3.3.4-3 Test Series 6 Void Fraction Error ............................................. 52
Figure 3.3.4-4 Test Series 6 Void Fraction Standard Deviation .......................... 53
Figure 3.3.4-5 Test Series 7 Void Fraction Error ............................................. 53
Figure 3.3.4-6 Test Series 7 Void Fraction Standard Deviation .......................... 54
Figure 3.3.4-7 Test Series 8 Void Fraction Error ............................................. 54
Figure 3.3.4-8 Test Series 8 Void Fraction Standard Deviation ..................................................... 55
Figure 3.4.1-1 Variation of Properties for Test Case 5T (Power Increase) ........................................ 56
Figure 3.4.1-2 Variation of Properties for Test Case 5T (Flow Reduction) ........................................ 57
Figure 3.4.1-3 Variation of Properties for Test Case 5T (Depressurisation) .................................... 57
Figure 3.4.1-4 Variation of Properties for Test Case 5T (Temperature Increase) ............................ 58
Figure AI-1 Test Series 1 Density Results ....................................................................................... 63
Figure AI-2 Test Series 2 Density Results ....................................................................................... 63
Figure AI-3 Test Series 3 Density Results ....................................................................................... 63
Figure AI-4 Test Series 4 Density Results ....................................................................................... 64
Figure AI-5 Test Series 1 Void Fraction (Calculated vs. Measured) Results ................................... 65
Figure AI-6 Test Series 1 Void Fraction (Calculated vs. Recalculated) Results .............................. 66
Figure AI-7 Test Series 2 Void Fraction (Calculated vs. Measured) Results .................................... 67
Figure AI-8 Test Series 2 Void Fraction (Calculated vs. Recalculated) Results .............................. 68
Figure AI-9 Test Series 3 Void Fraction (Calculated vs. Measured) Results .................................... 69
Figure AI-10 Test Series 3 Void Fraction (Calculated vs. Recalculated) Results ............................. 70
Figure AI-11 Test Series 4 Void Fraction (Calculated vs. Measured) Results .................................... 71
Figure AI-12 Test Series 4 Void Fraction (Calculated vs. Recalculated) Results ............................. 72
Figure AI-13 Test Series 1 Thermal Equilibrium Quality (Calculated vs. Measured) Results ............ 73
Figure AI-14 Test Series 1 Thermal Equilibrium Quality (Calculated vs. Recalculated) Results ......... 73
Figure AI-15 Test Series 2 Thermal Equilibrium Quality (Calculated vs. Measured) Results .......... 74
Figure AI-16 Test Series 2 Thermal Equilibrium Quality (Calculated vs. Recalculated) Results ......... 74
Figure AI-17 Test Series 3 Thermal Equilibrium Quality (Calculated vs. Recalculated) Results ...... 75
Figure AI-18 Test Series 4 Thermal Equilibrium Quality (Calculated vs. Recalculated) Results ...... 75
Figure AI-19 Axial Void Distribution Results of Run 1.2211 ........................................................... 78
Figure AI-20 Axial Void Distribution Results of Run 1.2223 ........................................................... 78
Figure AI-21 Axial Void Distribution Results of Run 1.2237 ........................................................... 79
Figure AI-22 Axial Void Distribution Results of Run 1.4326 ........................................................... 79
Figure AI-23 Axial Void Distribution Results of Run 1.4325 ........................................................... 80
Figure AI-24 CT Image of Test Case 1.1222 ................................................................................... 80
Figure AI-25 STAR-CD (PSI) Image of Test Case 1.1222 ................................................................. 81
Figure AI-26 NEPTUNE (EDF) Image of Test Case 1.1222 ............................................................. 81
Figure AI-27 CT Image of Test Case 1.1223 ................................................................................... 81
Figure AI-28 STAR-CD (PSI) Image of Test Case 1.1223 ................................................................. 82
Figure AI-29 NEPTUNE (EDF) Image of Test Case 1.1223 ............................................................. 82
Figure AI-30 CT Image of Test Case 1.2221 ................................................................................... 82
Figure AI-31 STAR-CD (PSI) Image of Test Case 1.2221 ................................................................. 83
Figure AI-32 NEPTUNE (EDF) Image of Test Case 1.2221 ............................................................. 83
Figure AI-33 CT Image of Test Case 1.2223 ................................................................................... 83
Figure AI-34 STAR-CD (PSI) Image of Test Case 1.2223 ................................................................. 83
Figure AI-35 NEPTUNE (EDF) Image of Test Case 1.2223 ............................................................. 84
Figure AI-36 CT Image of Test Case 1.2422 ................................................................................... 84
Figure AI-37 STAR-CD (PSI) Image of Test Case 1.2422 ................................................................. 85
NEA/NSC/R(2015)4

Figure AI-38 NEPTUNE (EDF) Image of Test Case 1.2422 .............................................................. 85
Figure AI-39 CT Image of Test Case 1.2423 ................................................................................... 85
Figure AI-40 STAR-CD (PSI) Image of Test Case 1.2423 ................................................................. 86
Figure AI-41 NEPTUNE (EDF) Image of Test Case 1.2423 .............................................................. 86
Figure AI-42 CT Image of Test Case 1.4311 ................................................................................... 86
Figure AI-43 NEPTUNE (EDF) Image of Test Case 1.4311 .............................................................. 87
Figure AI-44 CT Image of Test Case 1.4312 ................................................................................... 87
Figure AI-45 STAR-CD (PSI) Image of Test Case 1.4312 ................................................................. 87
Figure AI-46 NEPTUNE (EDF) Image of Test Case 1.4312 .............................................................. 88
Figure AI-47 CT Image of Test Case 1.5221 ................................................................................... 88
Figure AI-48 NEPTUNE (EDF) Image of Test Case 1.5221 .............................................................. 88
Figure AI-49 CT Image of Test Case 1.5222 ................................................................................... 89
Figure AI-50 NEPTUNE (EDF) Images of Test Case 1.5222 ............................................................. 89
Figure AI-51 CT Image of Test Case 1.6221 ................................................................................... 89
Figure AI-52 NEPTUNE (EDF) Image of Test Case 1.6221 .............................................................. 90
Figure AI-53 CT Image of Test Case 1.6222 ................................................................................... 90
Figure AI-54 NEPTUNE (EDF) Image of Test Case 1.6222 .............................................................. 90
Figure AI-55 CT Image of Test Case 2.1231 ................................................................................... 91
Figure AI-56 STAR-CD (PSI) Image of Test Case 2.1231 ................................................................. 91
Figure AI-57 NEPTUNE (EDF) Image of Test Case 2.1231 .............................................................. 91
Figure AI-58 CT Image of Test Case 2.1232 ................................................................................... 92
Figure AI-59 STAR-CD (PSI) Image of Test Case 2.1232 ................................................................. 92
Figure AI-60 NEPTUNE (EDF) Image of Test Case 2.1232 .............................................................. 92
Figure AI-61 CT Image of Test Case 2.1233 ................................................................................... 93
Figure AI-62 STAR-CD (PSI) Image of Test Case 2.1233 ................................................................. 93
Figure AI-63 NEPTUNE (EDF) Image of Test Case 2.1233 .............................................................. 93
Figure AI-64 CT Image of Test Case 2.3232 ................................................................................... 94
Figure AI-65 STAR-CD (PSI) Image of Test Case 2.3232 ................................................................. 94
Figure AI-66 NEPTUNE (EDF) Image of Test Case 2.3232 .............................................................. 94
Figure AI-67 CT Image of Test Case 2.3233 ................................................................................... 95
Figure AI-68 STAR-CD (PSI) Image of Test Case 2.3233 ................................................................. 95
Figure AI-69 NEPTUNE (EDF) Image of Test Case 2.3233 .............................................................. 95
Figure AI-70 CT Image of Test Case 2.4421 ................................................................................... 96
Figure AI-71 NEPTUNE (EDF) Image of Test Case 2.4421 .............................................................. 96
Figure AI-72 CT Image of Test Case 2.4422 ................................................................................... 96
Figure AI-73 STAR-CD (PSI) Image of Test Case 2.4422 ................................................................. 97
Figure AI-74 NEPTUNE (EDF) Image of Test Case 2.4422 .............................................................. 97
Figure AI-75 CT Image of Test Case 2.4551 ................................................................................... 97
Figure AI-76 STAR-CD (PSI) Image of Test Case 2.4551 ................................................................. 98
Figure AI-77 NEPTUNE (EDF) Image of Test Case 2.4551 .............................................................. 98
Figure AI-78 CT Image of Test Case 2.4552 ................................................................................... 98
Figure AI-79 STAR-CD (PSI) Image of Test Case 2.4552 ................................................................. 99
Figure AII-28 Test Series 6 Bundle-Averaged Thermal Equilibrium Quality – Lower Elevation...
124
Figure AII-29 Test Series 6 Bundle-Averaged Thermal Equilibrium Quality – Middle Elevation ...
125
Figure AII-30 Test Series 6 Bundle-Averaged Thermal Equilibrium Quality – Upper Elevation ...
125
Figure AII-31 Test Series 7 Bundle-Averaged Thermal Equilibrium Quality – Lower Elevation ...
126
Figure AII-32 Test Series 7 Bundle-Averaged Thermal Equilibrium Quality – Middle Elevation ...
126
Figure AII-33 Test Series 7 Bundle-Averaged Thermal Equilibrium Quality – Upper Elevation ...
127
Figure AII-34 Test Series 8 Bundle-Averaged Thermal Equilibrium Quality – Lower Elevation ...
127
Figure AII-35 Test Series 8 Bundle-Averaged Thermal Equilibrium Quality – Middle Elevation ...
128
Figure AII-36 Test Series 8 Bundle-Averaged Thermal Equilibrium Quality – Upper Elevation ...
128
Figure AII-37 Axial Void Distribution for Run 5.2332 ................................................................. 130
Figure AIII-1 Test Series 5T (Power Increase) – Lower Elevation Results ......................... 131
Figure AIII-2 Test Series 5T (Power Increase) – Middle Elevation Results ....................... 132
Figure AIII-3 Test Series 5T (Power Increase) – Upper Elevation Results ......................... 133
Figure AIII-4 Test Series 6T (Power Increase) – Lower Elevation Results ....................... 134
Figure AIII-5 Test Series 6T (Power Increase) – Middle Elevation Results ....................... 135
Figure AIII-6 Test Series 6T (Power Increase) – Upper Elevation Results ....................... 136
Figure AIII-7 Test Series 7T (Power Increase) – Lower Elevation Results ....................... 137
Figure AIII-8 Test Series 7T (Power Increase) – Middle Elevation Results ....................... 138
Figure AIII-9 Test Series 7T (Power Increase) – Upper Elevation Results ....................... 139
Figure AIII-10 Test Series 5T (Flow Reduction) – Lower Elevation Results ...................... 140
Figure AIII-11 Test Series 5T (Flow Reduction) – Middle Elevation Results ...................... 141
Figure AIII-12 Test Series 5T (Flow Reduction) – Upper Elevation Results ...................... 142
Figure AIII-13 Test Series 6T (Flow Reduction) – Lower Elevation Results ...................... 143
Figure AIII-14 Test Series 6T (Flow Reduction) – Middle Elevation Results ...................... 144
Figure AIII-15 Test Series 6T (Flow Reduction) – Upper Elevation Results ...................... 145
Figure AIII-16 Test Series 7T (Flow Reduction) – Lower Elevation Results ...................... 146
Figure AIII-17 Test Series 7T (Flow Reduction) – Middle Elevation Results ...................... 147
Figure AIII-18 Test Series 7T (Flow Reduction) – Upper Elevation Results ...................... 148
Figure AIII-19 Test Series 5T (Depressurisation) – Lower Elevation Results ...................... 149
Figure AIII-20 Test Series 5T (Depressurisation) – Middle Elevation Results ...................... 150
Figure AIII-21 Test Series 5T (Depressurisation) – Upper Elevation Results ...................... 151
Figure AIII-22 Test Series 6T (Depressurisation) – Lower Elevation Results ...................... 152
Figure AIII-23 Test Series 6T (Depressurisation) – Middle Elevation Results ...................... 153
Figure AIII-24 Test Series 6T (Depressurisation) – Upper Elevation Results ...................... 154
Figure AIII-25 Test Series 7T (Depressurisation) – Lower Elevation Results ...................... 155
Figure AIII-26 Test Series 7T (Depressurisation) – Middle Elevation Results ...................... 156
Figure AIII-27 Test Series 7T (Depressurisation) – Upper Elevation Results ...................... 157
Figure AIII-28 Test Series 5T (Temperature Increase) – Lower Elevation Results ............... 158
Figure AIII-29 Test Series 5T (Temperature Increase) – Middle Elevation Results .......... 159
Figure AIII-30 Test Series 5T (Temperature Increase) – Upper Elevation Results .......... 160
Figure AIII-31 Test Series 6T (Temperature Increase) – Lower Elevation Results .......... 161
Figure AIII-32 Test Series 6T (Temperature Increase) – Middle Elevation Results .......... 162
Figure AIII-33 Test Series 6T (Temperature Increase) – Upper Elevation Results ................. 163
Figure AIII-34 Test Series 7T (Temperature Increase) – Lower Elevation Results ............. 164
Figure AIII-35 Test Series 7T (Temperature Increase) – Middle Elevation Results .......... 165
Figure AIII-36 Test Series 7T (Temperature Increase) – Upper Elevation Results .......... 166
Figure AIV-1 Test Series 1 Pressure Drop Results ......................................................... 167
Figure AIV-2 Test Series 5 Pressure Drop Results .......................................................... 167
Figure AIV-3 Test Series 7T Pressure Drop Results .......................................................... 168
Figure AV.1.2-1 Cross-sectional Mesh Element Distribution for Mesh Levels 1-3 .............. 178
Figure AV.4.2-1 Vertical Flow Regime Map ........................................................................... 191
Figure AV.6.2-1 Cross-section view of grid level 1............................................................... 199
Figure AV.6.2-2 Cross-section view of grid level 2............................................................... 199
Figure AV.6.2-3 Cross-section view of grid level 3............................................................... 200
Figure AV.13.3-1 Diagram of 1/8 Symmetry ...................................................................... 242
List of Tables

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.3-1</td>
<td>PSBT Benchmark</td>
<td>15</td>
</tr>
<tr>
<td>1.4-1</td>
<td>List of Phase I Participants</td>
<td>17</td>
</tr>
<tr>
<td>2.2-1</td>
<td>Range of NUPEC PWR Test Facility Operating Conditions</td>
<td>20</td>
</tr>
<tr>
<td>2.2-2</td>
<td>Transient Parameters of NUPEC PWR Test Facility</td>
<td>20</td>
</tr>
<tr>
<td>2.2.1-1</td>
<td>Properties of Sub-channel Heating Elements</td>
<td>22</td>
</tr>
<tr>
<td>2.2.1-2</td>
<td>Assembly Data for Assemblies S1, S2, S3, S4</td>
<td>22</td>
</tr>
<tr>
<td>2.2.2-1</td>
<td>Assembly Data for Assemblies B5, B6, B7</td>
<td>24</td>
</tr>
<tr>
<td>2.2.2-2</td>
<td>Cosine Axial Power Distribution</td>
<td>25</td>
</tr>
<tr>
<td>2.2.2.1-1</td>
<td>Bundle Average Spacer Pressure Loss Coefficients</td>
<td>28</td>
</tr>
<tr>
<td>2.2.2.2-1</td>
<td>Properties of Heater Rods</td>
<td>28</td>
</tr>
<tr>
<td>2.2.3-1</td>
<td>Accuracy of Process Parameters in Void Distribution Measurement</td>
<td>31</td>
</tr>
<tr>
<td>2.2.3-2</td>
<td>Sources of Error for Void Distribution Measurement</td>
<td>32</td>
</tr>
<tr>
<td>2.2.3-3</td>
<td>Number of Gamma Ray Beams</td>
<td>33</td>
</tr>
<tr>
<td>2.2.3-4</td>
<td>Time Required to perform Void Fraction Measurements</td>
<td>33</td>
</tr>
<tr>
<td>3.1-1</td>
<td>Test Series for Void Fraction Measurements</td>
<td>42</td>
</tr>
<tr>
<td>3.2.1-1</td>
<td>Test Conditions for Steady-State Void Measurement Test Series 1</td>
<td>43</td>
</tr>
<tr>
<td>3.2.1-2</td>
<td>Test Conditions for Steady-State Void Measurement Test Series 2</td>
<td>43</td>
</tr>
<tr>
<td>3.2.1-3</td>
<td>Test Conditions for Steady-State Void Measurement Test Series 3</td>
<td>44</td>
</tr>
<tr>
<td>3.2.1-4</td>
<td>Test Conditions for Steady-State Void Measurement Test Series 4</td>
<td>44</td>
</tr>
<tr>
<td>3.2.2-1</td>
<td>Phase I Exercise 1 Participants and Code List</td>
<td>45</td>
</tr>
<tr>
<td>3.3.1-1</td>
<td>Test Conditions for Steady-State Void Measurement Test Series 5</td>
<td>48</td>
</tr>
<tr>
<td>3.3.1-2</td>
<td>Test Conditions for Steady-State Void Measurement Test Series 6</td>
<td>49</td>
</tr>
<tr>
<td>3.3.1-3</td>
<td>Test Conditions for Steady-State Void Measurement Test Series 7</td>
<td>49</td>
</tr>
<tr>
<td>3.3.1-4</td>
<td>Test Conditions for Steady-State Void Measurement Test Series 8</td>
<td>50</td>
</tr>
<tr>
<td>3.3.2-1</td>
<td>Phase I Exercise 2 Participants and Code List</td>
<td>50</td>
</tr>
<tr>
<td>3.4.1-1</td>
<td>Test Conditions for Transient Void Measurement Test Series 5T, 6T, 7T</td>
<td>56</td>
</tr>
<tr>
<td>3.4.2-1</td>
<td>Phase I Exercise 3 Participants and Code List</td>
<td>58</td>
</tr>
<tr>
<td>3.5.2-1</td>
<td>Phase I Exercise 4 Participants and Code List</td>
<td>60</td>
</tr>
<tr>
<td>AI-1</td>
<td>Results of Recalculation of Sub-channel-Averaged Void Fraction</td>
<td>76</td>
</tr>
<tr>
<td>AI-2</td>
<td>Results of Recalculation of Sub-channel-Averaged Thermal Equilibrium Quality</td>
<td>77</td>
</tr>
<tr>
<td>AI-1</td>
<td>Results of Recalculation of Bundle-Averaged Thermal Equilibrium Quality</td>
<td>129</td>
</tr>
<tr>
<td>AV.1.1-1</td>
<td>Studied configurations</td>
<td>174</td>
</tr>
<tr>
<td>AV.1.1-2</td>
<td>Summary of EARSM configurations</td>
<td>175</td>
</tr>
<tr>
<td>AV.1.2-1</td>
<td>Summary of meshes used</td>
<td>178</td>
</tr>
</tbody>
</table>
Table AV.4.2-1 RELAP5 Interfacial areas and heat transfer coefficients for vertical bubbly and slug flow regimes ................................................................. 191
Table AV.4.2-2 RELAP5-wall convective heat transfer ...................................................... 192
Table AV.4.2-3: RELAP5 -heat transfer correlations for a bundle, parallel flow only .......... 193
Table AV.4.2-4 RELAP5 -drift-flux void fraction correlations for vertical bubbly-slug flow .... 195
Table AV.6.2-1 Characteristics of the grids used in the simulations ...................................... 199
Table AV.9.3-1 Axial Nodalisation ...................................................................................... 218
Table AV.9.3-2 Axial Grid Locations .................................................................................. 219
Table AV.9.4-1 Axial Nodalisation ...................................................................................... 221
Table AV.9.4-2 Axial Grid Locations .................................................................................. 221
Table AV.11.2-1 – Geometric Parameters ........................................................................ 230
Table AV.11.3-1 – Geometric Parameters ......................................................................... 231
Table AV.11.4-1 Geometric Parameters ............................................................................ 233
Executive summary

This report summarised the first phase of the Nuclear Energy Agency (NEA) and the US Nuclear Regulatory Commission Benchmark based on NUPEC PWR Sub-channel and Bundle Tests (PSBT), which was intended to provide data for the verification of void distribution models in participants’ codes. This phase was composed of four exercises; Exercise 1: steady-state single sub-channel benchmark, Exercise 2: steady-state rod bundle benchmark, Exercise 3: transient rod bundle benchmark and Exercise 4: a pressure drop benchmark.

The experimental data provided to the participants of this benchmark is from a series of void measurement tests using full-size mock-up tests for both Boiling Water Reactors (BWRs) and Pressurised Water Reactors (PWRs). These tests were performed from 1987 to 1995 by the Nuclear Power Engineering Corporation (NUPEC) in Japan and made available by the Japan Nuclear Energy Safety Organisation (JNES) for the purposes of this benchmark, which was organised by Pennsylvania State University.

Twenty-one institutions from nine countries participated in this benchmark. Seventeen different computer codes were used in Exercises 1, 2, 3 and 4. Among the computer codes were porous-media, sub-channel, systems thermal-hydraulic code and Computational Fluid Dynamics (CFD) codes.

It was observed that the codes tended to overpredict the thermal equilibrium quality at lower elevations and under predict it at higher elevations. There was also a tendency to overpredict void fraction at lower elevations and underpredict it at high elevations for the bundle test cases. The overprediction of void fraction at low elevations is likely caused by the x-ray densitometer measurement method used. Under sub-cooled boiling conditions, the voids accumulate at heated surfaces (and are therefore not seen in the centre of the sub-channel, where the measurements are being taken), so the experimentally-determined void fractions will be lower than the actual void fraction.

Some of the best results were achieved by codes that used either turbulent mixing or dispersion terms for modelling cross-flow. It was also noted that, for the bundle cases, some of the codes did not correctly calculate the bundle-averaged thermal equilibrium quality, and this may indicate an inability to predict the correct void fraction. A time shift was noted in the void fraction results for the temperature increase transient cases, indicating that the test apparatus may have experienced unexpected heat transfer between the downcomer and test section. This heat transfer is only expected to be of significance in the transient test cases, as the steady-state cases allow the system to reach thermal equilibrium.
Chapter 1
Introduction

1.1 Introduction
Recently, the need to refine models for best-estimate calculations based on good-quality experimental data has arisen for various nuclear applications. One of the most extensive and valuable databases available was developed by the Nuclear Power Engineering Corporation (NUPEC) of Japan, consisting of both void distribution and departure from nucleate boiling (DNB) data for a representative pressurised water reactor (PWR) fuel assembly. A part of this database has been made available for the NUPEC PWR Sub-channel and Bundle Tests (PSBT) benchmark. This benchmark followed the highly successful NEA/NRC NUPEC BWR Full-size Fine-mesh Bundle Tests (BFBT) benchmark.

1.2 Benchmark Objective
The objective of the benchmark was twofold. First, the benchmark aimed to evaluate currently available computational approaches in an effort to understand the strengths and weaknesses of current thermal-hydraulic codes. Second, the benchmark was intended to encourage the development of the next generation of approaches that focus more on microscopic processes.

1.3 Definition of Benchmark Phases
The PSBT benchmark was divided into two separate phases, with each consisting of individual exercises. The structure of the benchmark phases, as well as a mapping showing which test series are included in each exercise, as shown in Table 1.3-1.

<table>
<thead>
<tr>
<th>Items of Data</th>
<th>Test Series</th>
</tr>
</thead>
<tbody>
<tr>
<td>Void fraction measurements data</td>
<td></td>
</tr>
<tr>
<td>- Steady-state void fraction in sub-channel by CT measurement</td>
<td>1, 2, 3, 4</td>
</tr>
<tr>
<td>- Steady-state void distribution image in sub-channel by CT measurement</td>
<td>1, 2</td>
</tr>
<tr>
<td>- Steady-state void fraction in rod bundle by chordal measurement</td>
<td>5, 6, 7, 8</td>
</tr>
<tr>
<td>- Steady-state void distribution image in rod bundle by chordal measurement</td>
<td>5, 6, 7, 8</td>
</tr>
<tr>
<td>- Transient void fraction in rod bundle by chordal measurement</td>
<td>5T, 6T, 7T</td>
</tr>
<tr>
<td>DNB measurements data</td>
<td></td>
</tr>
<tr>
<td>- Steady-state DNB data in rod bundle</td>
<td>0, 2, 3, 4, 8, 13</td>
</tr>
<tr>
<td>- Steady-state DNB detected location in rod bundle</td>
<td>4, 8, 13</td>
</tr>
<tr>
<td>- Steady-state fluid temperature distribution in rod bundle</td>
<td>1</td>
</tr>
<tr>
<td>- Transient DNB data in rod bundle</td>
<td>11T, 12T</td>
</tr>
</tbody>
</table>
1.3.1 Phase I – Void Distribution Benchmark

Exercise 1 – Steady-state single sub-channel benchmark. These test cases involved predicting void distribution in a single sub-channel under steady-state conditions.

Exercise 2 – Steady-state bundle benchmark. These test cases involved predicting void distribution in a bundle under steady-state conditions.

Exercise 3 – Transient bundle benchmark. These test cases involved predicting void distribution in a bundle under transient conditions.

Exercise 4 – Pressure drop benchmark. These test cases involved predicting the axial pressure drop across a bundle.

1.3.2 Phase II – Departure from Nucleate Boiling (DNB) Benchmark

Exercise 1 – Steady-state fluid temperature benchmark. These test cases involved predicting fluid temperatures at the exit of the heated section of a bundle.

Exercise 2 – Steady-state DNB benchmark. These test cases involved predicting DNB in a bundle under steady-state conditions.

Exercise 3 – Transient DNB benchmark. These test cases involved predicting DNB in a bundle under transient conditions.

1.4 Benchmark Team and Sponsorship

The benchmark activities are being performed as an international project supported by the US NRC and METI (Japan), and endorsed by the NEA. The benchmark team was organised based on the collaboration between the US and Japan as shown in Figure 1.4-1.

Figure 1.4-1 PSBT Benchmark Team [2]
There were a total of twenty-one (21) participants in Phase I. Table 1.4-1 summarises these participants, as well as the exercises in which they participated. It should be noted that some participants submitted results for multiple codes, which are summarised in each exercise.

**Table 1.4-1 List of Phase I Participants**

<table>
<thead>
<tr>
<th>Participant</th>
<th>Abbreviation</th>
<th>Country</th>
<th>Exercise I-1</th>
<th>Exercise I-2</th>
<th>Exercise I-3</th>
<th>Exercise I-4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Argonne National Laboratory</td>
<td>ANL</td>
<td>US</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>ANSYS GmbH</td>
<td>ANSYS</td>
<td>Germany</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>AREVA NP GmbH</td>
<td>AREVA</td>
<td>Germany</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Commissariat à l'énergie atomique et aux énergies alternatives (Grenoble)</td>
<td>CEA-Grenoble</td>
<td>France</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Commissariat à l'énergie atomique et aux énergies alternatives (Saclay)</td>
<td>CEA-Saclay</td>
<td>France</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Chalmers University</td>
<td>Chalmers</td>
<td>Sweden</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>CSA, Inc.</td>
<td>CSA</td>
<td>US</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Électricité de France</td>
<td>EDF</td>
<td>France</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Gesellschaft für Anlagen- und Reaktorsicherheit</td>
<td>GRS</td>
<td>Germany</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Helmholtz-Zentrum Dresden-Rossendorf</td>
<td>HZDR</td>
<td>Germany</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Institut de radioprotection et de sûreté nucléaire</td>
<td>IRSN</td>
<td>France</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Japan Nuclear Energy Safety Organization</td>
<td>JNES</td>
<td>Japan</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Korea Atomic Energy Research Institute</td>
<td>KAERI</td>
<td>Korea</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Karlsruhe Institute of Technology</td>
<td>KIT</td>
<td>Germany</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Kungliga Tekniska högskolan</td>
<td>KTH</td>
<td>Sweden</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>McMaster University</td>
<td>McMaster</td>
<td>Canada</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Nuclear Research Institute Rex plc</td>
<td>NRI</td>
<td>Czech Republic</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
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<tr>
<td>Paul Scherrer Institut</td>
<td>PSI</td>
<td>Switzerland</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Università di Pisa</td>
<td>UNIPI</td>
<td>Italy</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>US Nuclear Regulatory Commission</td>
<td>USNRC</td>
<td>US</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Westinghouse Electric Company</td>
<td>WEC/INVAP</td>
<td>US/Argentina</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
</tbody>
</table>
1.5 Report Outline

This report presents the final results of the four exercises of the Phase I: Void Distribution of the NEA/NRC PSBT benchmark.

Chapter 1 discusses the main objectives of the international PSBT benchmark. A definition of the benchmark phases and exercises is provided.

Chapter 2 discusses the NUPEC PWR PSBT facility and the specific methods used in the void distribution measurements.

Chapter 3 presents comparative analyses of submitted final results for the four exercises of Phase I: Steady-state single sub-channel results; Steady-state bundle results; Transient bundle results; and Pressure drop results.

Chapter 4 concludes the activities performed on the void distribution benchmark and discusses the major observations.

Appendix I contains the full set of code-to-data comparisons for Exercise I-1: Steady-state single sub-channel benchmark.


Appendix III contains the full set of code-to-data comparisons for Exercise I-3: Transient bundle benchmark.

Appendix IV contains the full set of code-to-data comparisons for Exercise I-4: Pressure drop benchmark.

Appendix V gives detailed description of the modelling approaches utilised by the participants.
Chapter 2
Void Distribution Benchmark

2.1 General
The first phase of the PSBT benchmark was intended to provide data for the verification of void distribution models in participants' codes. This phase was composed of four exercises: a steady-state single sub-channel benchmark, a steady-state rod bundle benchmark, a transient rod bundle benchmark, and a pressure drop benchmark.

2.2 Test Facility
The void distribution and DNB measurements took place at the NUPEC test facility shown in Figure 2.2-1. The facility was able to simulate the conditions found in PWRs. The same test loop was used for both benchmark phases, but different test sections were constructed to simulate single sub-channels and complete rod bundles. The range of operating conditions for the facility is given in Table 2.2-1 and the operating conditions for the four transient scenarios are given in Table 2.2-2.

Figure 2.2-1 NUPEC Test Facility [5]
Table 2.2-1 Range of NUPEC PWR Test Facility Operating Conditions

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure</td>
<td>4.9 – 16.6 MPa</td>
</tr>
<tr>
<td>Mass Velocity</td>
<td>550 – 4150 kg/m²s</td>
</tr>
<tr>
<td>Inlet Coolant Temperature</td>
<td>140 – 345 °C</td>
</tr>
</tbody>
</table>

Table 2.2-2 Transient Parameters of NUPEC PWR Test Facility

<table>
<thead>
<tr>
<th>Transient Scenario</th>
<th>Transient Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depressurisation</td>
<td>-0.03 MPa/s</td>
</tr>
<tr>
<td>Temperature Increase</td>
<td>1 °C/s</td>
</tr>
<tr>
<td>Flow Reduction</td>
<td>-25 %/s</td>
</tr>
<tr>
<td>Power Increase</td>
<td>15 %/s</td>
</tr>
</tbody>
</table>

2.2.1 Single Sub-channel Test Section and Assemblies

Figure 2.2.1-1 shows the test section used for the single sub-channel void distribution measurements. The heated section is 1.555 m long measured from the coolant inlet, with a measuring section 1.4 m above the start of the heated section. Figure 2.2.1-2 shows cross-sectional views of the four different sub-channel test assemblies. The location and number of heater elements changes, representing four different types of sub-channel found in a typical fuel assembly; central (typical), central (thimble), side, and corner.

Table 2.2.1-1 summarises the material and geometrical properties of the sub-channel heating elements.

The properties of each sub-channel assembly are given in Table 2.2.1-2. It should be noted that the rod bundles shown are simply for illustrative purposes, and the actual experimental test assembly took the form of those shown in Figure 2.2.1-2.
Figure 2.2.1-1 Test Section for Central Sub-channel Void Distribution Measurement

Figure 2.2.1-2 Cross-sectional View of Sub-channel Test Assembly
Table 2.2.1-1 Properties of Sub-channel Heating Elements

<table>
<thead>
<tr>
<th>Item</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heater</td>
<td></td>
</tr>
<tr>
<td>Outer radius (mm)</td>
<td>4.75</td>
</tr>
<tr>
<td>Thickness (mm)</td>
<td>0.85</td>
</tr>
<tr>
<td>Material</td>
<td>Inconel 600</td>
</tr>
<tr>
<td>Heating Method</td>
<td>Direct Heating</td>
</tr>
<tr>
<td>Insulator</td>
<td></td>
</tr>
<tr>
<td>Outer diameter (mm)</td>
<td>31</td>
</tr>
<tr>
<td>Material</td>
<td>Alumina</td>
</tr>
<tr>
<td>Pressure vessel</td>
<td></td>
</tr>
<tr>
<td>Inner Diameter (mm)</td>
<td>32</td>
</tr>
<tr>
<td>Thickness (mm)</td>
<td>4</td>
</tr>
<tr>
<td>Material</td>
<td>Titanium</td>
</tr>
</tbody>
</table>

Table 2.2.1-2 Assembly Data for Assemblies S1, S2, S3, S4

<table>
<thead>
<tr>
<th>Item</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Assembly (Subjected sub-channel)</td>
<td></td>
</tr>
<tr>
<td>S1</td>
<td>S2</td>
</tr>
<tr>
<td>Sub-channel type</td>
<td>Centre (Typical)</td>
</tr>
<tr>
<td>Number of heaters</td>
<td>4×1/4</td>
</tr>
<tr>
<td>Axial heated length (mm)</td>
<td>1555</td>
</tr>
<tr>
<td>Axial power shape</td>
<td>Uniform</td>
</tr>
</tbody>
</table>

■ : Subjected sub-channel  ○ : Heated rod  Ø : Thimble rod

2.2.2 Rod Bundle Test Section and Assemblies

Figure 2.2.2-1 shows the test section used for the bundle void distribution measurements. The effective heated length is 3658 mm, which is broken into three sections (upper, middle, lower), measuring at 3177 mm, 2669 mm, and 2216 mm, respectively. Coolant flows into the pressure vessel horizontally through the coolant inlet nozzle and down through the section between the flow channel and the pressure vessel. The coolant continues into the flow channel, flowing from the bottom of the pressure vessel up through the test assembly, where the bottom of the heated section is located 630 mm above the bottom of the pressure vessel.

According to experimental data, the area between the downcomer and test section was fully insulated so there would not be heat transfer between the two flows.

The properties of the bundle assemblies to be used are given in Table 2.2.2-1.
Figure 2.2.2-2 and Figure 2.2.2-3 show the two different radial power distributions, named A and B, respectively. All powers shown are relative powers.

Table 2.2.2-2 shows the axial power distribution (based on a cosine shape) that was used in the bundle tests.
**Table 2.2.2-1 Assembly Data for Assemblies B5, B6, B7**

<table>
<thead>
<tr>
<th>Item</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Assembly</td>
<td><img src="image1" alt="Assembly B5" /> <img src="image2" alt="Assembly B6" /> <img src="image3" alt="Assembly B7" /></td>
</tr>
<tr>
<td>Rods array</td>
<td>B5: 5x5</td>
</tr>
<tr>
<td></td>
<td>B6: 5x5</td>
</tr>
<tr>
<td></td>
<td>B7: 5x5</td>
</tr>
<tr>
<td>Number of heated rods</td>
<td>B5: 25</td>
</tr>
<tr>
<td></td>
<td>B6: 25</td>
</tr>
<tr>
<td></td>
<td>B7: 24</td>
</tr>
<tr>
<td>Number of thimble rods</td>
<td>B5: 0</td>
</tr>
<tr>
<td></td>
<td>B6: 0</td>
</tr>
<tr>
<td></td>
<td>B7: 1</td>
</tr>
<tr>
<td>Heated rod outer diameter (mm)</td>
<td>B5: 9.50</td>
</tr>
<tr>
<td></td>
<td>B6: 9.50</td>
</tr>
<tr>
<td></td>
<td>B7: 9.50</td>
</tr>
<tr>
<td>Thimble rod outer diameter (mm)</td>
<td>B5: -</td>
</tr>
<tr>
<td></td>
<td>B6: -</td>
</tr>
<tr>
<td></td>
<td>B7: 12.24</td>
</tr>
<tr>
<td>Heated rods pitch (mm)</td>
<td>B5: 12.60</td>
</tr>
<tr>
<td></td>
<td>B6: 12.60</td>
</tr>
<tr>
<td></td>
<td>B7: 12.60</td>
</tr>
<tr>
<td>Axial heated length (mm)</td>
<td>B5: 3658</td>
</tr>
<tr>
<td></td>
<td>B6: 3658</td>
</tr>
<tr>
<td></td>
<td>B7: 3658</td>
</tr>
<tr>
<td>Flow channel inner width (mm)</td>
<td>B5: 64.9</td>
</tr>
<tr>
<td></td>
<td>B6: 64.9</td>
</tr>
<tr>
<td></td>
<td>B7: 64.9</td>
</tr>
<tr>
<td>Radial power shape</td>
<td>B5: A</td>
</tr>
<tr>
<td></td>
<td>B6: A</td>
</tr>
<tr>
<td></td>
<td>B7: B</td>
</tr>
<tr>
<td>Axial power shape</td>
<td>B5: Uniform</td>
</tr>
<tr>
<td></td>
<td>B6: Cosine</td>
</tr>
<tr>
<td></td>
<td>B7: Cosine</td>
</tr>
<tr>
<td>Number of MV spacers</td>
<td>B5: 7</td>
</tr>
<tr>
<td></td>
<td>B6: 7</td>
</tr>
<tr>
<td></td>
<td>B7: 7</td>
</tr>
<tr>
<td>Number of NMV spacers</td>
<td>B5: 2</td>
</tr>
<tr>
<td></td>
<td>B6: 2</td>
</tr>
<tr>
<td></td>
<td>B7: 2</td>
</tr>
<tr>
<td>Number of simple spacers</td>
<td>B5: 8</td>
</tr>
<tr>
<td></td>
<td>B6: 8</td>
</tr>
<tr>
<td></td>
<td>B7: 8</td>
</tr>
<tr>
<td>MV spacer location (mm)</td>
<td>B5: 471, 925, 1378, 1832, 2285, 2739, 3247</td>
</tr>
<tr>
<td></td>
<td>B6: 471, 925, 1378, 1832, 2285, 2739, 3247</td>
</tr>
<tr>
<td></td>
<td>B7: 471, 925, 1378, 1832, 2285, 2739, 3247</td>
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<tr>
<td>NMV spacer location (mm)</td>
<td>B5: 2.5, 3755</td>
</tr>
<tr>
<td></td>
<td>B6: 2.5, 3755</td>
</tr>
<tr>
<td></td>
<td>B7: 2.5, 3755</td>
</tr>
<tr>
<td>Simple spacer location (mm)</td>
<td>B5: 237, 698, 1151, 1605, 2059, 2512, 2993, 3501</td>
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<tr>
<td></td>
<td>B6: 237, 698, 1151, 1605, 2059, 2512, 2993, 3501</td>
</tr>
<tr>
<td></td>
<td>B7: 237, 698, 1151, 1605, 2059, 2512, 2993, 3501</td>
</tr>
</tbody>
</table>

Heated rod  Thimble rod  MV: Mixing vane, NMV: No mixing vane

Spacer location is distance from bottom of heated length to spacer bottom face.

**Figure 2.2.2-2 Radial Power Distribution A**

<table>
<thead>
<tr>
<th>0.85</th>
<th>0.85</th>
<th>0.85</th>
<th>0.85</th>
<th>0.85</th>
</tr>
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<td>1.00</td>
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<td>1.00</td>
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Figure 2.2.2-3 Radial Power Distribution B

<table>
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</tr>
</tbody>
</table>

Table 2.2.2-2 Cosine Axial Power Distribution

<table>
<thead>
<tr>
<th>Node</th>
<th>Relative Power</th>
</tr>
</thead>
<tbody>
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<td>(Bottom)</td>
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<tr>
<td>1</td>
<td>0.42</td>
</tr>
<tr>
<td>2</td>
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<td>0.56</td>
</tr>
<tr>
<td>4</td>
<td>0.67</td>
</tr>
<tr>
<td>5</td>
<td>0.80</td>
</tr>
<tr>
<td>6</td>
<td>0.94</td>
</tr>
<tr>
<td>7</td>
<td>1.08</td>
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<td>1.22</td>
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<td>9</td>
<td>1.34</td>
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<td>10</td>
<td>1.44</td>
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<tr>
<td>11</td>
<td>1.51</td>
</tr>
<tr>
<td>12</td>
<td>1.55</td>
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<td>13</td>
<td>1.55</td>
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<td>1.51</td>
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</tr>
<tr>
<td>18</td>
<td>1.08</td>
</tr>
<tr>
<td>19</td>
<td>0.94</td>
</tr>
<tr>
<td>20</td>
<td>0.80</td>
</tr>
<tr>
<td>21</td>
<td>0.67</td>
</tr>
<tr>
<td>22</td>
<td>0.56</td>
</tr>
<tr>
<td>23</td>
<td>0.47</td>
</tr>
<tr>
<td>24</td>
<td>0.42</td>
</tr>
<tr>
<td>(Top)</td>
<td></td>
</tr>
</tbody>
</table>

*node size (152.42 mm)
2.2.2.1 Spacer Grid Data

There were three types of spacers instrumented along the axial length: simple spacer (SS), spacer with no mixing vanes (NMV), and spacer with mixing vanes (MV). The simple spacer has only dimples while NMV and MV have dimples and springs. The grids straps are made out of Inconel 600 alloy. Detailed geometrical description of the grids used in the experiment was not available to the benchmark. As a result, the benchmark team, with the assistance of a benchmark participant, was forced to develop a grid model based on the understanding that the grids used in the experiments were similar to grids for which data was readily available. Table 2.2.2.1-1 summarises the grid data that was available as part of the benchmark. Figure 2.2.2.1-1, Figure 2.2.2.1-2 and Figure 2.2.2.1-3 provide three-dimensional views of the simple spacer, non-mixing vane, and mixing vane grids. The simple spacer has dimples while the mixing vane and non-mixing vane grids have both dimples and springs. These dimples provide a gap (~0.1) around each heating rod, which prevents bowing of these rods when they linearly expand at high temperatures.

Table 2.2.2.1-1 provides the bundle average spacer pressure loss coefficients for the three types of grids. Depending on the participants’ computer code, and using the provided spacer data, each participant may choose the sub-channel grid loss coefficients or other required input values.
Figure 2.2.2.1-2 View of Non-Mixing Vane Spacer Grid

Figure 2.2.2.1-3 View of Mixing Vane Spacer Grid
### Table 2.2.2.1-1 Bundle Average Spacer Pressure Loss Coefficients

<table>
<thead>
<tr>
<th>Spacer Type</th>
<th>Loss Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simple Spacer (SS)</td>
<td>0.4</td>
</tr>
<tr>
<td>Non-Mixing Vanes Spacer (NMV)</td>
<td>0.7</td>
</tr>
<tr>
<td>Mixing Vanes Spacer (MV)</td>
<td>1.0</td>
</tr>
</tbody>
</table>

#### 2.2.2.2 Heater Rod Data

Table 2.2.2.2-1 summarises the material and geometrical properties of the heater rods used in the rod bundle tests. Figure 2.2.2.2-1 provides a cross-sectional view of the heater rods and gives dimensions.

<table>
<thead>
<tr>
<th>Item</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Heater</strong></td>
<td></td>
</tr>
<tr>
<td>Outer diameter</td>
<td>9.5 mm</td>
</tr>
<tr>
<td>Thickness (mm)</td>
<td>0.65</td>
</tr>
<tr>
<td>Material</td>
<td>Inconel 600</td>
</tr>
<tr>
<td>Heating Method</td>
<td>Direct Heating</td>
</tr>
<tr>
<td><strong>Insulator</strong></td>
<td></td>
</tr>
<tr>
<td>Outer diameter</td>
<td>8.2 mm</td>
</tr>
<tr>
<td>Inner diameter</td>
<td>5.8 mm</td>
</tr>
<tr>
<td>Material</td>
<td>Alumina</td>
</tr>
</tbody>
</table>

#### 2.2.3 Measurement Techniques

A gamma-ray transmission method was used to measure the density of the flow, which was converted to the void fraction of the gas-liquid two-phase flow. Figure 2.2.3-1 shows the procedure used to perform the void fraction measurements for the entire rod bundle. The top half of the figure shows the procedure used to perform the void fraction measurements for a single sub-channel. In the sub-channel experiments a narrow gamma-ray beam CT scanner was used to measure the sub-
channel averaged void fraction and a wide gamma-ray beam was used to measure the chordal averaged void fraction. For each sub-channel type - corner, side, or centre – a relationship between the sub-channel averaged and the chordal averaged void fractions was individually derived. These relationships were then used to correct the sub-channel averaged void fraction measured with the wide beam in the bundle tests.

The void measurement systems shown in Figure 2.2.3-1 consist of gamma-ray sources (137Cs); detectors; collimators, and signal processing units. The attenuation of the gamma-rays, which depends on the void fraction, was detected. The intensity of the gamma-ray source was determined to obtain the count-rate of the signal processing (30×10^4 cps).

The CT scanner system was used to determine the distribution of density/void fraction over the sub-channel at a steady-state flow and to define the sub-channel averaged void fraction. The system was operated by translate/rotate method. At each translation/rotation location, the intensity of gamma-ray attenuated by the object, the so-called “projection data”, was detected. An image reconstruction was then performed by a filtered back-projection algorithm to obtain the distribution of the linear attenuation coefficient. A sufficient measuring time was given in order to avoid the effect of the flow motion.

Two densitometer systems – in x- and y-directions - were used in the chordal averaged void fraction measurements in the single sub-channel tests. Each of them consisted of a gamma source and a detector. They were located at the same tables (the same elevation) as CT, which was fixed during the measurements.

A multi-beam system was used to measure each sub-channel void fraction of the rod bundle. Six transmission data of x-direction and six transmission data of y-direction between the rod and rod/channel wall were used to reconstruct the void fraction of the 36 sub-channels by an iterative method. These sub-channel void fractions corresponded to the chordal measurements of the single sub-channel tests. The relationships between the sub-channel averaged void fraction and the chordal averaged void fraction obtained in the single sub-channel tests were used to determine the sub-channel averaged void fractions in the rod bundle tests. Such measurements were performed simultaneously at three axial elevations.

Table 2.2.3-1 shows the accuracy of the various parameters involved in the experiment. Table 2.2.3-2 summarises the sources of error in the experiment.
Figure 2.2.3-1 Void Fraction Measurement Procedure

Subchannel Test

CT Measurement

Chordal Measurement

Bundle Test

Void Measurement Equipment

Subchannel Test

Bundle Test
Figure 2.2.3-2 illustrates the relationship between chordal and CT averaged densities as a function of pressure. It was used to determine the uncertainties inherent in the void measurements and to correct the measured values based on the pressure of the test case. The correlation between the chordal and CT averaged values is given by the best-fit curves and was introduced for the high- and low-pressure conditions, respectively. The reference averaged density was 500 kg/m$^3$. The uncertainty of the correlation was determined to be less than 18 kg/m$^3$, which was regarded as three standard deviations (3σ). Therefore, one standard deviation (1σ) is 6 kg/m$^3$.

Table 2.2.3-3 shows the number of gamma ray beams used in the fluid density measurement for both sub-channel and rod bundle exercises.

Table 2.2.3-4 shows the amount of time required to perform the density measurement.

**Table 2.2.3-1 Accuracy of Process Parameters in Void Distribution Measurement**

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Process parameters</td>
<td>1%</td>
</tr>
<tr>
<td>Pressure</td>
<td>1%</td>
</tr>
<tr>
<td>Flow</td>
<td>1.5%</td>
</tr>
<tr>
<td>Power</td>
<td>1%</td>
</tr>
<tr>
<td>Fluid temperature</td>
<td>1 Celsius</td>
</tr>
<tr>
<td>Void fraction measurement</td>
<td>3% void</td>
</tr>
<tr>
<td>Spatial resolution of one pixel</td>
<td>0.5 mm</td>
</tr>
<tr>
<td>CT measurement</td>
<td></td>
</tr>
<tr>
<td>Gamma-ray beam width</td>
<td>1 mm</td>
</tr>
<tr>
<td>Sub-channel averaged (steady-state)</td>
<td>3% void</td>
</tr>
<tr>
<td>Spatial resolution of one pixel</td>
<td>0.5 mm</td>
</tr>
<tr>
<td>Chordal measurement</td>
<td></td>
</tr>
<tr>
<td>Gamma-ray beam width (center)</td>
<td>3 mm</td>
</tr>
<tr>
<td>Gamma-ray beam width (side)</td>
<td>2 mm</td>
</tr>
<tr>
<td>Sub-channel averaged (steady-state)</td>
<td>4% void</td>
</tr>
<tr>
<td>Sub-channel averaged (transient)</td>
<td>5% void</td>
</tr>
<tr>
<td>Error source</td>
<td>Chordal Averaged</td>
</tr>
<tr>
<td>--------------------------------------</td>
<td>------------------</td>
</tr>
<tr>
<td></td>
<td>Steady-state</td>
</tr>
<tr>
<td>Effect of surrounding condition</td>
<td>0.1%</td>
</tr>
<tr>
<td>(magnetic-field and temperature) on</td>
<td></td>
</tr>
<tr>
<td>measurement system</td>
<td></td>
</tr>
<tr>
<td>Randomness of γ-ray source decay</td>
<td>0.02%</td>
</tr>
<tr>
<td>Correction error due to back ground</td>
<td>0.0%</td>
</tr>
<tr>
<td>Correction error due to counting loss</td>
<td>&lt;0.5%</td>
</tr>
<tr>
<td>Calibration error</td>
<td>0.1%</td>
</tr>
<tr>
<td>Correction error due to attenuation</td>
<td>0.0%</td>
</tr>
<tr>
<td>by surrounding water</td>
<td></td>
</tr>
<tr>
<td>Correction error due to scattering</td>
<td>&lt;0.2%</td>
</tr>
<tr>
<td>from multi γ-rays</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>&lt;0.55%</td>
</tr>
<tr>
<td>Sub-channel Density</td>
<td></td>
</tr>
<tr>
<td>Transfer to density</td>
<td>&lt;9 kg/m³</td>
</tr>
<tr>
<td>Distribution error to Sub-channel</td>
<td>&lt;5 kg/m³</td>
</tr>
<tr>
<td>Correlation error from Chordal</td>
<td>&lt;6 kg/m³</td>
</tr>
<tr>
<td>averaged to CT averaged</td>
<td></td>
</tr>
<tr>
<td>Sub-channel Density</td>
<td>&lt;20 kg/m³</td>
</tr>
<tr>
<td>Sub-channel Void*</td>
<td>0.040</td>
</tr>
<tr>
<td>Uncertainty (1σ)</td>
<td>4%</td>
</tr>
</tbody>
</table>

*Reference averaged density is 500 kg/m³.

**Figure 2.2.3-2 Relation Between Chordal and CT Averaged Densities (for S1)**
### Table 2.2.3-3 Number of Gamma Ray Beams

<table>
<thead>
<tr>
<th>Test assembly</th>
<th>CT Measurement</th>
<th>Chordal Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sub-channel</td>
<td>2 (X and Y direction)</td>
<td>2 (X and Y direction)</td>
</tr>
<tr>
<td>Rod bundle</td>
<td>-</td>
<td>6 beam × 2 × 3 section (total 36 beams)</td>
</tr>
</tbody>
</table>

### Table 2.2.3-4 Time Required to perform Void Fraction Measurements

<table>
<thead>
<tr>
<th>Item</th>
<th>CT Measurement</th>
<th>Chordal Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steady-state</td>
<td>5 s/step × 33 × h 17 step (it takes 2 h)*</td>
<td>100 s sampling cycle 0.1 s</td>
</tr>
<tr>
<td>Measurement</td>
<td>2 times</td>
<td>3 times</td>
</tr>
<tr>
<td>Transient</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time needed</td>
<td></td>
<td>200 s</td>
</tr>
<tr>
<td>Measurement</td>
<td></td>
<td>1 time</td>
</tr>
</tbody>
</table>

*“T” stands for translation and “R” for rotation – the CT scan measurements were obtained by a “translate/rotate” procedure.

### 2.3 Experimental Data Analysis

Based on participant feedback, several studies were performed to determine the validity of the benchmark data. These included: 1) study performed on re-calculation of the void fraction; 2) study performed on calculation of the quality; 3) study performed on the sub-channel CT masking; and 4) study performed on bundle test section downcomer region.

#### 2.3.1 Re-Calculation of Void Fraction

At the first PSBT workshop, it was noted by several participants that the “measured” void fractions (which were actually calculated from measured density data) were not consistent with void fractions calculated using the measured densities. As a result, a study was performed to recalculate the void fraction and quality for each test case in the void distribution benchmark.

Solving the standard equation for mixture density \( \bar{\rho} = \alpha \rho_f + (1 - \alpha) \rho_g \) for the void fraction gives \( \alpha = (\bar{\rho} - \rho_f) / (\rho_g - \rho_f) \), where the liquid and vapour densities \( \rho_l \) and \( \rho_g \), respectively) are assumed to be at saturation and the mixture density is taken from the benchmark data. After the recalculation, it was noted that the measured void fraction was consistently higher than the recalculated void fraction. This recalculation was only performed for the sub-channel test cases since those are the only test cases for which fluid density data were available.
2.3.2 Calculation of Quality

Upon completion of the study performed on void distribution, the benchmark team began a study of the calculation of quality based on the experimentally-determined densities.

It is recalled that quality can be expressed using mixture enthalpy. The equation is given as:

\[ x = \frac{h_{mix} - h_f}{h_g - h_f}, \]

where \( h_f \) and \( h_g \) are the liquid and vapour enthalpies, respectively. A number of different expressions were derived to determine the mixture enthalpy in the test sections assuming conservation of energy. After verifying that the axial power distribution was normalised for both the uniform and cosine power shapes, the following equations were obtained.

**Sub-channel Assembly**

All four sub-channel test sections utilised a uniform axial power distribution. Thus, for all sub-channel assemblies, the mixture enthalpy at the measurement section can be given by:

\[
h_{mix} = h_{in} + \frac{1400\text{mm}}{1555\text{mm}} Q[kW] \times \frac{3600\text{[S]}}{A[\text{m}^2]G[kg]} [\text{m}^2\text{h}]
\]

Figure 2.3.2-1 shows the resulting deviation of the experimental quality from the recalculated quality.
Bundle Assembly

Assembly B5 utilised a uniform axial power distribution, so the mixture enthalpies at the three measurement locations can be given as:

\[
\begin{align*}
    h_{mix} &= h_{in} + \frac{2216\text{mm}}{3658\text{mm}} Q [kW] \times \frac{3600 [\text{J}]}{A [\text{m}^2] G \frac{\text{kg}}{\text{m}^2\text{h}}} \\
    &\quad \text{Lower Elevation} \\
    \end{align*}
\]

\[
\begin{align*}
    h_{mix} &= h_{in} + \frac{2669\text{mm}}{3658\text{mm}} Q [kW] \times \frac{3600 [\text{J}]}{A [\text{m}^2] G \frac{\text{kg}}{\text{m}^2\text{h}}} \\
    &\quad \text{Middle Elevation} \\
    \end{align*}
\]

\[
\begin{align*}
    h_{mix} &= h_{in} + \frac{3177\text{mm}}{3658\text{mm}} Q [kW] \times \frac{3600 [\text{J}]}{A [\text{m}^2] G \frac{\text{kg}}{\text{m}^2\text{h}}} \\
    &\quad \text{Upper Elevation} \\
    \end{align*}
\]

Assemblies B6 and B7 utilised a cosine axial power shape. Recalling that the power shape is normalised, it is possible to determine what fraction of the total power has been imparted to the fluid between the flow inlet and the measurement sections. The mixture enthalpies for these two assemblies can be given as:

\[
\begin{align*}
    h_{mix} &= h_{in} + 0.6598 Q [kW] \times \frac{3600 [\text{J}]}{A [\text{m}^2] G \frac{\text{kg}}{\text{m}^2\text{h}}} \\
    &\quad \text{Lower Elevation} \\
    \end{align*}
\]

\[
\begin{align*}
    h_{mix} &= h_{in} + 0.8172 Q [kW] \times \frac{3600 [\text{J}]}{A [\text{m}^2] G \frac{\text{kg}}{\text{m}^2\text{h}}} \\
    &\quad \text{Middle Elevation} \\
    \end{align*}
\]

\[
\begin{align*}
    h_{mix} &= h_{in} + 0.9353 Q [kW] \times \frac{3600 [\text{J}]}{A [\text{m}^2] G \frac{\text{kg}}{\text{m}^2\text{h}}} \\
    &\quad \text{Upper Elevation} \\
    \end{align*}
\]

After applying these equations and calculating the qualities for each case, the following results were obtained. Figure 2.3.2-2, Figure 2.3.2-3, Figure 2.3.2-4 and Figure 2.3.2-5 show the deviation of experimental quality from the recalculated quality for Test Series 5, 6, 7, and 8, respectively.
The results of these studies can be applied by participants to their data in an effort to correct for the experimental values.

**Figure 2.3.2-2 Deviation of Measured Quality from Recalculated Quality for Test Series 5**

**Figure 2.3.2-3 Deviation of Measured Quality from Recalculated Quality for Test Series 6**
Figure 2.3.2-4 Deviation of Measured Quality from Recalculated Quality for Test Series 7

Figure 2.3.2-5 Deviation of Measured Quality from Recalculated Quality for Test Series 8
2.3.3 Study Performed on Sub-channel CT Masking

A study was performed at McMaster University regarding the masking effect of CT measurements on sub-channel void fraction [7]. Two types of uncertainties were identified. The first concerns a systematic mask effect that omits void at the near wall during sub-cooled boiling. From Figure 2.3.3-1 and Figure 2.3.3-2, it can be seen that, at high void fractions, the void congregates in the centre of the sub-channel. Conversely, at low void fractions, the highest void can be found along the near-walls. Due to the low fidelity of the CT scan technology available at the time, some of this near-wall void is masked, yielding a lower experimental void fraction than is reality. As a result, the CT measurements will not show any void until the void fraction is 3.8-7.8% (depending on assumptions). This uncertainty is revealed in post-processing of the data.

The second type of uncertainty associated with the CT measurements concerns shifting of the CT image (even if the mask is perfectly sized). Figure 2.3.3-3 illustrates the effect this shift can have on the measured void fraction. The McMaster team assumed a half-pixel size off-set and a half-pixel location off-set in their calculations and determined that, under sub-cooled boiling conditions, the lost void could be as high as 6.2% void (this uncertainty reduces to almost zero for bulk boiling conditions).

Since neither of these effects will be fully present (the blocked regions are likely between 0.5 and 1 pixel and are not fully liquid nor void), the McMaster team suggests a total uncertainty of 6.2% void.
2.3.4 Study Performed on Bundle Test Section Downcomer Region

A study was performed by M. Valette et al. at CEA Grenoble regarding the heat capacitance effect of the downcomer region in the bundle test section and the location of the fluid temperature measurement ([8]. The fluid temperature measurement occurred just before the coolant inlet nozzle above the downcomer region, so it can be reasonably assumed that there would be some time shift in the flow characteristics due to the time required for the flow to traverse the downcomer. It should be noted that this effect appears to only be significant for the temperature increase transients. The CEA-Grenoble team investigated the effect of the downcomer region and determined that the fluid temperature is reduced and shifted when the downcomer is accounted for. Figure 2.3.4-1 illustrates this effect on the fluid temperature, while Figure 2.3.4-2 shows the resulting effect on the void fraction (the dashed lines represent results with no downcomer region, while the solid lines represent the results using a full downcomer region).

Figure 2.3.4-1 Temperature Shift for Test Case 5T (TI)
The CEA-Grenoble team then investigated the time shift effect on test cases 6T (TI) and 7T (TI), as well as the two temperature increase transients from Phase II, 11T (TI) and 12T (TI). These results are presented in Figure 2.3.4-3 and Figure 2.3.4-4.
Based on their studies, the CEA-Grenoble team recommends a time shift of 10 seconds for the experimental void fraction data. When accounting for this time shift, the participant results show significant improvement when compared to the experimental data. In addition, it was noted that DNB occurred earlier when modelling the downcomer region than the experimental data suggests.
Chapter 3
Comparative Analyses of Submitted Final Results for Void Distribution

3.1 General

Table 3.1-1 summarises the test series used in the void distribution benchmark.

<table>
<thead>
<tr>
<th>Test series</th>
<th>Test section</th>
<th>Assembly</th>
<th>Test mode</th>
<th>Void measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Steady-state</td>
<td>Transient</td>
</tr>
<tr>
<td>1</td>
<td>Sub-channel</td>
<td>S1</td>
<td>Y</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>S2</td>
<td>Y</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>S3</td>
<td>Y</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>S4</td>
<td>Y</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Sub-channel</td>
<td>B5</td>
<td>Y</td>
<td></td>
</tr>
<tr>
<td>5T</td>
<td></td>
<td>B5</td>
<td>Y</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>B6</td>
<td>Y</td>
<td></td>
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<tr>
<td>6T</td>
<td></td>
<td>B6</td>
<td>Y</td>
<td></td>
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<td>B7</td>
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</table>

3.2 Exercise 1 – Steady-state Single Sub-channel

3.2.1 Selected Exercise Cases and Requested Computational Results

The available data for this exercise consisted of CT scan measurements of fluid density for four sub-channel types (central typical, central thimble, side, and corner), as well as images of the sub-channel void distribution for the central typical and central thimble sub-channels. The measured density was used to calculate the void fraction in the sub-channel.

The test matrixes for the steady-state single sub-channel void measurements – Test Series 1, 2, 3, and 4 – are given in Table 3.2.1-1, Table 3.2.1-2, Table 3.2.1-3 and Table 3.2.1-4, respectively.

The requested outputs for this exercise were sub-channel-averaged fluid density, sub-channel-averaged void fraction, and thermal equilibrium quality (all taken at the single measurement location) for all test cases. Additionally, axial void distribution was requested for five (5) selected cases. It was also requested that CFD participants submit in-channel void distribution images for comparison with the experimental CT images.
**Table 3.2.1-1 Test Conditions for Steady-State Void Measurement Test Series 1**

<table>
<thead>
<tr>
<th>Run No</th>
<th>Pressure* (kg/cm²)</th>
<th>Mass Flux (10⁶ kg/m²hr)</th>
<th>Power (kW)</th>
<th>Inlet Temperature (°C)</th>
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</thead>
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<td>169.1</td>
<td>10.98</td>
<td>50.0</td>
<td>334.7</td>
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<td>169.1</td>
<td>11.00</td>
<td>49.9</td>
<td>339.7</td>
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*1 kg/cm² = 98,066.5 Pascals (Pa)

**Table 3.2.1-2 Test Conditions for Steady-State Void Measurement Test Series 2**

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*1 kg/cm² = 98,066.5 Pascals (Pa)
Table 3.2.1-3 Test Conditions for Steady-State Void Measurement Test Series 3

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<th>Pressure (kg/cm²)</th>
<th>Mass Flux (10⁶ kg/m²·hr)</th>
<th>Power (kW)</th>
<th>Inlet Temperature (°C)</th>
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<td>203.9</td>
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</table>

*1 kg/cm² = 98,066.5 Pascals (Pa)

Table 3.2.1-4 Test Conditions for Steady-State Void Measurement Test Series 4

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<th>Run No</th>
<th>Pressure (kg/cm²)</th>
<th>Mass Flux (10⁶ kg/m²·hr)</th>
<th>Power (kW)</th>
<th>Inlet Temperature (°C)</th>
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<td>5.03</td>
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<td>214.0</td>
</tr>
</tbody>
</table>

*1 kg/cm² = 98,066.5 Pascals (Pa)

3.2.2 Participation and Submitted Results

There were a total of twenty (20) participants for Exercise 1. Sixteen (16) of these participants submitted void fraction results, and eight (8) submitted axial void distribution results. Table 3.2.2-1 lists these participants, as well as the codes for which results were submitted.
### Table 3.2.2-1 Phase I Exercise 1 Participants and Code List

<table>
<thead>
<tr>
<th>Participant</th>
<th>Code</th>
<th>Code Type</th>
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<tbody>
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<td>ANL</td>
<td>STAR-CD</td>
<td>CFD</td>
</tr>
<tr>
<td>ANSYS</td>
<td>ANSYS</td>
<td>CFD</td>
</tr>
<tr>
<td>EDF</td>
<td>NEPTUNE</td>
<td>CFD</td>
</tr>
<tr>
<td>GRS</td>
<td>ANSYS-CFX</td>
<td>CFD</td>
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<tr>
<td>HZDR</td>
<td>ANSYS-CFX</td>
<td>CFD</td>
</tr>
<tr>
<td>PSI</td>
<td>STAR-CD</td>
<td>CFD</td>
</tr>
<tr>
<td>EDF</td>
<td>THYC</td>
<td>Porous media</td>
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<td>F-COBRA-TF</td>
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<tr>
<td>CEA-Saclay</td>
<td>FLICA-OVAP</td>
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<td>CSA</td>
<td>VIPRE</td>
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<td>JNES</td>
<td>CHAMP-ITA</td>
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<tr>
<td>KAERI</td>
<td>MATRA</td>
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</tr>
<tr>
<td>KIT</td>
<td>SUBCHANFLOW</td>
<td>Sub-channel</td>
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<td>PSI</td>
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<td>PSI</td>
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<tr>
<td>UNIPI</td>
<td>CATHARE 2</td>
<td>System</td>
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</table>

The questionnaires submitted by the participants can be found in Appendix V.

The codes for which questionnaires and results were submitted vary significantly in the models used, as did the geometric considerations imposed on the solution. For example, a number of codes (such as ANSYS (ANSYS) and MATRA) have no specified flow regime map, while others (such as STAR-CD and THYC) assumed a bubbly flow. Others still (such as ASSERT-PV, SUBCHANFLOW, and TRACE (KTH)) have fully specified flow regime maps, usually considering bubbly, slug, churn, and turbulent flow regimes.

The axial nodalisation of the problem varied widely depending on code type. CFD codes, as expected, had significantly more nodes than the system and sub-channel codes: Both NEPTUNE and ANSYS (ANSYS) used nodalisation of ~100,000-1,000,000 nodes, while both KTH and PSI used about 30 axial nodes for TRACE. CATHARE 2 (UNIPI) and STAR-CD (PSI) both used approximately 100 axial nodes.

Finally, a variety of wall drag and heat transfer coefficients were also used. THYC, for example, used Gautier for monophasic and Chen for diphasic heat transfer, while FLICA (PSI) used the Blasius correlation for single-phase friction losses with the Friedel correlation as a two-phase multiplier. A number of codes used Dittus-Boelter for single-phase heat transfer and a variety of correlations (Jens-Lottes for FLICA (PSI)) were used.
3.2.3 Statistical Methodology

Mean error and standard deviation were calculated for each code for each test series. The mean error (where N is the total number of test cases) was represented as:

$$\bar{\alpha} = \frac{\sum_{n=1}^{N} \alpha^n}{N}.$$  

where the void fraction error for test case “n” is represented as:

$$\alpha^n = (\alpha^n_{\text{code}} - \alpha^n_{\text{exp}}).$$

The standard deviation was given as:

$$\sigma = \pm \sqrt{\frac{\sum_{n=1}^{N} (\alpha^n - \bar{\alpha})^2}{N - 1}}.$$  

3.2.4 Comparative Analysis of Participant Results

Appendix I contains the complete set of participant results for Exercise 1. Figure 3.2.4-1 summarises the mean error of participant void fraction measurements, while Figure 3.2.4-2 summarises the standard deviation of those results.
3.2.4.1 Axial Void Distribution

Many of the codes behaved similarly in the calculation of the axial void distribution. Since only one data point was available for each test case, it cannot be determined what the shape of the distribution actually looks like. In some cases, such as test case 1.2237 (Figure AI-21), all of the codes underpredicted the void fraction at the measurement location, while they all overpredicted in others, such as test case 1.2211 (Figure AI-19). In general, the CFD codes tended to predict higher void fractions axially, while the sub-channel codes did not show increased void until later in the bundle.

3.2.4.2 CFD In-Channel Sub-channel Void Distribution

Two participants submitted CFD in-channel void distribution images for comparison with the experimental CT scans. In general, the codes were able to model the radial void distribution reasonably well. There were some cases where the codes predicted the correct void fraction, but distributed it incorrectly. For example, the CT scan for test case 1.2423 (Figure AI-39) shows a low void fraction that is concentrated in the sub-channel “corners” away from the heated walls. However, both STAR-CD (Figure AI-40) and NEPTUNE (Figure AI-41) indicate a concentration of void along the walls.

In addition, at high void fractions, the CFD codes tended to predict high void at the walls, when CT imaging indicates a higher void in the centre of the sub-channel (which would be expected). This is especially evident in test cases like 1.4312. As shown in Figure AI-44, the void congregates in the centre of the sub-channel. However, both STAR-CD (Figure AI-45) and NEPTUNE (Figure AI-46) predict higher void at the walls.

3.2.5 Discussion on the Predicted Steady-State Single Sub-channel Void Distribution

There was no clear bias in the calculation of void fraction for any of the four sub-channels. Although some of the codes consistently predicted the correct thermal equilibrium quality, there was a tendency to overpredict it at the low elevation and underpredict it at the high elevation.
3.3 Exercise 2 – Steady-state Rod Bundle

3.3.1 Selected Exercise Cases and Requested Computational Results

The available data for this exercise consisted of chordal-averaged x-ray densitometer measurements of fluid density in the rod bundle. The measured density was then used to calculate the void fraction. The given values are the average of the void fraction over the four central sub-channels of the bundle. Images of the void distribution in the rod bundle were also available.

The test matrixes for the steady-state bundle void measurements - Test Series 5, 6, 7, and 8 - are given in Table 3.3.1-1, Table 3.3.1-2, Table 3.3.1-3 and Table 3.3.1-4, respectively.

The requested outputs for this exercise were region-averaged void fraction, bundle-averaged void fraction, and bundle-averaged thermal equilibrium quality (all given for each of the three measurement locations). In addition, axial void distribution was requested for one (1) selected case.

### Table 3.3.1-1 Test Conditions for Steady-State Void Measurement Test Series 5

<table>
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<th>Power (kW)</th>
<th>Inlet Temperature (°C)</th>
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*1 kg/cm² = 98,066.5 Pascals (Pa)
Table 3.3.1-2 Test Conditions for Steady-State Void Measurement Test Series 6

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*1 kg/cm² = 98,066.5 Pascals (Pa)

Table 3.3.1-3 Test Conditions for Steady-State Void Measurement Test Series 7

<table>
<thead>
<tr>
<th>Run No</th>
<th>Pressure (kg/cm²)</th>
<th>Mass Flux (10^6 kg/m²hr)</th>
<th>Power (kW)</th>
<th>Inlet Temperature (°C)</th>
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<tr>
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<td>2023</td>
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</table>

*1 kg/cm² = 98,066.5 Pascals (Pa)
## Table 3.3.1-4 Test Conditions for Steady-State Void Measurement Test Series 8

<table>
<thead>
<tr>
<th>Run No</th>
<th>Pressure (kg/cm²)</th>
<th>Mass Flux (10⁶ kg/m²hr)</th>
<th>Power (kW)</th>
<th>Inlet Temperature (°C)</th>
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<tr>
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<td>11.11</td>
<td>3514.9</td>
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<td>1025.2</td>
<td>148.6</td>
</tr>
</tbody>
</table>

*1 kg/cm² = 98,066.5 Pascals (Pa)*

## 3.3.2 Participation and Submitted Results

There were a total of seventeen (17) participants for Exercise 2. All sixteen submitted void fraction results, while two submitted axial void distribution results. Table 3.3.2-1 lists these participants, as well as the codes for which results were submitted.

### Table 3.3.2-1 Phase I Exercise 2 Participants and Code List

<table>
<thead>
<tr>
<th>Participant</th>
<th>Code</th>
<th>Code Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>EDF</td>
<td>THYC</td>
<td>Porous media</td>
</tr>
<tr>
<td>AREVA</td>
<td>F-COBRA-TF</td>
<td>Sub-channel</td>
</tr>
<tr>
<td>CEA-Saclay</td>
<td>FLICA-OVAP</td>
<td>Sub-channel</td>
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<td>CSA</td>
<td>VIPRE</td>
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<td>JNES</td>
<td>CHAMP-ITA</td>
<td>Sub-channel</td>
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<td>KAERI</td>
<td>MATRA</td>
<td>Sub-channel</td>
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<tr>
<td>KIT</td>
<td>SUBCHANFLOW</td>
<td>Sub-channel</td>
</tr>
<tr>
<td>McMaster</td>
<td>ASSERT-PV</td>
<td>Sub-channel</td>
</tr>
<tr>
<td>NRI</td>
<td>VIPRE</td>
<td>Sub-channel</td>
</tr>
<tr>
<td>PSI</td>
<td>FLICA</td>
<td>Sub-channel</td>
</tr>
<tr>
<td>WEC/INVAP</td>
<td>VIPRE</td>
<td>Sub-channel</td>
</tr>
<tr>
<td>CEA-Grenoble</td>
<td>CATHARE 3</td>
<td>System</td>
</tr>
<tr>
<td>Chalmers</td>
<td>RELAP-5</td>
<td>System</td>
</tr>
<tr>
<td>KTH</td>
<td>TRACE</td>
<td>System</td>
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<tr>
<td>PSI</td>
<td>TRACE</td>
<td>System</td>
</tr>
<tr>
<td>UNIPI</td>
<td>CATHARE 2</td>
<td>System</td>
</tr>
<tr>
<td>USNRC</td>
<td>TRACE</td>
<td>System</td>
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</tbody>
</table>
The questionnaires submitted by the participants can be found in Appendix V. The characteristics of many of the codes used in this exercise have been previously discussed. Some modelling considerations specific to this exercise include increasing the number of axial nodes and modelling spacer grids. A number of the codes (such as THYC) did not model spacer grid effects, while others [CATHARE 3 (CEA-Grenoble)] applied a pressure loss one cell in front of the spacer grid.

A number of cross-flow models were also used. THYC used Chexal-Lellouche for drift flux, as well as a no-slip condition and Cheng-Todreas for turbulent diffusivity, while CATHARE 3 (CEA-Grenoble) used a turbulent dispersion term. Yet other codes did not consider cross-flow effects.

### 3.3.3 Statistical Methodology

The mean error and standard deviation were calculated for each measurement location for each test series using the equations given in Section 3.2.3.

### 3.3.4 Comparative Analysis of Participant Results

Appendix II contains the complete set of participant results for Exercise 2. Figure 3.3.4-1, Figure 3.3.4-3, Figure 3.3.4-5 and Figure 3.3.4-7 summarise the error of participants’ void fraction predictions, while Figure 3.3.4-2, Figure 3.3.4-4, Figure 3.3.4-6 and Figure 3.3.4-8 summarise the standard deviation of these results.

**Figure 3.3.4-1 Test Series 5 Void Fraction Error**
Figure 3.3.4-2 Test Series 5 Void Fraction Standard Deviation

Figure 3.3.4-3 Test Series 6 Void Fraction Error
Figure 3.3.4-4 Test Series 6 Void Fraction Standard Deviation

Test Series 6 - Standard Deviation

Figure 3.3.4-5 Test Series 7 Void Fraction Error

Test Series 7 - Mean Error
3.3.4.1 Axial Void Distribution

Three participants submitted axial void distributions for the selected test case. These results are shown in Figure AI-37. The codes show similar behavior, but as there is no experimental data to compare to, it is difficult to say anything about their accuracy.

3.3.5 Discussion on the Predicted Steady-State Bundle Void Distribution

It was noted that the codes consistently overpredicted the void fraction at the lower elevation in the bundle. However, the results were generally improved at higher elevations, although some underprediction could be seen. Both of these observations are clearly represented in the plots of mean error for each test series.

The majority of the codes also consistently predicted the correct thermal equilibrium quality at the lower elevations, with the only exceptions being KTH’s TRACE and UNIPI’s CATHARE, which overpredicted the quality. All of the codes tended to underpredict the quality at the upper bundle elevations.

3.4 Exercise 3 – Transient Rod Bundle

3.4.1 Selected Exercise Cases and Requested Computational Results

The available data for this exercise consisted of chordal-averaged x-ray densitometer measurements of fluid density in the rod bundle. The measured density was then used to calculate the void fraction. The given values are the average of the void fraction over the four central sub-channels of the bundle.

Four transient scenarios (temperature increase, power increase, depressurisation, and flow reduction) were used in this exercise for each test series, yielding twelve total test cases. The test conditions are summarised in Table 3.4.1-1. All transient cases were analysed.

The boundary conditions for test series 5T are shown in Figure 3.4.1-1, Figure 3.4.1-2, Figure 3.4.1-3 and Figure 3.4.1-4. Similar boundary conditions are given in the benchmark specification for test series 6T and 7T.
The requested outputs for this exercise were region-averaged void fraction for each of the three measurement locations for each given time step.

Table 3.4.1-1 Test Conditions for Transient Void Measurement Test Series 5T, 6T, 7T

<table>
<thead>
<tr>
<th>Test Series</th>
<th>Assembly</th>
<th>Initial Conditions</th>
<th>Transients</th>
</tr>
</thead>
<tbody>
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<td></td>
<td>Pressure (kg/cm²a)</td>
<td>Mass flux (10⁶kg/m²h)</td>
</tr>
<tr>
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<td>B5</td>
<td>154.2</td>
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<td></td>
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<td>B6</td>
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<td></td>
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<td>157.2</td>
<td>11.92</td>
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<td>B7</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>158.8</td>
<td>11.99</td>
</tr>
</tbody>
</table>

Figure 3.4.1-1 Variation of Properties for Test Case 5T (Power Increase)
Figure 3.4.1-2 Variation of Properties for Test Case 5T (Flow Reduction)

5T - Flow Reduction

<table>
<thead>
<tr>
<th>Ratio to Initial value</th>
<th>Time (sec)</th>
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<tr>
<td>1.10</td>
<td>36</td>
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</tbody>
</table>

Figure 3.4.1-3 Variation of Properties for Test Case 5T (Depressurisation)

5T - Depressurization

<table>
<thead>
<tr>
<th>Ratio to Initial value</th>
<th>Time (sec)</th>
</tr>
</thead>
<tbody>
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<td>100</td>
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<tr>
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<tr>
<td>1.00</td>
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<td>160</td>
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<tr>
<td>1.10</td>
<td>180</td>
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</table>
3.4.2 Participation and Submitted Results

There were a total of sixteen (16) participants for Exercise 3. Table 3.4.2-1 lists these participants, as well as the codes for which results were submitted.

Table 3.4.2-1 Phase I Exercise 3 Participants and Code List

<table>
<thead>
<tr>
<th>Participant</th>
<th>Code</th>
<th>Code Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>EDF</td>
<td>THYC</td>
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</tr>
<tr>
<td>AREVA</td>
<td>F-COBRA-TF</td>
<td>Sub-channel</td>
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<tr>
<td>CEA-Saclay</td>
<td>FLICA-OVAP</td>
<td>Sub-channel</td>
</tr>
<tr>
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<td>CHAMP-ITA</td>
<td>Sub-channel</td>
</tr>
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<td>MATRA</td>
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<tr>
<td>KIT</td>
<td>SUBCHANFLOW</td>
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<td>KTH</td>
<td>TRACE</td>
<td>System</td>
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<tr>
<td>CEA-Grenoble</td>
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<td>System</td>
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<td>UNIPI</td>
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<td>System</td>
</tr>
<tr>
<td>USNRC</td>
<td>TRACE</td>
<td>System</td>
</tr>
</tbody>
</table>
The questionnaires submitted by the participants can be found in Appendix V. The characteristics of the codes used in this exercise have been previously discussed.

3.4.3 Comparative Analysis of Participant Results

Appendix III contains the complete set of participant results for Exercise 3.

3.4.4 Discussion on the Predicted Transient Bundle Void Distribution

A slight time shift can be seen in the void fraction results when they are compared to the experimental data for the temperature increase cases. It has been suggested that the structure between the downcomer and test section was not truly adiabatic and, as a result, there was some heat transfer between these regions that was responsible for this shift. Aside from that observation, the codes generally performed well in predicting the void fraction throughout the different transients, yielding better results at the highest elevation in the bundle and worse results at the lowest elevation. Some codes (such as KTH's version of TRACE) consistently underestimated the void fraction, especially at higher elevations. There was also consistent underprediction of void fraction at higher elevations for the depressurisation cases.

3.5 Exercise 4 – Pressure Drop

3.5.1 Selected Exercise Cases and Requested Computational Results

The only data available for code-to-data pressure drop comparison was the initial value of the pressure drop for the B7 bundle under the single-phase rated condition for the power increase transient in Test Series 7T (given as 1.6 kg/cm²). This value was used as a reference value for the rod bundle pressure drop calculations.

Code-to-code comparisons were performed on the pressure drop calculations for the typical central sub-channel. The boundary conditions include both single-phase and two-phase conditions. Exercise cases to be calculated correspond to Test Series 1 of the steady-state central sub-channel void measurements. The goal was to assess the wall friction and the two-phase multiplier models of the codes used.

Code-to-code comparisons were also performed on the pressure drop calculations for the bundle. Exercise cases to be calculated correspond to Test Series 5 of the steady-state bundle void measurements. The goal was to assess the pressure loss and the two-phase multiplier models of the codes used.

The requested outputs for this exercise were pressure drops across the bundle for each of the selected test cases.

3.5.2 Participation and Submitted Results

There were a total of sixteen (16) participants for Exercise 4. Table 3.5.2-1 summarises these participants as well as the codes for which results were submitted.
Table 3.5.2-1 Phase I Exercise 4 Participants and Code List

<table>
<thead>
<tr>
<th>Participant</th>
<th>Code</th>
<th>Code Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>GRS</td>
<td>ANSYS-CFX</td>
<td>CFD</td>
</tr>
<tr>
<td>HZDR</td>
<td>ANSYS-CFX</td>
<td>CFD</td>
</tr>
<tr>
<td>PSI</td>
<td>STAR-CD</td>
<td>CFD</td>
</tr>
<tr>
<td>EDF</td>
<td>THYC</td>
<td>Porous media</td>
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<tr>
<td>CSA</td>
<td>VIPRE</td>
<td>Sub-channel</td>
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<td>JNES</td>
<td>CHAMP-ITA</td>
<td>Sub-channel</td>
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<td>KAERI</td>
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<td>VIPRE</td>
<td>Sub-channel</td>
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<tr>
<td>PSI</td>
<td>FLICA</td>
<td>Sub-channel</td>
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<tr>
<td>CEA-Grenoble</td>
<td>CATHARE 3</td>
<td>System</td>
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<td>Chalmers</td>
<td>RELAP-5</td>
<td>System</td>
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<tr>
<td>KTH</td>
<td>TRACE</td>
<td>System</td>
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<td>PSI</td>
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<td>System</td>
</tr>
<tr>
<td>UNIPI</td>
<td>CATHARE 2</td>
<td>System</td>
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</tbody>
</table>

The questionnaires submitted by the participants can be found in Appendix V. A number of different models were used for single- and two-phase pressure drop. THYC used Colburn for axial 1-phase flow and HTFS as a two-phase multiplier. SUBCHANFLOW used Blasius and Armand correlations for single- and two-phase pressure drops.

Many codes used pressure loss coefficients for the grids. Some codes (such as CATHARE 2 (UNIPI), CATHARE 3 (CEA-Grenoble), and MATRA) modelled friction losses, as well as form losses at the grids and the bundle inlet and outlet, and losses due to gravity.

3.5.3 Comparative Analysis of Participant Results
Appendix IV contains the complete set of participant results for Exercise 4.

3.5.4 Discussion on the Predicted Bundle Pressure Drop
It was observed that there were major differences between codes in the reported values for the pressure drop in sub-channel S1. Since there were not experimental values given for pressure drop for these cases, or for the cases using bundle B5, it is not possible to determine which codes correctly predict the pressure drop. It was noted, however, that the codes yielded results for the bundle pressure drop cases that were more similar to each other. For the only case with an experimental data point, the codes generally performed well, with a maximum deviation of 0.6 kg/cm² (or a 37.5% deviation from the measured value of 1.6 kg/cm²).
Chapter 4
Conclusion

The PSBT benchmark was designed to provide a set of data for the development and validation of the next generation of thermal-hydraulic codes. It consisted of two phases: a void fraction benchmark and a departure from nucleate boiling benchmark. Data regarding the test sections and conditions were provided to participants for use in calculations. The code results from all participants were then compiled and analysed.

In the development of the benchmark specification, a number of support studies were performed. The experimental void fraction and quality were recalculated using the experimentally-determined fluid density for each of the benchmark test cases, and a deviation between these recalculated values and the measured values was observed. Studies were also conducted to determine the effect of the downcomer region on the fluid temperature and the effect of the CT mask on void fraction at sub-cooled boiling conditions.

The participants’ results for each benchmark exercise were analysed and conclusions were drawn. In the results for the first phase, it was observed that the codes tended to overpredict the thermal equilibrium quality at lower elevations and underpredict it at higher elevations. There was also a tendency to overpredict void fraction at lower elevations and underpredict it at high elevations for the bundle test cases. The overprediction of void fraction at low elevations is likely caused by the x-ray densitometer measurement method used. Under sub-cooled boiling conditions, the voids accumulate at heated surfaces (and are therefore not seen in the centre of the sub-channel, where the measurements are being taken), so the experimentally-determined void fractions will be lower than the actual void fraction. Some of the best results were achieved by codes that used either turbulent mixing or dispersion terms for modelling cross-flow. It was also noted that, for the bundle cases, some of the codes did not correctly calculate the bundle-averaged thermal equilibrium quality, and this may indicate an inability to predict the correct void fraction. A time shift was noted in the void fraction results for the temperature increase transient cases, indicating that the test apparatus may have experienced unexpected heat transfer between the downcomer and test section. This heat transfer is only expected to be of significance in the transient test cases, as the steady-state cases allow the system to reach thermal equilibrium.
Bibliography


Appendix I: Phase I Exercise 1 Results

Figure AI-1 Test Series 1 Density Results

Test Series 1 - Density (kg/m³)

Figure AI-2 Test Series 2 Density Results

Test Series 2 - Density (kg/m³)

Figure AI-3 Test Series 3 Density Results
Figure AI-5 Test Series 1 Void Fraction (Calculated vs. Measured) Results

Test Series 1 - Void Fraction (-)

Reference
Figure Al-6 Test Series 1 Void Fraction (Calculated vs. Recalculated) Results
Figure AI-7 Test Series 2 Void Fraction (Calculated vs. Measured) Results
Figure AI-8 Test Series 2 Void Fraction (Calculated vs. Recalculated) Results
Figure AI-9 Test Series 3 Void Fraction (Calculated vs. Measured) Results

Test Series 3 - Void Fraction (-)

Test Series 3 - Void Fraction (-)

Test Series 3 - Void Fraction (-)

Reference
Figure AI-10 Test Series 3 Void Fraction (Calculated vs. Recalculated) Results
Figure AI-12 Test Series 4 Void Fraction (Calculated vs. Recalculated) Results

Test Series 4 - Void Fraction (-)

- KIT (JUMPFLOW)
- EDF (THYC)
- JNES (CHAMP-ITA)
- CEA-Saclay (FLICA-CVAP)
- PSI (FLUC)
- AREVA (C-COBRA-TF)
- KAERI (MATRA)
- McMaster (ASSORT-PV)
- CSA (VIPRE)

Reference

Test Series 4 - Void Fraction (-)

- PSI (TRACE)
- KTH (TRACE)
- IRSN (CATHARE 2)
- CEA-Grenoble (CATHARE 3)
- UNIP (CATHARE 2)

Reference

Test Series 4 - Void Fraction (-)

- PSI (STAR-CO)

Reference
Figure AI-13 Test Series 1 Thermal Equilibrium Quality (Calculated vs. Measured) Results

Figure AI-14 Test Series 1 Thermal Equilibrium Quality (Calculated vs. Recalculated) Results
Figure AI-15 Test Series 2 Thermal Equilibrium Quality (Calculated vs. Measured) Results

Figure AI-16 Test Series 2 Thermal Equilibrium Quality (Calculated vs. Recalculated) Results
Figure AI-17 Test Series 3 Thermal Equilibrium Quality (Calculated vs. Recalculated) Results

Figure AI-18 Test Series 4 Thermal Equilibrium Quality (Calculated vs. Recalculated) Results
### Table A1-1 Results of Recalculation of Sub-channel-Averaged Void Fraction

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Table AI-2 Results of Recalculation of Sub-channel-Averaged Thermal Equilibrium Quality

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Figure AI-19 Axial Void Distribution Results of Run 1.2211

Figure AI-20 Axial Void Distribution Results of Run 1.2223
Figure AI-21 Axial Void Distribution Results of Run 1.2237

Run 1.2237

Figure AI-22 Axial Void Distribution Results of Run 1.4326

Run 1.4326
Figure AI-23 Axial Void Distribution Results of Run 1.4325

Figure AI-24 CT Image of Test Case 1.1222
Figure AI-28 STAR-CD (PSI) Image of Test Case 1.1223

Figure AI-29 NEPTUNE (EDF) Image of Test Case 1.1223

Figure AI-30 CT Image of Test Case 1.2221
Figure AI-31 STAR-CD (PSI) Image of Test Case 1.2221

Figure AI-32 NEPTUNE (EDF) Image of Test Case 1.2221

Figure AI-33 CT Image of Test Case 1.2223
Figure AI-34 STAR-CD (PSI) Image of Test Case 1.2223

Figure AI-35 NEPTUNE (EDF) Image of Test Case 1.2223

Figure AI-36 CT Image of Test Case 1.2422
Figure Al-37 STAR-CD (PSI) Image of Test Case 1.2422

Figure Al-38 NEPTUNE (EDF) Image of Test Case 1.2422

Figure Al-39 CT Image of Test Case 1.2423
Figure AI-40 STAR-CD (PSI) Image of Test Case 1.2423

Figure AI-41 NEPTUNE (EDF) Image of Test Case 1.2423

Figure AI-42 CT Image of Test Case 1.4311
Figure AI-43 NEPTUNE (EDF) Image of Test Case 1.4311

Figure AI-44 CT Image of Test Case 1.4312

Figure AI-45 STAR-CD (PSI) Image of Test Case 1.4312
Figure AI-46 NEPTUNE (EDF) Image of Test Case 1.4312

Figure AI-47 CT Image of Test Case 1.5221

Figure AI-48 NEPTUNE (EDF) Image of Test Case 1.5221
Figure AI-49 CT Image of Test Case 1.5222

Figure AI-50 NEPTUNE (EDF) Images of Test Case 1.5222

Figure AI-51 CT Image of Test Case 1.6221
Figure AI-52 NEPTUNE (EDF) Image of Test Case 1.6221

Figure AI-53 CT Image of Test Case 1.6222

Figure AI-54 NEPTUNE (EDF) Image of Test Case 1.6222
Figure AI-55 CT Image of Test Case 2.1231

Figure AI-56 STAR-CD (PSI) Image of Test Case 2.1231

Figure AI-57 NEPTUNE (EDF) Image of Test Case 2.1231
Figure AI-58 CT Image of Test Case 2.1232

Figure AI-59 STAR-CD (PSI) Image of Test Case 2.1232

Figure AI-60 NEPTUNE (EDF) Image of Test Case 2.1232
Figure AI-61 CT Image of Test Case 2.1233

Figure AI-62 STAR-CD (PSI) Image of Test Case 2.1233

Figure AI-63 NEPTUNE (EDF) Image of Test Case 2.1233
Figure AI-67 CT Image of Test Case 2.3233

Figure AI-68 STAR-CD (PSI) Image of Test Case 2.3233

Figure AI-69 NEPTUNE (EDF) Image of Test Case 2.3233
Figure Al-70 CT Image of Test Case 2.4421

Figure Al-71 NEPTUNE (EDF) Image of Test Case 2.4421

Figure Al-72 CT Image of Test Case 2.4422
Figure AI-73 STAR-CD (PSI) Image of Test Case 2.4422

Figure AI-74 NEPTUNE (EDF) Image of Test Case 2.4422

Figure AI-75 CT Image of Test Case 2.4551
Figure AI-76 STAR-CD (PSI) Image of Test Case 2.4551

Figure AI-77 NEPTUNE (EDF) Image of Test Case 2.4551

Figure AI-78 CT Image of Test Case 2.4552
Figure A1-82 STAR-CD (PSI) Image of Test Case 2.6433

Figure A1-83 STAR-CD (PSI) Image of Test Case 3.2231

Figure A1-84 STAR-CD (PSI) Image of Test Case 3.2232
Figure AI-85 STAR-CD (PSI) Image of Test Case 3.2451

Figure AI-86 STAR-CD (PSI) Image of Test Case 3.2452

Figure AI-87 STAR-CD (PSI) Image of Test Case 3.2453
Figure AI-91 STAR-CD (PSI) Image of Test Case 4.2257

Figure AI-92 STAR-CD (PSI) Image of Test Case 4.4455

Figure AI-93 STAR-CD (PSI) Image of Test Case 4.4456
Figure AI-94 STAR-CD (PSI) Image of Test Case 4.6461
Appendix II: Phase I Exercise 2 Results

Figure AII-1 Test Series 5 Region-Averaged Void Fraction Results – Lower Elevation
Figure AII-2 Test Series 5 Region-Averaged Void Fraction Results – Middle Elevation
Figure AII-3 Test Series 5 Region-Averaged Void Fraction Results – Upper Elevation

Test Series 5 - Region-Averaged Void Fraction (Upper Elevation)

- KIT (SUBCHANFLOW)
- EDF (THYC)
- JNES (CHAMP-ITA)
- CEA-Saclay (FLICA-0VAP)
- PSI (FLICA)
- AREVA (F-COBRA.TF)
- KAERI (MATRA)
- McMaster [ASSERT-PV]
- NRI (VIPRE)
- WEC/NVAP (VIPRE)
- CSA (VIPRE)

Reference

[Graph showing calculated vs measured void fraction for various institutions with reference line indicating agreement]

Test Series 5 - Region-Averaged Void Fraction (Upper Elevation)

- PSI (TRACE)
- KTH (TRACE)
- CEA-Grenoble (CATHARE 3)
- Chalmers (RELAP-5)
- UNIPI (CATHARE 2)
- USNRC (TRACE)

Reference
Figure AII-4 Test Series 6 Region-Averaged Void Fraction Results – Lower Elevation
Figure AII-5 Test Series 6 Region-Averaged Void Fraction Results – Middle Elevation
Figure AII-6 Test Series 6 Region-Averaged Void Fraction Results – Upper Elevation
Figure AII-7 Test Series 7 Region-Averaged Void Fraction Results – Lower Elevation
Figure AII-8 Test Series 7 Region-Averaged Void Fraction Results – Middle Elevation

Test Series 7 - Region-Averaged Void Fraction
(Middle Elevation)

Test Series 7 - Region-Averaged Void Fraction
(Middle Elevation)
Figure AII-9 Test Series 7 Region-Averaged Void Fraction Results – Upper Elevation

Test Series 7 - Region-Averaged Void Fraction (Upper Elevation)

- KIT (SUBCHANFLOW)
- EDF (THYC)
- JNES (CHAMP-ITA)
- CEA-Saclay (FLICA-OVAP)
- PSI (FLICA)
- AREVA (F-COBRA-TF)
- KAERI (MATRA)
- McMaster (ASSERT-FV)
- NRI (VIPRE)
- WEC/INVAP (VIPRE)
- CSA (VIPRE)

Reference

Test Series 7 - Region-Averaged Void Fraction (Upper Elevation)

- PSI (TRACE)
- KTH (TRACE)
- CEA-Grenoble (CATHARE 3)
- Chalmers (RELAP-5)
- UNIPI (CATHARE 2)

Reference
Figure All-10 Test Series 8 Region-Averaged Void Fraction Results – Lower Elevation

Test Series 8 - Region-Averaged Void Fraction (Lower Elevation)

- KIT (SUBCHANFLOW)
- EDF (THYC)
- JNES (CHAMP-ITA)
- CEA-Sarlay (FLUCA-DVAP)
- PSI (FLIC)
- AREVA (F-COBRA-TF)
- KAERI (MATRA)
- McMaster (ASSERT-PV)
- NRI (VIPRE)
- WEC/INVAP (VIPRE)
- CSA (VIPRE)

Reference

Test Series 8 - Region-Averaged Void Fraction (Lower Elevation)

- PSI (TRACE)
- KTH (TRACE)
- CEA-Grenoble (CATHARE 3)
- Chalmers (RELAP-5)
- UNIPI (CATHARE 2)
- USNRC (TRACE)

Reference
Figure AII-11 Test Series 8 Region-Averaged Void Fraction Results – Middle Elevation
Figure AII-12 Test Series 8 Region-Averaged Void Fraction Results – Upper Elevation

Test Series 8 - Region-Averaged Void Fraction (Upper Elevation)
Figure AII-13 Test Series 5 Bundle-Averaged Void Fraction – Lower Elevation

Test Series 5 - Bundle-Averaged Void Fraction (Lower Elevation)

Figure AII-14 Test Series 5 Bundle-Averaged Void Fraction – Middle Elevation

Test Series 5 - Bundle-Averaged Void Fraction (Middle Elevation)
Figure AII-15 Test Series 5 Bundle-Averaged Void Fraction – Upper Elevation

Figure AII-16 Test Series 6 Bundle-Averaged Void Fraction – Lower Elevation
Figure AII-17 Test Series 6 Bundle-Averaged Void Fraction – Middle Elevation

Figure AII-18 Test Series 6 Bundle-Averaged Void Fraction - Upper Elevation
Figure AII-19 Test Series 7 Bundle-Averaged Void Fraction – Lower Elevation

Test Series 7 - Bundle-Averaged Void Fraction (Lower Elevation)

Figure AII-20 Test Series 7 Bundle-Averaged Void Fraction – Middle Elevation

Test Series 7 - Bundle-Averaged Void Fraction (Middle Elevation)
Figure AII-23 Test Series 8 Bundle-Averaged Void Fraction – Middle Elevation

Figure AII-24 Test Series 8 Bundle-Averaged Void Fraction – Upper Elevation
Figure AII-25 Test Series 5 Bundle-Averaged Thermal Equilibrium Quality – Lower Elevation

Figure AII-26 Test Series 5 Bundle-Averaged Thermal Equilibrium Quality – Middle Elevation
Figure AII-27 Test Series 5 Bundle-Averaged Thermal Equilibrium Quality – Upper Elevation

Test Series 5 - Bundle-Averaged Thermal Equilibrium Quality (Upper Elevation)

Figure AII-28 Test Series 6 Bundle-Averaged Thermal Equilibrium Quality – Lower Elevation

Test Series 6 - Bundle-Averaged Thermal Equilibrium Quality (Lower Elevation)
Figure AII-29 Test Series 6 Bundle-Averaged Thermal Equilibrium Quality – Middle Elevation

Figure AII-30 Test Series 6 Bundle-Averaged Thermal Equilibrium Quality – Upper Elevation
Figure AII-31 Test Series 7 Bundle-Averaged Thermal Equilibrium Quality – Lower Elevation

Test Series 7 - Bundle-Averaged Thermal Equilibrium Quality (Lower Elevation)

- KIT (SUBCHANFLOW)
- JNES (CHAMP-ITA)
- CEA-Saclay (FLICA-OVAP)
- PSI (FLICA)
- PSI (TRACE)
- AREVA [F-COBRA-TF]
- KTH (TRACE)
- KAERI (MATRA)
- McMaster (ASSERT-PV)
- WEC/INVAP (VIPRE)
- UNIPI (CATHARE 2)

Reference

Figure AII-32 Test Series 7 Bundle-Averaged Thermal Equilibrium Quality – Middle Elevation

Test Series 7 - Bundle-Averaged Thermal Equilibrium Quality (Middle Elevation)

- KIT (SUBCHANFLOW)
- JNES (CHAMP-ITA)
- CEA-Saclay (FLICA-OVAP)
- PSI (FLICA)
- PSI (TRACE)
- AREVA [F-COBRA-TF]
- KTH (TRACE)
- KAERI (MATRA)
- McMaster (ASSERT-PV)
- WEC/INVAP (VIPRE)
- UNIPI (CATHARE 2)

Reference
Figure AII-33 Test Series 7 Bundle-Averaged Thermal Equilibrium Quality – Upper Elevation

Figure AII-34 Test Series 8 Bundle-Averaged Thermal Equilibrium Quality – Lower Elevation
Figure AII-35 Test Series 8 Bundle-Averaged Thermal Equilibrium Quality – Middle Elevation

Test Series 8 - Bundle-Averaged Thermal Equilibrium Quality (Middle Elevation)

Figure AII-36 Test Series 8 Bundle-Averaged Thermal Equilibrium Quality – Upper Elevation

Test Series 8 - Bundle-Averaged Thermal Equilibrium Quality (Upper Elevation)
## Table AII-1 Results of Recalculation of Bundle-Averaged Thermal Equilibrium Quality

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Figure AII-37 Axial Void Distribution for Run 5.2332

- KTH (TRACE)
- PSI (TRACE)
- PSI (FLICA)
Appendix III: Phase I Exercise 3 Results

Figure AIII-1 Test Series 5T (Power Increase) – Lower Elevation Results

Lower Elevation (Subchannel Codes Only)

Lower Elevation (System Codes Only)
Figure AIII-2 Test Series 5T (Power Increase) – Middle Elevation Results

### Middle Elevation (Subchannel Codes Only)

- Measured
- KIT (SUBCHANFLOW)
- EDF (THYC)
- INES (CHAMP-ITA)
- CEA-Saclay (FLICA-OVAF)
- PSI (FLICA)
- AREVA (F-COBRA-TF)
- KAERI (MATRA)
- McMaster (ASSERT-PV)
- NRI (VIPRE)
- WEC/INVAP (VIPRE)

### Middle Elevation (System Codes Only)

- Measured
- KTH (TRACE)
- IRSN (CATHARE 2)
- CEA-Grenoble (CATHARE 3)
- Chalmers (RELAP-5)
- UNIFI (CATHARE 2)
- USNRC (TRACE)
Figure AIII-3 Test Series 5T (Power Increase) – Upper Elevation Results

Upper Elevation (Subchannel Codes Only)

Upper Elevation (System Codes Only)
Figure AIII-4 Test Series 6T (Power Increase) – Lower Elevation Results

**Lower Elevation (Subchannel Codes Only)**

- Measured
- + KIT (SUBCHANFLOW)
- □ EDF (THYC)
- ✗ CEA-Saclay (FLICA-OVALP)
- ○ PSI (FLICA)
- △ AREVA (F-COBRA-TF)
- ▲ KAERI (MATRA)
- McMaster (ASSERT-PV)
- ★ NRI (VIPRE)
- + WEC/INVAP (VIPRE)

**Lower Elevation (System Codes Only)**

- Measured
- △ KTH (TRACE)
- ■ CEA-Grenoble (CATHARE 3)
- ○ Chalmers (RELAP-5)
- ▼ UNIP (CATHARE 2)
Figure AIII-5 Test Series 6T (Power Increase) – Middle Elevation Results

Middle Elevation (Subchannel Codes Only)

Middle Elevation (System Codes Only)
Figure AIII-6 Test Series 6T (Power Increase) – Upper Elevation Results
Figure AIII-7 Test Series 7T (Power Increase) – Lower Elevation Results

Lower Elevation (Subchannel Codes Only)

- Measured
- KIT (SUBCHANFLOW)
- EDF (THYC)
- CEA-Saclay (FLICA-OVAP)
- PSI (FLICA)
- AREVA (F-COBRA-TF)
- KAERI (MATRA)
- McMaster (ASSERT-PV)
- NRI (VIPRE)
- WEC/INVAP (VIPRE)

Lower Elevation (System Codes Only)

- Measured
- KTH (TRACE)
- CEA-Grenoble (CATHARE 3)
- Chalmers (RELAP-5)
- UNIPI (CATHARE 2)
Figure AIII-8 Test Series 7T (Power Increase) – Middle Elevation Results

Middle Elevation (Subchannel Codes Only)

Middle Elevation (System Codes Only)
Figure AIII-9 Test Series 7T (Power Increase) – Upper Elevation Results

Upper Elevation (Subchannel Codes Only)

- Measured
- KIT (SUBCHANFLOW)
- EDF (THYC)
- CEA-Saclay (FLICA-OVALP)
- PSI (FLICA)
- AREVA (F-COBRA-TF)
- KAERI (MATRA)
- McMaster (ASSERT-PV)
- NRI (VIPRE)
- WEC/INVAP (VIPRE)

Upper Elevation (System Codes Only)

- Measured
- KTH (TRACE)
- CEA-Grenoble (CATHARE 3)
- Chalmers (RELAP-5)
- UNIPI (CATHARE 2)
Figure AIII-10 Test Series ST (Flow Reduction) – Lower Elevation Results

**Lower Elevation (Subchannel Codes Only)**

- Measured
- KIT (SUBCHANFLOW)
- EDF (THYC)
- JNES (CHAMP-ITA)
- CEA-Saclay (FLICA-0VAP)
- PSI (FLICA)
- AREVA (F-COBRA-TF)
- KAERI (MATRA)
- McMaster (ASSERT-PV)
- NRI (VIPRE)
- WEC/INVAP (VIPRE)

**Lower Elevation (System Codes Only)**

- Measured
- KTH (TRACE)
- IRSN (CATHARE 2)
- CEA-Grenoble (CATHARE 3)
- Chalmers (RELAP-5)
- UNIFI (CATHARE 2)
- USNRC (TRACE)
Figure AIII-11 Test Series 5T (Flow Reduction) – Middle Elevation Results

Middle Elevation (Subchannel Codes Only)

- Measured
- KIT (SUBCHANFLOW)
- EDF (THYC)
- INES (CHAMP-ITA)
- CEA-Saclay (FLICA-OVAP)
- PSI (FLICA)
- AREVA (F-COBRA-TF)
- KAERI (MATRA)
- McMaster (ASSERT-PV)
- NRRI (VIRE)
- WEC/INVAP (VIPRE)

Middle Elevation (System Codes Only)

- Measured
- KTH (TRACE)
- IRSN (CATHARE 2)
- CEA-Grenoble (CATHARE 3)
- Chalmers (RELAP-5)
- UNIP (CATHARE 2)
- USNRC (TRACE)
Figure AIII-12 Test Series 5T (Flow Reduction) – Upper Elevation Results

**Upper Elevation (Subchannel Codes Only)**

- Measured
- + KIT (SUBCHANFLOW)
- ◦ EDF (THYC)
- ■ JNES (CHAMP-ITA)
- × CEA-Saclay (FLICA-OVAP)
- ○ PSI (FLICA)
- △ AREVA (F-COBRA-TF)
- ◊ KAERI (MATRA)
- ■ McMaster (ASSERT-PV)
- □ NRI (VIPRE)
- ◆ WEC/INVAP (VIPRE)

**Upper Elevation (System Codes Only)**

- Measured
- △ KTH (TRACE)
- ■ IRSN (CATHARE 2)
- □ CEA-Grenoble (CATHARE 3)
- ◊ Chalmers (RELAP-5)
- ■ UNIPI (CATHARE 2)
- □ USNRC (TRACE)
Figure AIII-13 Test Series 6T (Flow Reduction) – Lower Elevation Results

**Lower Elevation (Subchannel Codes Only)**

- Measured
- KIT (SUBCHANFLOW)
- EDF (THYC)
- JNES (CHAMP-ITA)
- CEA-Saclay (FLICA-OVAP)
- PSI (FLICA)
- AREVA (F-COBRA-TF)
- KAERI (MATRA)
- McMaster (ASSERT-PV)
- NRI (VIPRE)
- WEC/INVAP (VIPRE)

**Lower Elevation (System Codes Only)**

- Measured
- KTH (TRACE)
- CEA-Grenoble (CATHARE 3)
- Chalmers (RELAP-5)
- UNIPI (CATHARE 2)
Figure AIII-14 Test Series 6T (Flow Reduction) – Middle Elevation Results

Middle Elevation (Subchannel Codes Only)

Middle Elevation (System Codes Only)
Figure AIII-15 Test Series 6T (Flow Reduction) – Upper Elevation Results

Upper Elevation (Subchannel Codes Only)

- Measured
- KIT (SUBCHANFLOW)
- EDF (THYC)
- JNES (CHAMP-ITA)
- CEA-Saclay (FLICA-OVAP)
- PSI (FLICA)
- AREVA (F-COBRA-TF)
- KAERI (MATRA)
- McMaster (ASSERT-PV)
- NRi (VIPRE)
- WEC/INVAP (VIPRE)

Upper Elevation (System Codes Only)

- Measured
- KTH (TRACE)
- CEA-Grenoble (CATHARE 3)
- Chalmers (RELAP-5)
- UNIPI (CATHARE 2)
Figure AIII-16 Test Series 7T (Flow Reduction) – Lower Elevation Results

Lower Elevation (Subchannel Codes Only)

Lower Elevation (System Codes Only)
Figure AIII-17 Test Series 7T (Flow Reduction) – Middle Elevation Results

Middle Elevation (Subchannel Codes Only)

- Measured
- KIT (SUBCHANFLOW)
- EDF (THYC)
- INES (CHAMP-ITA)
- CEA-Saclay (FLICA-OVAP)
- PSI (FLICA)
- AREVA (F-COBRA-TF)
- KAERI (MATRA)
- McMaster (ASSERT-PV)
- NRi (VIPRE)
- WECP/INVAP (VIPRE)

Middle Elevation (System Codes Only)

- Measured
- KTH (TRACE)
- CEA-Grenoble (CATHARE 3)
- Chalmers (RELAP-5)
- UNIPI (CATHARE 2)
Figure AIII-18 Test Series 7T (Flow Reduction) – Upper Elevation Results

Upper Elevation (Subchannel Codes Only)

- Measured
- KIT (SUBCHANFLOW)
- EDF (THYC)
- JNES (CHAMP-ITA)
- CEA-Saclay (FLICA-OVAP)
- PSI (FLICA)
- AREVA (F-COBRA-TF)
- KAERI (MATRA)
- McMaster (ASSERT-PV)
- NRI (VIPRE)
- WEC/INVAP (VIPRE)

Upper Elevation (System Codes Only)

- Measured
- KTH (TRACE)
- CEA-Grenoble (CATHARE 3)
- Chalmers (RELAP-5)
- UNIPI (CATHARE 2)
Figure AIII-19 Test Series 5T (Depressurization) – Lower Elevation Results

**Lower Elevation (Subchannel Codes Only)**

- Measured
- KIT (SUBCHANFLOW)
- EDF (THYC)
- CEA-Saclay (FLICA-OVAP)
- PSI (FLICA)
- AREVA (F-COBRA-TF)
- KAERI (MATRA)
- McMaster (ASSERT-PV)
- NRI (VIPRE)
- WEC/INVAP (VIPRE)

**Lower Elevation (System Codes Only)**

- Measured
- KTH (TRACE)
- IRSN (CATHARE 2)
- CEA-Grenoble (CATHARE 3)
- Chalmers (RELAP-5)
- UNIFI (CATHARE 2)
- USNRC (TRACE)
Figure AIII-20 Test Series 5T (Depressurization) – Middle Elevation Results

### Middle Elevation (Subchannel Codes Only)

- **Measured**
- **KIT (SUBCHANFLOW)**
- **EDF (THYC)**
- **CEA-Saclay (FLICA-OVAP)**
- **PSI (FLICA)**
- **AREVA (F-COBRA-TF)**
- **KAERI (MATRA)**
- **McMaster (ASSERT-PV)**
- **NRI (VIPRE)**
- **WEC/INVAP (VIPRE)**

### Middle Elevation (System Codes Only)

- **Measured**
- **KTH (TRACE)**
- **IRSN (CATHARE 2)**
- **CEA-Grenoble (CATHARE 3)**
- **Chalmers (RELAP-5)**
- **UNIPI (CATHARE 2)**
- **USNRC (TRACE)**
Figure AIII-21 Test Series 5T (Depressurization) – Upper Elevation Results

Upper Elevation (Subchannel Codes Only)

- Measured
- KIT (SUBCHANFLOW)
- CEDF (THYC)
- CEA-Saclay (FLICA-OVAP)
- PSI (FLICA)
- AREVA (F-COBRA-TF)
- KAERI (MATRA)
- McMaster (ASSERT-PV)
- NRI (VIPRE)
- WEC/INVAP (VIPRE)

Upper Elevation (System Codes Only)

- Measured
- KTH (TRACE)
- IRSN (CATHARE 2)
- CEA-Grenoble (CATHARE 3)
- Chalmers (RELAP-5)
- UNIPI (CATHARE 2)
- USNRC (TRACE)
Figure AIII-22 Test Series 6T (Depressurization) – Lower Elevation Results

Lower Elevation (Subchannel Codes Only)

- Measured
- KIT (SUBCHANFLOW)
- EDF (THYC)
- CEA-Saclay (FLICA-OVAP)
- PSI (FLICA)
- AREVA (F-COBRA-TF)
- KAERI (MATRA)
- McMaster (ASSERT-PV)
- NRI (VIPRE)
- WEC/INVAP (VIPRE)

Lower Elevation (System Codes Only)

- Measured
- KTH (TRACE)
- CEA-Grenoble (CATHARE 3)
- Chalmers (RELAP-5)
- UNIPI (CATHARE 2)
Figure AIII-23 Test Series 6T (Depressurization) – Middle Elevation Results

**Middle Elevation (Subchannel Codes Only)**

- Measured
- KIT (SUBCHANFLOW)
- EDF (THYC)
- CEA-Saclay (FLICA-OVAR)
- PSI (FLICA)
- AREVA (F-COBRA-TF)
- KAERI (MATRA)
- McMaster (ASSERT-PV)
- NRI (VIPRE)
- WEC/INVAP (VIPRE)

**Middle Elevation (System Codes Only)**

- Measured
- KTH (TRACE)
- CEA-Grenoble (CATHARE 3)
- Chalmers (RELAP-5)
- UNIPI (CATHARE 2)
Figure AIII-24 Test Series 6T (Depressurization) – Upper Elevation Results

Upper Elevation (Subchannel Codes Only)

- Measured
- KIT (SUBCHANFLOW)
- EDF (THYC)
- CEA-Saclay (FLICA-OVAP)
- PSI (FLICA)
- AREVA (F-COBRA-TF)
- KAERI (MATRA)
- McMaster (ASSERT-PV)
- NRI (VIPRE)
- WEC/INVAP (VIPRE)

Upper Elevation (System Codes Only)

- Measured
- KTH (TRACE)
- CEA-Grenoble (CATHARE 3)
- Chalmers (RELAP-5)
- UNIPI (CATHARE 2)
Figure AIII-25 Test Series 7T (Depressurization) – Lower Elevation Results

Lower Elevation (Subchannel Codes Only)

- Measured
- KIT (SUBCHANFLOW)
- EDF (THYC)
- CEA-Saclay (FLICA-OVAP)
- PSI (FLICA)
- AREVA (F-COBRA-TF)
- KAERI (MATRA)
- McMaster (ASSERT-PV)
- NRI (VIPRE)
- WEC/INVAP (VIPRE)

Lower Elevation (System Codes Only)

- Measured
- KTH (TRACE)
- CEA-Grenoble (CATHARE 3)
- Chalmers (RELAP-5)
- UNIP (CATHARE 2)
Figure AIII-26 Test Series 7T (Depressurization) – Middle Elevation Results

Middle Elevation (Subchannel Codes Only)

Middle Elevation (System Codes Only)
Figure AIII-27 Test Series 7T (Depressurization) – Upper Elevation Results

Upper Elevation (Subchannel Codes Only)

- Measured
- KIT (SUBCHANFLOW)
- EDF (THYC)
- CEA-Saclay (FLICA-OVALP)
- PSI (FLICA)
- AREVA (F-COBRA-TF)
- KAERI (MATRA)
- McMaster (ASSERT-PV)
- NRI (VIPRE)
- WEC/INLAP (VIPRE)

Upper Elevation (System Codes Only)

- Measured
- KTH (TRACE)
- CEA-Grenoble (CATHARE 3)
- Chalmers (RELAP-5)
- UNIPI (CATHARE 2)
Figure AIII-28 Test Series 5T (Temperature Increase) – Lower Elevation Results

Lower Elevation (Subchannel Codes Only)

- Measured
- KIT (SUBCHANFLOW)
- EDF (THYC)
- CEA-Saclay (FLICA-OVAF)
- PSI (FLICA)
- AREVA (F-COBRA-TF)
- KAERI (MATRA)
- McMaster (ASSERT-PV)
- NRI (VIPRE)
- WEC/INVAP (VIPRE)

Lower Elevation (System Codes Only)

- Measured
- KTH (TRACE)
- IRSN (CATHARE 2)
- CEA-Grenoble (CATHARE 3)
- Chalmers (RELAP-5)
- UNIPI (CATHARE 2)
- USNRC (TRACE)
Figure AIII-29 Test Series 5T (Temperature Increase) – Middle Elevation Results

Middle Elevation (Subchannel Codes Only)

- Measured
- KIT (SUBCHANFLOW)
- EDF (THYC)
- CEA-Saclay (FLICA-OVAP)
- PSI (FLICA)
- AREVA (F-COBRA-TF)
- KAERI (MATRA)
- McMaster (ASSERT-PV)
- NRI (VIPRE)
- WEC/INAVP (VIPRE)

Middle Elevation (System Codes Only)

- Measured
- KTH (TRACE)
- IRSN (CATHARE 2)
- CEA-Grenoble (CATHARE 3)
- Chalmers (RELAP-5)
- UNIPI (CATHARE 2)
- USNRC (TRACE)
Figure AIII-30 Test Series 5T (Temperature Increase) – Upper Elevation Results

Upper Elevation (Subchannel Codes Only)

Upper Elevation (System Codes Only)
Figure AIII-31 Test Series 6T (Temperature Increase) – Lower Elevation Results

Lower Elevation (Subchannel Codes Only)

- Measured
- KIT (SUBCHANFLOW)
- EDF (THYC)
- CEA-Saclay (FLICA-OVAP)
- PSI (FLICA)
- AREVA (F-COBRA-TF)
- KAERI (MATRA)
- McMaster (ASSERT-PV)
- NRI (VIPRE)
- WEC/INVAP (VIPRE)

Lower Elevation (System Codes Only)

- Measured
- KTH (TRACE)
- CEA-Grenoble (CATHARE 3)
- Chalmers (RELAP-5)
- UNIP (CATHARE 2)
Figure AIII-32 Test Series 6T (Temperature Increase) – Middle Elevation Results

Middle Elevation (Subchannel Codes Only)

Middle Elevation (System Codes Only)
Figure AIII-33 Test Series 6T (Temperature Increase) – Upper Elevation Results

Upper Elevation (Subchannel Codes Only)

Upper Elevation (System Codes Only)
Figure AIII-34 Test Series 7T (Temperature Increase) – Lower Elevation Results

Lower Elevation (Subchannel Codes Only)

Lower Elevation (System Codes Only)
Figure AIII-35 Test Series 7T (Temperature Increase) – Middle Elevation Results

Middle Elevation (Subchannel Codes Only)

Middle Elevation (System Codes Only)
Figure AIII-36 Test Series 7T (Temperature Increase) – Upper Elevation Results

Upper Elevation (Subchannel Codes Only)

Upper Elevation (System Codes Only)
Appendix IV: Phase I Exercise 4 Results

Figure AIV-1 Test Series 1 Pressure Drop Results

Figure AIV-2 Test Series 5 Pressure Drop Results
Figure AIV-3 Test Series 7T Pressure Drop Results
Appendix V: Participants’ Questionnaires

Questionnaires were submitted for seventeen (17) of the codes for which results were submitted. These questionnaires are presented here as they were submitted to the benchmark team.
AV.1 ANSYS (ANSYS)

AV.1.1 Overall Questionnaire

1. Specify the governing transport equations, assumptions and simplifications

In the current study, the software ANSYS CFX was used, both in Versions 12.11 and 13.0. The flow under investigation is described in the framework of the currently most conventional CFD approach for the modelling of two-phase flows with significant volume fractions of both phases - the Eulerian two-fluid model derived under the assumption of interpenetrating continua. Material properties for both vapour and liquid had been specified by defining material properties based on IAPWS-IF97 water/water steam tables defined for the given range of temperature and pressure of the test cases. Phase volume fraction distribution results from solving the phase-specific continuity equations for volume fractions. Separate sets of momentum equations are solved for each phase, where buoyancy and interfacial momentum transfer due to drag and non-drag forces is taken into account. Momentum transport equations are supplemented by turbulence model equations, where the shear stress transport model (SST) and the explicit algebraic Reynolds stress model (EARSM) have been applied to the continuous phase (depending on the set-up, see Section 1.3) and a zero-equation disperse phase turbulence model together with the Sato bubble enhanced turbulence model have been used to describe the turbulence effects arising from the bubbly phase, bubble induced turbulence [2].

For the steam-water flow an energy equation is solved for liquid, while for the description of the nucleate sub-cooled boiling processes under consideration the vapour is assumed to be at saturation temperature at all times. The exchange of mass, momentum and heat between phases is modelled using the correspondent source terms in the phase-specific balance equations. For the dispersed bubbly flow assumed for the nucleate sub-cooled boiling processes the interfacial momentum transfer is modelled in terms of the Grace drag law due to the interphase drag between phases and the acting non-drag forces.

Regarding the consideration of the non-drag forces the current framework in ANSYS CFX [2] allows for the inclusion of the lift, the wall lubrication, the virtual mass and the turbulent dispersion force. Further forces can be added by user-defined source terms. In the present study, depending on the set-up of the calculations, different combinations of non-drag forces were used including the formulations for the lift force, the wall lubrication force formulation [9-11] and the Favre averaged drag (FAD) turbulent dispersion force formulation [3]. For details on the differences between the set-ups, see Section 1.3.

The modelling approach for wall boiling will be described in a separate section. Once the steam is produced at the wall, it will be assumed that the steam is at local pressure dependent saturation temperature at all times. Further, the steam condensates in the bulk sub-cooled liquid (TL < Tsat) with the mass transfer rate per unit volume:

\[ m = \max \left( \frac{h_{LG}(T_{sat} - T_L)A_{LG}}{H_{LG}}, 0 \right) \]  

(1.1.1)

With superheated liquid, fluid is evaporates at the rate:
\[ \dot{n} = \max \left( \frac{h_{LG} (T_L - T_{sat}) A_{LG}}{H_{LG}}, 0 \right) \]  

(1.1.2)

\( A_{LG} \) is the interfacial area, and \( h_{LG} \) is the interfacial heat transfer coefficient, calculated according to [7]:

\[ h_{LG} = \frac{k_L}{d_B} \frac{N_i \dot{n}}{d_B} = \frac{k_L}{d_B} \left( 2 + 0.6 \frac{Re^{1/2}}{Pr^{1/3}} \right) \]  

(1.1.3)

This relationship is valid for mass transfer at the interface of rather small bubbles with diameters well below 0.5 mm, which is confirmed by the result from the used bubble departure diameter correlations for the given high-pressure cases.

To close the phase transition model in the bulk bubbly flow, a phasic characteristic length scale for the mean bubble diameter \( d_B \) has to be provided. This can be obtained from applying a population balance model like homogeneous/inhomogeneous MUSIG model or a DQMOM model. Here, we follow the simplified approach of providing a local mean bubble diameter as proposed by [1,6] where both suggested calculating the local bubble diameter \( d_B \) as a linear function of liquid sub-cooling \( T_{sub} \):

\[ d_B = \frac{d_{B1} (T_{sub} - T_{sub,2}) + d_{B2} (T_{sub,1} - T_{sub})}{T_{sub,1} - T_{sub,2}} \]  

(1.1.4)

For typical nuclear energy applications, these authors proposed sub-cooled nucleate boiling under PWR conditions (high-pressure conditions) reference bubble diameters at the two reference sub-cooling conditions: \( d_{B1} = 0.1 \) mm at \( T_{sub,1} = 13.5 \) K and \( d_{B2} = 2 \) mm at \( T_{sub,2} = -5 \) K. In this study, these values were changed to \( d_{B1} = 0.15 \) mm and \( d_{B2} = 0.65 \) mm. The bubble diameter in the bulk has a direct influence on the interfacial area density, therefore, on the condensation or evaporation rates in the bulk and on any other interfacial mass, momentum and heat transfer processes.

### 1.1 Modelling Nucleate Sub-cooled Boiling at Heated Walls

The current implementation and exposure of the wall boiling model in the CFD physics preprocessor of ANSYS CFX 12.0 and 13.0 had predecessors in earlier versions of ANSYS CFX as beta model capabilities. Therefore, more detailed descriptions of the wall boiling modelling approach exist from earlier publications, referring to [4,5;12]. All this model development follows the general outline of the so-called wall heat flux partitioning algorithm developed by [6] (RPI wall boiling model). Since this initial model development was aimed more at 1d thermohydraulic modelling of the phenomenon, model enhancements and adjustments were necessary in various places of the model algorithm formulation in order to accommodate for the specific requirements of an implementation into a general 3d CFD solver.

Sub-cooled boiling is observed at heated surfaces, when the heat flux applied to the wall is too high to be transferred to the core flow of liquid by the single-phase convective-conductive mechanisms. The term “sub-cooled” means, that the saturation temperature is exceeded only in a local vicinity of the wall, whereas the average temperature in the bulk is still below saturation.

The point, where the local wall temperature reaches the saturation temperature, is considered as the onset of nucleate boiling. Steam bubbles are generated at the heated surface at nucleation sites, with the surface density of these sites depending on different factors, including the wall superheat.
With increasing wall superheat \((T_{\text{sup}} = TW - Tsat)\), the attached bubbles grow and then leave the wall at certain critical size. This critical size, called bubble departure diameter, may depend on the surface tension and on the forces acting on the bubbles from the surrounding fluid.

Heat transfer from the wall is then described as being carried by turbulent convection of liquid, by transient conduction/quenching due to the departing bubbles and by evaporation. Distribution of the entire wall heat flux between these mechanisms (wall heat partitioning) can be calculated by modelling each mechanism in terms of the nucleation site density, the size of departing bubbles, their detachment frequency, and waiting time until the next bubble appears on the same site (mechanistic modelling approach). This mechanistic modelling approach of the wall boiling process is required in the framework of the CFD code, since, for technical applications, it is mostly impossible to fully resolve the micro-phenomenon of steam bubble formation at the heated wall on the underlying numerical mesh and with the applied time scale of integration. Instead, the resulting steam production and enhanced heat transfer to the liquid is taken into account by the mechanistic model of wall boiling based on the wall heat flux partitioning algorithm. Once the steam bubbles are released from the nucleation sites, they move through the sub-cooled liquid, condensate by releasing the latent heat and thereby heating up the liquid.

Following the modelling approach of the wall heat flux partitioning, the applied wall heat flux on the heated surface is split into 3 parts: \(Q_C\), the turbulent convective heating of the liquid, \(Q_Q\), the quenching heat flux and \(Q_E\), the evaporative heat flux:

\[
Q_W = Q_C + Q_Q + Q_E
\]  

(1.1.5)

As already mentioned, in this model vapour is assumed to be saturated everywhere, and no part of the wall heat flux is taken into account for superheating of the vapour phase. The heat partitioning model considers the whole heated wall surface as being separated into two fractions: a) fraction \(A_2\) influenced by the vapour bubbles, formed on the wall and b) fraction \(A_1\) being the remaining wall surface area with \(A_1 = 1 - A_2\). The wall area fraction \(A_1\) represents the part of the wall surface that is not affected by the growing steam bubbles. Therefore, the wall heat flux for this part of the surface is modelled in a similar way as for the single-phase convective heat transfer into pure liquid, by using the turbulent wall function procedure as outlined in [5]. Given that, the convective heat flux can be written as:

\[
Q_C = A_1 h_C (T_W - T_L)
\]  

(1.1.6)

where \(h_C\) is the turbulent heat transfer coefficient, which depends on the velocity field and is modelled using the turbulent temperature wall function [5]. The wall area fraction \(A_1\) represents the remaining part of the surface, which exchanges heat with both phases. The already mentioned evaporative heat flux \(Q_E\) is consumed for the evaporation of the initially sub-cooled liquid:

\[
Q_E = \dot{m} (h_{G,sat} - h_L)
\]  

(1.1.7)

with:
\[ m = \rho_g \frac{\pi d_w^2}{6} N_a f \]
\[ = \rho_g A_{2F}' \frac{2}{3} d_w f \]
\[ = \rho_g \min \left( \frac{\pi a^2 d_w^2}{4}, 5 \right) \frac{2}{3} d_w N_a f \]  
(1.1.8)

resulting in:

\[ Q_E = \frac{2}{3} \rho_g d_w \min \left( \frac{\pi a^2 d_w^2}{4}, 5 \right) N_a f h_{LG} \]  
(1.1.9)

where \( m \) is the evaporation mass transfer rate per unit wall area, \( A_{2F}' \) is the non-limited wall area influenced by vapour bubble formation, \( h_{G, sat} \) and \( h_L \) are the specific enthalpies of the saturated vapour and sub-cooled liquid respectively, \( d_w \) is the bubble departure diameter, \( N_a \) is the nucleation site density, \( f \) is the bubble detachment frequency and \( h_{LG} \) is here the latent heat of evaporation. The quenching heat flux due to transient vapour bubble departure and cooling of the wall area \( A_2 \) by substituting fresh sub-cooled liquid is modelled as:

\[ Q_Q = A_2 h_Q \left( T_w - T_L \right) \]  
(1.1.10)

where \( h_Q \) is the quenching heat transfer coefficient. In the above relationships the area \( A_2 \) influenced by the growing vapour bubbles is related to the nucleation site density and the bubble departure diameter:

\[ A_2 = \min \left( \pi a^2 d_w^2, N_a, 1 \right) \]  
(1.1.11)

where \( d_w \) is the bubble departure diameter, \( N_a \) is the nucleation site density and \( a \) is an influence factor introduced by [6] and is assumed to be \( a=2 \).

In order to arrive at a closed model formulation for the above wall heat flux partitioning scheme, a larger number of closure models have to be provided. These are required for the following model parameters:

- \( N_a \), wall nucleation site density;
- \( d_w \), bubble departure diameter;
- \( f \), bubble detachment frequency;
- \( h_Q \), quenching heat transfer coefficient;
- bubble waiting time.
The required closure relationships are provided from correlations, following in most cases the used correlations in the original model formulation of the RPI wall boiling model [6] but providing alternatives or the possibility for the model user to introduce his own model correlation as a user-defined relationship instead. For more details on the different available sub-models please refer to the ANSYS CFX user documentation [2].

One particular and rather important correlation used in this model closure is introduced for the bubble departure diameter. Here the RPI wall boiling model uses a correlation established [8]:

\[
d_{\text{fr}} = \min \left( d_{\text{ref}}, \exp \left( -\frac{\Delta T_{\text{sub}}}{\Delta T_{\text{ref}}}, d_{\text{max}} \right) \right)
\]  

(1.1.12)

The parameters of the original model are dimensional (\(d_{\text{max}}=1.4 \text{ mm}, d_{\text{ref}}=0.6 \text{ mm}, \Delta T_{\text{ref}}=45 \text{ K}\)) and \(\Delta T_{\text{sub}}\) refers to the local liquid sub-cooling. These model data are specific for the model application to nucleate sub-cooled boiling under pressurised conditions and need to be revised in case of model application to different operating conditions.

1.2 Boundary Conditions for the Wall Boiling Model

The implementation of the wall boiling model for nucleate sub-cooled boiling in ANSYS CFX 13.0 supports the specification of either a prescribed wall heat flux, a prescribed wall temperature at the surface of the heated wall or the use of a fluid-solid interphase with prediction of heat conduction in the adjacent solid material by conjugate heat transfer model (CHT). Equation (6) provides, in the first two cases, the relationship to predict either the resulting wall temperature in dependence on the prescribed wall heat flux or vice versa. In these calculations for the PSBT benchmark the wall heat flux was directly specified in the boundary condition of the heater surface.

1.3 Studied Set-ups

In the current study, three different set-ups were chosen that are mostly identical to the baseline set-up described earlier in this section, but differ in the turbulence model for the liquid phase, as well as in the specified non-drag forces to couple the momentum equations of liquid and gaseous phase. These different set-ups are referred to as SST_TD (SST with turbulent dispersion force), SST_NDF (SST with additional non-drag forces) and EARSM.

The following table lists the differences between the different set-ups:

<table>
<thead>
<tr>
<th>Table AV.1.1-1 Studied configurations</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Setup 1: SST_TD</strong></td>
</tr>
<tr>
<td>Turbulence Model</td>
</tr>
<tr>
<td>Turbulent Dispersion</td>
</tr>
<tr>
<td>Lift Force</td>
</tr>
<tr>
<td>Wall Lubrication Force</td>
</tr>
</tbody>
</table>
For all set-ups stationary calculations were performed. However, for some cases the runs with
the set-up “EARSM” did not give acceptable results (high residuals with rather high imbalances). For
these steady-state simulations with non-acceptable convergence, additional transient runs were
performed on the coarsest mesh. By performing transient calculations good results could be
achieved for all these cases in terms of the achieved convergence level for each time step and the
imbalances of the simulation. The obtained results were then compared with the results of the
steady-state calculations. Thereby it can be shown that the steady-state results, even though their
convergence behaviour is not acceptable, still have a rather good agreement with the transient
results for all but one case (for the case 1.4122 the steady-state calculations did not converge at all).
Results of the comparison between the steady-state and the transient calculations for the set-up
EARSM are summarised in the table below:

<table>
<thead>
<tr>
<th>Case:</th>
<th>1.3221</th>
<th>1.4121</th>
<th>1.4122</th>
<th>1.4325</th>
<th>1.4326</th>
</tr>
</thead>
<tbody>
<tr>
<td>r_s (stationary)</td>
<td>0.111785</td>
<td>0.191804</td>
<td>0.616957</td>
<td>0.421181</td>
<td>0.810752</td>
</tr>
<tr>
<td>r_v (transient)</td>
<td>0.120700</td>
<td>0.189857</td>
<td>0.627388</td>
<td>0.418742</td>
<td>0.624408</td>
</tr>
</tbody>
</table>

2. Specify the numerical algorithm used (fully-implicit, fully explicit; semi-implicit)

ANSYS CFX is a computational fluid dynamics code that uses the node centred finite volume
method. The u-v-w-p system of the Navier-Stokes equations is solved in a coupled manner whereas
the transport equations for the volume fraction, thermal energy and turbulence model are solved in
a segregated manner.

The discretisation in space of the advection term is done using a high resolution scheme for the
calculations using SST as a turbulence model for the liquid phase and an upwind scheme in case of
calculations with EARSM.

For the discretisation in time, a pseudo time-step approach was used for the stationary
calculations. For the transient calculations, a second order backward facing Euler scheme was
employed. Therefore, the discretisation in time is a fully implicit numerical scheme.

3. Specify the two-phase models and formulations used (HEM, drift flux model, two-fluid model, etc.)

The multiphase flow model used in ANSYS CFX is an implementation of the two-fluid model. Two
sets of Navier-Stokes (N.S.) equations are solved, one for the liquid and one for the gaseous phase. These are coupled by interfacial forces (drag force, lift force) that act as source and sink terms in the
N.S. equations. Furthermore, two mass conservation equations are solved. The thermal phase
changes due to evaporation and condensation are taken into account as source/sink terms in these
equations. For the investigation of the PSBT benchmark cases the gaseous phase is assumed to be
always at saturation temperature which is calculated using IAPWS-IF97 water/water steam tables in
accordance to the local pressure. This additional assumption has two consequences. On the one
hand, computational effort can be reduced by solving only one energy equation for the liquid phase.
On the other hand, this leads to a simplification in the used RPI wall boiling model (see Section 1.1),
where, in turn, there is no direct heat exchange between the heated walls and the gaseous phase
(heat flux contribution from convective heat flux to vapor is neglected).

Additionally, for the fluid phase a set of transport equations is solved in dependence on the
different turbulence models used (SST and EARSM, [2]). For the gaseous phase, the zero-equation
disperse phase turbulence model is chosen that assumes that the turbulence viscosity in the
disperse phase is directly linked to the turbulence viscosity resulting from the turbulence model
solved for the continuous phase. The Reynolds stresses in the N.S. equation for the gaseous phase
are calculated using a turbulent eddy viscosity that is formed with the liquid phase quantities $k$ and $\omega$ ($v_{t,lg} = C \times v_{t,l}$) multiplied by a proportionality factor. The turbulence induced by the formation of the steam phase due to boiling is taken into account by the Sato model. More information on the solved transport equations and the used two-fluid model in ANSYS CFX can be found in [2].

4. Specify any optimisations of the code predictions that were performed by adjusting the model parameters to the experimental database

For the calculations in this study, two modifications of the standard models were made in order to better meet the requirements of the PSBT benchmark.

The first modification concerns the local bubble diameter $d_B$ for bubbles in the bulk fluid, which was calculated using the formulation [6]. The maximum bubble diameter $d_B^2$ was decreased from 2 mm to 0.65 mm whereas the minimum bubble diameter $d_B^1$ was increased from 0.1 mm to 0.15 mm.

The second change concerns the interfacial area density. In the original model for particulate disperse multiphase flows implemented in ANSYS CFD, the gaseous phase is always assumed to consist of spherical bubbles. Hence the interfacial area density can be calculated as:

$$A_{LG} = \frac{6 \cdot r_G}{d_B}$$

(1.1.13)

For high gas volume fraction, obviously, this relationship is no longer valid. For the case of gas volume fraction close to 1, the value for the interfacial area density should again decrease towards zero. This is performed using a blending function using the formulation (13) that is assumed to be valid up to a value for $r_G$ of 0.8 and the following formulation that is assumed to be valid for very high gas volume fractions (higher than 0.8):

$$A_{LG} = \frac{24 \cdot (1 - r_G)}{d_B}$$

(1.1.14)

For convergence and stability reasons the presented results, however, were produced using the standard formulation implemented in ANSYS CFX. This is done even though the modification would be physically more correct, especially in the EARSM cases, where there are some small regions with high gas volume fractions (> 0.8). But, because these regions are very small, it seems justifiable to use the original formulation.

AV.1.2 Phase I – Exercise 1

1. Specify the flow regime map used

ANSYS CFX uses no flow regime maps in a classical sense as it is done in standard thermo-hydraulic codes. However, the blending function for the interfacial area density described in Section 1.4 corresponds to a very simple flow regime map consisting only of two regimes. The assumptions made in formulation (13) for calculating the interfacial area density (spherical bubbles) correspond to a bubbly regime, whereas formulation (14) is the closest to a mist flow. Due to the powerful CFX command language (CCL) and the available user interfaces, users of ANSYS CFX are free to define any other suitable relationship for multi-phase flow parameters like local bubble diameter and interfacial area density. In particular, it is possible to account for the change in bubble size distribution e.g. with the discrete bubble size class model called MUSIG (Multiple Size Group model), where the interfacial area density is calculated based on the Sauter mean diameter of velocity groups. For the given benchmark, this model was not applied due to the increased computational effort required for the set of additional transport equations and to the fact that the target values of the benchmark, i.e. cross-sectional averaged steam volume fraction, are not very sensitive to this kind of model details.
Also other models used in the current study implicitly assume a bubbly flow regime of spherical, ellipsoidal and spherical-cap bubbles, e.g. the interfacial drag coefficient calculated in accordance with Grace drag law and in dependence on particular bubbly flow regime.

2. Specify the interfacial mass, momentum and energy exchange models

To calculate the interfacial heat transfer between liquid and gaseous phases, the two resistance model is used. The liquid side heat transfer coefficient is calculated using the correlation [7]. The gaseous side heat transfer coefficient is assumed to be equal to zero. Users of ANSYS CFX are free to use any other correlation for the interfacial heat transfer, which can be defined on CCL level.

The resulting heat flux corresponds to a thermal phase change and thus also corresponds to an interfacial transfer of mass. Knowing the interfacial heat flux, one calculates the interfacial mass flux according to Equations (1) and (2) and using the blending function for the interfacial area density described in Section 1.4.

To account for the interfacial momentum transport, the following formulations of forces were used:

Drag Force: drag coefficient $CD$ according to Grace [2]:

$$F_D = \frac{3}{4} \frac{C_D}{d_B^2} r_G \rho_L \left| \bar{U}_G - \bar{U}_L \right| \left( \bar{U}_G - \bar{U}_L \right)$$  

(1.1.15)

Turbulent Dispersion Force: FAD Turbulent Dispersion Force [3]:

$$F_{FD} = \frac{3}{4} \frac{C_D}{d_B \sigma} \rho_L \left| \bar{U}_G - \bar{U}_L \right| \left( \frac{\nabla r_G}{r_G} - \frac{\nabla r_L}{r_L} \right)$$  

(1.1.16)

Lift Force: lift coefficient $CL$ according to [9,10]

$$F_L = C_L r_G \rho_L \left( \bar{U}_G - \bar{U}_L \right) \times \frac{\nabla}{\bar{U}_L}$$  

(1.1.17)

Wall Lubrication Force: Formulation [11]:

$$F_{WL} = -C_{wall} r_G \rho_L \left| \bar{U}_L - \bar{U}_G \right|^2 \bar{n}_w$$  

(1.1.18)

$C_{wall}$: Wall lubrication coefficient, $\bar{n}_w$: unit normal pointing away from the wall

For details on the interfacial transport models refer to [2].

3. Specify the wall drag and heat transfer models

ANSYS CFX partially resolves the boundary layer in the near wall regions depending on the grid resolution. For the non-resolved part of the boundary layers, ANSYS CFX uses automatic wall functions for velocity and temperature. At the walls, a no-slip boundary condition was used for the liquid phase whereas for the gaseous phase a free slip boundary condition was set. As a boundary condition for the energy equation the non-heated walls were set to be adiabatic whereas for the heated ones the RPI wall boiling model with specified wall heat flux was used. The given wall heat flux for the particular test conditions of individual PSBT benchmark test cases was assumed to be uniform and constant throughout the heater surface. More details on the RPI wall boiling model are summarised in Section 1.1.
Table AV.1.2-1 Summary of meshes used

<table>
<thead>
<tr>
<th>MESHES</th>
<th>Mesh 1</th>
<th>Mesh 2</th>
<th>Mesh 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Axial Cells</td>
<td>155</td>
<td>310</td>
<td>620</td>
</tr>
<tr>
<td>Radial Cells</td>
<td>1160</td>
<td>4640</td>
<td>18560</td>
</tr>
<tr>
<td>Total Cells</td>
<td>$1.8 \times 10^5$</td>
<td>$1.4 \times 10^5$</td>
<td>$1.2 \times 10^7$</td>
</tr>
<tr>
<td>Total Nodes</td>
<td>$1.9 \times 10^6$</td>
<td>$1.5 \times 10^6$</td>
<td>$1.2 \times 10^7$</td>
</tr>
<tr>
<td>Minimum Mesh Angle [°]</td>
<td>42.6166</td>
<td>42.6217</td>
<td>42.6233</td>
</tr>
<tr>
<td>Minimum Determinant</td>
<td>0.890582</td>
<td>0.943188</td>
<td>0.971115</td>
</tr>
<tr>
<td>$y^*_\text{max}$</td>
<td>~161</td>
<td>~81</td>
<td>~41</td>
</tr>
</tbody>
</table>

4. Specify the axial nodalisation utilised (number of nodes, node size, variable axial nodding)

1.55 meters of the heated length were simulated in this study using inlet profiles for the velocity and turbulence quantities obtained by single-phase calculations in the same geometry from corresponding outlet cross-section after 1.55 m length of flow development. Taking advantage of the symmetry of the test facility only one fourth of the geometry was simulated (1/4th symmetry was set for pure convenience in the post-processing, also the geometry shows a 1/8 level of symmetry). For the calculations of this benchmark, a set of three consecutively refined meshes was created. Refinement from one mesh level to the next always corresponds to a refinement of factor 2 in every direction in space, meaning thus a multiplication with factor 8 of the used grid cells. Some details on the used meshes are summarised in the table above.

Figure AV.1.2-1 Cross-sectional Mesh Element Distribution for Mesh Levels 1-3

![Cross-sectional Mesh Element Distribution for Mesh Levels 1-3](image_url)
It should be noted that the meshes are much finer in radial than in axial direction. In axial direction, the grid cells have an equal mesh spacing of $\Delta z=1$ cm (Mesh 1), 0.5 cm (Mesh 2) and 0.25 cm (Mesh 03). In order to provide a better understanding of the meshing in the coordinate directions perpendicular to the main flow direction, Figure AV.1.2-1 shows the pictures of the meshes showing the cross-sectional mesh element distribution.

5. Specify the boundary conditions used

At the inlet of the sub-channel geometry velocity profiles were used for the velocity components of both the liquid and the gaseous phase. These were derived from single phase, isothermal calculations (liquid phase of the same sub-cooling as specified for the test case and with zero wall heat flux) of the flow through the sub-channel geometry of the same length of 1.55 m to allow for flow development. Corresponding simulations were carried out on Mesh 2.

The profiles were then obtained by export of the outlet profiles of these calculations. These profiles were derived both for SST and EARSM turbulence models. To fulfill the specified integral mass fluxes at the inlet, the axial components of the velocity profiles were multiplied with a correction factor that depends on the mesh resolution and the corresponding discretisation error in mass flow rate. Furthermore, the applied inlet profiles contain data of the turbulence quantities from these single-phase predecessor simulations (turbulent kinetic energy and eddy frequency for Set-up 1 and Set-up 2, turbulent kinetic energy and eddy dissipation for Set-up 3). These were then also used as inlet boundary conditions.

The specified pressure measured at the inlet was used as the outlet boundary condition. This simplification seems justified since the hydrostatic pressure drop is negligible compared to the absolute pressure level of the PSBT benchmark cases.

Because of the high order of symmetry of the geometry (1/8th symmetry), only one fourth of the geometry was calculated effectively and symmetry boundary conditions were used to take this into account.

The unheated as well as the heated walls were defined as no-slip wall for the liquid and free-slip walls for the gaseous phase. Moreover, at the heated wall a constant and uniform heat flux was specified according to the experimental set-up and the RPI wall boiling model was activated for this heated wall boundary (see Section 1.1).

AV.1.3 References


AV.2 CEA-Grenoble (CATHARE 3)

AV.2.1 Overall questionnaire

1. Specify the governing transport equations, assumptions and simplifications
   6 equation model: mass momentum and energy for liquid and steam.

2. Specify the numerical algorithm used (fully implicit, fully explicit; semi-implicit)
   Fully implicit for the 1D module and semi-implicit for the 3D module.

3. Specify the two-phase models and formulations used (HEM, drift flux model, two-fluid model, etc.)
   Two-fluid model.

4. Specify any optimisations of the code predictions that were performed by adjusting the model parameters to the experimental database
   Standard CATHARE 3 current version (V1 alpha) with adjustment of the liquid temperature turbulent dispersion based on Phase II ex 1 results; this adjustment was used for the phase II ex 2 simulations.

AV.2.2 Phase I – Exercise 1

1. Specify the flow regime map used
   For interfacial stress, bubbly/churn on the one hand and dispersed annular on the other hand, with a transition for wall to fluid heat transfer, liquid single phase, sub-cooled boiling, nucleate boiling, film boiling, dispersed droplet flow and steam single phase.

2. Specify the interfacial mass, momentum and energy exchange models

3. Specify the wall drag and heat transfer models
   Wall drag: drag coefficient are the product of a classical single phase drag by a two phase multiplier. Multipliers $c_8$ and $c_9$ are specified for each phase: Steam: $c_8 = \alpha^{1.25}$. Liquid: $c_9$ is based on the Lockhardt-Martinelli model. Heat transfer: Liquid convection: coefficient depending on laminar/turbulent regime and natural/forced convective regime. Nucleate boiling: Thom dimensional correlation $Q_{en} = H_{en}(T_w - T_{sat})^2$ with $H_{en} = 1.97 \times 10^3 \exp(0.23 \times 10^{-6} P)$.

   Net vapour generation point: Saha’s model: in sub-cooled boiling, a part of the wall heat flux directly produces steam while the remaining part heats the sub-cooled liquid CHF: predicted using look-up tables.
4. Specify the axial nodalisation utilised (number of nodes, node size, variable axial nodding, etc.).

31 cells ~ 50 mm long, regular nodding except at 1400 mm for precise void measurement location in front of a cell centre.

5. Specify the boundary conditions used

Pressure given in data imposed at the top of the heated length Inlet temperature (sub-cooled) and flow rate imposed at the bottom.

AV.2.3 Phase I – Exercise 2

1. Specify the cross-flow models used (diversion flow, void drift and turbulent mixing models)

Dispersion term $P_{dt} \nabla \alpha p_{dt}$ in the momentum equations with $P_{dt}$ calculated from a single phase turbulence formula for rod bundles:

$$k_l = 0.0367 V_i^2 Re^{-1/6}$$

See also question 5. Dispersion/diffusion term for temperature in energy balance, with coefficient checked on Phase II exercise 1 test:

associated turbulent viscosity $\nu_t = 0.5D_p \sqrt{k_i}$, where $k_i$ is turbulent kinetic energy.

2. Specify the flow regime map used

See exercise 1.

3. Specify the interfacial mass, momentum and energy exchange models

See exercise 1.

4. Specify the wall drag and heat transfer models

See Exercise 1.

5. Specify the turbulent mixing and void drift models used

Turbulent mixing proportional to the liquid turbulent kinetic energy is used through a void dispersion term in the 2 momentum equations. The turbulent kinetic energy is calculated using an algebraic model (Chandesris, Serre, Sagaut) without $k$-$\varepsilon$ transport equations in gas momentum equation:

$$\frac{\partial}{\partial t} (\alpha_z \rho_z V_z) + \frac{\partial}{\partial z} (\alpha_z \rho_z V_z V_z) + \alpha_z \nabla p = \text{wall friction} + \text{interfacial friction} + \text{added mass} + \text{dispersion} + \text{gravity}$$

Void dispersion term: $P_{dt} \nabla \alpha_z$ with $P_{dt} = 0.038 \rho_l V_i^2 Re^{-1/12}$

No specific void drift.
6. Specify any spacer grid effects on the void distribution if modelled
   No model. One cell in front of the grid height. Cross-section restriction and singular pressure drop located on corresponding nodes.

7. If symmetry used, specify the symmetry applied in the model
   No restricted domain due to symmetry. Results appear to be symmetric as expected.

8. Specify the axial nodalisation utilised (number of nodes, node size, variable axial nodding, spacer grids location with respect to the axial nodding, etc.)
   6x6x66 cell mesh. One planar cell by sub-channel. Variable axial meshing, 1 small cell per spacer grid and 3 larger cells in between.

9. Specify the boundary conditions used
   Pressure given in data imposed at the top of the heated length, uniform on the whole section. Inlet temperature (sub-cooled) and velocity imposed at the bottom, flat profile.

   **AV.2.4 Phase I – Exercise 3**
   Same models as in Exercise 2: steady results in Exercise 2 are obtained by full transient computations with given boundary conditions.

   **AV.2.5 Phase I – Exercise 4**

1. Specify the correlations/models used for single-phase and two-phase frictional pressure drop
   Same models as in Exercises 1 and 2.

2. Specify the components of the pressure drop used in the code
   The pressure field is the result of the 6 equation system solution. The computed pressure drop includes gravitational term, fluid acceleration (through the convective term of the 2 momentum equations) and wall friction on both phases.
AV.3 CEA-Saclay (FLICA-OVAP)

AV.3.1 Overall Questionnaire

1. Governing transport equations, assumptions and simplifications

A three-dimensional four equation drift flux model has been used, including the mixture mass balance equation, the mixture momentum balance equation, the mixture energy balance equation and the steam mass balance equation\(^1\):

**mixture mass**

\[ \frac{\partial}{\partial t} \left( \sum_{k=\text{v},\text{l}} \alpha_k \rho_k \right) + \nabla \cdot \left( \sum_{k=\text{v},\text{l}} \alpha_k \rho_k \mathbf{u}_k \right) = 0 \]  \hspace{1cm} (3.1.1)

where \( \alpha_k, \rho_k, \mathbf{u}_k \) are the volume fraction, the density and the velocity:

**mixture momentum**

\[ \frac{\partial}{\partial t} \left( \sum_{k=\text{v},\text{l}} \alpha_k \rho_k \mathbf{u}_k \right) + \nabla \cdot \left( \sum_{k=\text{v},\text{l}} \alpha_k \rho_k \mathbf{u}_k \otimes \mathbf{u}_k \right) + \nabla P - \nabla \cdot \left( \sum_{k=\text{v},\text{l}} \alpha_k \tau_k \right) = \rho \mathbf{g} + \mathbf{F}_w \]  \hspace{1cm} (3.1.2)

where \( P \) is the pressure, \( \mathbf{g} \) the gravity and \( \mathbf{F}_w \) the friction forces. The tensor \( \tau_k \) represents the viscous and the Reynolds stress terms for the phase \( k \). The mixture density \( \rho \) is defined as mixture energy:

\[ \rho = \sum_{k=\text{v},\text{l}} \alpha_k \rho_k \]

\[ \frac{\partial}{\partial t} \left( \sum_{k=\text{v},\text{l}} \alpha_k \rho_k E_k \right) + \nabla \cdot \left( \sum_{k=\text{v},\text{l}} \alpha_k \rho_k H_k \mathbf{u}_k \right) - \nabla \cdot \left( \sum_{k=\text{v},\text{l}} \alpha_k \mathbf{q}_k \right) = \mathbf{q}_w + \rho \mathbf{g} \cdot \mathbf{u} \]  \hspace{1cm} (3.1.3)

where \( E_k \) and \( H_k \) are the total energy and the total enthalpy of the phase \( k \), \( \mathbf{q}_k \) includes molecular and turbulent heat fluxes and \( \mathbf{q}_w \) is the volumetric source term of thermal power.

**steam mass:**

\[ \frac{\partial}{\partial t} \left( \alpha_v \rho_v \right) + \nabla \cdot \left( \alpha_v \rho_v \mathbf{u}_v \right) - \nabla \cdot \left( K_	ext{c} \nabla c \right) = \Gamma_v \]  \hspace{1cm} (3.1.4)

where \( c \) is the vapour concentration, defined as:

\[ c = \frac{\rho \alpha_v}{\rho} \]  \hspace{1cm} (3.1.5)

and \( K_	ext{c} \) is the corresponding diffusion coefficient. The term \( \Gamma_v \) represents the source terms for the vapour phase, including vapour generation on the walls or mass transfer within the bulk flow.

The model is closed by a drift flux correlation and a general equation of state with the assumption that, in presence of liquid, the vapour is in saturation conditions at the pressure of the system.

The model adopted for the void distribution benchmark is the drift-flux correlation.

FLICA-OVAP includes several Zuber-Findlay type correlations in order to estimate the relative velocity \( \mathbf{u}_r \) between the vapour velocity \( \mathbf{u}_v \) and the liquid velocity \( \mathbf{u}_l \). The general form of these correlations is:

\[ \mathbf{u}_v = C_0(j) \langle \mathbf{v}_{g,j} \rangle = C_0(j) + \langle \mathbf{V}_{g,j} \rangle \]  \hspace{1cm} (3.1.6)

\(^1\) Porosities are omitted for the sake of simplicity.
where \( C_0 \) is the distribution parameter, \( \langle j \rangle = \alpha u_v + (1 - \alpha)u_l \) is the area-averaged total volumetric flux and \( V_{g,l} \) is the void-weighted area-averaged drift velocity. The Chexal-Lellouche correlation was used in the PSBT calculations.

**Pressure drop**

Friction forces are given by the sum of distributed and singular pressure drops.

\[
F_W = F_{sing} + F_{fric}
\]  
(3.1.7)

Singular friction due to spacer or mixing grids or other pressure drops are given by:

\[
F_{sing} = -\frac{1}{2} \rho K_{sing} \| u \| u
\]  
(3.1.8)

where \( K_{sing} \) is an antisymmetric tensor. Distributed friction at walls is instead accounted for by:

\[
F_{fric} = -\frac{1}{2D_h} \rho \left( \begin{array}{c} f_w^x \\ f_w^y \\ f_w^Z \end{array} \right)
\]  
(3.1.9)

Where the different friction terms \( f_w \) are given by the product of the isothermal friction factor \( f_{iso} \), the heating wall correction \( f_{heat} \) and the two-phase flow multiplier \( f_{2\phi} \). In this analysis, the Chisholm correlation was used for \( f_{2\phi} \), whereas the heating wall correction was estimated by an in-house model already used in the FLICA-4 code.

**Diffusion effects**

To account for viscous and turbulent diffusion effects, the tensor \( \tau_k \) is introduced in the momentum equation, given by:

\[
\tau_{ij} = \mu_k \left( 1 + M_{tk,i} \right) \left( \frac{\partial u_k}{\partial x_j} + \frac{\partial u_j}{\partial x_k} - \frac{2}{3} \sum_{l=x,y,z} \frac{\partial u_l}{\partial x_l} \delta_{ij} \right)
\]  
(3.1.10)

where \( \mu_k, M_{tk,i} \) is the turbulent viscosity, which is limited to the liquid phase. An anisotropic formulation is used for turbulent viscosity:

\[
M_{tk,i} = M_{t0,i} (Re - Re_{t})^{b_M} f_M(f_{2\phi})
\]  
(3.1.11)

where \( Re = GD_h/\mu_l \) is the Reynolds number, \( M_{t0,i}, b_M, Re_{t} \) are parameters and \( f_M(f_{2\phi}) \) is a function of the two-phase flow multiplier.

Similarly, molecular and turbulent heat fluxes are given by:

\[
\sum_{k=v,l} \alpha_k q_k = \frac{\lambda_l}{c_{p,l}} \left( 1 + K_{t,l} \right) \nabla h_x
\]  
(3.1.12)

where \( h_x = xh_v + (1 - x)h_l \) is the flow enthalpy based on the actual quality \( x \). The turbulent conductivity is given by:

\[
K_{t,l} = K_{t0,l} (Re - Re_t)^{b_K} f_K(f_{2\phi})
\]  
(3.1.13)

where \( K_{t0,l}, b_K, Re_t \) are parameters and \( f_K(f_{2\phi}) \) is a function of the two-phase flow multiplier.

In this analysis, the value of \( M_{t0,i} \) and \( K_{t0,i} \) was varied as a function of the axial position. Two different values have been adopted for each parameter depending on whether the considered axial position was downwards a mixing or a spacer grid.
Wall temperature

Wall temperatures are estimated on the basis of the bulk temperature and the heat transfer coefficient as:

\[ T_w = T_b + \frac{q''}{h} = T_b + \frac{q''}{\text{Nu} \lambda / D_h} \]  \hspace{1cm} (3.1.14)

The Nusselt number and the bulk temperature depend on the heat transfer regime. Four different regimes can be distinguished: single-phase convection heat transfer, sub-cooled nucleate boiling (SNB), saturated nucleate boiling (SANB) and post critical heat flux heat transfer (post-CHF). In single-phase heat transfer and SNB, the bulk temperature is equal to the liquid phase temperature, whereas in SANB it is equal to the saturation temperature. The single phase heat transfer coefficient is estimated by the Dittus-Boelter correlation. The onset of significant void (OSV), which is the transition between single-phase heat transfer and SNB can be predicted with the Forster and Grief correlation in low-pressure conditions or the Jens and Lottes correlation in high-pressure conditions. Both correlations allow estimating the minimum wall superheating required to achieve net vapour generation. Vapour generation starts when wall temperature estimated with Dittus-Boelter correlation exceeds this value. In the present analysis, the onset of vapour generation and the corresponding wall temperatures are estimated by the Jens and Lottes correlation. Finally, in post-CHF conditions, the choice of correlation depends on the boiling characteristics, whether it is IAFB (inverted annular film boiling) or DFFB (dispersed flow film boiling).

The mass transfer term \( \Gamma_v \)

The mass transfer term \( \Gamma_v \) appearing as the steam mass balance equation is given by the sum of two contributions: the vapour generation on walls \( \Gamma_{wv} \) and the mass transfer between the liquid and the vapour phase \( \Gamma_{vl} \). In sub-cooled nucleate boiling, only a portion \( \chi_v \) of the heat flux transferred from the wall to the mixture is used to vaporise the liquid phase, whereas the remaining part is used to heat the liquid phase up. The vapour generation at walls is thus given by:

\[ \Gamma_{wv} = \frac{\chi_v q''}{h_{lv}D_{\text{heat}}} \]  \hspace{1cm} (3.1.15)

where \( \chi_v \) is a function of the saturation temperature, the liquid phase temperature, and the wall superheat required to have sub-cooled nucleate boiling.

The mass transfer between the two phases \( \Gamma_{vl} \) is instead given by:

\[ \Gamma_{vl} = \frac{q_{vl}}{h_{v}-h_{l}} \]  \hspace{1cm} (3.1.16)

where \( q_{vl} \) is the heat transferred between the two phase, given by:

\[ q_{vl} = K_{p0} \frac{G^2}{\log(1+Re/Re_0)} f(P, \rho, H_l, u, u_r) \rho c(x_{eq-c}) \]  \hspace{1cm} (3.1.17)

Numerical algorithm
The equations are solved with a collocated finite volume type scheme. This scheme allows solving the system on any type of structured or unstructured mesh that can be either conforming or non-conforming. The hyperbolic part of the system is approximated with a VFRoe-type scheme modified to be accurate at low Mach number. The diffusion part of the system is approximated with a diamond technique. An implicit time scheme used (Backward Euler) has been adopted for the convergence towards the steady-state or for the transient calculations.

**Two-Phase models and formulations used**

See Section 1.1 for the models used in the void distribution benchmark.

**Optimisation of the code predictions that were performed by adjusting the model parameters to the experimental database**

\( K_{v0} \) (see paragraph 1.1.5) was optimised based on results obtained for the steady-state single channel void distribution available by Series 1 to 4. The selected value is 1.5E-4.

**AV.3.2 Phase I – Exercise 1**

The models used to address steady-state sub-channel tests are described in paragraph 1.1. No particular flow map regime was used, but the flow regime is implicitly assigned by the drift flux correlation, that is the Chexal-Lellouche.

A uniform axial discretisation was used, consisting of 20 axial volumes.

At the inlet section, mass flux, mixture temperature and steam concentration (equal to 0) are imposed. Pressure is imposed at the outlet section.

**AV.3.3 Phase I – Exercise 2**

The models used to address steady-state sub-channel tests are described in paragraph 1.1. No particular flow map regime was used, but the flow regime is implicitly assigned by the drift flux correlation, that is the Chexal-Lellouche.

The presence of spacer and mixing grid was accounted for by appropriate singular pressure drop coefficients (see paragraph 1.1.3) and appropriate turbulent mixing coefficients.

As far as it concerns pressure drops, in both cases, a singular pressure drop coefficient of 1 was used.

The \( K_r \) and \( M_r \) coefficients were taken equal to 0.01, whereas in the case of mixing grid the selected value was 0.045.

A non-uniform axial discretisation was used, consisting of 33 axial volumes. Volumes are defined in order to have mixing and spacer grids coinciding with borders.

At the inlet section, mass flux, mixture temperature and steam concentration (equal to 0) are imposed. Pressure is imposed at the outlet section.
AV.3.4 Phase I – Exercise 3

The same settings than for the steady-state bundle benchmark were used.

For temperature increase and depressurisation transients, an empirical delay of 6 s was taken for the inlet temperature, i.e. the initial temperature is maintained during 6 s, and then the temperature variation is applied.
AV.4 Chalmers (RELAP-5)

AV.4.1 Overall questionnaire

1. The governing transport equations, assumptions and simplifications

Two phasic continuity equations:

\[
\frac{\partial}{\partial t} (\alpha_g \rho_g) + \frac{1}{A} \frac{\partial}{\partial x} (\alpha_g \rho_g v_g A) = \Gamma_g
\]

(4.1.1)

\[
\frac{\partial}{\partial t} (\alpha_f \rho_f) + \frac{1}{A} \frac{\partial}{\partial x} (\alpha_f \rho_f v_f A) = \Gamma_f
\]

(4.1.2)

\(\Gamma_g\) and \(\Gamma_f\) are the vapour and liquid generation, respectively. The relationship between the two quantities is (when no mass sources or sinks are present):

\[
\Gamma_f = -\Gamma_g
\]

(4.1.3)

Main assumptions and simplifications:

The interfacial mass transfer model assumes that total mass transfer can be partitioned into mass transfer \(\Gamma_{gi}\) at the vapour/liquid interface in the bulk fluid and mass transfer \(\Gamma_{iw}\) at the vapour/liquid interface in the boundary layer near the walls, i.e:

\[
\Gamma_g = \Gamma_{gi} + \Gamma_{iw}
\]

(4.1.4)

Two phasic momentum equations:

\[
\alpha_g \rho_g \frac{\partial v_g}{\partial t} + \frac{1}{2} \alpha_g \rho_g A \frac{\partial v_g^2}{\partial x} = -\alpha_g A \frac{\partial p}{\partial x} + \alpha_g \rho_g B_s A - (\alpha_g \rho_g A) \text{FGG}(v_g) - \Gamma_g A(v_{gi} - v_g)
\]

\[-(\alpha_g \rho_g A) \text{FGG}(v_g) - v_{gi} + \frac{\partial v_g}{\partial x} - v_g \frac{\partial v_g}{\partial x} \]

(4.1.5)

\[
\alpha_f \rho_f \frac{\partial v_f}{\partial t} + \frac{1}{2} \alpha_f \rho_f A \frac{\partial v_f^2}{\partial x} = -\alpha_f A \frac{\partial p}{\partial x} + \alpha_f \rho_f B_s A - (\alpha_f \rho_f A) \text{FGG}(v_f) - \Gamma_g A(v_{fi} - v_f)
\]

\[-(\alpha_f \rho_f A) \text{FGG}(v_f) - v_{fi} + \frac{\partial v_f}{\partial x} - v_f \frac{\partial v_f}{\partial x} \]

(4.1.6)

The force terms on the right sides are, respectively, the pressure gradient, the body force, wall friction, momentum transfer due to interface mass transfer, interface frictional drag and force due to virtual mass.
Main assumptions and simplifications:

- the Reynolds stresses are neglected;
- the phasic pressures are assumed equal;
- the interfacial pressure is assumed equal to the phasic pressures - The covariance terms are universally neglected;
- interfacial momentum storage is neglected;
- phasic viscous stresses are neglected;
- the interface force terms consist of both pressure and viscous stresses;
- the normal wall forces are assumed adequately modeled by variable area momentum flux formulation;
- the spatial derivative portion of the virtual mass term is neglected.

Two phase energy equations:

\[
\begin{align*}
\frac{\partial}{\partial t} (\rho g U g) + \frac{1}{A} \frac{\partial}{\partial x} (\rho g U g v g A) &= -P \frac{\partial a g}{\partial t} - P \frac{\partial}{\partial x} (a g v g A) + Q_{wg} + Q_{ig} - \Gamma g h g^* - \Gamma w h g^* + \text{DISS}_g \\
\frac{\partial}{\partial t} (\rho f U f) + \frac{1}{A} \frac{\partial}{\partial x} (\rho f U f v f A) &= -P \frac{\partial a f}{\partial t} - P \frac{\partial}{\partial x} (a f v f A) + Q_{wf} + Q_{if} - \Gamma f h f^* - \Gamma w h f^* + \text{DISS}_f
\end{align*}
\]

(4.1.7) (4.1.8)

\(Q_{wg}\) and \(Q_{wf}\) are the phasic wall heat transfer rates per unit volume, respectively. \(Q_{ig}\) and \(Q_{if}\) represent the interface heat transfer terms. \(h_g\) and \(h_f\) are the phasic enthalpies associated with wall interface mass transfer. \(h_g^*\) and \(h_f^*\) are the phasic enthalpies associated with bulk interface mass transfer. \(\text{DISS}_g\) and \(\text{DISS}_f\) are the sums of wall friction and pump effects.

Main assumptions and simplifications:

- the Reynolds heat flux is neglected;
- the covariance terms are universally neglected;
- interfacial storage is neglected;
- internal phasic heat transfer is neglected;
- dissipation effect due to interface mass transfer, interface friction and virtual mass are neglected.

2. The Numerical Algorithm

Semi-implicit.

3. The two-phase models and formulations

Two-fluid non-equilibrium model.
AV.4.2 Phase I – Exercise 2 and Exercise 3

1. Cross-flow model

No cross-flow was modelled.

2. The flow regime map

A vertical flow-regime map is used and is based on the work of Taitel and Dukler, and Ishii (see Figure 1).

![Vertical Flow Regime Map](image)

In the simulations under study, only vertical bubbly and slug flow regimes are involved.

3. Closure relations

- fluid energy equations;
- bulk interfacial heat transfer.

The volumetric heat transfer coefficients are coded as follows:

\[
H_{ip} = h_{ip} \alpha_{gf}
\]  (4.2.1)

where \( h_{ip} \) is the interfacial heat transfer coefficient for phase \( p \), and \( \alpha_{gf} \) is the interfacial area per unit volume. Table 1 shows the models that are implemented in RELAP5 for vertical bubbly and slug flow regimes and that are used to calculate such quantities.

Wall heat transfer correlations

In RELAP5, any mode number indicates the heat transfer phenomenon on which the transfer heat between heat structure surfaces and the fluid is based. Therefore, wall convection heat transfer correlations are associated to each mode number (see Table 2).

In addition, several hydraulic geometry types can be selected, and heat transfer correlations are associated to the geometry types, according to the mode of heat transfer. As regards a vertical bundle without cross-flow, that is the case chosen for these exercises, (see Table 3).
### Table AV.4.2-1 RELAP5 Interfacial areas and heat transfer coefficients for vertical bubbly and slug flow regimes

<table>
<thead>
<tr>
<th>Flow type</th>
<th>Mode number</th>
<th>Heat transfer phenomena</th>
<th>Correlations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bubbly</td>
<td>0</td>
<td>Non-condensable steam, water or superheated water</td>
<td>Kays, Dittus-Boelter, EDSU, Shah, Churchill-Chu, McAdams, Elenbaas, Petukhov-Kirillov, Swanson-Catton</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>Supercritical or single-phase liquid</td>
<td>Same as mode 0</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Single-phase liquid or sub-cooled wall with αg&lt;0.1</td>
<td>Same as mode 0</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Sub-cooled nucleate boiling</td>
<td>Chen</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>Saturated nucleate boiling</td>
<td>Same as mode 3</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>Sub-cooled transition boiling</td>
<td>Chen-Sundaram-Ozkaynak</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>Saturated transition boiling</td>
<td>Same as mode 5</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>Sub-cooled film boiling</td>
<td>Bromley, Sun-Gonzales-Ten, and mode 0 correlations</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>Saturated film boiling</td>
<td>Same as mode 7</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>Supercritical two-phase or single-phase gas</td>
<td>Same as mode 0</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>Filmwise condensation</td>
<td>Nusselt, Shah, Colburn-Hougen</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>Condensation in steam</td>
<td>Same as mode 10</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>Single-phase liquid or sub-cooled wall with αg&lt;0.1</td>
<td>Same as mode 0</td>
</tr>
<tr>
<td></td>
<td>3, 4</td>
<td>for horizontal bundles</td>
<td>Foster-Zuber, Polley-Ralston-Grant, EDSU</td>
</tr>
</tbody>
</table>

### Table AV.4.2-2 RELAP5-wall convective heat transfer

<table>
<thead>
<tr>
<th>Mode number</th>
<th>Heat transfer phenomena</th>
<th>Correlations</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Non-condensable steam, water or superheated water</td>
<td>Kays, Dittus-Boelter, EDSU, Shah, Churchill-Chu, McAdams, Elenbaas, Petukhov-Kirillov, Swanson-Catton</td>
</tr>
<tr>
<td>1</td>
<td>Supercritical or single-phase liquid</td>
<td>Same as mode 0</td>
</tr>
<tr>
<td>2</td>
<td>Single-phase liquid or sub-cooled wall with αg&lt;0.1</td>
<td>Same as mode 0</td>
</tr>
<tr>
<td>3</td>
<td>Sub-cooled nucleate boiling</td>
<td>Chen</td>
</tr>
<tr>
<td>4</td>
<td>Saturated nucleate boiling</td>
<td>Same as mode 3</td>
</tr>
<tr>
<td>5</td>
<td>Sub-cooled transition boiling</td>
<td>Chen-Sundaram-Ozkaynak</td>
</tr>
<tr>
<td>6</td>
<td>Saturated transition boiling</td>
<td>Same as mode 5</td>
</tr>
<tr>
<td>7</td>
<td>Sub-cooled film boiling</td>
<td>Bromley, Sun-Gonzales-Ten, and mode 0 correlations</td>
</tr>
<tr>
<td>8</td>
<td>Saturated film boiling</td>
<td>Same as mode 7</td>
</tr>
<tr>
<td>9</td>
<td>Supercritical two-phase or single-phase gas</td>
<td>Same as mode 0</td>
</tr>
<tr>
<td>10</td>
<td>Filmwise condensation</td>
<td>Nusselt, Shah, Colburn-Hougen</td>
</tr>
<tr>
<td>11</td>
<td>Condensation in steam</td>
<td>Same as mode 10</td>
</tr>
<tr>
<td>12</td>
<td>Single-phase liquid or sub-cooled wall with αg&lt;0.1</td>
<td>Same as mode 0</td>
</tr>
<tr>
<td>3, 4</td>
<td>for horizontal bundles</td>
<td>Foster-Zuber, Polley-Ralston-Grant, EDSU</td>
</tr>
</tbody>
</table>
Table AV.4.2.3: RELAP5 - heat transfer correlations for a bundle, parallel flow only

<table>
<thead>
<tr>
<th>Geometry</th>
<th>Laminar</th>
<th>Natural</th>
<th>Turbulent</th>
<th>Condensation</th>
<th>Nucleate boiling</th>
<th>Transition boiling</th>
<th>Film boiling</th>
<th>CHF</th>
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</thead>
<tbody>
<tr>
<td>110</td>
<td>Nu=4.36</td>
<td>Churchill-Chu or McAdams</td>
<td>Dittus-Boelter-Inayatov</td>
<td>Nusselt/Chato-Shah-Coburn-Hougen</td>
<td>Chen-Inayatov</td>
<td>Chen</td>
<td>Bromley</td>
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</table>

Near wall interphase heat transfer

The Saha-Zuber method of predicting the conditions necessary for net voids to exist is calculated. Then the mechanistic method proposed by Lahey’s method is applied for assigning a fraction of the total heat flux to liquid, which causes flashing at the wall. This model is used in RELAP5 during nucleate, transition and film boiling.

Direct heating

The direct heating between the gas and liquid becomes important when there is non-condensable gas present. Therefore, since it is not of interest for the current work, details are not reported.

Mass conversation equations

The code calculation of mass transfer is directly tied to the bulk interfacial heat transfer models. The vapour generation (or condensation) rates are established from energy balance considerations at the interface. A brief summary of the final result is presented as follows.

The interface vapourisation rate in the boundary layer near the walls can be written as:

\[
\Gamma_w = \frac{-Q_{if}}{h_g - h_f}
\]

(4.2.2)

with \(Q_{if}\) being the liquid interface heat transfer in the thermal boundary layer near the wall. Similarly, the interface condensation rate in the boundary layer near the walls can be written as:

\[
\Gamma_w = \frac{-Q_{ig}}{h_g - h_f}
\]

(4.2.3)

with \(Q_{ig}\) being the gas interface heat transfer in the thermal boundary layer near the wall. The interface vapourisation (or condensation) rate in the bulk fluid can be written as:

\[
\Gamma_{gl} = \frac{-H_g(T^s - T_g) + H_f(T^s - T_f)}{h_g^* - h_f^*}
\]

(4.2.4)
where $T^*$ is the saturation temperature corresponding to the total pressure $P$; $H_{ig}$ and $H_{il}$ are the gas and liquid interface heat transfer coefficient per unit volume.

By combining these equations with Equation 4, the final expression achieved for the total interface mass transfer is:

$$\Gamma_g = -\frac{H_{ig}(T^* - T_g) + H_{il}(T^* - T_l)}{h_g^* - h_l^*} + \Gamma_w$$

(4.2.5)

**Momentum conservation equations**

**Coefficient of virtual mass**

The coefficient of virtual mass is based on that used by Anderson, where the value for $C$ (see Equations 5 and 6) depends on the flow regime. A value of $C > \frac{1}{2}$ has been shown to be appropriate for bubbly or dispersed flows, while $C = 0$ may be appropriate for a separated or stratified flow. In RELAP5 a value of $C > \frac{1}{2}$ is used for all flow regimes. A formula based on void fraction is applied:

$$C = 0.5 \left( \frac{1 + 2\alpha_g}{1 - \alpha_g} \right) \quad \text{for } 0 \leq \alpha_g \leq 0.5$$

$$C = 0.5 \left( \frac{3 - 2\alpha_g}{\alpha_g} \right) \quad \text{for } 0.5 \leq \alpha_g \leq 1$$

(4.2.6)

The calculation of the drag due to the virtual mass effect (dynamic drag) is based on an objective and symmetric formulation of the relative acceleration. The inertial drag force per unit volume in the phasic momentum equations is written as:

$$FA_{gf} = -C(1 - \alpha_g)\rho \frac{\partial}{\partial t}(v_g - v_f)$$

(4.2.7)

**Interphase Friction**

In the finite difference equation for the difference momentum equation the following term appears:

$$(\rho_mFI)^n_j[(1 + f_x(C_1 - 1)]^n_j(v_g)^{n+1}_j - [1 + f_x(C_0 - 1)]^n_j(v_f)^{n+1}_j$$

(4.2.8)

which is the interfacial friction force. This term is the product of a global interfacial friction coefficient and a relative velocity. The global interfacial friction coefficient $FI$ is computed from:
where the interfacial force $F_i$ and the relative velocity between phases $v_R$ are computed according to two different models whose choice depends on the flow regime. In the case of vertical bubbly and slug flow regimes, the drift-flux models are used (the calculation of the individual interphase friction is based on such an approach as well). Otherwise, the drag coefficient model is employed. Table 4 shows further information about the drift-flux correlations in RELAP5. In the case of the current exercises, the EPRI correlation is applied.

### Table AV.4.2-4 RELAP5 -drift-flux void fraction correlations for vertical bubbly-slug flow

<table>
<thead>
<tr>
<th>Flow rates [kg/m²·s]</th>
<th>Rod bundles</th>
<th>small pipes D≤0.018m</th>
<th>Intermediate pipes 0.018m&lt;D≤0.08m</th>
<th>Large pipes D&gt;0.08m</th>
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<tbody>
<tr>
<td>G≥100</td>
<td>EPRI</td>
<td>Transition</td>
<td>Transition</td>
<td>Churn-turbulent bubbly flow According to Kataoka-Ishii</td>
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<tr>
<td>50≤G&lt;100</td>
<td>EPRI</td>
<td>Duber-Findlay Slug flow</td>
<td>Transition Kataoka-Ishii</td>
<td>Churn-turbulent bubbly flow Transition Kataoka-Ishii</td>
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<tr>
<td>-50≤G≤50</td>
<td>EPRI</td>
<td>Transition</td>
<td>Transition</td>
<td>Churn-turbulent bubbly flow Transition Kataoka-Ishii</td>
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<td>-100≤G&lt;50</td>
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<td>Transition</td>
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<td>G≤100</td>
<td>EPRI</td>
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#### Wall Drag

The field difference equations for the sum momentum equation and the difference momentum equation contain terms that represent the pressure loss due to wall shear from cell centre to cell centre of the cell volumes adjoining the particular junction that the momentum equation considers. The wall drag or friction depends on the phase of the fluid and on the flow regime characteristics.

The wall friction model is based on a two-phase multiplier approach in which the two-phase multiplier is calculated from the heat transfer and fluid flow service modified Baroczy correlation. The individual phasic wall friction components are calculated by using a technique derived from the Lockhart-Martinelli model. The model is based on the assumption that the frictional pressure drop may be calculated using a quasi-steady form of the momentum equation.

### 4. RELAP5 model of the test bundle

A RELAP5 model was developed for the test bundle and it consists of a one-dimensional hydrodynamic component “pipe” and one “heat structure”.

The “pipe” is characterised by 24 axial volumes. The size of each node is equal to 0.1524 m.

The heated rods are described with one single “heat structure”. Such “heat structure” is defined with 24 axial volumes (these volumes are coherently coupled with the hydraulic axial volumes) and 10 radial nodes. The radial mesh allows taking into account the three radial regions of the heated rods whose material composition is different (i.e. 1 node is used for the hollow, three nodes for the insulator and 6 nodes for the heater).

A time-dependent hydrodynamic volume is used in order to specify pressure and temperature of the fluid at the inlet. Such a volume is connected to the “pipe” through a time-dependent junction in which the mass flow of rate is given.
At the outlet, the “pipe” is connected to a “time-dependent volume” through a “single junction”. The total input power is provided in the form of a RELAP5 general table.

Proper Reynolds number independent forward flow energy loss coefficients are specified for those junctions located at the spacer grid positions (i.e. junction number: 1; 3,4; 6,7; 9,10; 12,13; 15,16; 18,19; 21,22).

AV.5 CSA (VIPRE)

AV.5.1 Overall questionnaire

1. Specify the governing transport equations, assumptions and simplifications

VIPRE-01 was developed from the COBRA series of codes. VIPRE-01 uses a sub-channel analysis concept where the fuel bundle is divided into a number of quasi-one-dimensional channels that communicate laterally by diversion cross-flow and turbulent mixing.

Conservation equations for mass, axial, and lateral momentum and energy are solved for fluid enthalpy, axial flow, lateral flow per unit length, and momentum pressure drop. The flow field is assumed to be incompressible and homogeneous. Several options are available to account for the effects of slip. A four-equation option is available that uses a drift flux approach to account for slip.

Fluid properties are functions of local enthalpy and pressure.

2. Specify the numerical algorithm used (fully implicit, fully explicit; semi-implicit)

VIPRE-01 uses a semi-implicit solution method.

3. Specify the two-phase models and formulations used (HEM, drift flux model, two-fluid model, etc.)

VIPRE-01 is an HEM code with several constitutive two-phase flow models including a drift-flux model.

Almost all two-phase models used were the default models recommended by the code developers. The EPRI void models were used which correlates sub-cooled as well as bulk boiling. The void/quality correlations are used to model the relationship between flowing quality and void fraction.

The EPRI model uses the Zuber-Findlay drift flux correlation with the EPRI void model coefficients.

The EPRI two-phase friction multiplier was used.

4. Specify any optimisations of the code predictions that were performed by adjusting the model parameters to the experimental database

Default models and coefficients were used – no parameter tuning was used.

AV.5.2 Phase I – Exercise 1 and Exercise 2

1. Specify the cross-flow models used (diversion flow, void drift, and turbulent mixing models)

The VIPRE-01 diversion cross-flow model is similar to other codes. The diversion cross-flow is driven by the transverse pressure gradients due to geometry or fluid density changes.

The VIPRE-01 turbulent mixing model was used to model the exchange of energy and momentum between adjacent channels due to turbulent mixing. This empirical model correlates the flow exchange as a function of the lateral gap width and the average flow in the adjacent channels.
2. Specify the flow regime map used
   N/A
3. Specify the interfacial mass, momentum and energy exchange models
   N/A
4. Specify the wall drag and heat transfer models
   The Blasius formulation for smooth tubes is used for wall drag. This is modified by the EPRI two-
   phase flow multiplier.
   The Dittus-Boelter correlation is used for single phase forced convection and the Thom heat
   transfer correlation is used in the nucleate boiling regime.
5. Specify the turbulent mixing and void drift models used
   Turbulent mixing is described above – void drift model was not used.
6. Specify any spacer grid effects on the void distribution if modelled
   The benchmark specification values for grid loss coefficients were used at the grid locations.
7. If symmetry used, specify the symmetry applied in the model
   The bundles were modelled in full detail, no symmetry assumptions were applied.
8. Specify the axial nodalisation utilised (number of nodes, node size, variable axial nodding,
   spacer grids location with respect to the axial nodding, etc.)
   Thirty-two (32) uniform axial nodes were used for the single sub-channel cases and thirty six (36)
   uniform axial nodes were used for the bundle cases. Calculated outputs (void/quality) were
   interpolated from the cell centre locations to obtain values for the measurement elevations.
   Spacer grid locations from benchmark specifications were used to locate the grid losses. These
   are then internally located at the nearest cell edge.

Specify the boundary conditions used
   The benchmark boundary conditions were specified as system pressure, inlet temperature, inlet
   mass flux corresponding to flow, and average power per rod corresponding to specified power.
AV.6 EDF (NEPTUNE)

AV.6.1 Overall questionnaire

1. Governing transport equations, assumptions and simplifications

The bi-fluid model implemented in the NEPTUNE_CFD code solves the 3D following balance equations:

- two mass balance equations (one for each phase);
- two momentum balance equations (one for each phase);
- two total enthalpy equations (one for each phase).

The detailed form of these equations can be found in [1,6]. The turbulence is calculated through the use of a second-order RANS model (Rij - ε) [6]. In our series of calculations, the diameter of the bubbles is considered as constant and equal to 0.3 mm (no interfacial area equation is solved).

2. Numerical algorithm used

All details concerning the numerical methods used in NEPTUNE_CFD can be found in [5]. The discretisation follows a three-dimensional full-unstructured finite-volume approach, with a collocated arrangement of all variables. The numerical algorithm used is a semi-implicit, pressure-based method where the system of equations is solved in two major fractional steps:

First, a prediction of the velocities based on the momentum equations.

Then, the coupling between phase fraction, pressure and energy through mass and energy equations and a simplified form of momentum equations.

3. Two-phase models and formulations used

As stated above, the model used is a two-fluid model.

4. Any optimisations of the code predictions that were performed by adjusting the model parameters to the experimental database

These results have been obtained without adjusting any of the model parameters; every parameter has been kept standard. Besides, as stated above, no interfacial area equation is solved: the diameter of the bubbles is considered equal to 0.3 mm.

AV.6.2 Phase I – Exercise 1

1. Flow regime map used

No flow regime map is used: the flow is considered as a bubbly flow.
2. Interfacial mass, momentum and energy exchange models

The interfacial momentum exchange models are:

- the Ishii correlation for the drag force (Ishii and Zuber, 1979).
- the Zuber correlation for the added mass coefficient (Zuber, 1964).
- the Tomiyama correlation for the lift force (Tomiyama et al. 2002).
- turbulent dispersion (Lance and Lopez de Bertodano, 1994).
- the interfacial mass and energy exchanges models are
  - for the liquid phase: a bulk condensation model based on the Ranz-Marshall correlation;
  - for the vapor phase: a return to saturation model with a constant time-scale.

3. Wall drag and heat transfer models

At the wall, the heat transfer model applied is the Kurul and Podowski model. (Kurul and Podowski, 1990).

4. Axial nodalisation used

Table AV.6.2-1 Characteristics of the grids used in the simulations

<table>
<thead>
<tr>
<th></th>
<th>Grid level 1</th>
<th>Grid level 2</th>
<th>Grid level 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of cells</td>
<td>154,812</td>
<td>602,040</td>
<td>1,561,152</td>
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<tr>
<td>Number of cells in the axial direction</td>
<td>400</td>
<td>520</td>
<td>520</td>
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<tr>
<td>Number of cells in a cross-section</td>
<td>388</td>
<td>1160</td>
<td>3008</td>
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<td>Cell size in the axial direction</td>
<td>4 mm</td>
<td>3 mm</td>
<td>3 mm</td>
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<tr>
<td>distance-to-wall of the boundary cells centres</td>
<td>0.25 mm</td>
<td>0.15 mm</td>
<td>0.1 mm</td>
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</table>

Figure AV.6.2-1 Cross-section view of grid level 1

Figure AV.6.2-2 Cross-section view of grid level 2
5. **Boundary condition used**

Inlet: mass flow rate and temperature imposed.

Outlet: Condition on the pressure.

Walls: uniform heat flux imposed; friction wall laws.

**AV.6.3 References**


AV.7 EDF (THYC)

AV.7.1 Overall questionnaire

1. Specify the governing transport equations, assumptions and simplifications
   2-phase “homogeneous mode” + Sub-cooled boiling
   4-equation model for 2-phase flows:
   • mass conservation for liquid-vapour mixing;
   • momentum conservation for liquid-vapour mixing;
   • energy conservation for liquid-vapour mixing;
   • vapour phase-related mass equation.
   Dynamic disequilibrium between phases by means of an algebraic model
   • vapour phase at saturation.
   Heat conduction equation in fuel rods
   • closure laws to be provided;
   • pressure loss tensor;
   • relative velocity;
   • vapour mass production rate;
   • mixing models;
   • turbulent shear stress tensor;
   • diffusive heat flux.

2. Specify the numerical algorithm used (fully implicit, fully explicit; semi-implicit)
   • fractional-step scheme and finite-volume method;
   • semi-implicit.

3. Specify the two-phase models and formulations used (HEM, drift flux model, two-fluid model, etc.).
   • homogeneous equilibrium model;
   • axial relative velocity/drift flux model = Chexal Lellouche;
   • transverse relative velocity/no slip.

4. Specify any optimisations of the code predictions that were performed by adjusting the model parameters to the experimental database
   Grid mixing factor adjusted with steady-state fluid temperature test series.
AV.7.2 Phase I – Exercise 1

1. Specify the flow regime map used

   Bubbly flow.

2. Specify the interfacial mass, momentum and energy exchange models

   - vapour production at the heated wall [OSV from Saha-Zuber; Wall heat flux repartition from CATHARE (cubic interpolation)];
   - liquid-vapour interfacial transfer within the flow (heat transfer from $Nu = 2(\text{Pe}/\rho)^{0.5}$; Interfacial area from empirical bubble diameter).

3. Specify the wall drag and heat transfer models

   Wall drag:
   - axial 1-phase flow = Colburn;
   - 2-phase flow multiplier = HTFS.

   Heat transfer model:
   - monophasic = Gautier;
   - diphasic = Chen.

4. Specify the axial nodalisation utilised (number of nodes, node size, variable axial nodding, etc.)

   - number of axial nodes = 64;
   - node size = (mean = 0.025 m; min = 0.002; max = 0.0282).
Specify the boundary conditions used.
Pressure: downstream
Mass Flow rate + enthalpy + quality: upstream

**AV.7.3 Phase I – Exercise 2**

1. **Specify the cross-flow models used (diversion flow, void drift and turbulent mixing models)**
   - axial relative velocity/drift flux model = Chexal Lellouche;
   - transverse relative velocity/no slip;
   - turbulent diffusivity in a bare bundle = Cheng Todreas;
   - turbulent Prandtl number = 1;
   - 2-phase multiplier = 1;
   - grid factor multiplier = 8.

2. **Specify the flow regime map used**
   Bubbly flow regime.

3. **Specify the interfacial mass, momentum and energy exchange models**
   - vapour production at the heated wall [OSV from Saha-Zuber; Wall heat flux repartition from CATHARE (cubic interpolation)];
   - liquid-vapour interfacial transfer within the flow (heat transfer from Nu = 2(Pe/p)^0.5 Interfacial area from empirical bubble diameter).

4. **Specify the wall drag and heat transfer models**
   **Wall drag:**
   - axial 1-phase flow = Colburn;
   - transverse flow pressure loss = Idel’cik;
   - angle factor = Kazakievic;
   - 2-phase flow multiplier = HTFS.
   **heat transfer model:**
   - monophasic = Gautier;
   - diphasic = Chen.

5. **Specify the turbulent mixing and void drift models used**
   No answer provided.
6. Specify any spacer grid effects on the void distribution if modelled
   Spacer grid effects on the void distribution not modelled.

7. If symmetry used, specify the symmetry applied in the model
   Symmetry not used.

8. Specify the axial nodalisation utilised (number of nodes, node size, variable axial
    nodding, spacer grids location with respect to the axial nodding, etc.);
   - number of axial nodes = 85;
   - node size = (mean = 0.10 m; min = 0.0435; max = 0.166).

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<td></td>
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</tr>
<tr>
<td>1.2927</td>
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<td></td>
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<tr>
<td>1.3357</td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
1,4156  MV
1,4621
1,5085
1,5550
1,6128  SS
1,6655
1,7183
1,7710
1,8726  MV
1,9181
1,9635
2,0090
2,0698  SS
2,1185
2,1673
2,2160
2,3296  MV
2,3618
2,3940
2,4267
2,4594
2,5278  SS
2,5749
2,6219
2,6690
2,7866  MV
2,8351
2,8835
2,9320
2,9848  SS
3,0329
3,0809
3,1290
3,1770
3,2436  MV
3,2927
3,3418
3,3909
9. Specify the boundary conditions used
Pressure: downstream.
Mass Flow rate + enthalpy + quality: upstream.

AV.7.4 Phase I – Exercise 3

1. Specify the cross-flow models used (diversion flow, void drift and turbulent mixing models).
   - axial relative velocity/drift flux model = Chexal Lellouche;
   - transverse relative velocity/no slip;
   - turbulent diffusivity in a bare bundle = Cheng Todreas;
   - turbulent Prandtl number = 1;
   - 2-phase multiplier = 1;
   - grid factor multiplier = 8.

2. Specify the flow regime map used
   Bubbly.

3. Specify the interfacial mass, momentum and energy exchange models
   No answer provided.

4. Specify the wall drag and heat transfer models
   Wall drag:
   - axial 1-phase flow = Colburn;
   - transverse flow pressure loss = Idel’cik;
• angle factor = Kazakievic;
• 2-phase flow multiplier = HTFS.

*heat transfer model:*
• monophasic = Gautier;
• diphasic = Chen.

5. Specify the turbulent mixing and void drift models used

No answer provided.

6. Specify any spacer grid effects on the void distribution if modelled

Spacer grid effects on the void distribution are not modelled.

7. If symmetry used, specify the symmetry applied in the model

Symmetry not used.

8. Specify the axial nodalisation utilised (number of nodes, node size, variable axial nodding, spacer grids location with respect to the axial nodding, etc.)

• number of axial nodes = 85;
• node size = (mean = 0.1 m ; min = 0.0435 ; max = 0.166).

9. Specify the boundary conditions used

• Pressure: downstream.
• Mass Flow rate + enthalpy + quality: upstream.

**AV.7.5 Phase I – Exercise 4**

1. Specify the correlations/models used for single-phase and two-phase frictional pressure drop

• axial 1-phase flow = Colburn;
• transverse flow pressure loss = Idel’cik;
• angle factor = Kazakievic;
• 2-phase flow multiplier = HTFS.

Specify the components of the pressure drop used in the code.

• Pressure loss coefficients of the grids:
  NMV => 0.88;
  MV => 1.06;
  SS => 0.8.
AV.8 JNES (CHAMP-ITA)

AV.8.1 Overall questionnaire

1. Specify the governing transport equations, assumptions and simplifications
   - two phase conservation equations (mass, momentum, energy);
   - discretisation by finite volume method (FVM) on structured grid of a three-dimensional Cartesian coordinate system;
   - porosity and permeability assumptions for rod shape.

2. Specify the numerical algorithm used (fully implicit, fully explicit; semi-implicit)
   - fully implicit method [Inter-Phase Slip-Algorithm (IPSA)];
   - Successive Over-Relaxation method (SOR) for inversing the matrix.

3. Specify the two-phase models and formulations used (HEM, drift flux model, two-fluid model, etc.)
   - two-fluid model.

4. Specify any optimisations of the code predictions that were performed by adjusting the model parameters to the experimental database
   - adjust bubble size used in correlation for optimising interface momentum and energy transfer;
   - increase in the thermal conductivity of liquid phase for simulating sub-cooled boiling near the wall.

AV.8.2 Phase I – Exercise 1

1. Specify the flow regime map used
   The dispersed phase is defined simply as the phase volume fraction of which is smaller than the other phase (the continuum phase).
2. Specify the interfacial mass, momentum and energy exchange models

As for the interfacial mass and energy exchange models:

\[
M_{1→g} = \frac{(q_{\text{interface→g}} - q_{1→\text{interface}})}{(h_{\text{saturation}}(T_{\text{interface}}) - h_{\text{saturation}}(T_{\text{interface}}))}
\]

\[
q_{\text{interface→g}} = \left(1.5\frac{r}{d}\right)\left(\frac{\lambda_g}{2d}\right) \left(2 + 0.37 \text{Re}^{0.33} \text{Pr}^{0.33}\right), \quad \text{Re} = \frac{\rho_g r \left|u_i - u_g\right| d}{\mu}, \quad \text{Pr} = \frac{C_p \mu_g}{\lambda_g}
\]

\[
q_{1→\text{interface}} = \left(1.5\frac{r}{d}\right)\left(\frac{\lambda_d}{2d}\right)
\]

here,

- \(M_{1→g}\): interfacial mass transfer from liquid phase to gas phase (kg/m³/s)
- \(q_{\text{interface→g}}\): interfacial heat transfer from interface to gas phase (W/m³/K)
- \(q_{1→\text{interface}}\): interfacial heat transfer from liquid phase to interface (W/m³/K)
- \(r\): volume fraction of dispersed phase
- \(\rho\): density (kg/m³)
- \(u\): velocity (m/s)
- \(d\): characteristic diameter of dispersed phase (m)
- \(\mu\): viscosity (Pa · s)
- \(\lambda\): conductivity (W/m/K)
- \(C_p\): heat capacity (J/kg/K)

(8.2.1)

As for the interfacial momentum exchange models:

\[
(ka)_{\text{mom}} = 0.75C_D \left(\frac{(1-r)\rho}{d}\right)\left|u_i - u_g\right| r (1-r)^{-2.65}
\]

\[
C_D = \frac{24}{\text{Re}} \left(1 + 0.15 \text{Re}^{0.937}\right), \quad \text{Re} = \frac{(1-r)\rho \left|u_i - u_g\right| d}{\mu}
\]

here,

- \((ka)_{\text{mom}}\): interfacial momentum transfer coefficient (N/m³/(m/s))
- \(r\): volume fraction of dispersed phase
- \(\rho\): density of continuum phase (kg/m³)
- \(u\): velocity (m/s)
- \(d\): characteristic diameter of dispersed phase (m)
- \(\mu\): viscosity of continuum phase (Pa · s)

(8.2.2)

3. Specify the wall drag and heat transfer models

- non-slip condition;
- heat conduction between wall and adjacent fluid mesh.
4. Specify the axial nodalisation utilised (number of nodes, node size, variable axial nodding, etc.)
   - 200 nodes, 10 mm and even nodding for S1 and S2 central sub-channel;
   - 400 nodes, 5 mm and even nodding for S3 side sub-channel;
   - 500 nodes, 4 mm and even nodding for S4 corner sub-channel.

5. Specify the boundary conditions used
   - velocity and temperature specified at inlet;
   - pressure specified at outlet;
   - heat generation in calculation cells adjacent to rod surface.

AV.8.3 Phase I – Exercise 2
1. Specify the cross-flow models used (diversion flow, void drift and turbulent mixing models)
   - No specific cross-flow model;
   - add pressure drop term in momentum equation of horizontal direction.

2. Specify the flow regime map used
   Same as Phase I Exercise 1.

3. Specify the interfacial mass, momentum and energy exchange models
   Same as Phase I Exercise 1.

4. Specify the wall drag and heat transfer models
   Same as Phase I Exercise 1.

5. Specify any spacer grid effects on the void distribution if modelled
   Add large pressure drop term in momentum equation of horizontal direction.

6. If symmetry used, specify the symmetry applied in the model
   None.

7. Specify the axial nodalisation utilised (number of nodes, node size, variable axial nodding, spacer grids location with respect to the axial nodding, etc.)
   - 44 nodes, 22.7 mm and even nodding for upper non-heating section;
   - 156 nodes, ≈20 mm and even nodding for heating section (excluding spacer grids location);
   - NMV and MV spacers are divided by two axial nodes;
   - Simple spacers are modeled by one axial node.

8. Specify the boundary conditions used
   Same as Phase I Exercise 1.
AV.8.4 Phase I – Exercise 3

1. Specify the cross-flow models used (diversion flow, void drift and turbulent mixing models)
   Same as Phase I Exercise 2.

2. Specify the flow regime map used
   Same as Phase I Exercise 1.

3. Specify the interfacial mass, momentum and energy exchange models
   Same as Phase I Exercise 1.

4. Specify the wall drag and heat transfer models
   Same as Phase I Exercise 1.

5. Specify any spacer grid effects on the void distribution if modelled
   Same as Phase I Exercise 2.

6. If symmetry used, specify the symmetry applied in the model
   Same as Phase I Exercise 2.

7. Specify the axial nodalisation utilised (number of nodes, node size, variable axial nodding, spacer grids location with respect to the axial nodding, etc.)
   Same as Phase I Exercise 2.

8. Specify the boundary conditions used
   Same as Phase I Exercise 1.

AV.8.5 Phase I – Exercise 4

1. Specify the correlations/models used for single-phase and two-phase frictional pressure drop
   Pressure drop can be calculated by solving discretised momentum equation.

2. Specify the components of the pressure drop used in the code
   No answer provided.
AV.9 KAERI (MATRA)

AV.9.1 Overall questionnaire

1. Specify the governing transport equations, assumptions and simplifications

The governing transport equations for sub-channel geometry were derived from integral balances on an arbitrary fixed control volume.

The flow is a transient, single component, two-phase mixture of liquid and vapour in thermodynamic equilibrium state.

Governing transport equations for the mixture can be written as:

**Continuity:**

\[ A_i \frac{\partial \langle \langle \rho_m \rangle \rangle_i}{\partial t} + \frac{\partial m_i}{\partial x} + \sum_j (w_{ij} + w_{i+j}) = 0 \]  \hspace{1cm} (9.1.1)

**Energy:**

\[ A_i \frac{\partial \langle \langle \rho_m \rangle \rangle_i \langle \langle h_m \rangle \rangle_i}{\partial t} + \frac{\partial (m_i \langle h \rangle_i)}{\partial x} + \sum_j w_{ij} \langle h^* \rangle_i = Q \]  \hspace{1cm} (9.1.2)

where,

\[ Q = \frac{\partial}{\partial x} \left( k \frac{\partial T}{\partial x} \right) A_i - \sum_j C_{ij} (T_i - T_j) - \sum_j w_{ij} (h_i - h_j) + \sum_n \xi_n \langle q^n \rangle \]  \hspace{1cm} (9.1.3)

**Axial momentum:**

\[ \frac{\partial m_i}{\partial t} + \frac{\partial}{\partial x} \left( \sum_k \alpha_k \rho_k u_k^* \right) A_i + \sum_j w_{ij} \langle u^* \rangle_i = -A \frac{\partial P}{\partial x} - F_x \]  \hspace{1cm} (9.1.4)

where,

\[ F_x = \frac{I}{2} \left[ \frac{f \rho_m^2}{d_{hi} \rho_m} + \frac{K}{\rho_m' \Delta x} \right] m_i + f \sum_j w_{ij} (u_i - u_j) + A_i \langle \langle \rho_m \rangle \rangle_i g \cos \theta \]  \hspace{1cm} (9.1.5)
Lateral momentum:

\[
\frac{\partial w_y}{\partial t} + \frac{\partial}{\partial x} \left( w_y \langle u_i \rangle \right) + \frac{1}{1} \sum_j w_j \langle v_j \rangle = \frac{S_{ij}}{1} \left( P_i - P_j \right) - F_{ij}
\]  

where,

\[
F_{ij} = \frac{1}{2} K_{ij} \left( \frac{w_j}{\rho s_i} \right) + s_j \langle \rho_i \rangle \sin \theta
\]

Important assumptions are:

- advection is allowed only across the fluid boundary;
- axial turbulent mixing is ignored;
- the works done by viscous stress, and by body force are ignored;
- the internal heat generation in the fluid is ignored;
- the gravity is the only significant body force;
- fluid-to-fluid viscous force is ignored;
- the transverse linear momentum diffusion due to transverse turbulent mixing is ignored.

2. Specify the numerical algorithm used (fully implicit, fully explicit; semi-implicit)
   Fully implicit.

3. Specify the two-phase models and formulations used (HEM, drift flux model, two–fluid model, etc.)
   HEM.

4. Specify any optimisations of the code predictions that were performed by adjusting the model parameters to the experimental database
   None.

AV.9.2 Phase I – Exercise 1

1. Specify the flow regime map used
   None.

2. Specify the interfacial mass, momentum and energy exchange models
   None.
3. Specify the wall drag and heat transfer models

Wall drag model:

Single-phase pressure drop model:

$$\Delta P_f = f \left( \frac{L}{d_h} \right) \frac{G^2}{2\rho} \quad (9.2.1)$$

$$f = 0.184 \times Re^{-0.2}$$

Two-phase pressure drop model:

$$\Delta P_f = \Phi \cdot f \left( \frac{L}{d_h} \right) \frac{G^2}{2\rho} \quad (9.2.2)$$

$$\Phi = \frac{(1 - \chi)^2}{(1 - \alpha)^{1.42}} \quad , \text{for } 0.0 < \alpha \leq 0.6$$

$$\Phi = 0.478 \times \frac{(1 - \chi)^2}{(1 - \alpha)^{3.2}} \quad , \text{for } 0.6 < \alpha \leq 0.9$$

$$\Phi = 1.73 \times \frac{(1 - \chi)^2}{(1 - \alpha)^{1.64}} \quad , \text{for } 0.9 < \alpha \leq 1.0$$

Heat transfer model: Not used.

4. Specify the axial nodalisation utilised (number of nodes, node size, variable axial nodding, etc.)

- number of nodes = 30;
- node size = 51.8 mm;
- axial nodding scheme = uniform.

5. Specify the boundary conditions used

Constant inlet flow and uniform exit pressure distribution.
AV.9.3 Phase I – Exercise 2

1. Specify the cross-flow models used (diversion flow, void drift and turbulent mixing models)

   Diversion cross-flow was calculated by the lateral momentum equation.

   Turbulent mixing model:

   Single-phase turbulent mixing model:

   \[ w'_{y} = \beta \cdot s_{y} \cdot G_{avg} \]  \hspace{1cm} (9.3.1)

   Two-phase mixing and void drift model:

   \[ w'_{y} = \beta \cdot s_{y} \cdot G_{avg} \]  \hspace{1cm} (9.3.2)

   Turbulent mixing parameter, \( \beta = 0.04 \)

2. Specify the flow regime map used

   None.

3. Specify the interfacial mass, momentum and energy exchange models

   None.

4. Specify the wall drag and heat transfer models

   Wall drag model:

   Single-phase pressure drop model:

   \[ \Delta P_{f} = f \left( \frac{L}{d_{hy}} \right) \frac{G^{2}}{2\rho} + \sum_{n=1}^{V} K_{grid,n} \frac{G^{2}}{2\rho} \]  \hspace{1cm} (9.3.3)

   \[ f = 0.184 \times Re^{-0.2} \]

   \[ K_{grid} = 1.0, 0.7, 0.4 \text{ for MV, NMV, SS grid, respectively}. \]
Two-phase pressure drop model:

\[ \Delta P_f = \Phi \cdot f \left( \frac{L}{d_{bl}} \right) \frac{G^2}{2\rho} \]  

(9.3.4)

\[ \Phi = \frac{(1 - \chi)^2}{(1 - \alpha)^{1.42}}, \text{ for } 0.0 < \alpha \leq 0.6 \]

\[ \Phi = 0.478 \times \frac{(1 - \chi)^2}{(1 - \alpha)^{2.2}}, \text{ for } 0.6 < \alpha \leq 0.9 \]

\[ \Phi = 1.73 \times \frac{(1 - \chi)^2}{(1 - \alpha)^{1.64}}, \text{ for } 0.9 < \alpha \leq 1.0 \]

Heat transfer model: Not used.

5. Specify the turbulent mixing and void drift models used

See answer to the question 1.

6. Specify any spacer grid effects on the void distribution if modelled

None.

7. If symmetry used, specify the symmetry applied in the model

Not used (full assembly is considered).

8. Specify the axial nodalisation utilised (number of nodes, node size, variable axial nodding, spacer grids location with respect to the axial nodding, etc.)

- number of nodes = 70;
- node size = 45.3 ~ 55.4 mm;
- axial nodding scheme = variable.

<table>
<thead>
<tr>
<th>Axial distance (mm)</th>
<th>Node size (mm)</th>
<th>Number of axial nodes</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 ~ 2216</td>
<td>55.4</td>
<td>40</td>
</tr>
<tr>
<td>2216 ~ 2669</td>
<td>45.3</td>
<td>10</td>
</tr>
<tr>
<td>2669 ~ 3177</td>
<td>50.8</td>
<td>10</td>
</tr>
<tr>
<td>3177 ~ 3658</td>
<td>48.1</td>
<td>10</td>
</tr>
</tbody>
</table>

Spacer grid location (except SS grids) w.r.t. axial nodding.
Table AV.9.3-2 Axial Grid Locations

<table>
<thead>
<tr>
<th>Spacer grid</th>
<th>Distance from the bottom, mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.5</td>
</tr>
<tr>
<td>2</td>
<td>471</td>
</tr>
<tr>
<td>3</td>
<td>925</td>
</tr>
<tr>
<td>4</td>
<td>1378</td>
</tr>
<tr>
<td>5</td>
<td>1832</td>
</tr>
<tr>
<td>6</td>
<td>2285</td>
</tr>
<tr>
<td>7</td>
<td>2739</td>
</tr>
<tr>
<td>8</td>
<td>3247</td>
</tr>
</tbody>
</table>

9. Specify the boundary conditions used
   Uniform inlet flow distribution and uniform exit pressure distribution.

AV.9.4 Phase I – Exercise 3

1. Specify the cross-flow models used (diversion flow, void drift and turbulent mixing models)
   Diversion cross-flow was calculated by the lateral momentum equation.
   Turbulent mixing model:
   Single-phase turbulent mixing model:

   \[ w'_{ij} = \beta s_{ij} G_{avg} \]  
   \[(9.4.1)\]

   Two-phase mixing and void drift model:

   \[ w'_{ij} = \beta s_{ij} G_{avg} \]  
   \[(9.4.2)\]

   Turbulent mixing parameter, \(\beta=0.04\).

2. Specify the flow regime map used
   None.

3. Specify the interfacial mass, momentum and energy exchange models
   None.
4. Specify the wall drag and heat transfer models

Wall drag model:

Single-phase pressure drop model:

\[
\Delta P_f = f \left( \frac{L}{d_{hy}} \right) \frac{G^2}{2 \rho} + \sum_{n=1}^{N} K_{grid,n} \frac{G^2}{2 \rho}
\]

\[f = 0.184 \times \text{Re}^{-0.2}
\]

\[K_{grid} = 1.0, \ 0.7, \ 0.4 \text{ for MV, NMV, SS grid, respectively.}
\]

Two-phase pressure drop model:

\[
\Delta P_f = \Phi \cdot f \left( \frac{L}{d_{hy}} \right) \frac{G^2}{2 \rho}
\]

\[\Phi = \frac{(1 - \chi)^2}{(1 - \alpha)^{1.42}}, \text{ for } 0.0 < \alpha \leq 0.6
\]

\[\Phi = 0.478 \times \frac{(1 - \chi)^2}{(1 - \alpha)^{2.2}}, \text{ for } 0.6 < \alpha \leq 0.9
\]

\[\Phi = 1.73 \times \frac{(1 - \chi)^2}{(1 - \alpha)^{1.64}}, \text{ for } 0.9 < \alpha \leq 1.0
\]

Heat transfer model: Not used (heat flux boundary condition was imposed for the transient analysis).

5. Specify the turbulent mixing and void drift models used

See answer to question 1.

6. Specify any spacer grid effects on the void distribution if modelled

None.

7. If symmetry used, specify the symmetry applied in the model

Not used (full assembly is considered).
8. Specify the axial nodalisation utilised (number of nodes, node size, variable axial nodding, spacer grids location with respect to the axial nodding, etc.)

- number of nodes = 70;
- node size = 45.3 ∼ 55.4 mm;
- axial nodding scheme = variable.

<table>
<thead>
<tr>
<th>Axial distance (mm)</th>
<th>Node size (mm)</th>
<th>Number of axial nodes</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 ∼ 2216</td>
<td>55.4</td>
<td>40</td>
</tr>
<tr>
<td>2216 ∼ 2669</td>
<td>45.3</td>
<td>10</td>
</tr>
<tr>
<td>2669 ∼ 3177</td>
<td>50.8</td>
<td>10</td>
</tr>
<tr>
<td>3177 ∼ 3658</td>
<td>48.1</td>
<td>10</td>
</tr>
</tbody>
</table>

Spacer grid location (except SS grids) w.r.t. axial nodding.

9. Specify the boundary conditions used

Uniform inlet flow distribution and uniform exit pressure distribution.

AV.9.5 Phase I – Exercise 4

1. Specify the correlations/models used for single-phase and two-phase frictional pressure drop

Single-phase pressure drop model:

$$\Delta P_f = f \left( \frac{L}{d_{hy}} \right) \frac{G^2}{2 \rho} + \sum_{n=1}^{K} K_{grid,n} \frac{G^2}{2 \rho}$$

(9.5.1)

$$f = 0.184 \times \text{Re}^{-0.2}$$

$$K_{grid} = 1.0, \ 0.7, \ 0.4 \ \text{for MV, NMV, SS grid, respectively.}$$
Two-phase pressure drop model:

\[ \Delta P_f = \Phi \cdot f \left( \frac{L}{d_y} \right) \frac{G^2}{2 \rho} \]

(9.5.2)

\[ \Phi = \frac{(1 - \chi)^2}{(1 - \alpha)^{1.42}} \], for \( 0.0 < \alpha \leq 0.6 \)

\[ \Phi = 0.478 \times \frac{(1 - \chi)^2}{(1 - \alpha)^{3.2}} \], for \( 0.6 < \alpha \leq 0.9 \)

\[ \Phi = 1.73 \times \frac{(1 - \chi)^2}{(1 - \alpha)^{1.64}} \], for \( 0.9 < \alpha \leq 1.0 \)

2. Specify the components of the pressure drop used in the code

- friction loss;
- form loss in spacer grids;
- acceleration loss;
- gravitation loss.
AV.10 KIT (SUBCHANFLOW)

AV10.1 Overall questionnaire

1. Specify the governing transport equations, assumptions and simplifications
   - 3d-mass conservation equation;
   - 3d-enthalpy conservation equation;
   - 3d-momentum conservation equation without lateral transport of lateral momentum;
   - lumped volume approximation in lateral direction -finite difference in axial direction.

2. Specify the numerical algorithm used (fully implicit, fully explicit; semi-implicit)
   Fully implicit axially upward flow, only.

3. Specify the two-phase models and formulations used (HEM, drift flux model, two– fluid model, etc.)
   HEM with vapor slip by empirical correlations.

4. Specify any optimisations of the code predictions that were performed by adjusting the model parameters to the experimental database
   Constant lateral mixing coefficient: 0.06 using “equal mass mixing”.

AV.10.2 Phase I – Exercise 1

1. Specify the flow regime map used
   Bubbly, transition, annular, hidden in correlations.

2. Specify the interfacial mass, momentum and energy exchange models
   HEM with slip correlation (Chexal Lellouche).

3. Specify the wall drag and heat transfer models
   Blasius, Dittus-Boelter.

4. Specify the axial nodalisation utilised (number of nodes, node size, variable axial nodding, etc.)
   24 equal distance axial cells.

5. Specify the boundary conditions used
   Pressure boundary at the top, flow boundary at the bottom.
AV.10.3 Phase I – Exercise 2

1. Specify the cross-flow models used (diversion flow, void drift and turbulent mixing models)
   Diversion flow, simple equal mass, constant coefficient.

2. Specify the flow regime map used
   Bubbly, transition, annular, hidden in correlations.

3. Specify the interfacial mass, momentum and energy exchange models
   HEM with slip correlation (Chexal Lellouche).

4. Specify the wall drag and heat transfer models
   Blasius, Dittus-Boelter.

5. Specify the turbulent mixing and void drift models used
   Constant lateral mixing coefficient: 0.06 using “equal mass mixing”.

6. Specify any spacer grid effects on the void distribution if modelled
   Not modelled.

7. If symmetry used, specify the symmetry applied in the model
   No symmetry used.

8. Specify the axial nodalisation utilised (number of nodes, node size, variable axial nodding, spacer grids location with respect to the axial nodding, etc.)
   24 equal distance axial cells.

9. Specify the boundary conditions used
   Pressure boundary at the top, flow boundary at the bottom, equal velocity for all channels.

AV.10.4 Phase I – Exercise 3

1. Specify the cross-flow models used (diversion flow, void drift and turbulent mixing models)
   Diversion flow, simple equal mass, constant coefficient.

2. Specify the flow regime map used
   Bubbly, transition, annular, hidden in correlations.

3. Specify the interfacial mass, momentum and energy exchange models
   HEM with slip correlation (Chexal Lellouche).

4. Specify the wall drag and heat transfer models
   Blasius, Dittus-Boelter.
5. Specify the turbulent mixing and void drift models used
   Constant lateral mixing coefficient: 0.06 using “equal mass mixing”.

6. Specify any spacer grid effects on the void distribution if modelled
   Not modelled.

7. If symmetry used, specify the symmetry applied in the model
   No symmetry used.

8. Specify the axial nodalisation utilised (number of nodes, node size, variable axial nodding, spacer grids location with respect to the axial nodding, etc.)
   24 equal distance axial cells.

9. Specify the boundary conditions used
   Pressure boundary at the top, flow boundary at the bottom, equal velocity for all channels.

   AV.10.5 Phase I – Exercise 4

1. Specify the correlations/models used for single-phase and two-phase frictional pressure drop
   No answer provided.

2. Specify the components of the pressure drop used in the code
   - Blasius, Armand;
   - Gravitation, spacers along heated zone, friction.
AV.11 KTH (TRACE)

AV.11.1 Overall questionnaire

1. Specify the governing transport equations, assumptions and simplifications

The TRACE code is based on the 6-equation time-averaged two-fluid model.

Time averaged mass equations:

\[ \frac{\partial}{\partial t} \left[ (1 - \alpha) \bar{\rho}_l \bar{V}_l \right] + \nabla \cdot \left[ (1 - \alpha) \bar{\rho}_l \bar{V}_l \bar{V}_l \right] = -\Gamma \]  

(11.1.1)

\[ \frac{\partial [\alpha \bar{\rho}_g]}{\partial t} + \nabla \cdot \left[ \alpha \bar{\rho}_g \bar{V}_g \right] = \bar{\Gamma} \]  

(11.1.2)

Time averaged energy equations:

\[ \frac{\partial}{\partial t} \left[ (1 - \alpha) \bar{\rho}_l \left( e_l + \frac{V_l^2}{2} \right) \right] + \nabla \cdot \left[ (1 - \alpha) \bar{\rho}_l \left( e_l + \frac{V_l^2}{2} \right) \bar{V}_l \right] \]

\[ = -\nabla \cdot \left[ (1 - \alpha) \bar{q}'_l \right] + \nabla \cdot \left[ (1 - \alpha) \bar{T}_l \cdot \bar{V}_l \right] + (1 - \alpha) \bar{\rho}_l \bar{g} \cdot \bar{V}_l - \bar{E}_l + \bar{q}_{d1} \]  

(11.1.3)

\[ \frac{\partial \left[ \alpha \bar{\rho}_g \left( e_g + \frac{V_g^2}{2} \right) \right]}{\partial t} + \nabla \cdot \left[ \alpha \bar{\rho}_g \left( e_g + \frac{V_g^2}{2} \right) \bar{V}_g \right] \]

\[ = -\nabla \cdot \left[ \alpha \bar{q}'_g \right] + \nabla \cdot \left[ \alpha \bar{T}_g \cdot \bar{V}_g \right] + \alpha \bar{\rho}_g \bar{g} \cdot \bar{V}_g - \bar{E}_g + \bar{q}_{dg} \]  

(11.1.4)

Time averaged momentum equations:

\[ \frac{\partial}{\partial t} \left[ (1 - \alpha) \bar{\rho}_l \bar{V}_l \right] + \nabla \cdot \left[ (1 - \alpha) \bar{\rho}_l \bar{V}_l \bar{V}_l \right] = \nabla \cdot \left[ (1 - \alpha) \bar{T}_l \right] + (1 - \alpha) \bar{\rho}_l \bar{g} - \bar{M}_l \]  

(11.1.5)

\[ \frac{\partial [\alpha \bar{\rho}_g \bar{V}_g]}{\partial t} + \nabla \cdot \left[ \alpha \bar{\rho}_g \bar{V}_g \bar{V}_g \right] = \nabla \cdot \left[ \alpha \bar{T}_g \right] + \alpha \bar{\rho}_g \bar{g} - \bar{M}_l \]  

(11.1.6)

The right hand side of the energy and momentum equations has been modified (revised) with engineering correlations.

In the energy equation, \( q' \) (heat flux) is modified in order to add energy flux owing to turbulence diffusion. The energy as a consequence of mass transfer at the interface is represented by the products of mass transfer rate and appropriate stagnation enthalpy at the interface, \( \Gamma h'_v \) and \( \Gamma h'_l \).
Work performed on the fluid is divided into the pressure terms in the stress tensor, and work performed by shear stress and by interfacial force terms which is depicted as \( W \).

In the momentum equation, pressure is isolated from the stress tensor and viscous shear stress terms are combined with the Reynolds stress into a single tensor \( R \).

Revised time averaged energy equations:

\[
\frac{\partial}{\partial t} \left[ (1 - \alpha) \bar{\rho}_l \left( e_l + \frac{V_l^2}{2} \right) \right] + \nabla \cdot \left[ (1 - \alpha) \bar{\rho}_l \left( \frac{e_l + P}{\bar{\rho}_l} + \frac{V_l^2}{2} \right) \bar{V}_l \right] = -\nabla \cdot \left[ (1 - \alpha) \bar{q}_l^r \right] + (1 - \alpha) \bar{\rho}_l \bar{g} \cdot \bar{V}_l - \Gamma h'_l + W_l + \bar{q}_{dl} \tag{11.1.7}
\]

\[
\frac{\partial}{\partial t} \left[ \alpha \bar{\rho}_g \left( e_g + \frac{V_g^2}{2} \right) \right] + \nabla \cdot \left[ \alpha \bar{\rho}_g \left( e_g + \frac{P}{\bar{\rho}_g} + \frac{V_g^2}{2} \right) \bar{V}_g \right] = -\nabla \cdot \left[ \alpha \bar{q}_g^r \right] + \alpha \bar{\rho}_g \bar{g} \cdot \bar{V}_g - \Gamma h'_g + \bar{W}_g + \bar{q}_{dg} \tag{11.1.8}
\]

Revised time averaged momentum equations:

\[
\frac{\partial}{\partial t} \left[ (1 - \alpha) \bar{\rho}_l \bar{V}_l \right] + \nabla \cdot (1 - \alpha) \bar{\rho}_l \bar{V}_l \cdot \bar{V}_l = \nabla \cdot \left[ (1 - \alpha) \bar{R}_l \right] + (1 - \alpha) \bar{\rho}_l \bar{g} - \bar{M}_l \tag{11.1.9}
\]

\[
\frac{\partial}{\partial t} \left[ \alpha \bar{\rho}_g \bar{V}_g \right] + \nabla \cdot \alpha \bar{\rho}_g \bar{V}_g \cdot \bar{V}_g = \nabla \cdot \left[ \alpha \bar{R}_g \right] + \alpha \bar{\rho}_g \bar{g} - \bar{M}_l \tag{11.1.10}
\]

The engineering correlations have been added and the TRACE flow model has been reformulated as a volume averaged form. Initially, the overbar is dropped and all variables are treated as time averages. Afterwards, the overbar is returned to the notation as a volume average of terms in the conservation equations.
Volume averaged mass equations:

\[
\frac{\partial [(1-\alpha)\rho_l]}{\partial t} + \nabla \cdot [(1-\alpha)\rho_l \overrightarrow{V_l}] = -\overrightarrow{q_l} \\
\]

(11.1.11)

\[
\frac{\partial [\alpha\rho_g]}{\partial t} + \nabla \cdot [\alpha\rho_g \overrightarrow{V_g}] = \Gamma \\
\]

(11.1.12)

Volume averaged energy equations:

\[
\frac{\partial [(1-\alpha)\rho_l \left( e_l + \frac{V_l^2}{2} \right) ]}{\partial t} + \nabla \cdot [(1-\alpha)\rho_l \left( e_l + \frac{P}{\rho_l} + \frac{V_l^2}{2} \right) \overrightarrow{V_l}] \\
= -\nabla \cdot [(1-\alpha)\overrightarrow{q_l}^e] + (1-\alpha)\rho_l \overrightarrow{g} \cdot \overrightarrow{V_l} - \Gamma h_l' + W_l + \overrightarrow{q_{dl}} \\
\]

(11.1.13)

\[
\frac{\partial [\alpha\rho_g \left( e_g + \frac{V_g^2}{2} \right) ]}{\partial t} + \nabla \cdot [\alpha\rho_g \left( e_g + \frac{P}{\rho_g} + \frac{V_g^2}{2} \right) \overrightarrow{V_g}] \\
= -\nabla \cdot [\alpha\overrightarrow{q_g}^e] + \alpha\rho_g \overrightarrow{g} \cdot \overrightarrow{V_g} - \Gamma h_g' + W_g + \overrightarrow{q_{dg}} \\
\]

(11.1.14)

Volume averaged momentum equations:

\[
\frac{\partial [(1-\alpha)\rho_l \overrightarrow{V_l}]}{\partial t} + \nabla \cdot [(1-\alpha)\rho_l \overrightarrow{V_l} \cdot \overrightarrow{V_l}] = \nabla \cdot [(1-\alpha)\rho_l \overrightarrow{R_l}] + (1-\alpha)\rho_l \overrightarrow{g} - M_l \\
\]

(11.1.15)

\[
\frac{\partial [\alpha\rho_g \overrightarrow{V_g}]}{\partial t} + \nabla \cdot [\alpha\rho_g \overrightarrow{V_g} \cdot \overrightarrow{V_g}] = \nabla \cdot [\alpha\overrightarrow{R_g}] + \alpha\rho_g \overrightarrow{g} - M_l \\
\]

(11.1.16)

Subsequently, a set of approximations is made:

1) “The volume average of a product is assumed to be equal to the product of volume. This is reasonable if the averaging volume is small enough, but eventually when applied within the finite volume context to reactor systems, the averaging volume will span flow channels. In this case, the approximation is good for most turbulent flow due to the flat profile across most of the flow cross-section. However, for laminar single phase flow in a circular channel cross-section, when the average of the product of two parabolic profiles is replaced by the product of the averages velocities, momentum flux terms will be low by 25%. Flows with rising droplets and falling wall film or certain vertical slug flow will also present problems [1]”.

2) “Only contributions from wall heat fluxes and heat fluxes at phase interfaces within the averaging volume are normally included in the volume average of the divergence of heat flux. An option exists to include the conduction heat flux within the fluid, but no
provision has been made for turbulent heat flux between averaging volumes. In effect, heat flux is a subgrid model. This approximation prevents accurate calculations of such phenomena as collapse of a steam bubble blocking natural circulation through a B&W candy-cane, or of the details of steam condensation at the water surface in an AP1000 core make-up tank. From a practical standpoint, lack of the volume to volume heat diffusion terms will not make a major difference in a simulation. For any normal spatial discretisation the numerical diffusion will significantly exceed the physical thermal diffusion [1].

3) “Only contributions from the stress tensor due to shear at metal surfaces or phase interfaces within the averaging volume are considered. No contributions due to shear between flows in adjacent averaging volumes are included. Again from a practical standpoint, numerical diffusion terms exceed any physical terms dropped by this approximation. However, code users need to understand that field equations with this approximation are not capable of modelling circulation patterns within a large open region regardless of the choice of mesh size [1].”

4) “Only those portions of the work terms $W_l$ and $W_g$ that contribute to change in bulk kinetic energy of motion are retained. Viscous heating is ignored, except as a special model within pump components, accounting for heating of the fluid by a pump rotor, through the direct heating source term $q_{dl}$ [1].”

2. Specify the numerical algorithm used (fully implicit, fully explicit; semi-implicit)

The TRACE code uses SETS and semi-implicit discretisation [1]. The calculations for this benchmark have been performed with the SETS method.

3. Specify the two-phase models and formulations used (HEM, drift flux model, two-fluid model, etc.)

The TRACE code uses 6-equation two-fluid model. The conservation equations are described earlier.

4. Specify any optimisations of the code predictions that were performed by adjusting the model parameters to the experimental data

The official version of the TRACE code has been used without any modifications. No adjustments have been made to the model parameters.

AV.11.2 Phase I - Exercise 1

1. Specify the flow regime map used

TRACE considers three distinct classes of flow regimes [1]:

- pre-CHF: these consist of the bubblyslug and the annularmist regimes;
- stratified: the horizontal stratified flow regime;
- post-CHF: this encompasses the “inverted” flow regimes that occur when the wall is too hot for liquid-wall contact.

The first exercise uses only the Pre-CHF flow regimes.

In TRACE, there is no explicit flow regime map for the determination of interfacial shear. Rather, the two primary regimes, bubblyslug and annularmist, are individually considered and then combined. The interfacial drag for the bubblyslug flow regime is based on a drift flux formulation.
and includes specific correlations for both pipes and rod bundles. The annular/mist flow regime combines the interfacial drag for an annular film with that for entrained droplets. Finally, the transition between these two primary flow regimes is discussed in Transition from Bubbly/Slug to Annular/Mist [1].

2. Specify the interfacial mass, momentum and energy exchanges models

The TRACE code includes a comprehensive set of closure models that cover the expected LWR operational, transient and accident conditions. The mass, momentum and energy exchange models are described in [1].

3. Specify the wall drag and heat transfer models

The wall drag is described in “Exercise 4 (Pressure Drop Benchmark” Section). The entire constitutive package is described in [1].

4. Specify the axial nodalisation utilised (number of nodes, node size, variable axial nodding, etc.)

All tests were discretised with 20 uniform axial nodes, 0.0775 m long. The node hydraulic diameter, volume and flow area depend on the test geometry (see Table 1).

<table>
<thead>
<tr>
<th>Test</th>
<th>(D_h) (m)</th>
<th>Volume (m(^3))</th>
<th>Flow area (m(^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.0078395</td>
<td>3.75E-06</td>
<td>4.83E-05</td>
</tr>
<tr>
<td>2</td>
<td>0.0078395</td>
<td>3.75E-06</td>
<td>4.83E-05</td>
</tr>
<tr>
<td>3</td>
<td>0.0060961</td>
<td>2.27E-06</td>
<td>2.92E-05</td>
</tr>
<tr>
<td>4</td>
<td>0.0051376</td>
<td>1.81E-06</td>
<td>2.07E-05</td>
</tr>
</tbody>
</table>

5. Specify the boundary conditions used

The inlet boundary conditions are specified by the fluid velocity, void fraction and fluid temperature (FILL component). The same velocity was used for liquid and vapour. The pressure is also defined to specify fluid thermodynamic conditions, but it has no direct effect on the node downstream. The length and volume of the FILL component are the same as the node downstream.

The outlet boundary conditions are specified by the pressure (BREAK component). The temperature is also defined to specify fluid thermodynamic conditions, but it has no direct effect on the node upstream. The length and volume of the BREAK component are the same as the node upstream.
AV.11.3 Phase I - Exercise 2

1. Specify the cross-flow models used (diversion flow, void drift and turbulent mixture models)
   This is not applicable for TRACE 1D component.

2. Specify the regime map used
   The regime map is described in “Exercise 1 (Steady State Single Sub-channel Benchmark” Section).

3. Specify the interfacial mass, momentum and energy exchange models
   The TRACE code includes a very comprehensive set of closure models that cover the expected LWR operational, transient and accident conditions. The mass, momentum and energy exchange models are described in the Theory Manual [2].

4. Specify the wall drag and heat transfer models
   The wall drag is described in “Exercise 4 (Pressure Drop Benchmark” Section).

5. Specify the turbulent mixing and void drift models used
   This is not applicable for TRACE 1D component.

6. Specify any spacer grid effect on the void distribution if modelled
   This is not applicable for TRACE 1D component.

7. If symmetry used, specify the symmetry applied in the model
   This is not applicable for TRACE 1D component.

8. Specify the axial nodalisation utilised (number of nodes, node size, variable axial nodding, spacer grids location with respect to the axial nodding, etc.)
   All tests were discretised with 24 uniform axial nodes, 0.15241667 m long. The node hydraulic diameter, volume and flow area depend on the test geometry (see Table 2).

<table>
<thead>
<tr>
<th>Test</th>
<th>D_h (m)</th>
<th>Volume (m³)</th>
<th>Flow area (m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>9.70E-03</td>
<td>3.72E-04</td>
<td>2.44E-03</td>
</tr>
<tr>
<td>6</td>
<td>9.70E-03</td>
<td>3.72E-04</td>
<td>2.44E-03</td>
</tr>
<tr>
<td>7</td>
<td>9.43E-03</td>
<td>3.69E-04</td>
<td>2.39E-03</td>
</tr>
<tr>
<td>8</td>
<td>9.70E-03</td>
<td>3.72E-04</td>
<td>2.44E-03</td>
</tr>
</tbody>
</table>

The spacer grids are located on the edges of the axial node. The locations of the spacer grids are shown in Table 3.
### Table AV.11.3-2 Axial Grid Locations

<table>
<thead>
<tr>
<th>Edges</th>
<th>Spacer grid</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>yes</td>
</tr>
<tr>
<td>2</td>
<td>no</td>
</tr>
<tr>
<td>3</td>
<td>yes</td>
</tr>
<tr>
<td>4</td>
<td>yes</td>
</tr>
<tr>
<td>5</td>
<td>yes</td>
</tr>
<tr>
<td>6</td>
<td>no</td>
</tr>
<tr>
<td>7</td>
<td>yes</td>
</tr>
<tr>
<td>8</td>
<td>yes</td>
</tr>
<tr>
<td>9</td>
<td>no</td>
</tr>
<tr>
<td>10</td>
<td>yes</td>
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<tr>
<td>11</td>
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<td>12</td>
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<td>15</td>
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<td>21</td>
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<td>23</td>
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</tr>
<tr>
<td>24</td>
<td>yes</td>
</tr>
<tr>
<td>25</td>
<td>yes</td>
</tr>
</tbody>
</table>

9. Specify the boundary conditions used

The boundary conditions are described in “Exercise 1 (Steady State Single Sub-channel Benchmark” Section).

**AV.11.4 Phase I - Exercise 3**

1. Specify the cross-flow models used (diversion flow, void drift and turbulent mixture models)

This is not applicable for TRACE 1D component.
2. Specify the regime map used

The regime map is described in “Exercise 1 (Steady State Single Sub-channel Benchmark” Section).

3. Specify the interfacial mass, momentum and energy exchange models

The TRACE code includes a very comprehensive set of closure models that cover the expected LWR operational, transient and accident conditions. The mass, momentum and energy exchange models are described in the Theory Manual [2].

4. Specify the wall drag and heat transfer models.

The wall drag is described in “Exercise 4 (Pressure Drop Benchmark” Section).

5. Specify the turbulent mixing and void drift models used

This is not applicable for TRACE 1D component.

6. Specify any spacer grid effect on the void distribution if modelled

This is not applicable for TRACE 1D component.

7. If symmetry used, specify the symmetry applied in the model

This is not applicable for TRACE 1D component.

8. Specify the axial nodalisation utilised (number of nodes, node size, variable axial nodding, spacer grids location with respect to the axial nodding, etc.)

All tests were discretised with 24 uniform axial nodes, 0.15241667 m long. The node hydraulic diameter, volume and flow area depend on the test geometry (see Table 4). The location of the spacer grids is shown Table 3.

<table>
<thead>
<tr>
<th>Test</th>
<th>$D_h$ (m)</th>
<th>Volume (m$^3$)</th>
<th>Flow area (m$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5T</td>
<td>9.70E-03</td>
<td>3.72E-04</td>
<td>2.44E-03</td>
</tr>
<tr>
<td>6T</td>
<td>9.70E-03</td>
<td>3.72E-04</td>
<td>2.44E-03</td>
</tr>
<tr>
<td>7T</td>
<td>9.43E-03</td>
<td>3.65E-04</td>
<td>2.39E-03</td>
</tr>
</tbody>
</table>

9. Specify the boundary conditions used

The boundary conditions are described in “Exercise 1 (Steady-State Single Sub-channel Benchmark” Section). The time dependent boundary conditions are modelled by providing parameter vs. time table.
AV.11.5 Phase I - Exercise 4

1. Specify the correlations/models used for single-phase and two-phase frictional pressure drop

Three types of frictional pressure losses are modelled in TRACE:

- wall drag, due to the fluid-wall shear;
- form drag, due to geometry specific pressure losses;
- interfacial drag, due to the shear between the two-phases.

Wall Drag

In TRACE formulation, the frictional pressure gradient due to wall drag is given by:

\[ \frac{dP}{dz} \big|_f = -C_{wl} \cdot |V_l| \cdot V_l - C_{wg} \cdot |V_g| \cdot V_g \]  \hspace{1cm} (11.5.1)

Single-phase

The coefficient of the wall drag is given by:

\[ C_{wk} = f_{wk} \cdot \frac{4}{D_h} \cdot \frac{1}{2} \rho_k = f_{wk} \cdot \frac{2\rho_k}{D_h} \]  \hspace{1cm} (11.5.2)

K corresponds to the phase of the coolant and f is the Fanning friction factor. TRACE uses the Churchill formula to calculate the Fanning friction factor. This formula has the advantage that it can be used for laminar, transition and turbulent flow. The formula is introduced as follows:

\[ f_w = 2 \left[ \left( \frac{8}{Re} \right) \frac{12}{12} + \frac{1}{(a+b)^{3/2}} \right]^{1/12} \]  \hspace{1cm} (11.5.3)

where a and b are:

\[ a = \left( 2.457 \cdot \ln \left( \frac{1}{Re} \right) ^{0.89} \frac{1}{0.27} \right)^{16} b = \left( \frac{3.753 \cdot 10^4}{Re} \right)^{16} \]  \hspace{1cm} (11.5.4)
Two-phase

TRACE uses different wall drag coefficients depending on the flow regime. The wall drag is applied to the liquid phase, hence, Equation (1.4.1) becomes:

$$\frac{dP}{dz} = -C_{wl} \cdot |V_l| \cdot V_l$$

(11.5.5)

Bubbly/Slug

For the bubbly/slug flow regime with nucleate boiling in the wall, the wall drag coefficient used by TRACE is:

$$C_{wl} = f_{wl} \cdot \frac{2\rho_l}{D_h} \cdot (1 + C_{NB})^2$$

(11.5.6)

where $f_{wl}$ is the Fanning friction factor calculated using the Churchill formula, and $C_{NB}$ is given by:

$$C_{NB} = \text{Min} \left\{2 , 155 \cdot \frac{d_B}{D_h} \cdot [\alpha \cdot (1 - \alpha)]^{0.62} \right\}$$

(11.5.7)

where $d_B$ is the bubble diameter. The bubble diameter is a function of liquid mass flux and the database covers mass flux from $500 \text{ kg/m}^2\text{s}$ to $1800 \text{ kg/m}^2\text{s}$.

Transient from Bubbly/Slug to Annular/Mist

For void fractions below 80% the bubbly/slug wall drag is used. For void fractions above 90% the annular flow wall drag model is used. For void fraction between 80% and 90%, the two regimes are interpolated:

$$C_{wl} = w_{fBS} \cdot C_{wl,BS} + (1 - w_{fBS}) \cdot C_{wl,AM}$$

(11.5.8)

where the bubbly/slug weighting factor is:

$$w_{fBS} = \left(\frac{0.9 - \alpha}{0.9 - 0.8}\right)$$

(11.5.9)

Annular/Mist

The equation to calculate the wall drag coefficient is:

$$C_{wl} = f_{film} \cdot \frac{2\rho_l}{D_h}$$

(11.5.10)
where
\[ f_{\text{film}} = \left( f_{\text{lam}}^3 + f_{\text{turb}}^3 \right)^{1/3} \]  \hspace{1cm} (11.5.11)

\[ f_{\text{lam}} = \frac{16}{Re_{2\Phi,l}} \]  \hspace{1cm} (11.5.12)

\[ f_{\text{turb}} = \left\{ 3.6 \cdot 10^{-3} \left[ \left( \frac{\phi}{0.37} \right)^{1.11} \right] \right\}^2 \]  \hspace{1cm} (11.5.13)

\[ Re_{2\Phi,l} = \frac{|G_j|D_h}{\mu_l} = \frac{(1-\alpha)\rho_j|V_j|D_h}{\mu_l} \]  \hspace{1cm} (11.5.14)

2. Specify the components of the pressure drop used in the code

See answer to the previous question.

Nomenclature

- \( e \) = Internal energy
- \( \vec{g} \) = gravity vector
- \( h \) = heat transfer coefficient
- \( h_{\text{sg}} \) = gas saturation enthalpy
- \( n \) = current-time quantity
- \( n+1 \) = new-time quantity
- \( q' \) = heat flux
- \( q_d \) = power deposited directly to the gas or liquid
- \( w \) = wall
- \( A \) = area
- \( C \) = shear coefficient
- \( D \) = diameter
- \( E_l \) = rate of energy transfer per unit volume across phase interfaces
- \( G \) = mass flux
- \( M_l \) = rate of momentum transfer per unit volume across phase interfaces
- \( P \) = pressure
- \( \text{Re} \) = Reynolds number
- \( T \) = stress Tensor
- \( \vec{V} \) = velocity vector
- \( \alpha \) = gas volume fraction
- \( \beta \) = momentum-convection temporal expansion flags
- \( \rho \) = density
- \( \Gamma \) = Interfacial mass-transfer rate (positive from liquid to gas)
- \( \theta \) = azimuthal

AV.11.6 References

AV.12 McMaster (ASSERT-PV)

AV.12.1 Overall questionnaire

1. Specify the governing transport equations, assumptions and simplifications

ASSERT assumes that the liquid and vapour phases in a flow have unequal velocity and unequal temperature (UVUT). The code models the sub-channels as a series of control volumes governed by a set of 5 conservation equations based on the two-fluid formulation of Ishii. Mass, momentum and energy conservation are solved for the flow as a “mixture”. In addition, a set of equations specifically for the liquid and vapour energy are solved.

2. Specify the numerical algorithm used (fully implicit, fully explicit; semi-implicit)

The governing equations for the control volumes are solved using Newton’s method – an implicit method.

3. Specify the two-phase models and formulations used (HEM, drift flux model, two-fluid model, etc.)

ASSERT utilises the drift-flux model based on both Zuber-Findlay and Ishii.

4. Specify any optimisations of the code predictions that were performed by adjusting the model parameters to the experimental database

The lateral mixing source terms are strongly influenced by the mixing vane geometry. In order to approximate their contributions, the diversionary cross-flow term was adjusted in the following manner:

1. CAD models of the simple spacer and mixing vanes were constructed based on the benchmark specifications.

2. The blocked area of each sub-channel was computed for the spacers/vanes:
   a. Equivalent k-factors for each sub-channel were approximated by using Idelchik’s formula for a thin-edged orifice. Subscript “block” refers the area (A) or perimeter (P) at the blockage, while “up” refers to the upstream value.

\[
\begin{align*}
  k_{equiv} &= k_{loss} + k_{frict} \\
  \epsilon &= \frac{A_{block}}{A_{up}} \\
  k_{loss} &= \left(\frac{0.5\epsilon + \epsilon}{1 - \epsilon}\right)^2 \\
  k_{frict} &= \frac{fL_{up}}{4A_{up}} \left[ \frac{P_{block}}{P_{up}} \left(\frac{1}{\epsilon}\right)^3 - 1 \right]
\end{align*}
\]

(12.1.1)
3. Diversionary cross-flows are modelled using the Carlucci method [1], which applies an obstruction multiplier ($F_{OBS}$) to the Rogers & Tahir turbulent mixing correlation ($w'_{hom}$).

$$
\begin{align*}
  w'_{hom} &= F_{OBS} \left[ 0.0018 \mu \left( \frac{S}{D_h} \right)^{-0.4} Re^{0.9} \right] \\
  F_{OBS} &= \left( 1 + A_{obs} k \exp \left( -B_{obs} \frac{z}{d_h} \right) \right) 
\end{align*}
$$

(12.1.2)

- The $k$-factor in the $F_{OBS}$ was derived based on the spacer/vane geometry as previously discussed. $A_{obs}$ and $B_{obs}$ scale the magnitude of the multiplier as a function of the number of hydraulic diameters downstream of the obstruction.
- Experiments with similar mixing vanes indicate that lateral momentum decays to ~50% of its initial value roughly 20 $D_h$ downstream of the obstruction [2]. Based on this, $B_{obs}$ was set to 0.033 in the model.
- $A_{obs}$ was estimated using 1 case in the fluid temperature database (01-3233). The error between the predicted and experimental fluid temperature was minimised with $A_{obs} = 49.50$.

The same adjusted factors were used for both phases of the benchmark.
AV.13 PSI (FLICA)

AV.13.1 Overall questionnaire

1. Specify the governing transport equations, assumptions and simplifications

Mixture mass conservation:

\[
\frac{\partial \rho}{\partial t} + \frac{\partial \rho u_i}{\partial x_i} = 0.
\]  

(13.1.1)

Mixture momentum conservation:

\[
\frac{\partial \rho u_i}{\partial t} + \frac{\partial \rho u_i u_j}{\partial x_j} = -\frac{\partial}{\partial x_j} [\rho c(l - c)u_i u_j] - \frac{\partial \rho}{\partial x_i} + \frac{\partial}{\partial x_j} \left( \sum_{k=\nu,\lambda} \alpha_k \alpha_{ij}^k \right) + c_i + \rho g_i.
\]  

(13.1.2)

Mixture energy conservation:

\[
\frac{\partial \rho E}{\partial t} + \frac{\partial \rho E u_i}{\partial x_i} = -\frac{\partial}{\partial x_i} [\rho c(l - c)u_i (H_v - H_i)] - \frac{\partial q_i}{\partial x_i} + \frac{\partial}{\partial x_j} \left( \sum_{k=\nu,\lambda} \alpha_k \alpha_{ij}^k u_k \right) + Q + \rho g_i u_i.
\]  

(13.1.3)

Balance equation for the vapour mass concentration:

\[
\frac{\partial \rho c}{\partial t} + \frac{\partial \rho c u_i}{\partial x_i} = -\frac{\partial}{\partial x_i} [\rho c(l - c)u_i] + \frac{\partial}{\partial x_i} \left( \frac{\partial c}{\partial x_i} \right) + \Gamma_v.
\]  

(13.1.4)

2. Specify the numerical algorithm used (fully implicit, fully explicit; semi-implicit)

Fully implicit algorithm (Implicit Roe / VF9 scheme).
3. Specify the two-phase models and formulations used (HEM, drift flux model, two-fluid model, etc.)

Drift flux model (Chexal-Lellouche model).

4. Specify any optimisations of the code predictions that were performed by adjusting the model parameters to the experimental database

For single channel analysis

- turbulence Multiplier $K_t = M_t = 0.01$;
- recondensation Coefficient $K_{\text{re}} = 1.0 \times 10^{-4}$.

For bundle analysis

- turbulence Multiplier $K_t = M_t = 0.01$ (B5, 6 and 8);
- turbulence Multiplier $K_t = M_t = 0.05$ (B7);
- recondensation Coefficient $K_{\text{re}} = 7.5 \times 10^{-4}$.

AV.13.2 Phase I – Exercise 1

1. Specify the flow regime map used

Single-phase and nucleate boiling regimes were considered in this benchmark.

2. Specify the interfacial mass, momentum and energy exchange models

Interfacial mass:

$$\Gamma_{lv} \propto \frac{K_{v0} H_{lv} (T_f - T_v)}{h_{lv}}$$

(13.2.1)

3. Specify the wall drag and heat transfer models

Single phase friction: Blasius correlation.

Two-phase multiplier: Friedel correlation.

Heating wall corrector:

$$f_p = 1 - \frac{P_{ch}}{P_m} \cdot \frac{T_p - T_l}{L + a_2 \cdot \left(\frac{T_p + T_l - 2 \times 273.15}{a_3}\right)^{a_4}}$$

(13.2.2)

Single-phase heat transfer: Dittus-Boelter correlation.

Nucleate Boiling: Jens-Lottes correlation.
\[ T_w - T_{\text{sat}} = a \cdot \Phi^b \cdot \exp\left(\frac{-P}{\rho_0}\right) \]  
(13.2.3)

Nucleation on heating wall (for sub-cooled boiling):

\[ \Gamma^{\text{pu}} \propto \frac{\chi \Phi}{h_{ij}} \]  
(13.2.4)

where, \( \chi \) is the ratio of heat flux used for nucleate boiling.

4. Specify the axial nodalisation utilised (number of nodes, node size, variable axial nodding, etc.)
   - number of nodes: 32;
   - axial nodding: (0.025 m x 1), (0.05 m x 30), (0.03 m x 1).

5. Specify the boundary conditions used
   - inlet: mass flux, enthalpy;
   - outlet: pressure;
   - heater: Power.

AV.13.3 Phase I – Exercise 2

1. Specify the cross-flow models used (diversion flow, void drift and turbulent mixing models)
   Turbulent mixing modelling by a mixing length approach:
   Turbulent viscosity:
   \[ \mu_i' = \mu_i M_i' = \mu_i M_i \left(\text{Re} - \text{Re}^*\right)^{\gamma} \cdot Y_0^C \]  
(13.3.1)

   Turbulent conductivity:
   \[ k_i' = \frac{\lambda_i}{C_{\rho i}} K_i' = \frac{\lambda_i}{C_{\rho i}} \left(\text{Re} - \text{Re}^*\right)^{\delta} \cdot Y_0^C \]  
(13.3.2)

2. Specify the flow regime map used
   Same as Exercise 1.

3. Specify the interfacial mass, momentum and energy exchange models
   Same as Exercise 1.

4. Specify the wall drag and heat transfer models
   Same as Exercise 1.
5. Specify the turbulent mixing and void drift models used
   Same as Exercise 1.

6. Specify any spacer grid effects on the void distribution if modelled
   Modelled by singular pressure loss coefficient.

7. If symmetry used, specify the symmetry applied in the model
   1/8 symmetric model was used.

8. Specify the axial nodalisation utilised (number of nodes, node size, variable axial nodding, spacer grids location with respect to the axial nodding, etc.)
   - number of nodes: 100;
   - axial nodding: uniform.

9. Specify the boundary conditions used
   Same as Exercise 1.

AV.13.4 Phase I – Exercise 3
Questions 1-9 : same as Exercise 2.

AV.13.5 Phase I – Exercise 4

1. Specify the correlations/models used for single-phase and two-phase frictional pressure drop
   Same as Exercise 1.

2. Specify the components of the pressure drop used in the code
   Wall frictional pressure drop and singular pressure drop (form loss).
AV.14 PSI (STAR-CD)

AV.14.1 Overall questionnaire

1. Specify the governing transport equations, assumptions and simplifications
   The governing transport equations solved are the conservation laws of mass, momentum and
   energy for each of the two phases. These equations are solved in three dimensions. Steady-state
   flow is assumed so that the transient terms are omitted.

2. Specify the numerical algorithm used
   The numerical algorithm used is IPSA (InterPhase Slip Algorithm). It is fully implicit, using the
   pressure-correction based method extended to multiphase flows.

3. Specify the two-phase models and formulations used
   The two-fluid six-equation model is used.

4. Specify any optimisations of the code predictions that were performed by adjusting the model
   parameters to the experimental database
   No model parameter adjustment was made specifically for this benchmark exercise.

AV.14.2 Phase I – Exercise 1

1. Specify the flow regime map used
   No flow regime map is used. Bubbly flow is assumed to exist everywhere.

2. Specify the interfacial mass, momentum and energy exchange models
   Interfacial momentum transfer includes models for drag force, turbulent drag force, virtual mass
   force and momentum transfer due to mass transfer.
   Interfacial mass transfer is due to evaporation or condensation as computed by the boiling
   model.
   Interfacial energy transfer is due to temperature difference between the two phases and the
   saturation temperature.

3. Specify the wall drag and heat transfer models
   Wall drag is calculated by standard wall function used in CFD codes. Wall boiling heat transfer is
   calculated by the “wall heat partitioning” model of Kurul and Podowski.

4. Specify the axial nodalisation utilised
   Heated length is divided into 100 parts in axial direction (axial length of each cell is equal to 0.0155 m).
5. Specify the boundary conditions used

Boundary conditions include: uniform profile inlet, pressure outlet, constant heat flux at heated wall and adiabatic wall for unheated section.
AV.15 PSI (TRACE)

AV.15.1 Overall questionnaire

1. Specify the governing transport equations, assumptions and simplifications

Volume averaged mass conservation:

\[
\frac{\partial}{\partial t} \left[ (1 - \alpha) \rho_f \right] + \nabla \cdot \left[ (1 - \alpha) \rho_f \vec{V}_f \right] = -\overline{F}
\]

(15.1.1)

\[
\frac{\partial (\alpha \rho_g)}{\partial t} + \nabla \cdot \left[ \alpha \rho_g \vec{V}_g \right] = \overline{F}
\]

(15.1.2)

Volume averaged momentum conservation:

\[
\frac{\partial \left[ (1 - \alpha) \rho_f \vec{V}_f \right]}{\partial t} + \nabla \cdot \left[ (1 - \alpha) \rho_f \vec{V}_f \vec{V}_f \right] = \nabla \cdot \left[ (1 - \alpha) \vec{R}_f \right] + (1 - \alpha) \rho_f \vec{g} - \overline{M}_f
\]

(15.1.3)

\[
\frac{\partial \left[ \alpha \rho_g \vec{V}_g \right]}{\partial t} + \nabla \cdot \left[ \alpha \rho_g \vec{V}_g \vec{V}_g \right] = \nabla \cdot \left[ \alpha \vec{R}_g \right] + \alpha \rho_g \vec{g} + \overline{M}_g
\]

(15.1.4)

Volume averaged energy conservation:

\[
\frac{\partial \left[ (1 - \alpha) \rho_f (e_f + \frac{V_f^2}{2}) \right]}{\partial t} + \nabla \cdot \left[ (1 - \alpha) \rho_f (e_f + \frac{P}{\rho_f} + \frac{V_f^2}{2}) \vec{V}_f \right] = -\nabla \cdot \left[ (1 - \alpha) \vec{q}_f \right] + (1 - \alpha) \rho_f \vec{g} - \Gamma \vec{h}_f + W_f + \overline{q}_f
\]

(15.1.5)

\[
\frac{\partial \left[ \alpha \rho_g (e_g + \frac{V_g^2}{2}) \right]}{\partial t} = \nabla \cdot \left[ \alpha \rho_g \left( e_g + \frac{P}{\rho_g} + \frac{V_g^2}{2} \right) \vec{V}_g \right] - \nabla \cdot \left[ \alpha \vec{q}_g \right] + \alpha \rho_g \vec{g} + \Gamma \vec{h}_g + W_g + \overline{q}_g
\]

(15.1.6)
2. Specify the numerical algorithm used (fully implicit, fully explicit; semi-implicit)
   Semi-implicit algorithm.

3. Specify the two-phase models and formulations used (HEM, drift flux model, two-fluid model, etc.)
   Two-fluid model.

4. Specify any optimisations of the code predictions that were performed by adjusting the model parameters to the experimental database
   No model parameter was adjusted.

AV.15.2 Phase I – Exercise 1

1. Specify the flow regime map used
   Single-phase, sub-cooled boiling and nucleate boiling regimes were considered in this benchmark.

2. Specify the interfacial mass, momentum and energy exchange models
   - interfacial heat transfer for bubbly flow regime: Rand-Marshall correlation (IAC: Ishii and Mishima model);
   - interfacial heat transfer for cap bubble/slug flow regime: Rand-Marshall correlation with the consideration of small bubbles;
   - interfacial heat transfer for sub-cooled boiling regime: Lahey and Moody model.

3. Specify the wall drag and heat transfer models
   - single phase friction: Churchill formula;
   - two-phase friction multiplier: Void fraction based two-phase multiplier;
   - single-phase heat transfer: Gnielinski correlation;
   - bubbly/slug flow regime: multipliers by Aggour and Rezkallah and Sims;
   - sub-cooled boiling: Lahey’s mechanistic model.

4. Specify the axial nodalisation utilised (number of nodes, node size, variable axial nodding, etc.)
   - number of nodes: 32;
   - axial nodding: (0.025 mx1), (0.05 mx30), (0.03 mx1).

5. Specify the boundary conditions used
   - inlet: mass flow rate, temperature, pressure;
   - outlet: pressure;
   - heater: power.
AV.15.3 Phase I – Exercise 2

1. Specify the cross-flow models used (diversion flow, void drift and turbulent mixing models)
   Special cross-flow model was not used.

2. Specify the flow regime map used
   Same as Exercise 1.

3. Specify the interfacial mass, momentum and energy exchange models
   Same as Exercise 1.

4. Specify the wall drag and heat transfer models
   Same as Exercise 1.

5. Specify the turbulent mixing and void drift models used
   Same as Exercise 1.

6. Specify any spacer grid effects on the void distribution if modelled
   Modelled by K-factors.

7. If symmetry used, specify the symmetry applied in the model
   Fully geometry was modelled.

8. Specify the axial nodalisation utilised (number of nodes, node size, variable axial nodding, spacer grids location with respect to the axial nodding, etc.)
   Number of nodes: 25.
   Axial nodding: uniform.

9. Specify the boundary conditions used.
   Same as Exercise 1.
AV.16 UNIPI (CATHARE 2)

AV.16.1 Overall questionnaire

1. Specify the governing transport equations, assumptions and simplifications
   - 3 equations per liquid phase plus 3 equations per vapor phase: energy, mass, momentum balance equations;
   - 6 principal variables: P, Hl, Hg, α, vl, vg.

2. Specify the numerical algorithm used (fully implicit, fully explicit; semi-implicit)
   - fully implicit (when using 1D module, i.e. sub-channels benchmark) and semi-implicit (when using three-dimensional module, i.e. bundle benchmark) discretization;
   - finite volumes (mass, energy) and finite differences (momentum) discretization, first order upwind scheme for convective terms.

3. Specify the two-phase models and formulations used (HEM, drift flux model, two-fluid model, etc.)
   - 2 phase thermal hydraulic code. 2-fluid 6-equation model.

4. Specify any optimisations of the code predictions that were performed by adjusting the model parameters to the experimental database
   - None.

AV.16.2 Phase I – Exercise 1

1. Specify the flow regime map used
   - No answer provided.

2. Specify the interfacial mass, momentum and energy exchange models
   - No answer provided.

3. Specify the wall drag and heat transfer models
   - No answer provided.

4. Specify the axial nodalisation utilised (number of nodes, node size, variable axial nodding, etc.)
   - The sub-channels are represented with and AXIAL component and the axial length is 1.555 m. It is subdivided into 100 uniform meshes.

5. Specify the boundary conditions used
   - inlet: mass flow rate and coolant temperature;
   - outlet: pressure;
   - wall: heat flux according to the test specification.

AV.16.3 Phase I – 2

1. Specify the cross-flow models used (diversion flow, void drift and turbulent mixing models)
   - No answer provided.
2. Specify the flow regime map used
   No answer provided.

3. Specify the interfacial mass, momentum and energy exchange models
   No answer provided.

4. Specify the wall drag and heat transfer models
   No answer provided.

5. Specify the turbulent mixing and void drift models used
   No answer provided.

6. Specify any spacer grid effects on the void distribution if modelled
   Spacer grids are modelled as junctions with a form loss factor from 0.8-1.0 depending on the type of grid (i.e. $K_{MV-grid}=1$; $K_{SS-grid}=0.8$).

7. If symmetry used, specify the symmetry applied in the model
   No symmetry.

8. Specify the axial nodalisation utilised (number of nodes, node size, variable axial nodding, spacer grids location with respect to the axial nodding, etc.)
   - three-dimensional component (THREED) Cartesian coordinate;
   - meshing: 6 elements in X direction; 6 elements in Y direction; and 36 elements in Z direction.

9. Specify the boundary conditions used
   - inlet: mass flow rate and coolant temperature;
   - outlet: pressure;
   - wall: heat flux according with the test specifications, the total power is the result of the contribution of each independent sub-channel.

AV.16.4 Phase I – Exercise 3

1. Specify the cross-flow models used (diversion flow, void drift and turbulent mixing models)
   No answer provided.

2. Specify the flow regime map used
   No answer provided.

3. Specify the interfacial mass, momentum and energy exchange models
   No answer provided.

4. Specify the wall drag and heat transfer models
   No answer provided.

5. Specify the turbulent mixing and void drift models used
   No answer provided.
6. Specify any spacer grid effects on the void distribution if modelled

Spacer grids are modelled as junctions with a form loss factor from 0.8-1.0 depending on the type of grid (i.e. $K_{MV-grid}=1$; $K_{SS-grid}=0.8$).

7. If symmetry used, specify the symmetry applied in the model

No symmetry.

8. Specify the axial nodalisation utilised (number of nodes, node size, variable axial nodding, spacer grids location with respect to the axial nodding, etc.)

- three-dimensional component (THREED) Cartesian coordinate;
- meshing: 6 elements in X direction; 6 elements in Y direction; and 36 elements in Z direction.

9. Specify the boundary conditions used

- inlet: mass flow rate and coolant temperature;
- outlet: pressure;
- wall: heat flux according with the test specifications, the total power is the result of the contribution of each independent sub-channel.

AV.16.5 Phase I – Exercise 4

1. Specify the correlations/models used for single-phase and two-phase frictional pressure drop

No answer provided.

2. Specify the components of the pressure drop used in the code

- friction loss;
- form loss applied at the spacer grids and at bundle inlet and outlet;
- gravity.
AV.17 WEC/INVAP (VIPRE)

AV.17.1 Overall questionnaire

1. Specify the governing transport equations, assumptions and simplifications
   The governing equations of the VIPRE-W code are the same as those in the original VIPRE-01 code (Reference 1), based on the sub-channel concept from the COBRA code. Conservation equations of mass, axial and lateral momentum and energy are solved for fluid density, enthalpy, axial flow, cross-flow, and pressure distributions. The flow field is assumed to be homogeneous and incompressible, but empirical models are available to account for sub-cooled boiling and two-phase flow effects.

2. Specify the numerical algorithm used (fully implicit, fully explicit; semi-implicit)
   The numerical algorithm is semi-implicit with the use of the empirical void model.

3. Specify the two-phase models and formulations used (HEM, drift flux model, two-fluid model, etc.)
   The following two-phase flow models were used for the benchmark exercise: the Lallouche/Zolotar sub-cooled void model (also referred to as the EPRI model), the homogeneous bulk boiling model, and the homogeneous two-phase flow friction multiplier.

4. Specify any optimisations of the code predictions that were performed by adjusting the model parameters to the experimental database
   No change to the model parameters was made.

AV.17.2 Phase I – Exercise 1

1. Specify the flow regime map used
   No answer provided.

2. Specify the interfacial mass, momentum and energy exchange models
   No answer provided.

3. Specify the wall drag and heat transfer models
   No answer provided.

4. Specify the axial nodalisation utilised (number of nodes, node size, variable axial nodding, etc.)
   No answer provided.

5. Specify the boundary conditions used
   No answer provided.
AV.17.3 Phase I – Exercise 2

1. Specify the cross-flow models used (diversion flow, void drift and turbulent mixing models)

   The cross-flow resistance ($K_G$) model is listed below:

   \[ K_G = 2.66 \times \text{Re}_L^{0.2} \]  
   \[ (17.3.1) \]

   where $\text{Re}_L$ is the Reynolds number based on the lateral flow.

   The turbulent mixing in sub-channels was modelled using the following empirical correlation:

   \[ \Delta Q = -w' \times \Delta h \times \Delta X \]  
   \[ (17.3.2) \]

   where

   - $\Delta Q$ = energy exchange due turbulent mixing (W or Btu/hr);
   - $w'$ = lateral turbulent flow per unit length (kg/s/m or lbm/hr-ft);
   - $\Delta h$ = enthalpy difference between two sub-channels (J/kg or Btu/lbm);
   - $\Delta X$ = axial nodal length (m or ft).

   \[ w' = \text{ABETA} \times G_{AVG} \times S \]  
   \[ (17.3.3) \]

   where

   - $\text{ABETA}$ = empirical coefficient (<0.07);
   - $G_{AVG}$ = average axial mass flow in the connected channels (kg/s/m² or lbm/s/ft²);
   - $S$ = rod-to-rod gap width (m or ft).

2. Specify the flow regime map used

   N/A

3. Specify the interfacial mass, momentum and energy exchange models

   N/A

4. Specify the wall drag and heat transfer models

   The axial friction factor ($f$) for turbulent flow is defined as:

   \[ f = 0.184 \times \text{Re}^{0.2} \]  
   \[ (17.3.4) \]

5. Specify the turbulent mixing and void drift models used

   Please see answer to Item 1 above.

6. Specify any spacer grid effects on the void distribution if modelled
Effects of the mixing vane spacer grids on turbulent mixing were considered as a function of grid spacing.

7. If symmetry used, specify the symmetry applied in the model
   N/A

8. Specify the axial nodalisation utilised (number of nodes, node size, variable axial nodding, spacer grids location with respect to the axial nodding, etc.)
   A total of 82 axial nodes were used in the VIPRE-W model. The nodal length varied from 1.8 inches to 2.0 inches to match the grid elevations.

9. Specify the boundary conditions used.
   The core boundary conditions were obtained from the benchmark problem specifications [2].

   AV.17.4 Phase I – Exercise 3

1. Specify the cross-flow models used (diversion flow, void drift and turbulent mixing models)
   Same as above.

2. Specify the flow regime map used
   Same as above.

3. Specify the interfacial mass, momentum and energy exchange models
   Same as above.

4. Specify the wall drag and heat transfer models
   Same as above.

5. Specify the turbulent mixing and void drift models used.
   Same as above.

6. Specify any spacer grid effects on the void distribution if modelled
   Same as above.

7. If symmetry used, specify the symmetry applied in the model
   Same as above.

8. Specify the axial nodalisation utilised (number of nodes, node size, variable axial nodding, spacer grids location with respect to the axial nodding, etc.)
   Same as above.
9. Specify the boundary conditions used
   Same as above.

   **AV.17.5 Phase I – Exercise 4**

   1. Specify the correlations/models used for single-phase and two-phase frictional pressure drop
      No answer provided.

   2. Specify the components of the pressure drop used in the code
      No answer provided.

   **AV.17.6 References**
