ENERGY AND ENVIRONMENT DEPT. «DIPARTIMENTO DESTEC» – GRNSPG (San Piero a Grado)*

UNIVERSITA' DI PISA
56100 PISA - ITALY

A comment on

Overview of Scaling Methodologies and Approaches

F. D'Auria* *retired from*

EASI-SMR WORKSHOP 1 ON SCALING ISSUES

16-18 DECEMBER 2025, ENEA/SIET, BOLOGNA/PIACENZA, ITALY

PREFACE

Rather than a regular (classic) scaling presentation, e.g., including equations, tables, experimental data, test facility design, etc. …

SOME SCALING 'FACTS' ARE PRESENTED

TOGETHER WITH CONSEQUENCES

Then, the scope (*for the presentation*) is

NUCLEAR REACTOR THERMAL-HYDRAULICS

i.e., water-cooled nuclear reactor (WCNR) with focus on transient scenarios where 2-phase conditions and CHF/DNB occur (*this does NOT imply irrelevance of 1-phase conditions for scaling*).

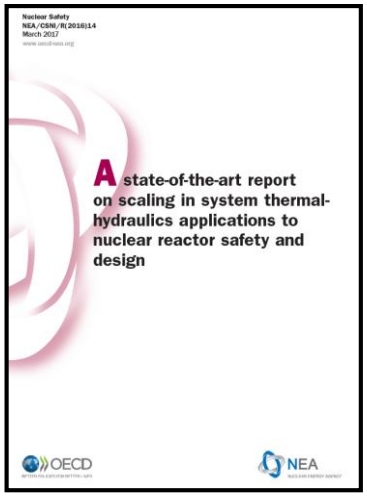
SCALING FRAMEWORKS

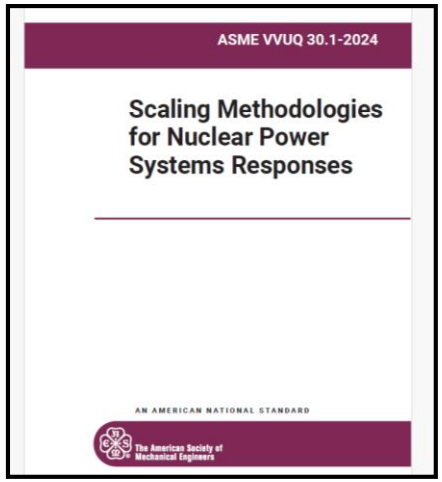
- EDUCATION AND LEARNING
- DESIGN OF FACILITIES & EXPERIMENTS
- (DEMONSTRATION OF) CODES CAPABILITY
- SAFETY/LICENSING OF WCNR
- … ETC.

… the framework-objective for scaling analysis needs identification

HISTORY FLASH

- The ‘scaling issue’ identified and characterized in the 60’s of previous century
- > 50.000 man-years devoted to ‘scaling-issue’ (& Billions USD), including
  - > 50 scaled ITF (designed-constructed-operated)
  - several hundreds scaled SETF
  - > 1000 Basic Test Facilities where scaling is considered
  - several thousands experiments (including CT) performed
  - > 1000 correlations, models, codes (dealing with scaling) developed & validated
  - scaling approaches (‘linear’, ‘time preserving’, ‘… mind …’, etc.). methods (H2TS, FSA, DSS, etc.), non-dimensional quantities (Re, Pr, Nu, etc.).
- Internationally agreed reports have been published (below)





FACTS (to explain scaling)

> 50.000 man-years …

In order to grasp the knowledge from ‘ > 50.000’ man years, each of

- **Internationally agreed report (e.g. reading of)**
- **Applying Buckingham theorem**
- **10 analyses of ITF experiments (see also below)**
- **Application of PIRT + H2TS (or FSA, DSS)**
- **Designing-constructing, operating 1 (one) ITF**
- **Developing and validating a scaling model/correlation**
- **Organizing Workshop, Training, etc.**
- **Developing and solving PDE**

is not sufficient to progress (the knowledge)

although relevant for Education

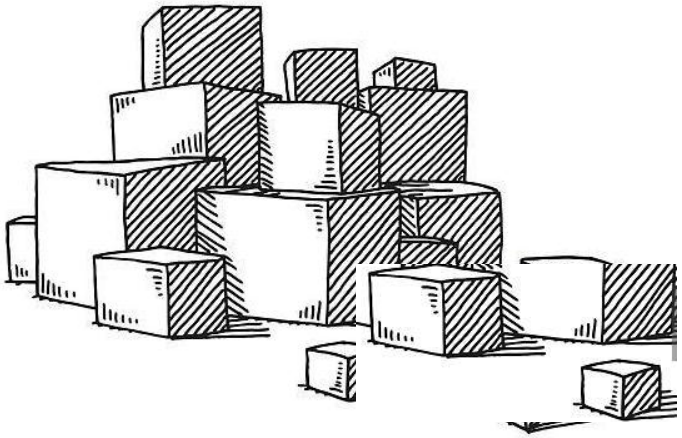
FACTS (to explain scaling)

> 50.000 man-years … Why not AI?

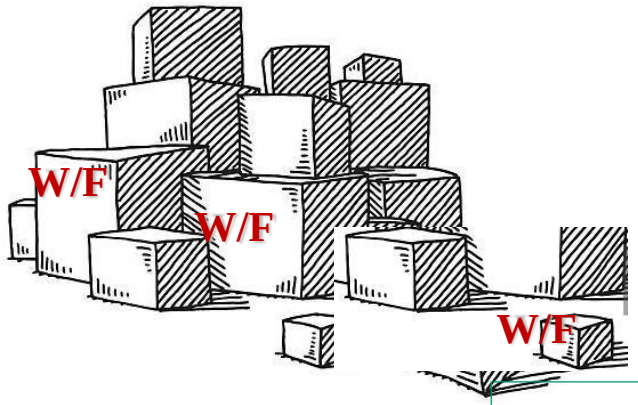
Even AI can be confused:

- **It is possible to build a house from bottom left stones**
- **It is NOT possible to build a house from bottom right stones, without knowing that some stones are Weak or Fake (W/F)**

POSSIBLE PROGRESS



NOT POSSIBLE PROGRESS



FACTS (to explain scaling)

- Relevance of Expertise -

Scaling Connection: Expertise (*for construction*) overpasses established knowledge (*at the time*)

Scaling Connection: Same as above & Scaled Model not sufficient for

* Justifying the (*construction of*) Prototype

* Evaluating Safety Margins

Scaling Connection: A surgeon, after 1000 operations has more experience than after 10 operations

* Next slide

FACTS (to explain scaling)

- Relevance of Expertise -

* Some explanatory notes

Case of Coliseum & Brunelleschi's Dome:

The expertise not documented in books allowed construction

Case of Scaling

The expertise not documented in books allows scaling analyses

Case of surgeon doctor

The expertise from 1000 operations cannot be transcribed in books

Case of Scaling

The expertise from the analysis of 100 ITF experiments cannot be transcribed in books

***Furthermore, as in the case of scaling** (from Brunelleschi's dome and surgeon doctor, respectively):*

- *The final product may remain unprovable*
- *A young person cannot start his career having the experience of 1000 operations.*

FACTS (to explain scaling)

- ASME & Turbulence -

The ASME Scaling Report needed a ≈ four-years approval-rejection process by a top-level Steering Committee (*members not involved with transient 2-phase thermal-hydraulics*). Why?

Errors (& acceptance of errors) in scaling are so large (wide) to be un-common and unbelievable within scientific fields outside (transient) nuclear thermal-hydraulics

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

Lack of detailed knowledge of turbulence is at the basis of above, e.g., in a domino effect leading to:

- **Averaging approximations,**
- **Compensating errors,**
- **i.e. inadequate modeling and scaling capabilities.**

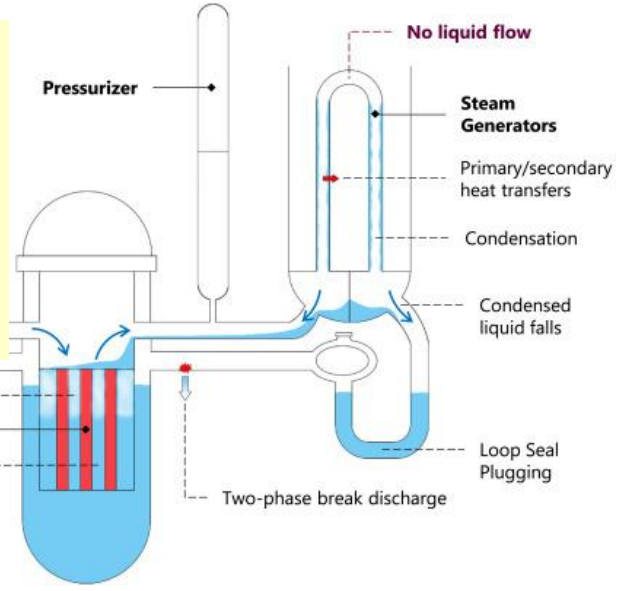
Overcoming inadequate knowledge of turbulence (🡐 *bottom left, spotted since 500 years or more*), needs a 'guru-type' expertise.

FACTS (to explain scaling)

- Loop Seal Formation-Clearing (LSFC)-

(Nuclear thermal-hydraulics) Scientists are well familiar with LSFC, e.g. during SBLOCA, NC reflux-condensing type of scenario.

Is LSFC reproducible in a scaled experiment (with suited timing / consequences – e.g. CHF)? … No.



Not a safety issue

… Due to following key motivation:

LSFC depends upon values of parameters (*these are either input or output in code calculations*) that are within the respective uncertainty ranges. I.e., LSFC may occur or not (*and/or timing for LSFC can be largely affected*) depending upon small changes of those values.

Examples of concerned parameters are local pressure drops at geometric discontinuities, heat transfer coefficient across SG tubes, CCFL coefficients at the inlet of SG tubes, core bypass sizes in RPV, MCP trip and coastdown.

LSCF not (scaling) reproducible … 'guru' type expertise to evaluate (scaling) impact-relevance

… Furthermore,

LSF may cause CHF and Rod Surface Temperature (RST) excursion.

RST excursion occurs during time LSF-LSC; because of core power, this is ≈ 100 s, causing PCT values < 1000 K.

NOT SCALABLE (ENTITIES)

- Sample List, 1 of 2 -

❖ **Edge Sharpness (e.g. orifices, CL-RPV, SG-tube entrance: NOT KNOWN.**

Edge sharpness is not measured in nuclear reactors. It has significant impact upon local pressure drops (i.e. scaled model vs prototype). No scaling factor deals with edge sharpness.

❖ **DP = f (Re, α, geometry), or 'K*loss*' from empirical formulation of DP : NOT KNOWN.**

'f ( )' is not known, then, it cannot be scaled. Its knowledge is essential for the prediction of any transient scenario in WCNR.

❖ **Heat Losses depend upon experiment and environment conditions.**

Heat Losses cannot be scaled; better heat losses coming from scaling laws cannot be imposed..

❖ **Thicknesses of (passive) structures, flanges, etc., derive from structural mechanics.**

Thicknesses are connected with thermal energy stored in (and released/acquired by) structures and, in the case of a model, cannot be scaled according to scaling laws.

NOT SCALABLE (ENTITIES)

- *Sample List, 2 of 2* -

❖ **HTA of (passive) Structures, flanges, etc., derive from geometry laws.**

HTA are connected with thermal power exchange of structures and, in the case of a model, <u>cannot be scaled</u> according to scaling laws. It is well established that in the case of 1/1000 volume design factor, HTA can be 30 times larger than the ideal (scaled) value.

❖ **Nuclear Fuel Material, Burn-up during reactor life, Neutron-flux interaction with TH-parameters, γ-heating, etc,**

All of above <u>is not scaled</u> in any model. Their role is essential in (scaling-modeling of) specific scenarios like 2-phase instabilities in boiling systems.

❖ **. . .**

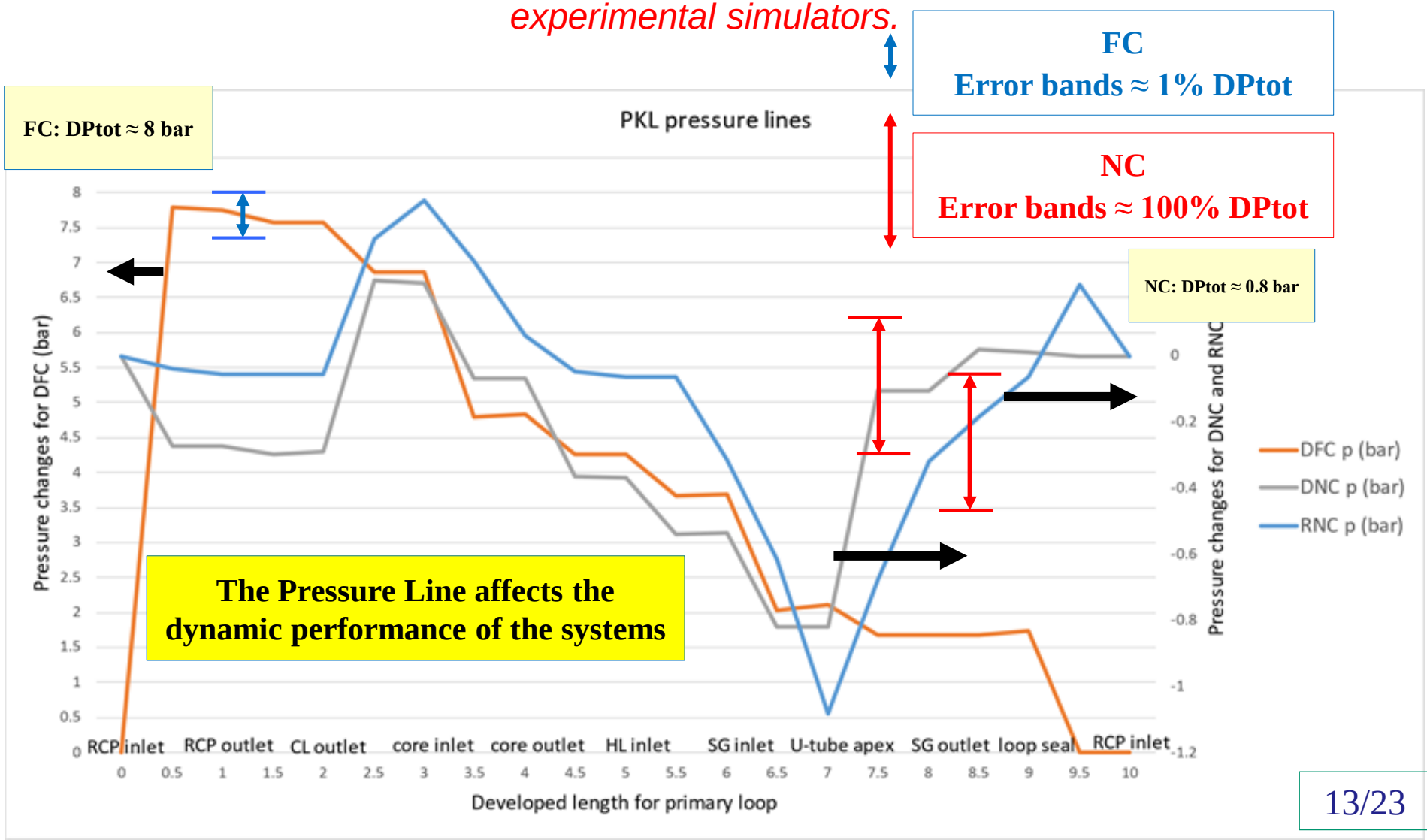
. . .

Systematic Kv-scaled analyses, e.g. supporting (scaling) uncertainty are needed … again 'guru' type of expertise

SCALING AND NC-BASED PASSIVE SYSTEMS

A SCALABLE ENTITY *NOT CONSIDERED IN DESIGNS*:THE PRESSURE LINE

A key scaling parameter (typically) not considered in the design of passive system experimental simulators.



SCALING AND NC-BASED PASSIVE SYSTEMS

THE PRESSURE LINE

Availability of the pressure line

Owing to limitations of predictive models for DP, e.g. DP = f (Re, α, geometry),

a) the existence of experimental data is needed, at least in 1-phase flow, … but

b) no data exist for the prototype, &

c) 'quality' data imply the availability of a pump to establish DP having 'reasonable error' … then

d) There is no proof that any built NC model 'simulates' the prototype dynamic performance (true, for CMT loop, PRHR loop, NC-RPV, etc.). *… Furthermore,*

e) Computing the DP line via CFD (much better than doing nothing) does not ensure sufficient accuracy in 1-phase flow and implies large errors in 2-phase flows.

*f) Adopting pumps to establish DP lines (reasonable errors in 1-phase flow) should be a requirement for NC system experimental simulators. (... **the challenge for 2-phase flow remains ...**)*

SCALING - STATUS

DISTORTIONS

- **SCALING DISTORTIONS ARE UNAVOIDABLE (can be addressed by Kv-scaled)**
- **RESOLVING ANY DISTORTIONS MAY IMPLY SIGNIFCANT RESOURCES**
- **THE AVAILABLE (SCALING) DATABASE SUPPORTS THE SAFETY DEMONSTRATION OF EXISTING WCNR (DB extension is needed for new reactors).**
- **DISTORTIONS & COMPENSATING ERRORS UNAVOIDABLY CONNECTED ◄► KNOWLEDGE/MODELING OF TURBULENCE**

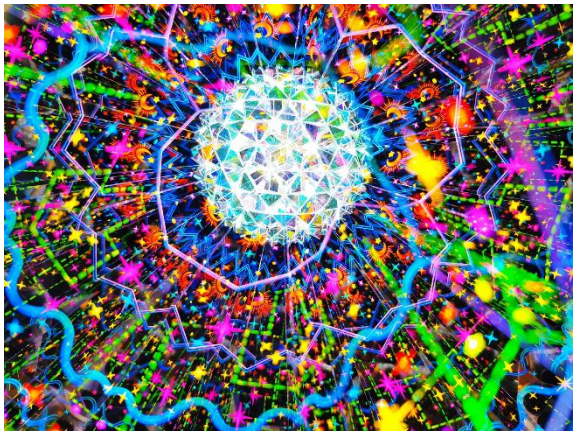
SCALING - TOPICS

NOT PART OF THIS PRESENTATION

- Scaling approaches (*time preserving, volume & power scaling, 'mind scaling', etc.*)
- Scaling models (*H2TS, FSA, DSS, …*)
- PDE at the basis of non-dimensional groups (*Buckingham theorem*)
- Design of Scaled ITF and SETF, Experiments (*model vs prototype*) & the Scaling DB
- Scaling of exp-data (*not possible*), code-calc-data (*not possible*) & errors (*possible*)
- Counterpart Tests, Similar Tests
- The paradoxes of: **(a)** SS & FD flow; **(b)** CCFL scaling (*+ similar situations*); **(c)** CHF unavoidable error; **(d)** compensating errors; **(e)** non-scalable entities; **(f)** etc.
- Scaling distortions and Kv-scaled analyses (*also … scaling as part of BEPU &licesning*)
- Design Factors & Scaling Factors (*or, non-dimensional groups*)
- Accuracy evaluation and UQ for Scaling Factors
- IUQ for Scaling Factors (*… a dead-end*)
- Scaling Pyramid, Scaling Bridges
- Scaling Roadmap (*demonstration of scaling capabilities of codes & ITF/SETF design*)
- FFTBM to quantify/assess scaling distortions

SCALING - FUTURE

A KALEIDOSCOPE OF INFORMATION



… WHAT TO DO?

It is (*very*) ambitious to plan a progress (*i.e. moving the boundaries of the knowledge*) in the area. In the presence of:

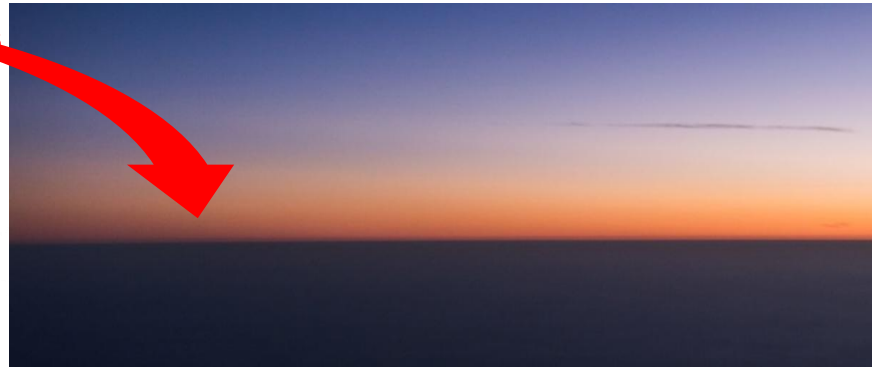
- **The kaleidoscope of "infinite" information**
- **Huge and unrepeatable investments in the past**

YOU MAY:

- **"Critically" consider the OECD/NEA S-SOAR & the ASME-VVUQ documents**
- **Consider the present document [including "focusing on a scaling framework"]**
- **Follow the CONUSAF Scaling Benchmark [next slide]**

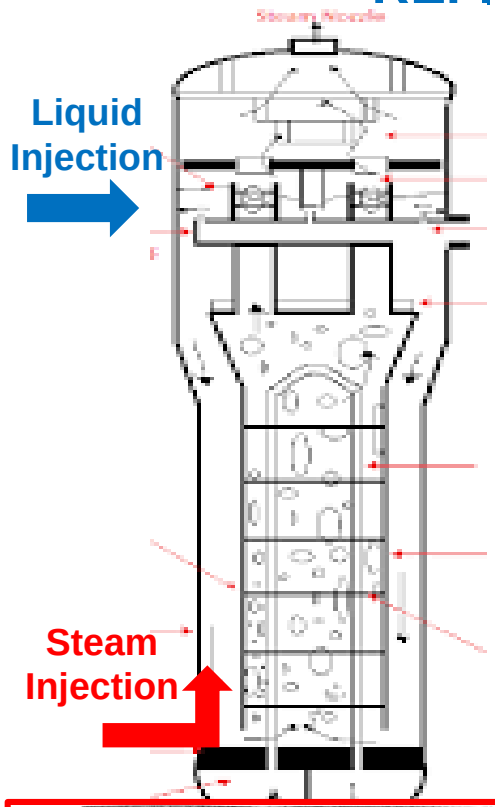
…. e.g., 100 ITF experiments analyses

From darkness of ignorance to sunshine of knowledge



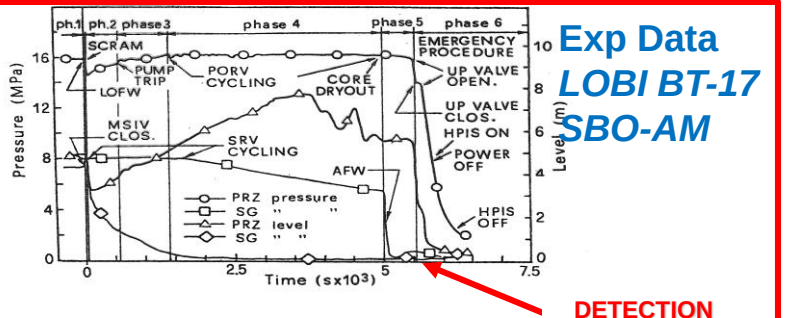
CONUSAF SCALING BENCHMARK - 2026

REFILLING OF AN EMPTY SG (secondary side)



WHEN CHANGING THE (SCALED) THICKNESS OF THE DOWNCOMERAND THE PRESSURE, WHAT HAPPENS:

- **To flooding-CCFL?**
- **To heat transfer from hot wall to falling (film-jet) liquid?**
- **Transient liquid level formation in the bottom?**



Exp Data
LOBI BT-17
SBO-AM

DETECTION OF A FLAW

Fig. 3 - LOBI BT-17 experiment: pressure in primary side and in steam generator and level in pressurizer and steam generator downcomer.

SCENARIO INVESTIGATED ≈ 40 YEARS BEFORE: SEVERE FAILURE OF CODE-MODELING (confirmed 20 years ago).

IS THE MODELING IMPROVED?

CAN SCALING BE HANDLED TODAY?

CONCLUSIONS

- **ATTEMPTING TO PROGRESS OVER > [50.000 MAN-YEARS & BILLION USD] INVESTMENTS IS AMBITIOUS (*or, simply, not possible*)**

- **THE SCALING DB TO DEMONSTRATE THE SAFETY OF EXISTING REACTORS IS ENOUGH (*not the same is true for new reactors*)**

- **SCALING IS NOT A MATTER FOR MATHEMATICIANS OR THEORETICAL PHYSICISTS ALONE (*at least until complete knowledge of turbulence is available*)**

- **PATIENCE AND PERSEVERANCE NEEDED TO ANALYZE SEVERAL DOZEN SCALED ITF EXPERIMENTS (*including CT*).**

- **UNDERSTANDING DEEPLY EACH OF THE SCALING TOPICS (*not an exhaustive list provided*) IS A PREREQUISITE TO PROGRESS**

(MORE) FORMAL SCALING PRESENTATIONS

(… available to discuss any related topic)

ENERGY AND ENVIRONMENT DEPT. «DIPARTIMENTO DESTEC» – GRNSPG (San Piero a Grado)

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Presentation of OECD activities to update the (ASME) Scaling Analysis Document

F. D'Auria

SESSION: PD-A AN OVERVIEW OF ASME VVUQ STANDARD COMMITTEES AND OECD NEA ACTIVITIES

MAY 19-24, 2024 - LUCCA, ITALY
BEPU 2024
BEST ESTIMATE PLUS UNCERTAINTY INTERNATIONAL CONFERENCE
Multi-Physics Multi-Scale Simulations with Accuracy and Uncertainty
Towards a broader and consistent application in safety assessment and licensing

University of Pisa
DESTEC-GRNSPG
Nuclear Research Group in San Piero a Grado (Pisa) - Italy

SCALING IN SYSTEM THERMAL-HYDRAULICS APPLICATIONS TO NUCLEAR REACTOR SAFETY AND DESIGN:

A STATE OF THE ART REPORT (OECD/NEA/CSNI S-SOAR)

LEAD AUTHORS: Bestion D. (CEA, Grenoble, France), D'Auria F. (UNIPI, Pisa, Italy, Editor), Lien P. (NRC, Washington D.C., US), Nakamura H. (JAEA, Tokai-Mura, Japan)

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OECD/NEA/CSNI 19th Plenary Meeting of the Working Group on Analysis and Management of Accidents (WGAMA)
OECD Conference Centre, 2, rue André Pascal, 75016 Paris (F)
September 20-23,2016

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

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THE SCALING ISSUE IN NUCLEAR THERMAL-HYDRAULICS

The success of power-to-volume scaling applied to Full-Height Full Pressure Integral Test Facilities

F. D'Auria

NURETH-15 Pisa – Conference Workshop W19
Relevance and Purpose of Scaling Analysis for the development of Better Simulation Thermal-Hydraulic Tools

May 11, 2013 – Hotel Bonanno, Pisa (Italy)23