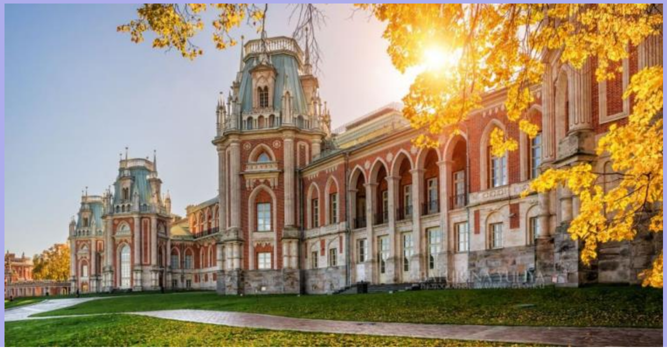
University of Pisa
DESTEC-GRNSPG
Nuclear Research Group in San Piero a Grado (Pisa) - Italy

IMPROVING SAFETY: CURRENT AND FUTURE NUCLEAR REACTORS

F. D’Auria

N. Debrecin, H. Glaeser

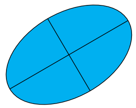


5th International Summer School on Engineering Computing in Nuclear Technology

Russian Federation, Moscow, Kashirskoe shosse, 31
June 29 – July 10, 2020

LIST OF CONTENT

- MOTIVATION
- BACKGROUND → OBJECTIVE
- THE ELEMENTS FOR THE PROPOSAL
  - ALARA
  - BEPU
  - E-SM
  - IA
  - ERT



- THE ADDITIONAL SAFETY BARRIER
- FINAL REMARKS
- APPENDICES (nuclear fuel, motivations, from Fermi to…)

MOTIVATION – I, slide 1 of 3

THE NUCLEAR FUEL WEAKNESS - *USNRC (draft) RG after 2014*

Characterizing LOCA breakaway oxidation – RG 1.222 (17)

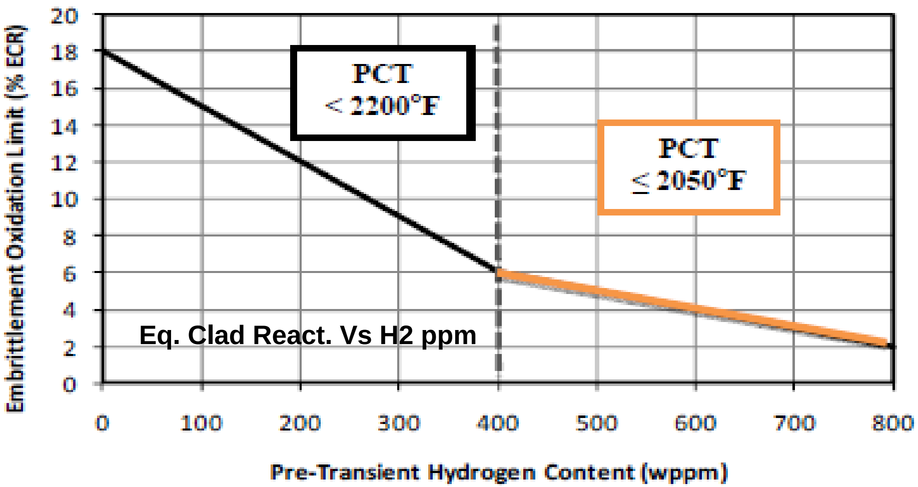
> ***H2 that enters the clad promotes rapid embrittlement (alloy composition dependent).***

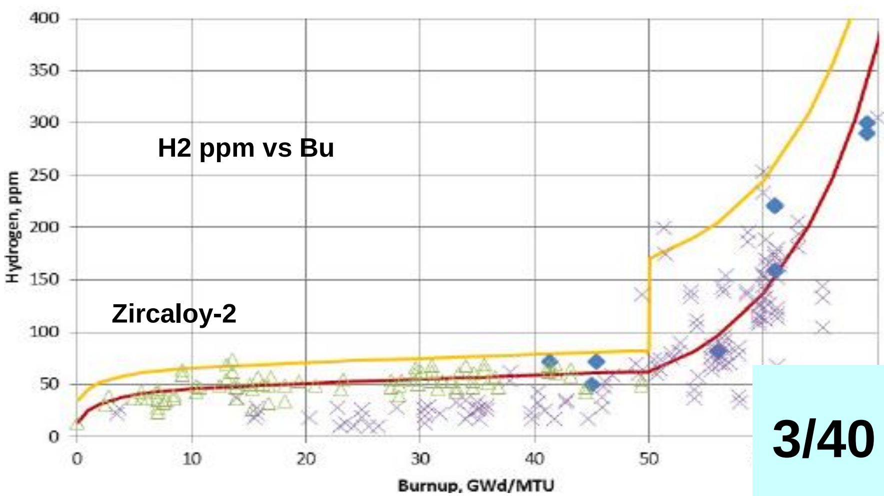
Determining Post Quench Ductility (PQD) – RG 1.223 (18)

> ***High PCT (1200 °C) and high local clad oxidation (17%) may not ensure PQD. High Bu makes the situation worse.***

Establishing (new) limits for Zr-Alloy clad material – RG 1.224 (19)

> ***An alloy-specific cladding H2 uptake model is required. Accounting for oxygen ingress on the ID is needed for Bu > 30.***





MOTIVATION – I, slide 2 of 3

THE NUCLEAR FUEL WEAKNESS

Literature overview – Support information in Appendix 1

[FAILURES WITH PARAMETER RANGES WITHIN DBA BOUNDARIES]

- ***BALLOONING: burst, pressure, temperature and time (recently measured) showing clad temperature values (at burst) as low as 500 °C – 600 °C.***
- ***OXIDE: oxide and oxide thickness (a function of Bu) 'enlarge fuel failure region', inducing spalling, hydride formation and embrittlement***
- ***HOOP STRESS: individual nuclear fuel rod stress calculation now possible during the in-core fuel cycles: wide range results are predicted***
- ***PCMI & PCI/SCC: complex failure mechanisms better understood, brittle rupture (frequently) possible.***
- ***SNF: Clad weakness also affects releases from SNF and consequent radiological impact upon the environment (a function of Bu and LHGR)***

… ➔ THE BARRIER *(B1, see below)* **CONSTITUTED BY CLAD IS NOT RELIABLE**

MOTIVATION – I, slide 3 of 3

FURTHERMORE – *Literature overview*

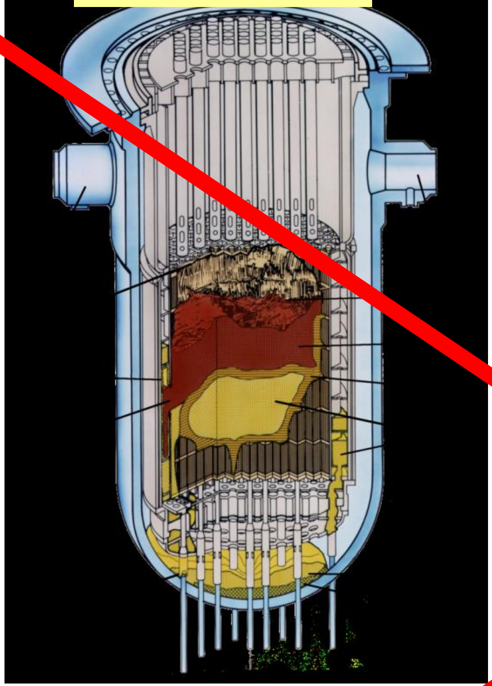
ATR (Accident Tolerant Fuel), *i.e. new material intended to prolong cladding life, the coated cladding supporting extended exposure to high temperature (1300 – 1400 °C) during LOCA, RIA and BDBA, the SiC (Silicon Carbide) cladding characterized by high melting point and minimal reaction with water (expected for commercial use in 2022),* ***will not change the provided picture and the inevitable weakness of B1*** *(see below)****.***

Fuel integrity following mechanical loads generated by the pressure wave dependent upon the Break Opening Time (BOT) in case of LBLOCA is not ensured: *no experimental evidence available, current computational capability questionable****.***

MOTIVATION – II, slide 1 of 1

THE NUCLEAR DISASTERS

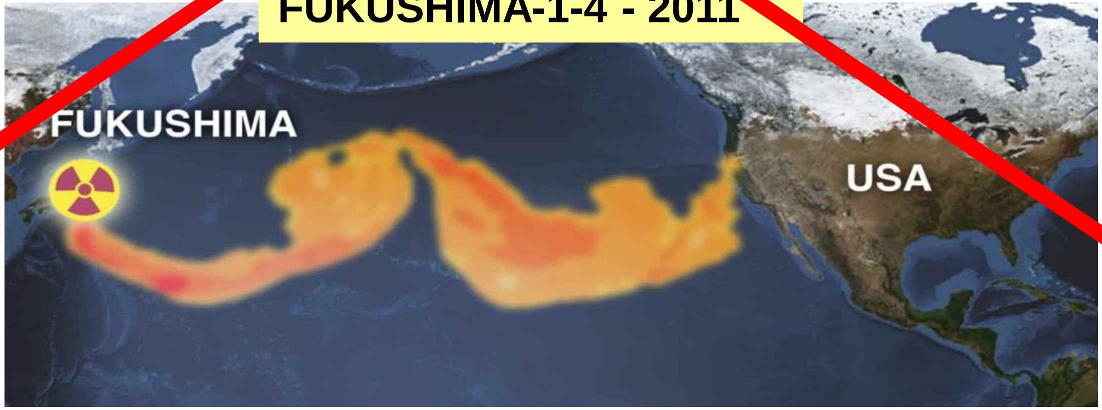
TMI-2 - 1979



CHERNOBYL-4 - 1986

(2) WE MUST WORK TO MINIMIZE THE POSSIBILITY OF OCCURRENCE OF THOSE EVENTS AND THEIR CONSEQUENCES

FUKUSHIMA-1-4 - 2011



BACKGROUND

THE ELEMENTS FOR THE PROPOSAL

ALARA ***(As-Low-As-Reasonably-Achievable) is an early <u>principle</u>, adopted for Radioprotection & disconnected from DSA.***

IA ***(Independent Assessment) is a <u>requirement</u>, pursued only in principle: a wish rather than an achievement .***

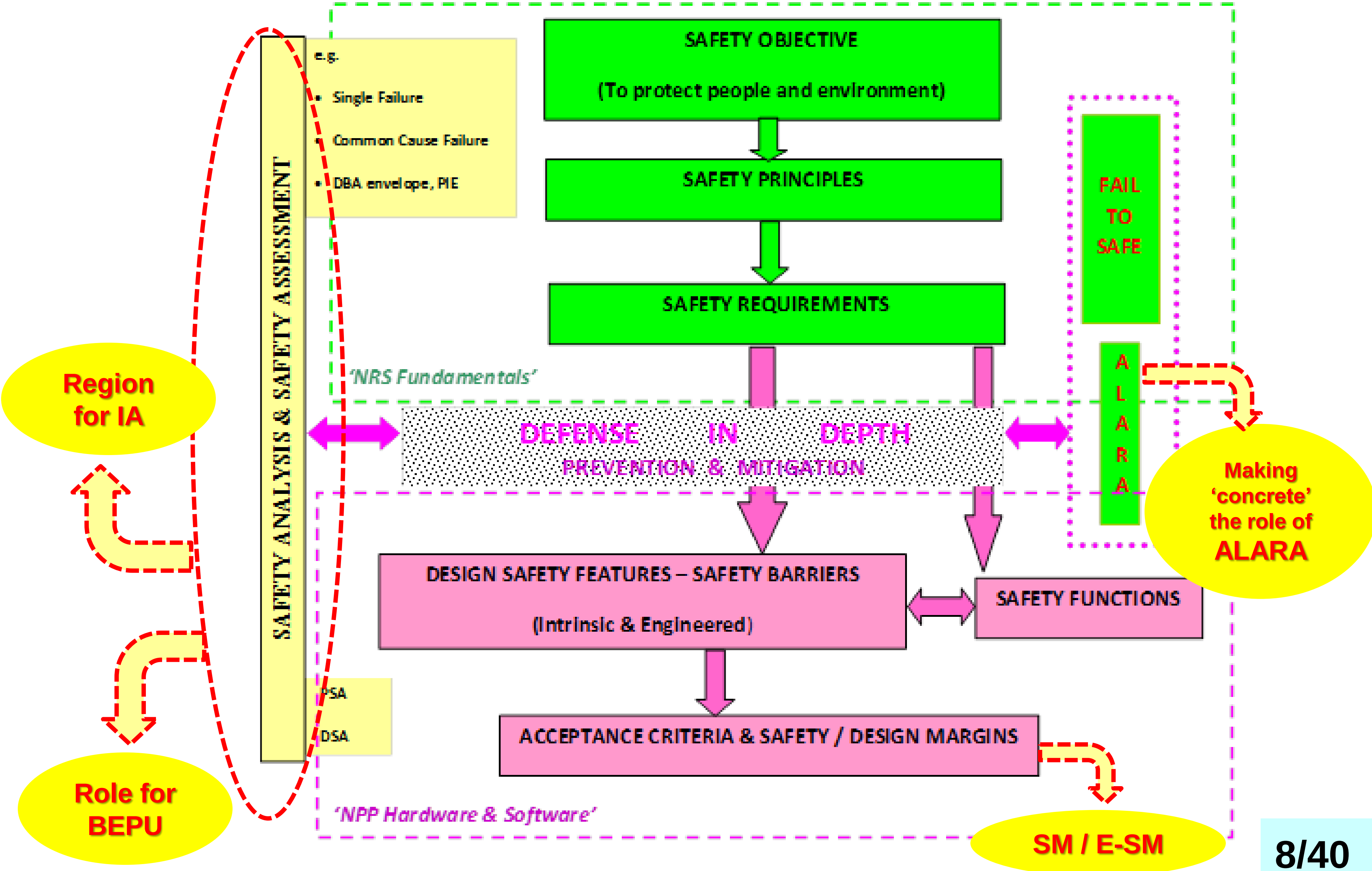
BEPU ***(Best Estimate Plus Uncertainty) is a key <u>approach</u> [origin of the term: nuclear thermal-hydraulics and AA during the '90s], not commonly accepted.***

E-SM ***(Extended Safety Margin) is derived from SM, i.e. an established <u>concept</u> in nuclear reactor safety***

ERT ***(Emergency Rescue Team) is a <u>virtual entity</u>: it shall be mandatory after Fukushima.***

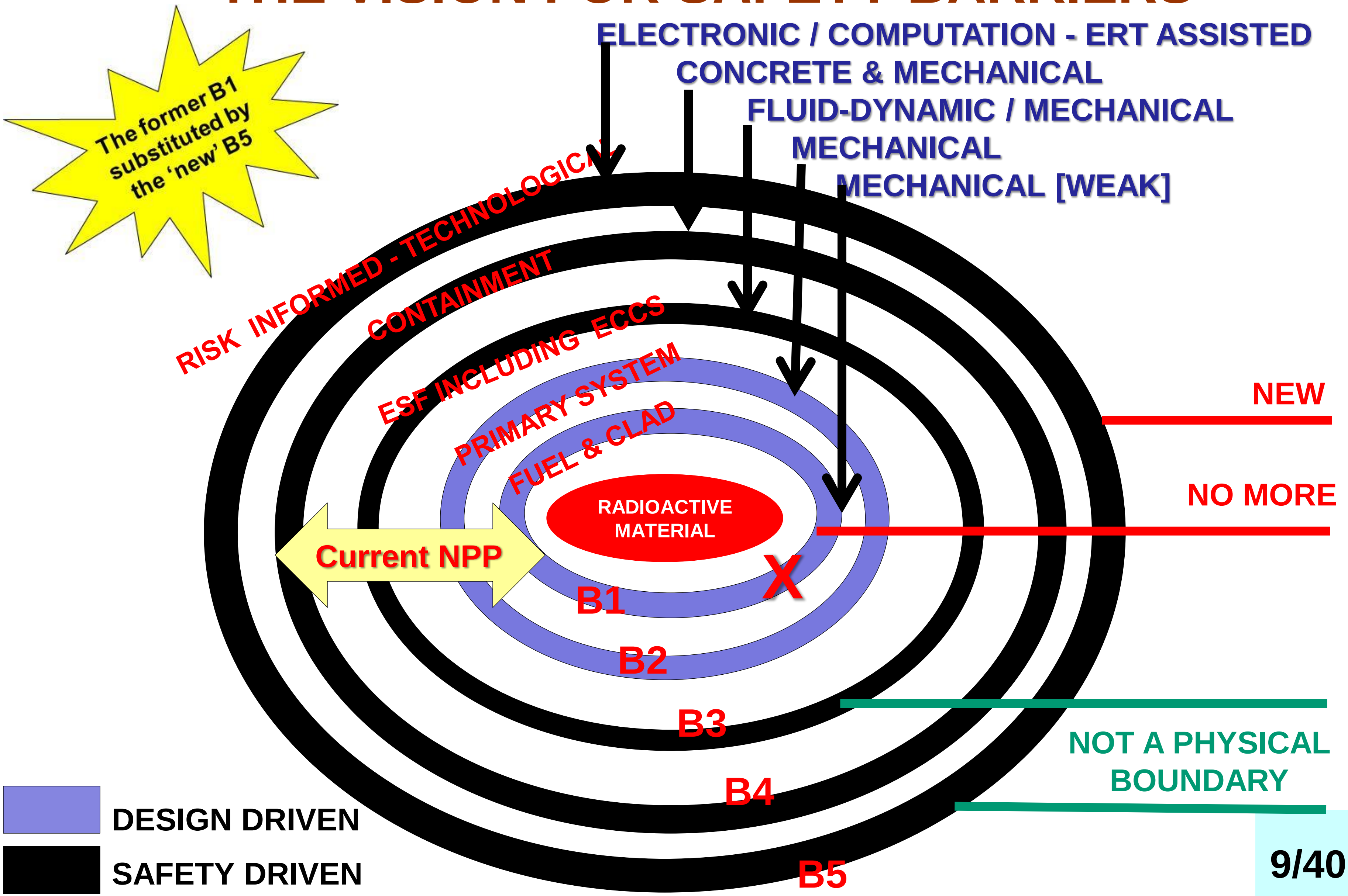
BACKGROUND

THE VISION FOR NRS



BACKGROUND

THE VISION FOR SAFETY BARRIERS



OBJECTIVE

TO PROPOSE

THE BASES

FOR CONSTITUTING AN

ADDITIONAL SAFETY BARRIER

AGAINST THE RELEASE OF FISSION PRODUCTS

THE BEPU FEATURES

A HISTORIC OUTLINE

1970 ← NRC – Interim Acceptance Criteria

← NRC – Appendix K to 10 CFR 50.46

1990

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).

g) The BEMUSE study within the OECD/CSNI (end of 00's) ← NRC – RG 1.203

2010 ← Atucha-2 BEPU Chapter 15

2020 → BEPU-FSAR

THE BEPU FEATURES – Accident Analysis

SAFETY ANALYSIS / LICENSING – 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

THE BEPU FEATURES – BEPU & ALARA

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

THE BEPU FEATURES

WHAT IS BEPU?- CONSTITUTIVE ELEMENTS

- ✓ 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

DRAFT-IAEA
V&V – 2017

Verification and Validation of Thermal-Hydraulic System Codes for Nuclear Safety Analyses

KEY ELEMENTS OF BEPU

V & V

VERIFICATION
ESTABLISHED QA PRACTICE

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

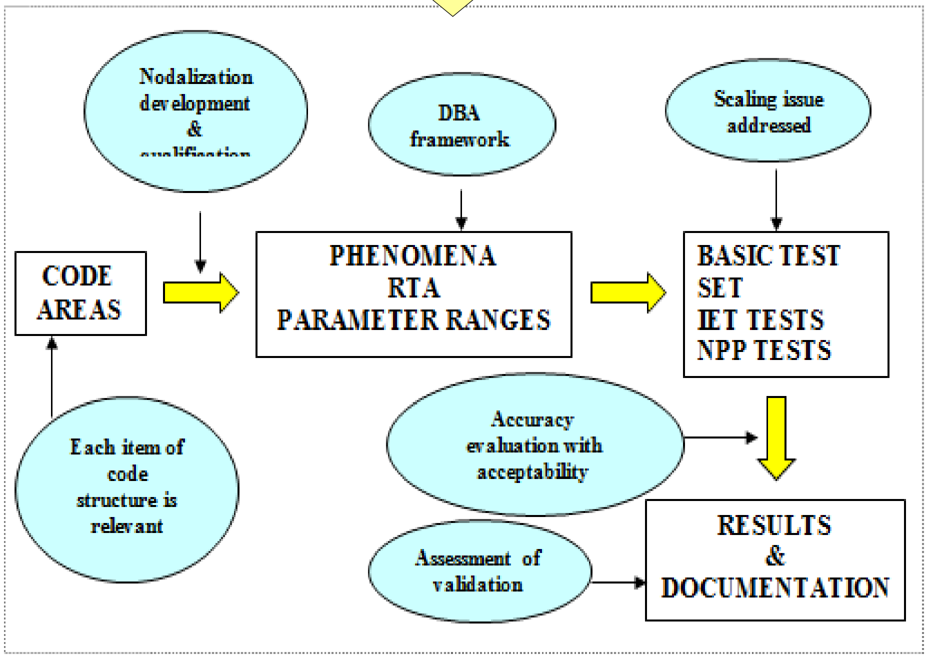
Functional Requirements of the Code → **Code Verification Plan**
- Objectives
- Approach
- Schedule
- Plan for testing

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



RECENT CONCEPTS:

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

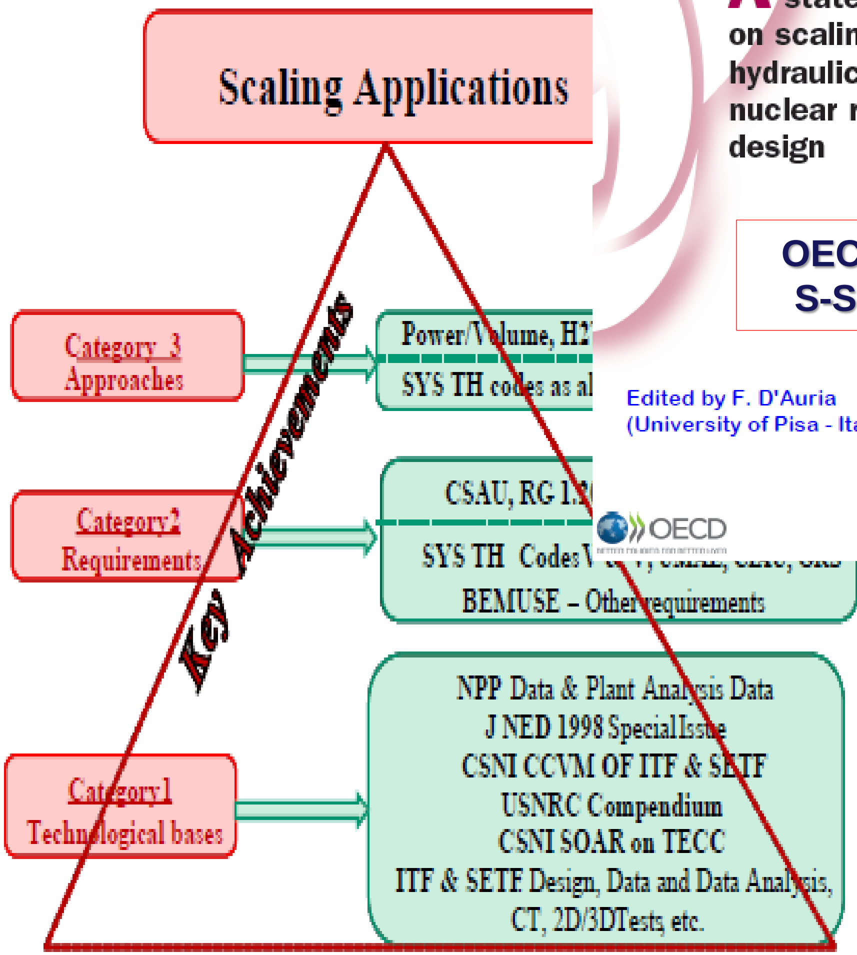
KEY ELEMENTS OF BEPU

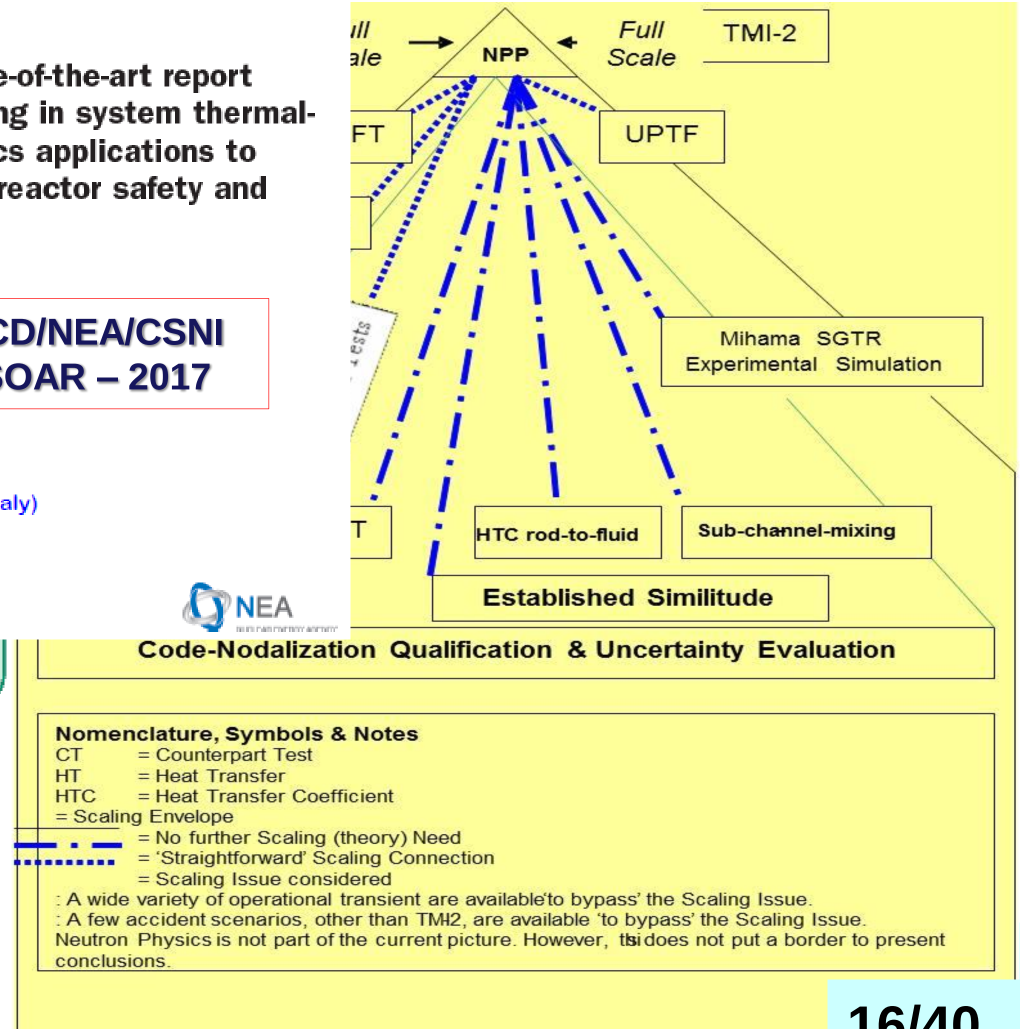
Nuclear Safety
NEA/CSNI/R(2016)14
March 2017
www.oecd-nea.org

SCALING

HIERARCHY & KNOWLEDGE MANAGEMENT

'BRIDGES' & ACHIEVEMENTS

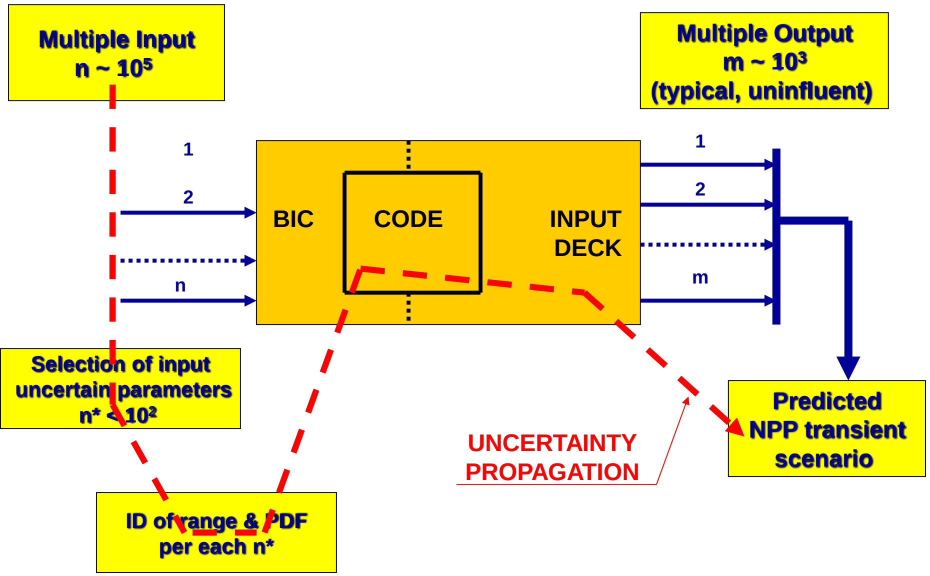




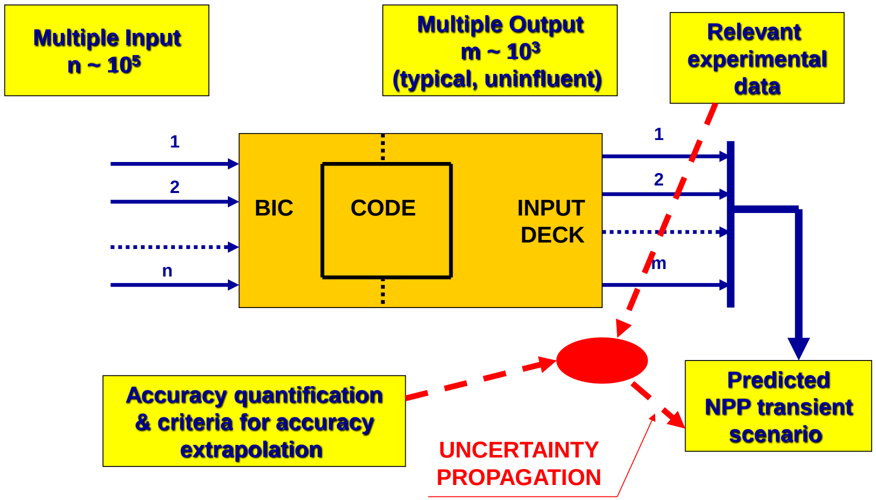
KEY ELEMENTS OF BEPU

UNCERTAINTY

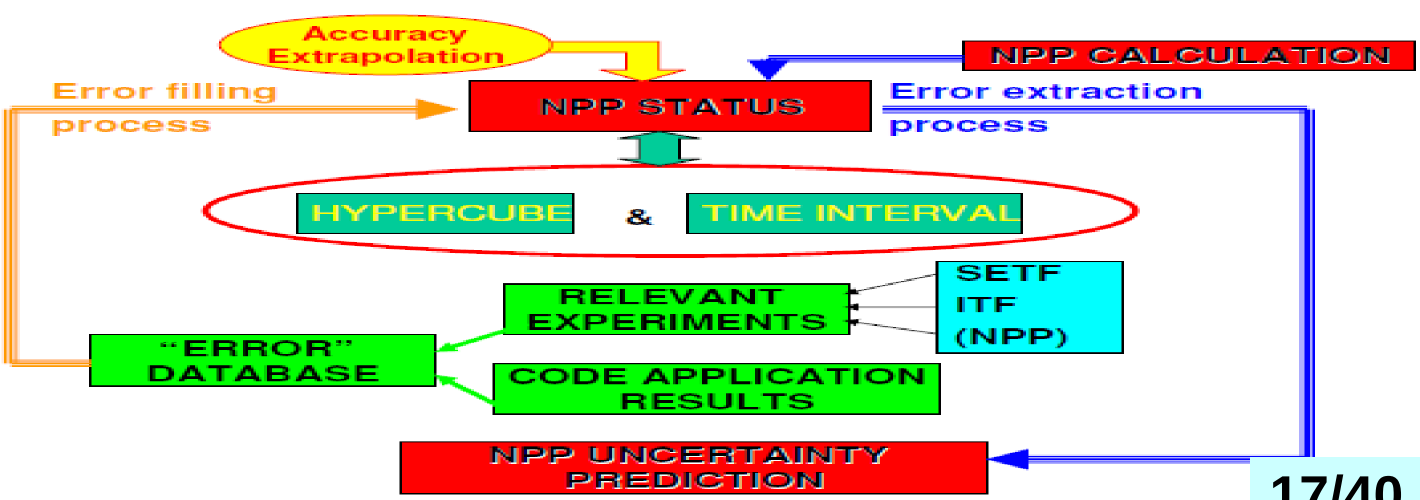
1 - PROPAGATION OF CODE INPUT "UNCERTAINTIES"



2 - PROPAGATION OF CALCULATION OUTPUT "ERRORS"



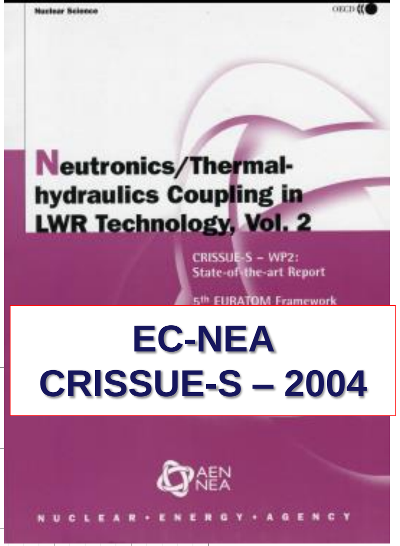
ERROR FILLING PROCESS AND ERROR EXTRACTION PROCESS



IAEA
SRS-52 – 2008

KEY ELEMENTS OF BEPU

CODE COUPLING



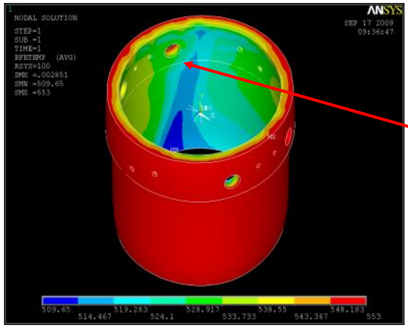
EC-NEA CRISSUE-S – 2004

Fracture Mechanics

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

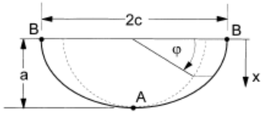
No.	Wall thickness (mm)	Crack depth (mm)	Crack length (mm)
1	102 – 305	¼ Wall thickness	½ Wall thickness
2	> 305	¼ (305)	½ (305)
3	< 102	¼ (102)	½ (102)

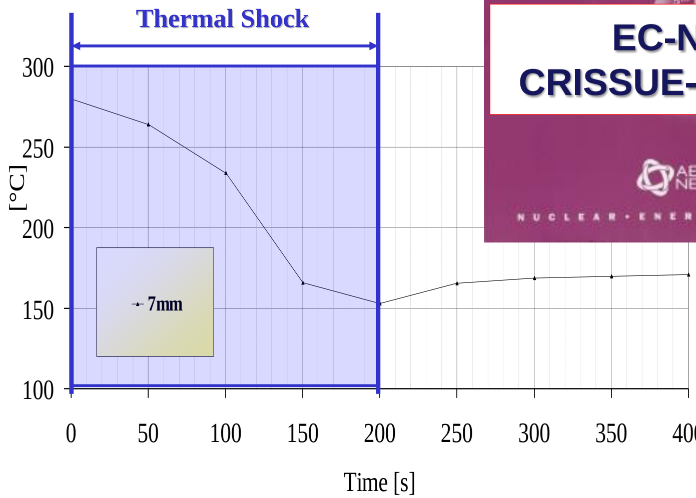
Crack position



RPV wall thickness = 290 mm

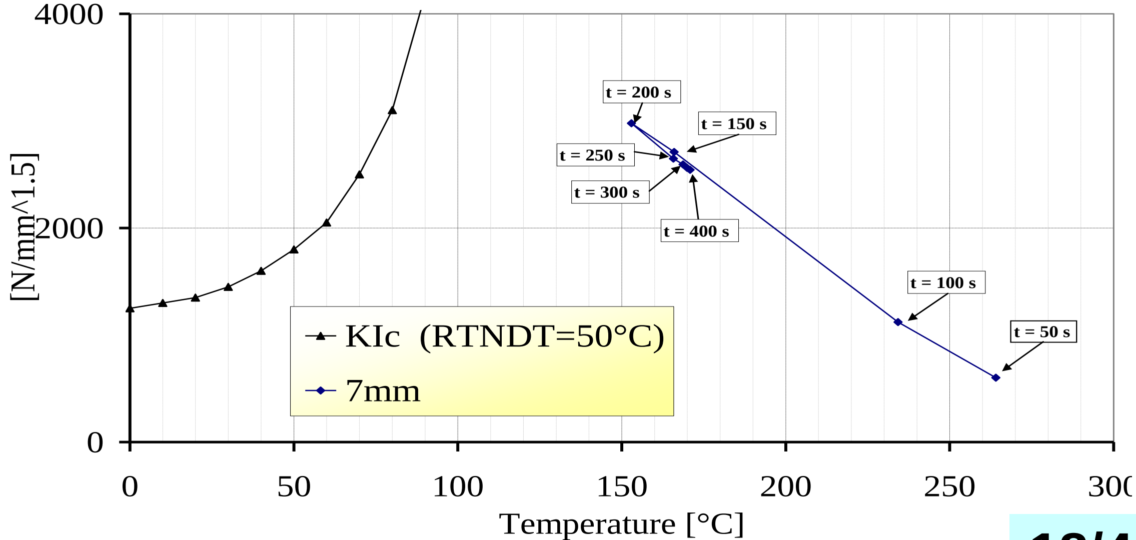
a = Crack Depth ~ 7 mm





Temperature at crack tip

KEY RESULT ➔



KEY ELEMENTS OF BEPU

(TH) DATABASE / APPLICATION

NA-SA / UNIPI
ARN (REGULATORY BODY) - APPROVED 2012

We are here!

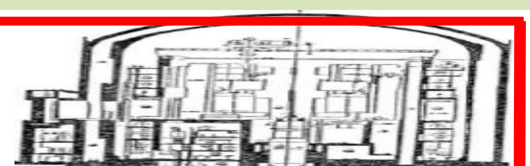
ACCIDENT ANALYSIS / FSAR – CHAPT. 15

LICENSING ← → BEPU ← Other Disciplines + PSA

UNCERTAINTY

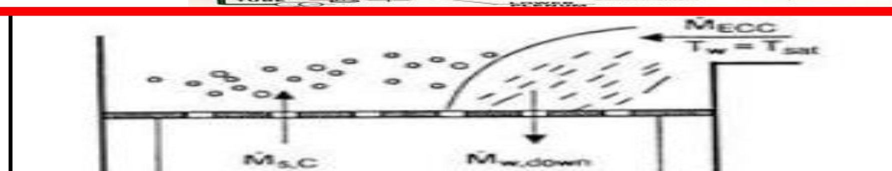
DATA

NPP



ITF

SETF



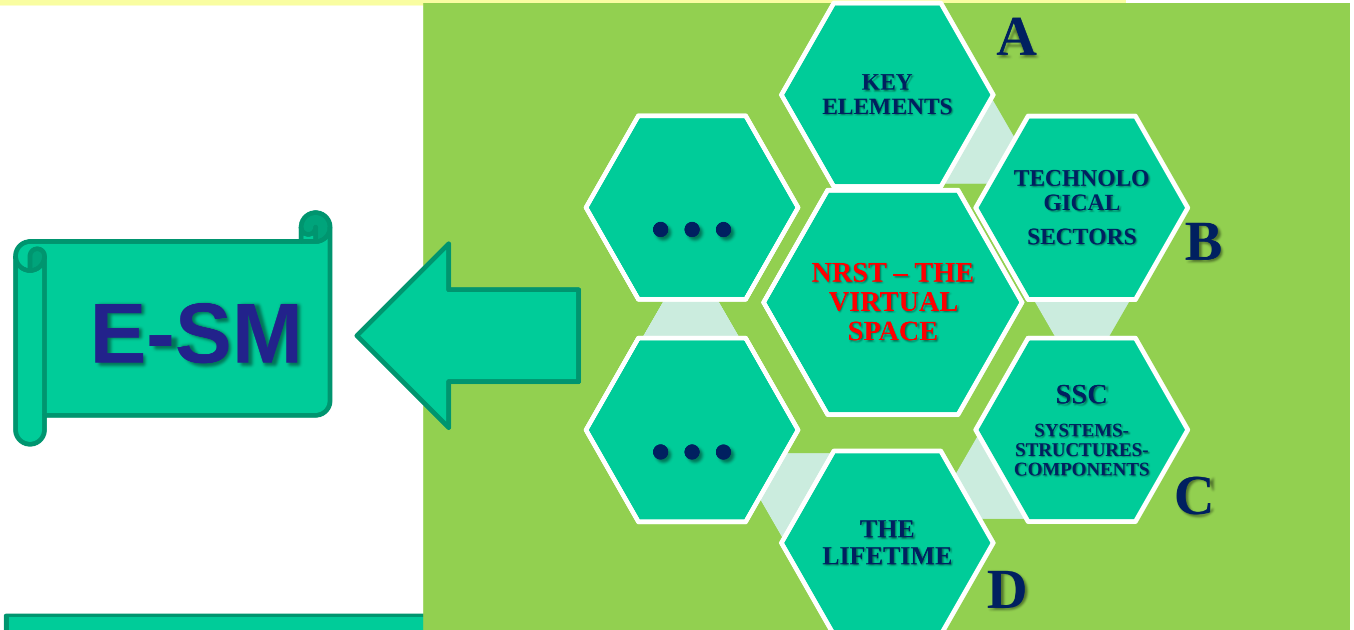
BASIC

SYS TH CODE DEVELOPMENT

V & V - SCALING

ENHANCING THE SM CONCEPT

E-SM CONTRIBUTED BY BEPU-FSAR



NRST : THE KEY ELEMENTS
THE 'A' LIST – 6 topics –

KEY ELEMENTS

A1) Safety Principles, i.e. SP-1 to SP-10;

A2) DID Levels, i.e. DL-1 to DL-5;

A3) Safety Barriers, i.e. SB-1 to SB-6;

A4) Safety Functions, i.e.SF-1 to SF-19;

A5) PSA Elements, i.e. PE-1 to PE-n;

A6) DSA Elements, i.e. DE-1 to DE-m.

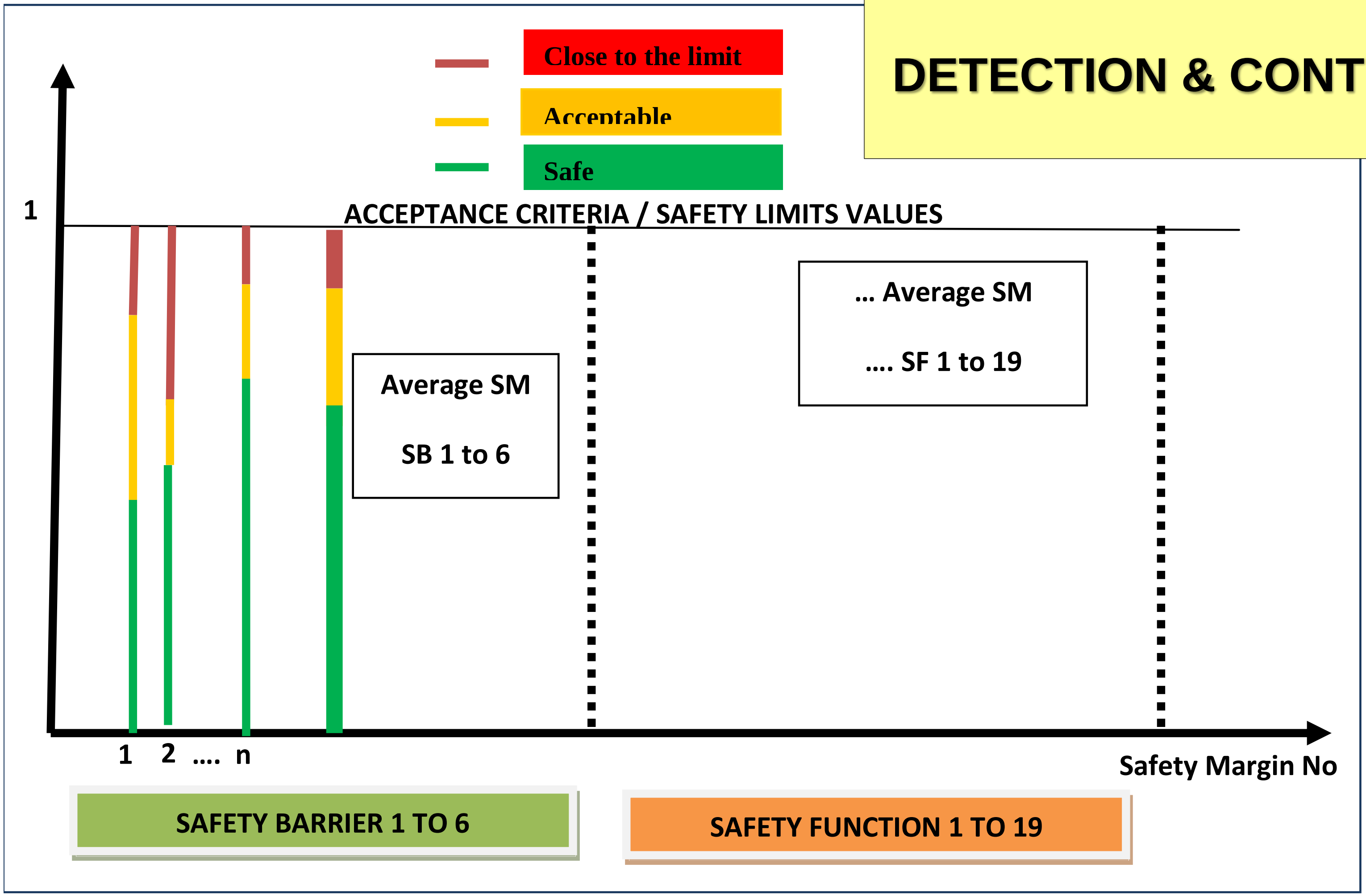
A 'FEW' 10E4 E-SM DEFINITIONS

ENHANCING THE SM CONCEPT

E-SM CONTRIBUTED BY BEPU-FSAR

AROUND 10E4 E-SM

DETECTION & CONTROL



ISSUES WITH CURRENT IA

ISSUES

NPP COMPLEXITY

(efforts needed for IA 'too large' out of industry)

SAFETY DEPENDING UPON DETAILS

(details un-known out of industry; issue is proprietary information)

INDUSTRY ENGAGED IN CONTINUOUS CHANGES / IMPROVEMENTS

(changes not necessarily qualified, e.g. passive systems)

IA ONLY POSSIBLE WITH LATEST BE TECHNIQUES

(expertise may not be available out of industry)

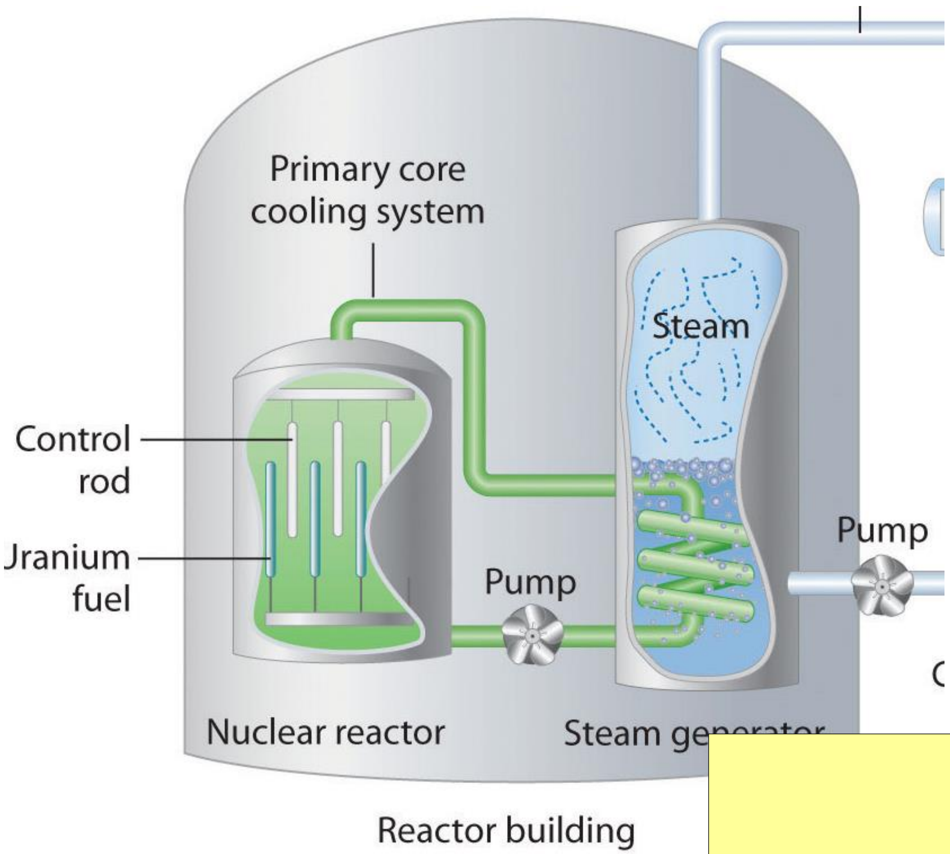
EXPERT ANALYSTS NOT NECESSARILY AWARE OF LICENSING DETAILS

(the licensing framework is complex, too)

ERT

EMERGENCY RESCUE TEAM (20)

- To constitute a national (or regional) Emergency Rescue Team (ERT) capable of physically intervening in a failed NPP Unit having own devices and access locations in each Unit: this might be seen, as a new (active) barrier part of the defense-in-depth and summing up with the current (mostly passive) standard barriers.



1. ERT ELEMENTS

- Helicopter
- DG + pump
- Team (of around 5)

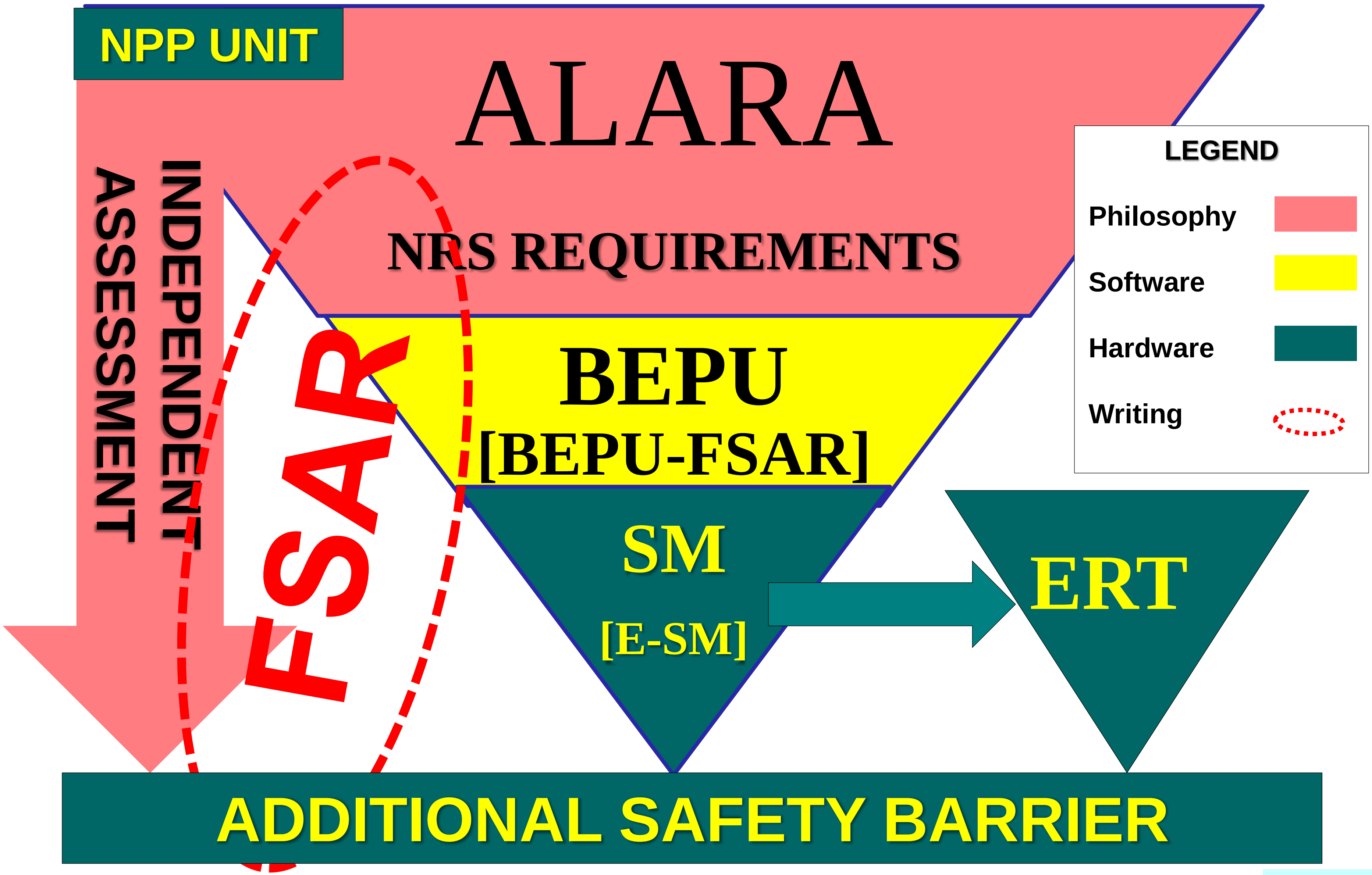
2. ERT OPERATION RANGE

About 500 km in a Country or geographical region targeting (typically) 10 NPP

3. ERT WORKING MODE

Plug-in pump delivery side to known (3-5) NPP ERT-connectors

Integrating ALARA, BEPU, E-SM, IA, ERT



ADDITIONAL SAFETY BARRIER

One may state that:

***a principle** (ALARA taken from fundamentals of the technology)* **+**

***a requirement** (IA, becoming actual)* **+**

***an approach** (BEPU, becoming practical)* **+**

***a concept** (E-SM established in nuclear reactor safety, now expanded)* **+**

***a virtual entity** (ERT, becoming physical)* **=**

a ‘new’ SAFETY BARRIER

FINAL REMARKS - slide 1 of 3

- FURTHER EVALUATION OF CURRENT STATUS -

- ***NOT-RECOGNIZING*** *the weakness of the barrier constituted by clad,*
- ***DELETING LBLOCA*** *from the list of DBA (equals admitting no control of the technology),*

HAVE A CONSEQUENCE:

LOW (TECHNICIANS AND) PUBLIC ACCEPTANCE!

FINAL REMARKS - slide 2 of 3

- FIVE ELEMENTS FOR THE NEW SAFETY BARRIER -

1) ***ALARA*** *at the origin of* ***BEPU.***
2) ***BEPU*** *based on V&V, Scaling, Code Coupling, Uncertainty, and Database. BEPU extended to the entire* ***FSAR*** *(analytical parts).*
3) ***E-SM*** *(comprehensive and systematic set of) derivable with support from BEPU.*
4) ***IA*** *based on BEPU and making possible BEPU*
5) ***ERT*** *a (very) simple product of current technology*

SUMMARY

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

FINAL REMARKS - slide 3 of 3

- THE NEW NPP -

Reporting (again) the words of Australian-Chinese colleagues who analyzed the framework of the Fukushima event: "… upgrading and strengthening a nuclear regulatory system is not optional but imperative to prevent the next core meltdown."

1) ***… STRENGTHENING REGULATORY FRAMEWORK***

2) ***RISK OF CORE MELT LOWERED*** *(to be demonstrated)* ***FOR A FACTOR 10 - 1000.***

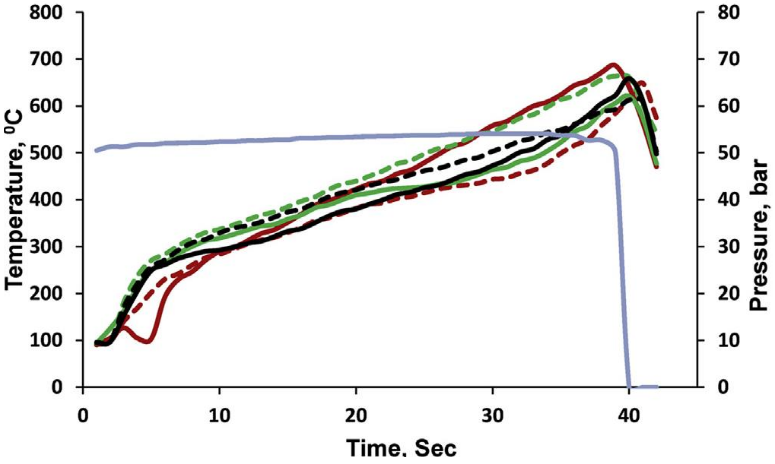
3) ***PROBABILITY OF CORE MELT*** *(target)* ***TO THE LEVEL OF METEORITE FALL ON THE NPP.***

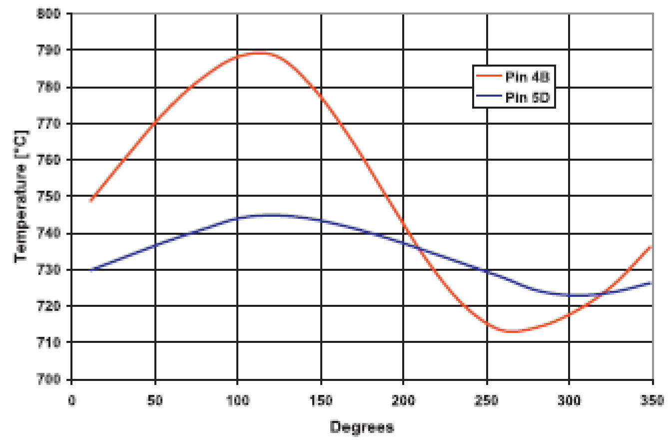
4) ***COST OF NEW BARRIER ≈ 1% CURRENT NPP.***

APPENDIX 1 – (SUPPORT TO) MOTIVATION

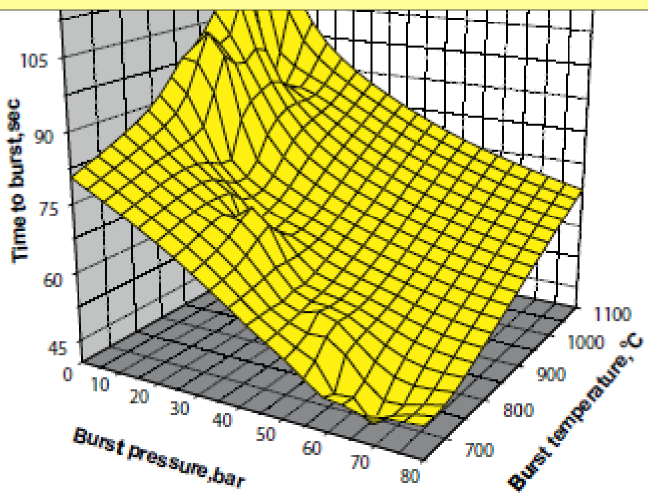
THE NUCLEAR FUEL WEAKNESS – *Literature overview*

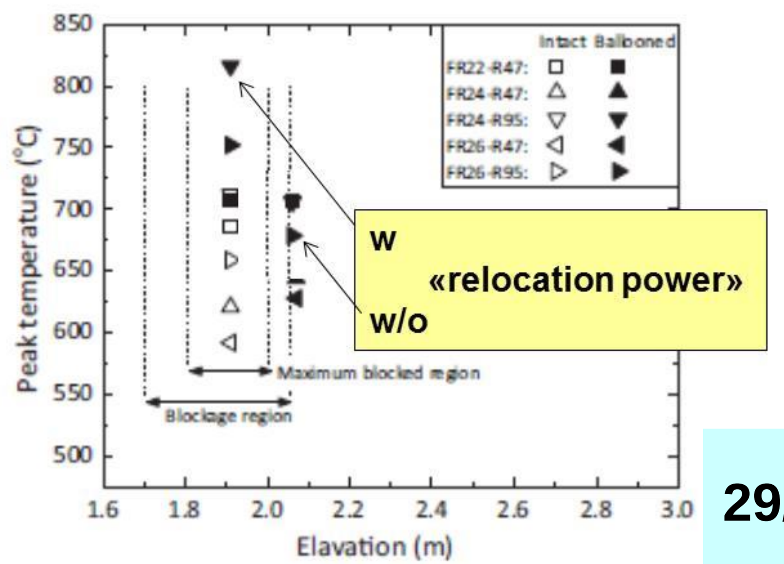
BALLOONING: pressure and temperature during experiments w/o (15), (11) and w relocation (14) considered; azimuthal temperature asymmetry (6)





Burst pressure, temperature, time

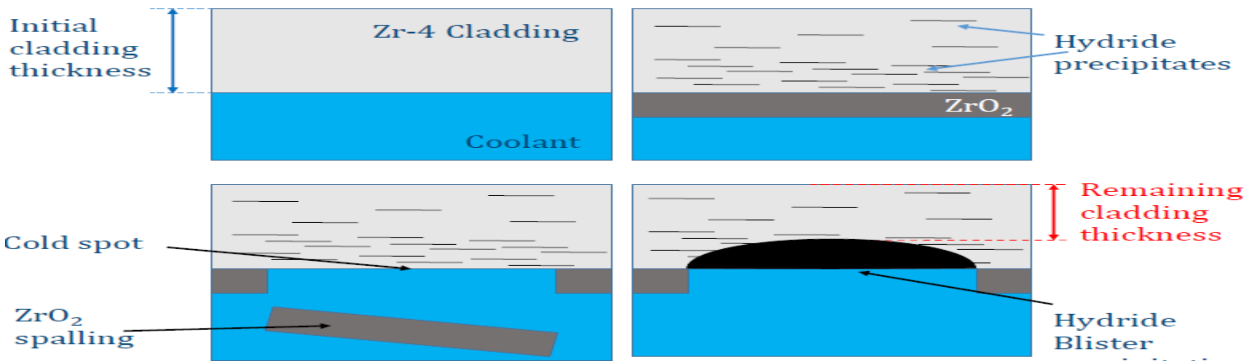


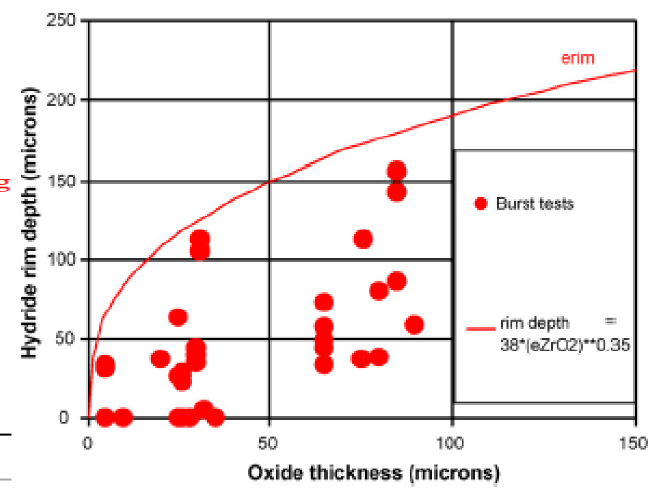


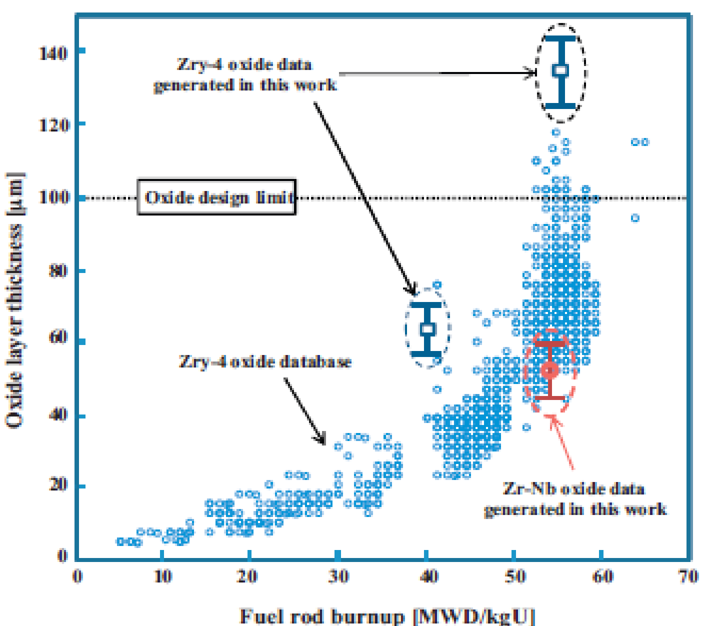
APPENDIX 1 – (SUPPORT TO) MOTIVATION 2 OF 5

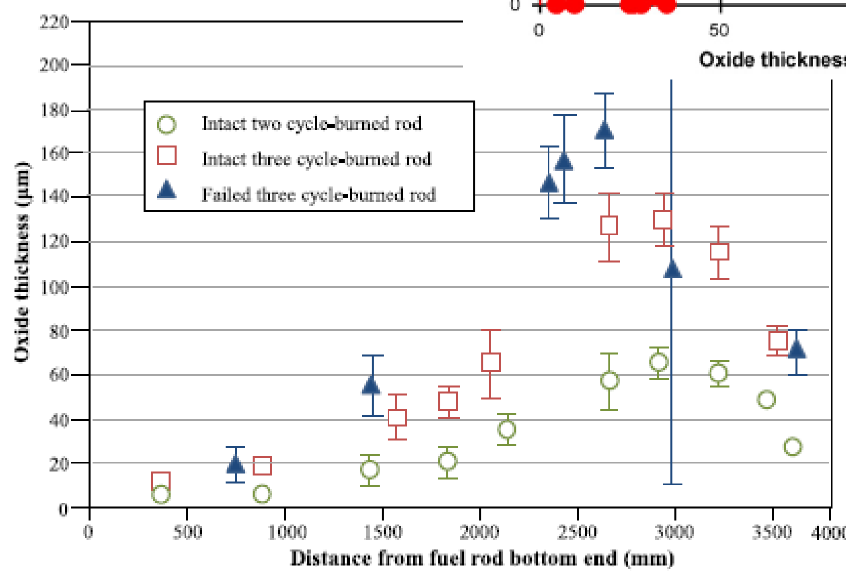
THE NUCLEAR FUEL WEAKNESS – *Literature overview*

OXIDE THICKNESS (11) vs Bu and failures (3). Hydride rim depth vs oxide thickness and burst failures (7) and sketch of spalling and hydriding (8)-(9)



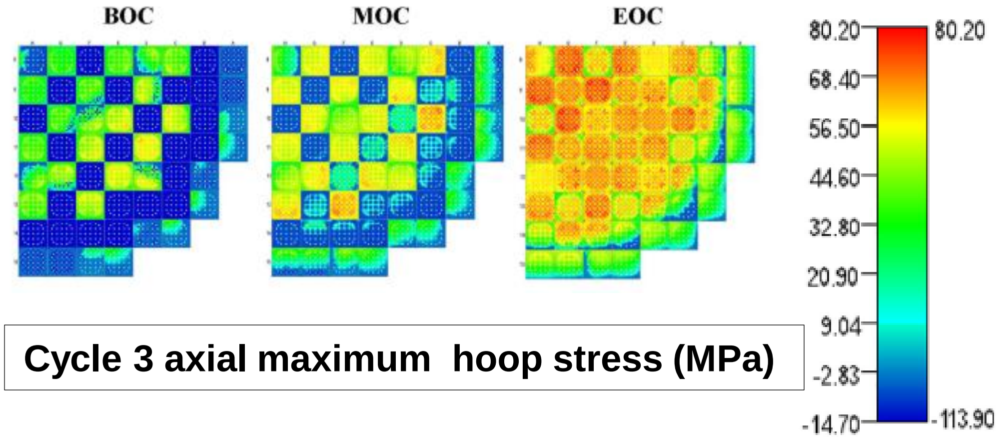




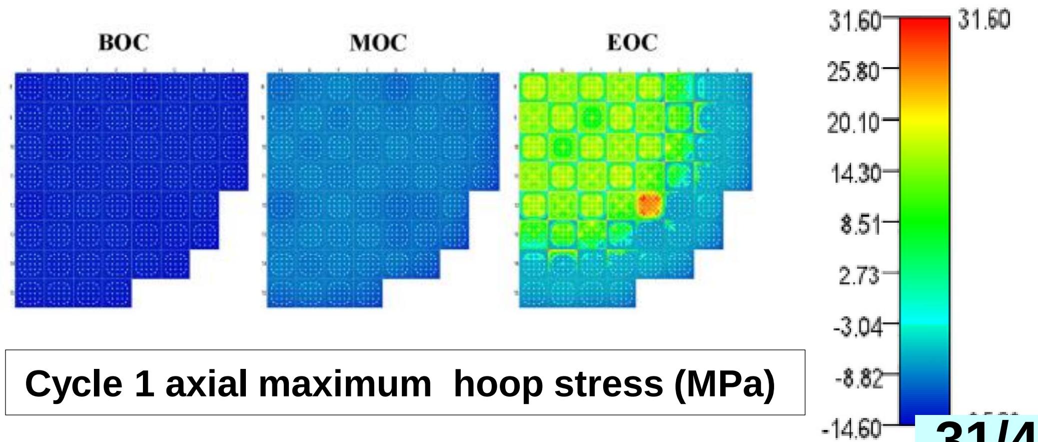


THE NUCLEAR FUEL WEAKNESS – *Literature overview*

- ***HOOP STRESS: detailed NPP (Watts, US) calculations are possible showing widely changing conditions, including Bu effect (10)***



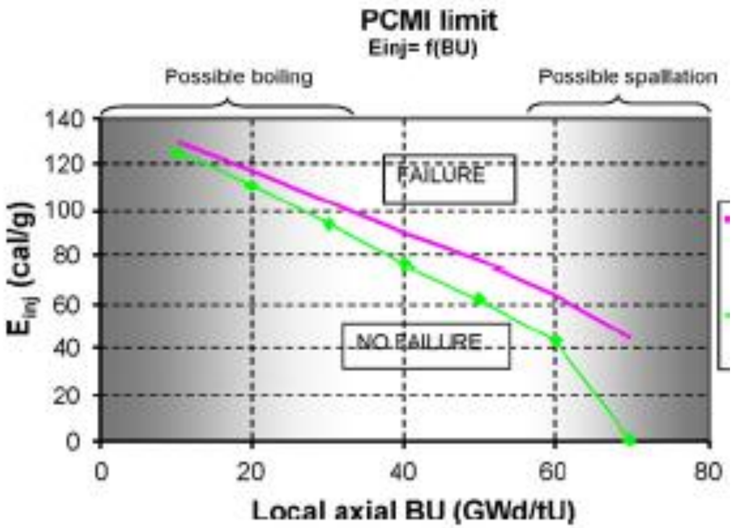
Cycle 3 axial maximum hoop stress (MPa)



Cycle 1 axial maximum hoop stress (MPa)

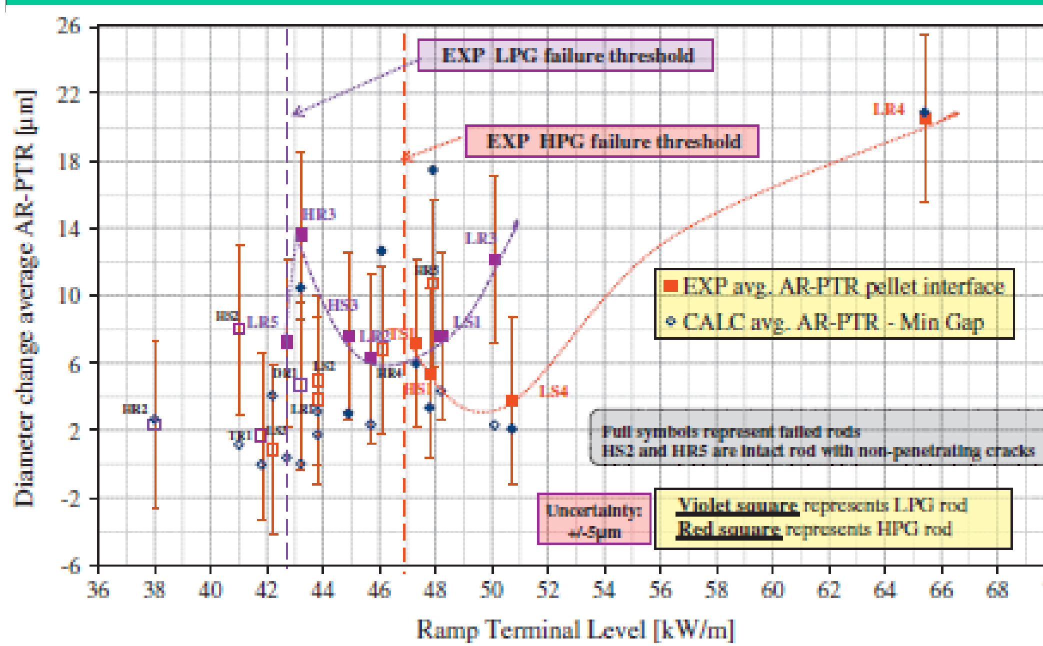
THE NUCLEAR FUEL WEAKNESS – *Literature overview*

PCMI failures – RIA (7) and PCI/SCC failures, IR project for BWR, (5).



The model assumes that SCC failures begin as an inter-granular fracture due to cesium–iodine chemical attack (in presence of oxygen potential) and independent of applied stress, … that leads to cracks propagation. Clads fail with small diameter changes at relatively low values of LHGR (final ramp).

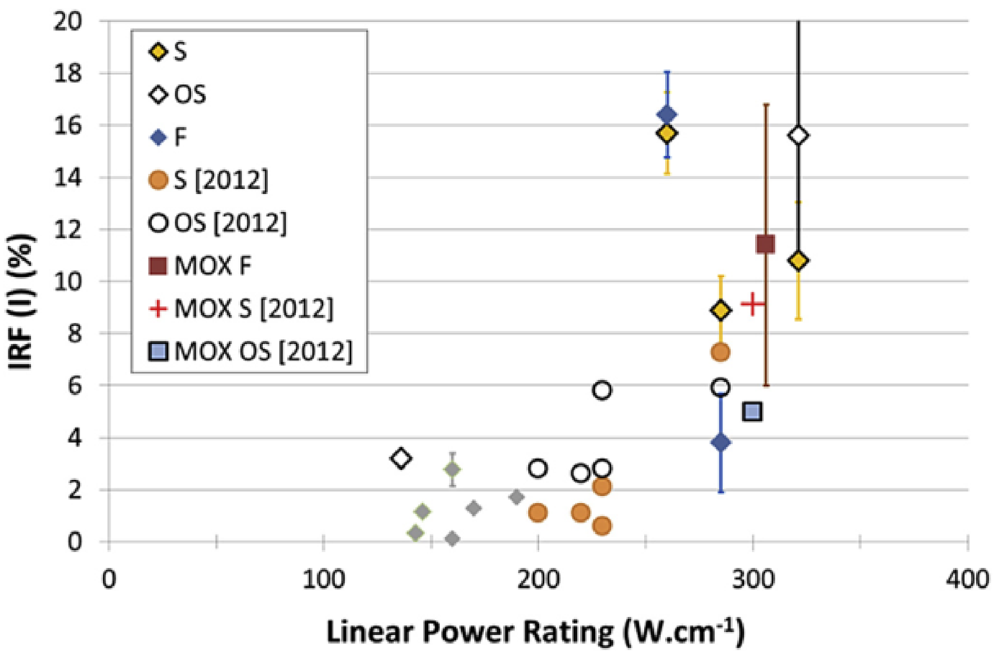
Early (2010) RIA code results showing Bu effect upon clad failures (see also effect of oxide thickness- this appendix, slide 2 of 5).



THE NUCLEAR FUEL WEAKNESS – *Literature overview*

SNF: Instant Release Fraction at high Bu (40 -60) sharply increases when LHGR > 20 kw/m (1)

Part 1 - When the SNF is disposed of in an underground repository, the radionuclides may gradually be released after failure of the canister and subsequent water ingress. The release rate of radionuclides differs depending on their chemical properties, their chemical speciation in the fuel, as well as the location where they are segregated within the SNF.



Part 2 - The release of soluble segregated elements from the accessible gap, cracks and grain boundaries is fast. Most of their inventory is released within a few months or even days. The quantity of these rapidly released inventories normalized to the total nuclide inventories is commonly called the Instant Release Fraction (IRF) … they can significantly contribute to or even dominate the calculated dose exposure.

APPENDIX 2 – REFERENCES

*1. J. NM 2017, vol 484 - Instant release of fission products in leaching experiments with high burnup nuclear fuels in the framework of the Euratom project FIRST, K. Lemmens, *, E. Gonzalez-Robles, B. Kienzler, E. Curti , D. Serrano-Purroy, R. Sureda , A. Martínez-Torrents, O. Roth, E. Slonszki, T. Mennecart , I. Günther-Leopold,Z. Hozer*

2. J. RSER 2013, vol 17 - Accident like the Fukushima unlikely in a country with effective nuclear regulation: Literature review and proposed guidelines, Q. Wang , Xi Chen, Xu Yi-chong

3. J. NM 2011, vol 418 - The effect of fuel rod oxidation on PCMI-induced fuel failure, K-T. Kim

4. J. EFA 2011, vol 17 - Investigation of failure behavior of two different types of Zircaloy clad tubes used as nuclear reactor fuel pins, M.K. Samal, G. Sanyal, J.K. Chakravartty

5. J. ANE 2012, vol 50 - Modeling of BWR Inter-Ramp Project experiments by means of TRANSURANUS code, D. Rozzia, A. Del Nevo, M. Adorni, F. D'Auria

6. J. NED 2014, vol 268 - Dynamic ballooning analysis of a generic PWR fuel assembly using the multi-rod coupled MATARE code, L. Ammirabile, S. P. Walker

7. J. NED 2010, vol 240 - A consistent approach to assess safety criteria for reactivity initiated accidents, C. Sartoris, A. Taisne, M. Petit, F. Barré, O. Marchand

8. IAEA 2015, Conf. Fuel - IAEA–CN–226 ID122, - On the impact of the fuel assembly design evolution in the spent fuel management , J. M. García de la Infanta

9. J. NST 2006, vol 43 - Influence of Outer Zirconia Transient Cracking and Spalling on Thermomechanical Behavior of High Burnup Fuel Rod Submitted to RIA, V. Georgenthum, J. Desquines,V. Bessiron

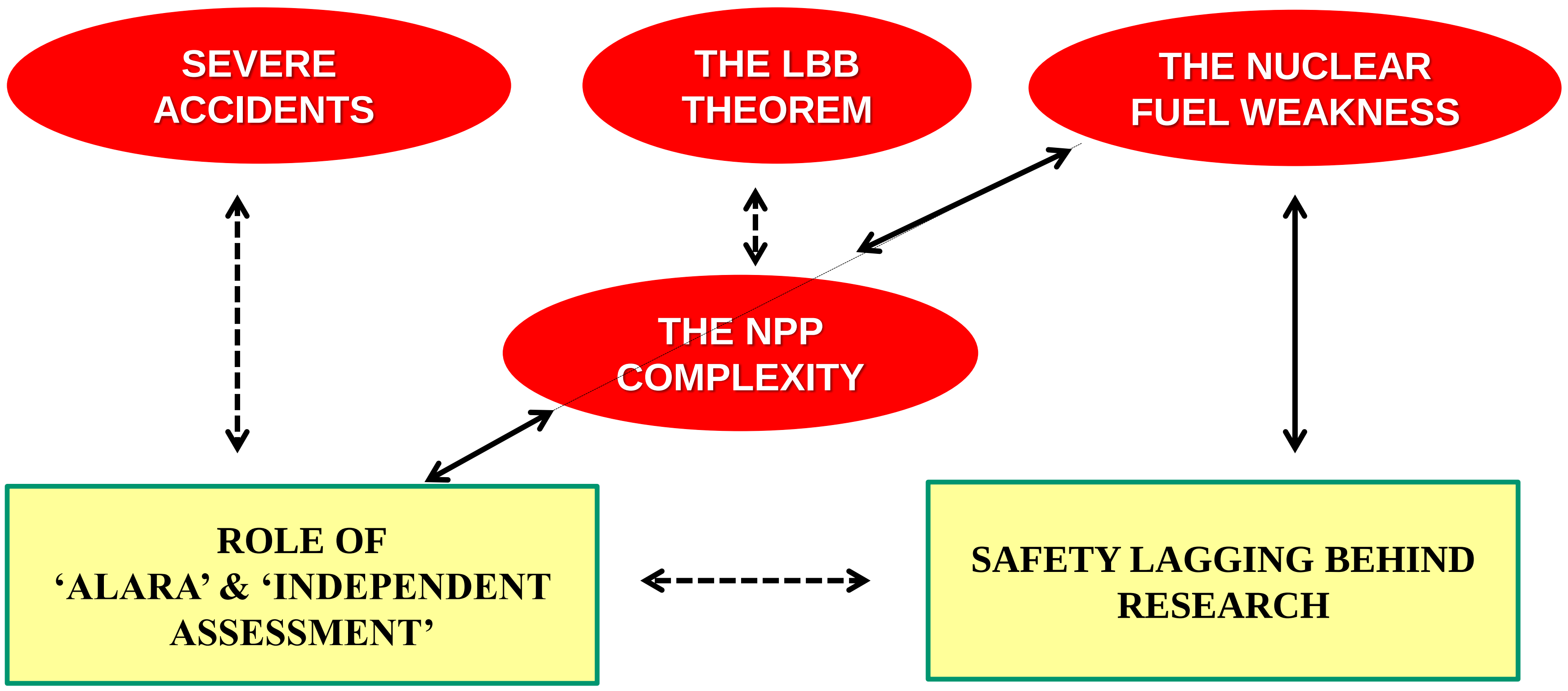
10. J. NED 2018, vol 327 - Pellet-clad mechanical interaction screening using VERA applied to Watts Bar Unit 1, Cycles 1–3 ,S. Stimpson, J. Powers, K. Clarno, R. Pawlowski, R. Gardner, S. Novascone, K. Gamble, R. Williamson

APPENDIX 2 – REFERENCES

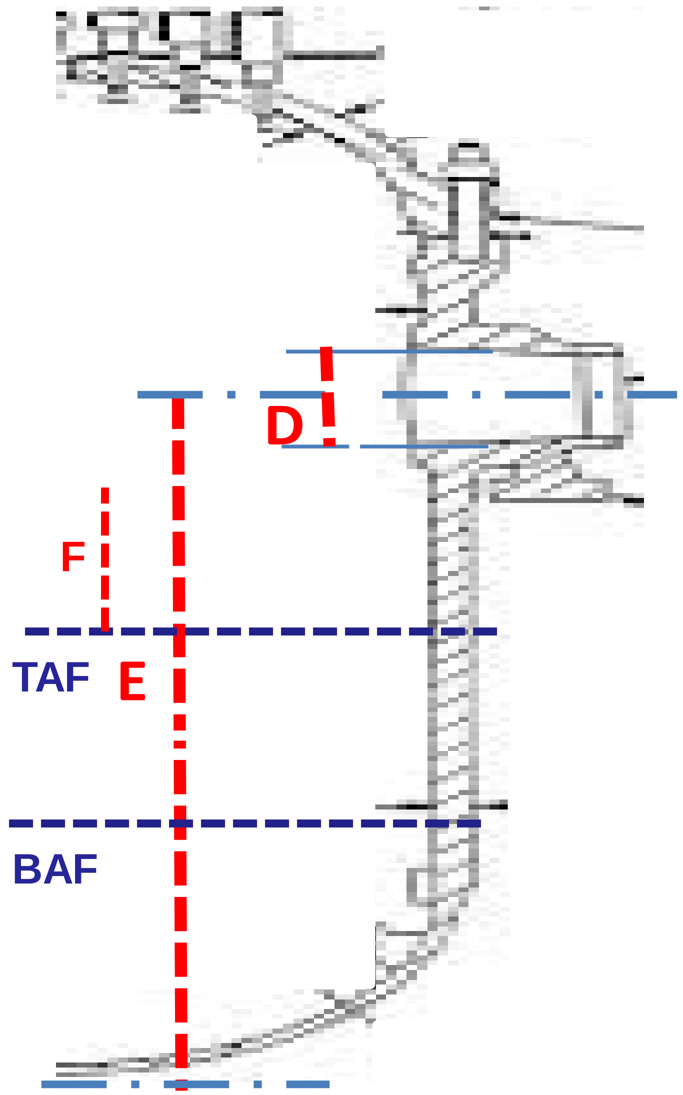
11. J. NED 2011, vol 241 - Oxide thickness-dependent transient cladding hoop stress, K-T. Kim, D. W. Jerng
12. J. CALPHAD, 2016, vol 55 - Application of thermochemical modeling to assessment/evaluation of nuclear fuel behavior, T. M. Besmann, J.W. McMurray, S. Simunovic
13. J. NM 2018, vol 500 - Phenomenology of BWR fuel assembly degradation, M. Kurata, M. Barrachin, T. Haste, M. Steinbrueck
14. J. NED 2017, vol 312 - Effects of fuel relocation on reflood in a partially-blocked rod bundle, B. J. Kim, J. Kim, K. Kim, S. W. Bae, S-K. Moon
15. J. NM 2017 - Study of clad ballooning and rupture behavior of Indian PHWR fuel pins under transient heating condition in steam environment, T. K. Sawarn, S. Banerjee, S. S. Sheelvantra, J.L. Singh, V. Bhasin
16. J. NED 2014, vol 280 - Study of clad ballooning and rupture behavior of fuel pins of Indian PHWR under simulated LOCA condition, T. K. Sawarn, S. Banerjee, K.M. Pandit, S. Anantharaman
17. USNRC, 2018, RG 1.222, draft
18. USNRC, 2018, RG 1.223, draft
19. USNRC, 2018, RG 1.224, draft
20. J. STNI 2012 -. The Fukushima event: the outline and the technological background, F. D’Auria, G. Galassi, P. Pla, M. Adorni, 2012.
21. J. NED 2017, vol 324 - Strengthening nuclear reactor safety and analysis, F. D'Auria, N. Debrecin, H. Glaeser

… other called in the text

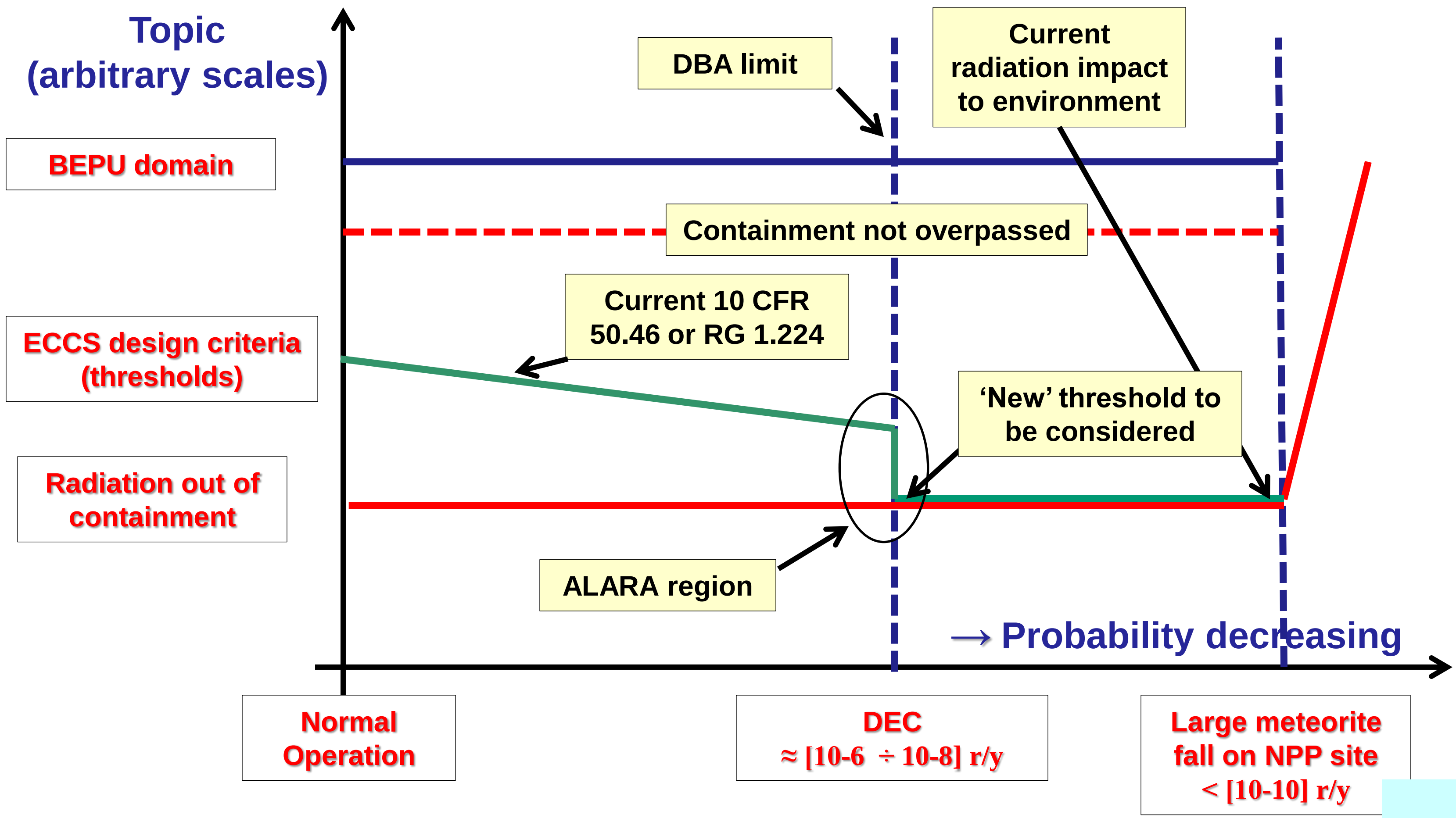
APPENDIX 3 – MOTIVATIONS (A GLOBAL VIEW)



APPENDIX 3 – MOTIVATIONS (LBLOCA & PWR design)



APPENDIX 3 – MOTIVATIONS (Regulatory Framework)



APPENDIX 4 – FROM FERMI TO … 1 of 2

1896, 1897	**A.H. Becquerel, M. Curie, P.Curie:** The Natural Radiation
1897	**J.J. Thomson: The Electron** [the atom is not indivisible]
1905	**A. Einstein :** E = mc2
1911	**E. Rutherford:** [”idea of an atom with a minute massive centre ”]
1923	**E. Fermi (commenting E = mc2):** [”… energy in one gram of matter greater than energy produced by three years of a 1000 HP engine … ”]
1930, 1931 1932	**W. Bothe, H. Becker, I. Curie-Joliot, F. Joliot, J. Chadwick:** The Neutron
1934 – Oct. 22	**E. Fermi:** [”… neutrons slow down in paraffin and induce artificial radioactivity in Uranium…”] CIF
1938	**L. Meitner, O. Frisch / O. Hahn, F. Strassmann:** The Fission
1942 – Dec. 2,	**E. Fermi:** The pile — [The Italian navigator has landed in the New World]

THE DISCOVERIES

I

THE FERMI AGE

II

EMERGENT NUCLEAR PHYSICS

→ THE NUCLEAR ERA

APPENDIX 4 – FROM FERMI TO … 1 of 2