DIPARTIMENTO DI INGEGNERIA MECCANICA, NUCLEARE E DELLA PRODUZIONE – GRNSPG (San Piero a Grado)

UNIVERSITA' DI PISA
56100 PISA - ITALY

FROM BASES IN THERMAL-HYDRAULICS TO APPLICATIONS IN NUCLEAR REACTOR SAFETY: THE BEPU APPROACH

F. D'Auria

inac 2013 International Nuclear Atlantic Conference

The Benefits of Nuclear Technology for Social Inclusion

Keynote Lecture at XVIII ENFIR

Nov. 24-29, 2013 . Centro de Convenções
Recife, Pernambuco, Brazil

FOREWORD & OBJECTIVE -1

What is Thermal-Hydraulics (TH)? … The way to predict

- **Pressure drops and heat transfer,**
- **Void fraction (… what is void fraction?),**
- **Transient performance of Nuclear Plants,**
- **Safety margins,**

… or, the way to

- **Design experiment and analyze measurements,**

… or (according to Nam Dinh) … The way

- **To produce colorful and impressive images,**
- **For endless attempts of using PDE which are 'incompatible' with physics …**

FOREWORD & OBJECTIVE -2

The (old) idea is to connect Science and Technology.

The (ambitious) objectives are:

- **to show how the fundamental understanding and the basic research are functional for the technology of a complex system;**
- **To shed light on the question what is TH**

LIST OF CONTENT

- **FUNDAMENTALS**

The Motion of a Bubble, The Turbulence, The Length Scale, The Risk and the Residual Risk

- **NUCLEAR SAFETY & THERMAL-HYDRAULICS**
- **A HYSTORIC OUTLINE**

- **FROM FUNDAMENTALS TO APPLICATIONS**

Flow Regimes, Critical Heat Flux, Two-Phase Critical Flow, The Principles of Thermodynamics, The Equations & the Numerical Algorithms → The Natural Circulation, The Countercurrent Flow Limitation, The Blow-down, The Reflood, The Stability

- **THE COMPUTER CODE & THE VALIDATION**

Addressing the Scaling Issue, Need for Uncertainty & Approaches

- **THE BEST-ESTIMATE 'PLUS' UNCERTAINTY (BEPU): HUMAN CIVILIZATION ←→ BEPU**

FUNDAMENTALS: BUBBLE MOTION

"How is it possible that you are calculating the transient evolution of two phase mixtures in complex geometrical systems, when I am not capable to predict the movement of a single bubble in a simple vertical tube after 42 years of experiments?"

… we cannot calculate the motion of a bubble, but we do calculate the average motion of an infinity of bubbles and a variety of flow configurations … and we (claim to) know the error … and (we estimate that) the error is acceptable

FUNDAMENTALS: TURBULENCE

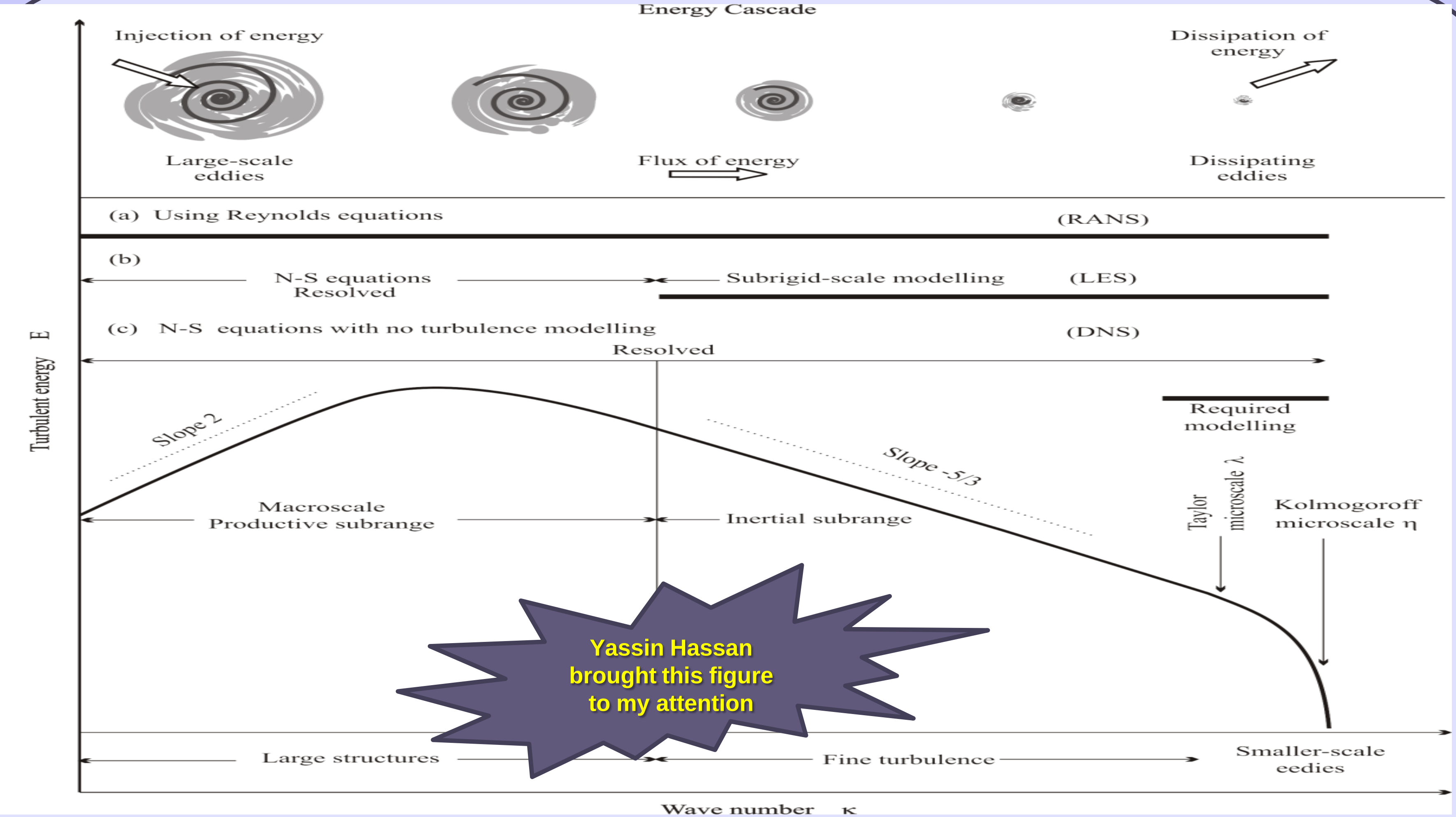
- **the state or quality of being turbulent;**
- **a state or condition of confusion, movement or agitation, disorder;**
- **chaotic or unstable eddying motion in a fluid;**
- **the most important unsolved problem in classical physics.**

When I met God, I am going to ask him two questions: Why relativity? And why turbulence? I really believe he will have an answer for the first. (Heisenberg)

Yassin Hassan brought this figure to my attention

Leonardo da Vinci (1452-1519) drawing and statement of coherent vortices around piers (the Royal Library, Windsor Castle)

FUNDAMENTALS: TURBULENCE



THE ENERGY CASCADE:

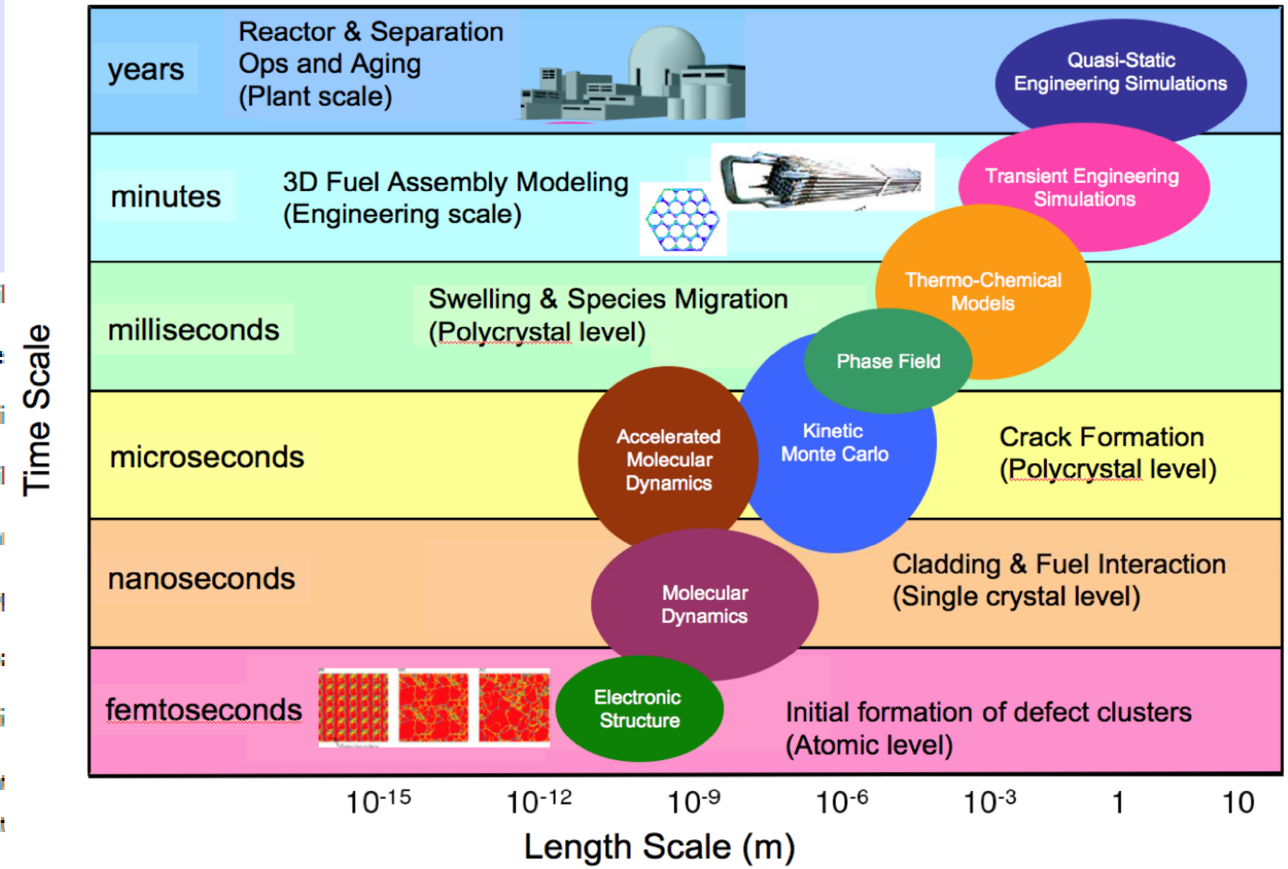
- The turbulence is introduced in the system at the scale of system energy.
- The turbulence is removed from the system at the scale of small vortices.

FUNDAMENTALS: THE LENGTH SCALE

FOR NUCLEAR PLANT

Dimension of a neutron:	$1 \cdot 10^{-15}$ m	(responsi
Dimension of a nucleus	$1 \cdot 10^{-14}$ m	(storing e
Dimension of an atom	$1 \cdot 10^{-10}$ m	(radioacti
Roughness	$1 \cdot 10^{-6 \div -5}$ m	(responsi
Thickness of fuel rod gap	$1 \cdot 10^{-4}$ m	(key para
Spacer grid details	$1 \cdot 10^{-3}$ m	(design o
Fuel rod radius	$1 \cdot 10^{-2}$ m	(design p
Core hydraulic diameter	$1 \cdot 10^{-2}$ m	(core regi
Neutrons mean free path	$1 \cdot 10^{-1}$ m	('modera
Fuel bundle edge	$1 \cdot 10^{-1}$ m	(horizont
Core radius/height	$1 \cdot 10^{0}$ m	(key parameter for overall produced power)
Piping diameter	$1 \cdot 10^{-1 \div 0}$ m	(key piping for primary system)
Vessel diameter/height	$1 \cdot 10^{1}$ m	(to accommodate the core)
Containment diameter/height	$1 \cdot 10^{2}$ m	(to accommodate the primary circuit)
Turbine axis length	$1 \cdot 10^{2}$ m	(to minimize the cost of electricity)

FOR A COMPLEX SYSTEM



FUNDAMENTALS: THE RISK

THE RISK (FOR ANY SYSTEM):

Any action (even the ‘no-action’ to avoid building the system) implies a risk:

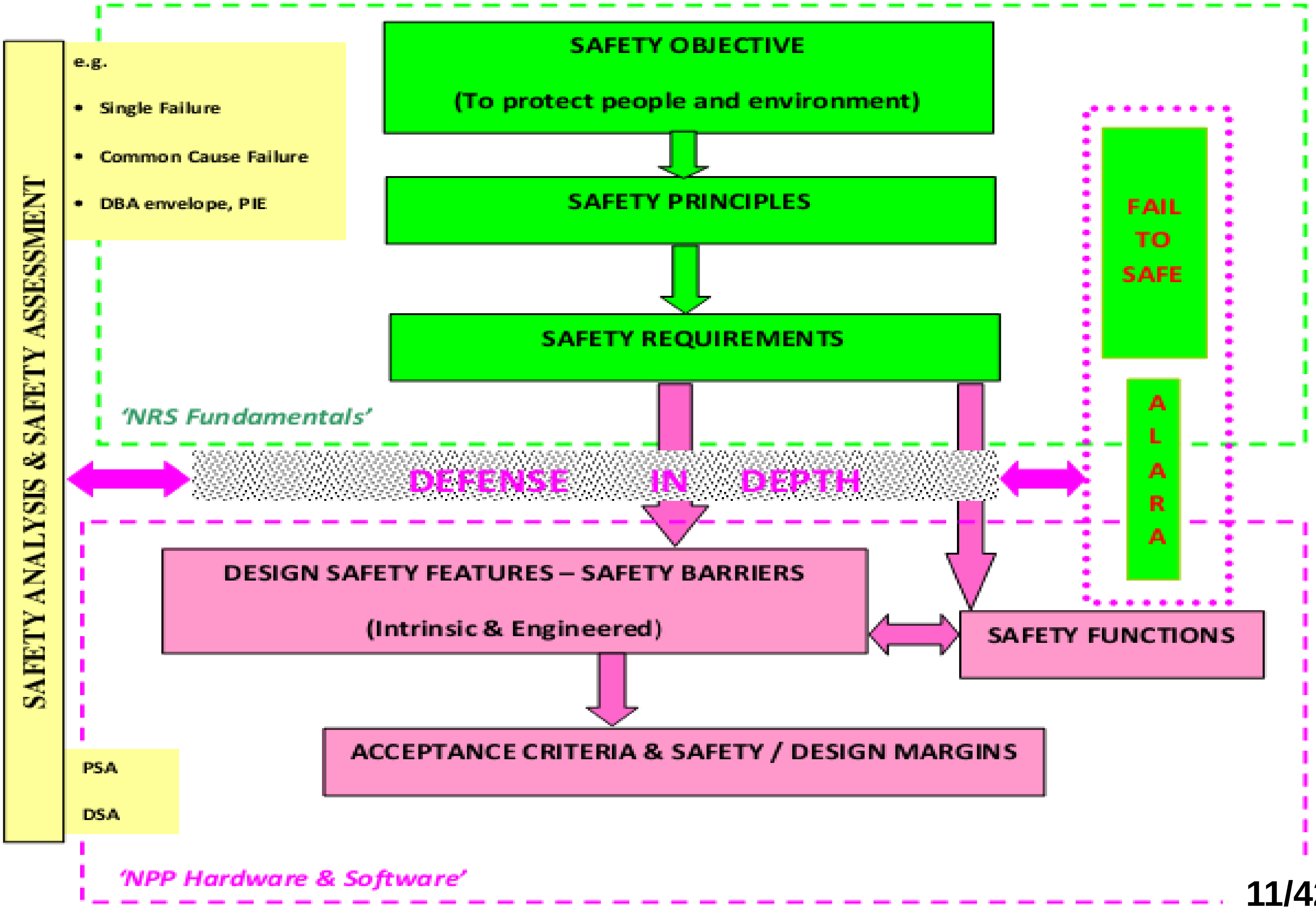
- **the risk must be managed and minimized;**
- **residual risk shall be accepted.**

FUNDAMENTALS

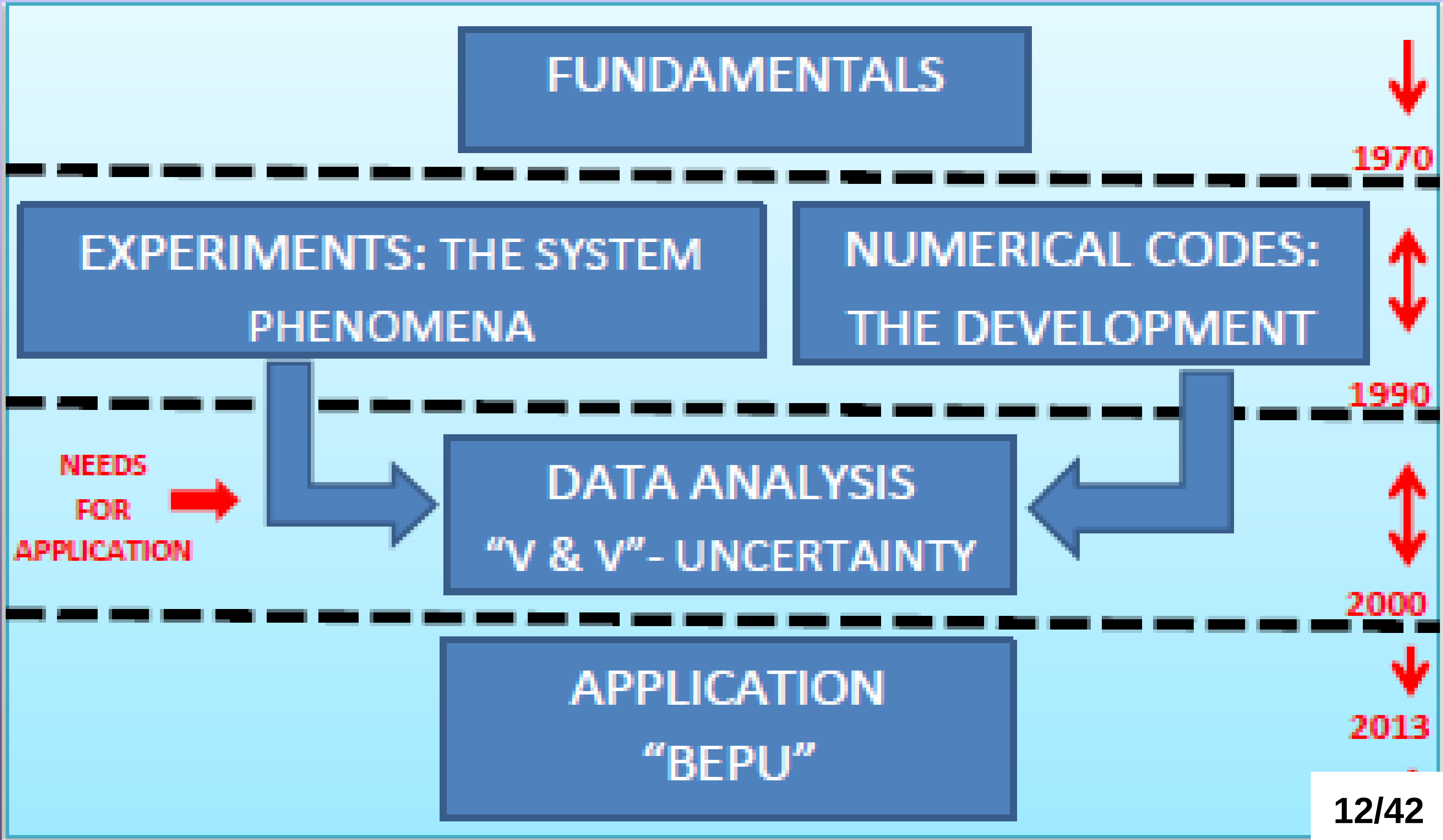
THE FRAMEWORK FOR THE DISSERTATION

(reformulated)

How to pass from the fundamentals of thermal-hydraulics (i.e. the motion of a bubble and the un-resolved issue of turbulence) to the simulation of the transient performance of a nuclear plant (covering 10E17 orders of magnitude for length) contributing to demonstrating the risk acceptability.

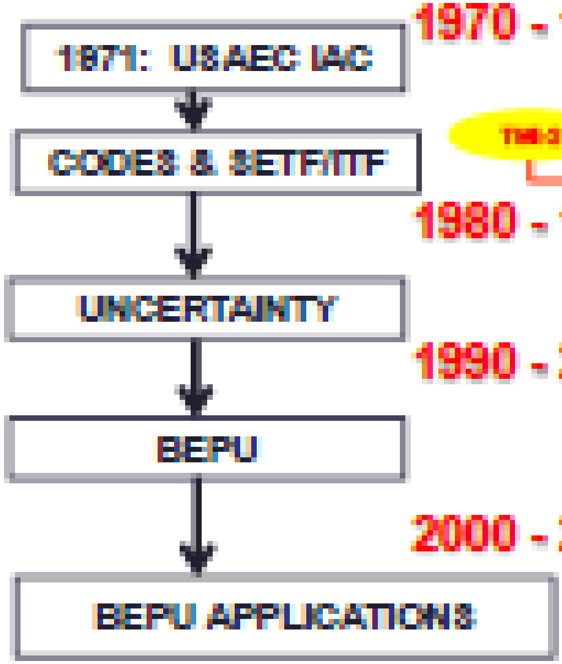

SAFETY OBJECTIVE
(To protect people and environment)
SAFETY PRINCIPLES
SAFETY REQUIREMENTS
e.g.
• Single Failure
• Common Cause Failure
• DBA envelope, PIE
SAFETY ANALYSIS & SAFETY ASSESSMENT
'NRS Fundamentals'
FAIL TO SAFE
A L A R A
DEFENSE IN DEPTH
DESIGN SAFETY FEATURES – SAFETY BARRIERS
(Intrinsic & Engineered)
SAFETY FUNCTIONS
ACCEPTANCE CRITERIA & SAFETY / DESIGN MARGINS
PSA
DSA
'NPP Hardware & Software'

NUCLEAR SAFETY AND THERMAL-HYDRAULICS



A HISTORICAL OUTLINE *(for nuclear thermal-hydraulics)*

1942 The Fermi Pile	The Thermal Capacity of Graphite.
Up to 1960	Heat Transfer & Pressure Drops.
1960 - 1970	TH Fundamentals; TPCF; Blow-down; CHF/DNB.
1970 - 1980	LBLOCA – 'Conservatism'; TPCF; CHF/DNB; Code Design.
TMI-2 → 1979; 1980 - 1990	SBLOCA – BE / 'Realism'; Scaling; 2D/3D; CCFL; NC; Code V & V.
1990 - 2000	AM; CFD; Uncertainty; Code V & V; Code Application.
2000 - 2010	Licensing: BEPU (Code Application & Scaling); Passive SYS TH.
	BEPU Integration with: 3D NK, Structural Mechanics, CFD.



A HISTORICAL OUTLINE *(for nuclear thermal-hydraulics)*

A PERSPECTIVE WITH ACTORS, STAKE-HOLDERS AND KEY DOCUMENTS

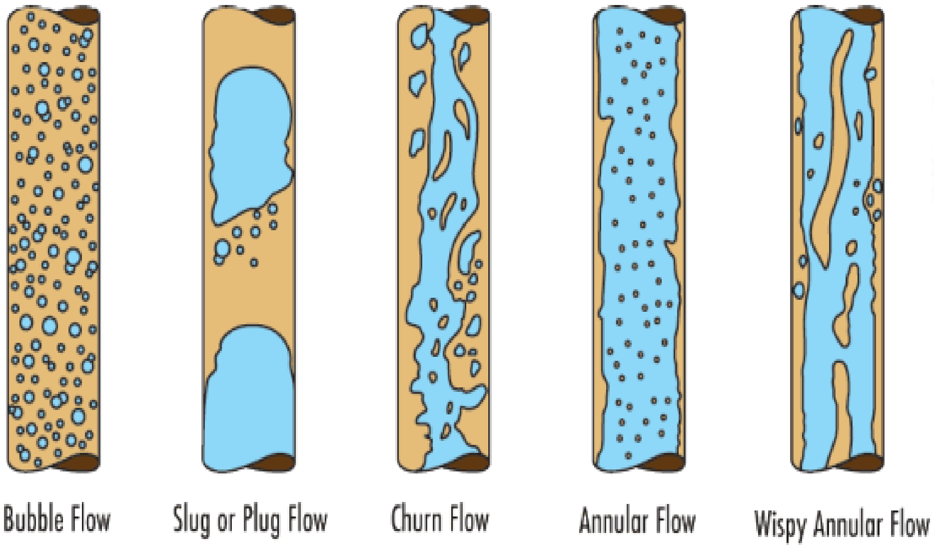
ACTORS & STAKE-HOLDERS*	➜	Authors of Textbooks, US NRC, International & National Institutions, Industry, NURETH (Conferences), Journals

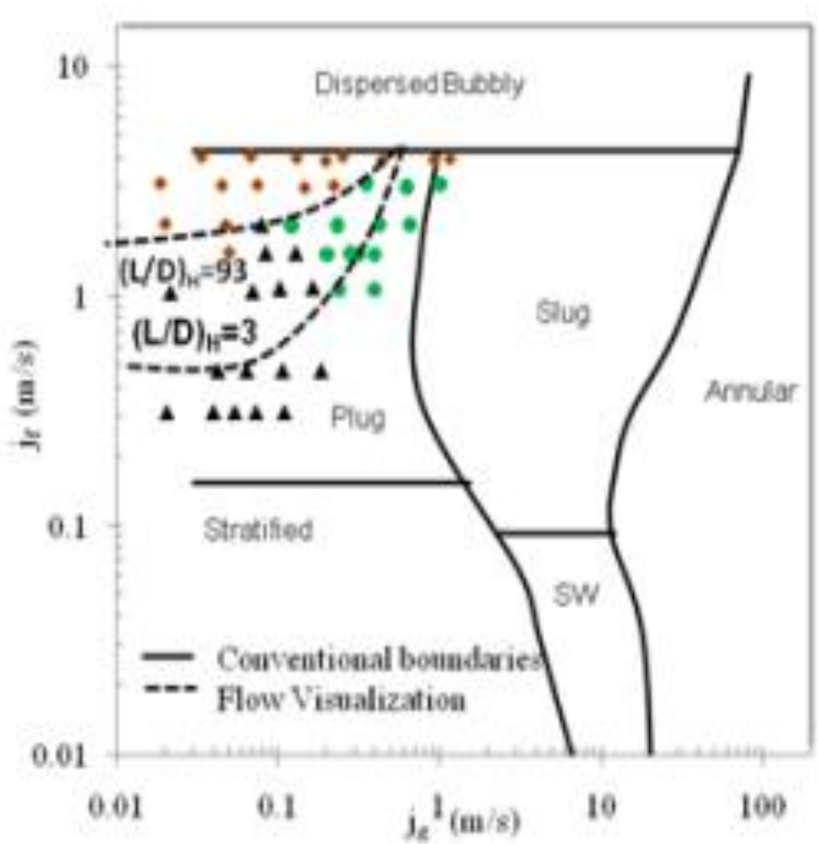
PERIOD OR EVENT	KEY WORDS/PHENOMENA	KEY DOCUMENT
Fermi Fission Reaction (1942)	Thermal Capacity (of graphite).	
Up to 1960	Heat Transfer & Pressure Drops.	E.g.: Dittus-Boelter eq. for HTC, Multiplier Approach for TPPD.
1960-1970	TH Fundamentals; TPCF; Blow-down; CHF/DNB.	E.g.: Moody and H-F models for TPCF, LUT for CHF.
1970-1980	LBLOCA – Conservatism; TPCF; CHF/DNB; Code Design.	USNRC IAC for ECCS, App. K to 10 CFR 50.46.
1980-1990	SBLOCA – BE; V & V & Scaling; 2D/3D; CCFL; NC; Code Validation.	CSAU, USNRC Compendium, CSNI SOAR on TECC, CCVM-ITF
1990-2000	AM; CFD; UM; Code Validation & Application.	CCVM-SETF, UMS**, USNRC RG 1.157, UMAE, GRS-method
2000-2010 2012	Licensing: BEPU (Code Application) & Scaling; Passive System Thermal-hydraulics.	USNRC RG 1.203, IAEA SRS 23 and 52, IAEA SSG-2, BEMUSE**, NURESIM**, NURISP**, CASL**
After 2012	Consolidation in the above areas. ***	NURESAFE**, CASL, PREMIUM**

FROM FUNDAMENTALS TO APPLICATIONS

TWO-PHASE FLOW REGIMES

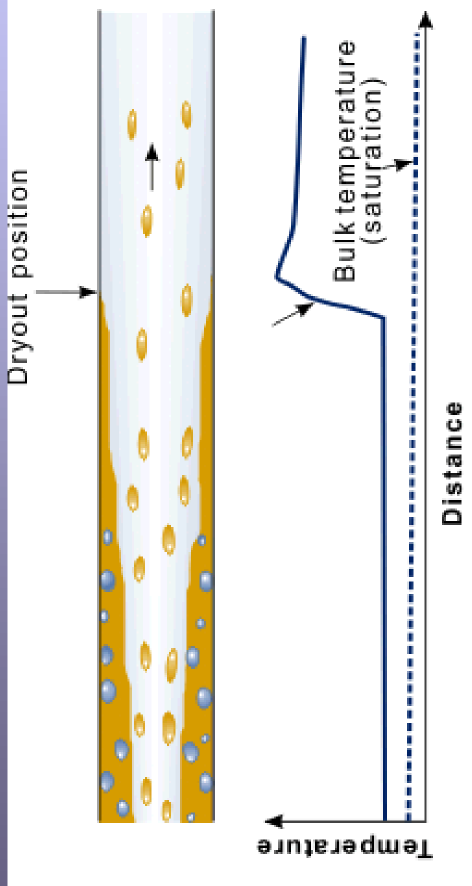
From images to flow maps

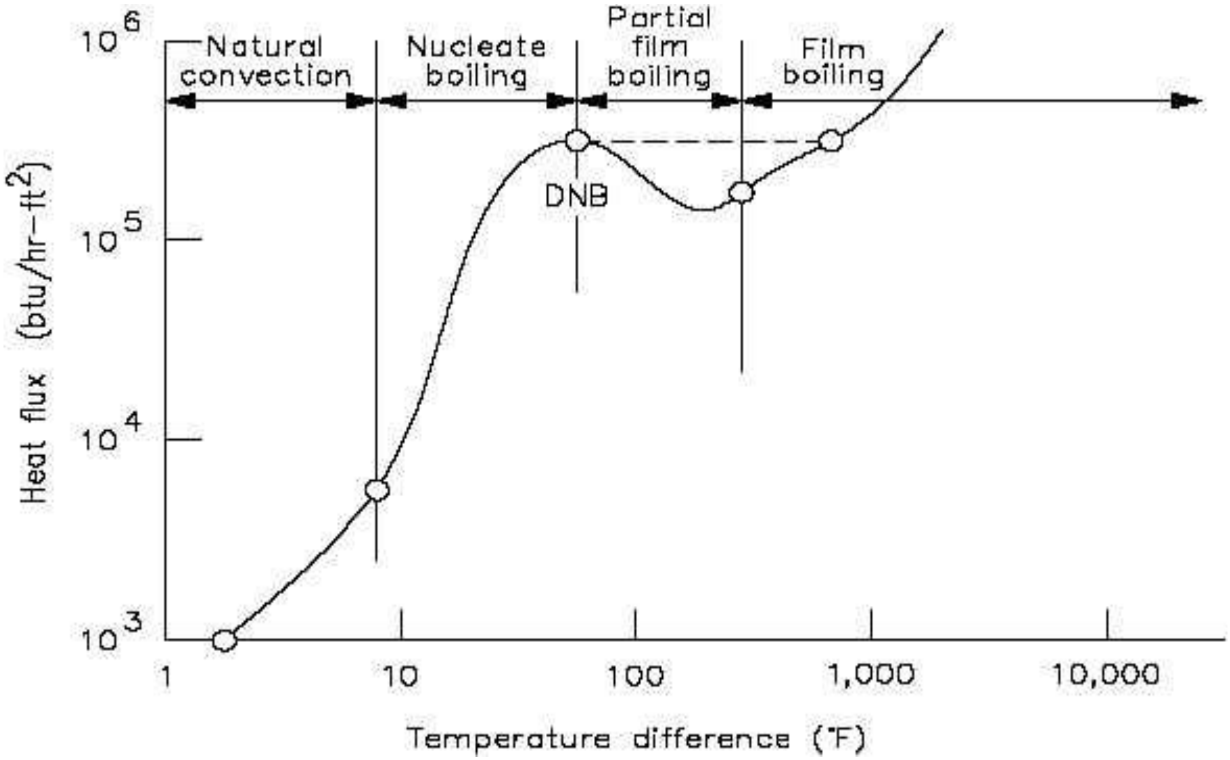




FROM FUNDAMENTALS TO APPLICATIONS

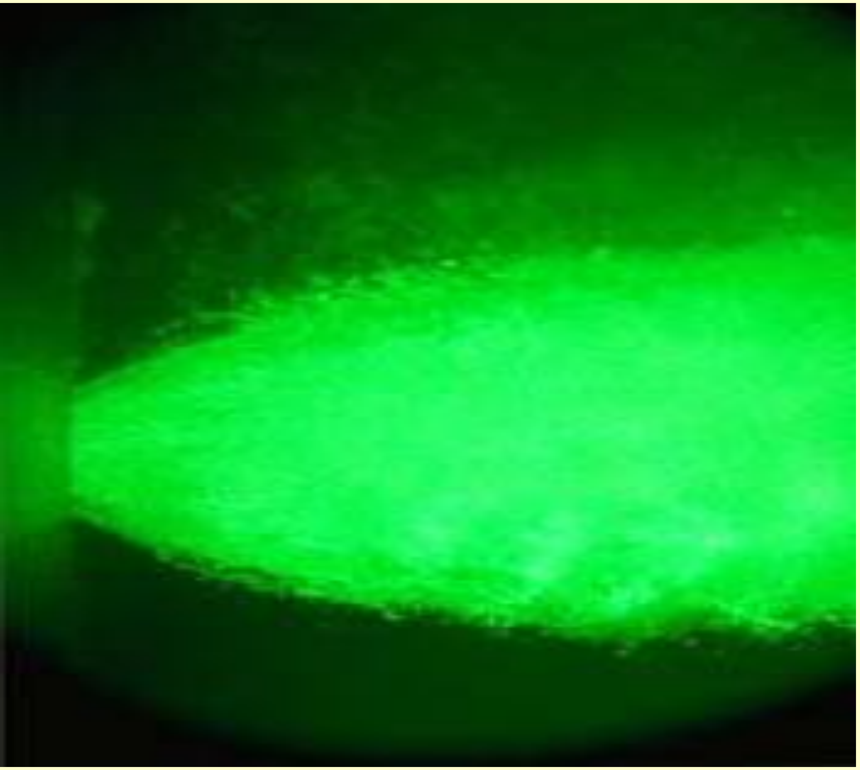
CRITICAL HEAT FLUX

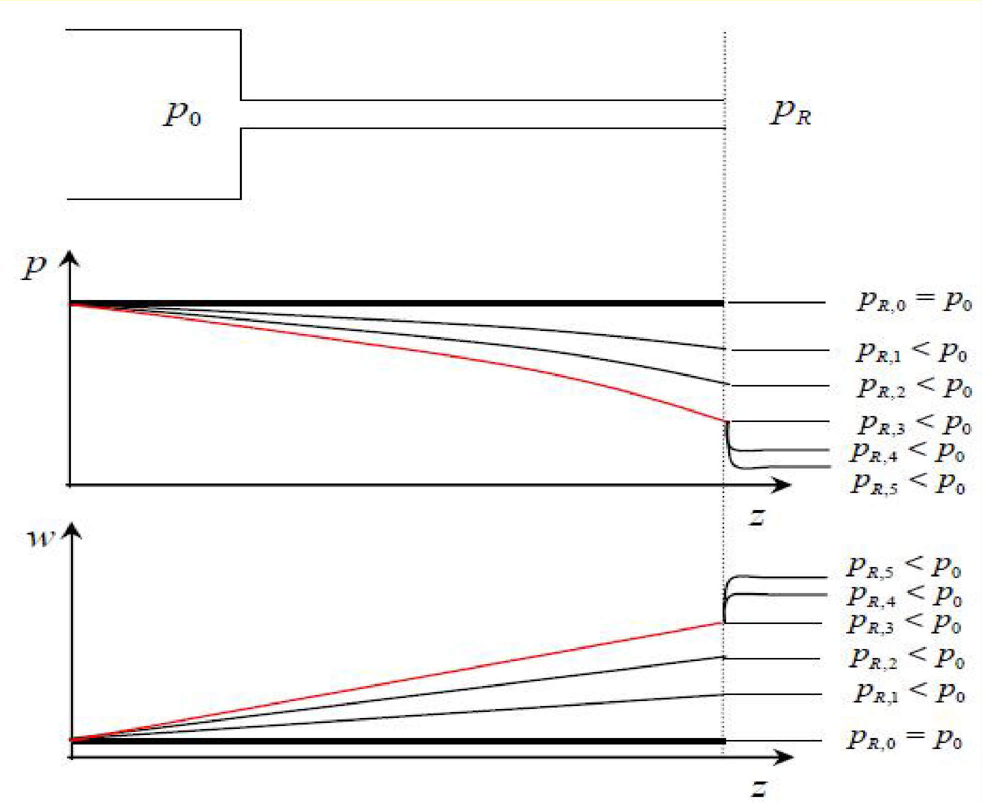




FROM FUNDAMENTALS TO APPLICATIONS

TWO-PHASE CRITICAL FLOW





FROM FUNDAMENTALS TO APPLICATIONS

THE PRINCIPLES OF THERMODYNAMICS

The Zeroth Law: there is no heat flow between objects that are the same temperature.

The First Law: heat cannot be created or destroyed. This is also known as the law of conservation of energy.

The Second Law: the entropy of a closed system always increases if work is done, or if work is wasted.

The Third Law: an engine can convert 100% of the heat into work only if its exhaust temperature were absolute zero.

THE EQUATIONS & THE NUMERICAL ALGORITHMS

$$\Gamma\frac{\partial \mathbf{Q}_v}{\partial t}+\frac{\partial \mathbf{E}}{\partial x}+\frac{\partial \mathbf{F}}{\partial y}+\frac{\partial \mathbf{G}}{\partial z}=\frac{\partial \mathbf{E_v}}{\partial x}+\frac{\partial \mathbf{F_v}}{\partial y}+\frac{\partial \mathbf{G_v}}{\partial z}+\mathbf{S}$$

$$\Gamma=\begin{bmatrix}
\frac{1}{C_\phi^2} & 0 & 0 & 0 & -\frac{1}{C_{\phi\beta}^2} & \rho_g-\rho_l & \rho_v-\rho_l\\
\frac{u}{C_\phi^2} & \rho_m & 0 & 0 & -\frac{u}{C_{\phi\beta}^2} & (\rho_g-\rho_l)u & (\rho_v-\rho_l)u\\
\frac{v}{C_\phi^2} & 0 & \rho_m & 0 & -\frac{v}{C_{\phi\beta}^2} & (\rho_g-\rho_l)v & (\rho_v-\rho_l)v\\
\frac{w}{C_\phi^2} & 0 & 0 & \rho_m & -\frac{w}{C_{\phi\beta}^2} & (\rho_g-\rho_l)w & (\rho_v-\rho_l)w\\
\frac{e_l\phi_l}{C_l^2}+\frac{e_g\phi_g}{C_g^2}+\frac{e_v\phi_v}{C_v^2} & \rho_m u & \rho_m v & \rho_m w & \rho_l\phi_l c_{vl}+\beta_T c_{vl}\phi_l T-\frac{1}{2}\left(\frac{u^2+v^2+w^2}{C_{\phi\beta}^2}\right) & \rho_g e_g-\rho_l e_l & \rho_v e_v-\rho_l e_l\\
\frac{\phi_g}{C_g^2} & 0 & 0 & 0 & -\frac{\beta_g^2\phi_g}{C_g^2} & \rho_g & 0\\
\frac{\phi_v}{C_v^2} & 0 & 0 & 0 & -\frac{\beta_v^2\phi_v}{C_v^2} & 0 & \rho_v
\end{bmatrix}$$

The eigenvalues of the transformation matrix give the speed of sound

FROM FUNDAMENTALS TO APPLICATIONS

THE NATURAL CIRCULATION

SYSTEM PHENOMENA

KEY EQUATIONS

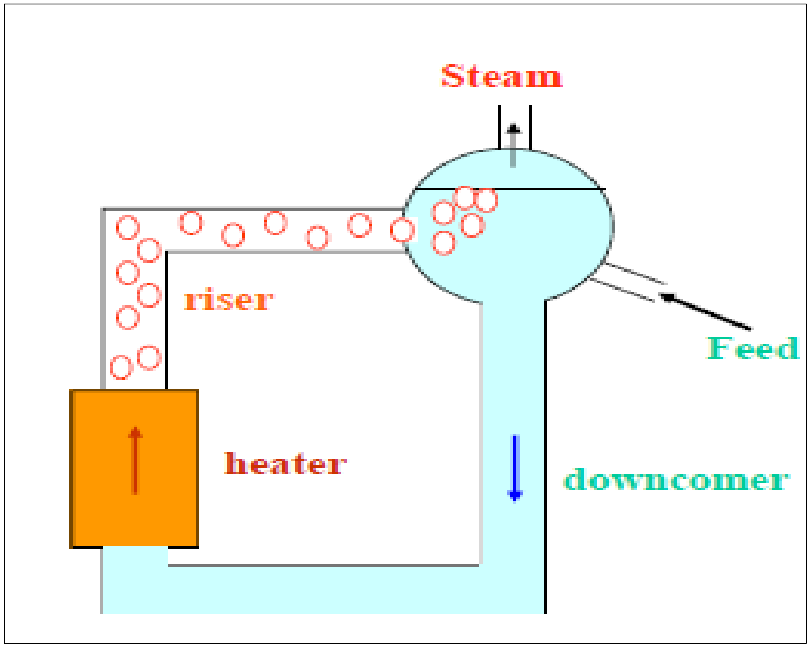
$$\Delta p_{driving} = \Delta p_{res}$$

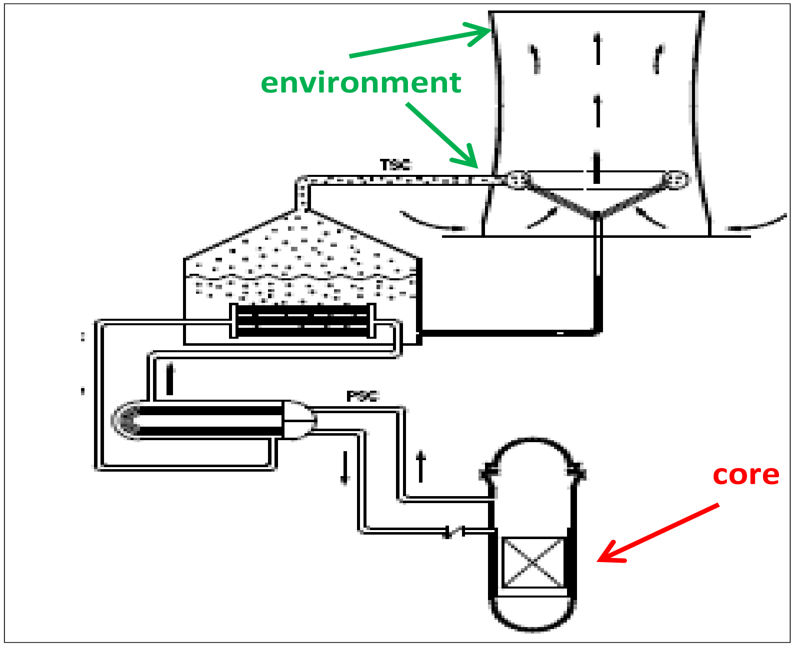
Where

$\Delta p_{driving} = [K]\ H\ (\rho_{cold} - \rho_{hot}) = F\ (G, Q)$

$\Delta p_{res} = \Sigma\ (\Delta p_{local} + \Delta p_{distributed}) = F'\ (G, Q)$

➔ **G vs Q**

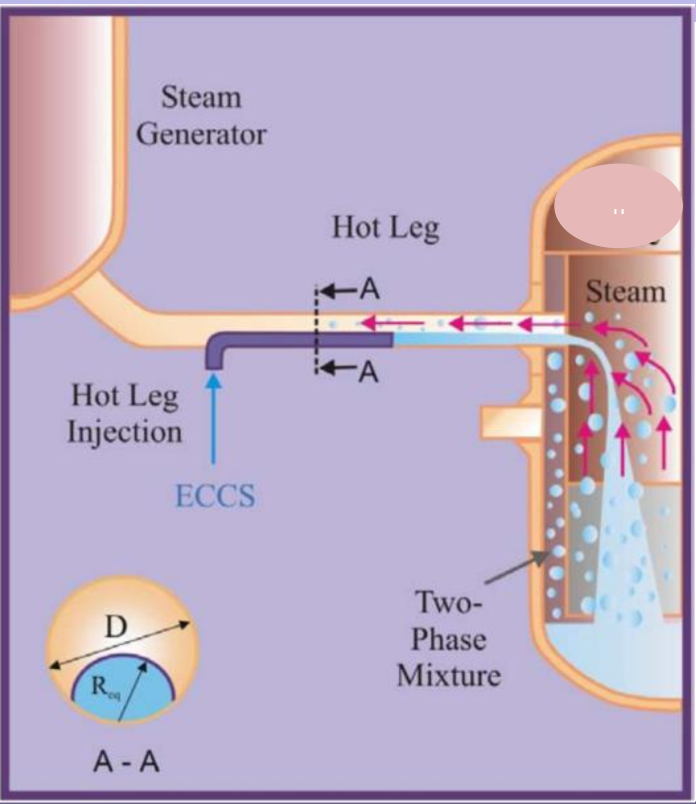


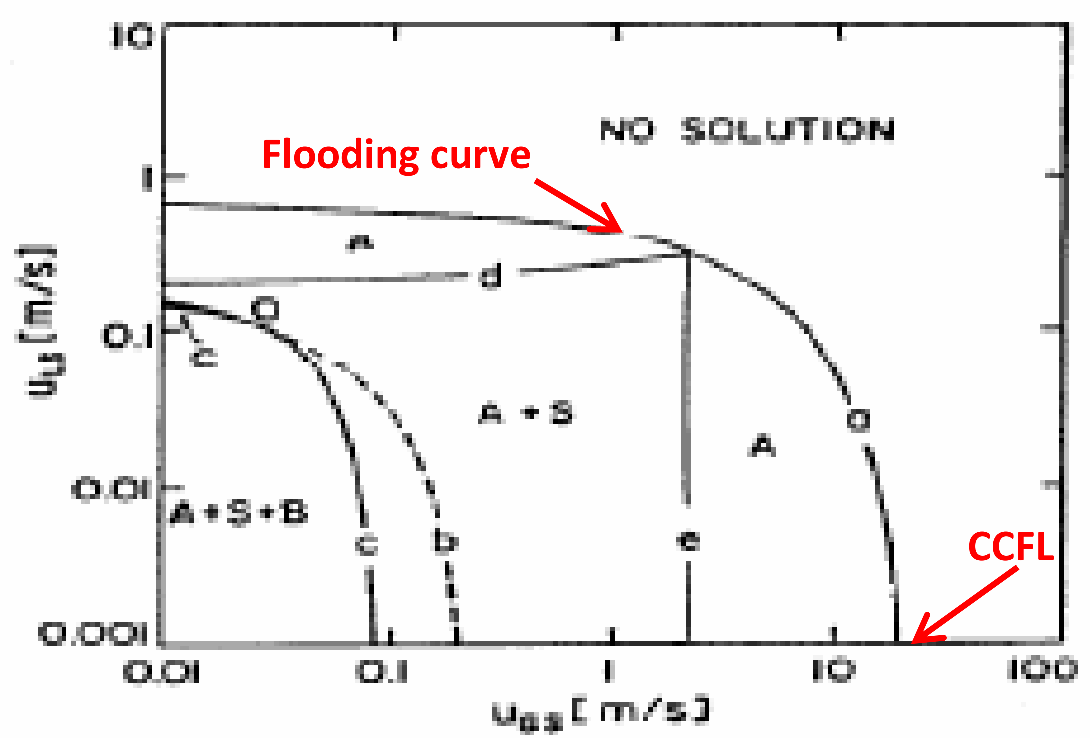


FROM FUNDAMENTALS TO APPLICATIONS

SYSTEM PHENOMENA

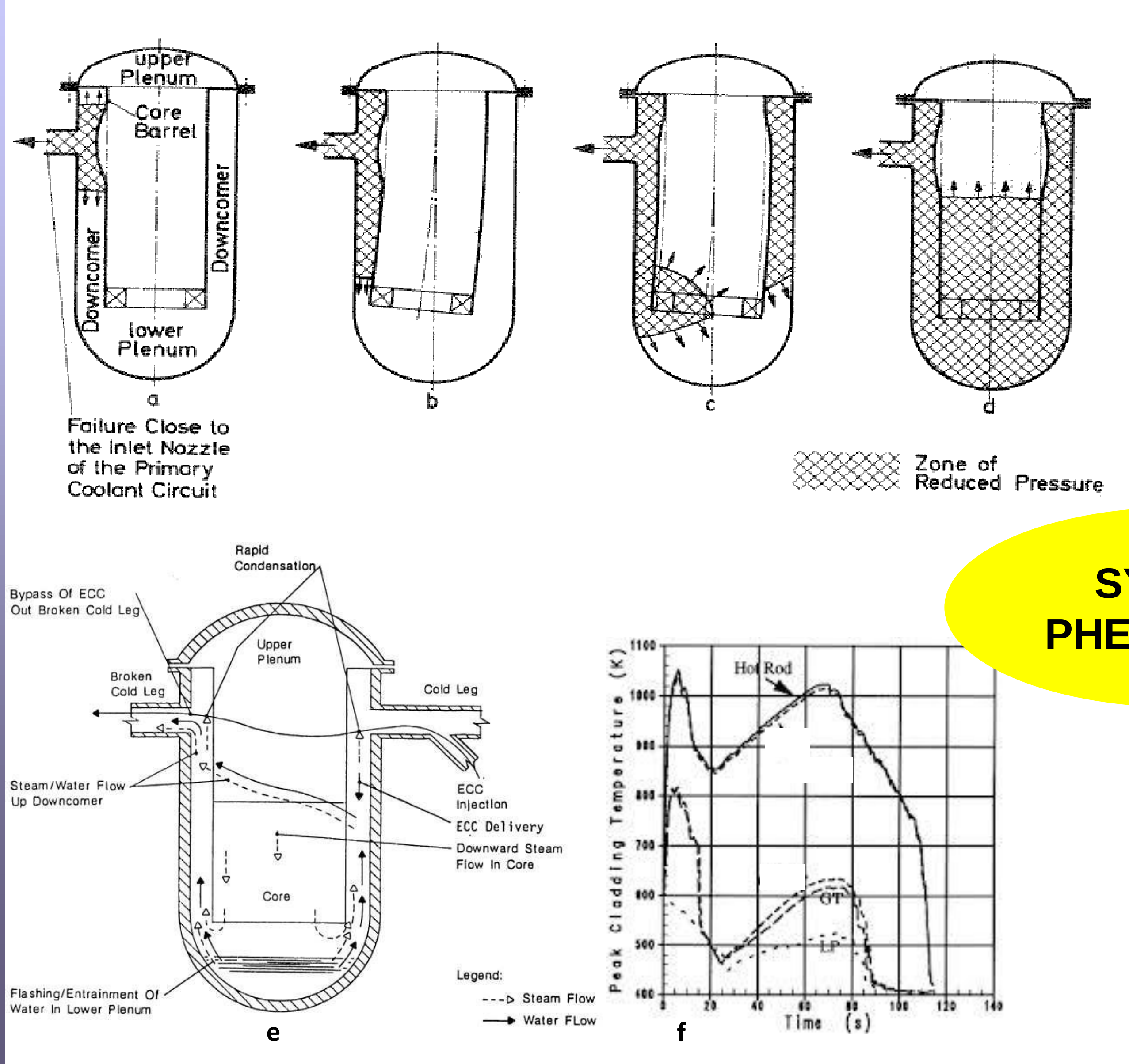
THE COUNTERCURRENT FLOW LIMITATION IN HOT LEG





FROM FUNDAMENTALS TO APPLICATIONS

THE BLOWDOWN: MECHANICAL & THERMAL EFFECTS

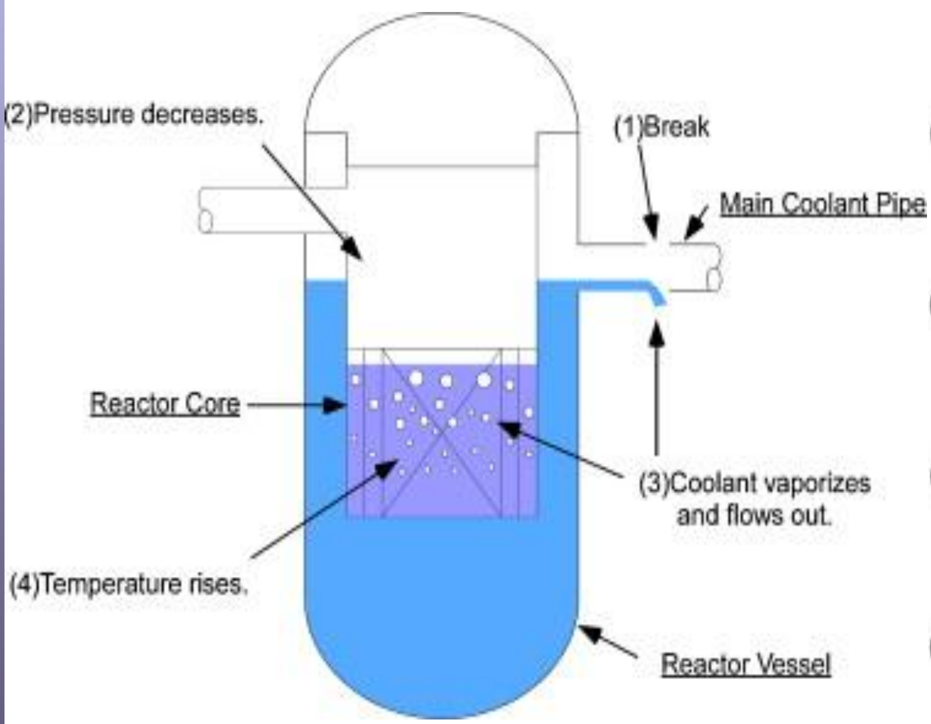


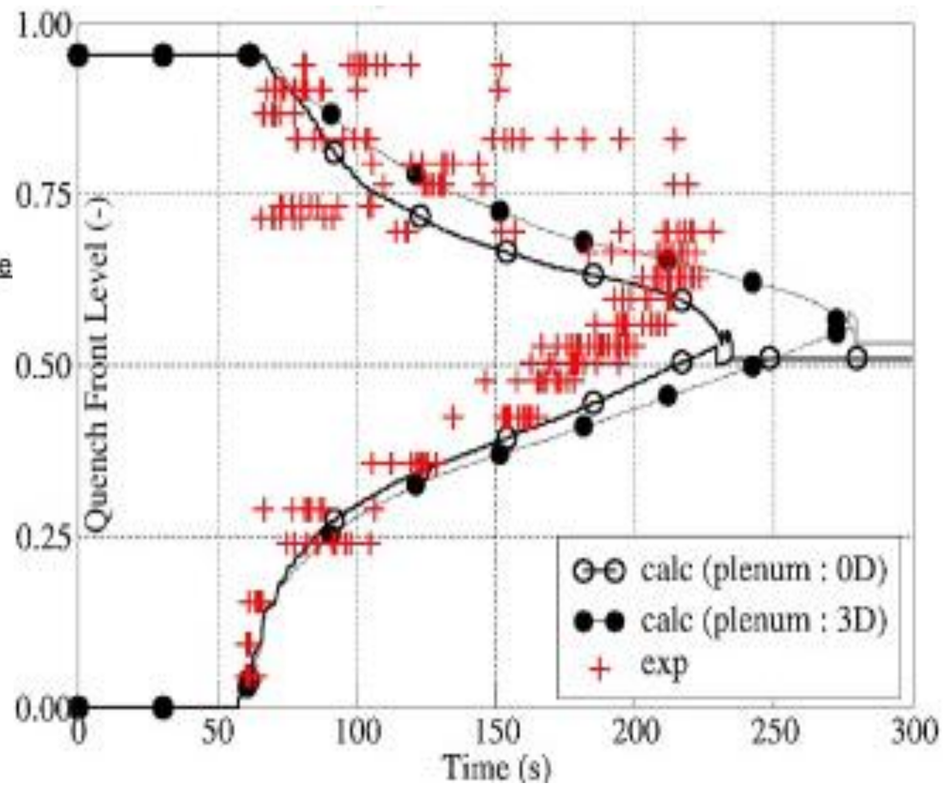
SYSTEM PHENOMENA

FROM FUNDAMENTALS TO APPLICATIONS

SYSTEM PHENOMENA

THE REFLOOD: THE QUENCH FRONT

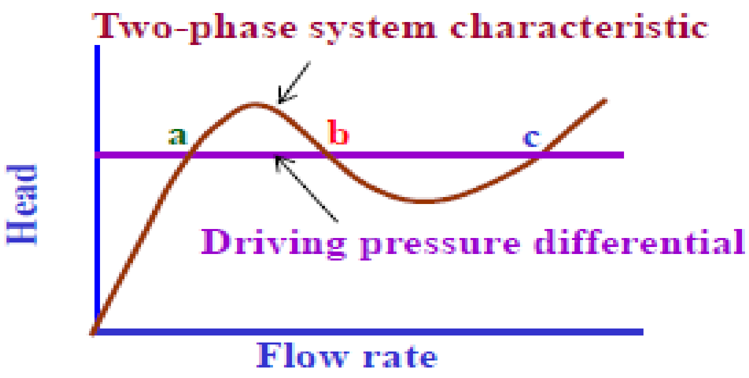




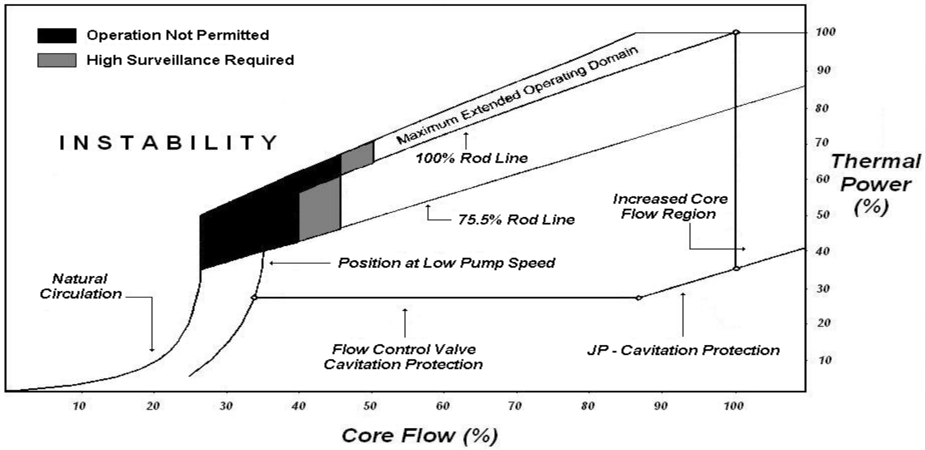
FROM FUNDAMENTALS TO APPLICATIONS

SYSTEM PHENOMENA

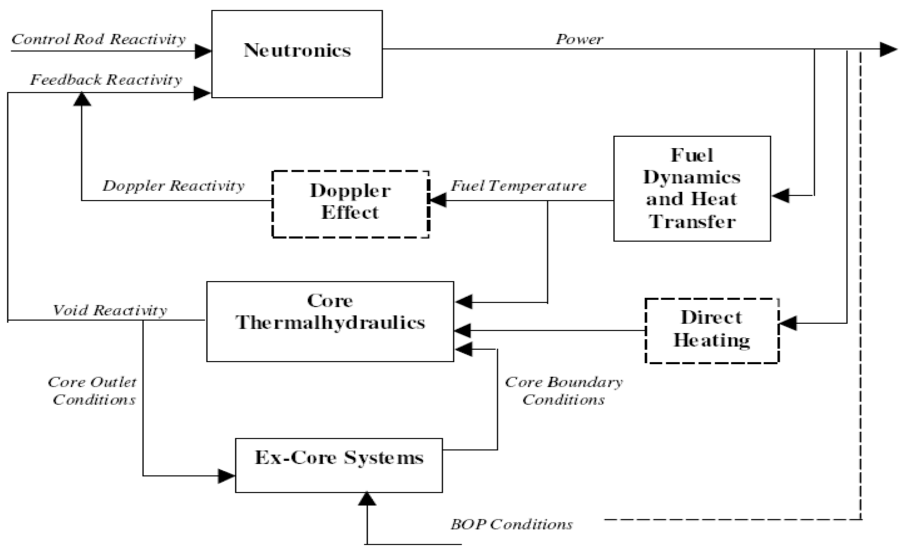
THE STABILITY FOR TWO PHASE SYSTEMS



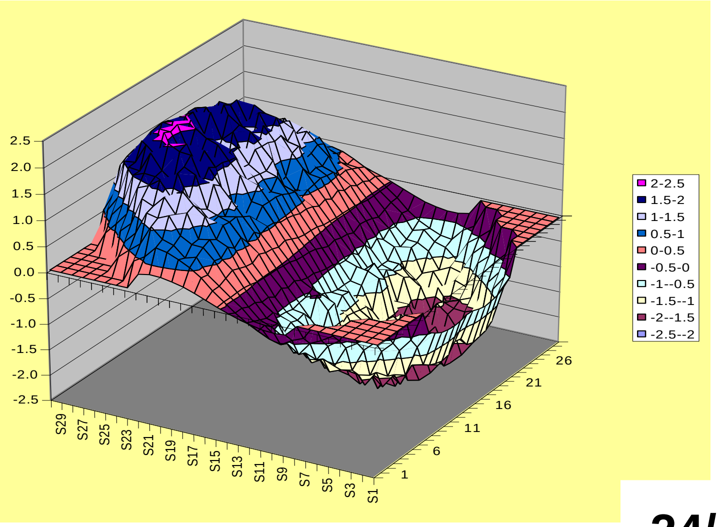
a)



b)



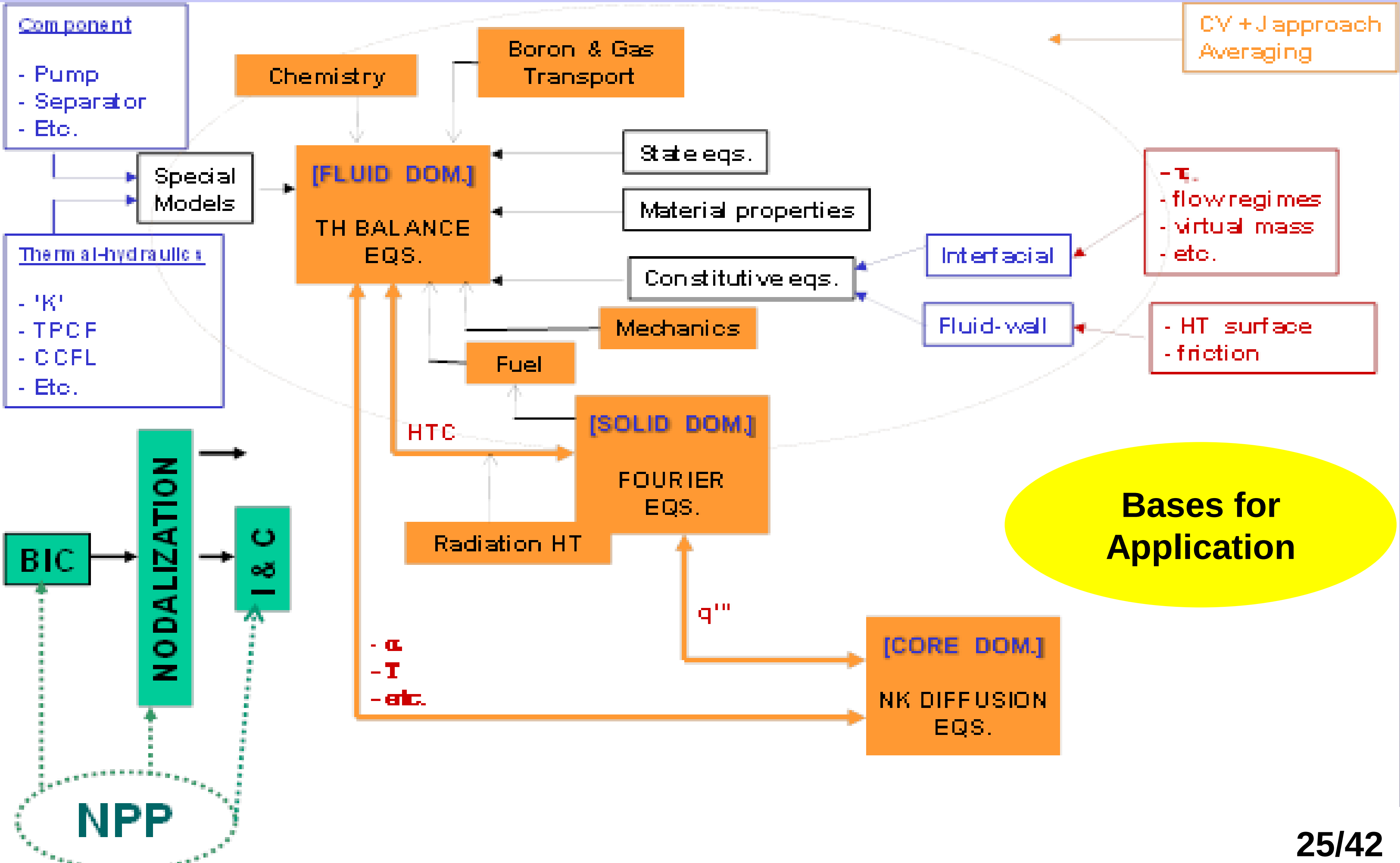
c)



d)

THE COMPUTER CODE & THE VALIDATION

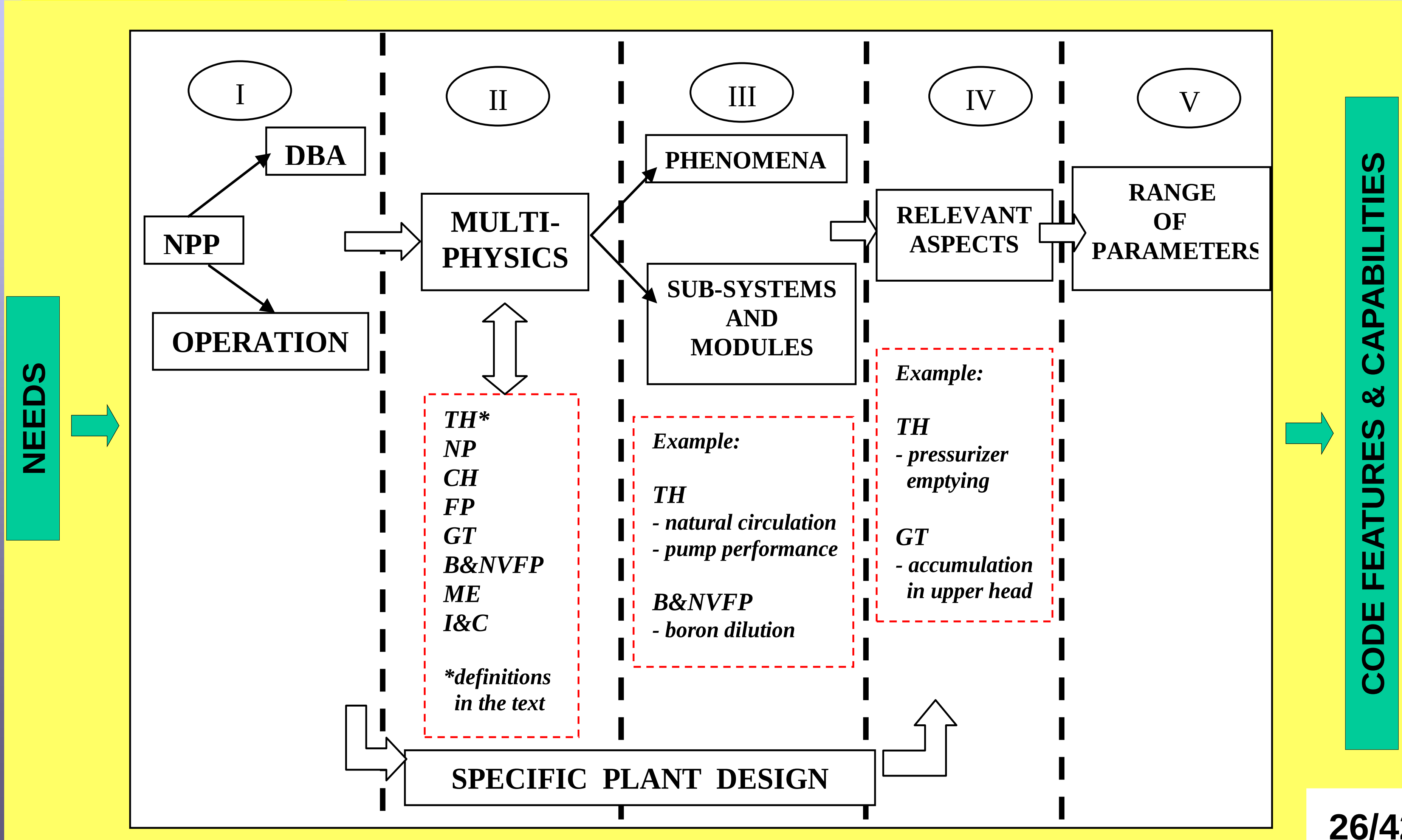
THE CODE STRUCTURE & FEATURES



THE COMPUTER CODE & THE VALIDATION

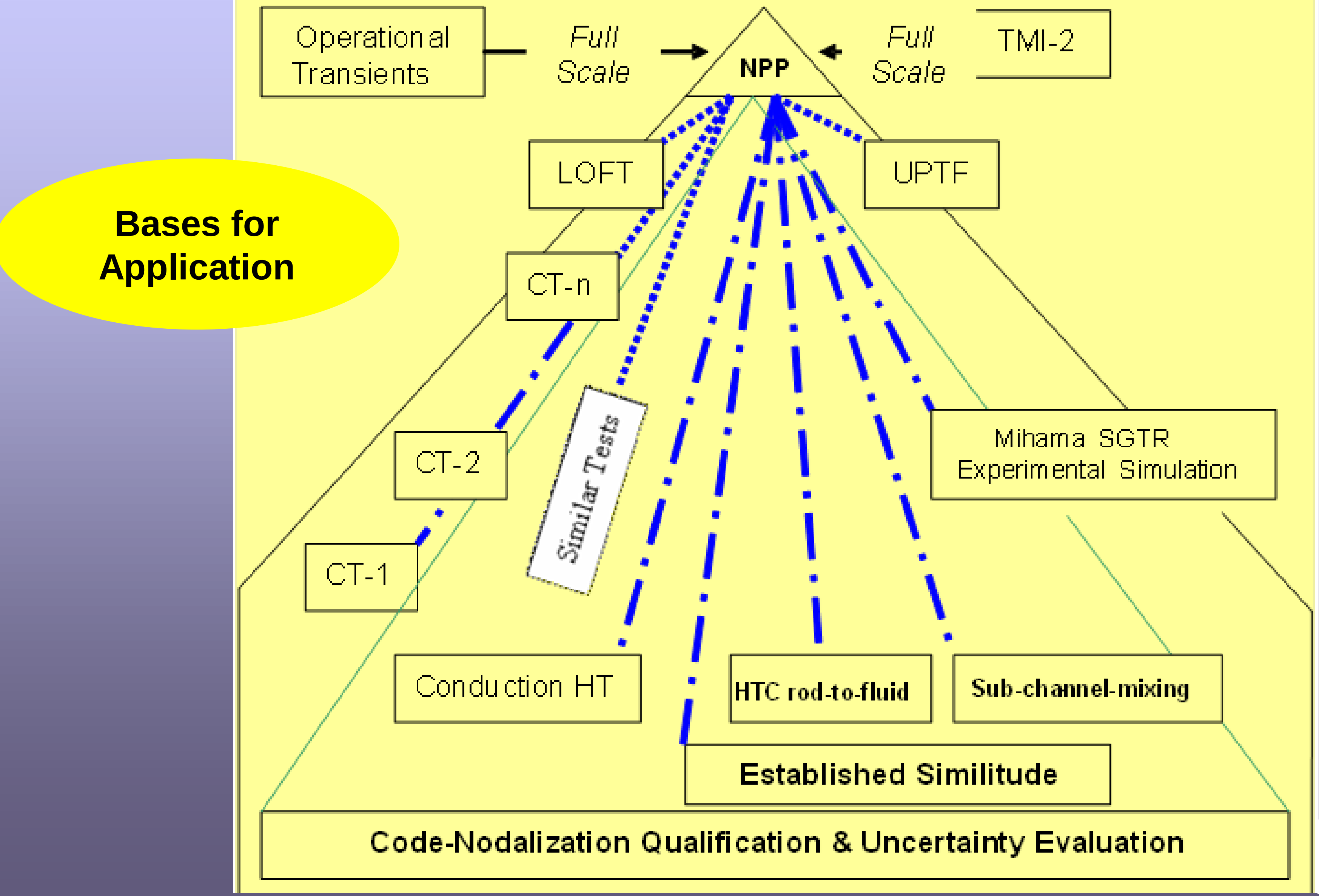
Bases for Application

THE VALIDATION PROCESS



THE COMPUTER CODE & THE VALIDATION

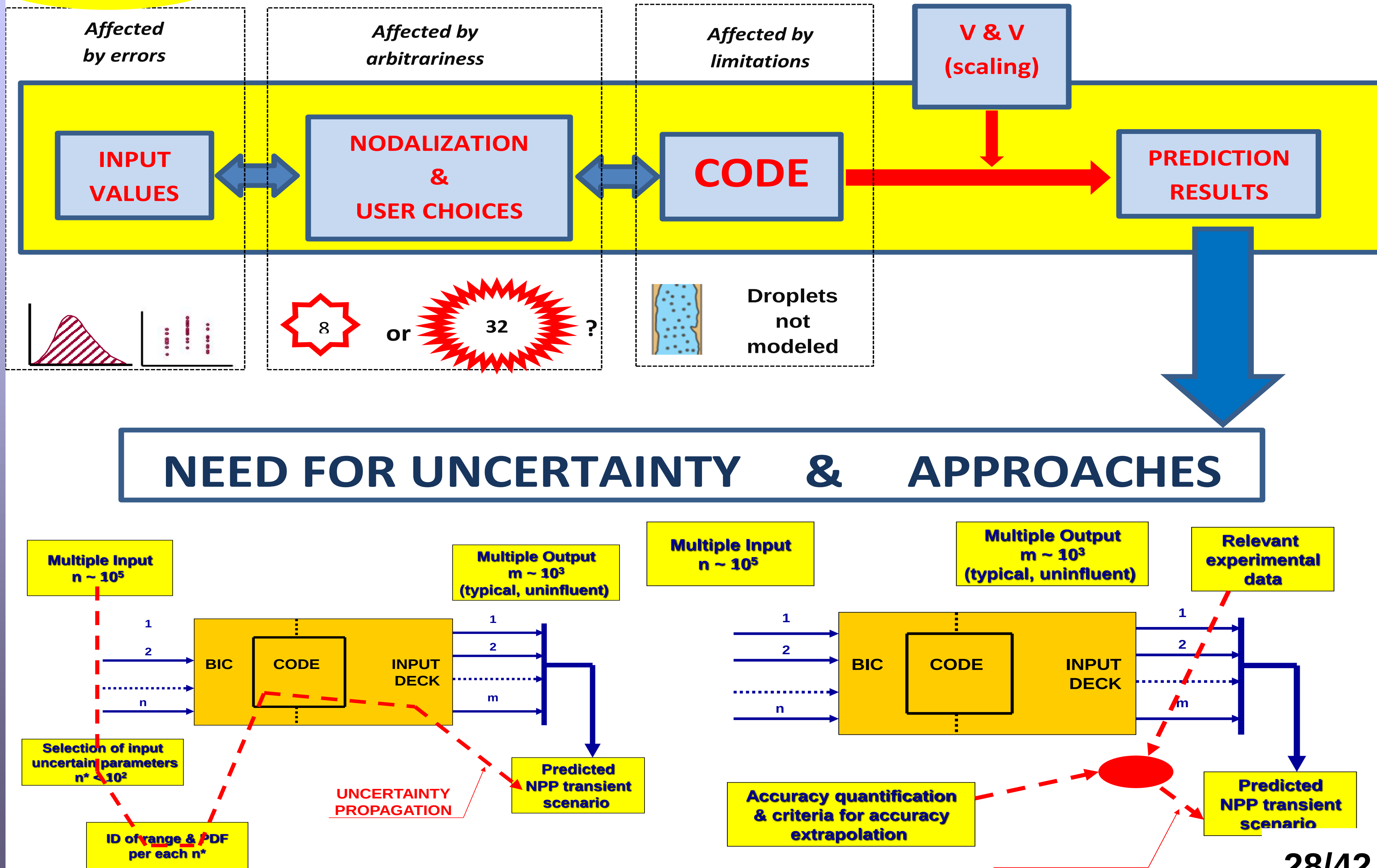
ADDRESSING THE SCALING ISSUE



THE COMPUTER CODE & THE VALIDATION

THE UNCERTAINTY

Bases for Application

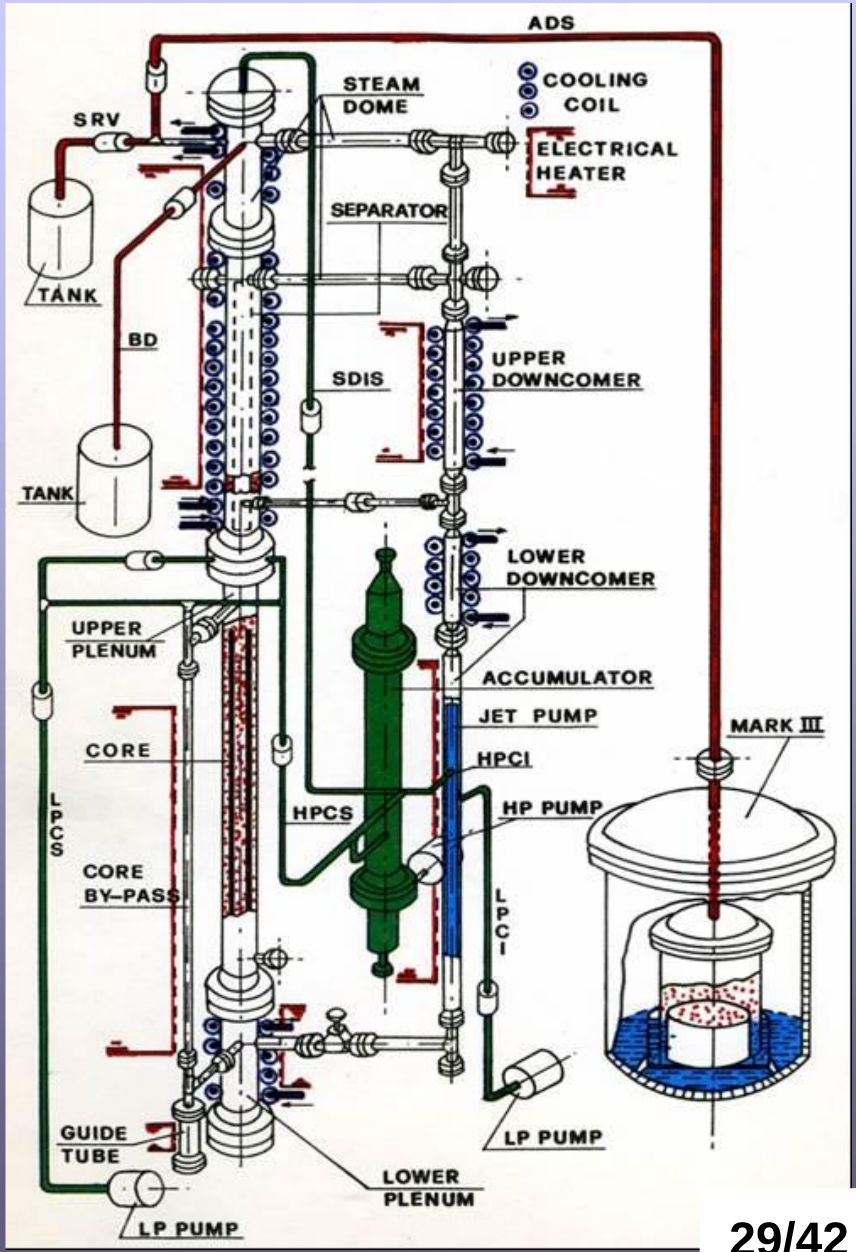


THE COMPUTER CODE & THE VALIDATION

Role of Experimental Facilities: Synthesis for the Process of Validation

PIPER-ONE: AN EXPERIMENTAL FACILITY SUITABLE FOR

- **Understanding physics**
- **Assessing the Scaling Laws**
- **Code Validation**
- **Addressing the Scaling Issue**
- **Enlarging the "Error Database"**



THE BEST ESTIMATE ‘PLUS’ UNCERTAINTY

‘*PERFECT*’ UNDERSTANDING & KNOWLEDGE OF ‘*ALL*’ ELEMENTS IN NUCLEAR THERMAL-HYDRAULICS

⇓

EXPERT IN THERMAL-HYDRAULICS

THE EXPERT LOOKS LIKE A WILD-TRAVELER ENTERING A GHOST CITY

THE WILD TRAVELER UNDERSTANDS EVERYTHING OF THE CITY … BUT HE DOES NOT KNOW WHAT TO DO … CIVILIZATION IS LACKING

THE BEST ESTIMATE ‘PLUS’ UNCERTAINTY

THE GHOST CITY

Bricks, compounds of bricks, infrastructures
(and humans) contribute for a consistent operation

HUMANS BRINGING CIVILIZATION

The visualized network shall be imagined as one working possibility for the town

THE BEST ESTIMATE 'PLUS' UNCERTAINTY (BEPU)

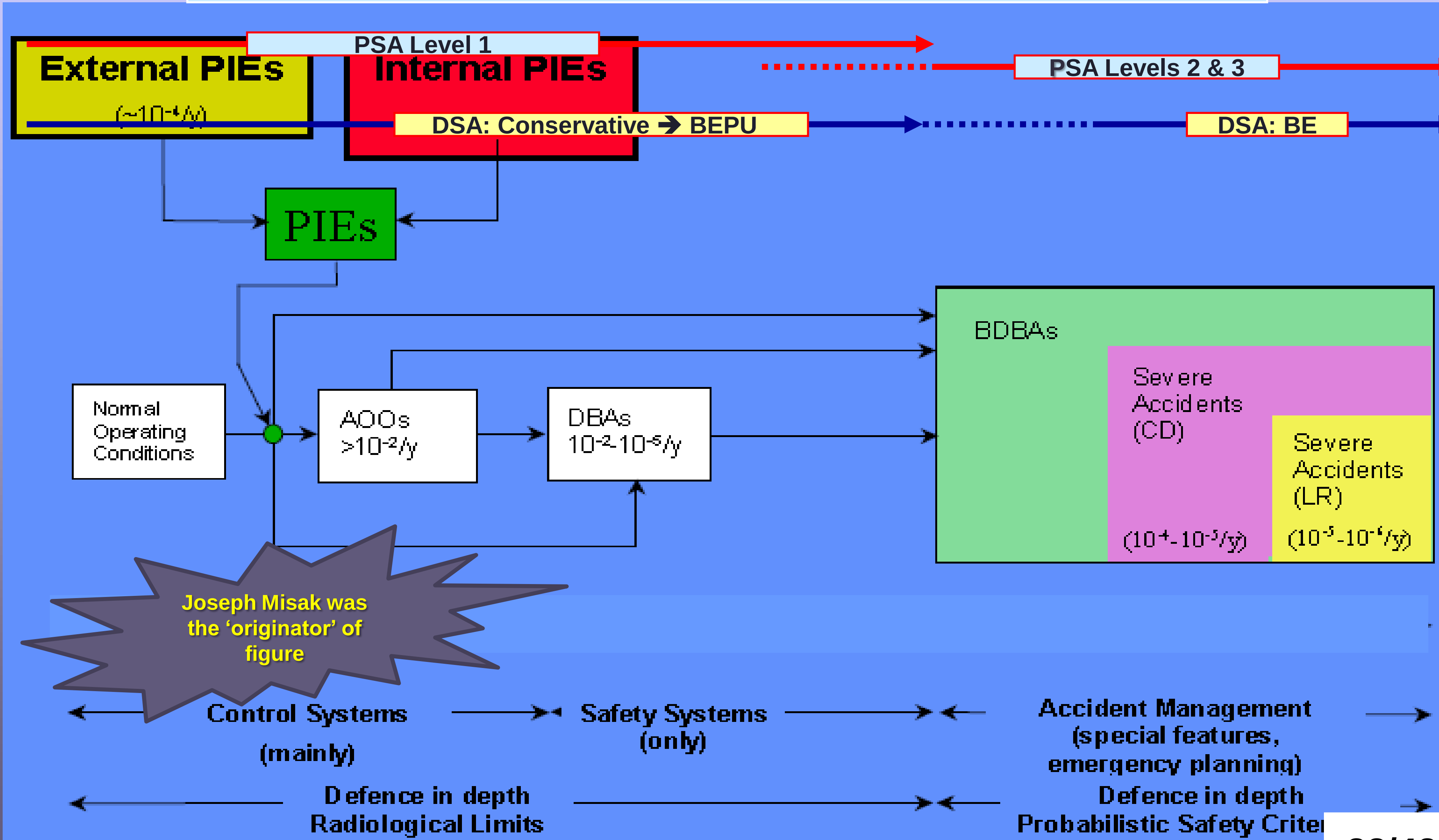
EQUIVALENT TO CIVILIZATION

(FOR THERMAL-HYDRAULICS)

… IT IS NOT EASY TO SUMMARIZE WHAT MEANS CIVILIZATION

THE BEST ESTIMATE ‘PLUS’ UNCERTAINTY

THE LICENSING CONTEXT



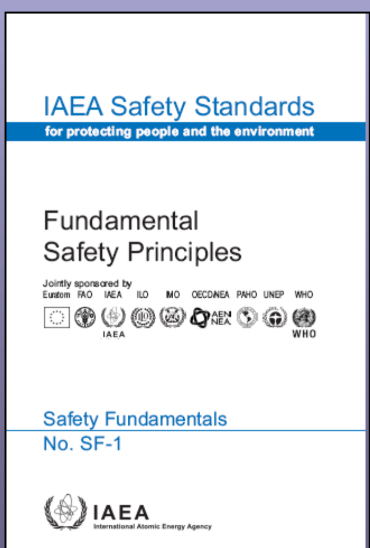
THE BEST ESTIMATE ‘PLUS’ UNCERTAINTY

IAEA HIERARCHIC SET OF DOCUMENTS

Joseph Misak was the ‘originator’ of figure

SAFETY FUNDAMENTALS

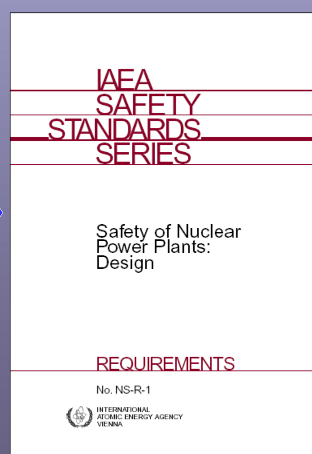
Principles 5 and 8



2006

SAFETY REQUIREMENTS

Comprehensive & detailed analysis required



2000

SAFETY REQUIREMENTS:
Safety Assessment for Facilities and Activities
GS-R-4

2008

SAFETY GUIDES

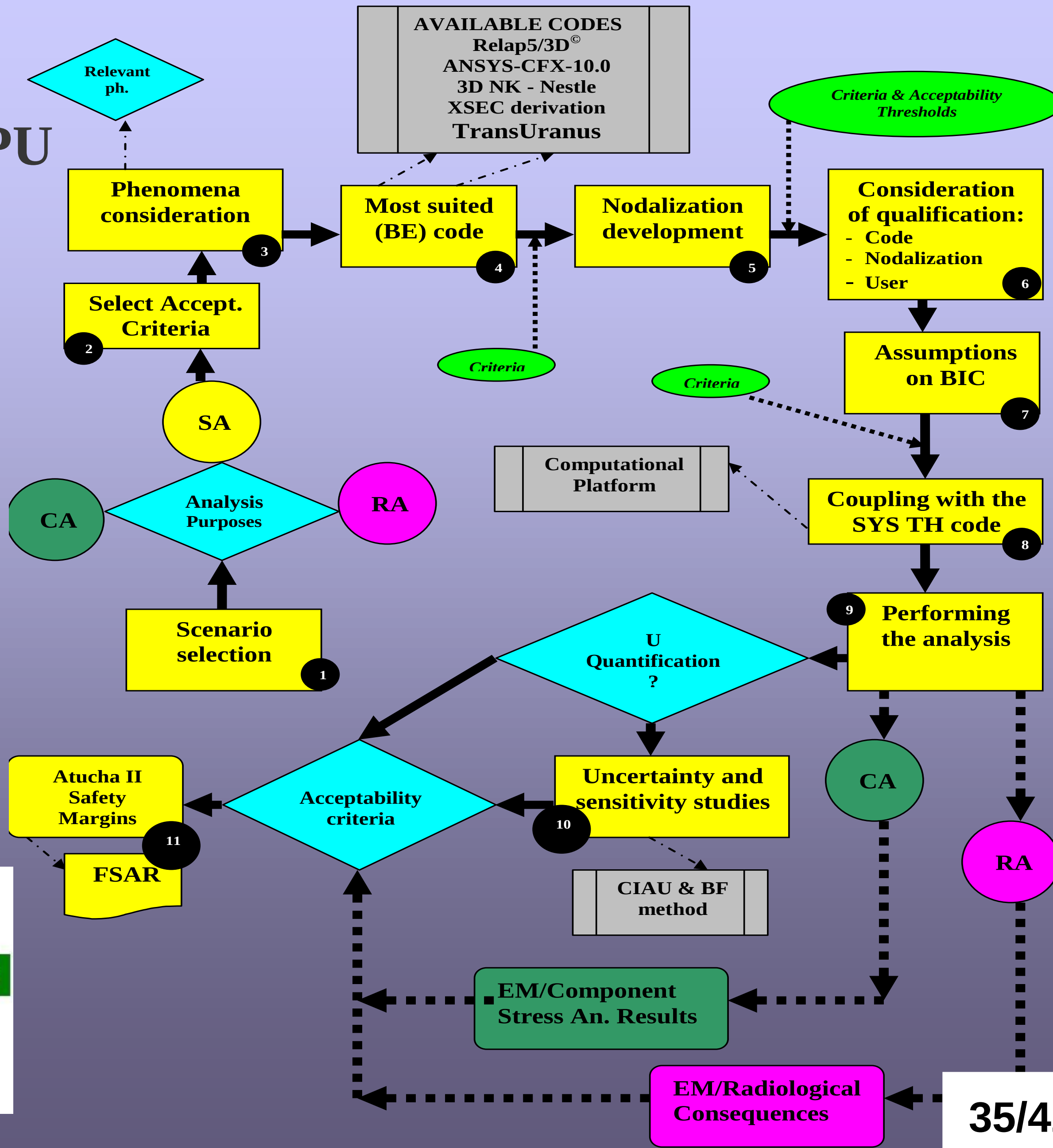
New SGs provide guidance on performing DSA and PSA and their application

Development & Application of Level 1 PSA for NPPs **SSG-3**	Development & Application of Level 2 PSA for NPPs **SSG-4**	Deterministic Safety Analysis for NPPs **SSG-2**

2008/09

THE BEST ESTIMATE ‘PLUS’ UNCERTAINTY

The Road-Map for BEPU



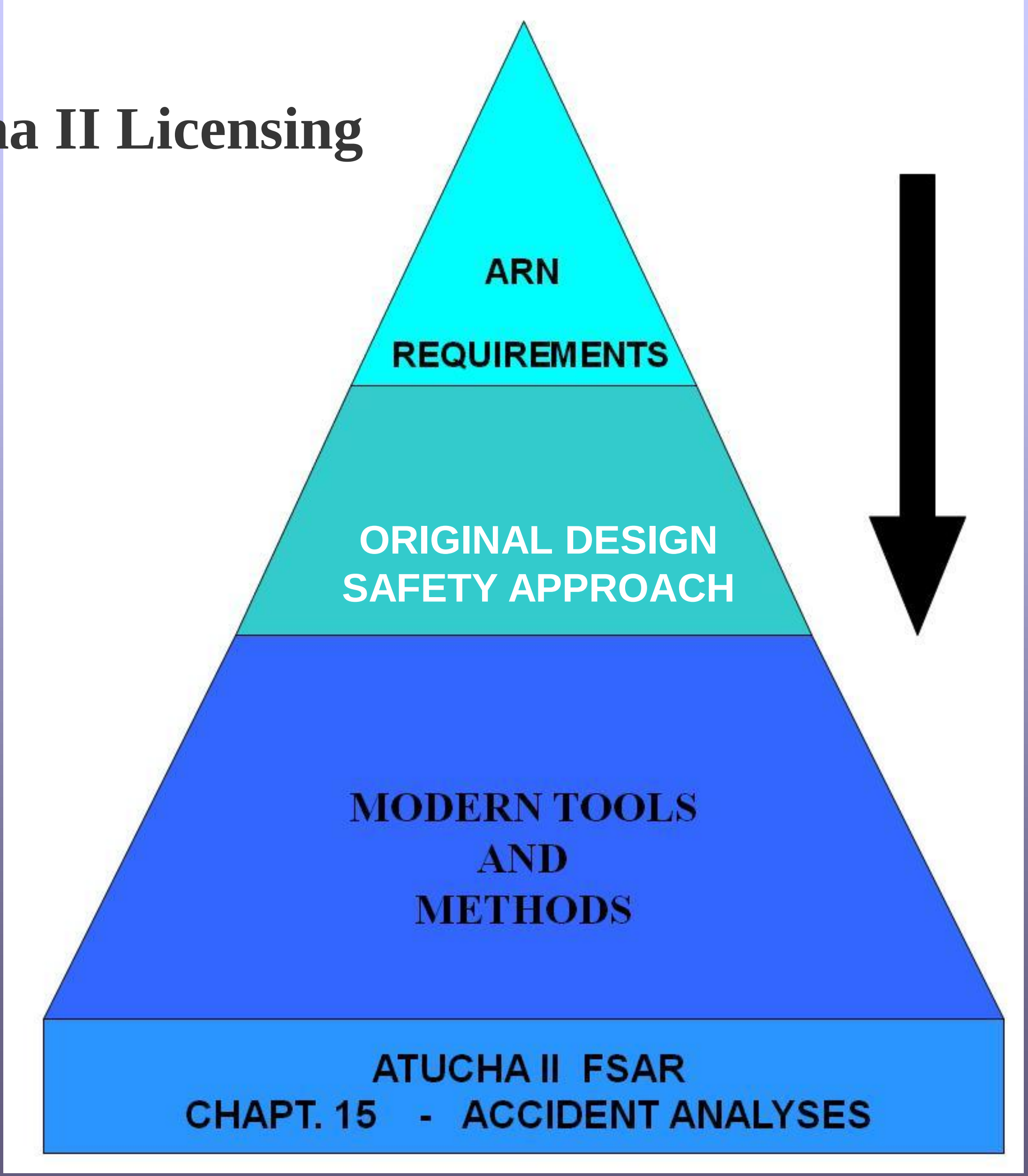
SYSTEM ANALYSIS

COMPONENT ANALYSIS

RADIOLOGICAL CONSEQUENCES ANALYSIS

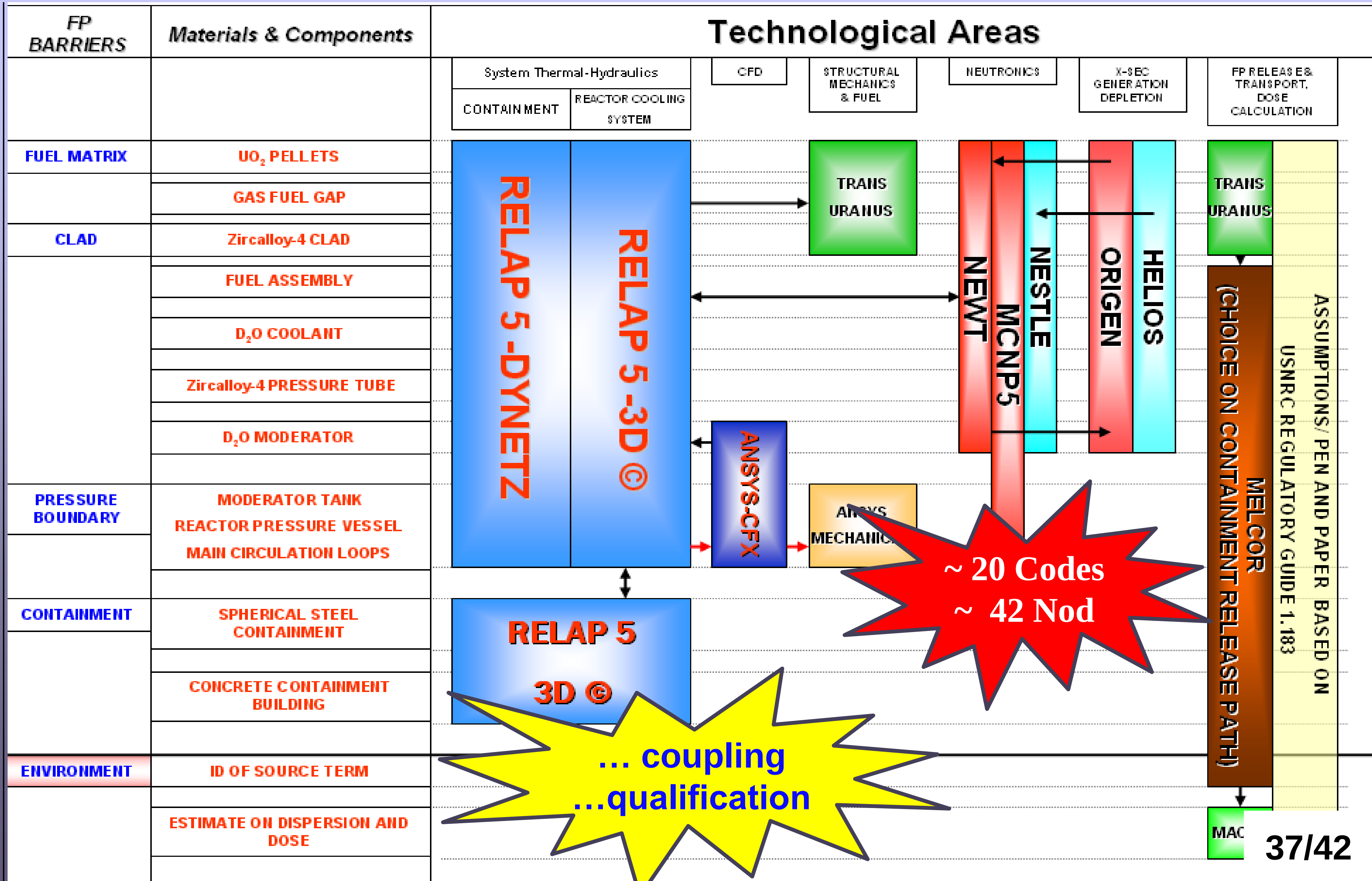
THE BEST ESTIMATE 'PLUS' UNCERTAINTY

The Atucha II Licensing



THE BEST ESTIMATE ‘PLUS’ UNCERTAINTY

THE COMPUTATIONAL TOOLS



CONCLUSIONS

PART 1 OF 5: ADDRESSING THE QUESTION
WHAT IS (NUCLEAR) THERMAL-HYDRAULICS?

A DISCIPLINE WHICH (OR IN RELATION TO WHICH):

0) **IS ONE OF THE PILLARS FOR NPP DESIGN AND NRS**

1) **IS TIGHTLY LINKED WITH EXPERIMENTS**

2) **ADOPTED EQUATIONS ARE 'INCOMPATIBLE' WITH PHYSICS:** THE AVERAGING PROCESS IS ONE ORIGIN FOR THIS, BUT THE WAY TO PRODUCE RESULTS

3) **DEFICIENCIES OF MODELS ARE STUDIED/UNDERSTOOD**

4) **V & V AND UNCERTAINTY MAKE THE DISCIPLINE VALUABLE** (FROM THE TECHNOLOGICAL VIEWPOINT)

CONCLUSIONS

PART 2 OF 5: CONNECTING THE ITEMS AT FUNDAMENTALS
A) THE LENGTH SCALE

Topic	Design Range		Length Scale	Time Scale	Technology Applicability**
* ➔	(m)	(Pa)	(m)	(s)	-
Complex System	**-**		**-15 ÷ 1**	**-15 ÷ 8**	**-**
Geometry for NPP	**-4 ÷ 2**	**-**	**-**	**-**	**Design**
Pressure for NPP	**-**	**2 ÷ 7**	**-**	**-**	**Design**
Flow Regimes	-		-3 ÷ 0	-3	Design & Safety
CHF			-2	0	Design & Safety
TPCF			-2 ÷ 0	-3 ÷ 1	Safety
The Principles and the Equations			> -6 ÷ 8	> -10^{+} ÷ 8	Design & Safety
Natural Circulation			1 ÷ 2	2 ÷ 4	Design & Safety
Flooding & CCFL			-1	1 ÷ 2	Safety
Blow-down			-2 ÷ 1	-3 ÷ 4	Safety
Reflood			-2 ÷ 0	0 ÷ 2	Safety
Density Wave Instability			-1 ÷ 1	-1 ÷ 0	Design
The Numerical Code			-2 ÷ 2	-4 ÷ 5	Design & Safety
V & V Process including Scaling			See the Numerical Code		Safety (primarily)
The Uncertainty Method					
The BEPU Approach					
The PIPER-ONE Facility	-1 ÷ 1	5 ÷ 7	-1 ÷ 1	2 ÷ 4	Safety

CONCLUSIONS

PART 3 OF 5: CONNECTING THE ITEMS AT FUNDAMENTALS
B) THE BUBBLE, THE TURBULENCE, THE RISK

Averaging and empiricism are the answers to the complexity of bubble flows and to the lack of knowledge for turbulence

NUCLEAR THERMAL-HYDRAULICS IS NEEDED TO CALCULATE THE RISK:
THE ERROR (UNCERTAINTY) MUST BE CONSIDERED
(the risk is unavoidable and the 'residual' risk must be accepted)

CONCLUSIONS

PART 4 OF 5: SUMMARY

<BEPU> EQUIVALENT TO

CIVILIZATION

FOR NUCLEAR THERMAL-HYDRAULICS APPLICATIONS

CONCLUSIONS

PART 5 OF 5: LOOK AT THE FUTURE

THE TOWN

(or the knowledge in nuclear thermal-hydraulics including the BEPU-civilization)

RISKS TO BE BURIED BY THE DUST OF OBLIVION