Department of NUCLEAR ENGINEERING
NC STATE UNIVERSITY

Validation of Traditional and Novel Core Thermal-Hydraulic Modeling and Simulation Tools

Issues in Validation Benchmarks: NEA OECD/US NRC NUPEC BWR Full-size Fine-mesh Bundle Test (BFBT) Benchmark

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NEKVaC/NUC Workshop
"Multi-Physics Model Validation"
Session: Verification and Validation of Advanced Simulation Codes

June 28, 2017

Needs

- The need for model refinements for best-estimate calculations on high-fidelity data bases was identified during the 4th OECD/NRC BWR Turbine Trip Benchmark Workshop in 2002

- It was explicitly expressed that such investigations should not be limited to macroscopic approaches but should also include next generation analysis tools (i.e. CFD codes)

- A sound experimental data base was supplied by NUPEC (Nuclear Power Engineering Cooperation), which performed a large series of full-size BWR and PWR assembly void and critical flux measurements between 1987 and 1995

- Measurements comprised of State-of-the-Art CT technology for visualization of void distribution on small scales, as well as steady-state and transient critical power test series

BFBT Benchmark

Phase I – Void Distribution Benchmark

Exercise 1 – Steady-state sub-channel grade benchmark
Exercise 2 – Steady-state microscopic grade benchmark
Exercise 3 – Transient macroscopic grade benchmark
Exercise 4 – Uncertainty analysis of void distribution benchmark

Phase II – Critical Power Benchmark

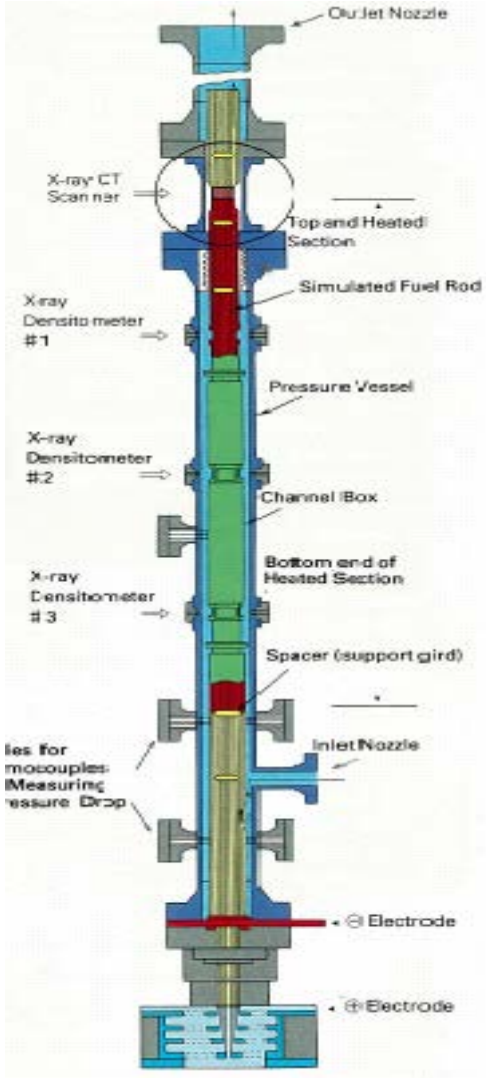
Exercise 0 – Steady-state pressure drop benchmark
Exercise 1 – Steady-state critical power benchmark
Exercise 2 – Transient critical power benchmark
Exercise 3 – Uncertainty analysis of critical power benchmark

! *Very good database for applying uncertainty and sensitivity analysis techniques → The benchmark is utilized in Phase II of the OECD LWR UAM benchmark*

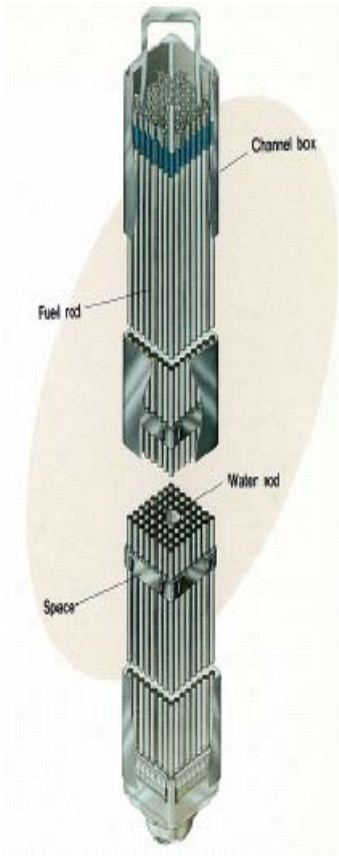
BFBT Benchmark

PARTICIPANT	CODES	COUNTRY
KAERI	MARS 3D Module (COBRA-TF)	Korea
KAERI	MATRA	Korea
Westinghouse&KTH	MONA 3	Sweden
KTH	TRACE v50rc1	Sweden
KTH	RELAP 5 Mod3.3 Patch 0.3	Sweden
FZK	CFX 10.0	Germany
FZK	CFX 5.7.1	Germany
FZK	TRACE v5.0 rc2	Germany
FZK	TwoPorFlow	Germany
CEA	Neptune System	France
CEA	NEPTUNE-FLICA-4	France
NUPEC	CAPE_Mod 1.0	Japan
AREVA NP GmbH	F-COBRA-TF 1.4	Germany
AREVA NP GmbH	IVA	Germany
PSU	COBRA-TF	USA
TEPCO	NASCA 2.12	Japan
UPM	COBRA-TF	Spain
UNIPI	RELAP-3D 2.2.4	Italy
ANL	STAR-CD 3.26	USA
Westinghouse	VIPRE-W & MEFISTO	USA
US NRC	TRACE 5.141	USA
CSA/EPRI	VIPRE-I	USA

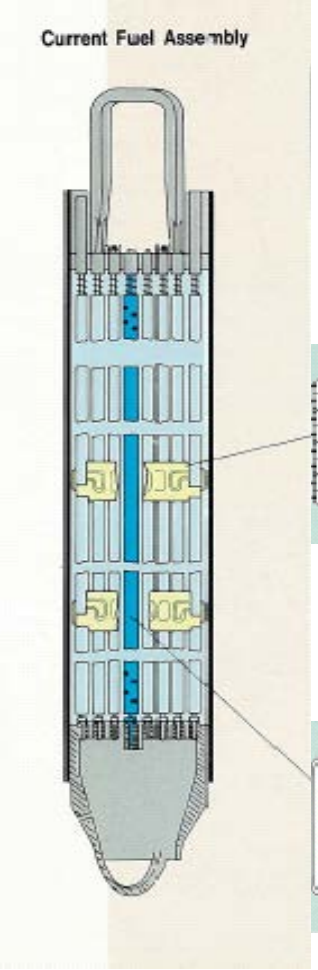
BFBT Void Fraction Measurements



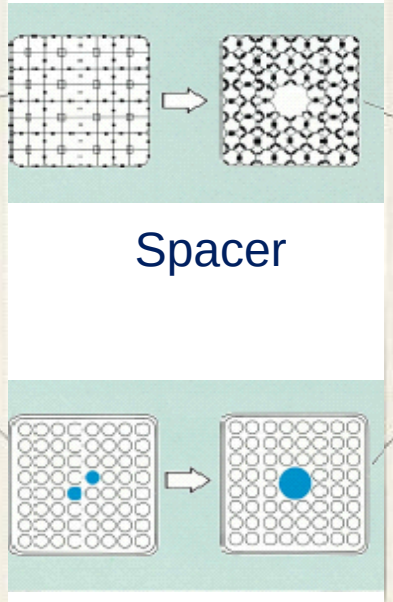
Test Section



BWR Fuel Assembly

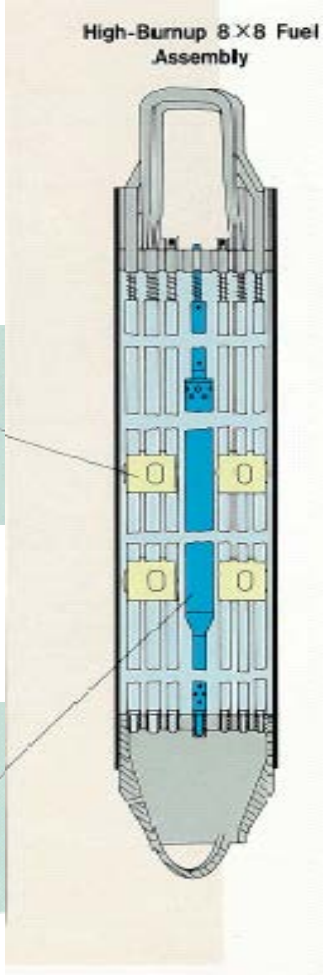


8 × 8



Spacer

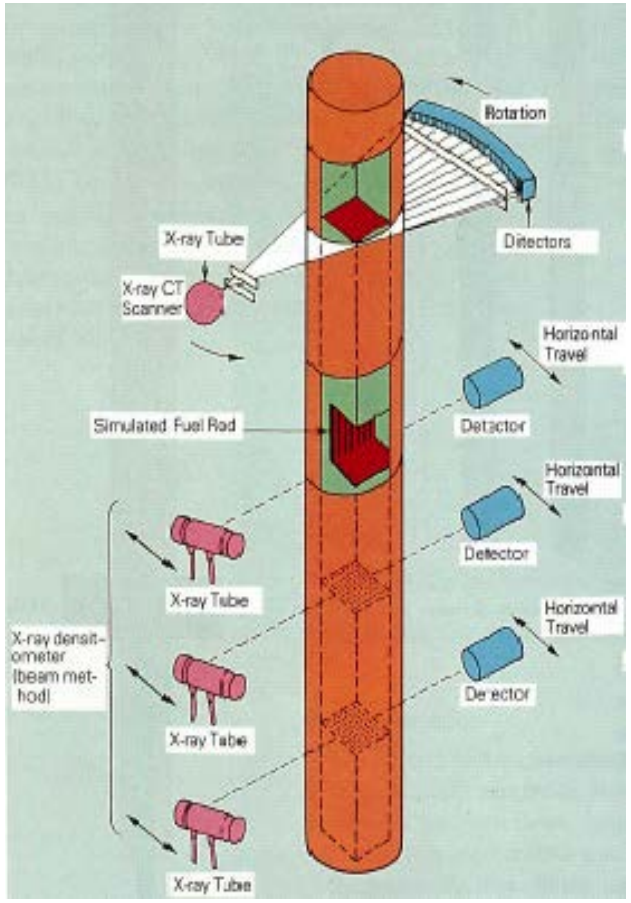
Water rod



High-burnup 8 × 8

BFBT Void Fraction Measurements

Spatial resolution = 0.3 mm
Scanning time = 15 s
Accuracy of void fraction:
Pixel = 8 %
Sub-channel = 3 %
Cross-sectional = 2 %



Void fraction measurement system

512 × 512 = 0.26 M pixels

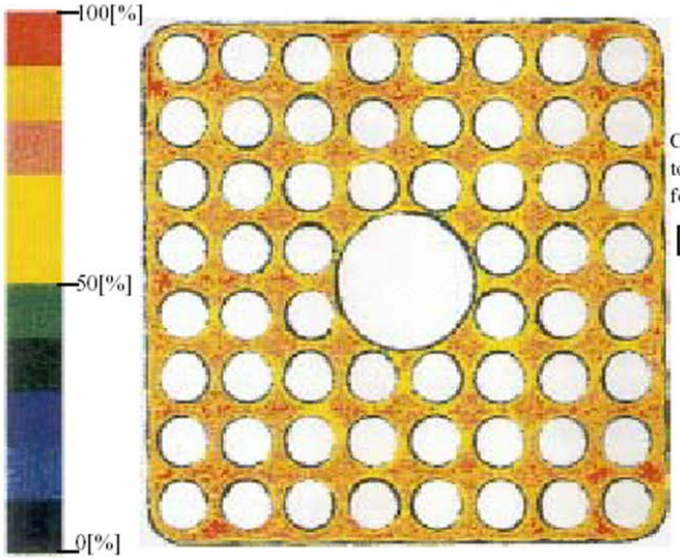


Photo Image

Conversion to ASCII format bitmap

	1	2	3	4	5	.	.	.	.	n-3	n-2	n-1	n
1	00	00	00	00	00	00	00	00	00	00	00	00	00
2	0x	xx	1x	xx	2x	xx	3x	xx	4x	xx	5x	xx	xx
3	0a	aa	1a	aa	2a	aa	3a	aa	4a	aa	5a	aa	aa
4	00	00	00	00	00	00	00	00	00	00	00	00	00
5	1x	xx	2x	xx	3x	xx	4x	xx	5x	xx	6x	xx	xx
.	1a	aa	2a	aa	3a	aa	4a	aa	5a	aa	6a	aa	aa
.	00	00	00	00	00	00	00	00	00	00	00	00	00
.	2x	xx	3x	xx	4x	xx	5x	xx	6x	xx	7x	xx	xx
.	2a	aa	3a	aa	4a	aa	5a	aa	6a	aa	7a	aa	aa
n-3	00	00	00	00	00	00	00	00	00	00	00	00	00
n-2	3x	xx	4x	xx	5x	xx	6x	xx	7x	xx	8x	xx	xx
n-1	3a	aa	4a	aa	5a	aa	6a	aa	7a	aa	8a	aa	aa
n	00	00	00	00	00	00	00	00	00	00	00	00	00

Test assembly type

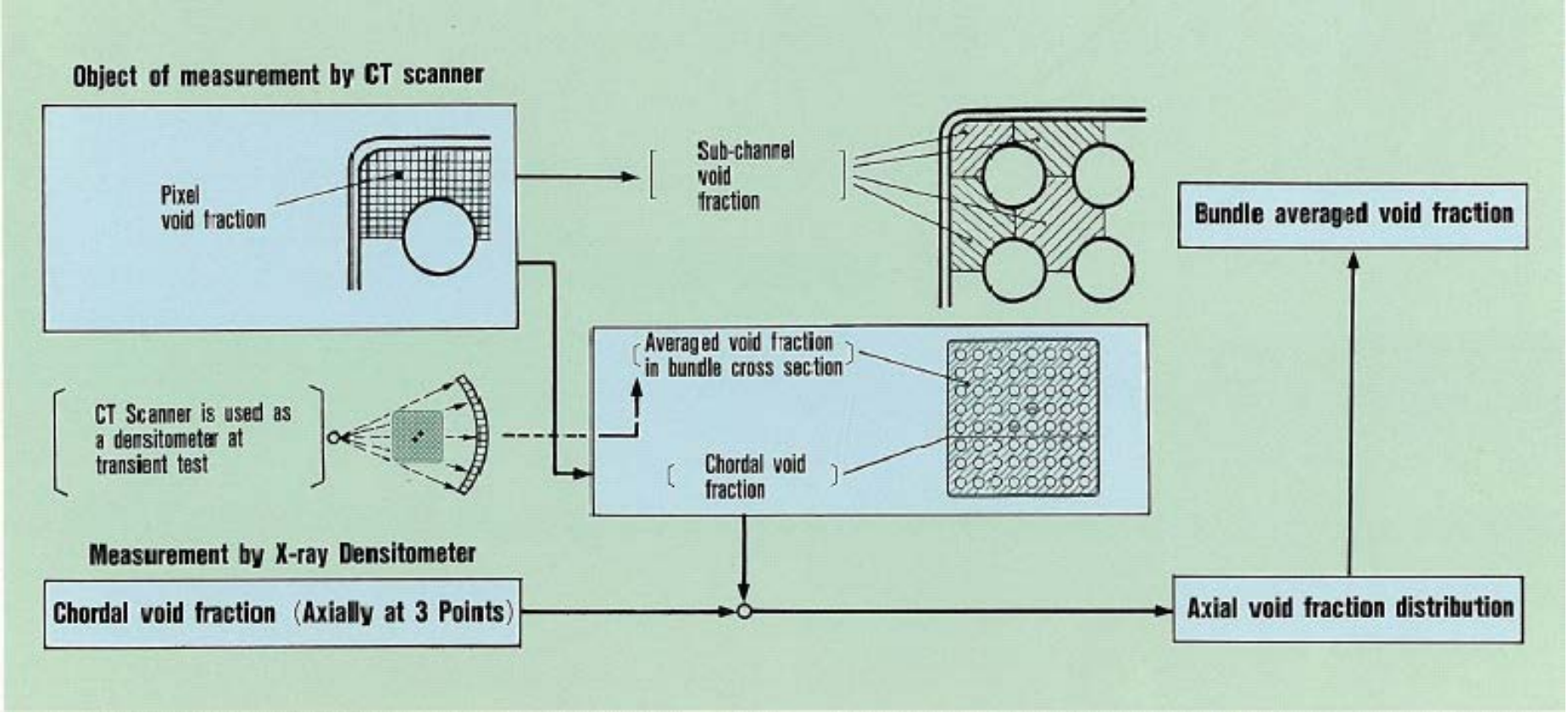
System pressure= X.X MPa

Flow rate = X.X kg/m^2-s

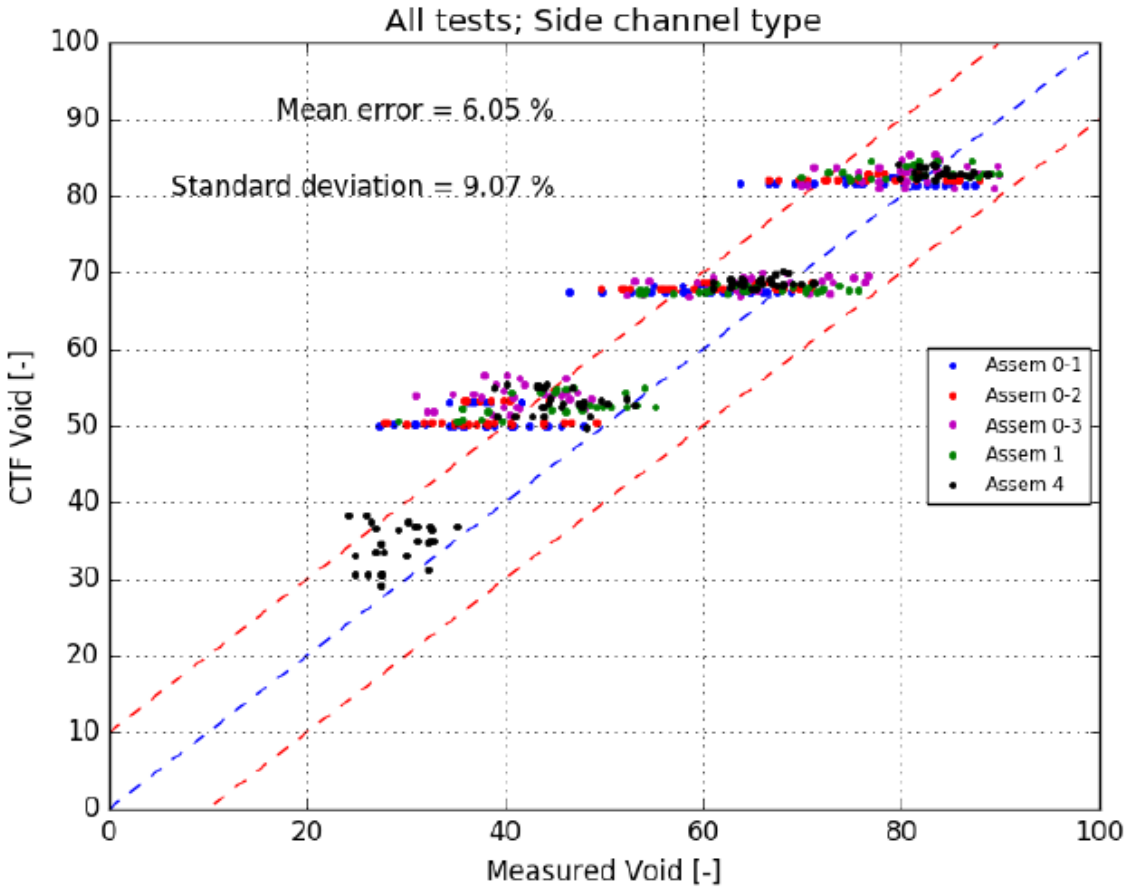
Digital Data

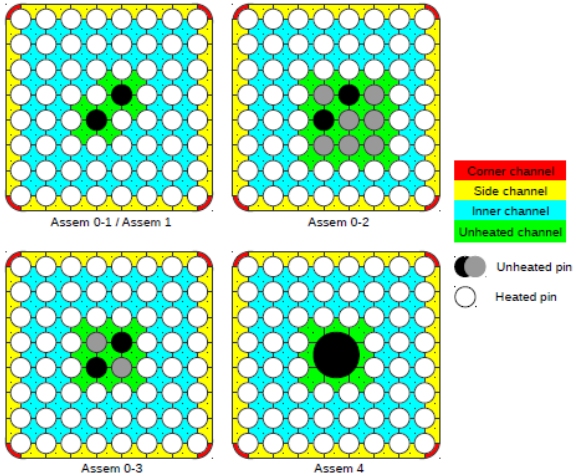
BFBT Void Fraction Measurements

Data Reduction of Void Distribution Measurements



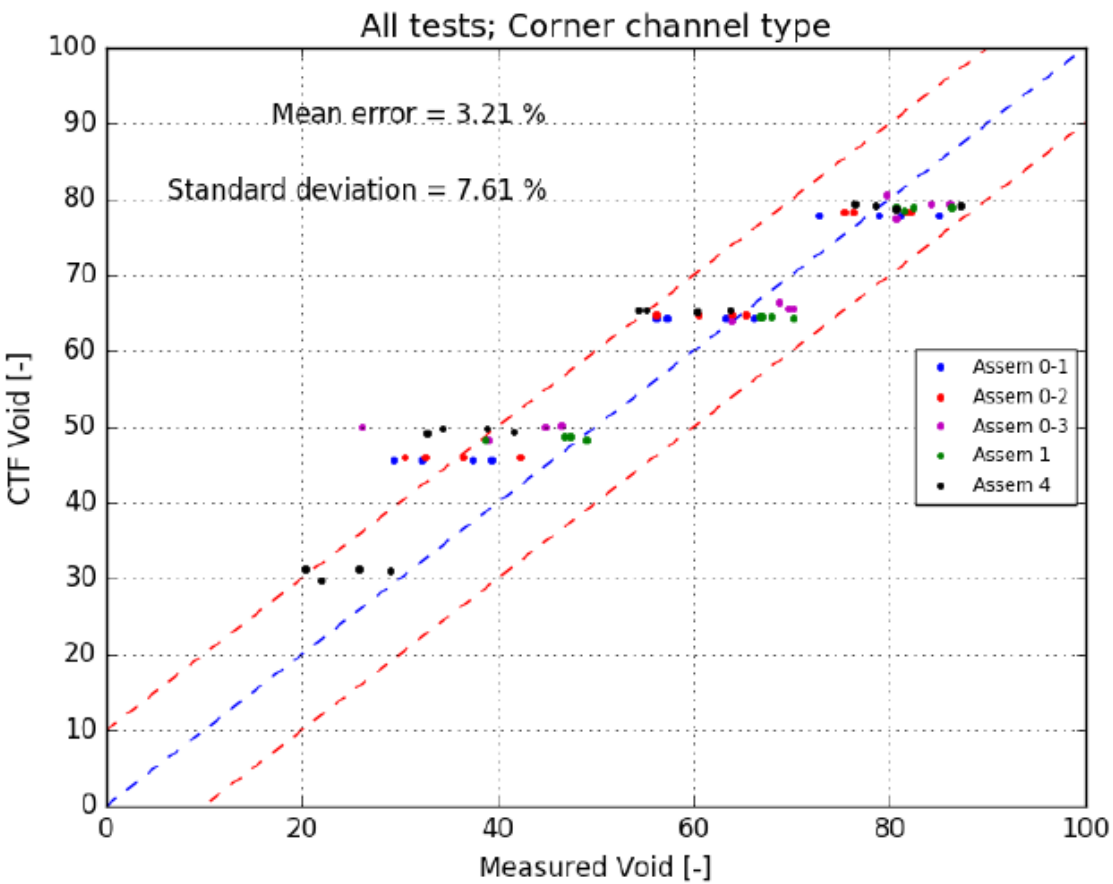
Issue with Symmetry Void Measurements

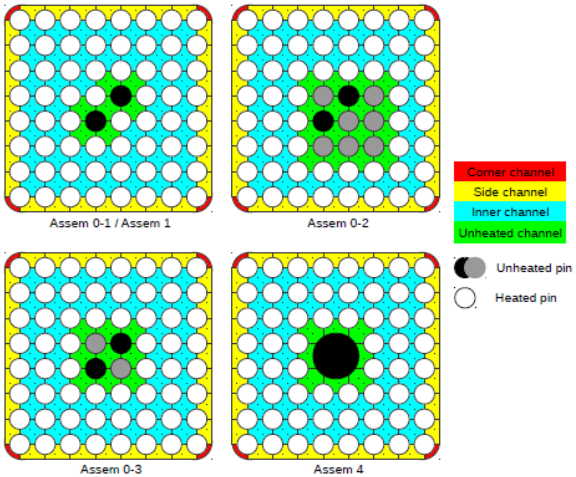




Side channel void predictions

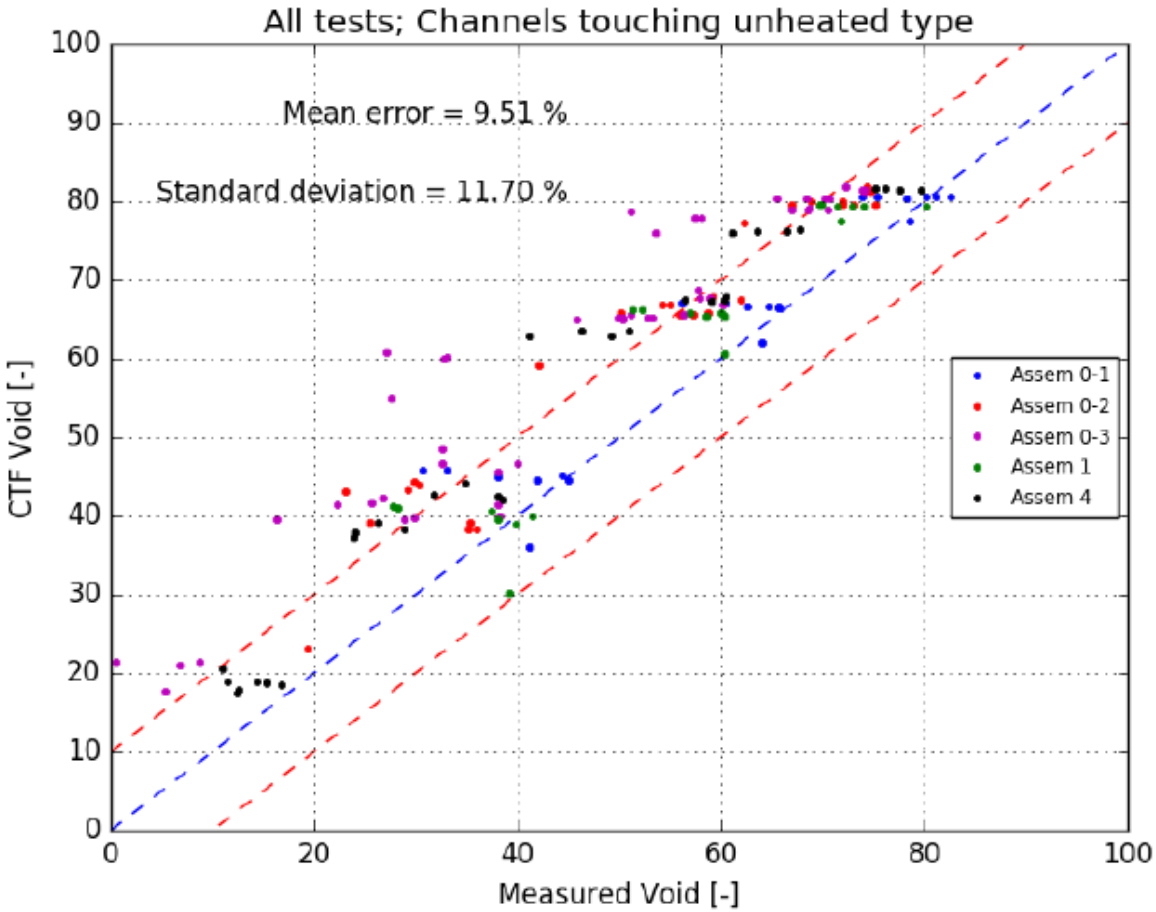
Issue with Symmetry Void Measurements

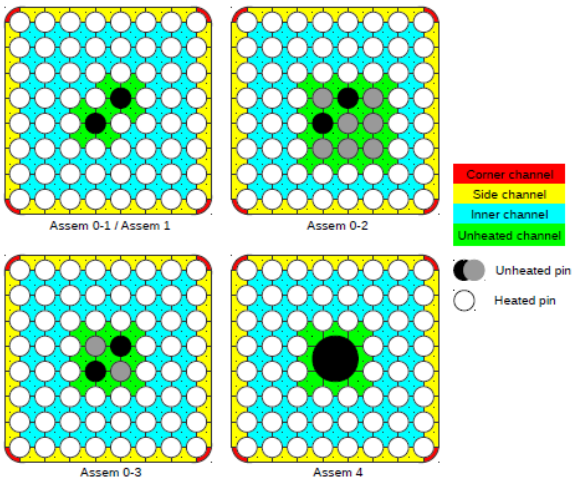




Corner channel void predictions

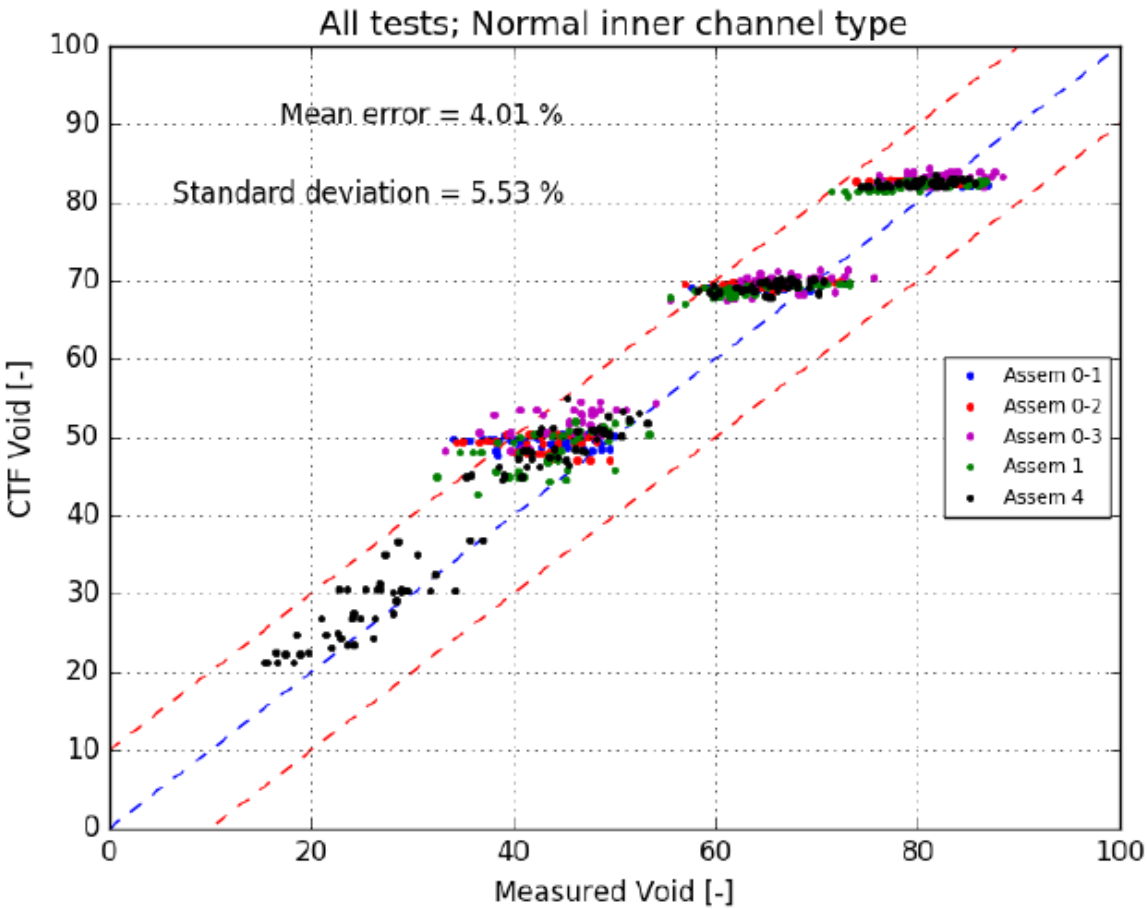
Issue with Symmetry Void Measurements

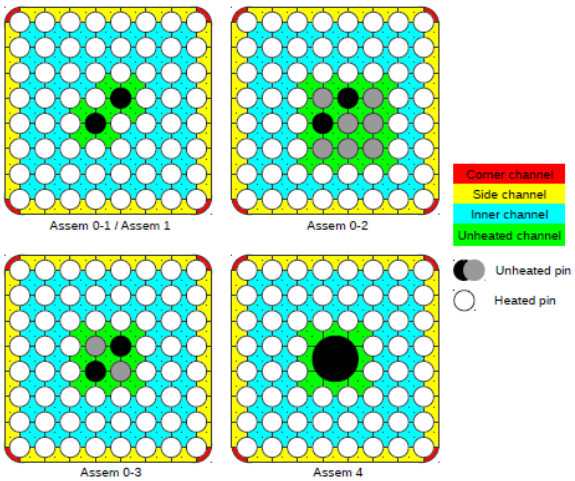




Void predictions near unheated channels

Issue with Symmetry Void Measurements





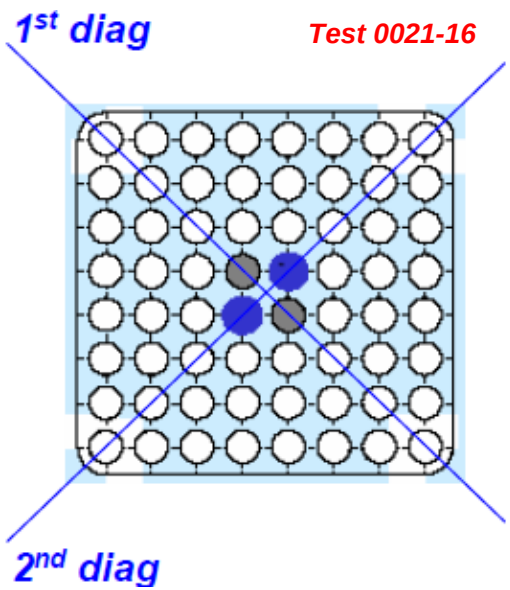
Inner channel void predictions

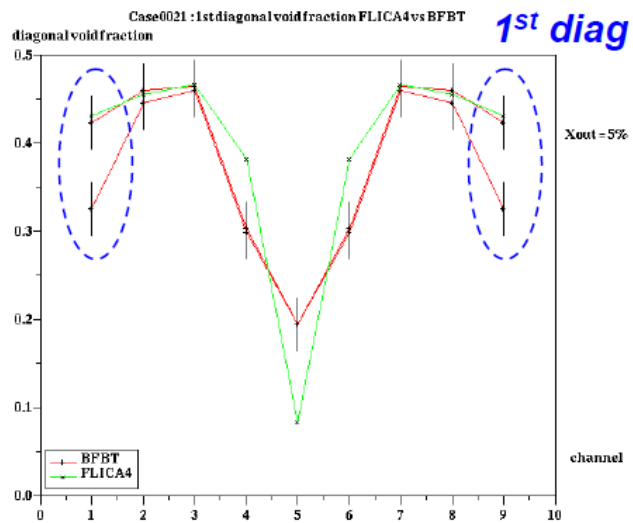
Issue with Symmetry Void Measurements

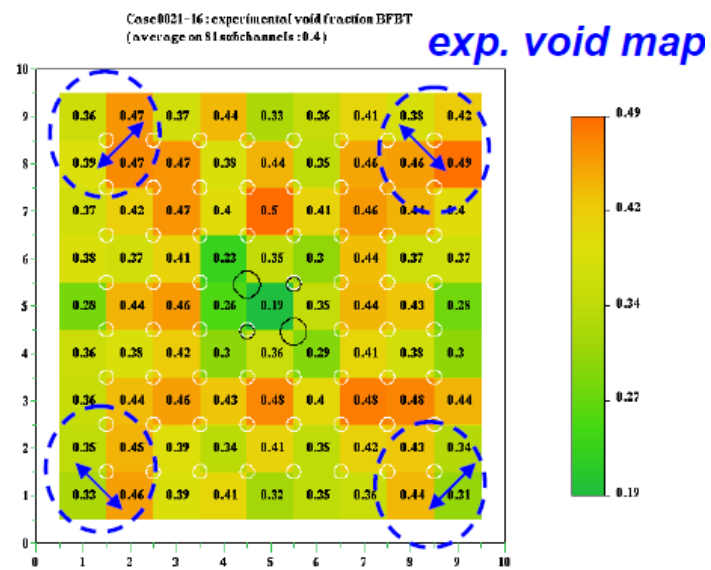
Source: *M. MARTIN, "BFBT Benchmark - Analysis of experimental data for duplicated tests : Effects of rod displacements on subchannel void distributions"*, BFBT-5, Garching, Germany, April 2008

BFBT Benchmark - *Effects of rod displacements on subchannel void distributions (Analysis of experimental data for duplicated tests)*

Experimental subchannel void distributions were showing non-symmetrical results for symmetrical test conditions (discrepancies higher than the given measurement error of 3%)

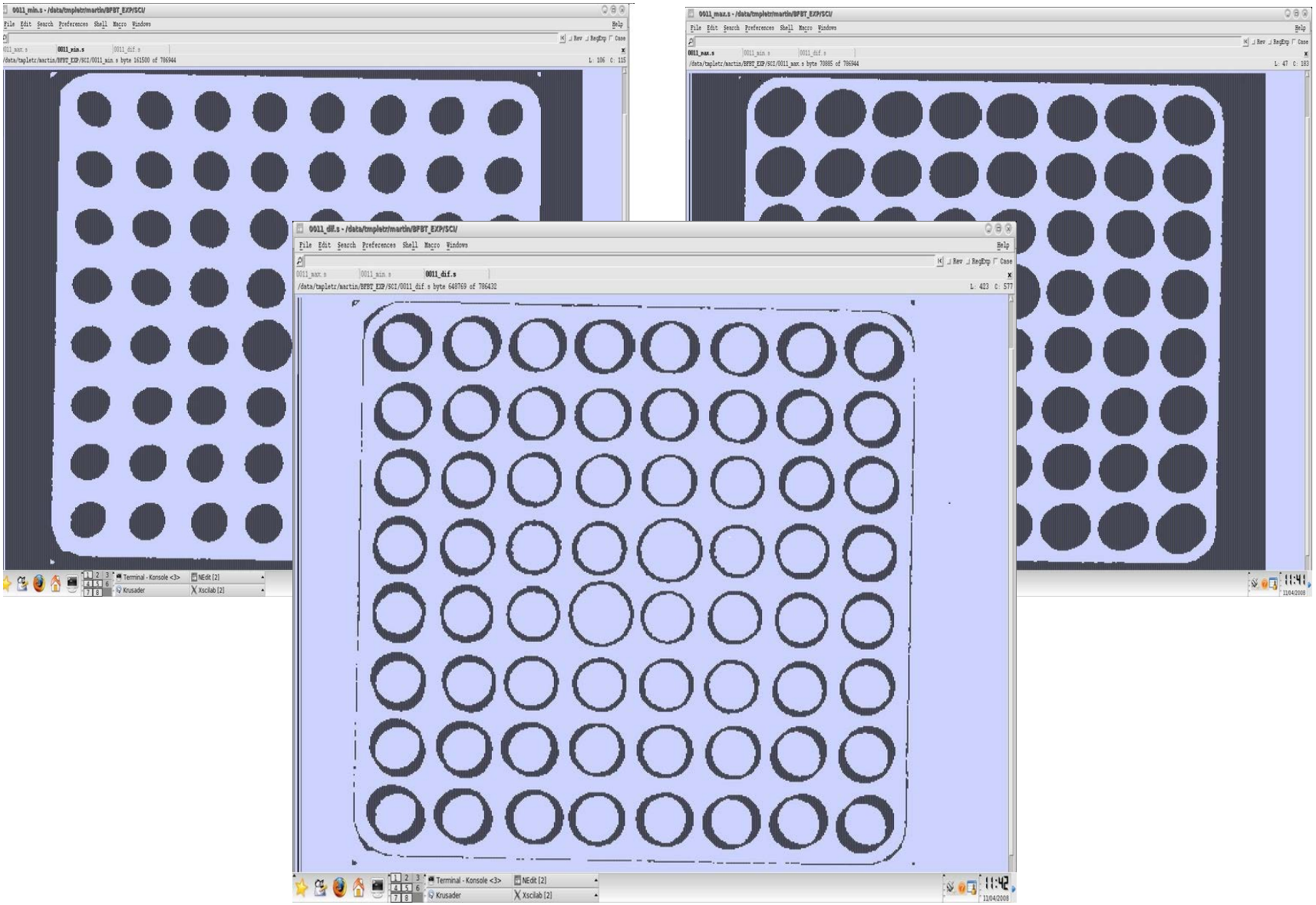






Issue with Symmetry Void Measurements

Source: M. MARTIN, "BFBT Benchmark - Analysis of experimental data for duplicated tests : Effects of rod displacements on subchannel void distributions", BFBT-5, Garching, Germany, April 2008



Issue with Symmetry Void Measurements

Source: M. MARTIN, "BFBT Benchmark - Analysis of experimental data for duplicated tests : Effects of rod displacements on subchannel void distributions", BFBT-5, Garching, Germany, April 2008

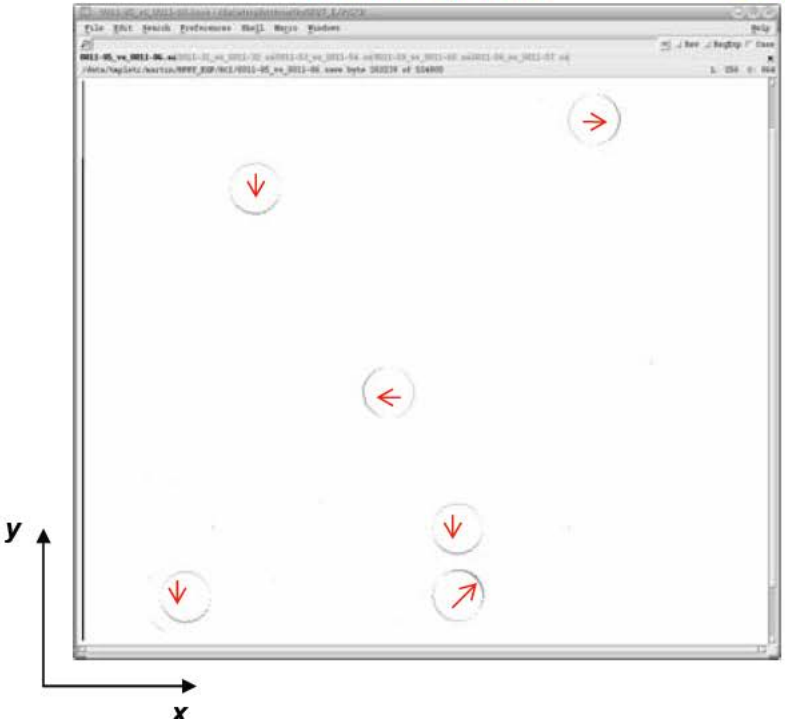
Duplicated tests with a weak displacement of few rods

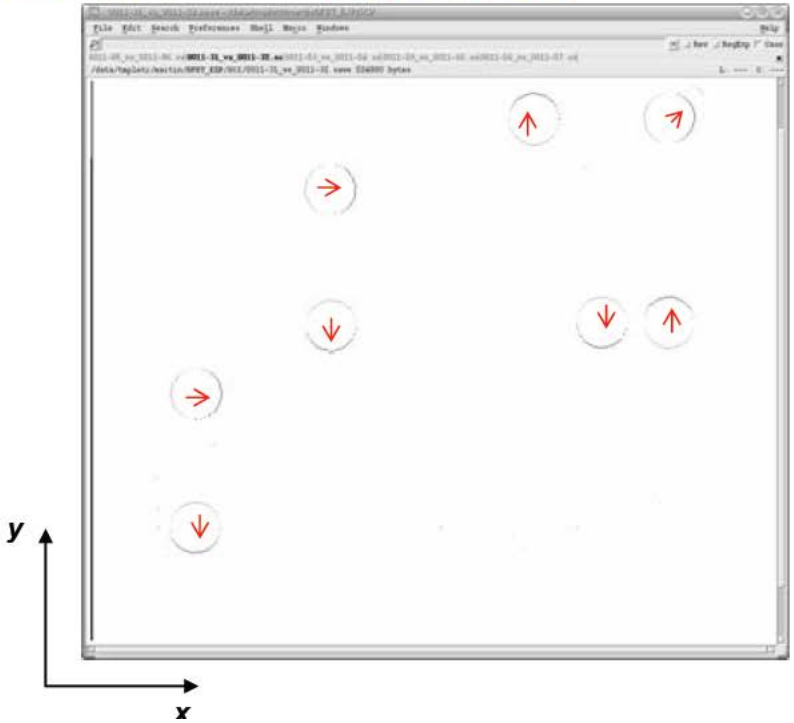
- !! Radial location of the rods: comparison of "rod prints" deduced from 512x512 void map
- !! For duplicated tests, the superposition of structures can be checked
- !! The bounding box is positioned similarly in twin tests (no "box prints" can be found)
- !! Displacement by 1-2 pixels for few rods regularly scattered within the bundle (no overall deviation)

0011-85 vs 0011-86
6 rods displaced

« Eclipse of structures »

0011-31 vs 0011-32
8 rods displaced





Issue with Symmetry Void Measurements

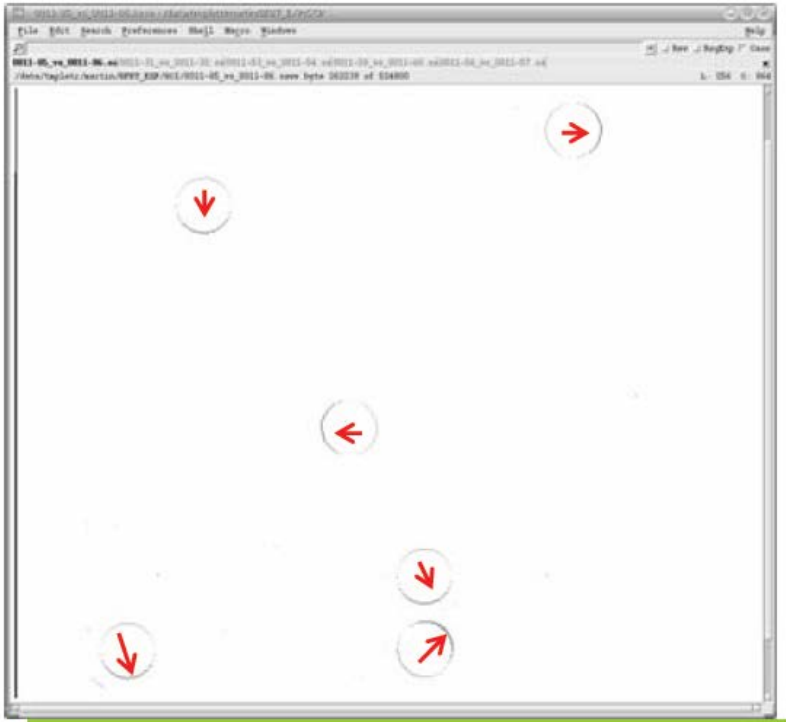
Source: M. MARTIN, "BFBT Benchmark - Analysis of experimental data for duplicated tests : Effects of rod displacements on subchannel void distributions", BFBT-5, Garching, Germany, April 2008

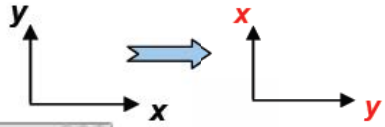
- ✓ Example of duplicated tests : 0011-85 vs 0011-86
  - ✓ comparison of "rod prints" deduced from 512 x 512 void map
  - ✓ comparison of "subchannel maps" of measured void fraction

⇒ Differences in subchannel void maps are exactly located where rod displacements can be found (under the following assumption : the x-y axis must be permuted for subchannel void map)

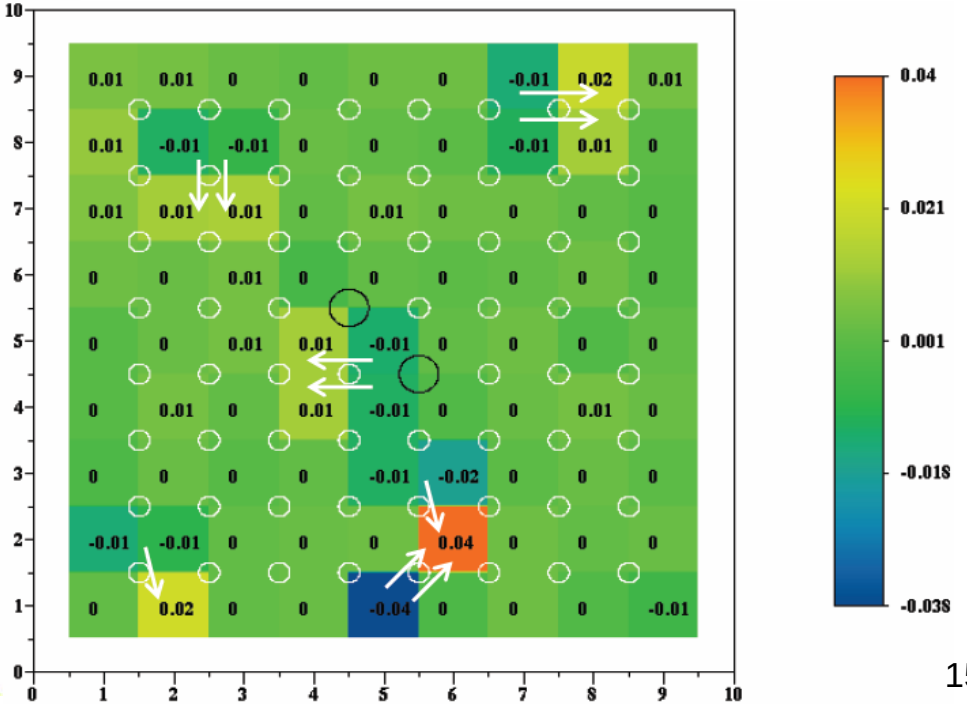
⇒ A rod displacement by 1 pixel results in a subchannel void difference by 1-2%

1. Displacements of rods





2. Differences in subchannel void fraction



Issue with Symmetry Void Measurements

Source: *M. MARTIN, "BFBT Benchmark - Analysis of experimental data for duplicated tests : Effects of rod displacements on subchannel void distributions"*, BFBT-5, Garching, Germany, April 2008

Duplicated tests with a significant rotation of the whole bundle

- !! Radial location of the rods: comparison of "rod prints" deduced from 512 x 512 void map
- !! For duplicated tests, the superposition of structures can be checked
- !! The bounding box is positioned similarly in twin tests (no "box prints" can be found)
- !! Overall rotation of the bundle resulting in displacements by 5 pixels of peripheral rods

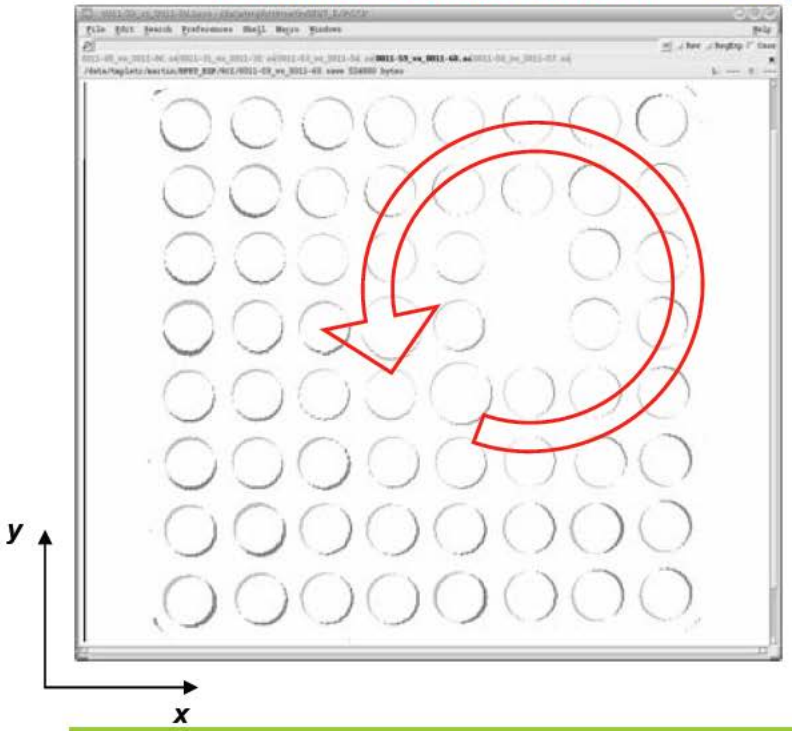
0011-59 vs 0011-60

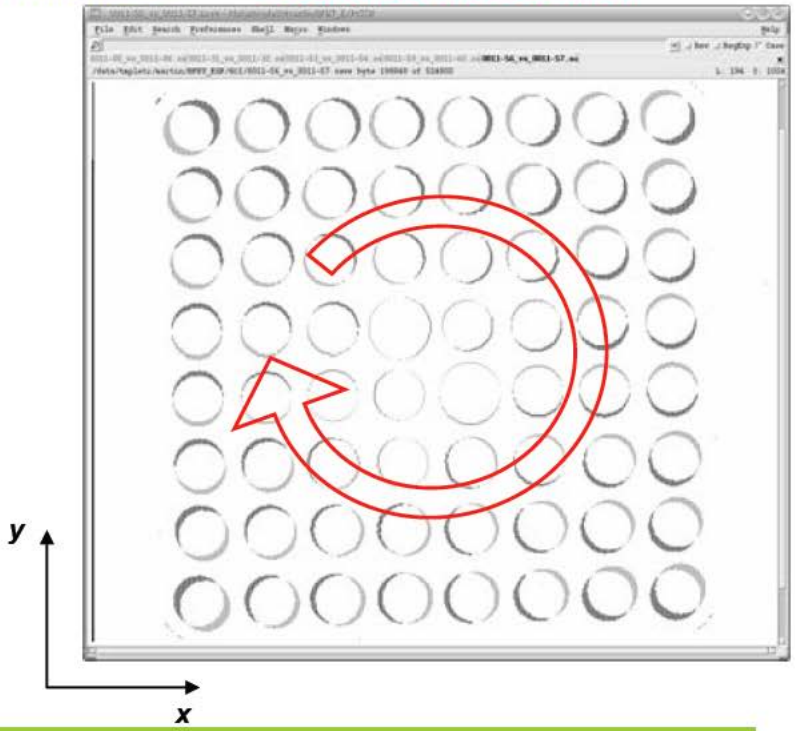
overall non-centred rotation

« Eclipse of structures »

0011-56 vs 0011-57

overall centred rotation





Issue with Symmetry Void Measurements

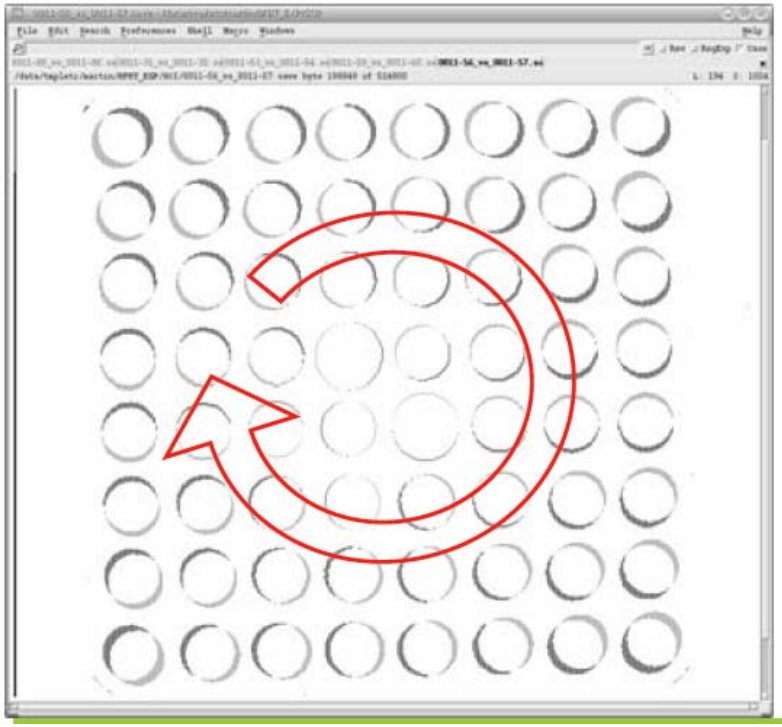
Source: M. MARTIN, "BFBT Benchmark - Analysis of experimental data for duplicated tests : Effects of rod displacements on subchannel void distributions", BFBT-5, Garching, Germany, April 2008

- ✓ Example of duplicated tests : 0011-56 vs 0011-57
  1. comparison of "rod prints" deduced from 512 x 512 void map
  2. comparison of "subchannel maps" of measured void fraction

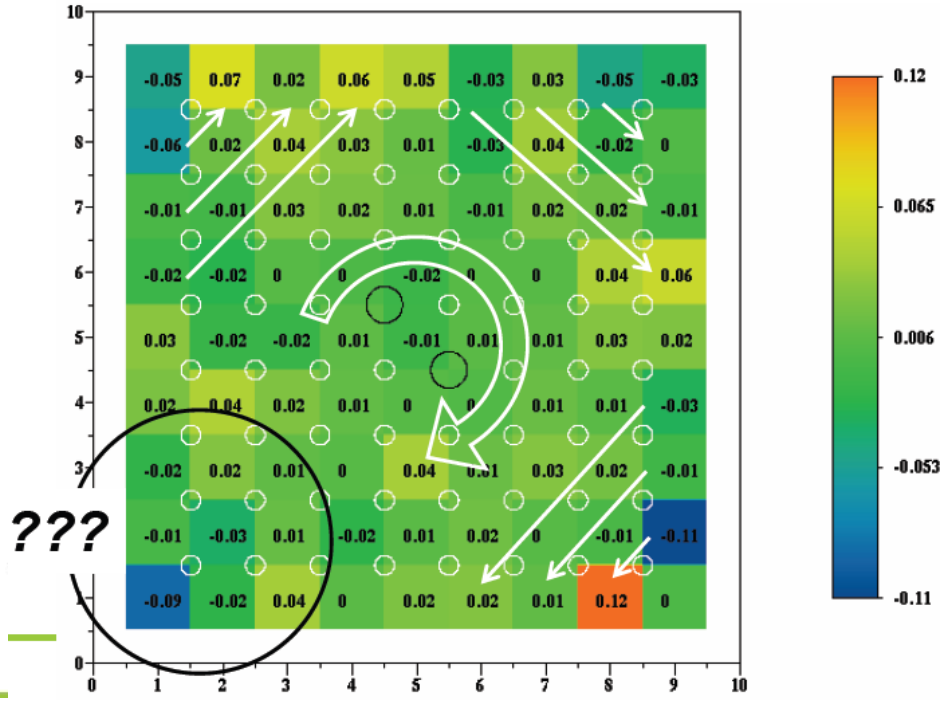
⇒ Distortions in subchannel void maps are consistent with the bundle rotation observed (under the following assumption : the x-y axis must be permuted for subchannel void map)

⇒ Rod displacements by 5 pixels result in a subchannel void difference by 5-10%

1. Overall rotation of the whole bundle



2. Differences in subchannel void map



Issue with Symmetry Void Measurements

Source: *M. MARTIN, "BFBT Benchmark - Analysis of experimental data for duplicated tests : Effects of rod displacements on subchannel void distributions"*, BFBT-5, Garching, Germany, April 2008

- From fine-scale void maps, angular distortions can be observed both for the rod bundle and the channel box.
- Source of distortions: a physical misplacement of the bundle due to a rotation of grids **OR** an angular bias artificially introduced by the CT-scanner?

From analysis of duplicated tests:

1. Weak displacements of few rods → small discrepancies in SC void maps
2. Large rotation of the whole bundle → high angular distortion in SC void maps

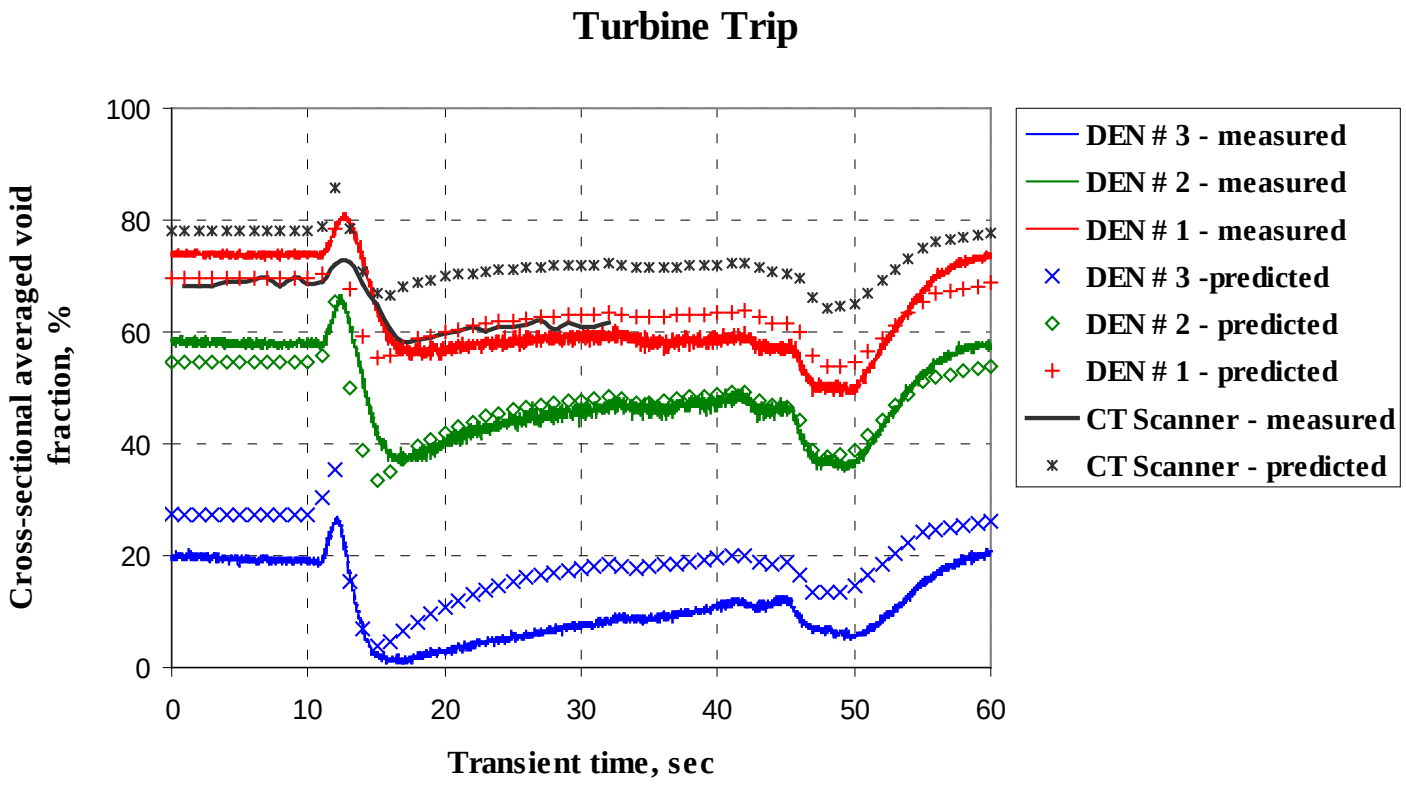
From the fine-scale void map to the subchannel void map, the x-y axis should be permuted to ensure consistency between rod displacements and void map distortions

Considering the observed distortions, the following must clarify:

1. The x-y axis for subchannel void map in respect to x-y axis for fine-scale void map
2. The definition and position of the "subchannel filter"
3. The geometrical uncertainties to propagate through the code

Uncertainties of alley void measurements (by DENSITOMETER)

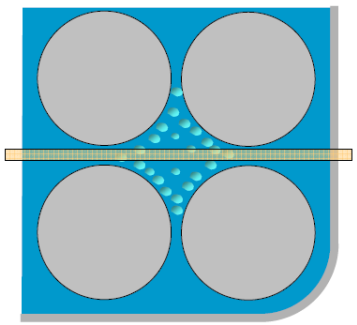
BFBT Benchmark – *CT-scan vs. X-ray densitometer measurements of void fraction*



Uncertainties of alley void measurements (by DENSITOMETER)

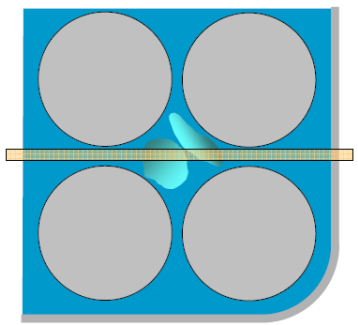
Bubbly flow

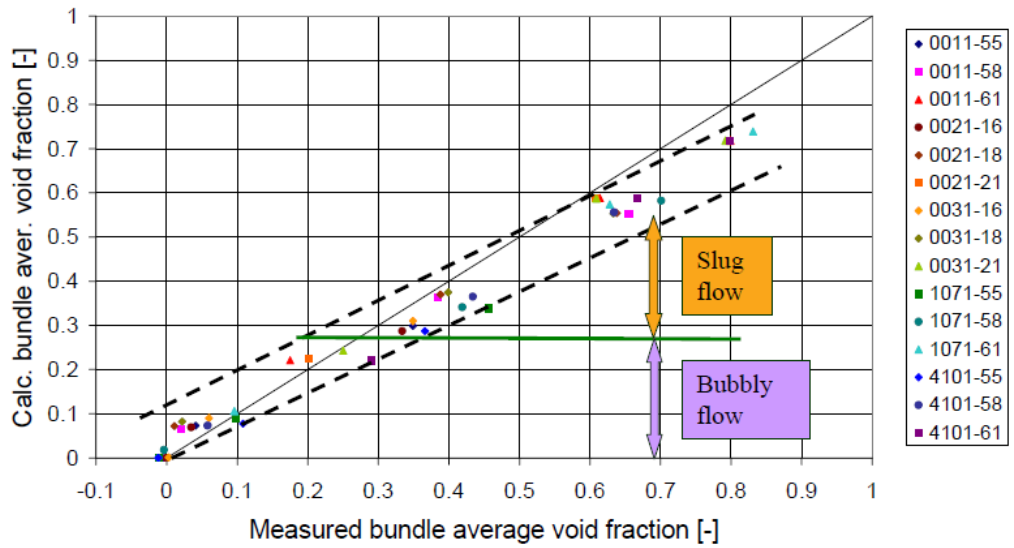
- void concentrated near walls
- void under predicted in alley measurement



Slug flow

- void concentrated in center of sub-channel
- void over predicted in alley measurement

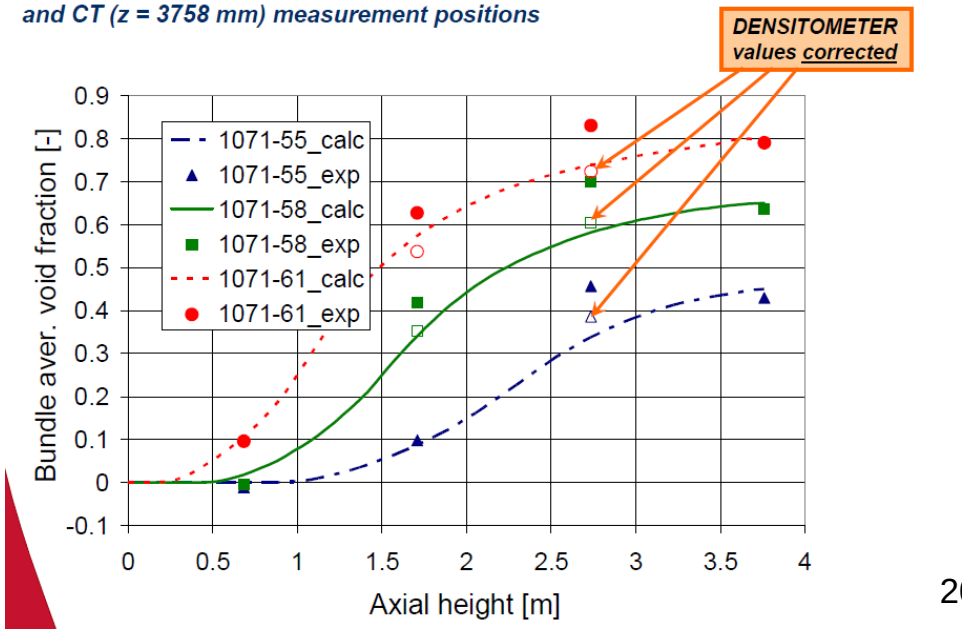




$$\alpha_{corrected} = \frac{\hat{\alpha}_{measured,DEN}}{\underbrace{-0.001\,\hat{\alpha}_{measured,DEN} + 1.231}_{\text{correction factor } DCR}}$$ *(Assembly 0-1)*

$$\alpha_{corrected} = \frac{\hat{\alpha}_{measured,DEN}}{\underbrace{-0.001\,\hat{\alpha}_{measured,DEN} + 1.167}_{\text{correction factor } DCR}}$$ *(Assembly 4)*

DEN#3 (z = 682 mm), DEN#2 (z = 1706 mm), DEN#1 (z = 2730 mm), and CT (z = 3758 mm) measurement positions



What should we do …?
Measured data are "signals from the real world"!

- Use raw data or "filtered" data for model validation?

  → or maybe raw data with "true" uncertainties?

- Can experimentalists provide "true" uncertainties?

More questions can be asked, but let's stop here …