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SCALING AND SCALING ROLE WITHIN BEPU APPROACH - The $\mu\lambda$-I^{3}TF

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Nuclear Thermal-Hydraulic Integral Effect Tests

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PREFACE

***BEPU* (Best Estimate Plus Uncertainty) is the key approach for modern NRS (Nuclear Reactor Safety). BEPU took the origin within the nuclear thermal-hydraulics and the Accident Analysis and is ready to cover the overall domain of NRS.**

***Scaling* is one element of BEPU (other than the topic of a recently completed effort in the frame of the OECD/NEA/CSNI).**

As a vision for the future, the conceptual design of a *Thermal-hydraulics Ideal Test Facility (the $\mu\lambda$- I^3 TF)*, consistent with BEPU and scaling findings, is proposed.

OBJECTIVE & LIST OF CONTENT

OBJECTIVE

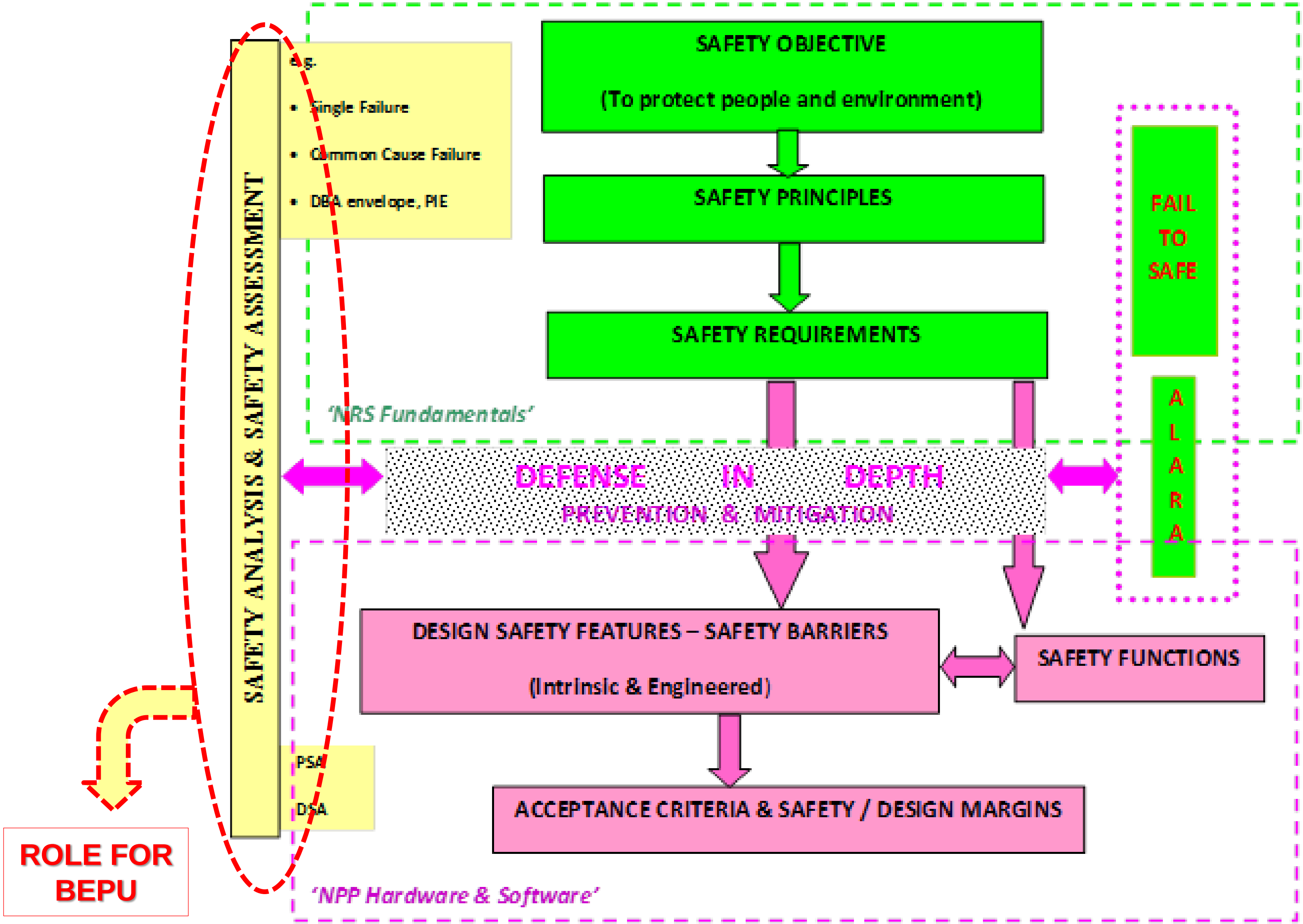
To outline BEPU, Scaling (as one element of BEPU) and the conceptual design of a test facility (as a consequence of BEPU)

LIST OF CONTENTS

- **PART 1: Outline of BEPU**
- **PART 2: Scaling (selected info from the OECD/NEA/CSNI S-SOAR)**
- **PART 3: Conceptual design of the $\mu\lambda$- *I*^{3} *TF***
- **SUMMARY REMARKS**

PART 1 - OUTLINE OF BEPU

THE NRS FRAMEWORK



SAFETY OBJECTIVE

(To protect people and environment)

SAFETY PRINCIPLES

SAFETY REQUIREMENTS

'NRS Fundamentals'

e.g.

- Single Failure
- Common Cause Failure
- DBA envelope, PIE

SAFETY ANALYSIS & SAFETY ASSESSMENT

FAIL TO SAFE

ALARA

DEFENSE IN DEPTH

PREVENTION & MITIGATION

DESIGN SAFETY FEATURES – SAFETY BARRIERS

(Intrinsic & Engineered)

SAFETY FUNCTIONS

ACCEPTANCE CRITERIA & SAFETY / DESIGN MARGINS

PSA

DSA

'NPP Hardware & Software'

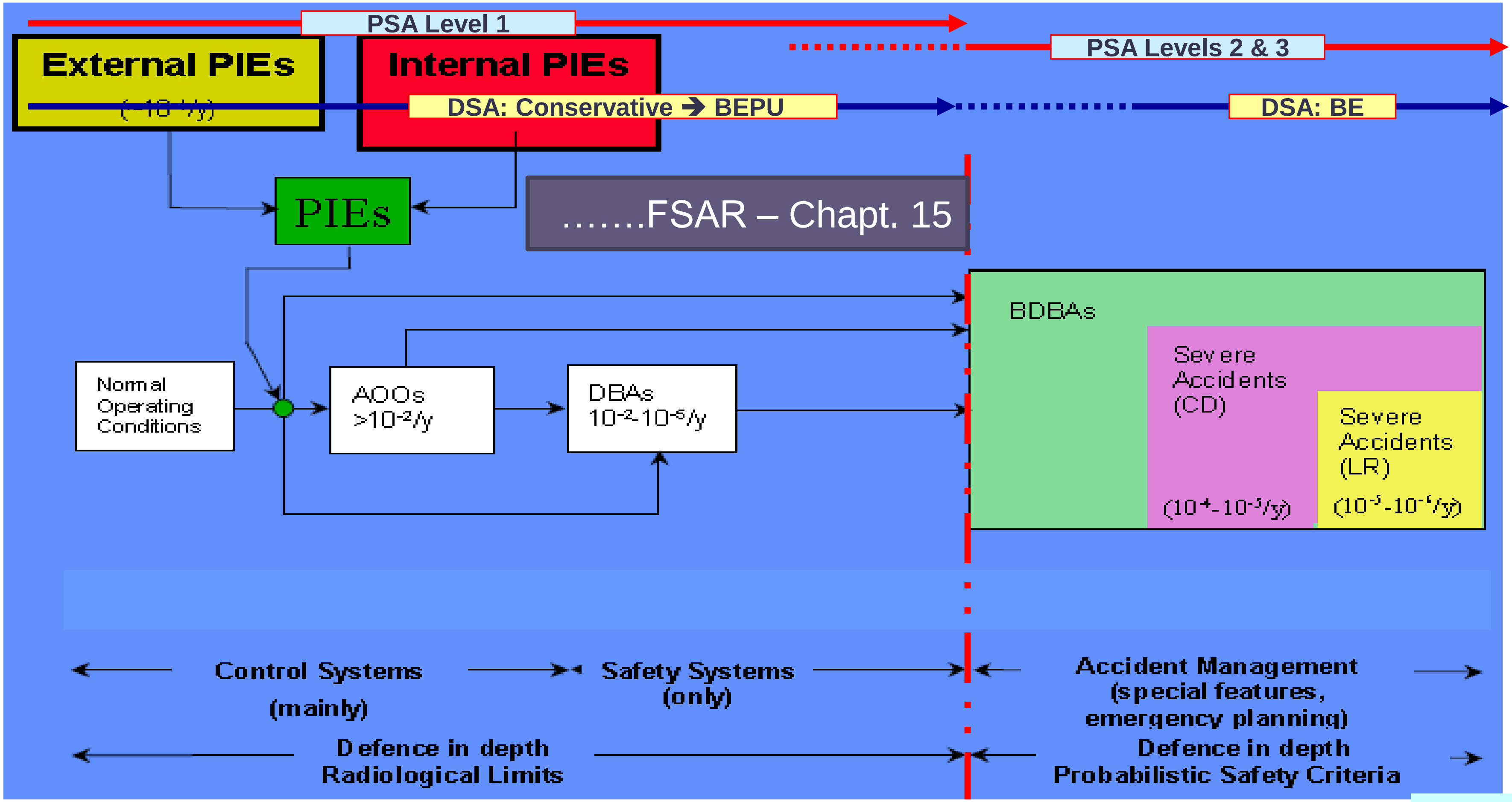
ROLE FOR BEPU

PART 1 - OUTLINE OF BEPU

THE BEPU ORIGIN: NUCLEAR TH & AA

IAEA ‘REGULATORY’ FRAMEWORK (Misak, 2007)

Updated 2011 , 2012, Dusic, D’Auria



PSA Level 1

PSA Levels 2 & 3

External PIEs

($\sim 10^{-1}$/y)

Internal PIEs

DSA: Conservative → BEPU

DSA: BE

PIEs

…….FSAR – Chapt. 15

Normal Operating Conditions

AOOs $>10^{-2}$/y

DBAs 10^{-2}-10^{-6}/y

BDBAs

Severe Accidents (CD)

(10^{-4}-10^{-5}/y)

Severe Accidents (LR)

(10^{-5}-10^{-6}/y)

Control Systems (mainly)

Safety Systems (only)

Accident Management (special features, emergency planning)

Defence in depth Radiological Limits

Defence in depth Probabilistic Safety Criteria

PART 1 - OUTLINE OF BEPU

THE 'SPOT' HISTORY

1970 ← NRC – Interim Acceptance Criteria

← NRC – Appendix K to 10 CFR 50.46

a) OECD/CSNI efforts in the area of code validation (80's).

b) The US NRC CSAU (beginning of 90's) ← NRC – RG 1.157

c) The 'Wilks formula' and the 'accuracy extrapolation' (90's).

d) The UMS study within the OECD/CSNI (end of 90's)

e) The 'Internal Assessment of Uncertainty' (end of 90's) ← Angra-2 BE LB-LOCA

f) The IAEA SRS-52 and SSG-2 (middle of 00's).

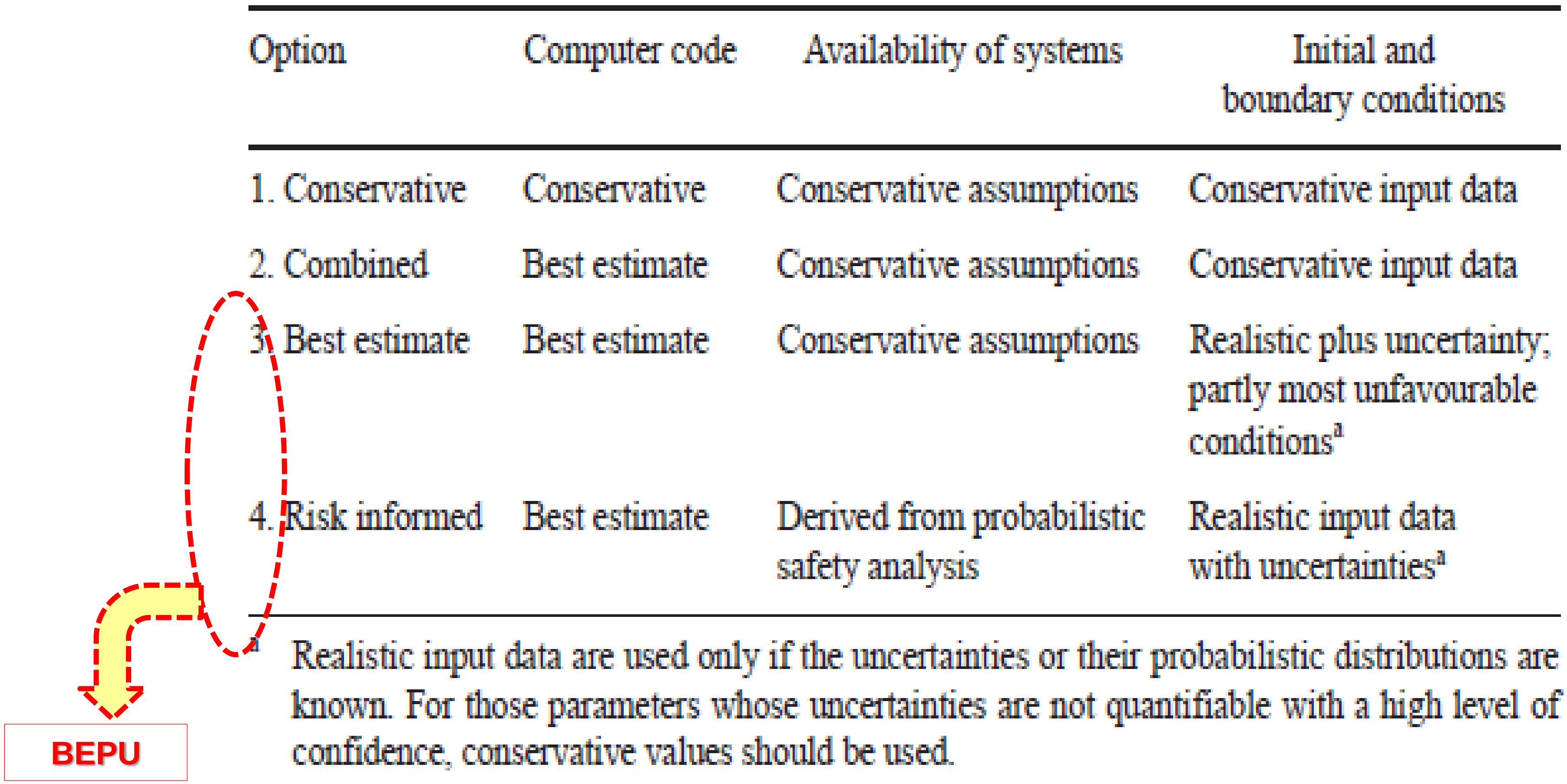
← NRC – RG 1.203

g) The BEMUSE study within the OECD/CSNI (end of 00's)

2010 ← Atucha-2 BEPU Chapter 15

PART 1 - OUTLINE OF BEPU

POSSIBILITIES FOR SAFETY ANALYSIS – IAEA SSG-2, 2010



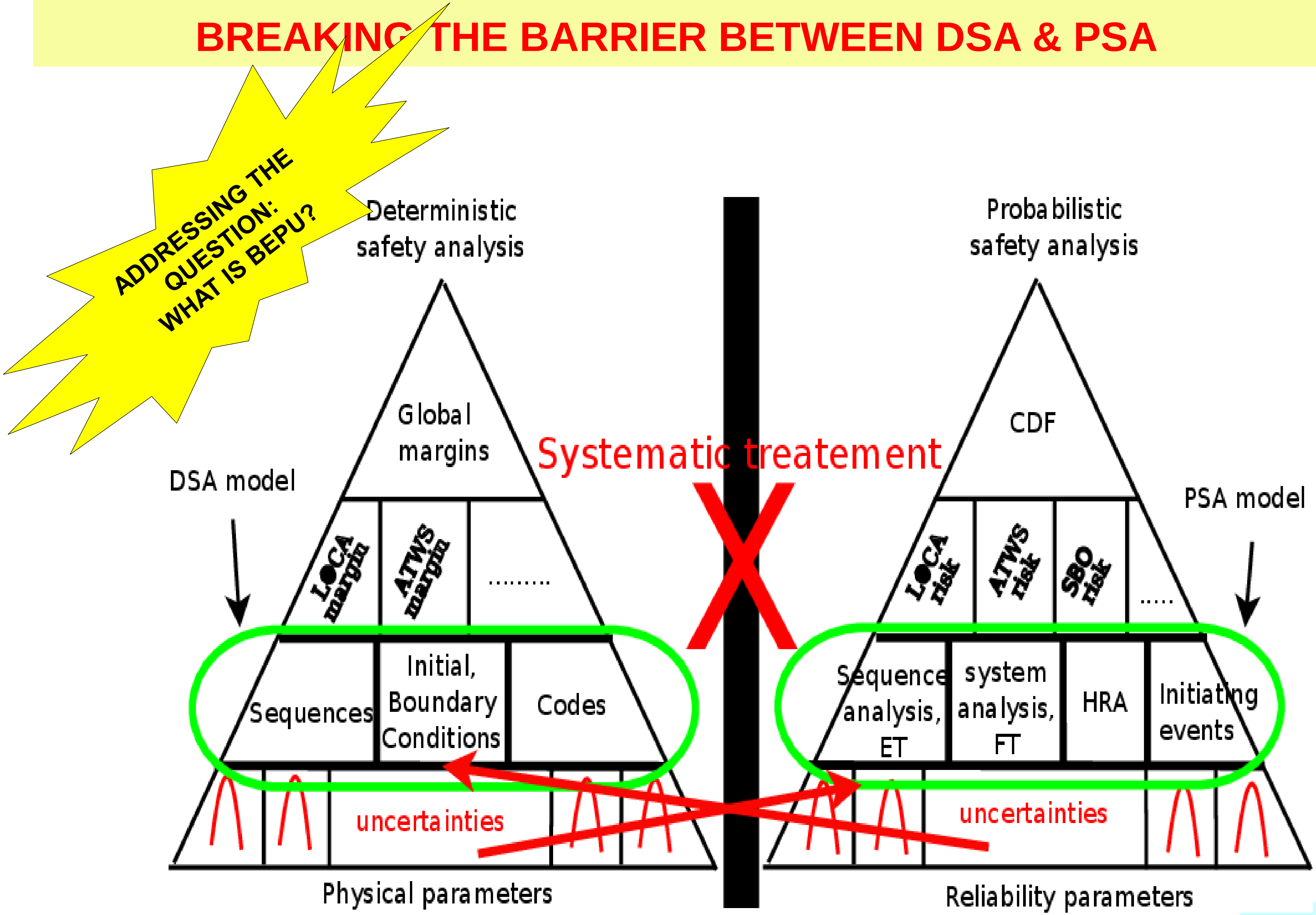
Option	Computer code	Availability of systems	Initial and boundary conditions
1. Conservative	Conservative	Conservative assumptions	Conservative input data
2. Combined	Best estimate	Conservative assumptions	Conservative input data
3. Best estimate	Best estimate	Conservative assumptions	Realistic plus uncertainty; partly most unfavourable conditions[a]
4. Risk informed	Best estimate	Derived from probabilistic safety analysis	Realistic input data with uncertainties[a]

[a] Realistic input data are used only if the uncertainties or their probabilistic distributions are known. For those parameters whose uncertainties are not quantifiable with a high level of confidence, conservative values should be used.

BEPU

PART 1 - OUTLINE OF BEPU

BREAKING THE BARRIER BETWEEN DSA & PSA



ADDRESSING THE QUESTION: WHAT IS BEPU?

PART 1 - OUTLINE OF BEPU

SOME FEATURES – WHAT IS BEPU?

- **The BEPU is a logical process which connects the understanding in NRS (and licensing) with nuclear TH.**

- **The starting point for BEPU are the physical phenomena. This implies the DBA envelope.**

- **BEPU implies the existence of qualified computational tools dealing with different disciplines, input decks or nodalizations and a method to evaluate the uncertainty.**

- **BEPU needs the existence of qualified procedures for the application of the computational tools.**

- **BEPU needs the existence of qualified code users and of maven capable of evaluating the acceptability of analysis.**

- **BEPU needs the existence of ’legal’ acceptance criteria.**

- **The application of BEPU implies the knowledge of the licensing process.**

- **The structure of the FSAR must be adapted to BEPU including the design of the core, the experimental data drawn during the commissioning, the design of EOP, etc.**

- **Any BEPU report should be a living document.**

BEPU
≡
ALARA

PART 1 - OUTLINE OF BEPU

CONSTITUTIVE ELEMENTS (some of)

- ✓ Computational tools / SYS TH codes – design and development
- ✓ Computational tools / SYS TH codes – V & V procedures
- ✓ Computational tools / SYS TH codes – procedures for application
- ✓ Computational tools / nodalizations (or input decks) – development
- ✓ Computational tools /nodalizations – V & V procedures
- ✓ Computational tools / code-coupling software – design and development
- ✓ Uncertainty methods / design and development
- ✓ Uncertainty methods / qualification procedures
- ✓ NPP parameters database
- ✓ Postulated Initiating Events (PIE)
- ✓ Phenomena / physical aspects which characterize PIE
- ✓ Databases for code and nodalization qualification
- ✓ Scaling demonstration / procedures and database
- ✓ Users of computational tools / qualification
- ✓ DSA – PSA integration
- ✓ Instrumentation and Control (I & C) modeling
- ✓ Documentation requirements for each elements
- ✓ Licensing framework – acceptance criteria, safety margins, procedures, etc.

V & V *; UNC;

COUPLING*; DB*;

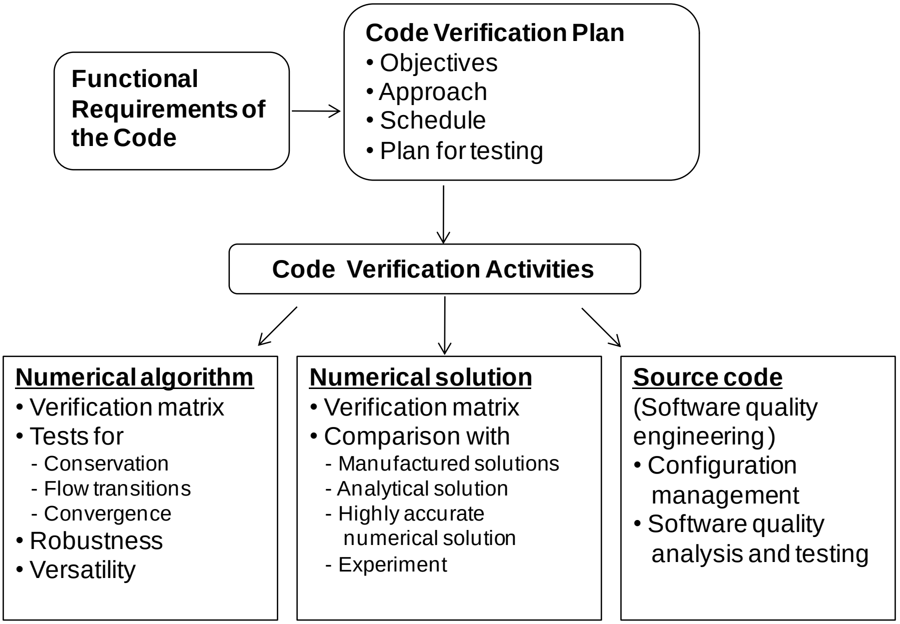
SCALING **

*** slides below**
**** PART 2**

ADDRESSING THE QUESTION: WHAT IS BEPU?

PART 1 - OUTLINE OF BEPU
V & V

VERIFICATION
ESTABLISHED QA PRACTICE



Functional Requirements of the Code

Code Verification Plan
- Objectives
- Approach
- Schedule
- Plan for testing

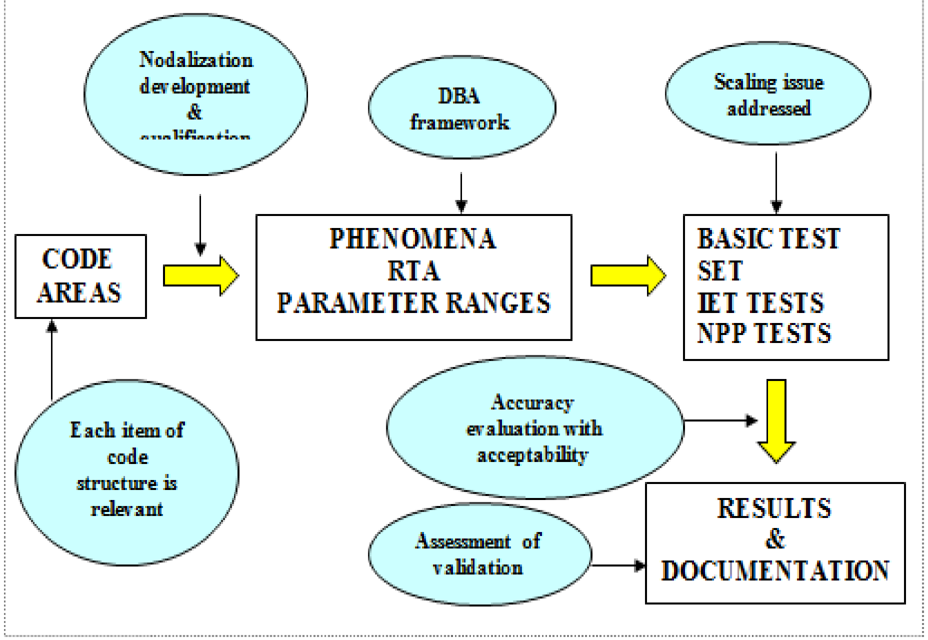
Code Verification Activities

Numerical algorithm
- Verification matrix
- Tests for
  - Conservation
  - Flow transitions
  - Convergence
- Robustness
- Versatility

Numerical solution
- Verification matrix
- Comparison with
  - Manufactured solutions
  - Analytical solution
  - Highly accurate numerical solution
  - Experiment

Source code
(Software quality engineering)
- Configuration management
- Software quality analysis and testing

VALIDATION: STARTING FROM
SETF & ITF CCVM + FFTBM FOR ACCURACY QUANTIFICATION



MORE RECENT CONCEPTS:

- ➢ **ASSESSMENT OF VALIDATION**
- ➢ **(MINIMUM) INDEPENDENT ASSESSMENT FOR CODE USER**

PART 1 - OUTLINE OF BEPU

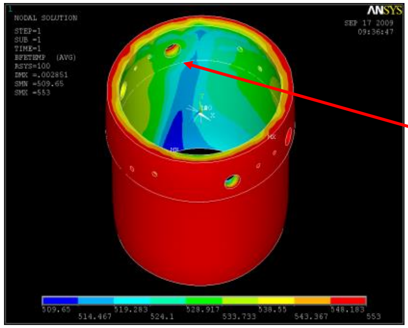
(CODE) COUPLING

Fracture Mechanics

The **crack shape** is assumed elliptical (two-dimensional crack) and the dimensions are taken from the ASME XI:

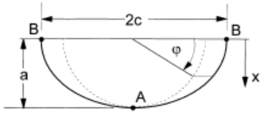
No.	Wall thickness (mm)	Crack depth (mm)	Crack length (mm)
1	102 – 305	¼ Wall thickness	½ Wall thickness
2	> 305	¼ (305)	½ (305)
3	< 102	¼ (102)	½ (102)

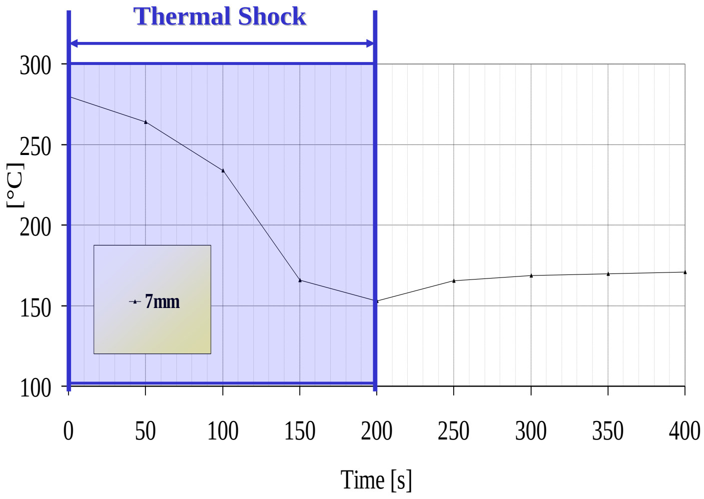
Crack position



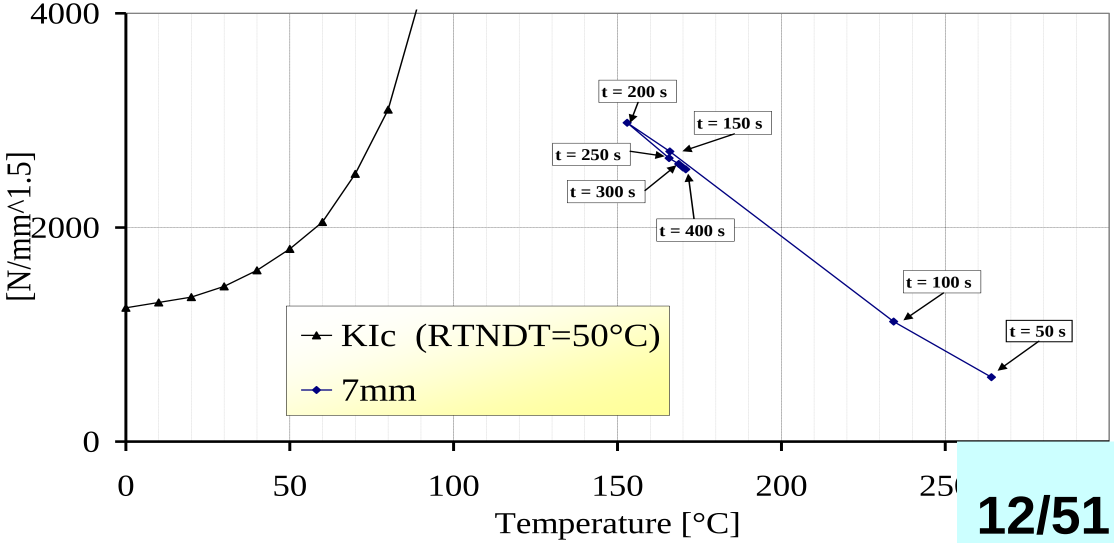
RPV wall thickness = 290 mm

a = Crack Depth ~ 7 mm





Temperature at crack tip



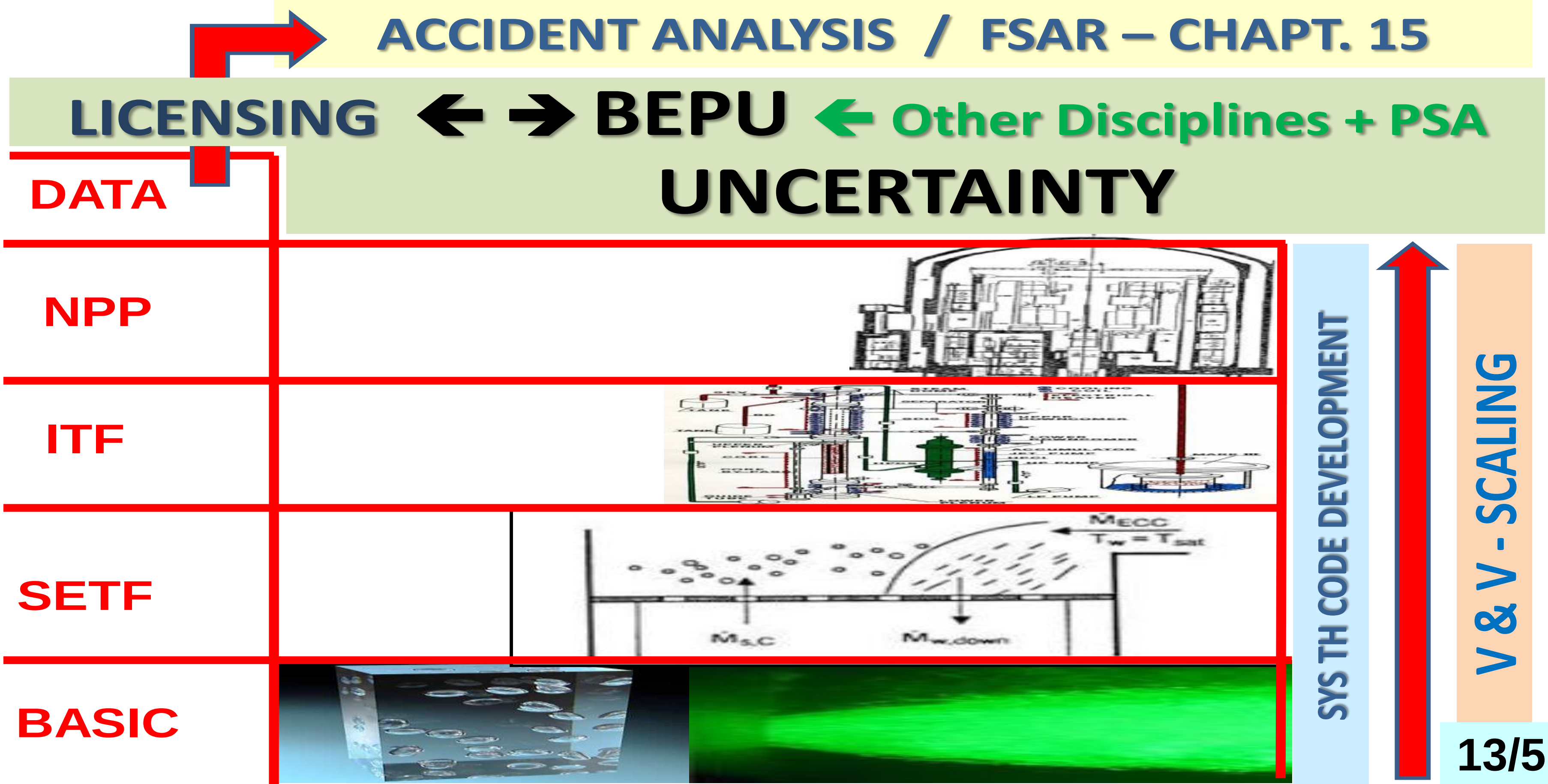
KEY
RESULT ➔

PART 1 - OUTLINE OF BEPU

(TH) DATABASE

THE PROCESS

We are here!



ACCIDENT ANALYSIS / FSAR – CHAPT. 15

LICENSING ← → BEPU ← Other Disciplines + PSA

UNCERTAINTY

DATA

NPP

ITF

SETF

BASIC

SYS TH CODE DEVELOPMENT

V & V - SCALING

PART 1 - OUTLINE OF BEPU

THE ENVISAGED FUTURE

… BEYOND (current) BEPU

TO APPLY THE [TH] BEPU TECHNOLOGY
(V & V – SCALING – UNCERTAINTY – CODE COUPLING – PSA …)
TO ANY ANALYSIS NEEDED FOR NPP SAFETY

We may go there!

BEPU – (I) FSAR

PART 2 – SCALING

Background (Definition) & Scope

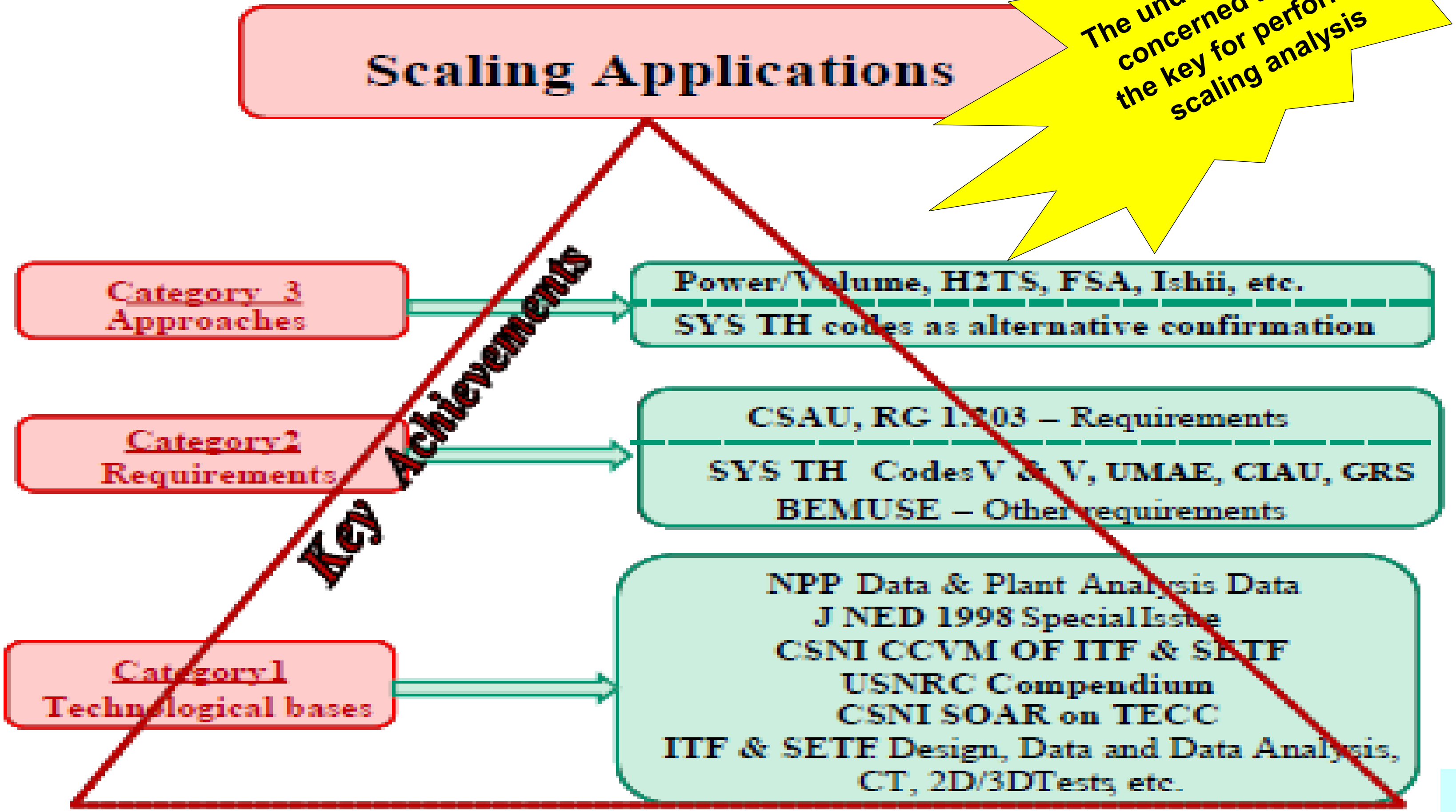
‘Scaling’, ‘scaling issue’ and ‘addressing the scaling issue’ indicate the actions, the methods and the approaches aimed at connecting the parameter values related to experiments with Nuclear Power Plant conditions; the subject parameter values are applicable and qualified under the reduced-scale conditions; the reduced-scale conditions imply values of geometry, pressure, or power, or combinations, smaller than the values characterizing the NPP conditions. Scaling is the process of converting any plant parameters at reactor conditions to those either in experiments or in numerical code results in order to reproduce the dominant prototype phenomena in the model. Scaling issue indicates the difficulty and complexity of the process and the variety of connected aspects. Addressing the scaling issue refers to a process of demonstrating the applicability of those actions performed in scaling.

The scaling-issue arises from the impossibility of obtaining transient data from the prototype system under off-nominal conditions.

The scope is restricted to reactors that use water as coolant in design conditions and in transients that occur before the loss of the core geometric integrity (DBA).

PART 2 – SCALING

The Database of Scaling Knowledge



Scaling Applications

Key Achievements

Category 3
Approaches

Power/Volume, H2TS, FSA, Ishii, etc.
SYS TH codes as alternative confirmation

Category2
Requirements

CSAU, RG 1.203 – Requirements
SYS TH Codes V & V, UMAE, CIAU, GRS
BEMUSE – Other requirements

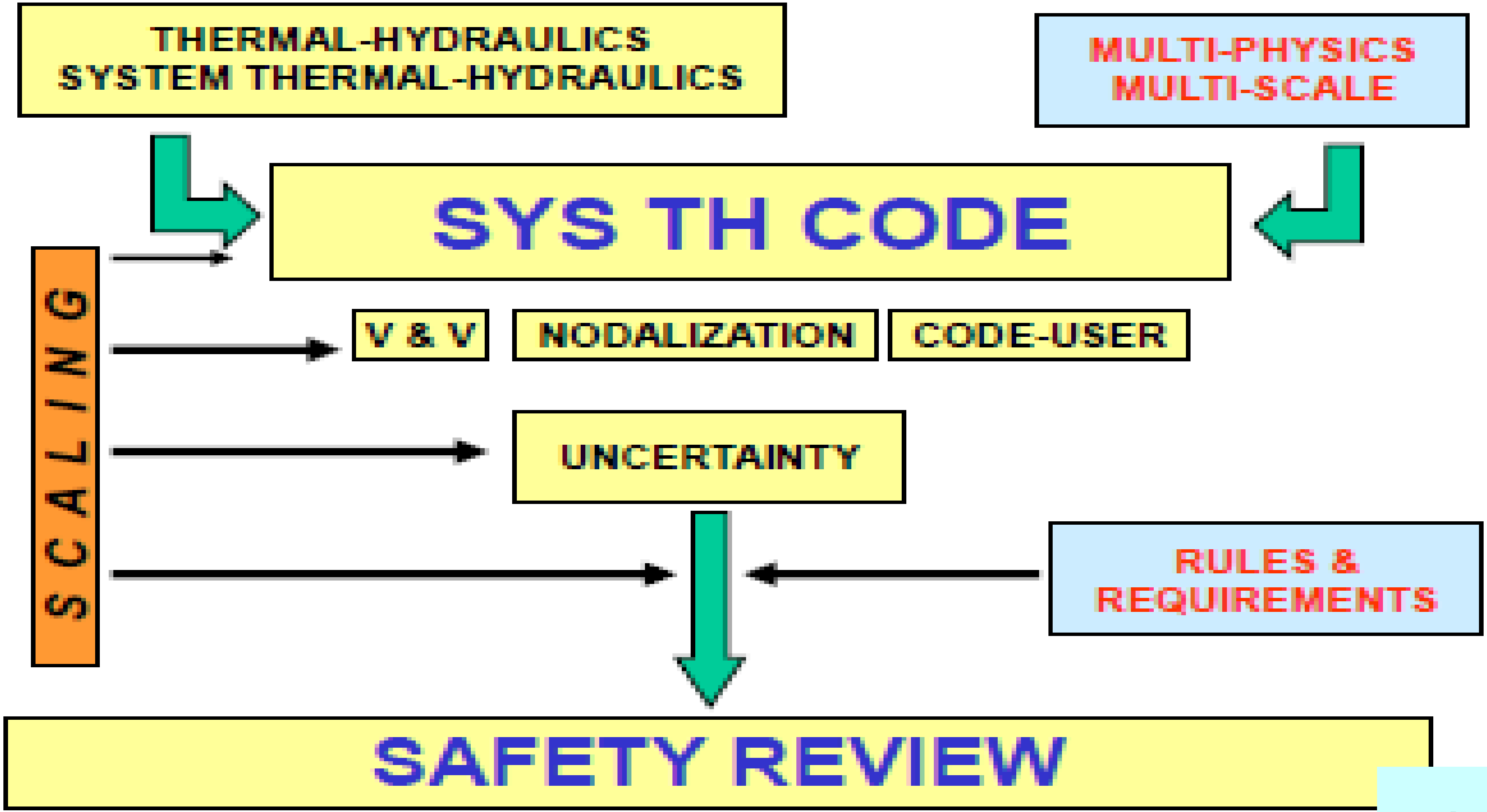
Category1
Technological bases

NPP Data & Plant Analysis Data
J NED 1998 Special Issue
CSNI CCVM OF ITF & SETF
USNRC Compendium
CSNI SOAR on TECC
ITF & SETF Design, Data and Data Analysis,
CT, 2D/3DTests, etc.

The understaanding of concerned topics is the key for performing scaling analysis

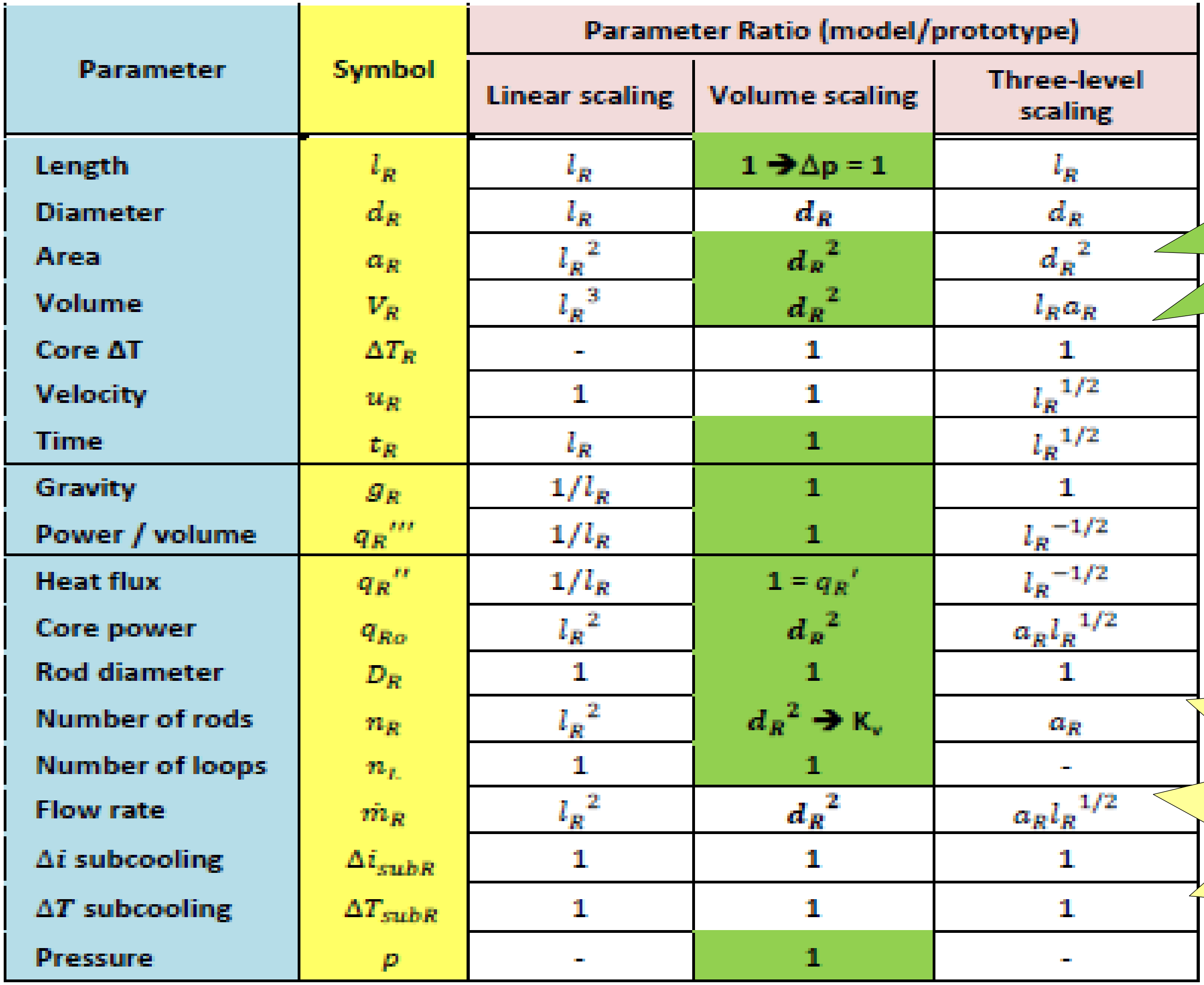
PART 2 – SCALING

The Role of Scaling in SYS TH code Application



PART 2 – SCALING

Linear-Scaling; Volume-Scaling; Three-level Scaling



Parameter	Symbol	Parameter Ratio (model/prototype)		
		Linear scaling	Volume scaling	Three-level scaling
Length	l_R	l_R	1 ➔ $\Delta p = 1$	l_R
Diameter	d_R	l_R	d_R	d_R
Area	a_R	$l_R{}^2$	$d_R{}^2$	$d_R{}^2$
Volume	V_R	$l_R{}^3$	$d_R{}^2$	$l_R a_R$
Core ΔT	ΔT_R	-	1	1
Velocity	u_R	1	1	$l_R{}^{1/2}$
Time	t_R	l_R	1	$l_R{}^{1/2}$
Gravity	g_R	$1/l_R$	1	1
Power / volume	q_R'''	$1/l_R$	1	$l_R{}^{-1/2}$
Heat flux	q_R''	$1/l_R$	$1 = q_R'$	$l_R{}^{-1/2}$
Core power	q_{Ro}	$l_R{}^2$	$d_R{}^2$	$a_R l_R{}^{1/2}$
Rod diameter	D_R	1	1	1
Number of rods	n_R	$l_R{}^2$	$d_R{}^2$ ➔ K_v	a_R
Number of loops	n_L	1	1	-
Flow rate	$\dot{m}_R$	$l_R{}^2$	$d_R{}^2$	$a_R l_R{}^{1/2}$
Δ*i* subcooling	Δi_{subR}	1	1	1
Δ*T* subcooling	ΔT_{subR}	1	1	1
Pressure	p	-	1	-

Design Scaling Factors in green cells

Full height full pressure Volume(-to –Power) Scaling adopted in major (most expensive) test Programs

PART 2 – SCALING

(start of) Use of complex balance equations (1983)

Three-level Scaling (Ishii-1983)

Level 1: an integral or a global-scaling analysis to conserve the $1\!-\!\Phi$ and $2\!-\!\Phi$ NC flow

$1\!-\!\Phi$

ber, $$T_i^* \equiv \left[\frac{l_o/u_o}{\delta^2/\alpha_s}\right]_i = \frac{\text{Transport time}}{\text{Conduction time}}$$

$$Bi_i \equiv \left[\frac{h\delta}{k_s}\right]_i = \frac{\text{Wall convection}}{\text{Conduction}}$$

$2\!-\!\Phi$

$$N_{thi} \equiv \left[\frac{f_w l}{d}\right]_i \left[\frac{1+x(\Delta\rho/\rho_g)}{(1+x\Delta\mu/\mu_g)^{0.25}}\right]\left[\frac{a_o}{a_i}\right]^2$$

$$N_{pch} \equiv \left[\frac{4q_o'''\delta l_o}{d u_o \rho_f i_{fg}}\right]\left[\frac{\Delta\rho}{\rho_g}\right]$$

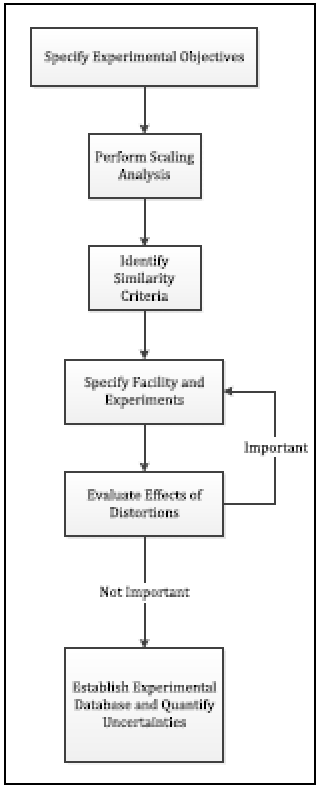
1) **DIFFERENT SCALING FACTORS FOR 1-Φ AND 2-Φ NC FLOWS**

2) **COMPROMISES NEEDED**

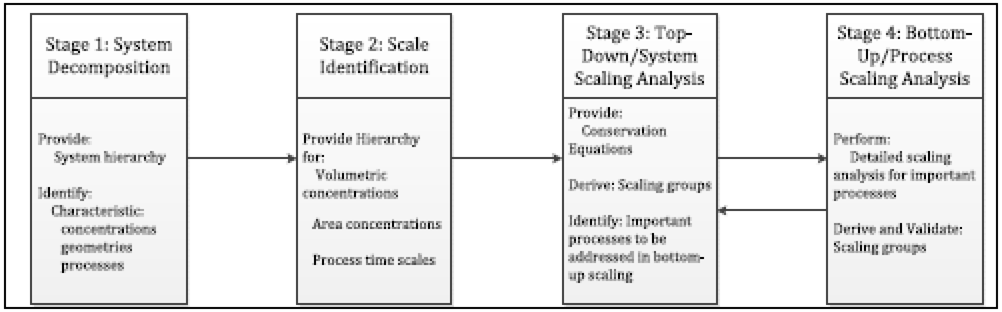
PART 2 – SCALING

H2TS (Zuber-1991)

THE FRAMEWORK



THE TWO TIERS



Stage 1: System Decomposition

Provide:
System hierarchy

Identify:
Characteristic:
concentrations
geometries
processes

Stage 2: Scale Identification

Provide Hierarchy for:
Volumetric concentrations

Area concentrations

Process time scales

Stage 3: Top-Down/System Scaling Analysis

Provide:
Conservation Equations

Derive: Scaling groups

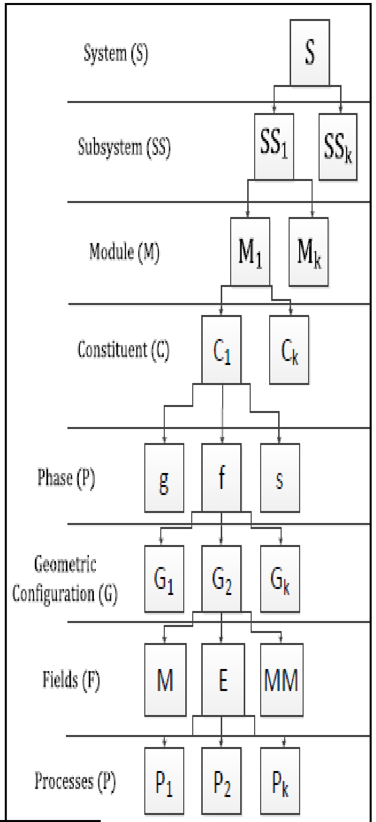
Identify: Important processes to be addressed in bottom-up scaling

Stage 4: Bottom-Up/Process Scaling Analysis

Perform:
Detailed scaling analysis for important processes

Derive and Validate: Scaling groups

THE SYSTEM DECOMPOSITION



For constituent C in phase P in geometrical configuration G (e.g., liquid in a certain configuration - film, droplet, jet, etc. - in a certain location within a CV):

THE VOLUME (V) FRACTION
THE CHARACTERISTIC V SPATIAL SCALE
THE CHARACTERISTIC V TIME CONSTANT & FREQUENCY

$$\frac{V_{CPG}}{V_{CV}} = \alpha_C \alpha_{CP} \alpha_{CPG}$$

$$\frac{A_{CPG}}{V_{CV}} = \alpha_C \alpha_{CP} \alpha_{CPG} \frac{1}{L_{CPG}}$$

$$\tau_{CV} = \frac{V_{CV}}{\dot{V}} = \frac{1}{\omega_{CV}}$$

PART 2 – SCALING

H2TS (Zuber-1991)

The characteristic area (A) frequency inside a V (ωCPG) is connected with the frequency of a specific process (ωi) in order to establish the hierarchy of the temporal scale,

$$\omega_i = \frac{j_i A_{CPG}}{\psi V_{CV}} = \alpha_C \alpha_{CP} \alpha_{CPG} \frac{j_i}{\psi} \frac{1}{L_{CPG}} = \alpha_C \alpha_{CP} \alpha_{CPG} \omega_{CPG}$$

Key-1 step of the H2TS: in a subscale facility that maintains temporal similarity with respect to the process

$$\Pi_i = \frac{\tau_{CV}}{\tau_i} = \omega_i \tau_{CV}$$

$$(\Pi_i)_M = (\omega_i \tau_{CV})_M = (\omega_i \tau_{CV})_P = (\Pi_i)_P \text{ or}$$

$$\left[\frac{(\omega_i \tau_{CV})_M}{(\omega_i \tau_{CV})_P}\right]_R = 1$$

Definition of distortion

$$DF = \frac{(\Pi_i)_P - (\Pi_i)_M}{(\Pi_i)_P}$$

PART 2 – SCALING

FSA (Zuber-2005)

For a given phenomenon inside a Control Volume, one may define:

AOC = Φ = dF / dt (if concerned variable F is the momentum, AOC is the force)

Characteristic time, t_{ref} *(from exp or from aggregate frequency using different AOC)*

FRC (fractional rate of change), ω_i, (from AOC and t_{ref})

λ_i = Characteristic or turnover length

Namely,

Equivalent to $\Pi_{i,k}$ in H2TS

$$\omega_i = 1/F \bullet dF/dt = \Phi / F; \qquad \lambda_i = F / A; \qquad \Omega_i = \omega_i \bullet t_{ref}$$

***where A is the signal transfer area; λ and Ω are also called effect metrics*.**

In nuclear thermal-hydraulics:

- *Control Volume is a well established concept which contributes to the key (scaling) issue of averaging*

PART 2 – SCALING

FSA (Zuber-2005)

The FSA paradigm

Processes having the same effect metric Ω are similar*: their state variables have been changed by the same fractional amount. *[Process time and FRC (ωi) are not necessarily preserved]*.

For instance, in the case of rod cooling, ωi (and Ωi) results to be a function of HTC.

If the value of HTC or the expression of HTC is approximate, the FSA will not reveal this (HTC and related error can be different at different scales). Comparison with experimental data needed (this may not be an output of the FSA application). Definitely, FSA processes established information: it provides a different view on existing information

**In nuclear thermal-hydraulics (as well as in any safety-technology science) any paradigm (any assumption) should be connected with a validation process*

PART 2 – SCALING

DSS (Reyes-2015)

Origin of Dynamic System Scaling (DSS)

To overcome the limitation of Πi (H2TS) and Ωi (FSA) which are generated point-wise in time (even though at different times). The DSS with similar origin of H2TS and FSA is proposed trying to incorporate the dynamic response of a thermal-hydraulic process into the scaling framework.

Variables at the basis of DSS

$$\beta(t)=\frac{1}{\Psi_o}\iiint_V \psi(\vec{x},t)\,dV$$

Non-dimensional, formally corresponding to Πi in H2TS

β

$$\frac{d\beta}{dt}=\omega$$

Formally corresponding ωi in FSA

ω

$\beta/\omega=\tau$; and **t**

Characteristic time (see tref in FSA) and clock time

τ

$$D=\frac{d\tau-dt}{dt}$$

Time ratio, such that $\tau_2-\tau_1=\int_{t_1}^{t_2}(1+D)\,dt$

PART 2 – SCALING

DSS (Reyes-2015)

The DSS paradigm from the comparison with H2TS and FSA

To overcome the limitation of Πi (H2TS) and Ωi (FSA) which are generated point-wise in time (even though at different times). The DSS (similar origin of H2TS and FSA) incorporates the dynamic response of a system.

BALANCE EQUATIONS

H2TS: Π & DF	FSA: ω & Ω	DSS: β, ω, & τ
$\frac{d\Psi^+}{dt^+} = \varphi^+_{i,\max} + \sum_{i=1}^{n} \frac{\omega_{FRC,i,0}}{\omega_{FRC,\max}} \varphi_i^+$	$\frac{d\Psi^+}{d\Omega_{FSA,e}} = \varphi_e^*$	$\frac{d\beta}{d\tilde{t}} = \tilde{\Omega}$

The importance ranking in FSA is performed by relating the individual FRC's to the effective FRC. The effect metric, $\Omega_{FSA,e}$ is used to create the similarity criteria since it captures the relationship of all the agents-of-change.

However the effect metric is still a static quantity which depends only on fixed reference values chosen by the analyst and does not account for the evolution and relationship between the different agents-of-change through time.

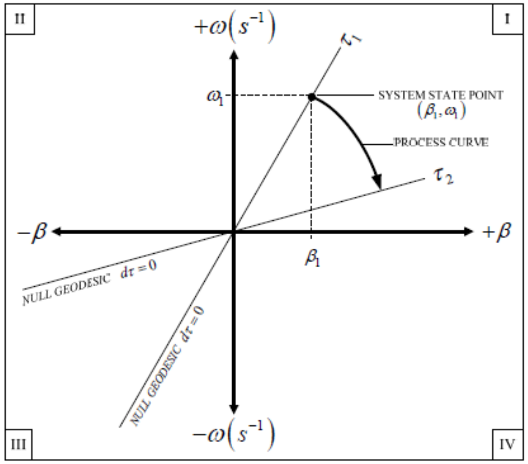
The main differentiator between the DSS and H2TS/FSA is the consideration of the dynamic aspect. DSS defines the dimensionless (normalized) time by dividing time by the action, τ_S, which is defined as the integral of the temporal displacement rate, D, over the transient:

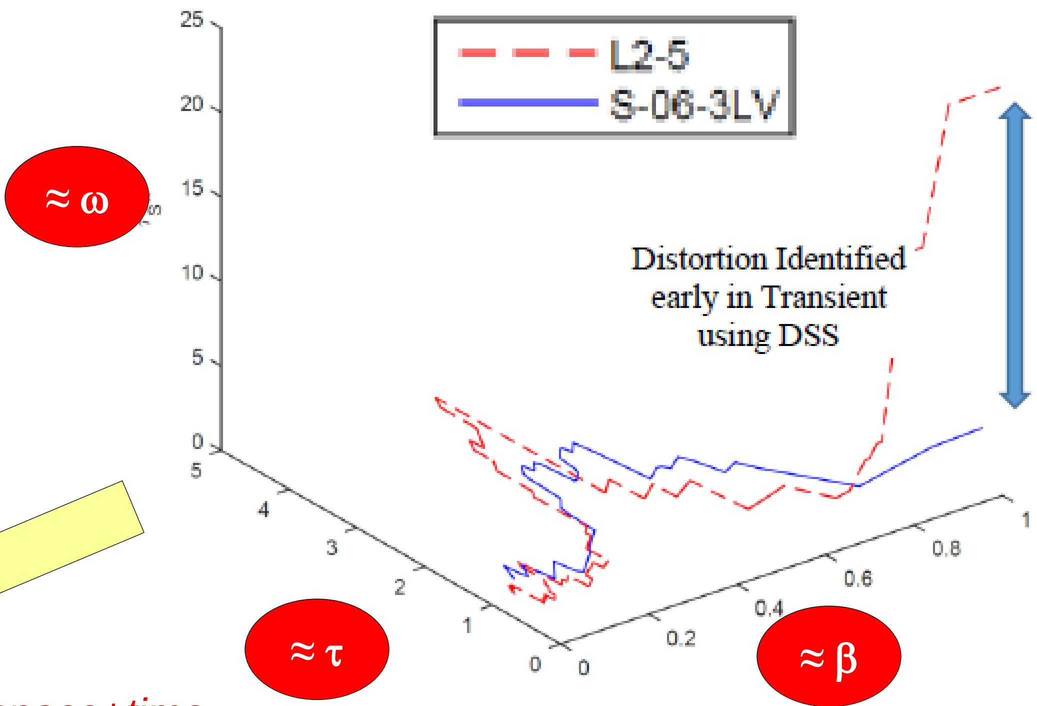
PART 2 – SCALING

DSS (Reyes-2015)

The DSS paradigm

The system moves in the space β, ω, τ: similarity ←→ equivalence of trajectories.





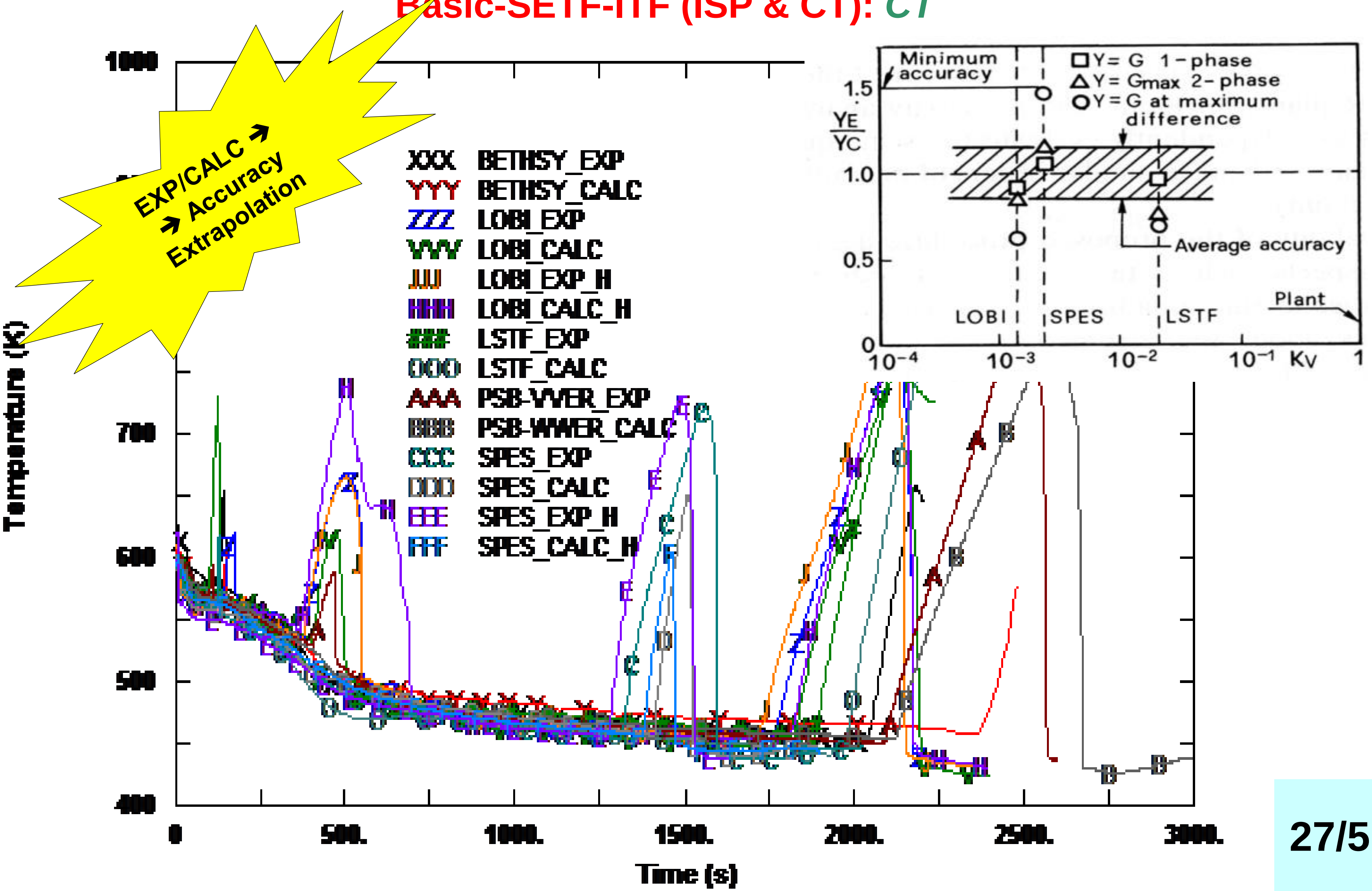
Distortion Identified early in Transient using DSS

Distortions identified in the phase-space+time. The phase-space+time concept already utilized in CIAU (2000) to characterize the error in the comparison exp-calc.

Open issue: consequences from identification of distortions

PART 2 – SCALING

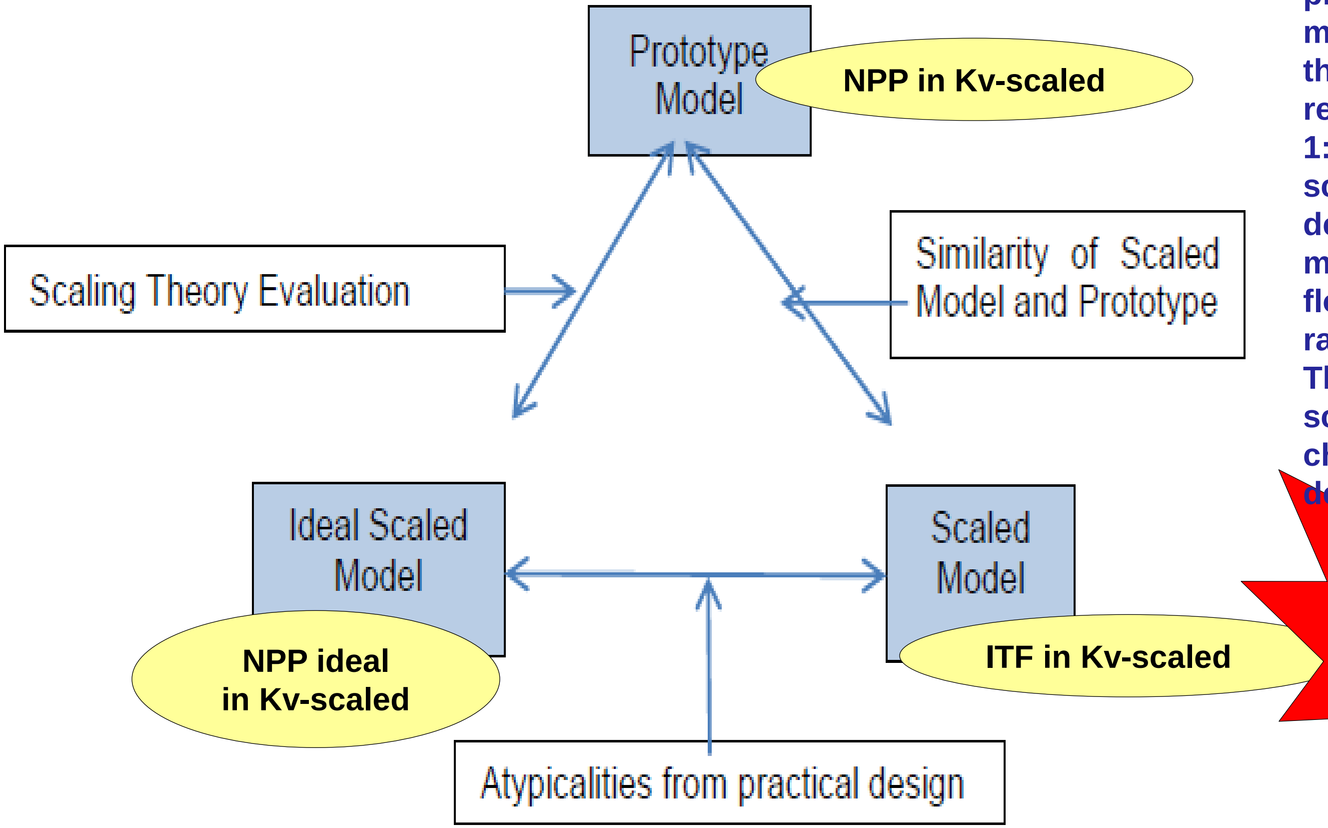
Basic-SETF-ITF (ISP & CT): *CT*



EXP/CALC → Accuracy → Extrapolation

PART 2 – SCALING

Nodalization & Code Scaling-up capability
Flash idea for Triad method (1998)



APPLICATION

The Relap5 code was used to calculate MSLB to compare the prototype and the ideal scaled model. Initial calculations showed that the scaling ratio of the reactor’s response time was not (or close) to 1: 2 as from the design obtained by a scaling method. the pressure decrease in the scaled model is much faster than expected. When the flow was choked, the areal scaling ratio needed special consideration. This condition resulted in a flow area scale ratio of 1: 200 at the location of choked flow, rather than 1: 100 as determined from the scaling method.

This shows how/why a code is more powerful than a scaling method

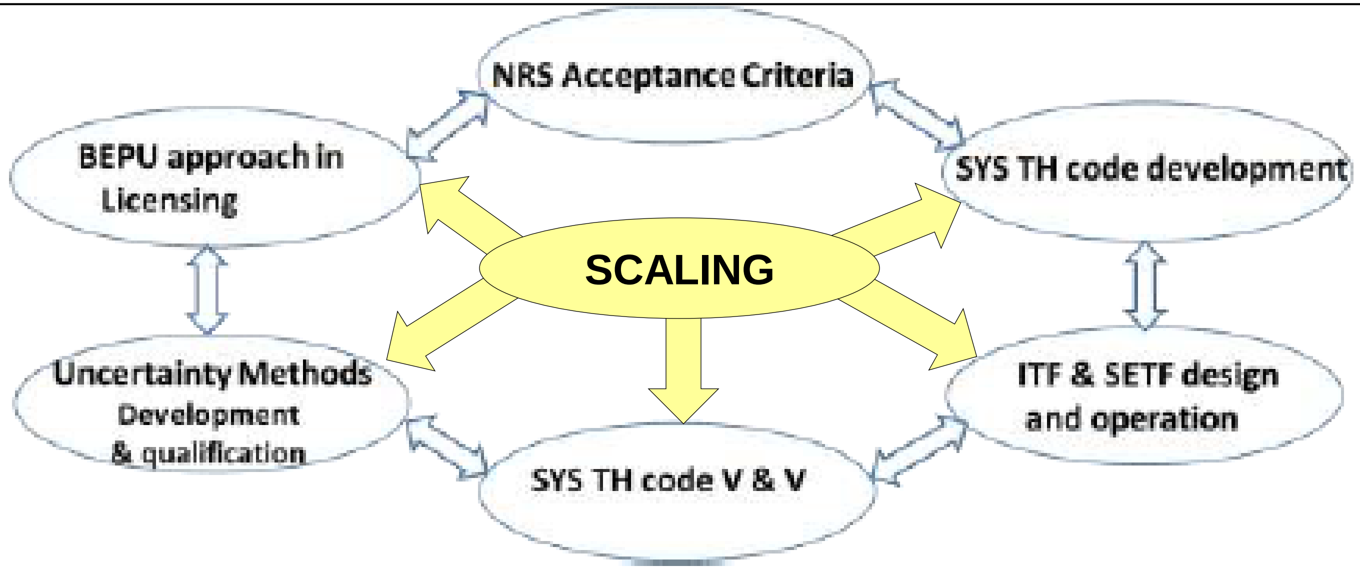
PART 2 – SCALING

V & V, Scaling and Code Application ➔ Uncertainty

Scaling has a key role in Uncertainty Methods

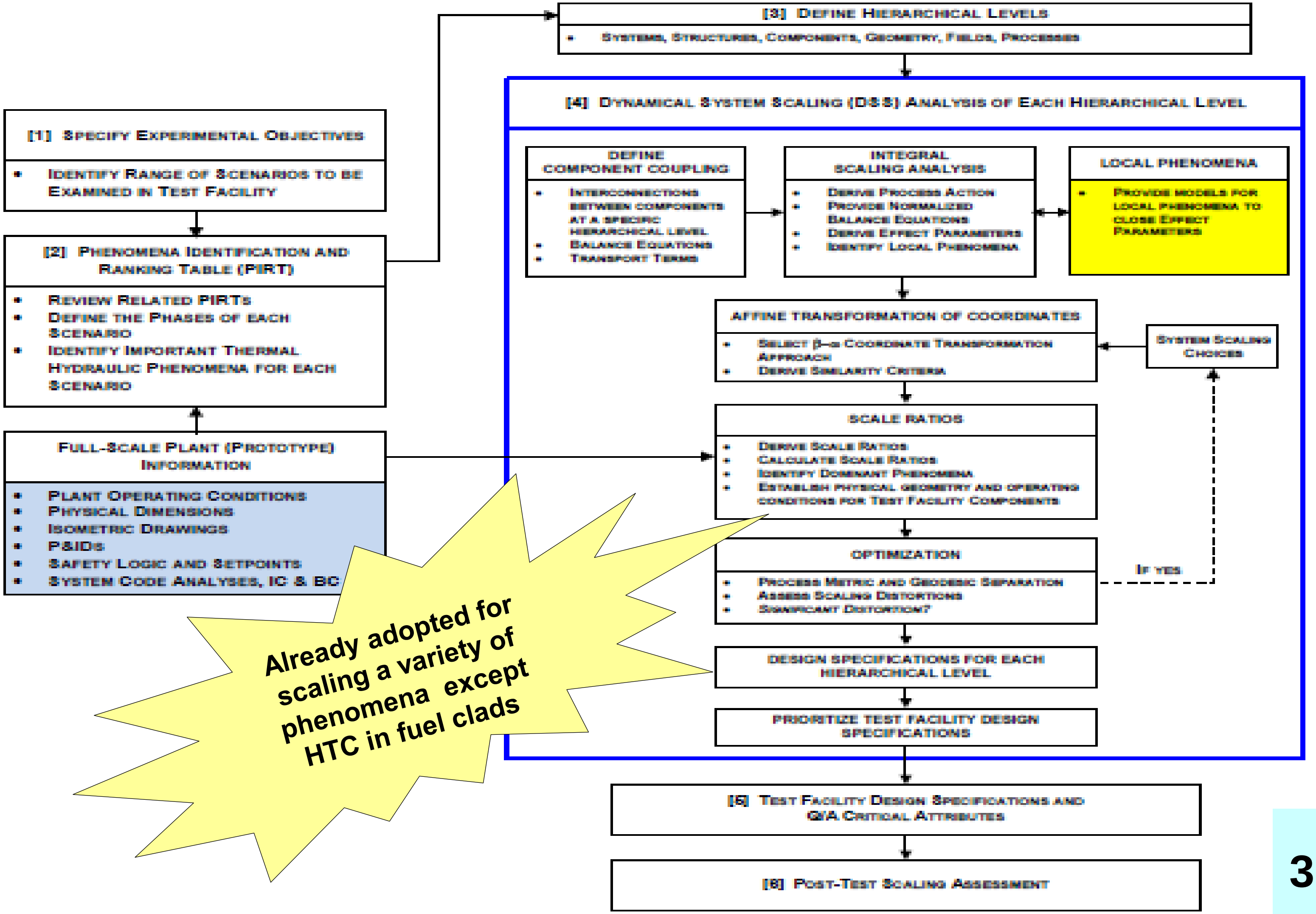
The description of Uncertainty Methods outside the framework for S-SOAR. However, attention given to the connection Scaling/Uncertainty.

Hereafter, the framework for code application to NRS (with role for scaling)



PART 2 – SCALING

*The DSS-based scaling roadmap for ITF/SETF design – Chapter 3**



[1] Specify Experimental Objectives
- Identify Range of Scenarios to be Examined in Test Facility

[2] Phenomena Identification and Ranking Table (PIRT)
- Review Related PIRTs
- Define the Phases of each Scenario
- Identify Important Thermal Hydraulic Phenomena for each Scenario

Full-Scale Plant (Prototype) Information
- Plant Operating Conditions
- Physical Dimensions
- Isometric Drawings
- P&IDs
- Safety Logic and Setpoints
- System Code Analyses, IC & BC

[3] Define Hierarchical Levels
- Systems, Structures, Components, Geometry, Fields, Processes

[4] Dynamical System Scaling (DSS) Analysis of Each Hierarchical Level

DEFINE COMPONENT COUPLING
- Interconnections between components at a specific hierarchical level
- Balance Equations
- Transport Terms

INTEGRAL SCALING ANALYSIS
- Derive Process Action
- Provide Normalized Balance Equations
- Derive Effect Parameters
- Identify Local Phenomena

LOCAL PHENOMENA
- Provide models for local phenomena to close Effect Parameters

AFFINE TRANSFORMATION OF COORDINATES
- Select β–α Coordinate Transformation Approach
- Derive Similarity Criteria

System Scaling Choices

SCALE RATIOS
- Derive Scale Ratios
- Calculate Scale Ratios
- Identify Dominant Phenomena
- Establish physical geometry and operating conditions for Test Facility Components

OPTIMIZATION
- Process Metric and Geodesic Separation
- Assess Scaling Distortions
- Significant Distortion?

If yes

DESIGN SPECIFICATIONS FOR EACH HIERARCHICAL LEVEL

PRIORITIZE TEST FACILITY DESIGN SPECIFICATIONS

[5] Test Facility Design Specifications and Q/A Critical Attributes

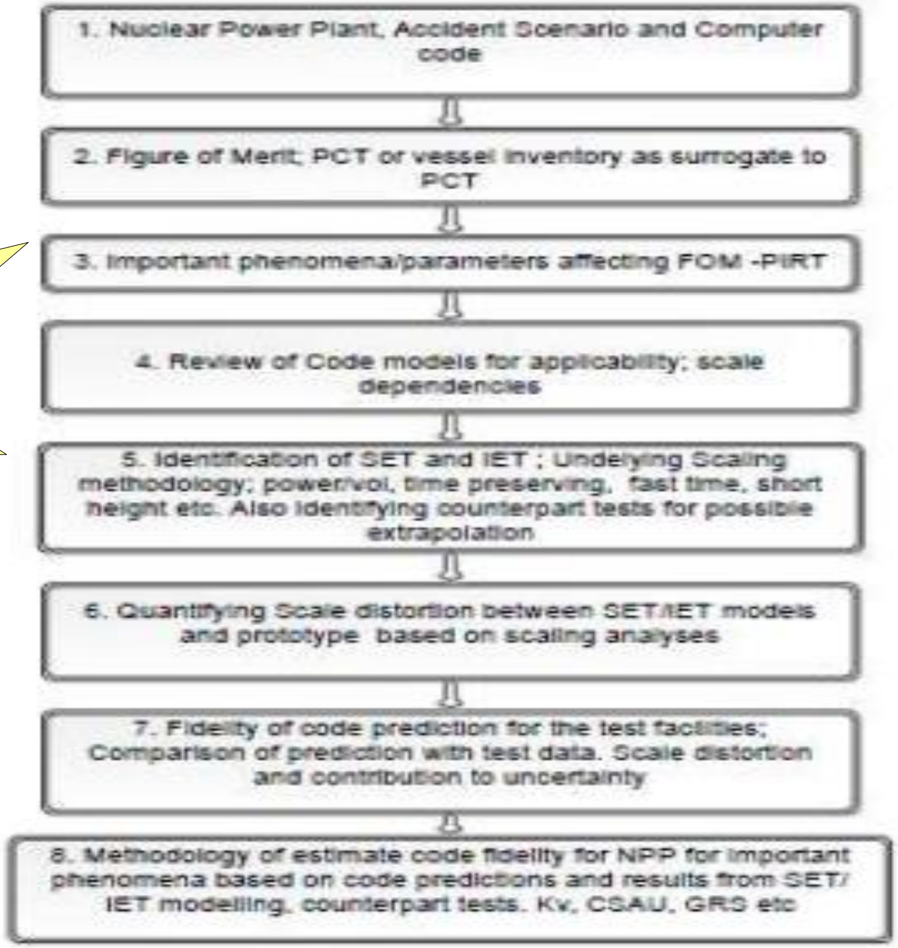
[6] Post-Test Scaling Assessment

Already adopted for scaling a variety of phenomena except HTC in fuel clads

PART 2 – SCALING

*The CSAU based scaling roadmap in NRS – Chapter 4**

See also
H2TS
CSAU
EMDAP



1. Nuclear Power Plant, Accident Scenario and Computer code

2. Figure of Merit; PCT or vessel inventory as surrogate to PCT

3. Important phenomena/parameters affecting FOM -PIRT

4. Review of Code models for applicability; scale dependencies

5. Identification of SET and IET ; Underlying Scaling methodology; power/vol, time preserving, fast time, short height etc. Also identifying counterpart tests for possibile extrapolation

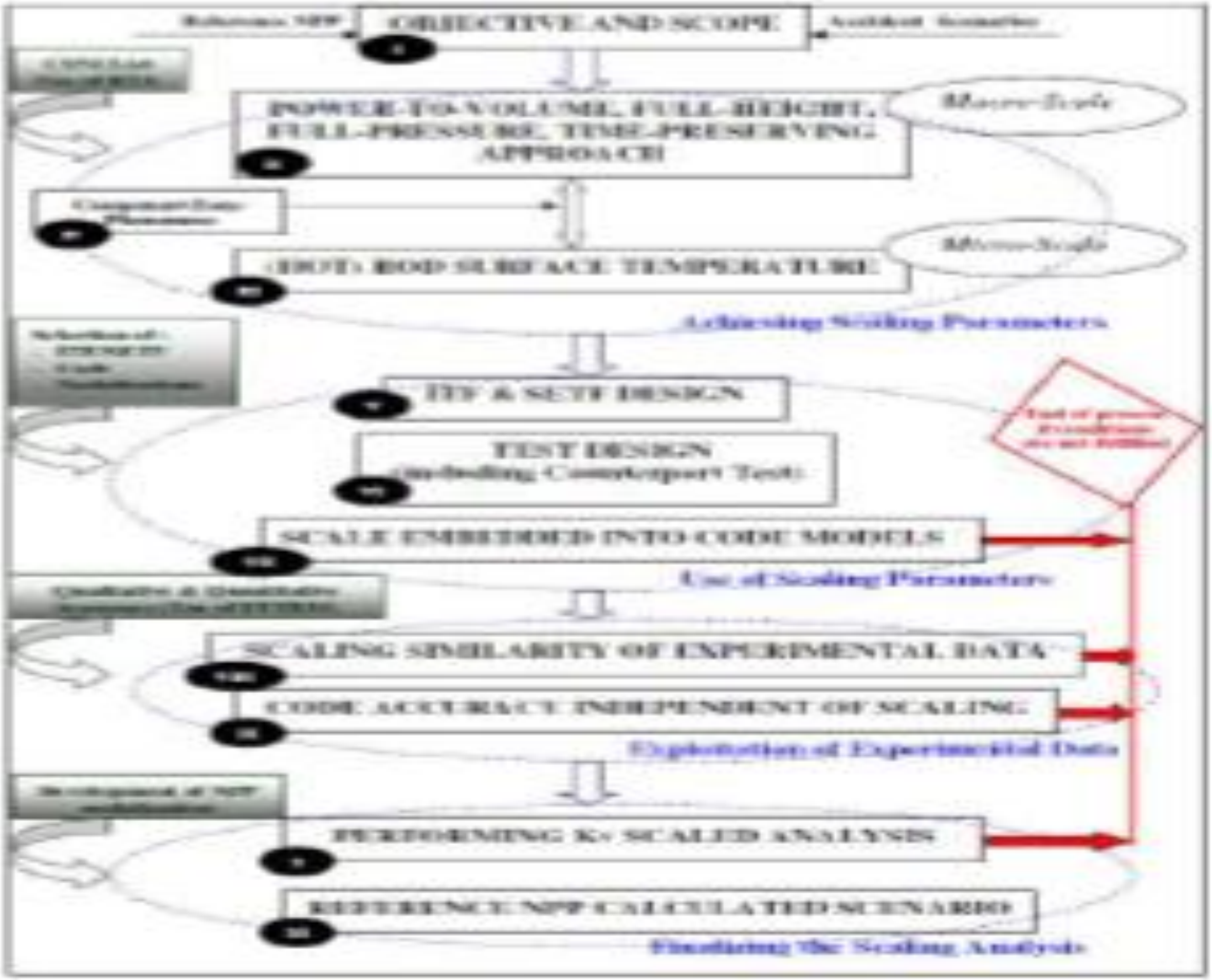
6. Quantifying Scale distortion between SET/IET models and prototype based on scaling analyses

7. Fidelity of code prediction for the test facilities; Comparison of prediction with test data. Scale distortion and contribution to uncertainty

8. Methodology of estimate code fidelity for NPP for important phenomena based on code predictions and results from SET/ IET modelling, counterpart tests. Kv, CSAU, GRS etc

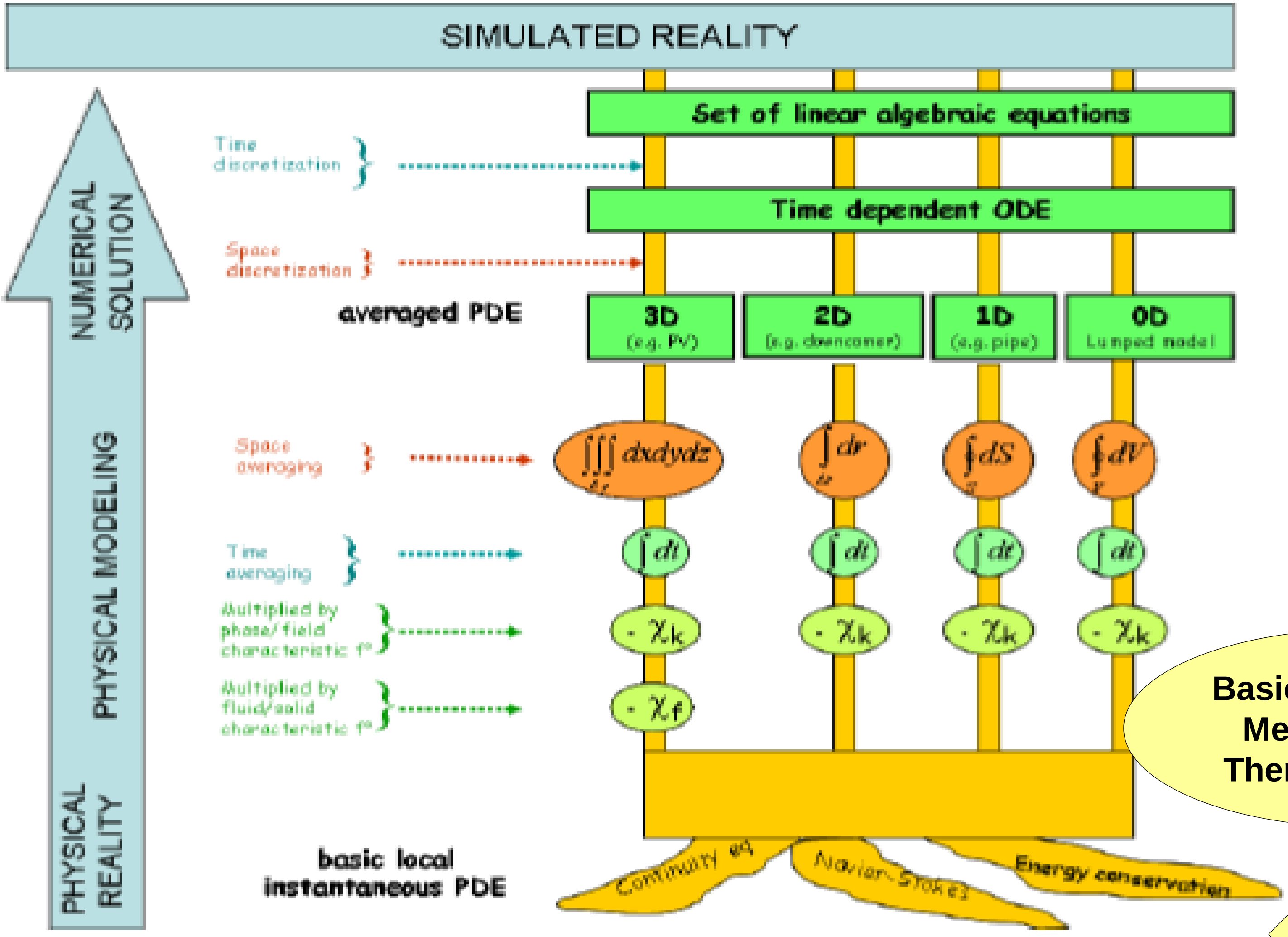
PART 2 – SCALING

*The BEPU-proposed scaling roadmap in NRS – Chapter 4**



PART 2 – SCALING

The long way between 'reality' and 'simulated reality'



Basic Principles of Mechanics and Thermodynamics

PART 2 – SCALING

The 1-D, 2-fluid (2 field) balance equations

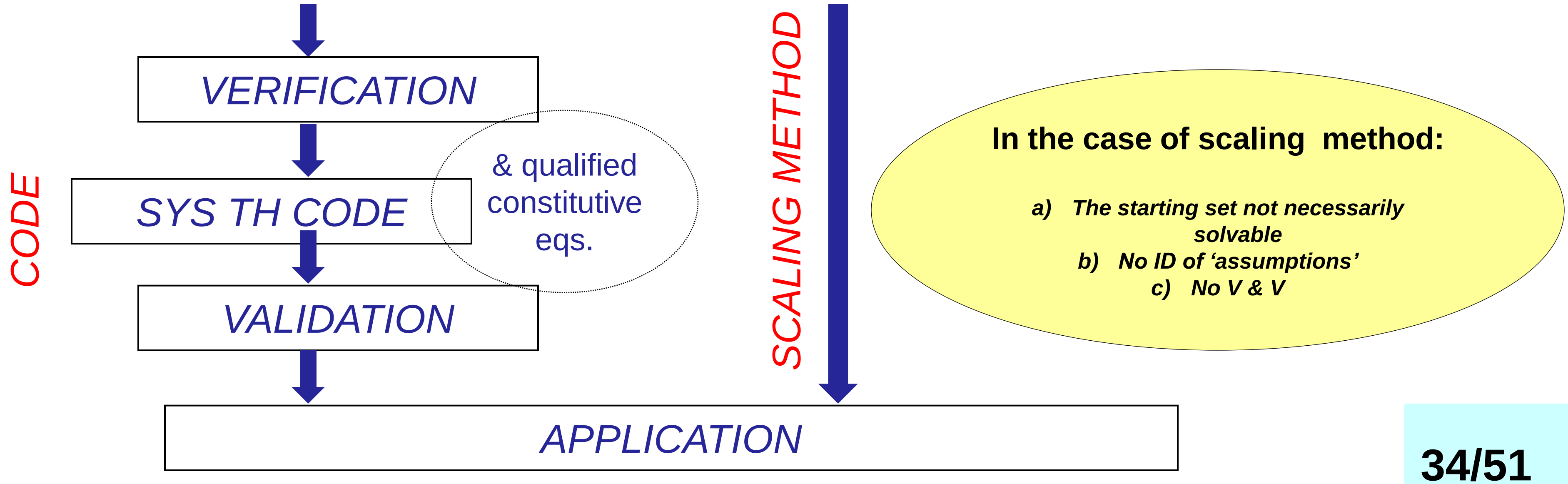
The formulation results from double time and space averaging and from <u>many simplifying</u> assumptions.

$$A\frac{\partial \alpha_k\rho_k}{\partial t} + \frac{\partial A\alpha_k\rho_k V_k}{\partial z} = A\Gamma_{ik}$$

$$A\frac{\partial \alpha_k\rho_k V_k}{\partial t} + \frac{\partial A\alpha_k\rho_k V_k V_k}{\partial z} + A\alpha_k\frac{\partial P}{\partial z} = A\,\alpha_k\rho_k g_z - AF_{ik} - \chi_w\tau_{wk}$$

$$A\frac{\partial \alpha_k\rho_k(H_k + V_k{}^2/2)}{\partial t} + \frac{\partial A\alpha_k\rho_k U_k(H_k + V_k{}^2/2)}{\partial z} - A\alpha_k\frac{\partial P}{\partial t}$$

$$= A\,\alpha_k\rho_k g_z V_k \; + \chi_w q_{wk} + AQ_{ik} + A\Gamma_{ik}(H_k + Vi^2/2) + AF_{ik}V_k + \chi_w\tau_{wk}V_k$$



In the case of scaling method:

a) The starting set not necessarily solvable
b) No ID of ‘assumptions’
c) No V & V

PART 2 – SCALING

Main findings from S-SOAR

1. **KEY SCALING ACTIVITIES DEAL WITH (related roadmaps exist, item 14 below):**
   - **Design of ITF/SETF**
   - **Demonstration of scaling capabilities for codes applied in NRS.**
2. **SIMILARITY DEMONSTRATION BETWEEN M & P IMPORTANT (both above items)**
3. **DEEP UNDERSTANDING OF PHENOMENA NEEDED (basic issue for TH)**
4. **ANY TOOL AND METHOD MAY REVEAL USEFUL (although with limitations)**
5. **EXPERIMENTAL DB IS ESSENTIAL (although direct data extrapolation not feasible)**
6. **HUGE COST OF THE EXPERIMANTAL DB IN THE PAST (not repeatible)**
7. **EACH SETF/ITF IS USEFUL FOR UNDERSTANDING SCALING.**
8. **SCALING METHODS USEFUL TO REDUCE THE COST OF EXPERIMENTS (namely reduced height ITF have been built. However, full height – full pressure-scaled ITF data are the only way to preserve all non-dimensional numbers controlling the flow regime and heat- transfer regimes in core.**
9. **CT PRODUCE HIGHLY VALUABLE SCALING DATA.**
10. **LARGE SCALE FACILITIES (e.g., UPTF) ALLOWED THE ID OF SCALING EFFECTS NOT CAPTURED BY SCALING METHODS.**
11. **SCALING AS A PART OF CODE VALIDATION (‘Kv-scaled’ or ‘triad’ methods available)**
12. **LIST OF BEST PRACTICE GIVEN TO PROVE THE CODE SCALE CAPABILITY.**
13. **SCALING CLOSELY CONNECTED WITH UNCERTAINTY (CSAU, UMAE/CIAU, GRS)**
14. **KEY ROLE OF SCALING ROADMAPS.**
15. **(HOWEVER) EXPERTISE NEEDED FOR SCALING ANALYSES.**

PART 2 – SCALING

Recommendations from S-SOAR

1. **SCALING PLUS PIRT, ITF/SETF, BEPU, SYST TH, CFD, UNCERTAINTY ARE KEY WORDS TO ADDRESS NRS ISSUES.**

2. **SYS TH CODES SUPPORTED BY CT VALIDATION NEEDED FOR SCALING.**

3. **ADVANCED REACTORS (PASSIVE SYSTEMS) NEED MORE EXP DATA.**

4. **WELL (MORE) INSTRUMENTED TESTS NEEDED FOR CFD CODE VALIDATION.**

5. **PRECISION TARGETS NEEDED INCLUDING FOR THE QUANTIFICATION OF SCALING DISTORTIONS.**

6. **FULL HEIGHT SCALING RECOMMENDED NAMELY FOR NC SIMULATION.**

7. **SCALING TRAINING RECOMMENDED (SCALING AND V & V AND UQ).**

8. **REVISITING SCALABILITY OF SYS THE CODES RECOMMENDED.**

9. **INTEGRATED ROLE OF CFD AND SYS TH CODED ENVISAGED IN MULTI-SCALE 3-D 2Φ .**

PART 3

THE μλ–I^3 TF

PREFACE - WHY THE PROPOSAL

- ***PART 1*** *– WHAT ARE THE IMPLICATIONS FOR NUCLEAR TH FROM BEPU (≡ ALARA, OR, ‘TO DO THE BEST WE CAN’)?*
- ***PART 2*** *– WHAT POSSIBLE OUTCOME FROM THE S-SOAR (I.E. TO IMPROVE THE SCALING UNDERSTANDING)?*

PART 3

PART 3

THE μλ–I^3 TF

THE μλ–I^3 TF *ACRONYM*

μ = Modular
λ = Large, Advanced, Multi Basis & Discipline Apparatus
I^3 TF = Ideal *(three times)* Test Facility

Where:

- Modular implies changeable pieces and components and possibility to assemble several ITF & SETF. Modularity for: a) NPP reference unit; b) component design
- Multi-Basis implies the possibility to use different scaling/design approaches and methods
- Multi-Discipline implies the need of different expertises in nuclear technology and safety
- Ideal has the same meaning as BEPU: something that should be done and is not done

PART 3

THE μλ–I^3 TF

THE REFERENCE NPP & TARGETS

- *NPP REF → PWR (because of its diffusion)*
- *POWER → 1400 MWe (looking at the future)*
- *No OF LOOP → 2 (3) & 4 (modular facility)*
- *SPECIFIC DESIGN/UNIT →TBS (to be selected)*
- *SETF / ITF → BOTH (part of 'modularity')*
- *PASSIVE SYSTEMS → YES (part of 'modularity')*

To move the frontier-of-knowledge in TH (rather than addressing safety needs)

… + three Cross-Link Tables for the design (see below)

PART 3

THE μλ–I^3 TF

SIMULATION TARGETS – IT scenarios; >> Examples <<

- ***LBLOCA** (DP wave, jet thrust/impingement, stress & strains on RPV internals)*
- ***SBLOCA** (RPV bypasses effect, boron dilution, LPIS design pressure)*
- ***ATWS** (NK feedback, MCP trip as countermeasure, actuation of boron tanks)*
- ***NC** (boiling/condensation stability, max NC flow, reliability, flow reversal)*
- ***SBO-LOOSP** (high pressure NC, BWR-cont response, high pressure CHF)*
- ***CRE** (RPV pressurization, PRZ surge-line design, transient NB)*
- ***AM RELEVANT** (NC restart, non-condensable effect, asymmetric SG)*
- ***PS-&-CONT** (break flow reversal, TPCF/Bernoulli-flow transition, long term cooling)*

Cross-Link Table (CLT-1): DBA envelope vs selected scenarios

PART 3

THE μλ–I³ TF

SIMULATION TARGETS – SET phenomena; >> Examples <<

- *Characterization of DP at geom disc.s (DP vs Re, α) and flow reversal.*
- *CCFL in several locations.*
- *TPCF in several conditions: multiple TPCF-locations and TPCF-section-shift.*
- *Stratification in CL / HL (1Φ and 2Φ).*
- *Stratification in pools (e.g. when using passive systems).*
- *Pressure wave propagation (also depending upon α).*
- *3D effects, e.g. on CHF (radial/axial power distribution, grids, etc.).*
- *Early quench (measuring and characterization).*
- *Reflood, e.g. conditions for 'homogeneous reflood' (if any).*
- *MCP characterization in 1Φ and 2Φ; locked or unlocked and flow stagnation.*
- *Crud effect upon PCT (mostly LBLOCA).*
- *Ballooning and H2 production and PS to CO transport and TH effects.*
- *[Possibly] to achieve rod surface T > 1200 K and radiation HT investigation.*
- *Mixing (CL, HL, DC, LP), focusing on PTS and NK reactivity.*

Cross-Link Table (CLT-2): scenarios vs phenomena

PART 3

THE $\mu\lambda$–I^3 TF

KEY INNOVATION *>>>> Examples <<<<*

- *DP wave (-) propagation versus break opening time: void generation, loads.*
- *DP wave (+) propagation: void collapse after MSIV closure (SG & BWR)*
- *NC under flow reversal: need of DC heating.*
- *TPCF: transition to Bernoulli flow, multiple locations, critical section shift.*
- *CCFL: effect of different scaling methods.*
- *REFLOOD: early (partial quench) rewet .*
- *FUEL: ballooning, H2 production, crud effect.*
- *CONT: coupling with PS, oscillation in PSP (BWR).*
- *STRATIFICATION 1Φ and 2Φ in CL / HL: effect of different scaling methods.*
- *STABILITY: coupling of two stable NC systems leading to instability.*
- *COMPONENT testing: MCP, Valves, separators (in SG) .*
- *CFD: instrumentation consistent with CFD needs.*
- *INSTRUMENTATION: establishing precision targets.*
- *SCALING: different approaches, methods and resulting hardware/BIC*
- *MULTI-DISCIPLINARY: see next slide.*

PART 3

THE μλ–I^3 TF

MULTI-DISCIPLINARY ISSUES >> Examples in addition to TH<<

- *MECHANICS: stress and strain upon RPV internals.*
- *MECHANICS: PTS local stress measurement.*
- *MECHANICS: PTS 'global' loads for RPV (depending upon constraints).*
- *CHEMISTRY: H2 production form metal water reaction.*
- *MECHANICS-FUEL: clad ballooning.*
- *NEUTRON PHYSICS: ATWS and CRE feedback from measurements.*
- *NEUTRON PHYSICS: design of ATWS and CRE experiments.*
- *MECHANICS: component performance (pumps, valves, etc.).*
- *CHEMISTRY: H2 and Boron transport including crystallization (boron).*
- *CHEMISTRY-FUEL: crud characteristics.*
- *PSA (& RELIABILITY): design confirmation for experiments & passive SYS.*

+

- *SUB-CHANNEL*
- *CONTAINMENT*
- *CFD*

PART 3
THE μλ–I³ TF

SCALING – BASIS

REFERENCE FACILITY

DESIGN FACTORS FROM BASIC PRINCIPLES** (e.g. D'Auria & Galassi, J NED, 2010)**:

- ***VOLUME-TO -POWER scaling** (this also accounts for VOLUME-TO-MASS)*
- ***FULL HEIGHT***
- ***FULL PRESSURE***
- ***OPERATIONAL (FULL) POWER***
- ***FULL LINEAR POWER** (K_N = K_V, where N = number of electrical rods)*
- ***VOLUME-TO-MASS-FLOWRATE preserved** ($K_A \approx K_V$, as far as possible, to preserve K_{DP} = 1, see next slide, and horizontal lengths [L] as needed, in the attempt to keep prototypical the transit time across the loop)*

CONSEQUENCES

- ***TIME PRESERVED** (action: to quantify and minimize distortions due to structural heat release)*
- ***HEAT FLUX FROM ELECTRICAL FUEL RODS PRESERVED***

PART 3

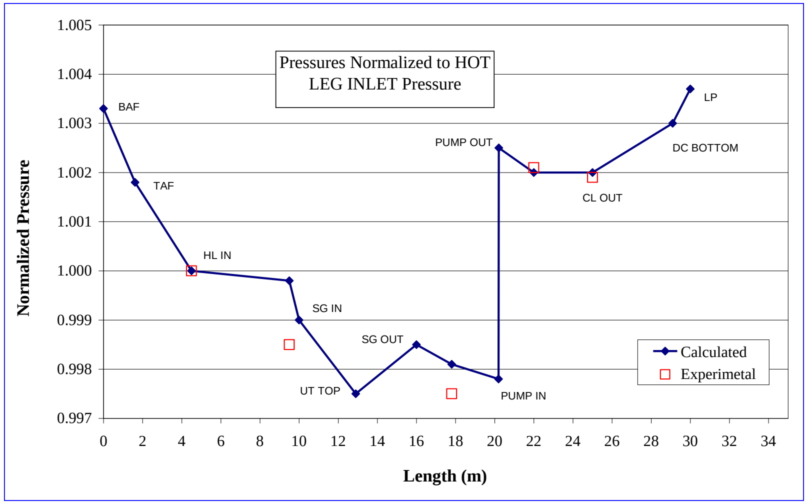
THE μλ–I^3 TF

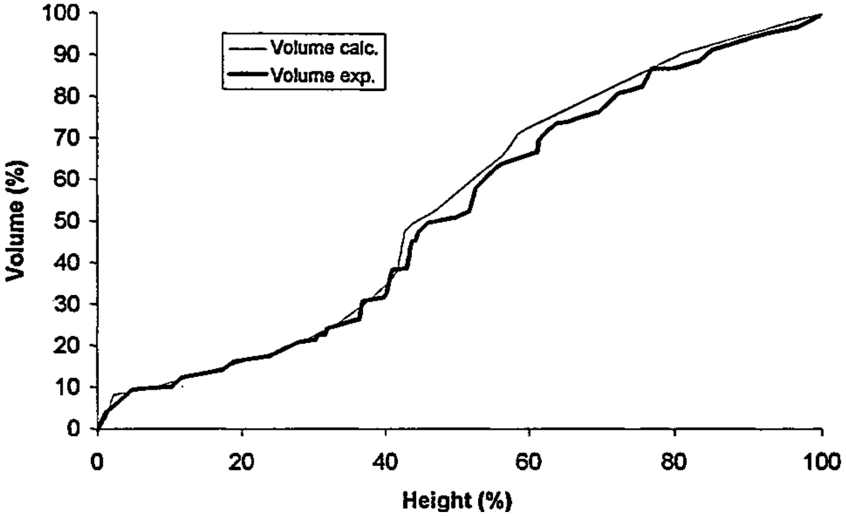
SCALING – BASIS

MANDATORY TO BE PRESERVED

THE DP vs L CURVE

THE V vs H CURVE





THE DP vs L CURVE
under flow reversal

PART 3

THE $\mu\lambda$–I^3 TF

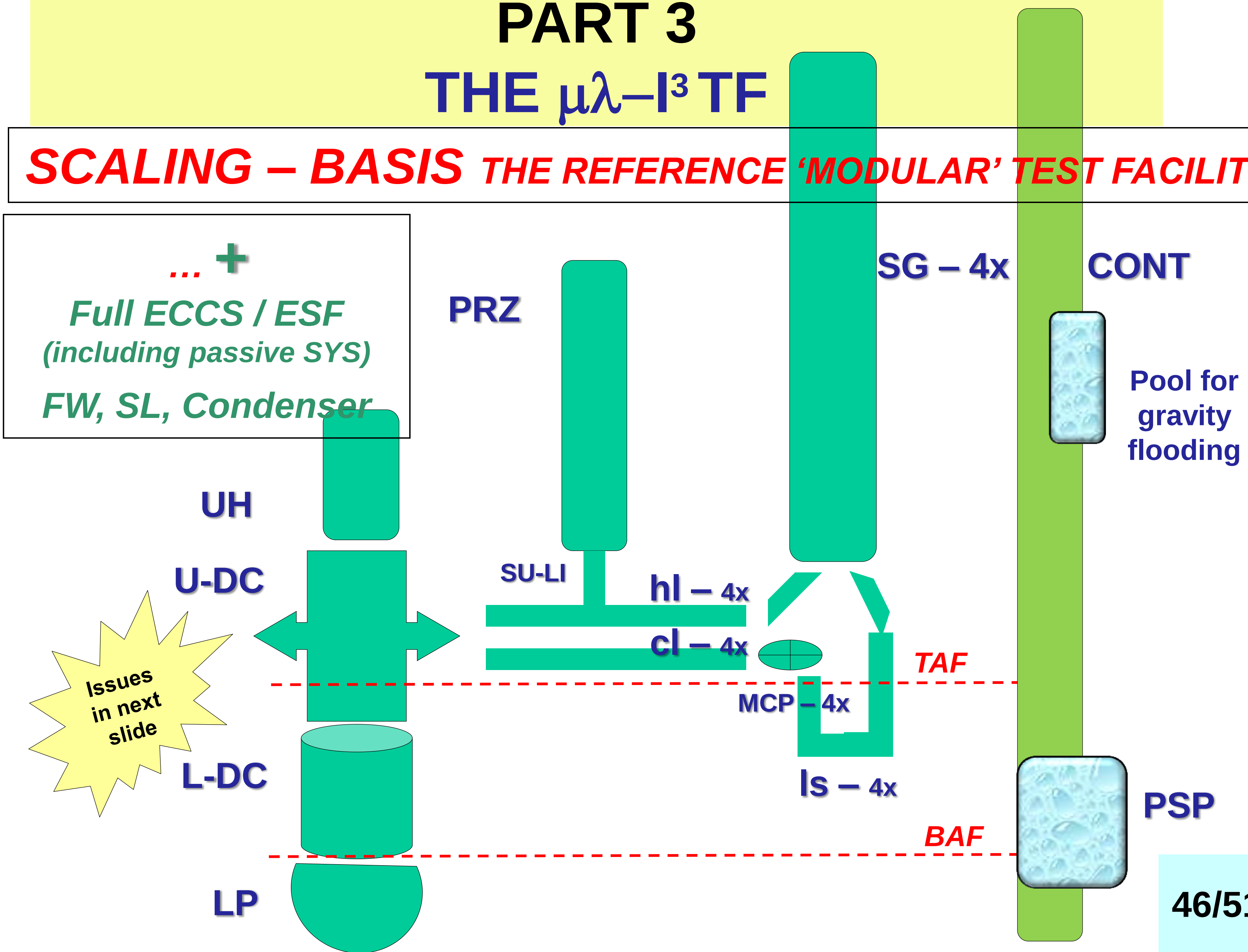
SCALING – BASIS *THE REFERENCE 'MODULAR' TEST FACILITY*

… +

Full ECCS / ESF

(including passive SYS)

FW, SL, Condenser



PART 3

THE $\mu\lambda$–I^3 TF

SCALING – BASIS complexity of components

1

U-DC

Modularity implications:

- *4 HL nozzles*
- *4 CL at HL elevation*
- *4 CL nozzle s at ‘lower’ elevation*
- *DVI nozzles (e.g. 2)*
- *All nozzles having FA 1.6 times larger than $K_V = K_A$*
- *RPV constraints suitable for absorbing and measuring LOCA forces*

2

LP

Cannot be prototypical: see technological challenges . Then,

- *DP to be preserved*
- *Scaling of mixing to be studied*

4

CORE

Electrical rods (or groups of rods) separately powered. Then,

- *H2 production in selected rods*
- *Ballooning in selected rods*

3

UP and UH

Modularity implications:

- *UP and UH prototypical for reference design*
- *Internals to be adapted to design and to scale method*
- *Bypass: UP-DC, UP-UH and UP-LP to de adapted to the design (& measurable flows)*

Cross-Link Table (CLT-3): <u>phenomena vs instrumentation</u>

PART 3

THE $\mu\lambda$–I^3 TF

SCALING – BASIS

THE ROLE OF OTHER SCALING METHODS (Ishii, H2TS, FSA, DSS)

Tentatively, fifty (50) experiments to be performed in the initial configuration. Test types according to simulations targets. In addition, CT related to existing ITF. This constitutes the reference DB for scaling studies.

MODULARITY

FOR SCALING METHODS: the following components (other than BIC values) to be designed according to specific scaling :

- **L-DC, SU-LI, HLs, CLs, LSs**
- **Elevation of L-DC and core (& SG) according to reduced height scaling**

FOR REACTOR DESIGN: the following components (other than BIC values) to be designed according to specific NPP reference design:

- **No of Loops**
- **CL and LS axes elevation, PRZ, SU-LI**
- **SG & CONT**

PART 3

THE μλ–I³ TF

THE TECHNOLOGICAL CHALLENGES

1) ***Max Kv:*** *(e.g. Kv = 1/50 implies 100 MWe electrical power).*
2) ***Max cost / design of electrical rods*** *(indirectly heated, full linear power, one side connectors, individual power control): Kv = 1/50 ➔ ≈ 1000 rods.*
3) ***LBLOCA simulation: this implies a Min Kv value*** *(TPCF in DC, thermal power from structures, ECC bypass, etc.).*
4) ***Distorted LP configuration:*** *because of electrical rods scaling distortions may reveal so large to make inconvenient the construction.*
5) ***Seals for electrical fuel rods:*** *leakages and dissipation of power at cold connector (into LP) are the challenges.*
6) ***Construction of U-DC (part of RPV) module:*** *the consequence of modularity is the (high) cost.*

PART 3

THE μλ–I^3 TF

THE Kv AND THE TRIPLE ‘I’

THE MEANINGFUL Kv: > 1/50

≥ Min-Kv where 3D effects (maybe distorted) become influential

Therefore, the facility, three times ‘Ideal’:

- ❑ ***Technological challenges* - I^1**
- ❑ ***Proprietary data*** *(needed)* - **I^2**
- ❑ ***Cost*** *(the order of 100 M\$, plus ≈10 M\$/year)* - **I^3**

SUMMARY REMARKS

PART 1

BEPU: must be pursued. Any further delay is not justifiable for safety. Safety Assessment (Licensing) must be independent of Vendor-Owner ➔ BEPU-based I-FSAR.

PART 2

SCALING: Applicable conclusions already given

PART 3

THE $\mu\lambda$–I^3 TF: the design is consistent with scaling S-SOAR; the construction is consistent with BEPU. It implies:

- Motivations for researchers in TH
- Synergies with different NRS topics
- Moving forward the frontier of knowledge in nuclear TH (namely CFD)
- Improving public confidence toward Nuclear Energy (together with BEPU).
- Connecting with planned or not-yet-planned developments in basic TH

The problems for potential implementation are associated with triple ‘I’.