Avenues in Computational Design and Safety of Nuclear Reactors

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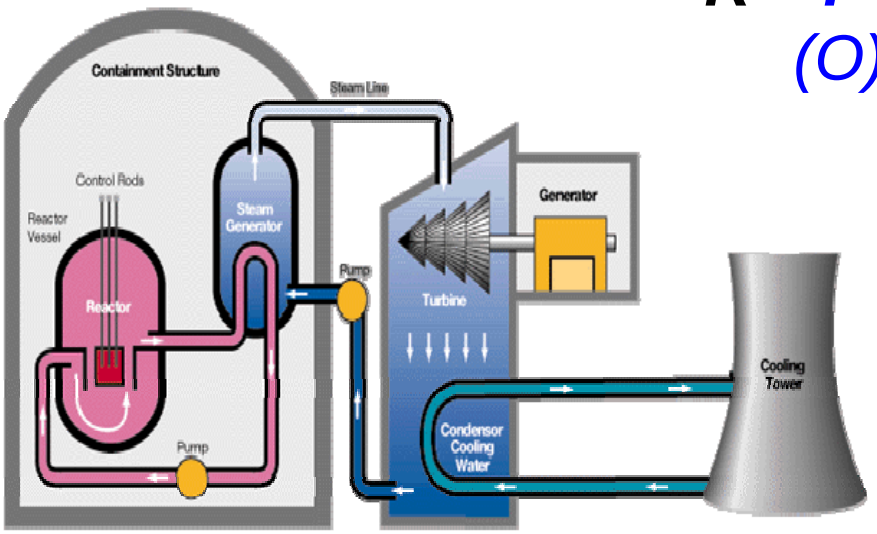
Contents

Decision Making in Nuclear Industry

$$R = P \times C$$

$$(O)x(o)$$



VS.

Experiments (Scaling)

Simulation-Based Learning

Large Uncertainties

2-3 Generations

Full-Scale Testing

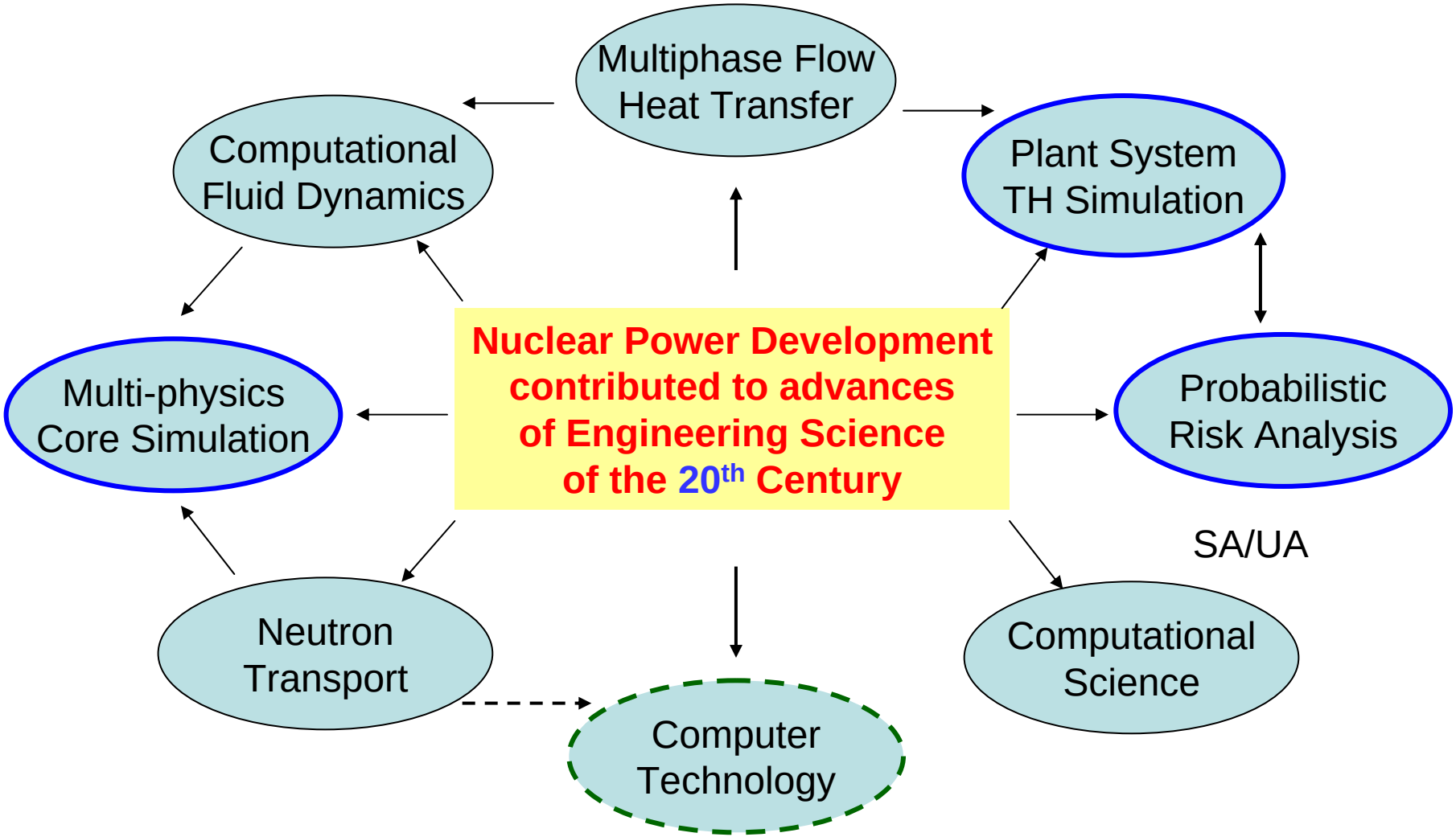
Trials-and-Errors

Statistics Available

 # Generations

In Silico Evolution of Nuclear Power

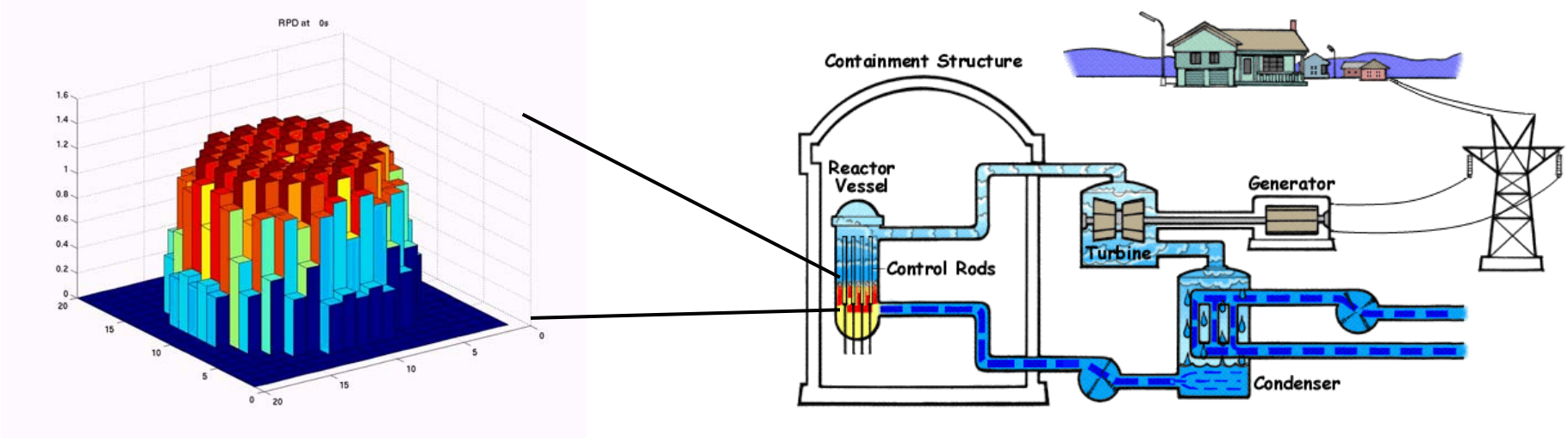
Computational Nuclear Reactor Engineering



Intellectual Values and Technologies

Current Practice

+ + Improved Tools



Reactor Core Neutron Kinetics

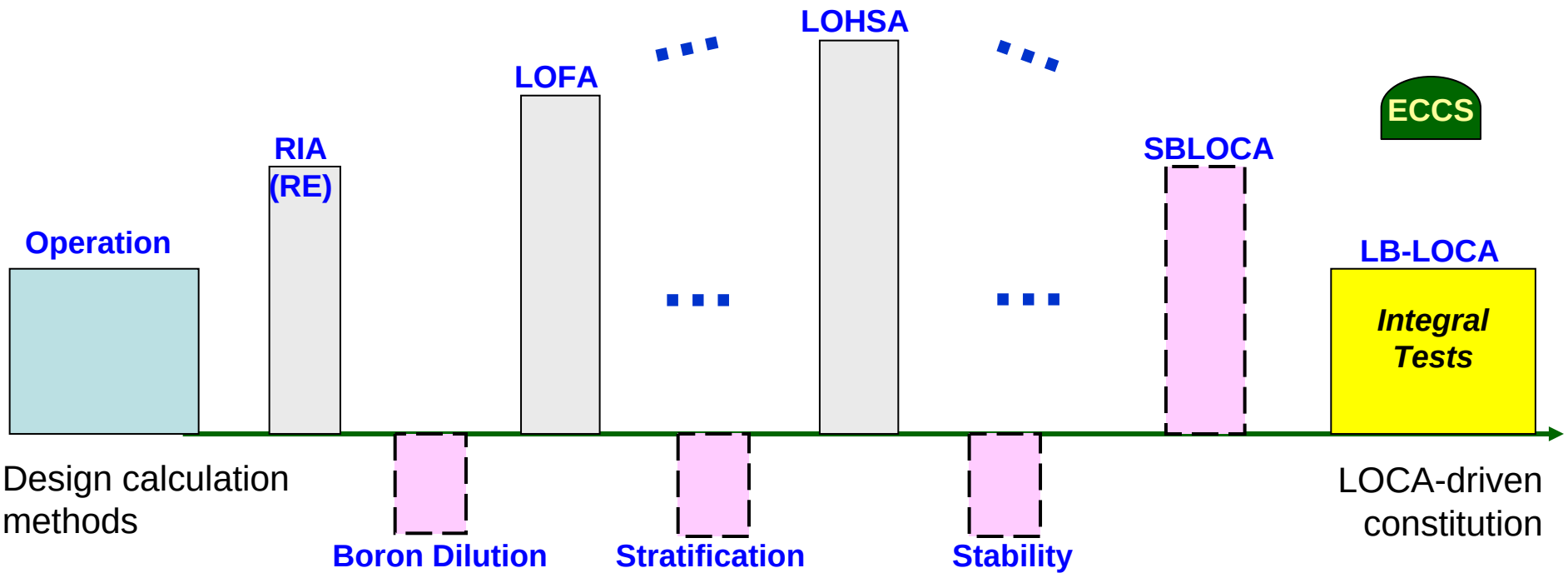
- governing equations – 3D neutron kinetics
- simulate detail power distribution inside reactor core

Primary System Thermal-Hydraulics

- governing equations – 1D two-phase fluid flow
- simulate response of the entire plant

Current Practice

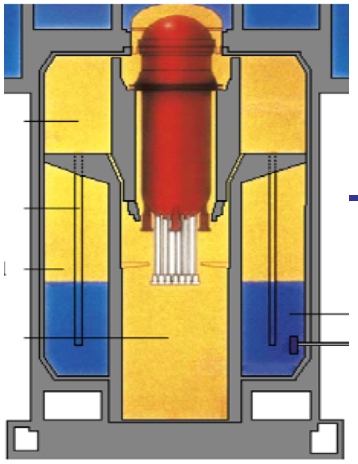
– – Validated Codes …*vs* … Invalid Calculations



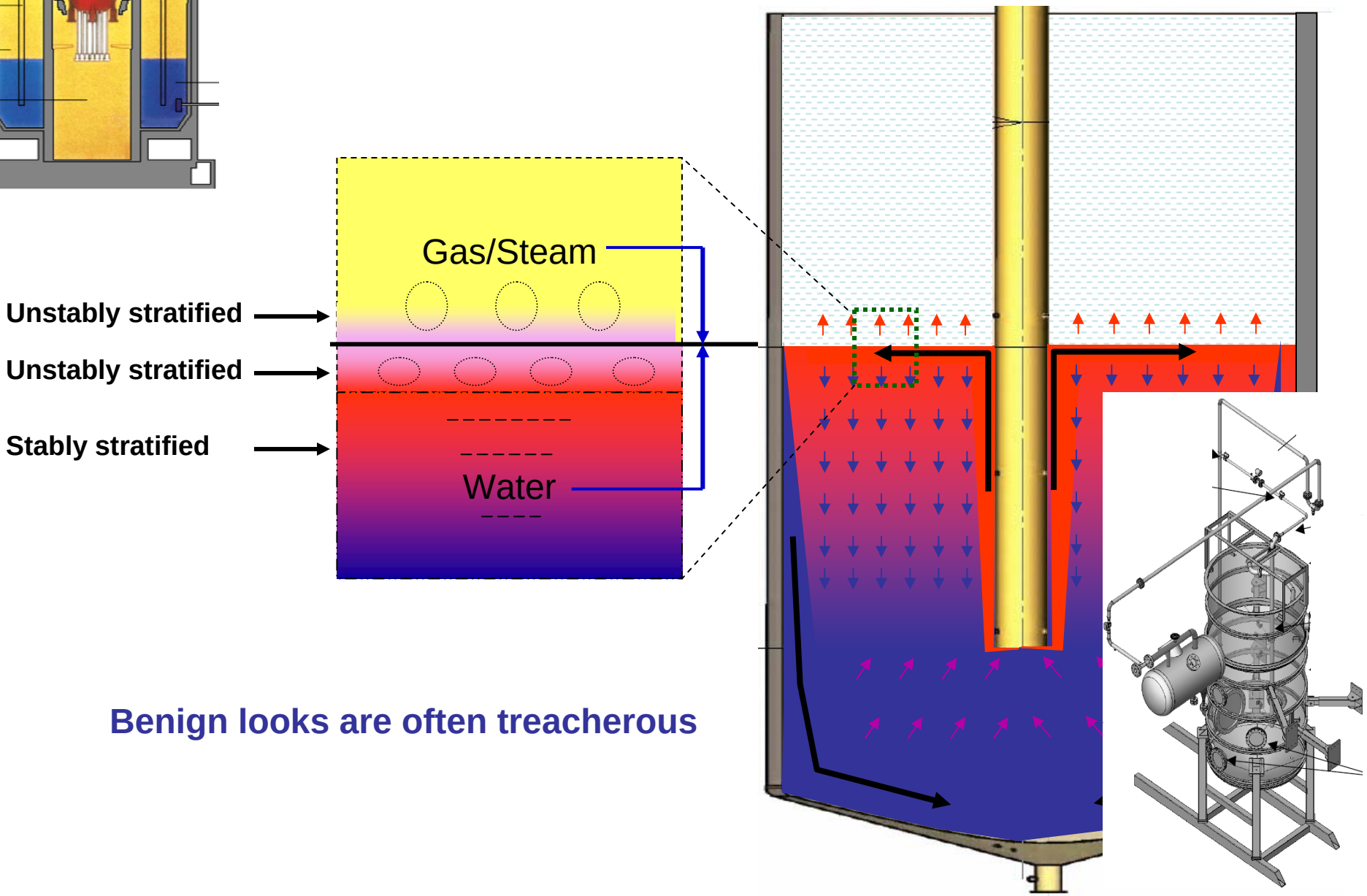
Strategy:
Divide-and-Conquer

Strategy:
Conservatism

Both strategies become increasingly inadequate



Conservatism vs. Evolving Nature of Safety Threats

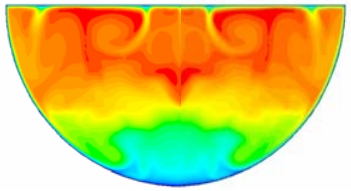


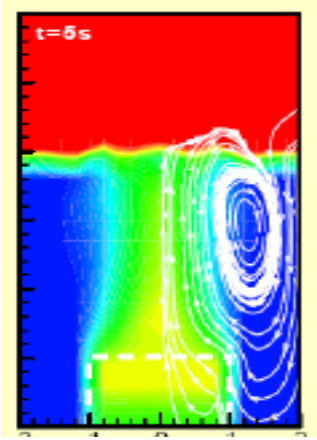
Benign looks are often treacherous

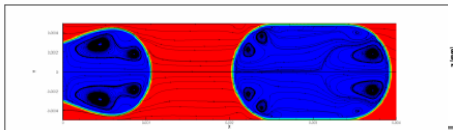
The Practice

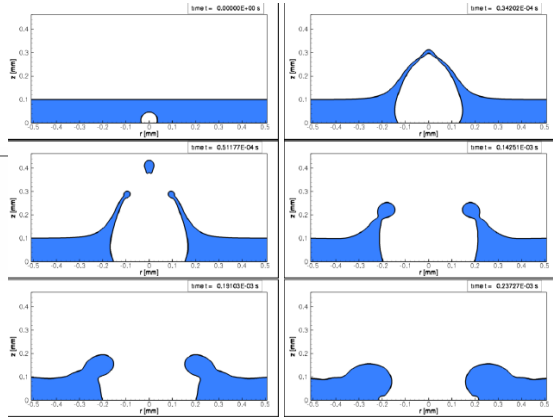
- **Industry practice: safety analysis, *licensing*, regulation**

  - “Best-Estimate” Coupled NK-TH System Codes
  - Probabilistic Risk Analysis (PRA)
  - *Computational Fluid Dynamics (CFD)*

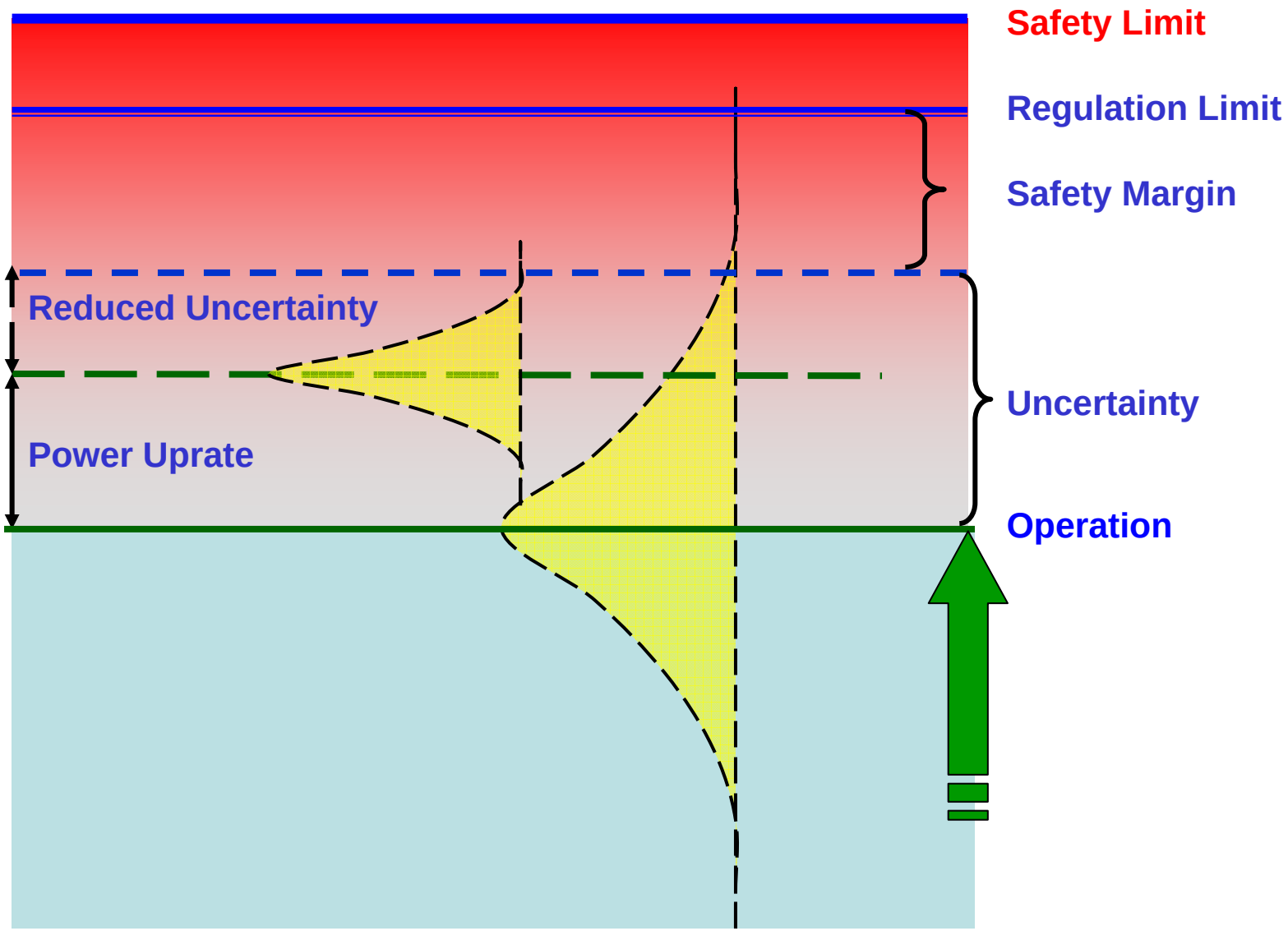








The Trend


Safety Limit
Regulation Limit
Safety Margin
Reduced Uncertainty
Power Uprate
Uncertainty
Operation

The Needs

- Industry practice: safety analysis, licensing, regulation
- Confidence in reactor safety margins
- Predictability of rare events
- Optimal and reliable performance
- New quality in reactor performance

The Challenges

Responding to the Challenges: New Generation Toolkit

- Industry practice: safety analysis, licensing, regulation
- Confidence in reactor safety margins
  - ***Class I: Advanced Accident Simulation Codes***
- Predictability of rare events
  - ***Class II: Search Engine***
- Optimal and reliable performance
  - ***Class III: Plant "Fingerprint" and Total Diagnostics***
- New quality in reactor performance
  - ***Class IV: Micro-scale Control***

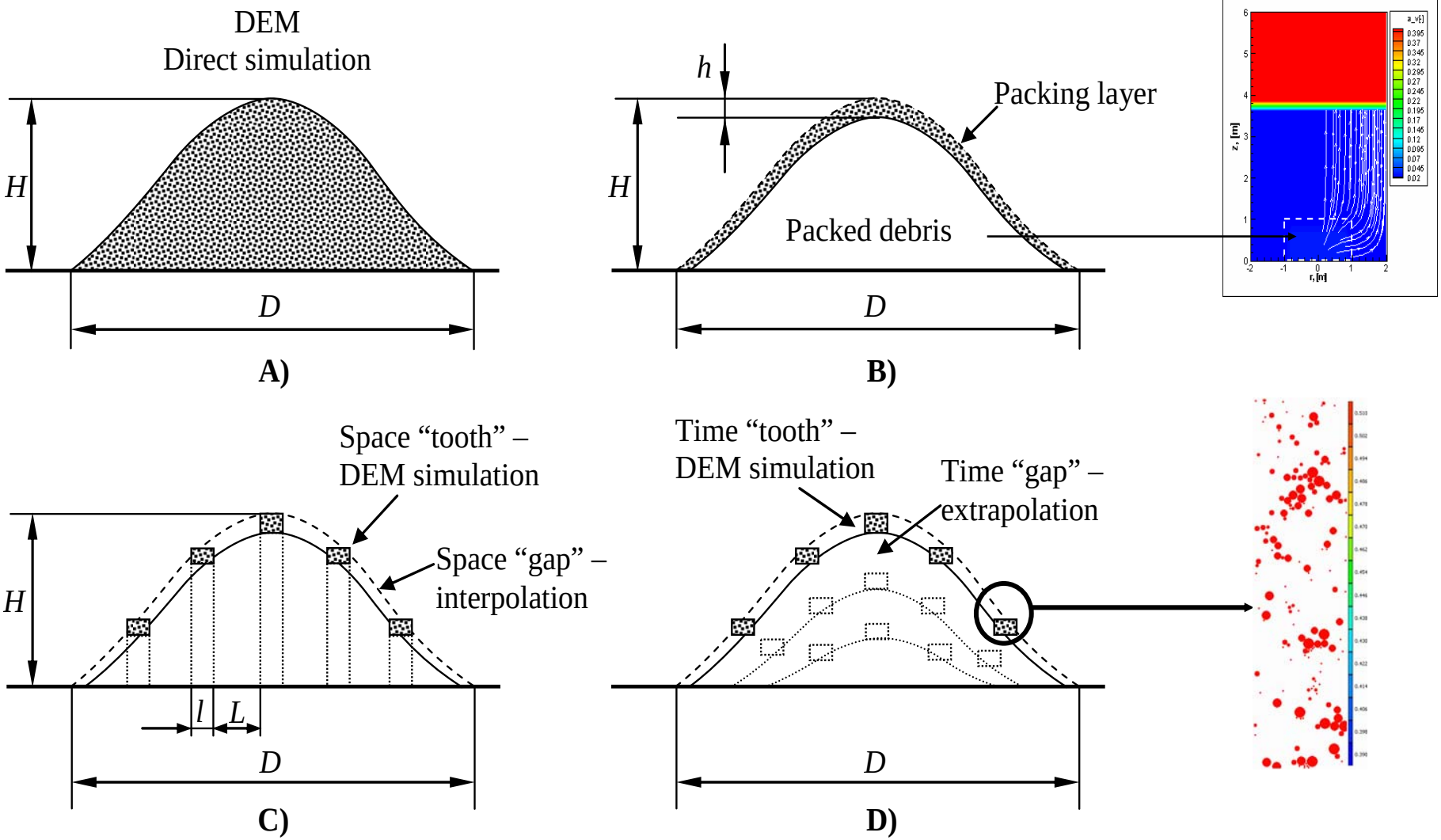
Class I: Advanced Accident Analysis Codes

➢ *for High-Fidelity Quantification of Safety Threats*

- **Predictive Capability**
  - ❖ **Physics-based**
    - ❑ **Fundamentally well-posed hyperbolic, conservative models, that ensure objectivity**
  - ❖ **Multi-scale treatment**
    - ❑ **Adaptive model refinement**
  - ❖ **Parallelized computation. Nonlinear, implicit solvers**
  - ➢ **"DNA" free of basic diseases**

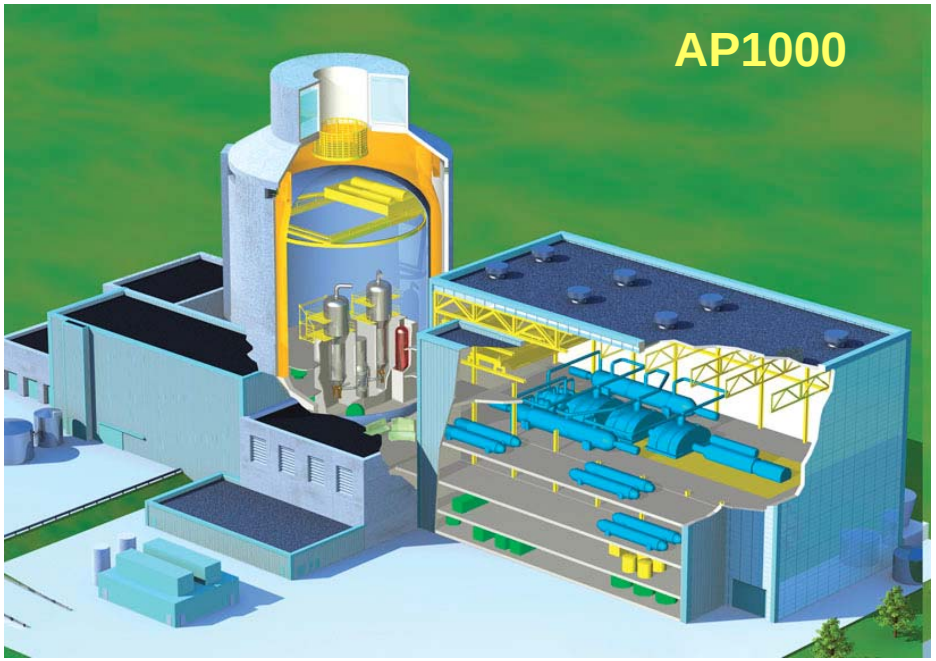
- ❖ **Scenario-driven (licensing)**
- ❖ **No numerical convergence.**
- ❖ **Flow regime maps tailored to certain DBA**
- ❖ **Hard-wired models**
- ❖ **Methods/platforms/solvers of the 1960s-1980s.**
  - ❑ **Compensation of errors**
- ➢ **"Lego" body.**

“Gap-Tooth” Simulation Platform for Reactor Analysis

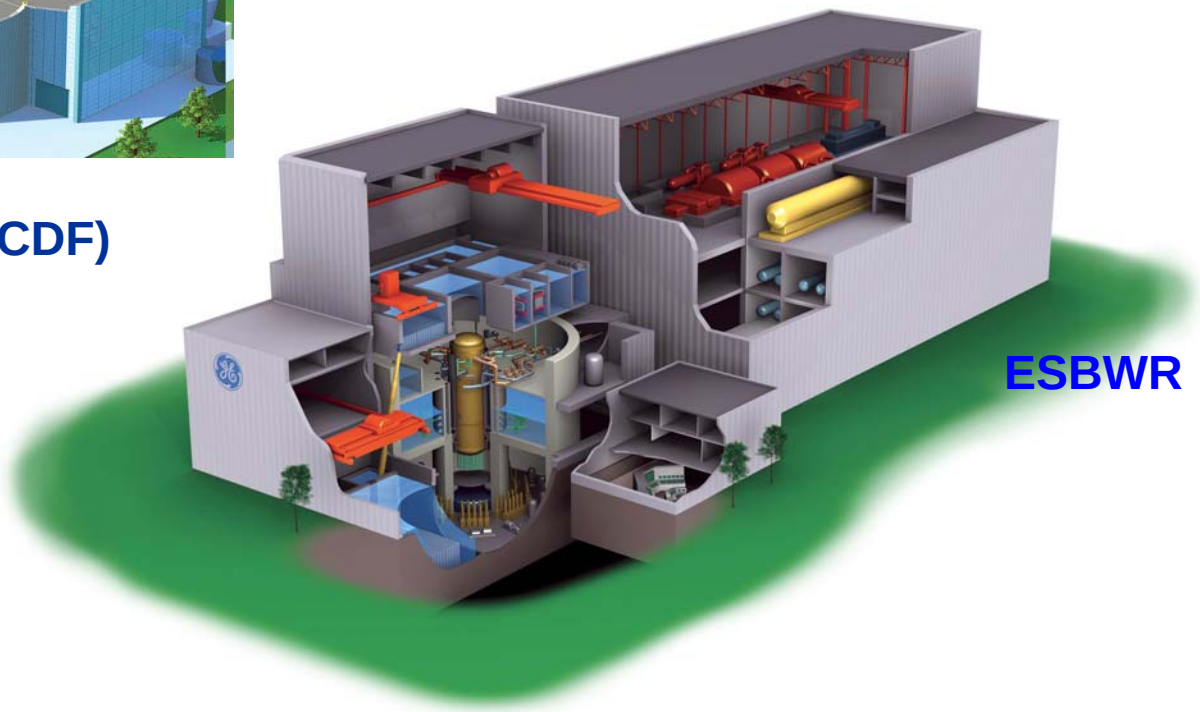


Computational saving: 10^2…10^4

Nuclear Renaissance



- **Major advances in technology**
  - ✓ Reduced number of components
  - ✓ Passive safety features
- **Evolutionary design**



- **Core Damage Frequency (CDF)**

  (10^{-7}…10^{-8})/reactor•year.

Natural Circulation-Driven Operation and Safety

Safety Analysis of Advanced Passive Plants

- Natural circulation is delicate, 3D
- Two-phase and multi-component (air/H_2/steam) NC ...→ complex.
- 3D TH *vs.* 1D and 0D models

- New systems, lack PRA insights
- Process-controlled failures (vs. equipment-related failures)
- ***Need a New Way to Characterize and Analyze Passive Systems***

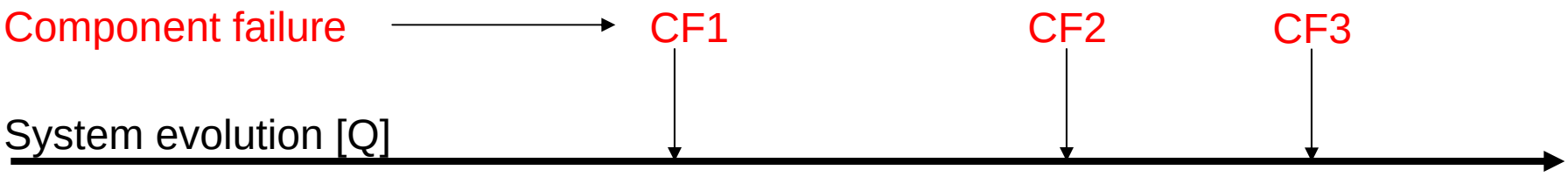
- **Quantification:**
  ... *less* valves,
  ... *more* physics
- **Uncertainty:**
  ... *reduce* aleatory
  ... *increase* epistemic

Conservation Law

(Conservation of Headache)

Class II: Search Engine

➢ ***to Identify Plant Vulnerability and Potentially Risk-Significant Sequences***

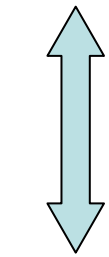


$\mathcal{P}$(CF1) $\mathcal{P}$ (CF2) $\mathcal{P}$ (CF3)

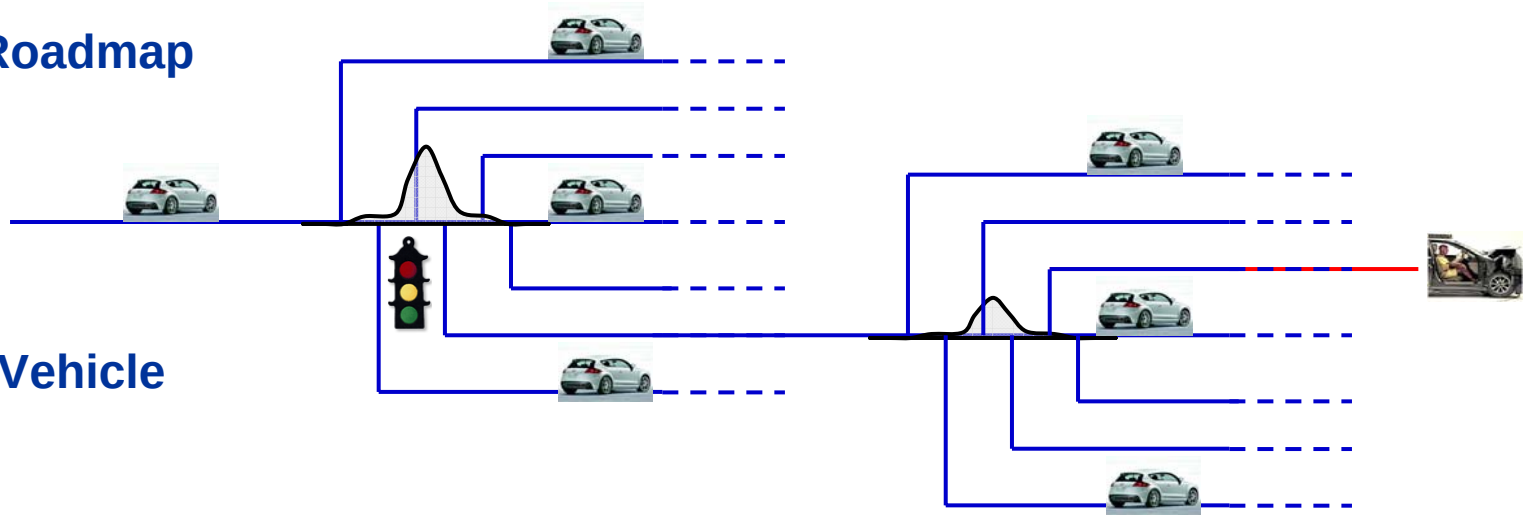
$\mathcal{P}(CF1) = f([Q])$

$\mathcal{P}(CF1) = f_U([Q]_U)$

Probabilistic Roadmap



Deterministic Vehicle



Class III: Plant Fingerprint and Total Diagnostics

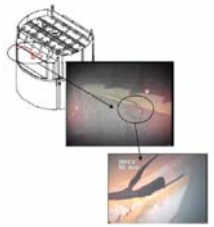
➢ *to Achieve Optimal and Reliable Performance*

- "Fingerprinting":
  - core power (neutron), flow (T, P, u, c)
  - spatio-temporal fluctuations (n, T, P, u, vibrations)

- Computational characterization of the plant's operating regimes (incl. slight variations)
  HNT, CFD, FSI

- Consistent with the plant's monitoring system and diagnostic techniques

➢ Detect Problems before They Actually Become Ones.

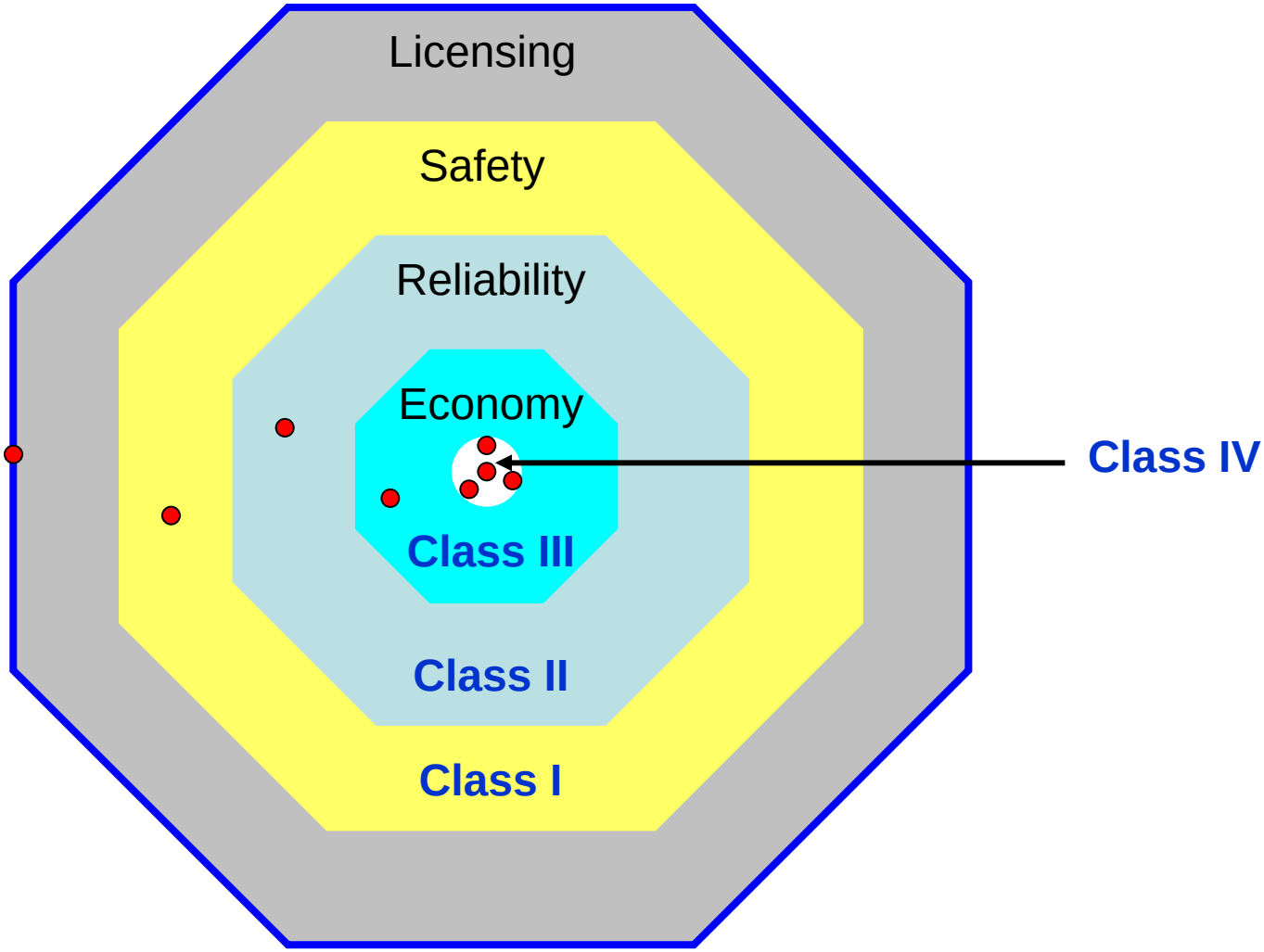


Smooth Run

Fuel performance
... in TH.

Exploiting the Diagnostic Value of "Noises"

The Enabling Technology



Years of the plant operation with no surprise.

Ability to handle "event" expeditiously when it strikes …

Synergistic Use of Tools to Effectively Manage Rare "Events"

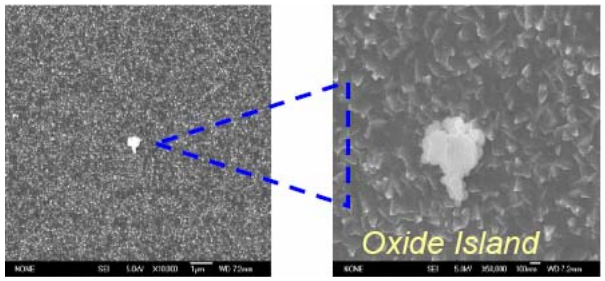
The New-Generation Tools enable

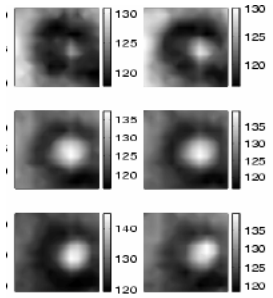
- **High-quality analysis of the plant behavior during the event**
- **Sound understanding of consequences of other "what-ifs"**
- **Analysis of options and making decision on corrective measures**
- **Common understanding with, and acceptance by, the regulator**
- **Putting the authority and the public at ease**

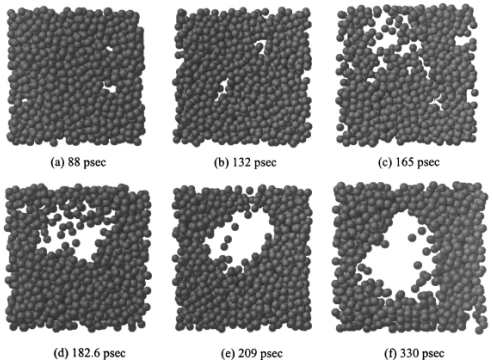
➢ **Safety & *$$$***

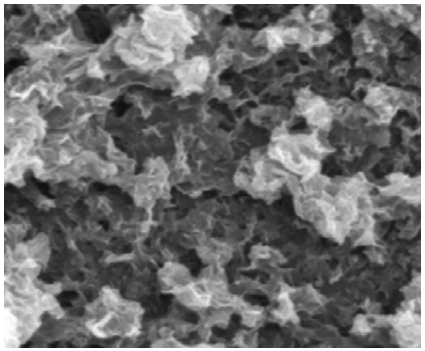
Class IV: Microscale Control to Leapfrog Reactor Performance

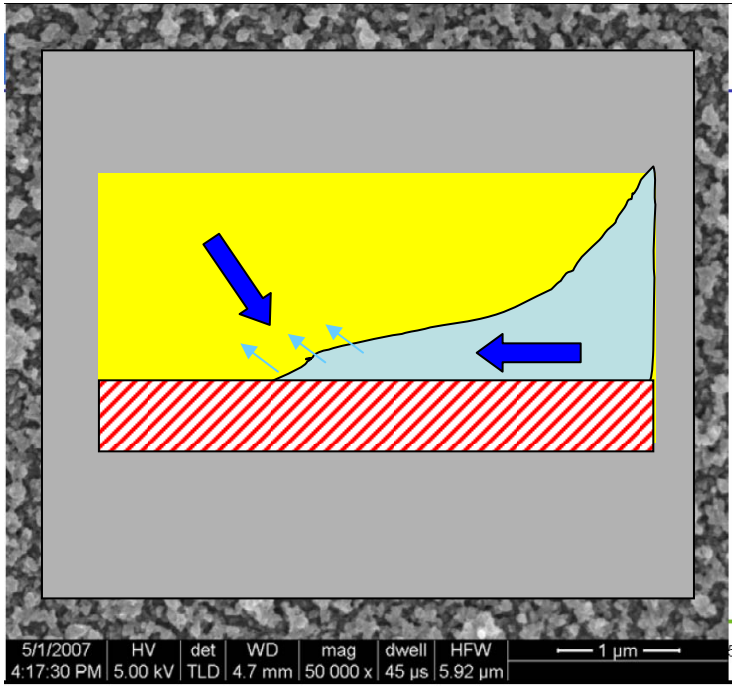
"There's Plenty of Room at the Bottom", *Richard P. Feynman* (1959)





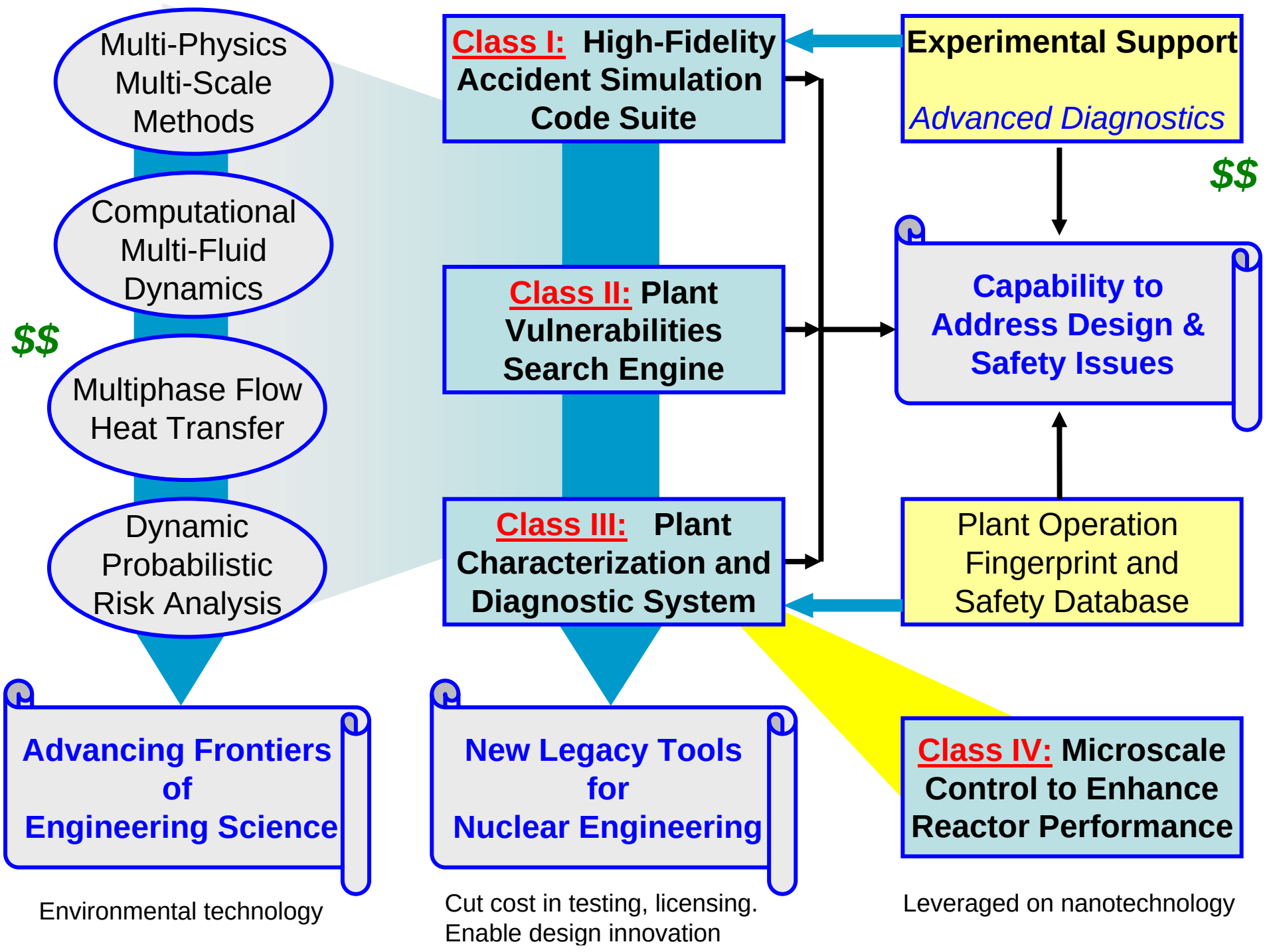






- **Microphysics (microhydrodynamics, nucleation, inter-molecular forces, coolant-surface wettability, crud deposition, coolant chemistry, radiation-induced surface activation, etc.) governs reactor performance.**

Computational and Experimental Nanotechnology


Multi-Physics Multi-Scale Methods
Computational Multi-Fluid Dynamics
$$
Multiphase Flow Heat Transfer
Dynamic Probabilistic Risk Analysis
Class I: High-Fidelity Accident Simulation Code Suite
Class II: Plant Vulnerabilities Search Engine
Class III: Plant Characterization and Diagnostic System
Experimental Support
Advanced Diagnostics
$$
Capability to Address Design & Safety Issues
Plant Operation Fingerprint and Safety Database
Advancing Frontiers of Engineering Science
New Legacy Tools for Nuclear Engineering
Class IV: Microscale Control to Enhance Reactor Performance
Environmental technology
Cut cost in testing, licensing.
Enable design innovation
Leveraged on nanotechnology

Overall Assessment of Need and Impact

	Class I "accident analysis"	**Class II** "search engine"	**Class III** "fingerprint & diagnostics"	Remarks
Urgency of the development	**Very High**	High	Medium	ALWR
	High	Low	No	Others
Live without it in ***near term***	No	Yes	Yes	2015 - # ALWRs in operation
Live without it in ***mid term***	–	No	Yes	2025
Live without it in ***long term***	–	–	No	> 2025 - ## ALWRs in operation
Impact – on Safety	Very High	High	Medium	
Impact - on Economic	High (*regulation*)	High (*regulation*)	Very High (*reliability*)	

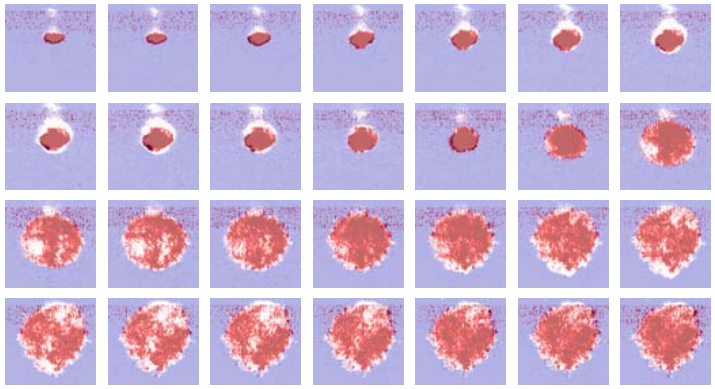
The Implementation Challenges

	Class I "accident analysis"	**Class II** "search engine"	**Class III** "fingerprint & diagnostics"	Remarks
Readiness of methodology	Medium	Low	Medium	Theory, math models, algorithms
Readiness of supporting knowledge	Low	Very Low	Medium	I : Physical closures II: Equipment data III: Plant operation data
Readiness of technology	Medium	Low	Low (*diagnostics*)	Computing power
Opposing factors/forces	Comfort (industry-reg.)	Divided D-P communities	Preparedness of workforce	Inertia over two decades of "conservation"
Essential Supplements	Experiments	DPRA Model/Data	Diagnostic Techniques	Investment
Maturation	10 years	15-20 years	10-15 years	Industry, NRC, Interna-tional collaboration

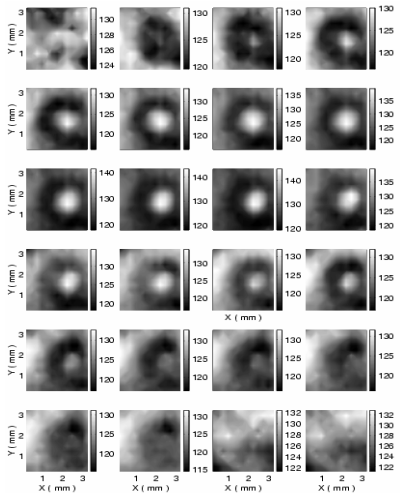
Experimental Support

Fundamental, Locally-Scaled Experiments w/ Advanced Diagnostics

Anatomy of Droplet Explosion

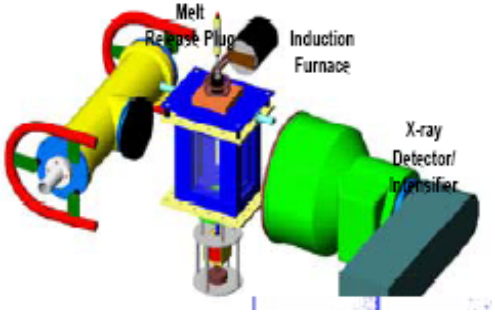


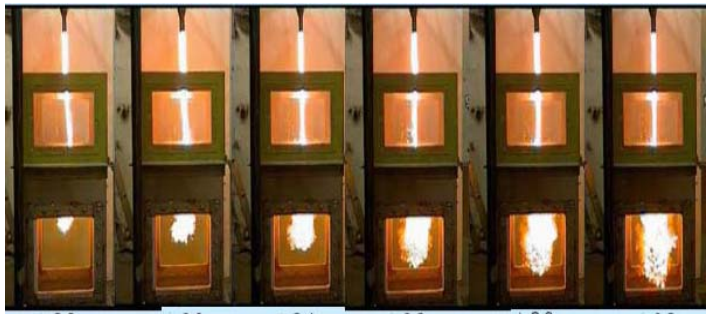
Anatomy of Boiling at High Heat Flux



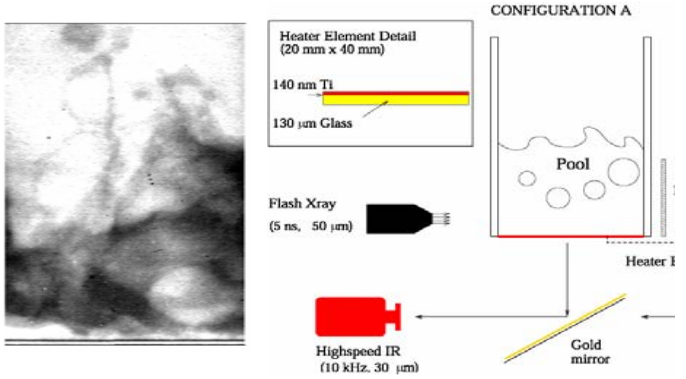
Advanced Codes Require New Class of Sub-grid-scale Models and Detailed Data

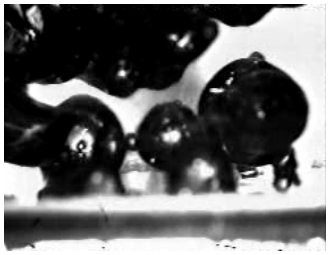
Synchronous High-Speed Imaging Photo- (100kfps) and X-ray (10kfps)

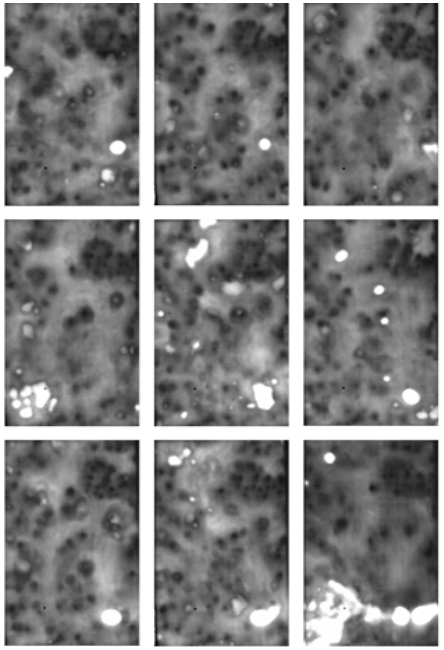




Synchronous High-Speed Imaging Photo-, X-Ray and IR (20kfps)







Concluding Remarks

- **Due to economic and safety requirements, the plant safety technology has become increasingly complex ... *even when it looks simpler*.**

- **The key to the plant's economic and safe operation is in managing the complexity of *rare*, but potentially high-consequence "events".**

- **Due to the multi-faceted nature and different focus of plant operation in normal and abnormal regimes, *panoply* of analysis tools is needed.**

- ***Timely* investment in Computational Safety has far-reaching impact.**

Thank You.