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**VVER-1000 AND VVER-440 SYSTEM TRANSIENT
ANALYSES AT UNIVERSITY OF PISA**

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FRAMEWORK AND OBJECTIVE

FRAMEWORK

- APPLICATION OF THE BE THERMALHYDRAULIC SYSTEM (**SYS-TH**) CODES TO THE TECHNOLOGY OF LWR.

OBJECTIVE

- REVIEW OF METHODOLOGIES AND OF RESULTS FROM CODE APPLICATIONS. EMPHASIS GIVEN TO VVER-440 AND VVER-1000.

CONTENT

- **CODE DEVELOPMENT**
- **CODE ASSESSMENT:**
 - EXPERIMENTAL DATA & THE SCALING ISSUE
 - QUALITATIVE ACCURACY EVALUATION
 - QUANTITATIVE ACCURACY EVALUATION: THE **FFTBM METHOD**
- **PROCEDURES FOR CONSISTENT CODE APPLICATION:**
 - NODALISATION DEVELOPMENT
 - NODALISATION QUALITY AT THE 'STEADY STATE' LEVEL
 - NODALISATION QUALITY AT THE 'ON-TRANSIENT' LEVEL
- **UNCERTAINTY METHODS**
 - UNCERTAINTY APPROACHES
 - THE UMAE (UNCERTAINTY METHOD)
 - THE CIAU (CODE WITH CAPABILITY OF **INTERNAL ASSESSMENT** OF UNCERTAINTY)
- **COUPLED CODES**
 - 3-D NEUTRON KINETICS / SYS-TH
 - SYS-TH / CFD / STRUCTURE MECHANICS
- **RESULTS FROM CODE APPLICATION**
 - TOOLS AVAILABLE
 - VVER-440
 - VVER-1000
 - OTHERS

CODE DEVELOPMENT

- SYS-TH CODES HAVE BEEN DEVELOPED BY A RESTRICTED NUMBER OF QUALIFIED INSTITUTIONS AROUND THE WORLD.
- FOUR/FIVE SYS-TH CODES ACHIEVED A REASONABLE LEVEL OF MATURITY AND DIFFUSION.
- THE EFFORT TO DEVELOP (INCLUDING DEVELOPMENTAL ASSESSMENT) A SYS-TH CODE: ABOUT 100 MAN-YEARS AND 10 YEARS TIME.

➤ PRESENT CAPABILITIES/CHARACTERISTICS:

- SIX PARTIAL DIFFERENTIAL EQUATIONS
- UVUT,
- 1-D 'EXTENDED' TO 3-D **POROUS MEDIA** APPROACH,
- USE OF SEVERAL TENS CONSTITUTIVE-CLOSURE-EMPIRICAL EQUATIONS.

➤ IN-PROGRESS AND FUTURE DEVELOPMENTS:

- ADDITIONAL BALANCE EQUATION (INTERFACIAL TRANSPORT).
- (LIMITED) IMPROVEMENT: NUMERICS, WATER PROPERTIES, CONSTITUTIVE MODELS.
- **OPEN MEDIA** APPROACH
 - CFD: 1-PHASE CAPABILITY AVAILABLE,
 - TWO-PHASE MACROSCOPIC, WITH FLOW RECONSTRUCTION: WITHIN TEN YEARS.
 - TWO-PHASE MICROSCOPIC, FULL SUB-CHANNEL MODELING: DIFFERENT 'TEN YEARS' WITH CURRENT COMPUTATIONAL CAPABILITY GROWTH.

CODE ASSESSMENT

EXPERIMENTAL DATA & THE SCALING ISSUE

➤ **KEY-WORDS:**

- DEVELOPMENTAL ASSESSMENT COMPLETED,
- FUNDAMENTAL TESTS (EXPERIMENTAL AND NUMERICAL BENCHMARK),
- SETF MATRIX,
- ITF MATRIX INCLUDING VVER-PHENOMENA,
- NPP APPLICATION.

Comprehensive SETF and ITF matrices exist including hundreds ITF and thousands SETF experiments, respectively.

- THE SCALING ISSUE TO BE ADDRESSED BY ANALYZING SIMILAR EXPERIMENTAL SCENARIOS AT DIFFERENT GEOMETRIC SCALE.

CODE ASSESSMENT

QUALITATIVE ACCURACY EVALUATION

THIS IMPLIES:

- UNDERSTANDING OF PHYSICAL PHENOMENA,
- CLASSIFICATION OF PHYSICAL PHENOMENA,
- UNDERSTANDING OF THE DIFFERENCES BETWEEN MEASURED AND PREDICTED VALUES AND TIME TRENDS: I.E. PRIORITISATION OF THE ROOT CAUSES FOR DISCREPANCIES.
- PERFORMING SENSITIVITY STUDIES.
- AVAILABILITY OF METHODS FOR QUALITATIVE ACCURACY EVALUATION: **PIRT**, OR **RTA** CHARACTERIZED BY SVP, NDP, IPA AND TSE.

CODE ASSESSMENT

QUANTITATIVE ACCURACY EVALUATION: THE FFTBM METHOD

THIS IMPLIES:

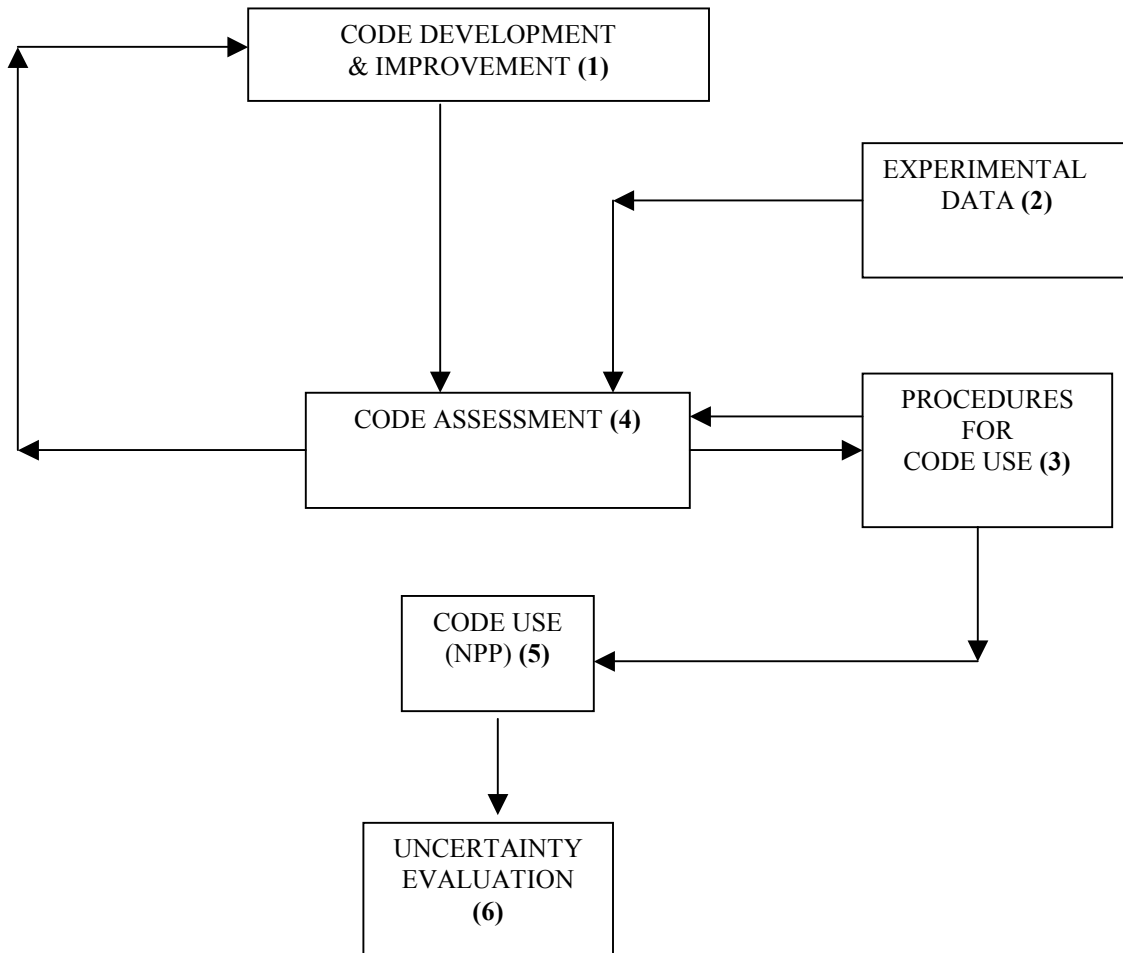
- ASSIGNING AN 'OBJECTIVE RATE' TO AN OCCURRING ERROR. ERROR IS CONSTITUTED BY THE DISCREPANCY BETWEEN MEASURED AND PREDICTED VALUES, IN THE GENERAL CASE, OF A TIME-VARYING TREND.

THE FFTBM (FAST FOURIER TRANSFORM BASED METHOD) IS AVAILABLE FROM THE UNIVERSITY OF PISA AND RECENTLY IMPLEMENTED INTO THE ACAP TOOL DEVELOPED BY US NRC.

THE FFTBM HAS BEEN WIDELY APPLIED TO A NUMBER OF 'COMPARISONS EXP-CALC' INVOLVING SETF AND ITF EXPERIMENTS, OECD/ISP, IAEA/SPE, NPP DATA.

CODE ASSESSMENT & APPLICATION:

PROCESS FOR A CONSISTENT APPLICATION OF A THERMOHYDRAULIC SYSTEM CODE



- (1) → page 4
- (2) → page 5
- (3) & (4) → pages 6 & 7, see also pages 9 to 11
- (5) → pages 19 to 24
- (6) → pages 12 to 15

PROCEDURES FOR CONSISTENT CODE APPLICATION

NODALISATION DEVELOPMENT

THE **NODALISATION** IS THE RESULT OF A BRAINSTORMING PROCESS AIMING AT ‘TRANSFERRING’ INFORMATION FROM THE (NPP) GEOMETRIC-MATERIAL CONFIGURATION TO THE CODE.

THE FOLLOWING ASPECTS PLAY A ROLE:

- USER EXPERTISE,
- COMPUTER POWER,
- CODE CHARACTERISTICS,
- GOALS OF THE SIMULATION,
- REQUIRED LEVEL OF DETAIL,
- USER MANUAL.

A **NODALISATION** HAVING 10^3 HYDRAULIC NODES AND 10^4 MESH POINTS FOR CONDUCTION HEAT TRANSFER REPRESENTS THE CURRENT CAPABILITIES.

CONSISTENT SETS OF CRITERIA MUST BE FOLLOWED WHEN DEVELOPING A **NODALISATION**.

PROCEDURES FOR CONSISTENT CODE APPLICATION

NODALISATION QUALITY AT THE 'STEADY STATE' LEVEL

BEFORE THE USE FOR THE PREDICTION OF TRANSIENT SCENARIOS, THE **NODALISATION** MUST PROVE ITS CAPABILITY IN PREDICTING THE NOMINAL OR 'STEADY-STATE' PERFORMANCE OF THE INVOLVED SYSTEM.

CRITERIA OR THRESHOLDS OF ACCEPTABILITY ARE AVAILABLE TO PROVE THE **NODALISATION** QUALITY AT THE STEADY STATE LEVEL, E.G. ACCEPTABLE ERROR FOR:

- PRESSURE, TEMPERATURE, MASS FLOWRATES, ETC.
- PRESSURE DISTRIBUTION ALONG THE LOOP,
- POWER BALANCE,
- VOLUME DISTRIBUTION ALONG THE HEIGHT.

PROCEDURES FOR CONSISTENT CODE APPLICATION

NODALISATION QUALITY AT THE 'ON-TRANSIENT' LEVEL

BEFORE THE USE FOR THE PREDICTION OF TRANSIENT SCENARIOS, THE NODALISATION MUST PROVE ITS CAPABILITY IN PREDICTING THE EXPECTED PHENOMENA.

THE 'KV-SCALED' APPROACH CAN BE ADOPTED. NPP NODALISATION IS USED TO CALCULATE ITF EXPERIMENTS:

- DISCREPANCIES BETWEEN PREDICTED AND MEASURED TIME TRENDS MUST BE UNDERSTOOD.**
- THE FFTBM TOOL CAN BE USED TO 'QUANTIFY' THE DISCREPANCIES.**

UNCERTAINTY METHODS

UNCERTAINTY APPROACHES

A) PROPAGATION OF INPUT ERRORS

- MOST OF THE CURRENT UNCERTAINTY METHODS,
- NEED OF ENGINEERING JUDGEMENTS TO:
 - SELECT INPUT PARAMETERS,
 - FIX RANGE OF VARIATION,
 - ASSIGN PDF.
- ERROR PROPAGATION OCCURS THROUGH 'UNCERTAIN' CODE/MODEL.

B) PROPAGATION OF OUTPUT ERRORS

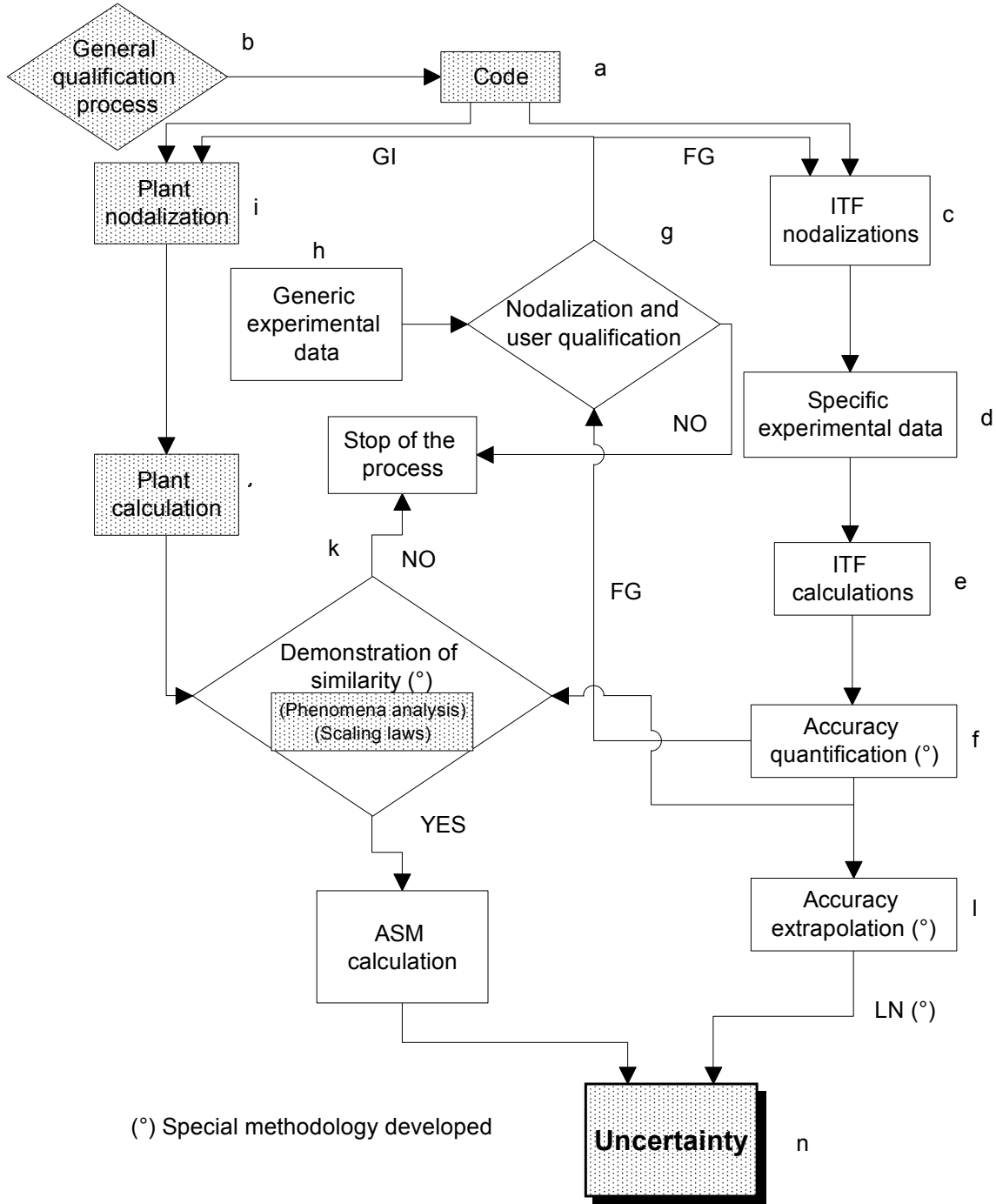
- IMPLIES THE AVAILABILITY OF RELEVANT EXPERIMENTAL DATA,
- NO THEORETICAL JUSTIFICATION FOR THE ERROR PROPAGATION,
- LIMITED POSSIBILITY TO TRACK THE ORIGIN OF THE ERROR.

C) DETERMINISTIC APPROACH

- USER DRIVEN:
 - EXPERTISE NEEDED AT EACH STEP,
 - NO AUTOMATISATION (MAN-RESOURCES NEEDED),
 - USER DEPENDENT RESULTS.

UNCERTAINTY METHODS

THE UMAE (UNCERTAINTY METHOD)



UNCERTAINTY METHODS

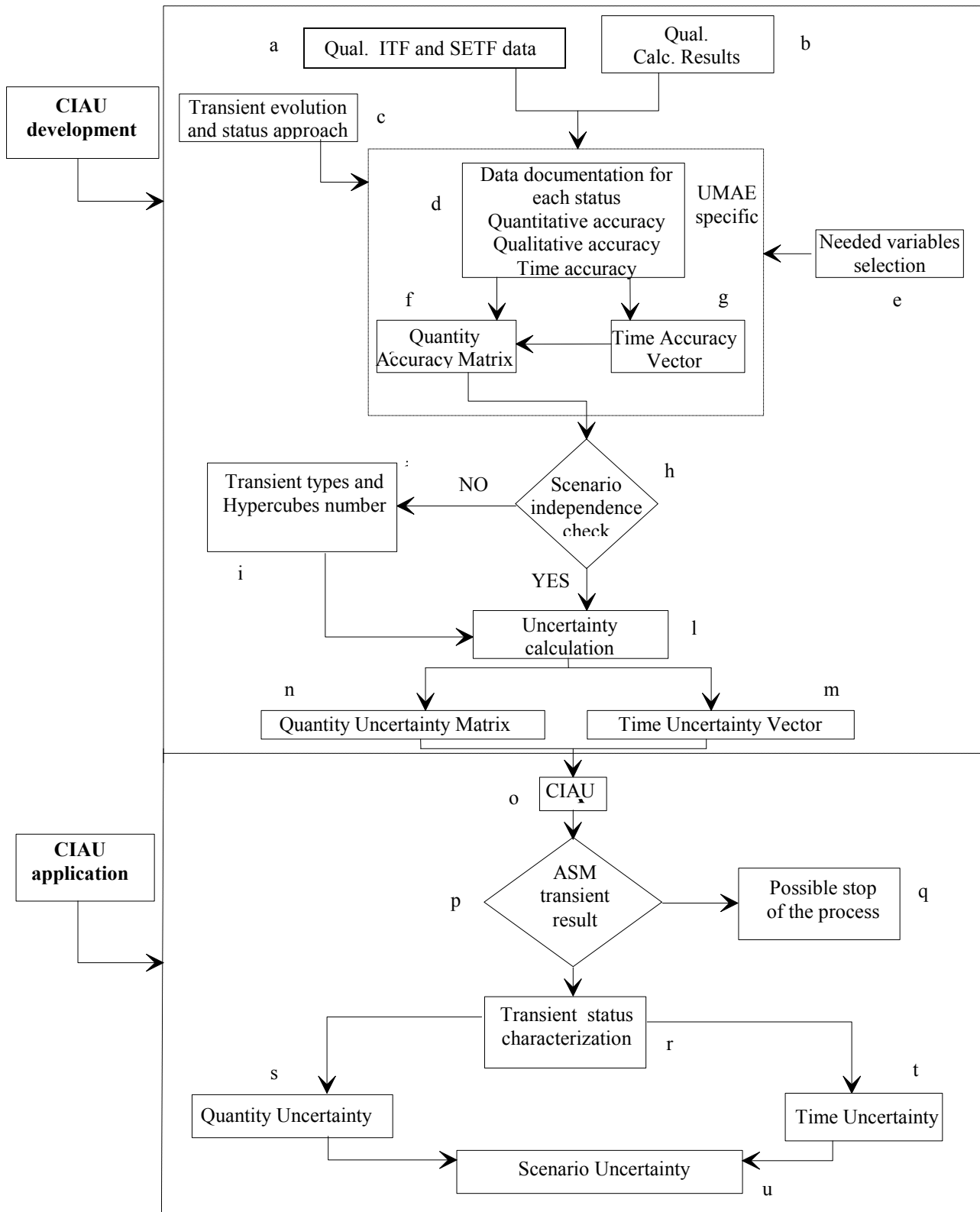
THE CIAU: CODE WITH CAPABILITY OF INTERNAL ASSESSMENT OF UNCERTAINTY

THE NEEDS

- A) CODE RESULTS ARE AFFECTED BY USER CHOICES. THE USER OF UNCERTAINTY METHODS MAY ALSO HEAVILY AFFECT RESULTS PREDICTED BY UNCERTAINTY METHODS. THE COMBINATION OF THE TWO EFFECTS MAY BE NOT TOLERABLE.
- B) THE APPLICATION OF ANY UNCERTAINTY METHOD MAY REQUIRE EXPERTISE AND/OR RESOURCES NOT EASILY AVAILABLE.
- C) THE UNCERTAINTY MUST BE A CHARACTERISTIC OF THE CODE QUALITY OR OF THE QUALIFICATION LEVEL.

THE *IDEA*

- 1) ANY TRANSIENT SCENARIO ASSUMED IN THE REFERENCE SYSTEMS CAN BE CHARACTERIZED BY THE TIME AND BY A LIMITED NUMBER OF VARIABLES. THE BOUNDARIES OF VARIATION FOR THOSE VARIABLES AND THE TIME ARE IDENTIFIED.
- 2) THE BOUNDARIES AND THE TRANSIENT TIME ARE SUBDIVIDED INTO INTERVALS. HYPERCUBES RESULT FROM THE COMBINATION OF VARIABLES INTERVALS.
- 3) THE NPP STATUS IS FORMED BY THE COMBINATION OF ONE HYPERCUBE AND ONE TIME INTERVAL.
- 4) IT IS ASSUMED THAT UNCERTAINTY CAN BE ASSOCIATED TO ANY NPP STATUS.



Simplified flow diagram of the CIAU

COUPLED CODES

- CODES COUPLING WIDELY KNOWN TO SAFETY ANALYSTS TO PERFORM ANALYSES INVOLVING COMPUTATIONAL CAPABILITIES IN DIFFERENT DISCIPLINES.
- RECENT AVAILABILITY OF **CFD** AND **3-D TRANSIENT NEUTRON KINETICS** CODES AND OF POWERFUL COMPUTERS.
- ATTENTION FOCUSED TOWARD ‘TWO COUPLINGS’ OF CURRENT INTEREST AT UNIVERSITY OF PISA.

1) 3-D NEUTRON KINETICS / SYS-TH

- ASYMMETRIC AND ‘LOCAL’ CORE SIMULATION (INCLUDING SUB-CHANNEL CODE COUPLING),
- ATWS,
- **BET** -ESTIMATE EVALUATION, INCLUDING LOCA CASES.

2) SYS-TH / CFD / STRUCTURE MECHANICS

- FLUID MIXING (ALSO RELEVANT FOR NEUTRONICS),
- PRESSURIZED THERMAL SHOCK,
- LOADS FROM WATER HAMMER.

RESULTS FROM CODE APPLICATION

TOOLS AVAILABLE 1/2

CODES			
N	ID	ORIGIN	NOTES
1	Relap5/mod3.3	US NRC	TH-SYS
2	Relap5-3D ©	DOE – Idaho	TH-SYS
3	Cathare	CEA	TH-SYS
4	Quabbox	GRS	NEU-3D
5	Parcs	US NRC	NEU-3D
6	Nestle	DOE - Idaho	NEU-3D
7	Casmo	ENEL	X-SEC
8	N3S	EdF	CFD
9	Fluent	Comm. license	CFD
10	Trio	CEA	CFD (delivery in progress)
11	Ansys	Comm. license	Structural Mechanics

OTHER			
N	ID	ORIGIN	NOTES
1	UMAE	U. Pisa	Uncertainty Method
2	CIAU	U. Pisa	Uncertainty Method
3	FFTBM	U. Pisa	Accuracy quantification
4	Various connected with TH-SYS code application	U. Pisa	Nod. dev., Nod. qua, User qua., Qual. acc ev., various post-processors, etc.
5	TECPLOT	Comm. license	Post processor, e.g. 3-D video clips

RESULTS FROM CODE APPLICATION

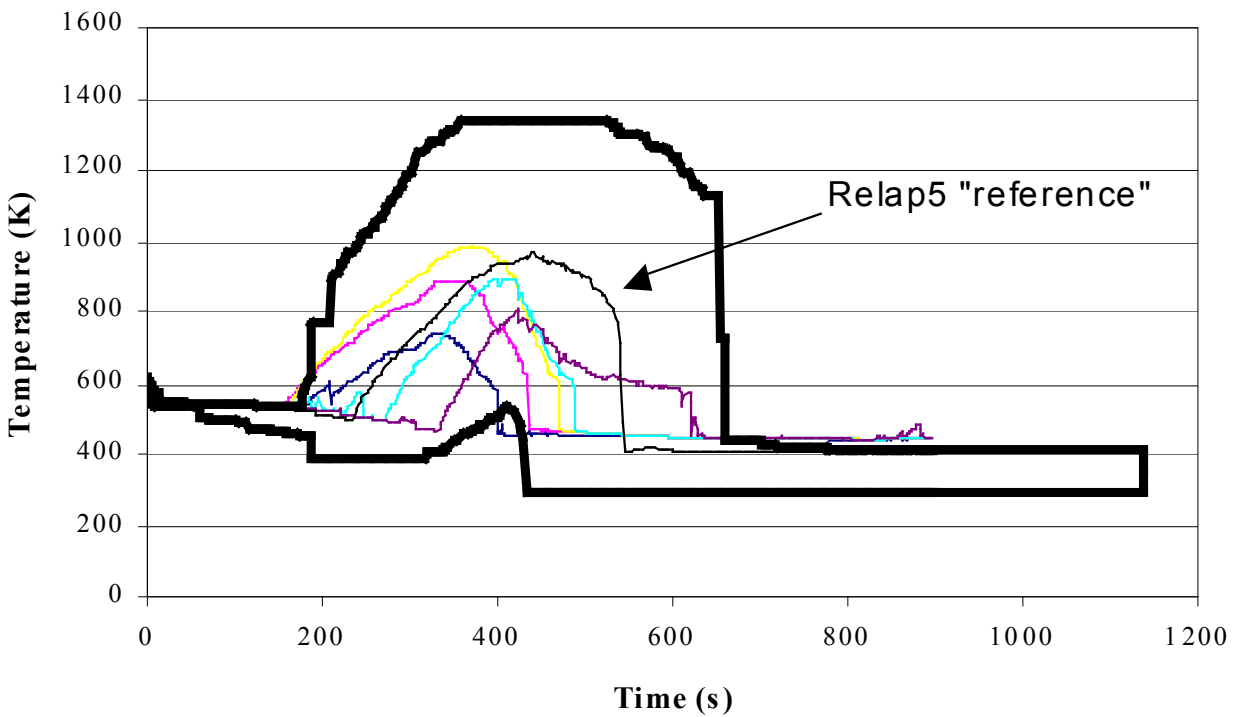
TOOLS AVAILABLE 2/2

NODALISATIONS			
N	NPP/TYPE	DESIGNER	CODES
1	Krsko/PWR	W	R5
2	Angra-1/PWR	W	R5
3	Angra-2/PWR	KWU	R5
4	3-L/PWR	FRA	Cathare
5	TMI-1/2	B&W	R5, Quabbox, Parcs, Nestle
6	EP-1000	W	R5
7	AP-600	W	R5
8	EPR	NPI	R5
9	AP-1000	W	R5, Parcs (assumed X-sec)
10	KZ-5/VVER-1000	GI	R5
11	KZ-3/VVER-440	GI	R5, Cathare
12	AR-2/VVER-440	GI	R5
13	PWR-PUN	W	R5
14	Caorso/BWR-5	GE	R5
15	Montalto/BWR-6	GE	R5
16	Ringhals/BWR	ABB	R5
17	PB/BWR-5	GE	R5, Parcs, Nestle
18	Research reactor	Various	R5
19	Prototypes	Various	R5
INTEGRAL TEST FACILITIES (ITF)			
20	‘All’ PWR ITF simulators	Various	R5, Cathare
21	‘All’ VVER ITF simulators	Various	R5, Cathare. Excluded PSB
22	‘All’ BWR ITF simulators	Various	R5, Cathare
23	RD-14M	AECL	R5
24	PANDA/SBWR	GE	R5

RESULTS FROM CODE APPLICATION

VVER-440

APPLICATION OF UNCERTAINTY METHOD “LOCA-200 MM”



CIAU results:

Demonstration that CATHARE results ‘are bounded’ by the uncertainty bands related to the RELAP5 calculation

RESULTS FROM CODE APPLICATION

VVER-1000

SYS-TH CODE APPLICATION & ADDRESSING THE SCALING ISSUE:

NATURAL CIRCULATION PERFORMANCE

PAG 1/2

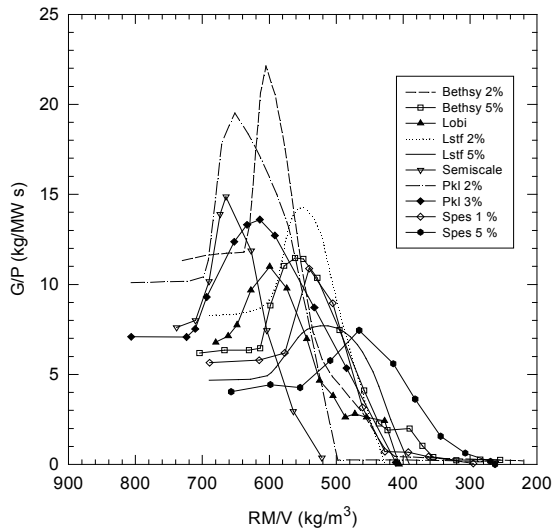


Fig. 2 – Natural Circulation system behaviour measured in ten experiments performed in six PWR simulators

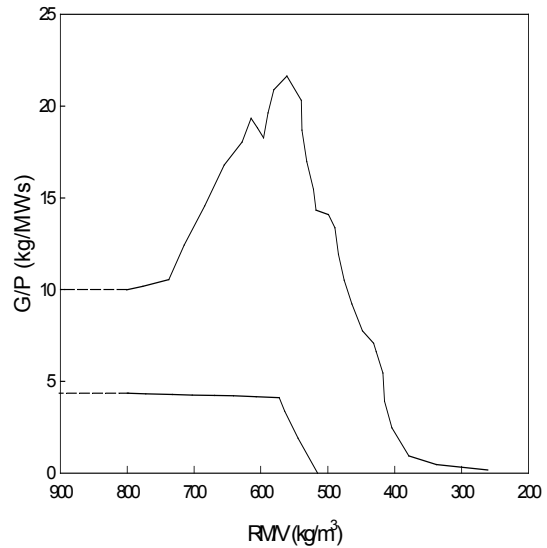


Fig. 3 Natural Circulation Flow Map achieved from the envelope of measured curves in PWR simulator

RESULTS FROM CODE APPLICATION

VVER-1000

SYS-TH CODE APPLICATION & ADDRESSING THE SCALING ISSUE: NATURAL CIRCULATION PERFORMANCE

PAG 2/2

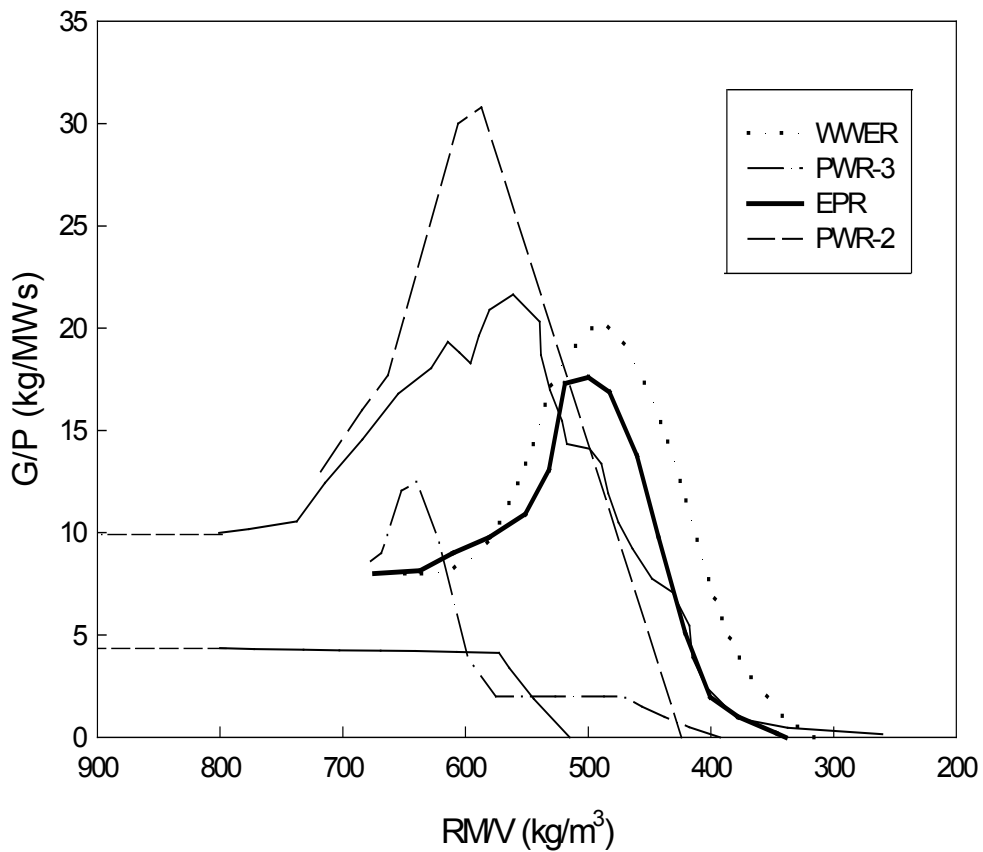


Fig. 4 – Evaluation of the NCP for PWR-2, PWR-3, WVER-1000 and EPR by using the NCFM.

RESULTS FROM CODE APPLICATION

VVER-1000

COUPLED SYS-TH / CFD / STRUCTURE MECHANICS CODE
APPLICATION:

PRESSURIZED THERMAL SHOCK
FOLLOWING
MSLB – NO MCP TRIP – EFW & HPIS ON

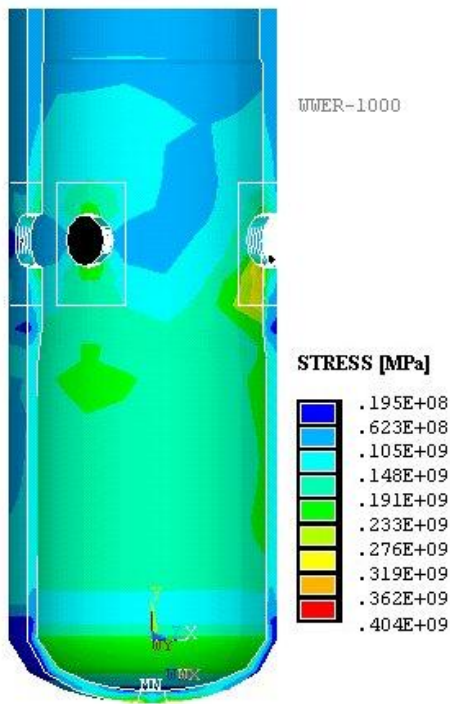


Fig. 8- Stress status of downcomer at 20 s after scram

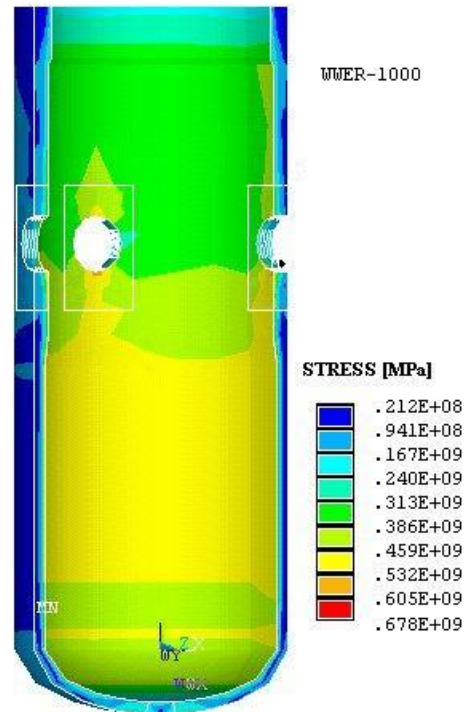


Fig. 9 - Stress status of downcomer at 800 s after scram (tangential stress)

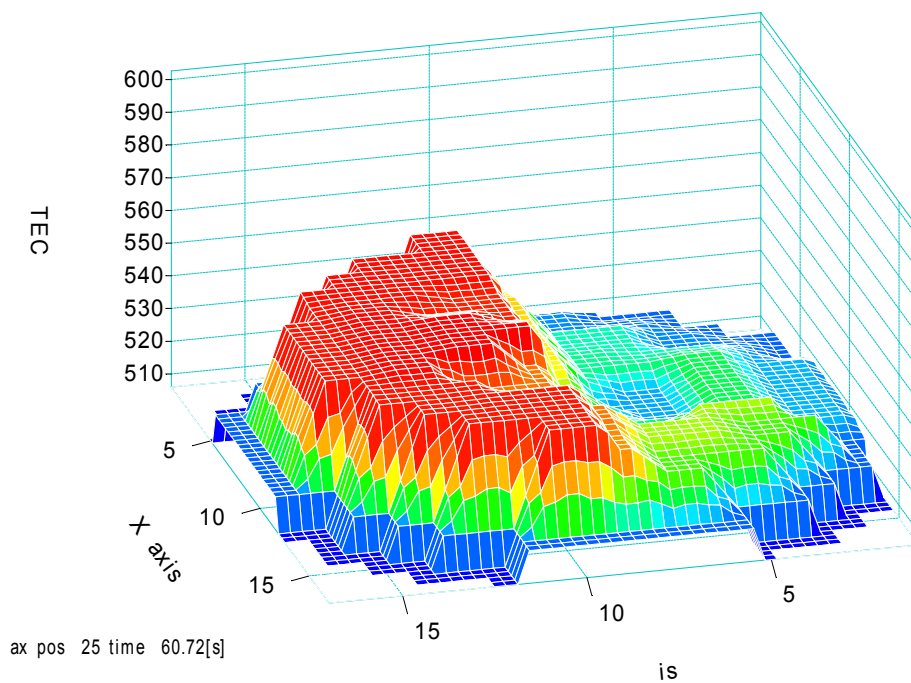
RESULTS FROM CODE APPLICATION

OTHERS

TMI-1 & W NPP

COUPLED 3-D NEU / SYS-TH / CODE APPLICATION:

**‘LOCAL’ CORE POWER RISE
FOLLOWING
MSLB – NO MCP TRIP – EFW & HPIS ON
PAG 1/2**



CORE OUTLET FLUID TEMPERATURE PROFILE AT THE TIME OF PEAK
POWER (2ND PEAK).

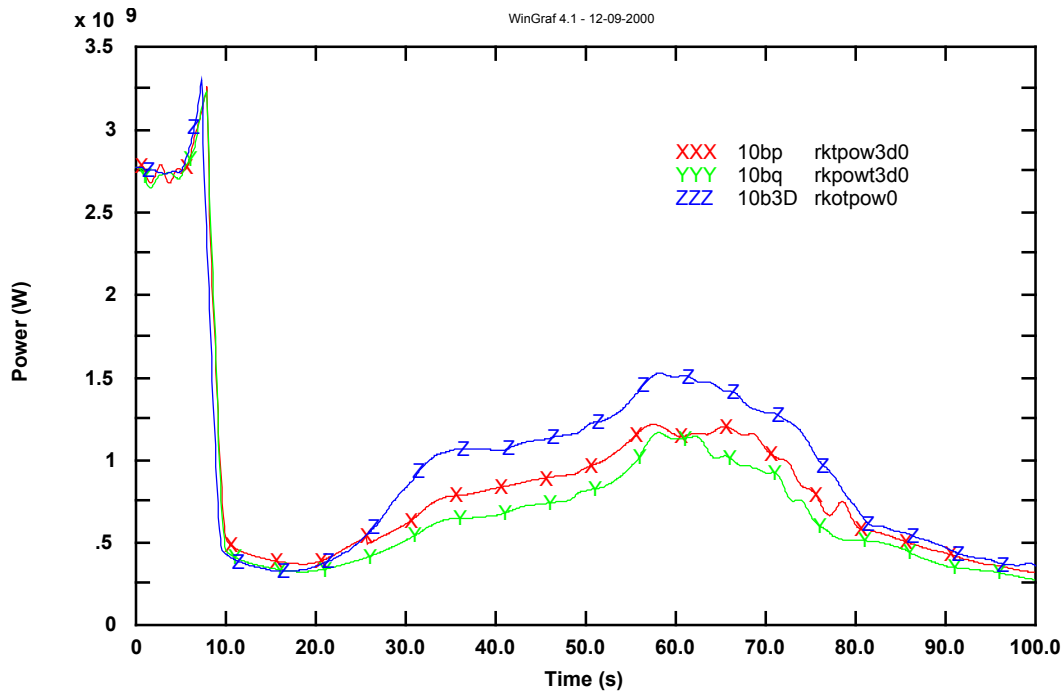
RESULTS FROM CODE APPLICATION

OTHERS

TMI-1 & W NPP

COUPLED 3-D NEU / SYS-TH / CODE APPLICATION:

**'LOCAL' CORE POWER RISE
FOLLOWING
MSLB – NO MCP TRIP – EFW & HPIS ON**
PAG 2/2



CORE TOTAL POWER CALCULATED BY THREE DIFFERENT COUPLED CODES: RELAP5/PARCS, RELAP5/QUABBOX, RELAP5-3D/NESTLE.

SUMMARY/CONCLUSIONS

- **SYS-TH CODE QUALITY NOT YET AT A LEVEL SUITABLE FOR CODE USE AS A ‘BLACK BOX’:**
 - USER EXPERTISE STILL DECISIVE FOR OBTAINING MEANINGFUL RESULTS,
 - USER TRAINING NEEDED. COMPARISON BETWEEN CODE PREDICTED RESULTS AND ITF EXPERIMENTAL DATA NECESSARY TO UNDERSTAND CODE LIMITATIONS,
 - ‘POROUS MEDIA’ / UVUT / 3D CHARACTERIZE CURRENT APPROACH.
- **PROCEDURES EXIST SUITABLE FOR DIFFERENT STEPS OF CODE APPLICATIONS.**
- **BEST ESTIMATE CODE APPLICATIONS MUST BE SUPPLEMENTED BY UNCERTAINTY EVALUATION.**
- **COUPLED CODES AND POWERFUL COMPUTERS OPEN NEW HORIZONS TO SAFETY AND DESIGN ANALYSES IN NUCLEAR TECHNOLOGY.**
- **FULL TWO-PHASE ‘OPEN-MEDIA’ APPROACH MAY NEED TENS OF YEARS BEFORE REALIZATION.**