NEAMS Fall 2010 PI Meeting
L'Enfant Plaza Hotel ,Washington DC
October 20, 2010

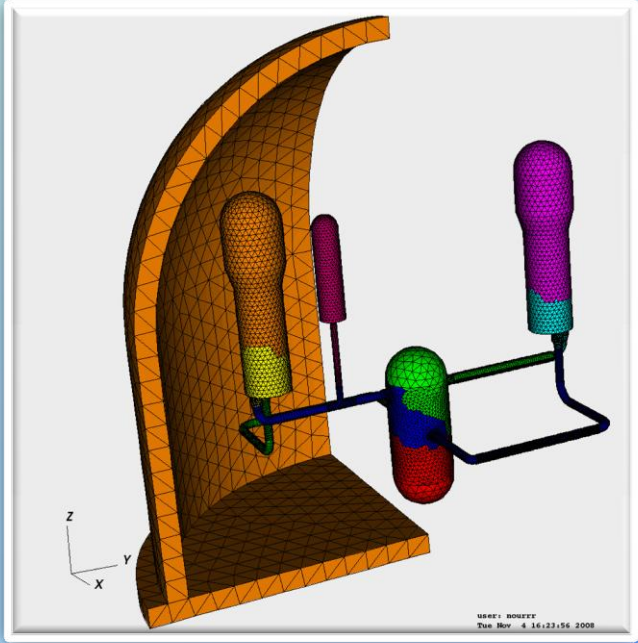
Idaho National Laboratory

R7: Next-Generation System Code for Nuclear Reactor Safety Simulation to Support RISMC

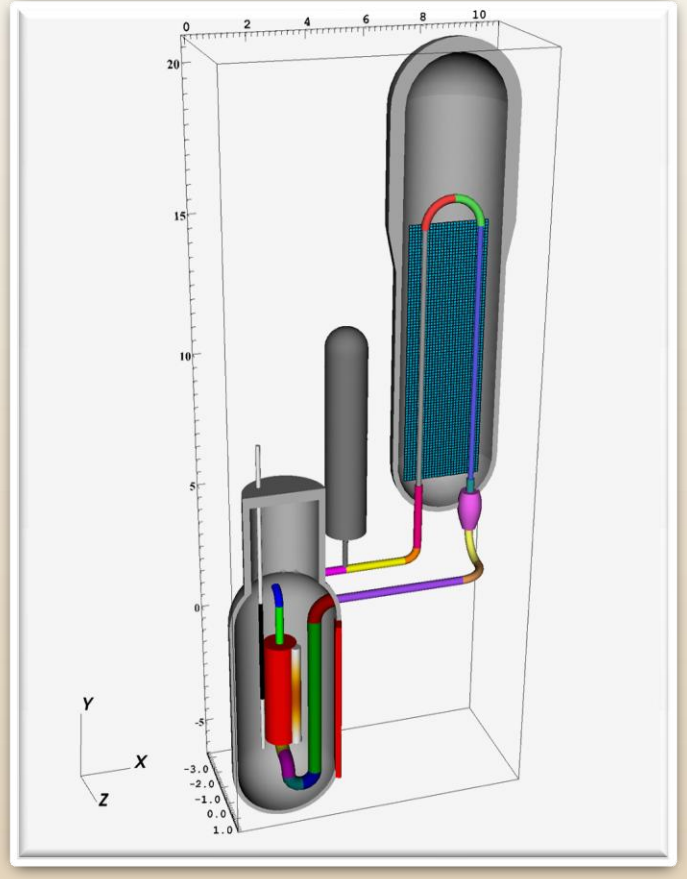
Dr. Robert Nourgaliev
Dr. Nam Dinh
Dr. Robert Youngblood

Reactor Safety Simulation Group
Idaho National Laboratory (INL)

With contributions from:
Dr. Ralph Nelson (LANL)
Dr. Laura Swiler (SNL)
Dr. Brian Williams (LANL)



Outline



I. Introductory Remarks

Definitions, Background, Goals

II. R7: development status

Highlights of code architecture, numerics and (multi-) physics

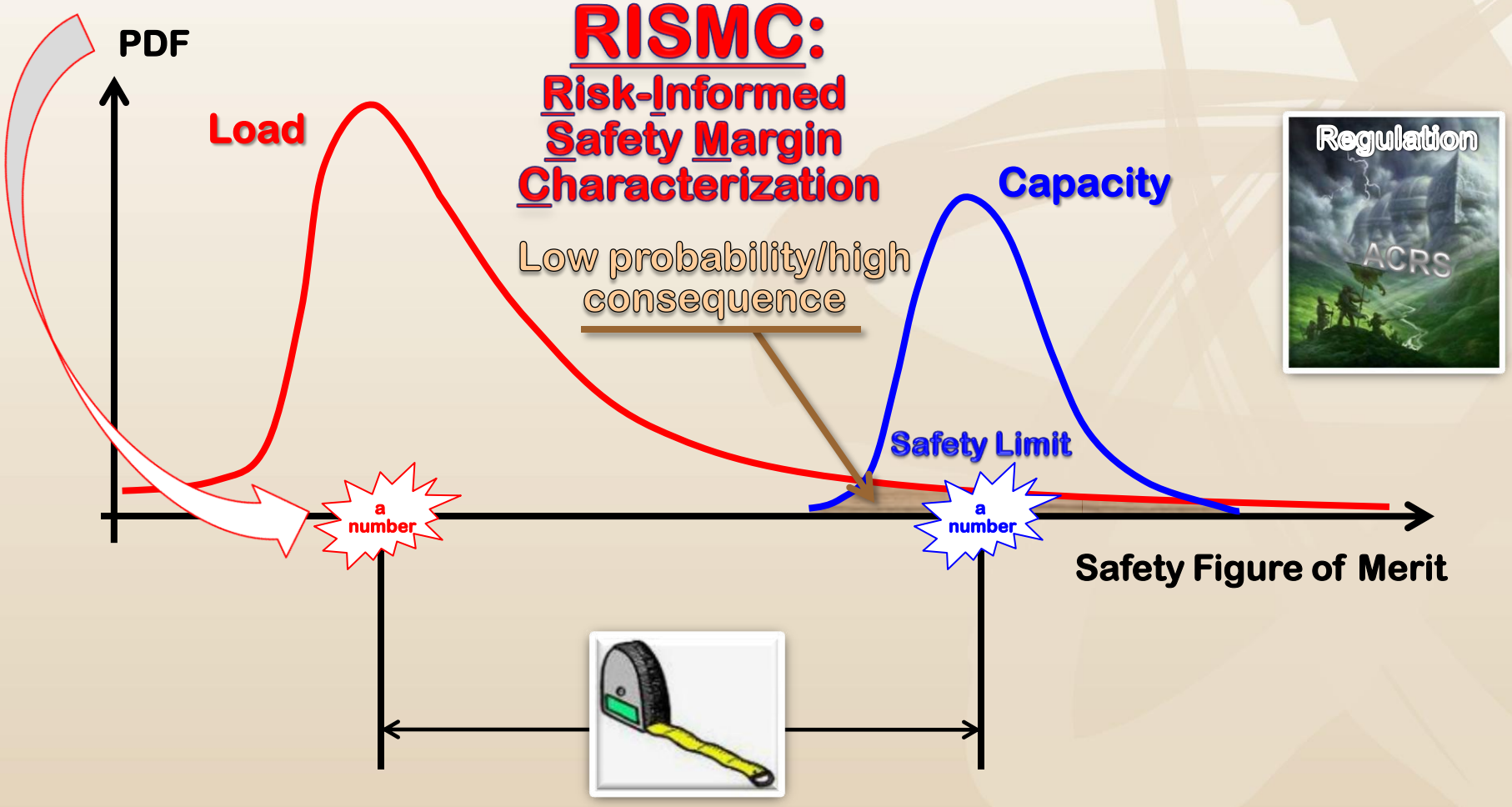
III. Application examples

- Accuracy/convergence, efficiency
- Uncertainty Quantification
- Risk and decision making (RISMC demo)
- Plant ageing demo

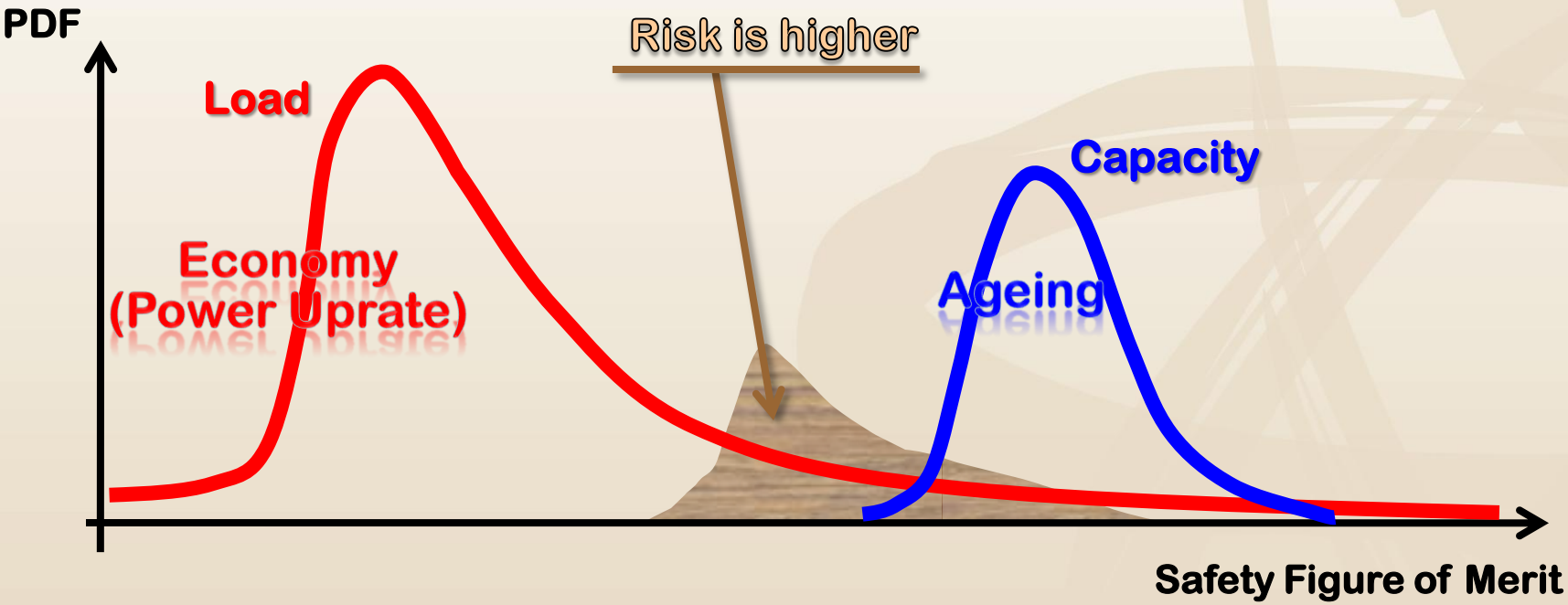
I. Introduction

Nuclear Reactor Safety

Current ("Legacy") Codes: RELAP5, TRACE, CATHARE

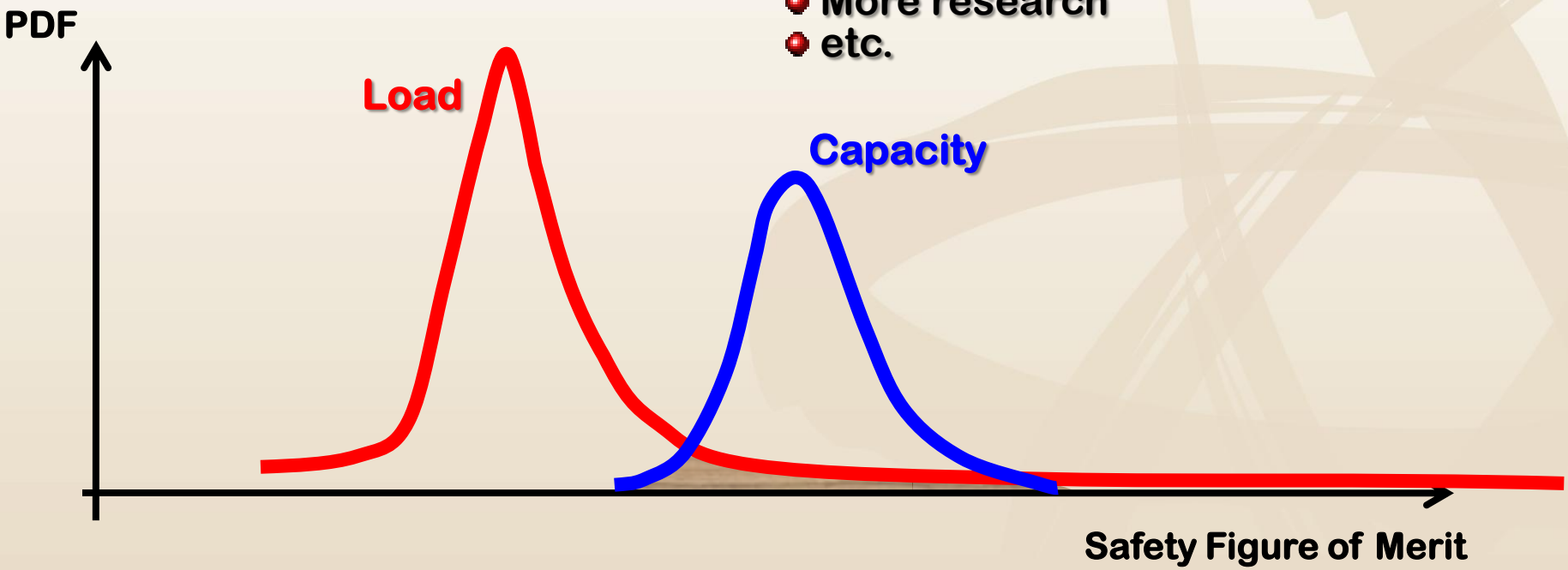


Nuclear Reactor Safety



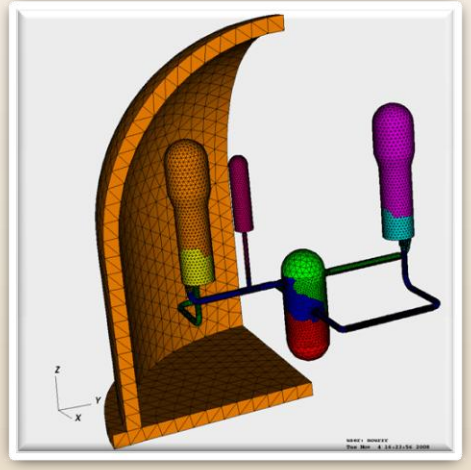
Nuclear Reactor Safety

- Change in operational procedures
- Inspection procedures
- More research
- etc.



Next Generation Safety Analysis Codes

Safety margin characterization
Balance between design, operation and safety code
Help in decision making
Licensing
Risk monitoring/forecast



Goals:
Reactor Safety and Risk Assessment and Management

Probabilistic Risk Assessment (PRA)

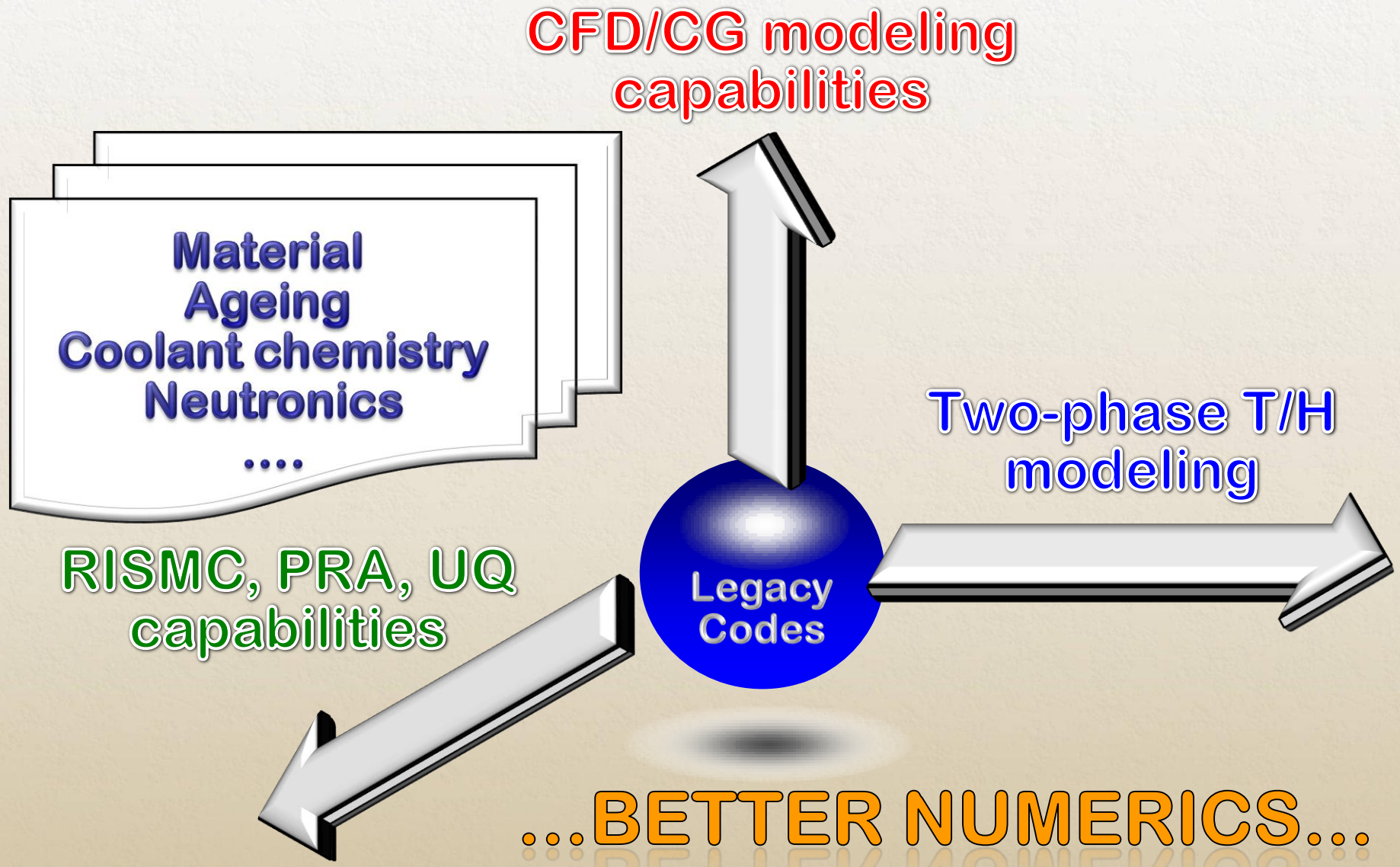
Simulator: Training

LOCA, DBA
(Legacy codes: RELAP5, Trac, TRACE, CATHARE)

Non-DBA
(plant ageing)

System vulnerability search engine

R&D Thrust Directions



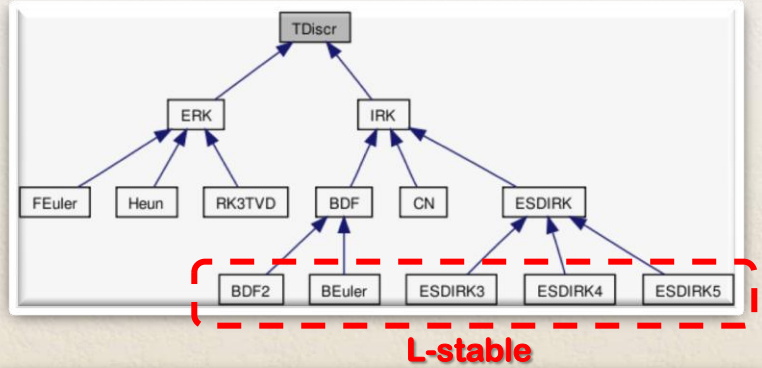
II. Code Development Status

Version β-2: highlights

Recovery DG (1D)
(up to 12th-order)

Reconstructed DG (2D & 3D unstructured-grid)
(3rd-order and higher)

- Object-oriented (C++)
- Parallel (MPICH)
- High-order in space
- Fully-implicit, L-stable, High-order in time
- State-of-the-art linear algebra (Krylov-based, JFNK, PETSc)
- All-speed capabilities, t/d consistent real fluid EOSs
- Advanced 2-phase flow modeling
- Boron and corrosion product transport
- 3D CFD/SM capabilities (Coarse-Grain, RANS, LES Turbulence)
- Neutronics: 3D nodal diffusion
- Uncertainty Quantification enabled (integration with DAKOTA)
- "VU-assessed", with subversion control (Trac web-based), extensive verification and documentation ("ANT" Manual, Doxygen – html-based Manual), 3D visualization, GUI, regression testing



✓ Homogeneous Equilibrium (+Interfacial Slip) Model

❑ Two-fluid 6-equation hyperbolic 1-pressure (+interfacial pressure) model

❑ Two-fluid 7-equation hyperbolic 2-pressure model (DEM)

Version β-2: highlights

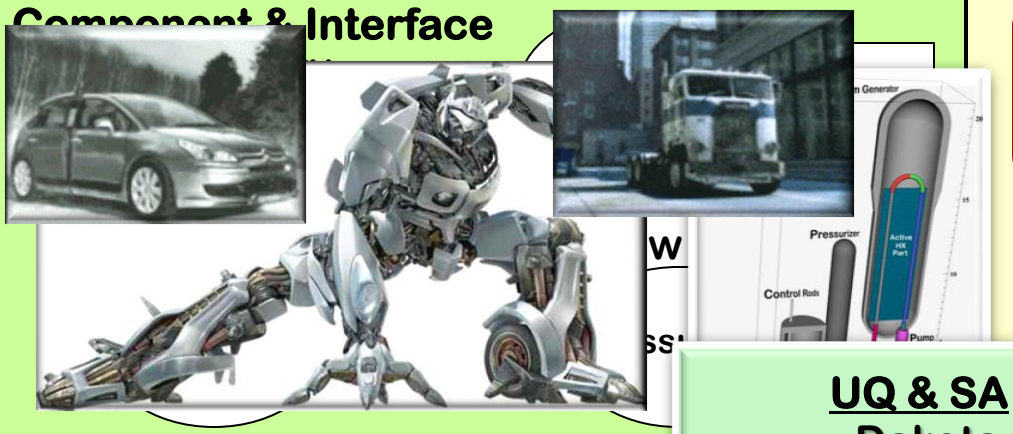
I/O, GUI, code control utilities

Pre/Post-Processors
(CuBiT, ViSiT, Paraview, ParMeTiS)

Component Factory

Computational engine
Time discretization,
Transient control

Component & Interface



Linear Algebra,
Nonlinear Solvers
PETSc
Trilinos

UQ & SA
Dakota
ADIC (FSA & Adjoint)

Component utilities
and
Library of templates

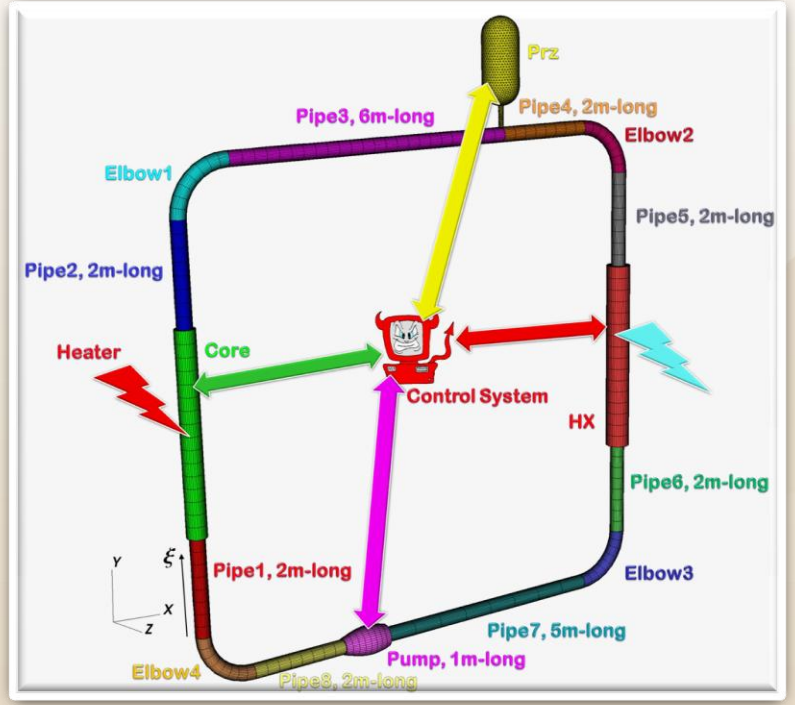
Closure Library

Material Library

III. Application Examples

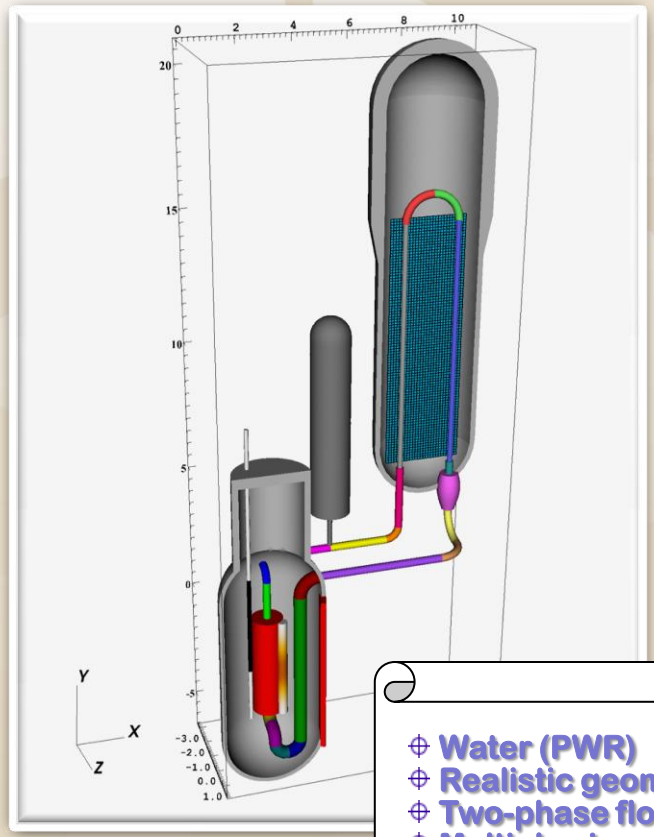
Examples

1. RISMC Demo



- Natural/Forced Convection
- Space-time accuracy
- Control system
- Coupling with RISK tools

2. PWR-I



- Water (PWR)
- Realistic geometry
- Two-phase flow
- Multiphysics
- Space accuracy
- Ageing

RISMC demo
(Risk-Informed Safety Margin Characterization)

RISMC demo

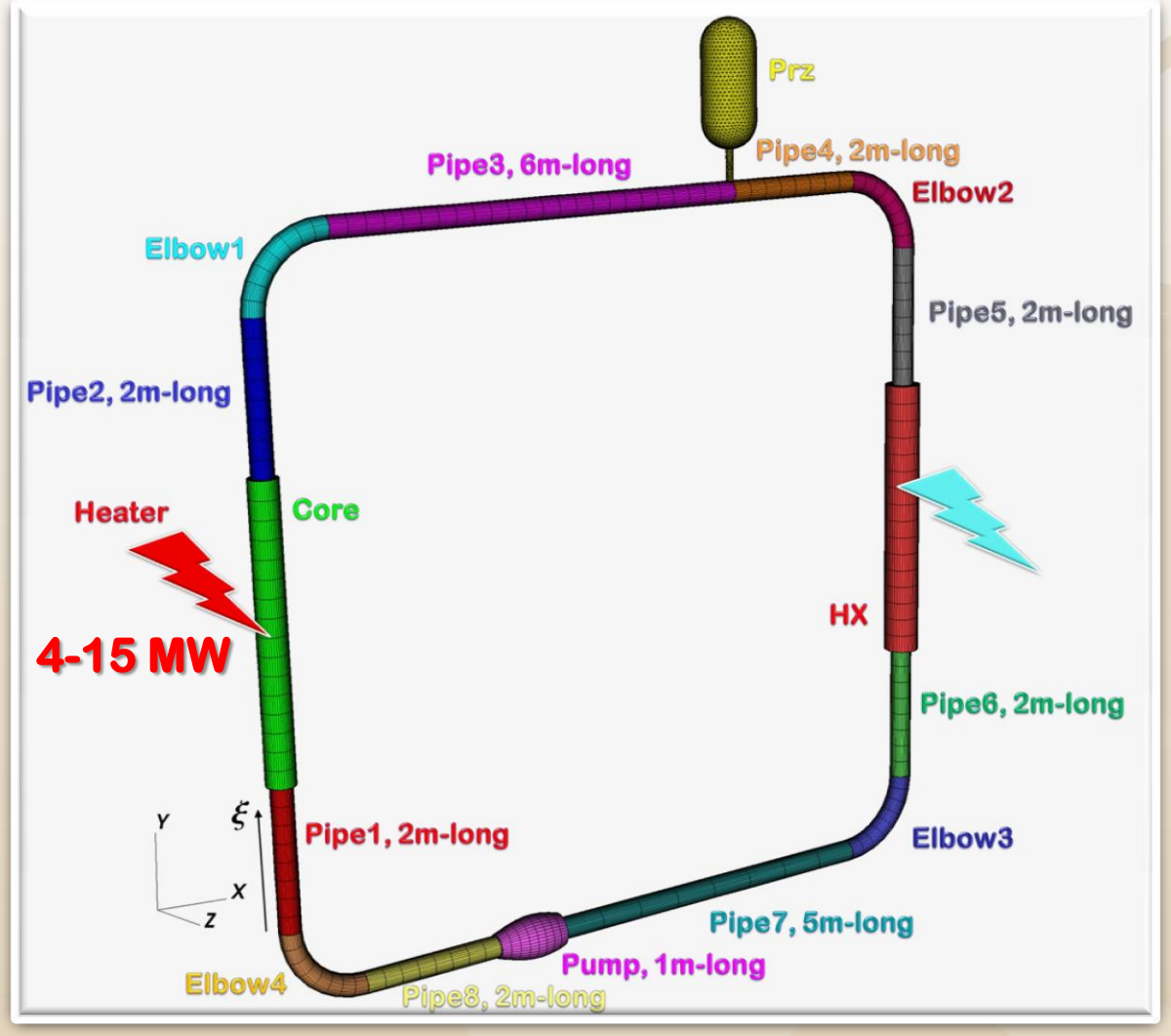
21 components:

8 pipes
4 elbows
Pump
Core
Heater/Neutronics
Pressurizer (Prz)
Heat exchanger (HX)
Prz control
Pump control
CRP control

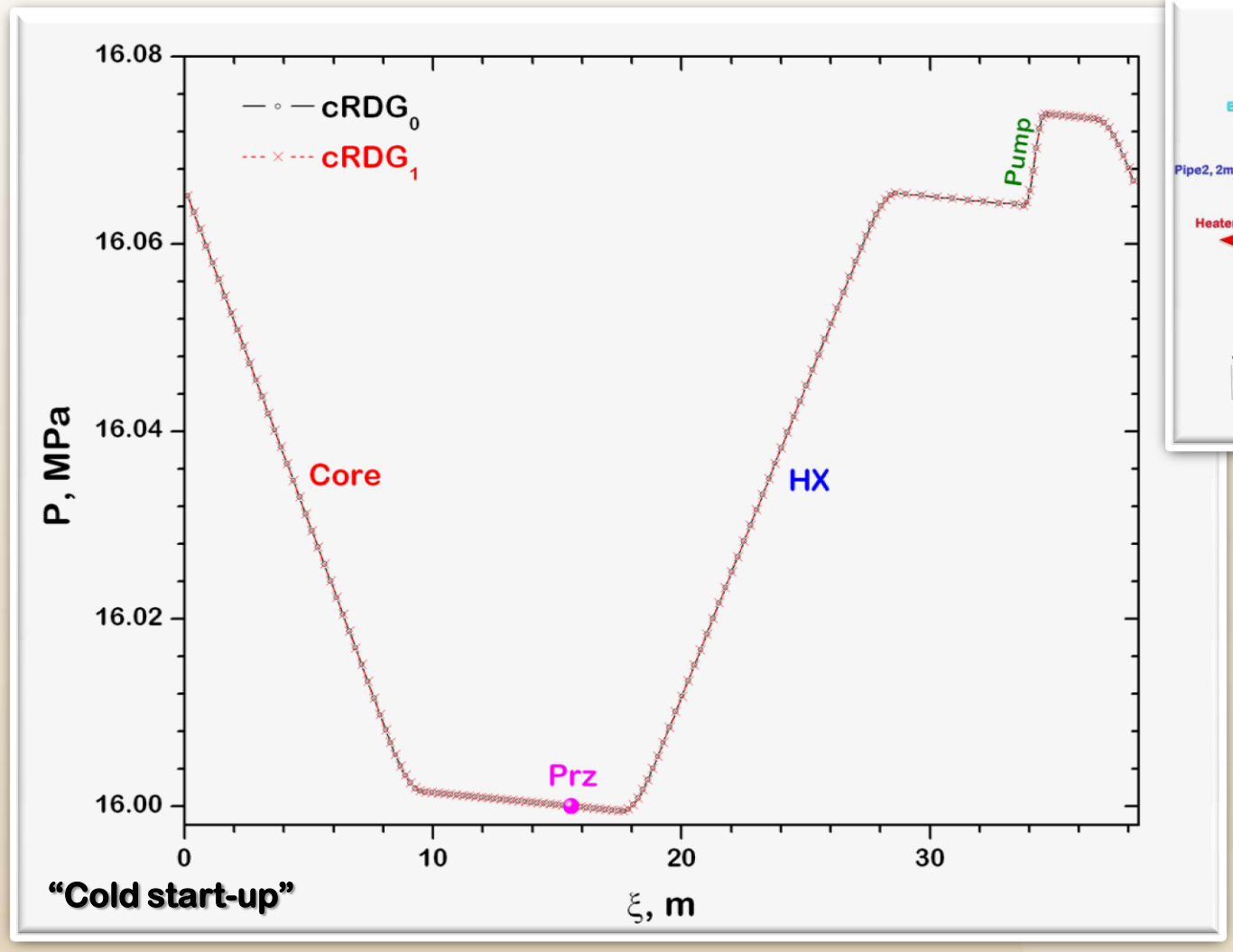
Working fluid:

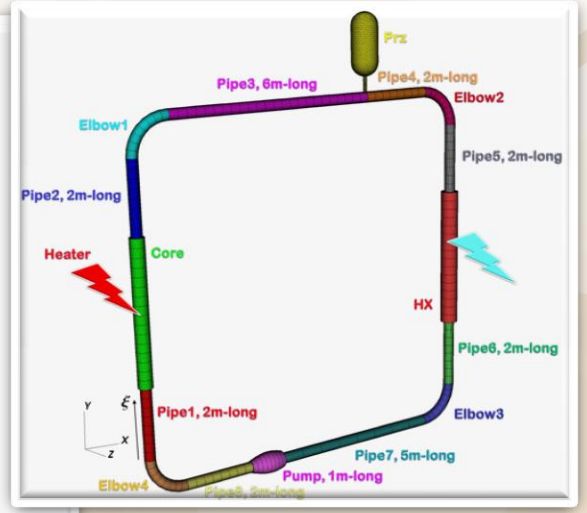
Water (16 MPa, 340° C)

Combined forced and natural circulation



RISMC demo





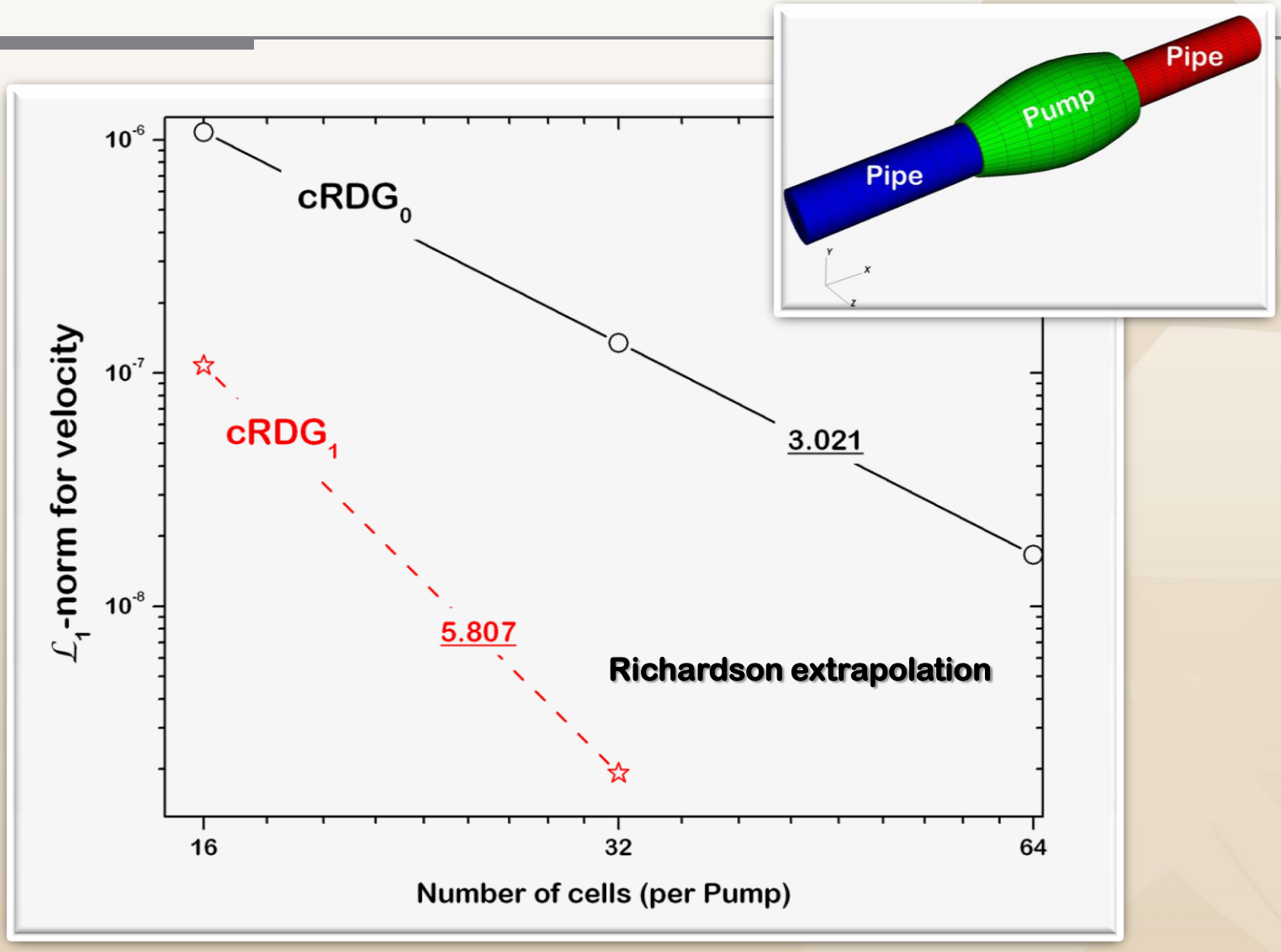
Steady-state:

20-30 time steps,
$CFL_{acou}=10^4\text{-}10^8$
($CFL_{mat}=10^2\text{-}10^6$)

CPU time:
~20 sec
to get t=3 hrs

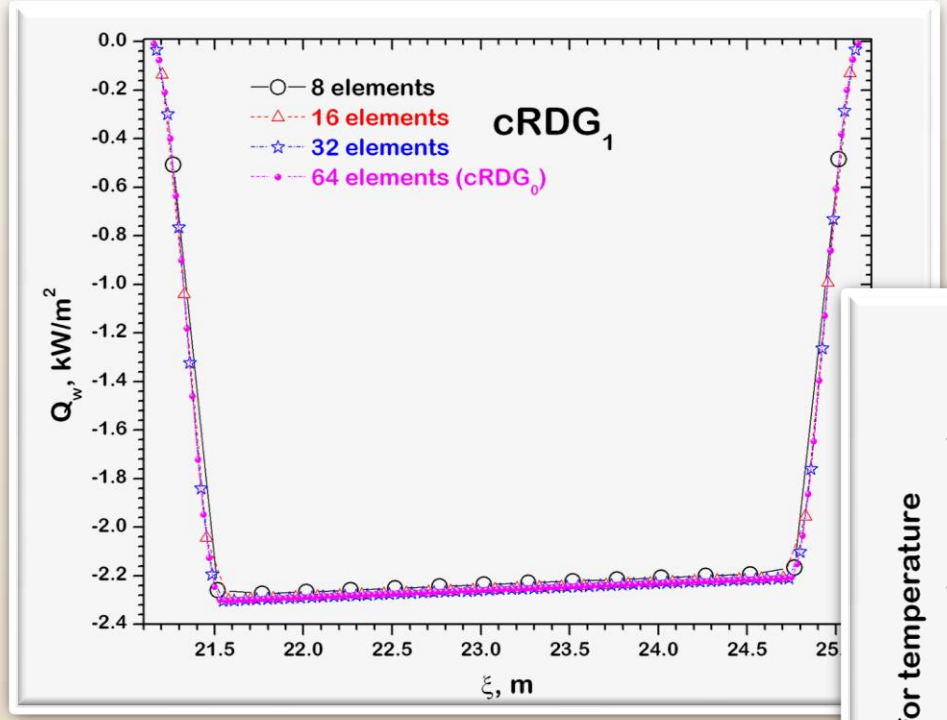
RISMC demo

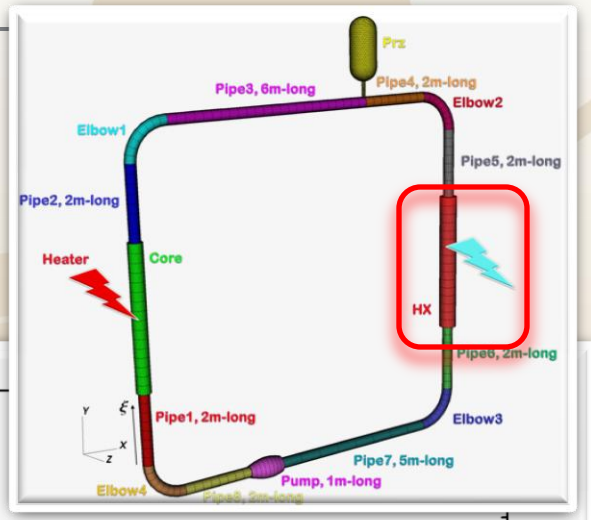
Verification: Space convergence

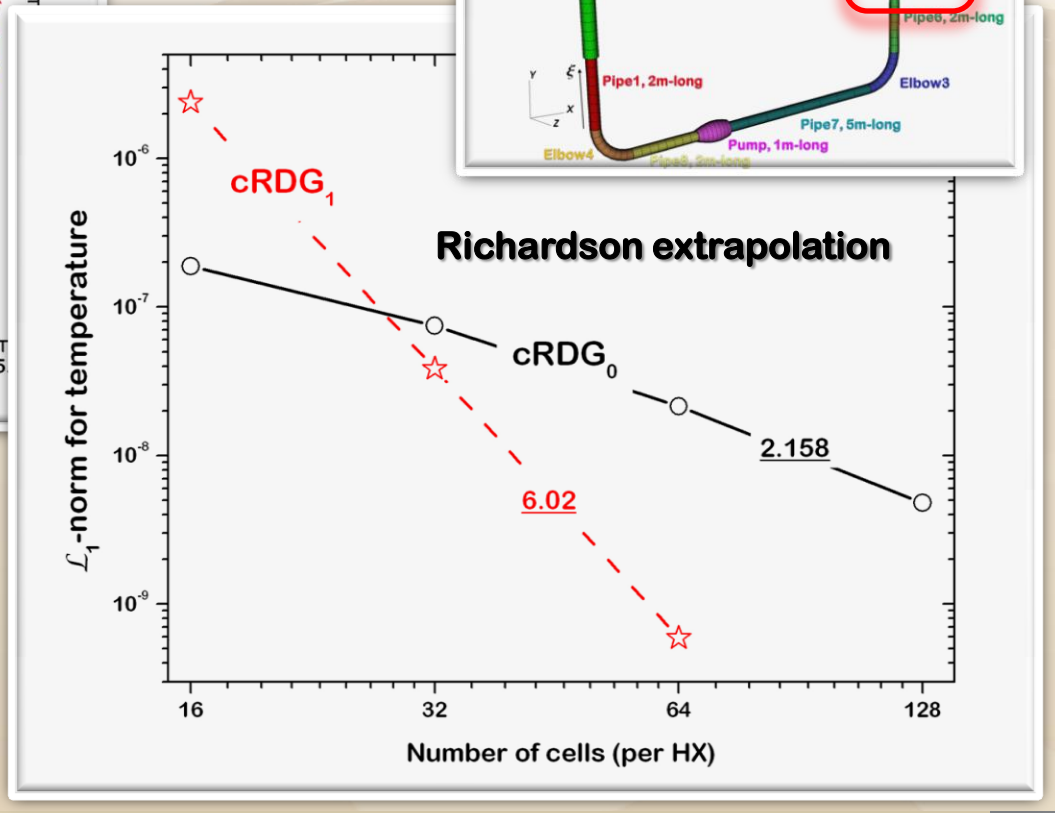


RISMC demo

Verification: Space convergence

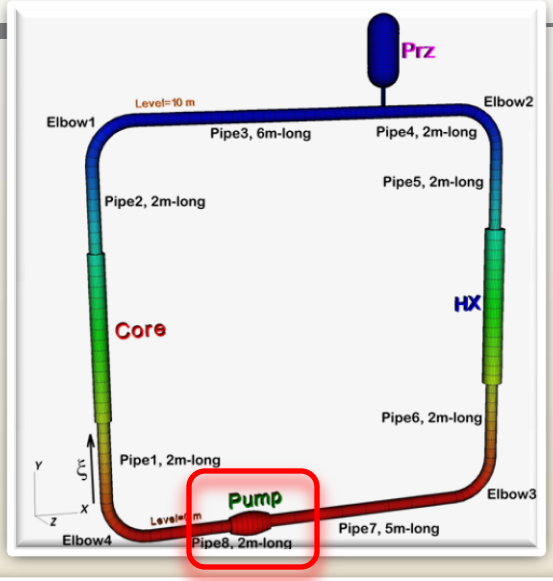


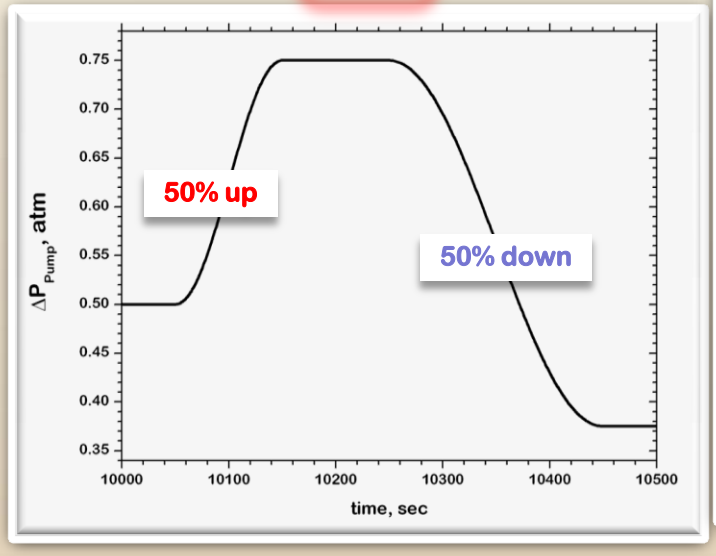




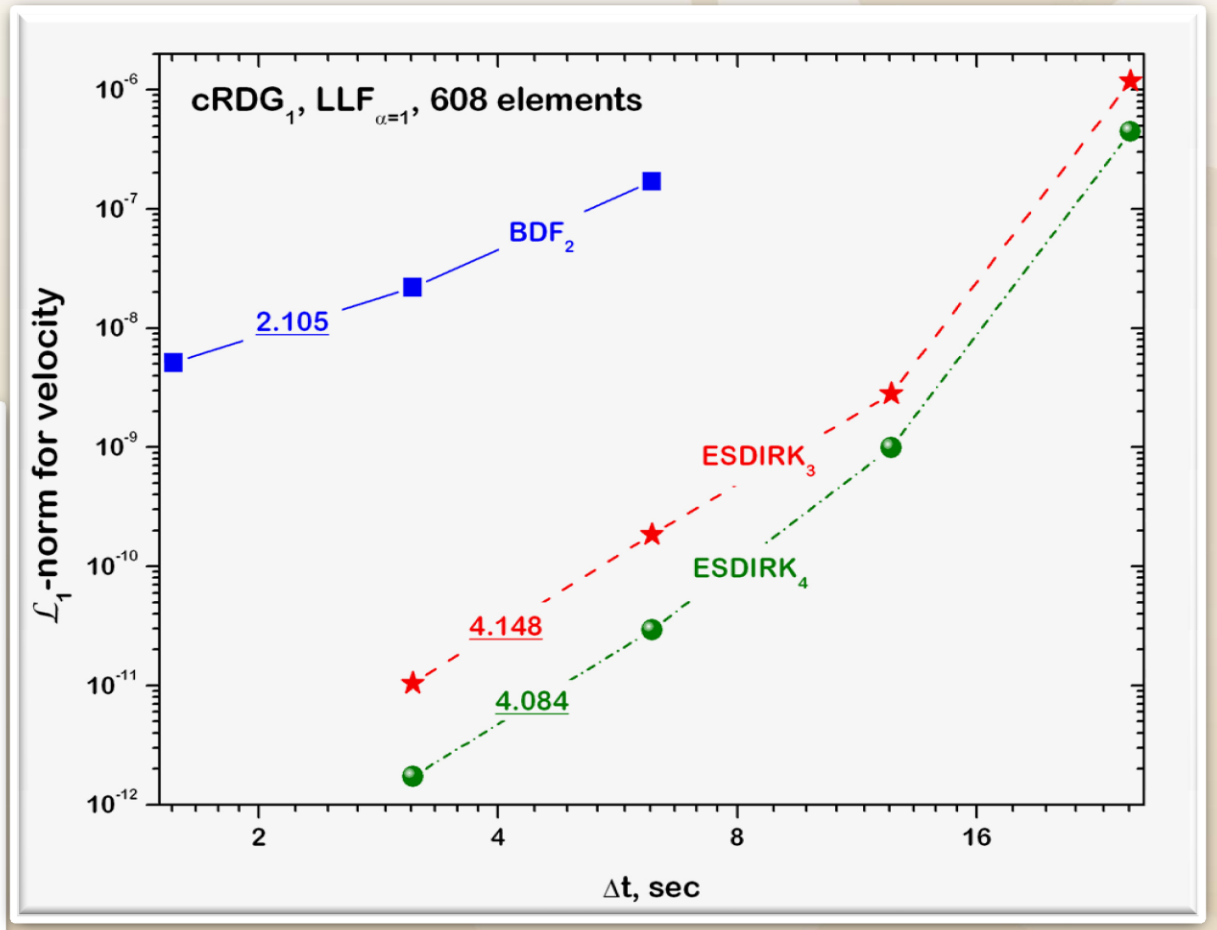
RISMC demo

Verification: Time convergence



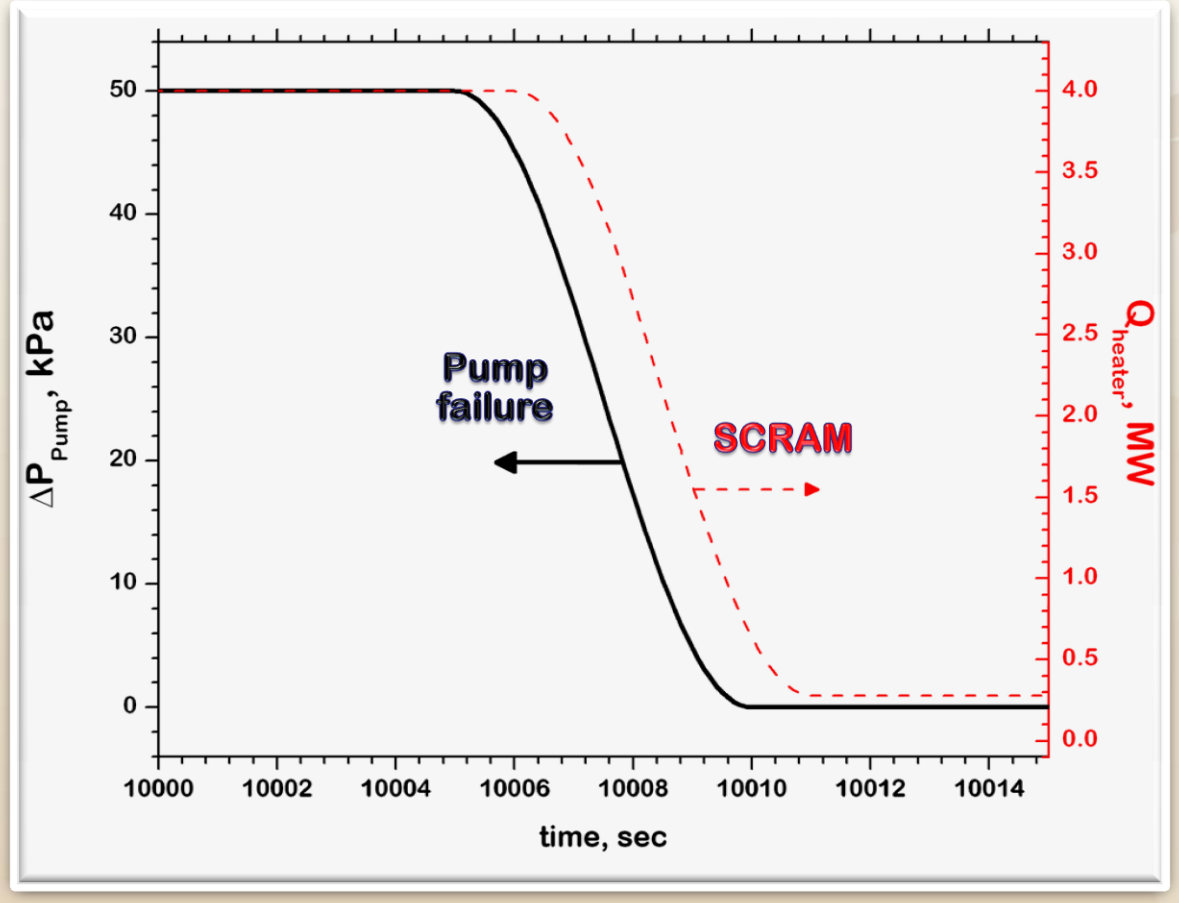


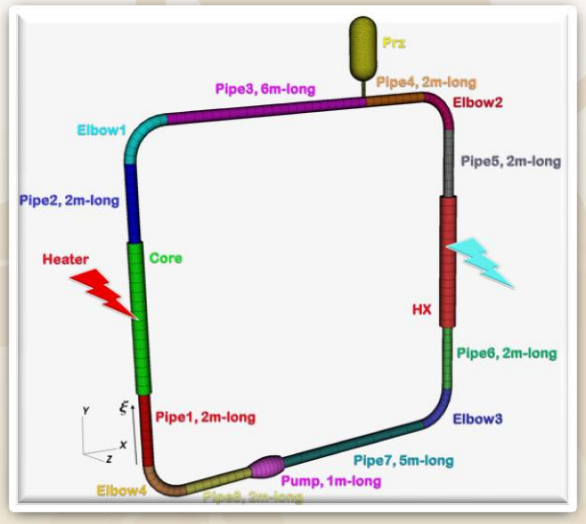
Pump transient



RISMC demo

Pump failure with SCRAM





RISMC demo

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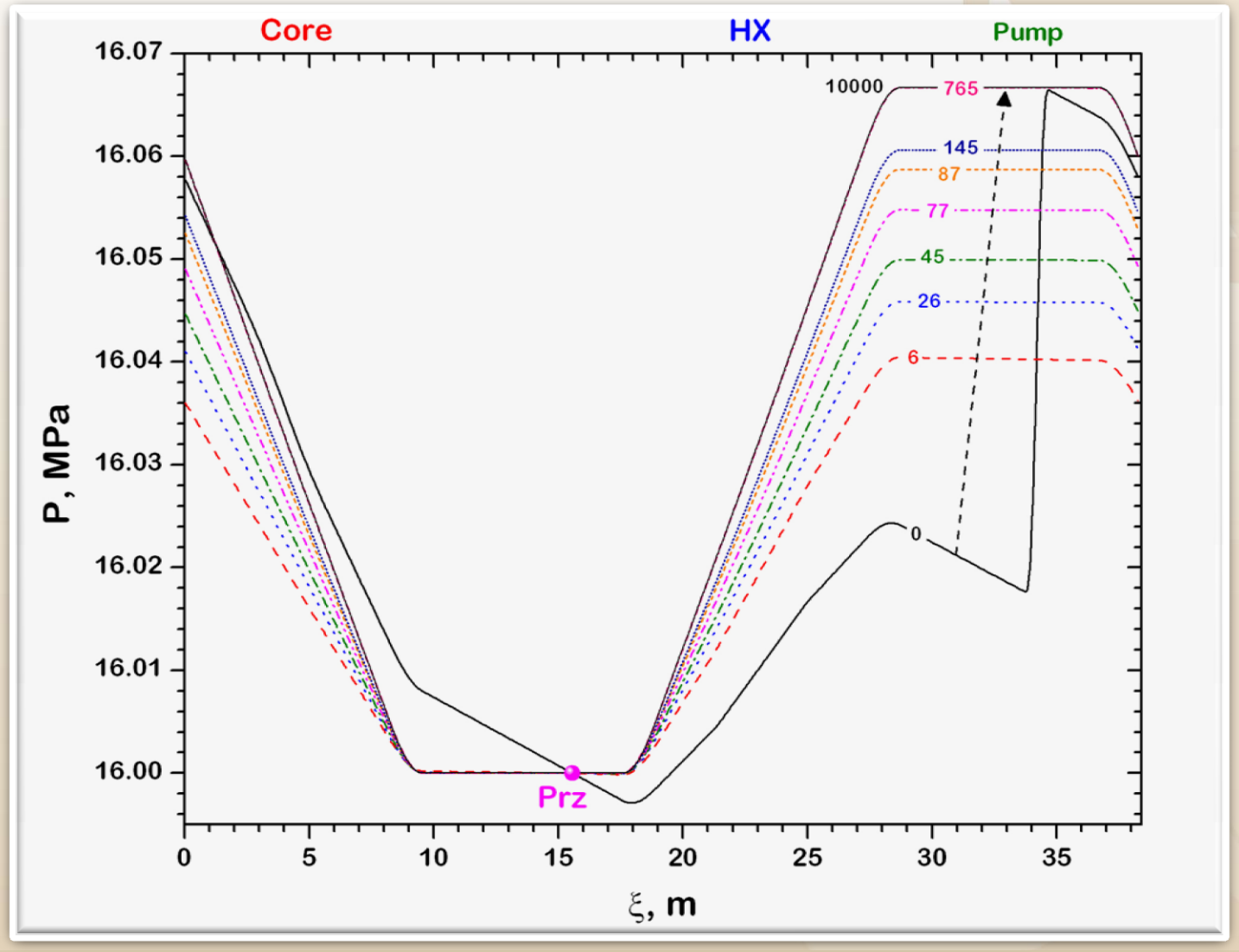
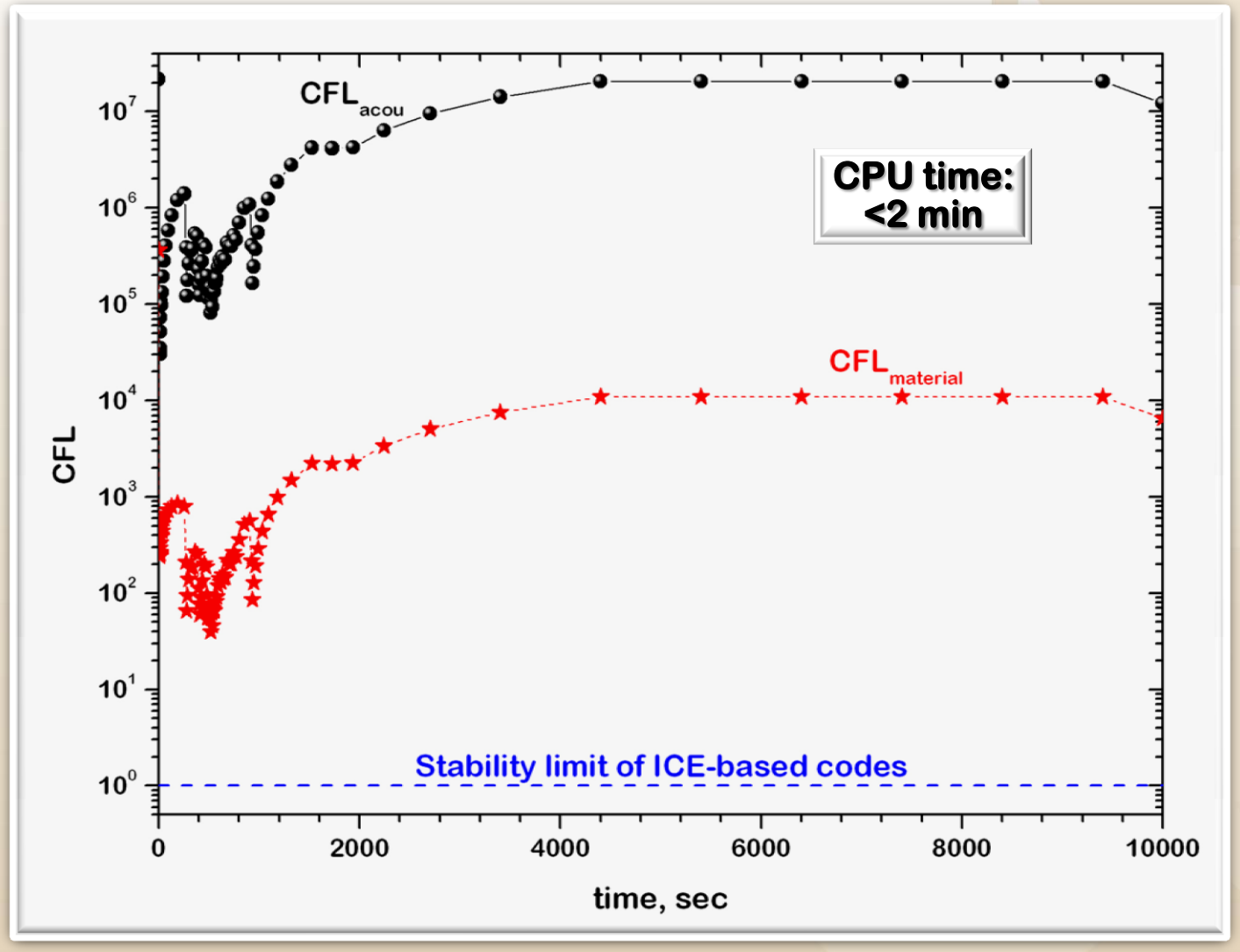
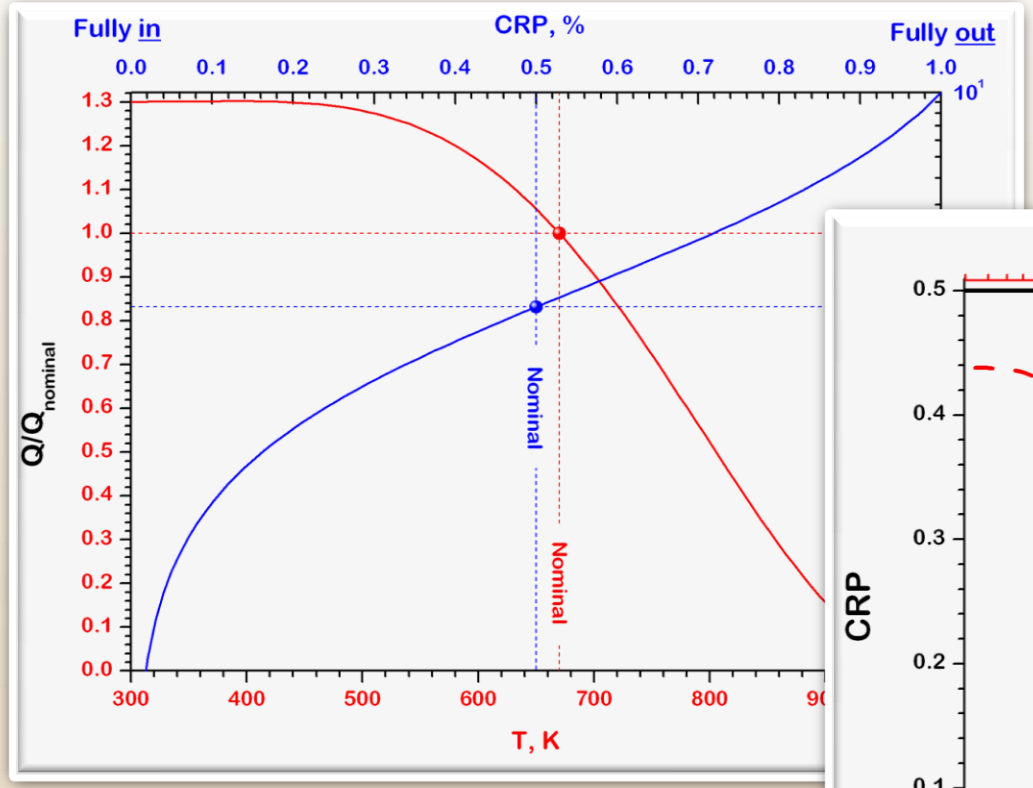
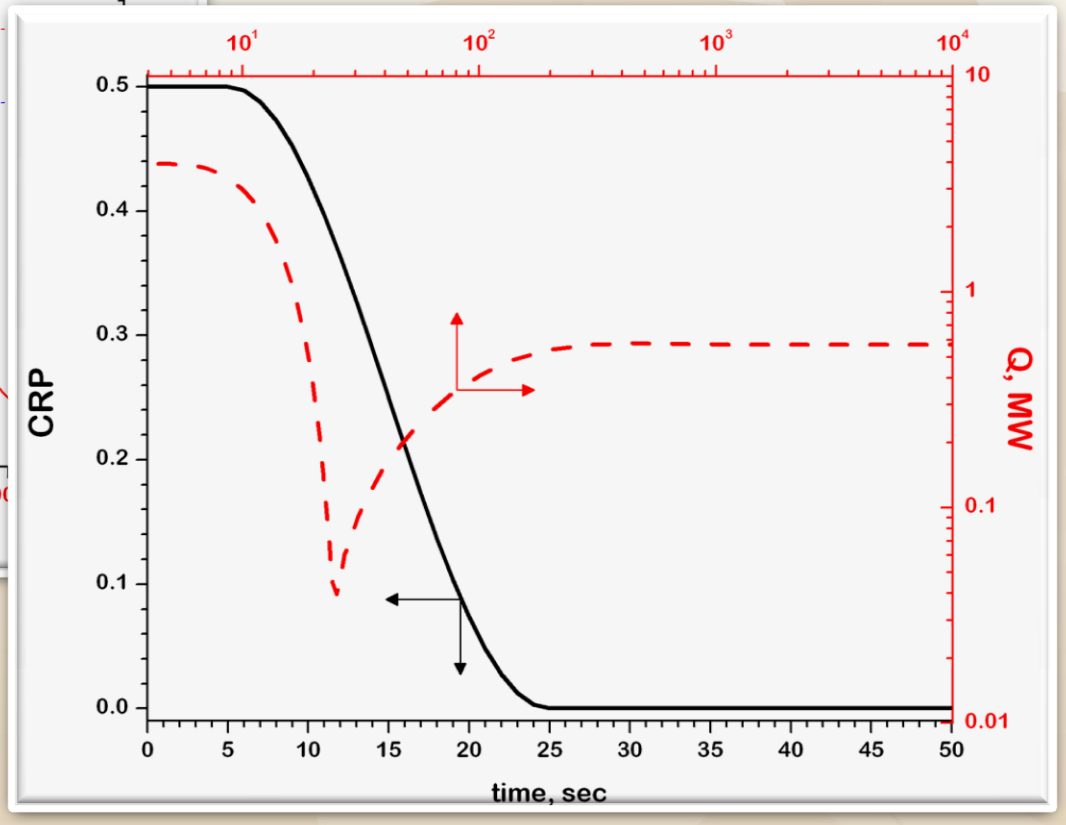


RISMC demo

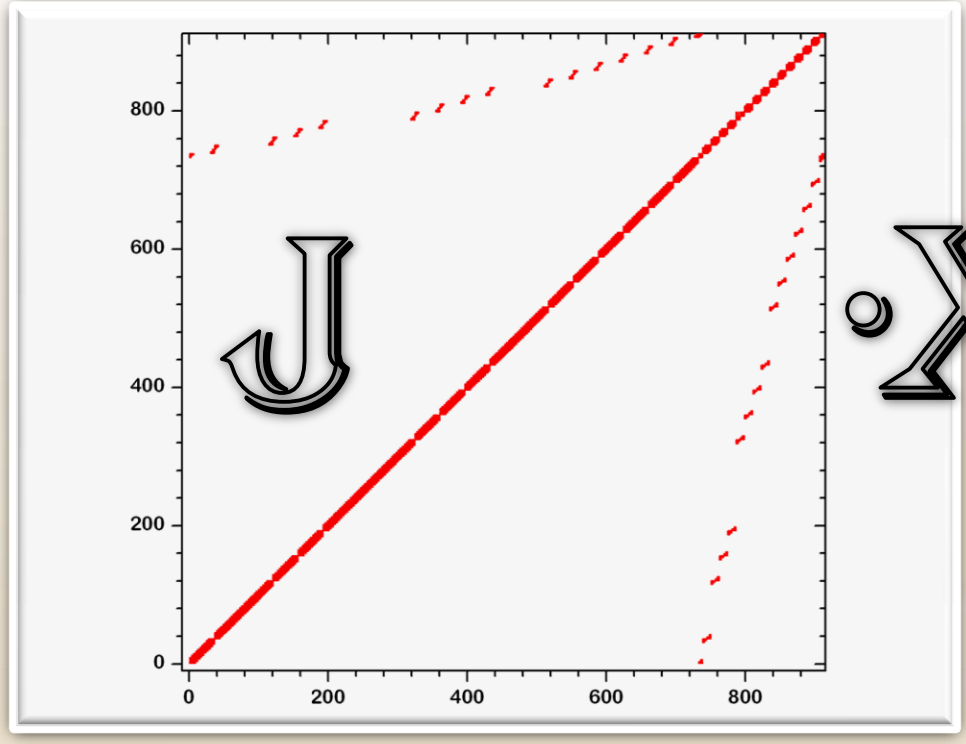

CFL acou
CPU time: <2 min
CFL material
Stability limit of ICE-based codes
CFL
time, sec
10^0
10^1
10^2
10^3
10^4
10^5
10^6
10^7
0
2000
4000
6000
8000
10000

SCRAM (with neutronics feedbacks)





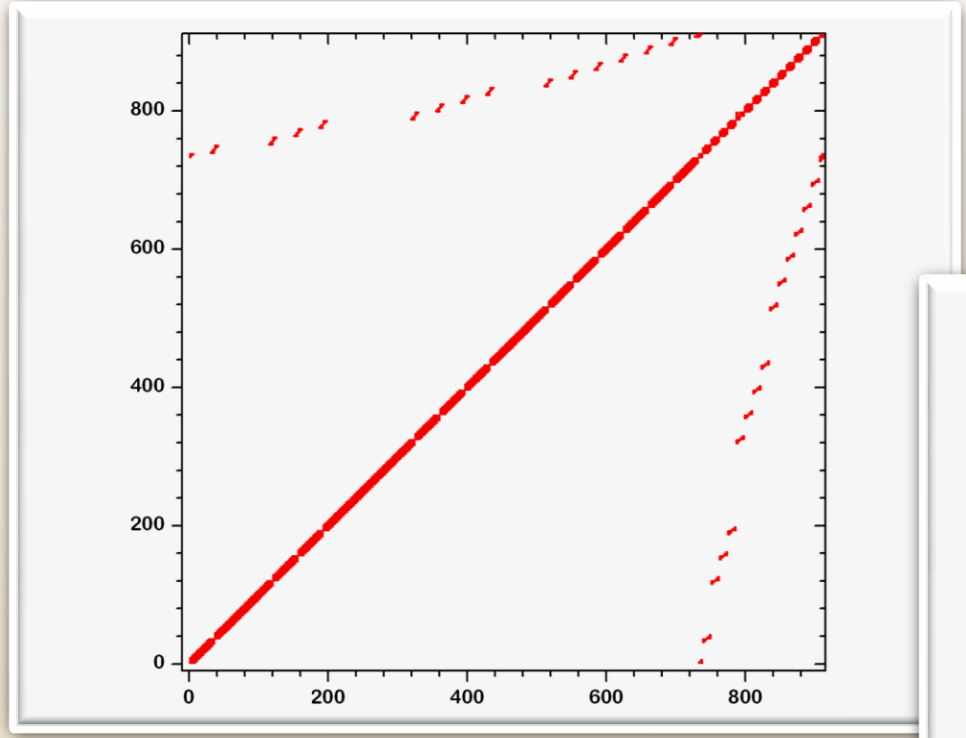
SCRAM (with neutronics feedbacks)



$$\cdot X = -RES$$

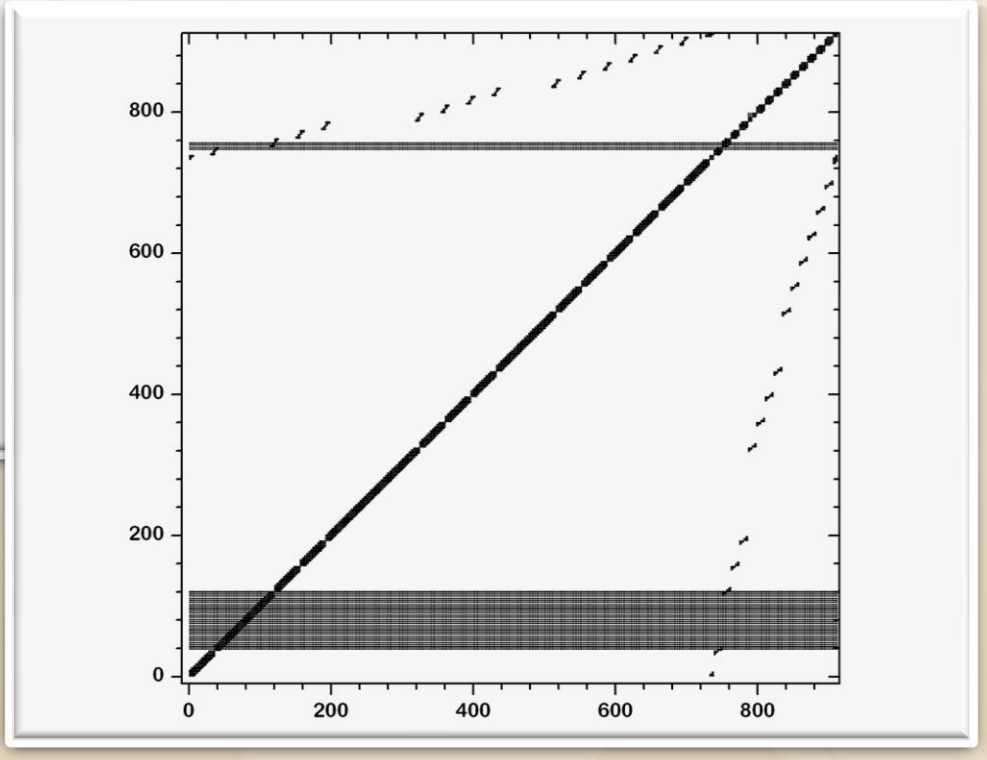
Doppler effects ignored

SCRAM (with neutronics feedbacks)

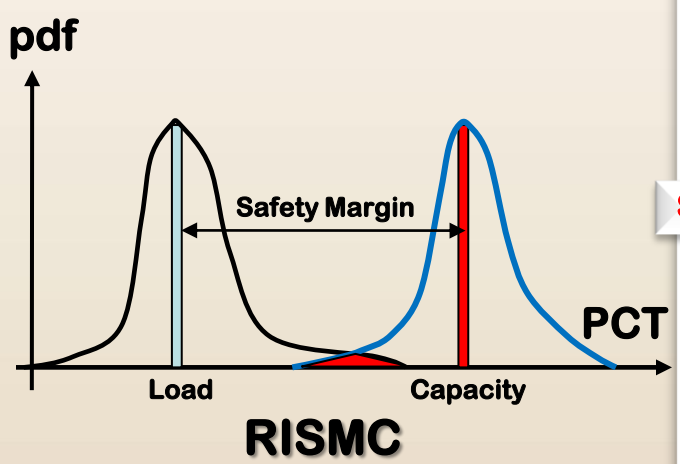


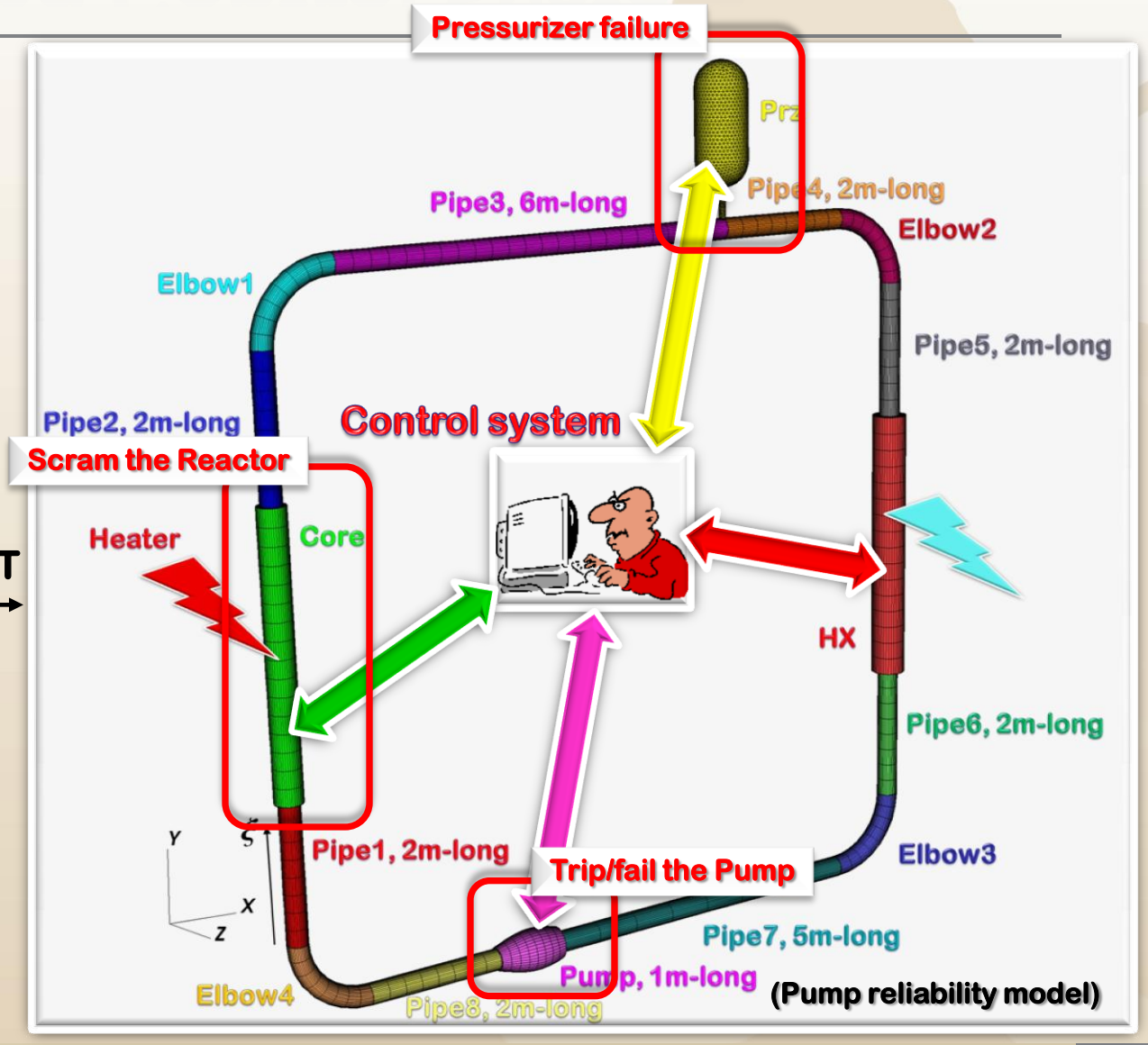
Doppler effects ignored

With Doppler effects

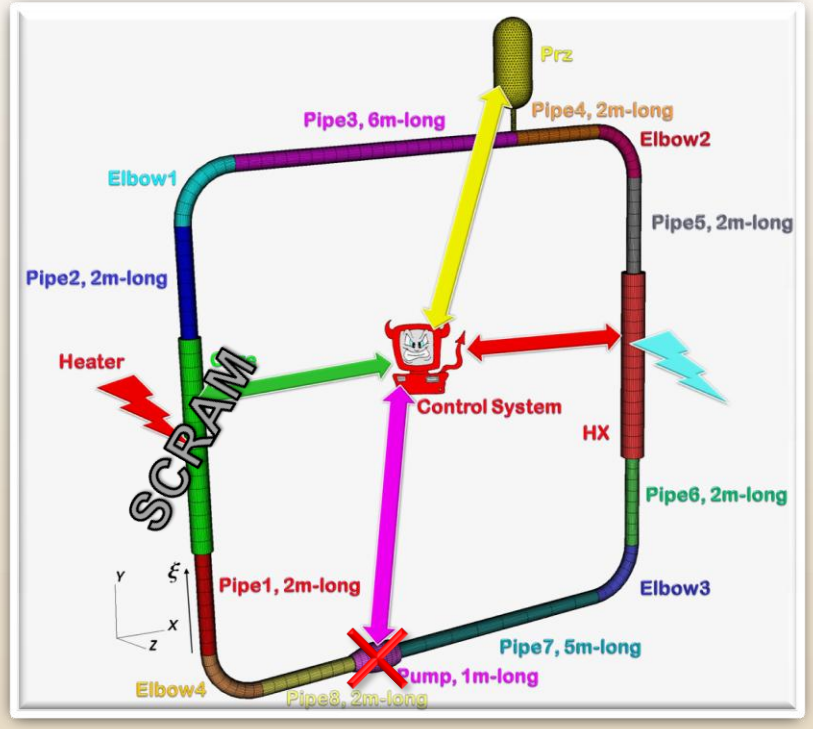


Adding Control System





A. Pump failure with SCRAM



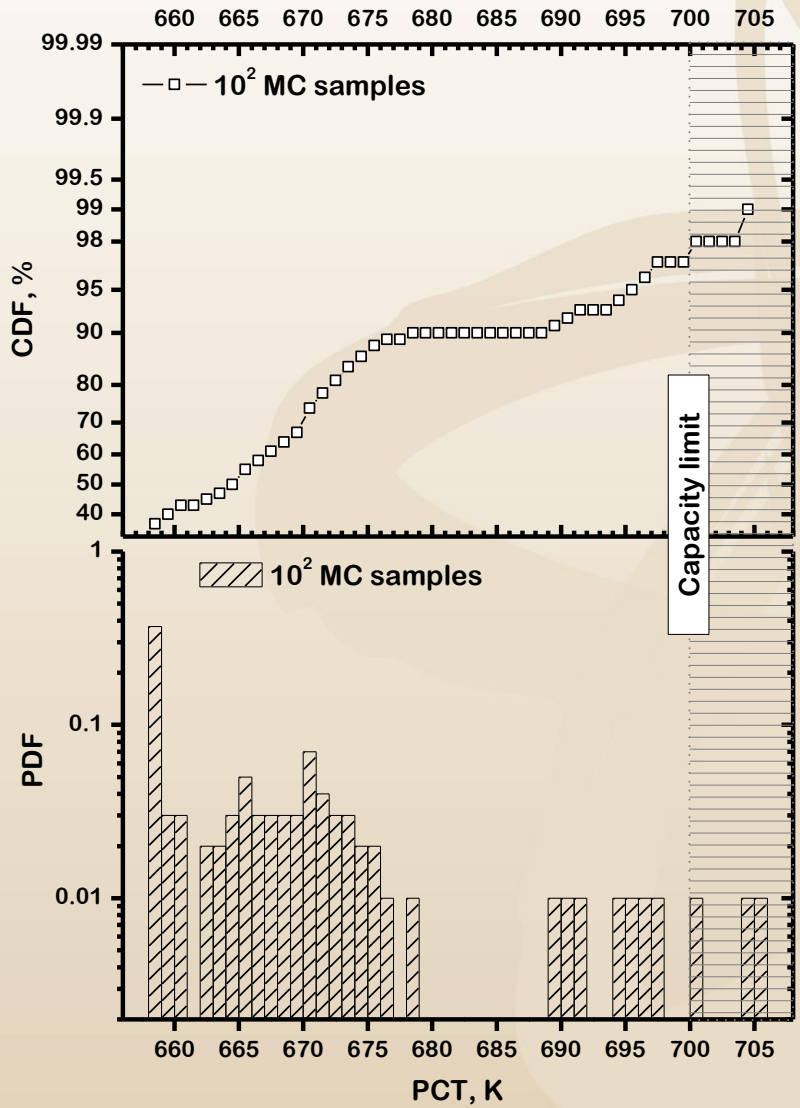
Uncertain parameters:

1. τ_{pump}: how long it takes to stop the pump (10-100s)
2. τ_{delay}: how long it takes to start SCRAM (1-100s)
3. CRP_{end}: Final position of control rods (from 0.05 to 0.55)
4. τ_{CRP}: duration of the SCRAM (from 10 to 50s)

Task: Compute Load Curve (FOM - PCT)

A. Pump failure with SCRAM

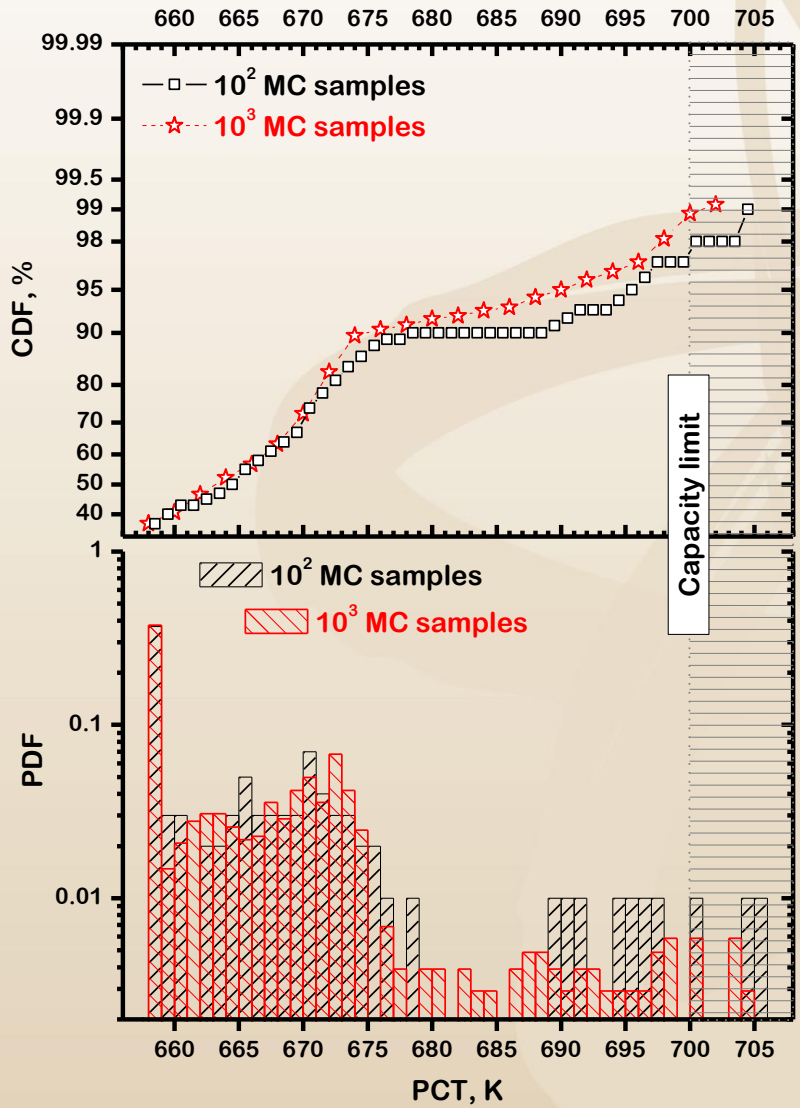
Load Curve for PCT



95/95

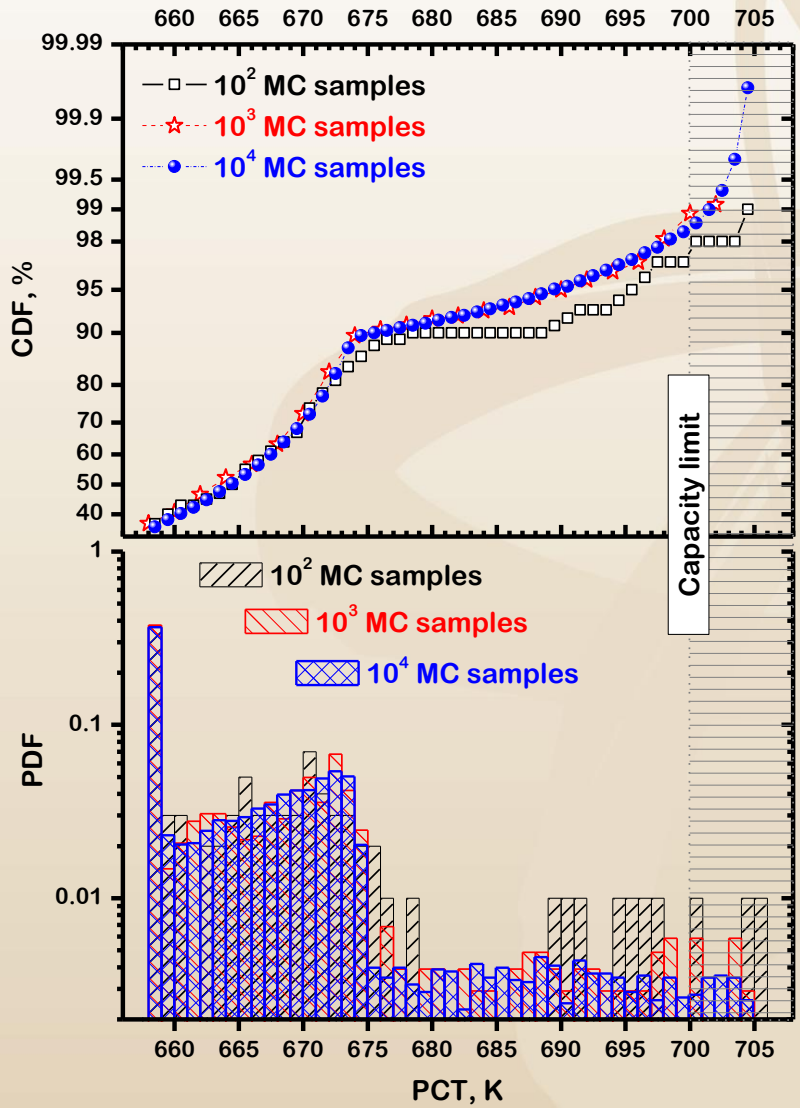
A. Pump failure with SCRAM

Load Curve for PCT



A. Pump failure with SCRAM

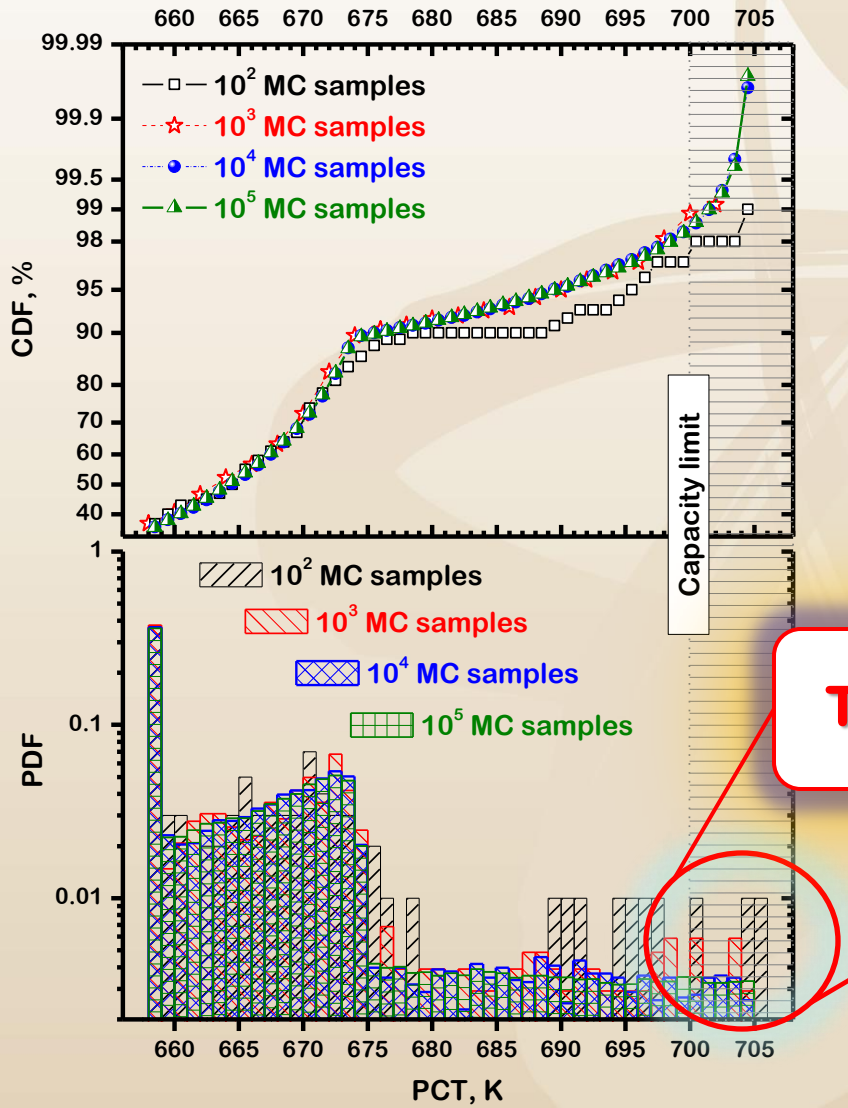
Load Curve for PCT



A. Pump failure with SCRAM

Load Curve for PCT

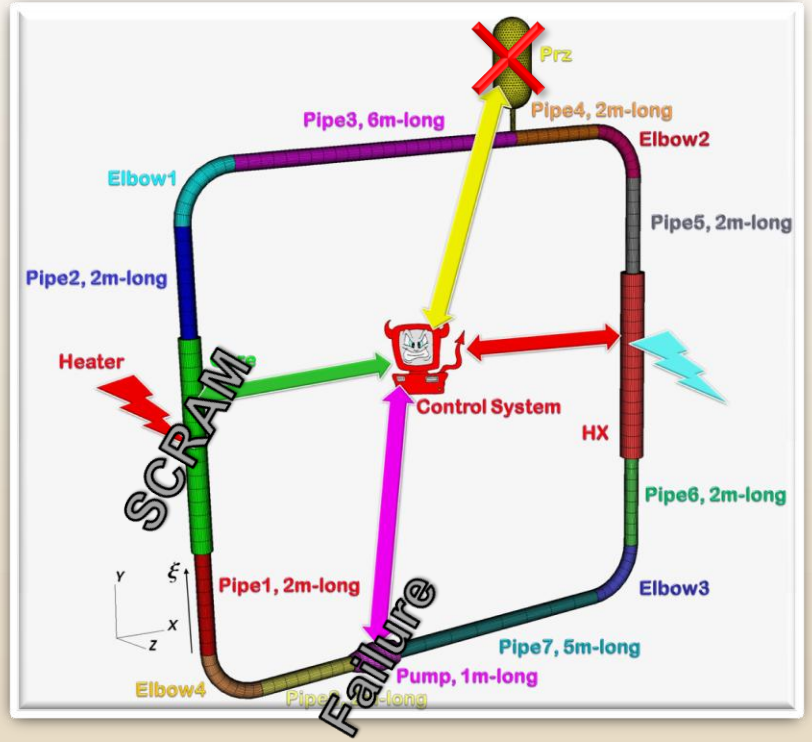
100,000 runs in ~16hrs on 512 CPUs of ICESTORM



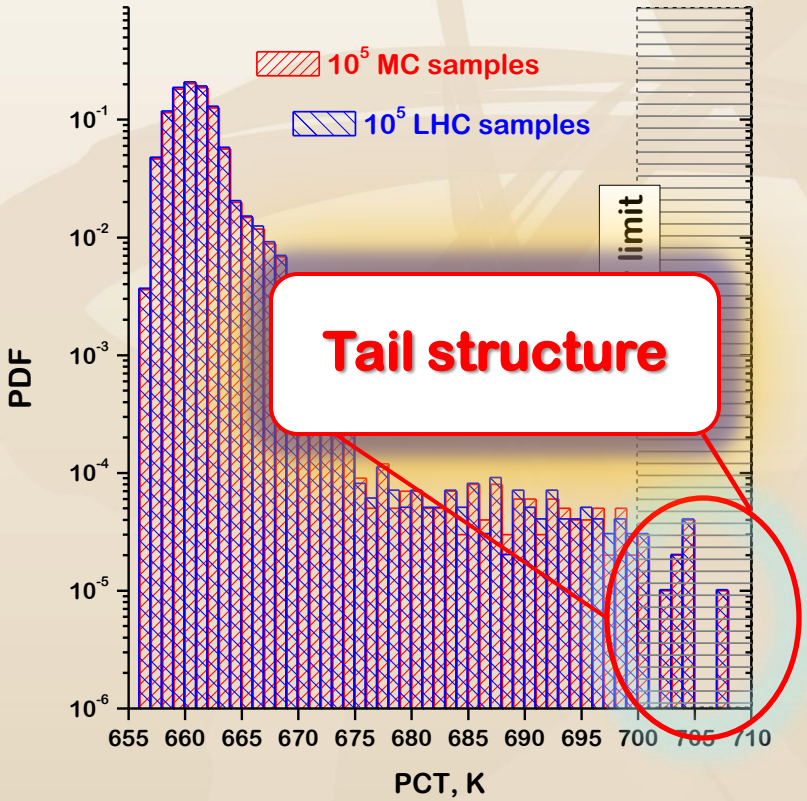
Tail structure

B. Pressurizer failure

8 scenario parameters
12 modeling/IC/BC parameters
1 discretization parameter



Load Curve for PCT



B. Pressurizer failure

SNL (DAKOTA):

Analytic reliability methods
(transforming the uncertainty quantification problem to an optimization one, where the goal is to find the "most probable point" of failure (MPP))

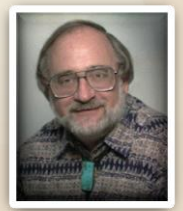
Laura Swiler, SNL

Stochastic expansion methods
(develop an approximation of a random response function in terms of finite-dimensional series expansions: polynomial chaos expansion (PCE) and stochastic collocation (SC))

LANL:

Bayesian-based methods
(Combining LHS sampling with orthogonal ray skeleton, eliminating "inactive" parameters)

Brian Williams, LANL


Ralph Nelson, LANL

NCSU:

Efficient Subspace Method (ESM)
(Reducing parameter space by analyzing and SVD of the covariance matrix) + combining with stochastic expansion methods

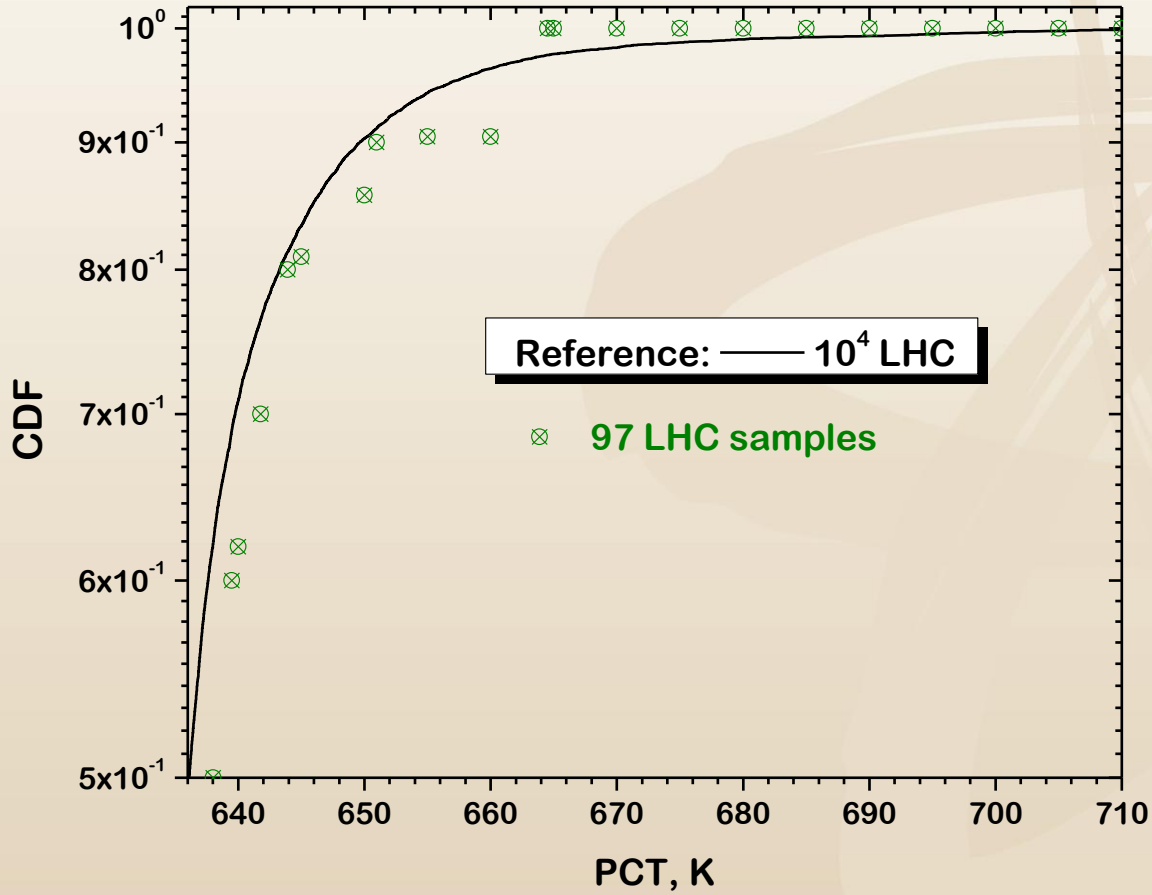
Hany S. Abdel-Khalik, NCSU

C. Pressurizer failure

(6 scenario parameters)

Polynomial Chaos Expansion (PCE):

(develop an approximation of a random response function in terms of finite-dimensional series expansions)

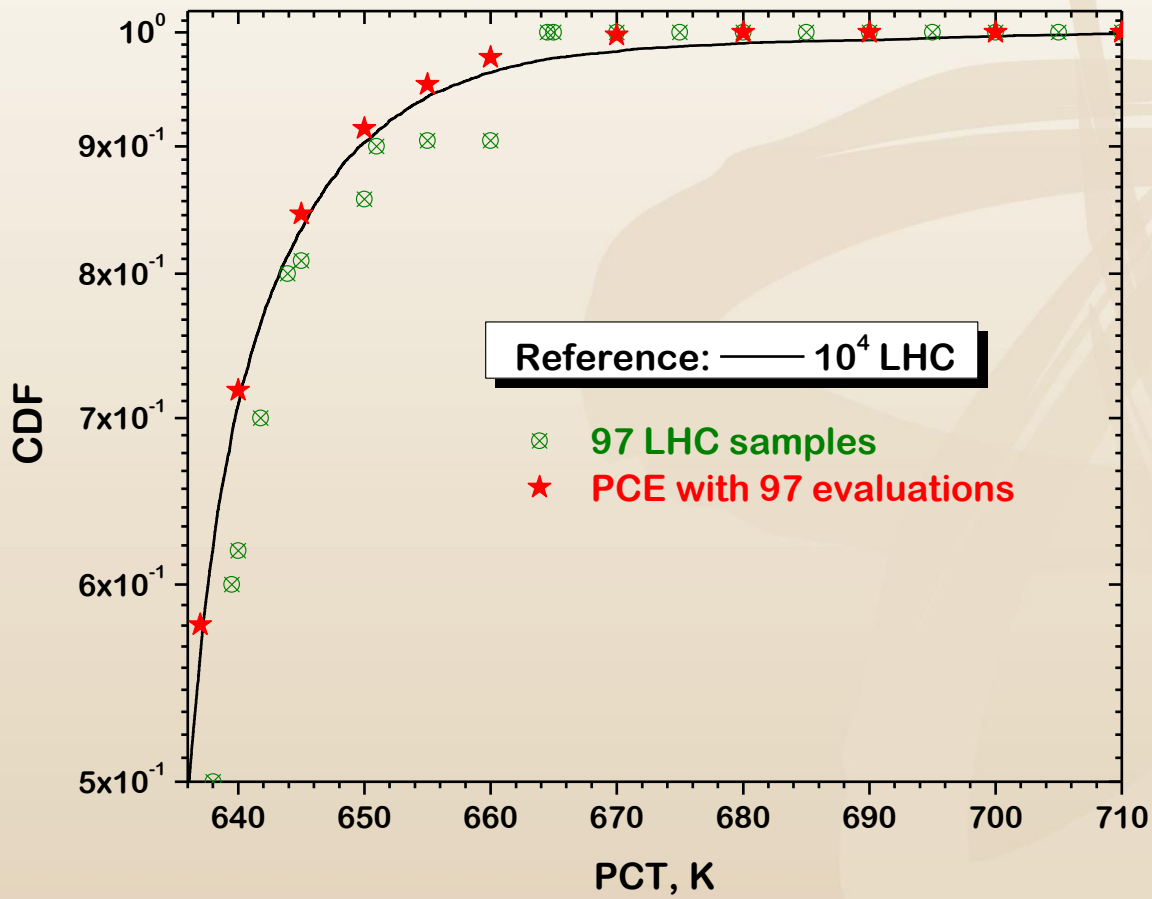


C. Pressurizer failure

(6 scenario parameters)

Polynomial Chaos Expansion (PCE):

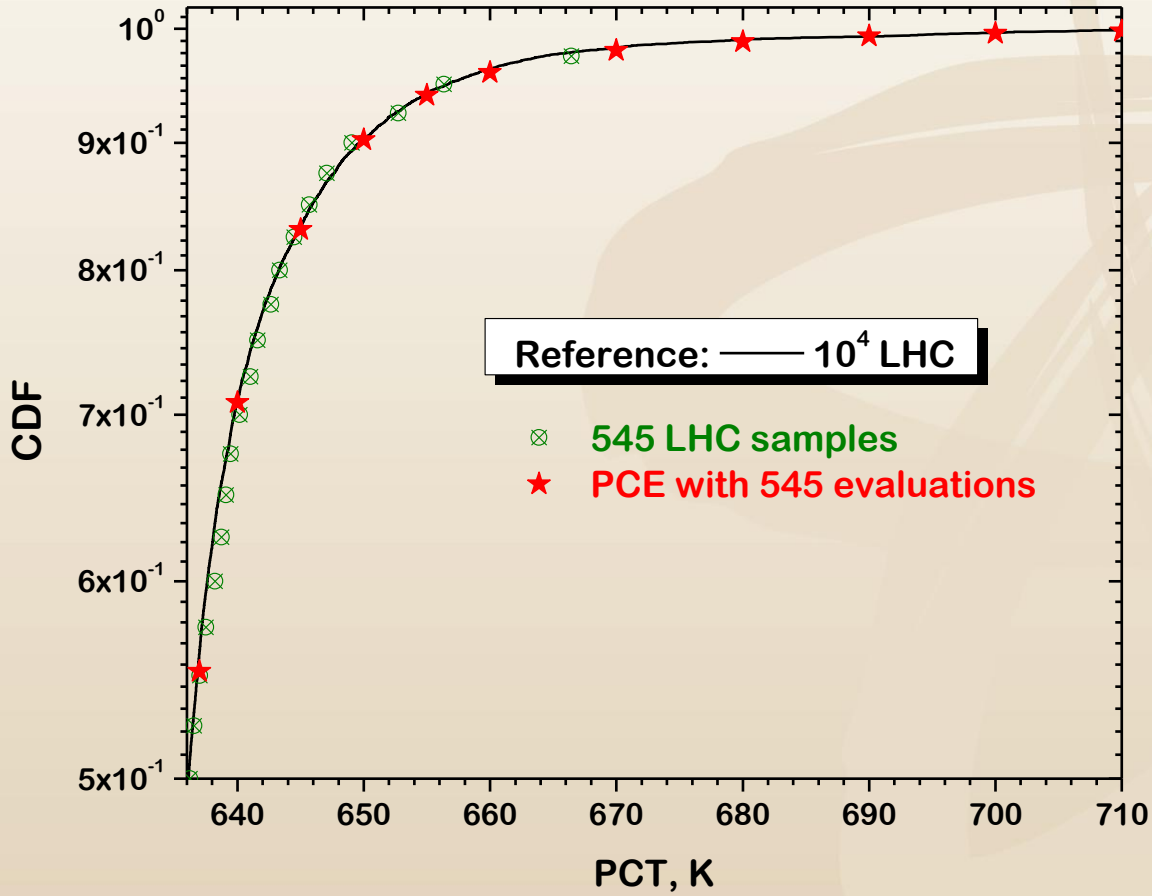
(develop an approximation of a random response function in terms of finite-dimensional series expansions)



C. Pressurizer failure

(6 scenario parameters)

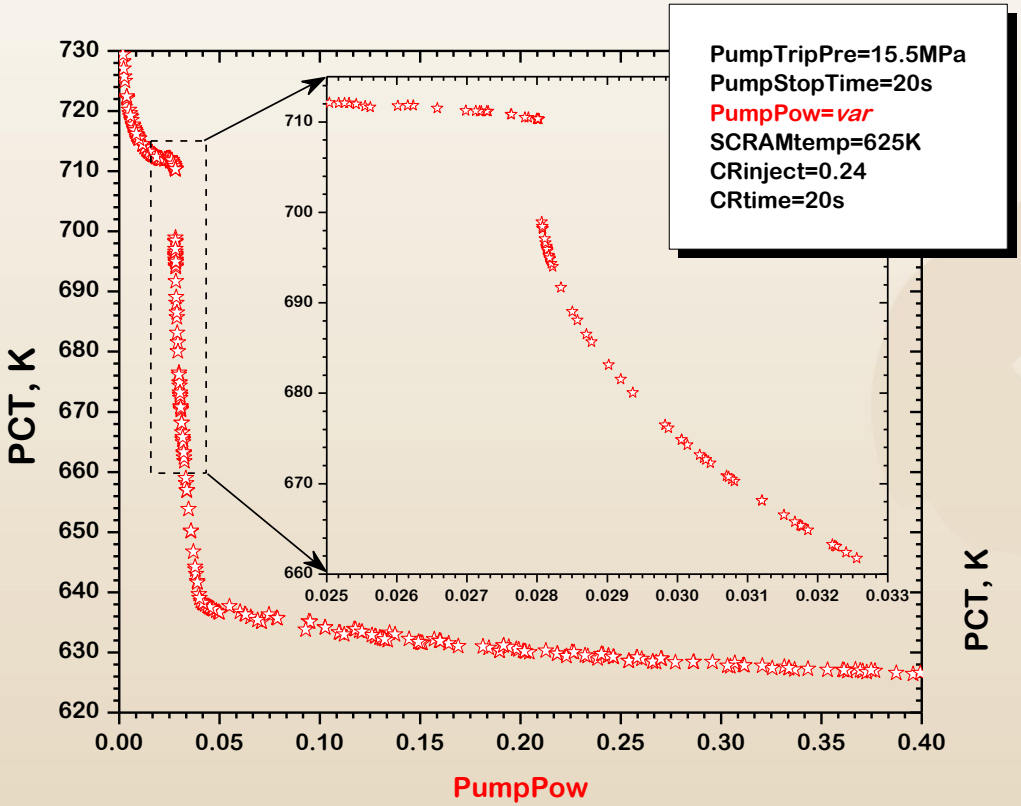
Polynomial Chaos Expansion (PCE):



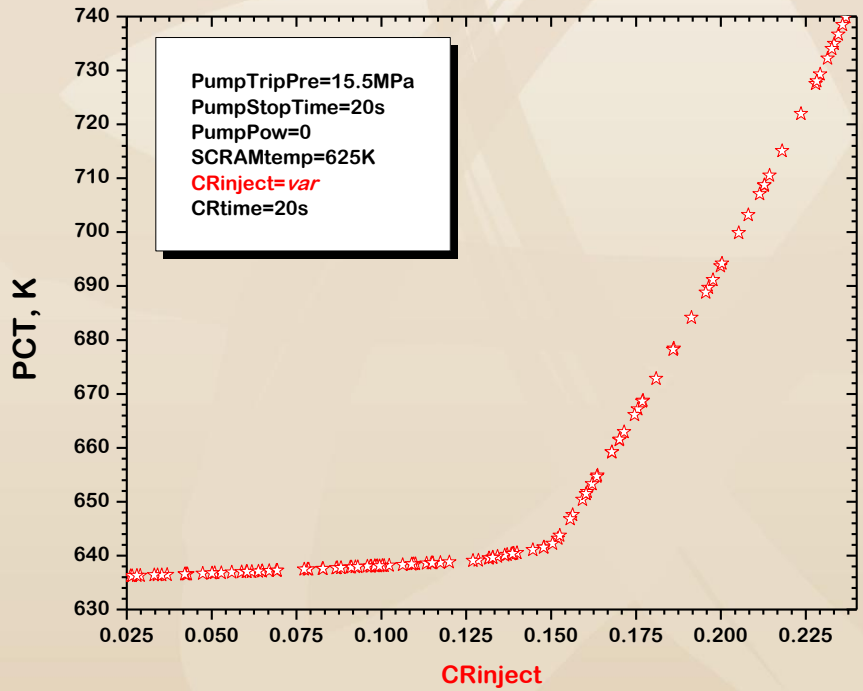
C. Pressurizer failure

(6 scenario parameters)

Sensitivity to end pump power



Sensitivity to end CR position



RISMC demo: Case Studies

LWRS (+CASL)

(EPRI involved)

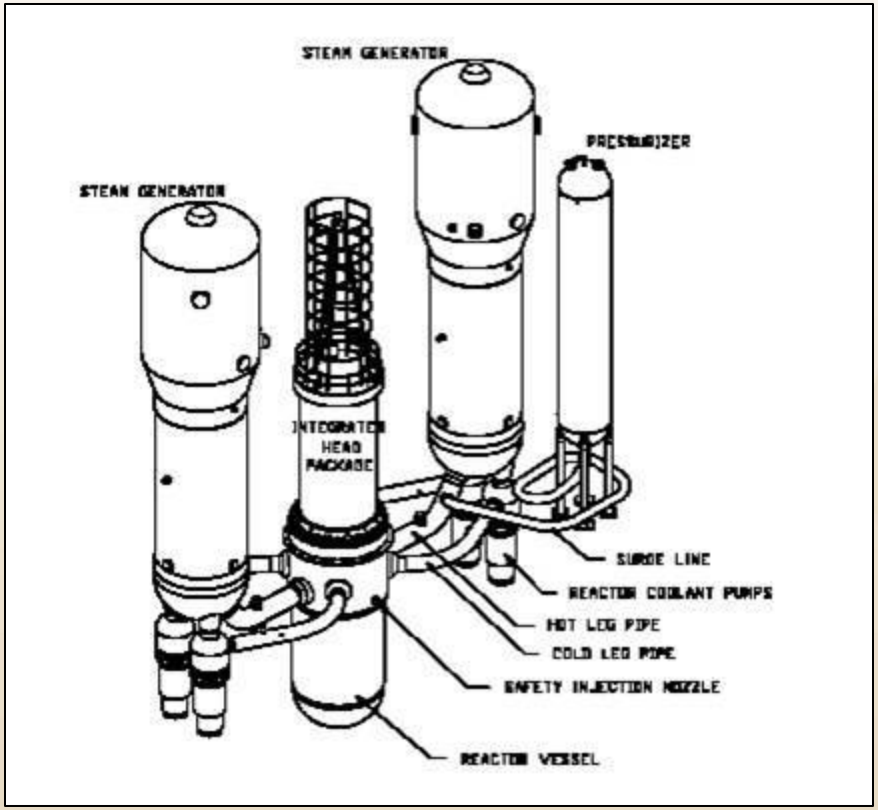
I. "Feed and Bleed"
(ageing accentuated)

Build R_7 input deck for a "4-Loop Westinghouse PWR" (~2 years)

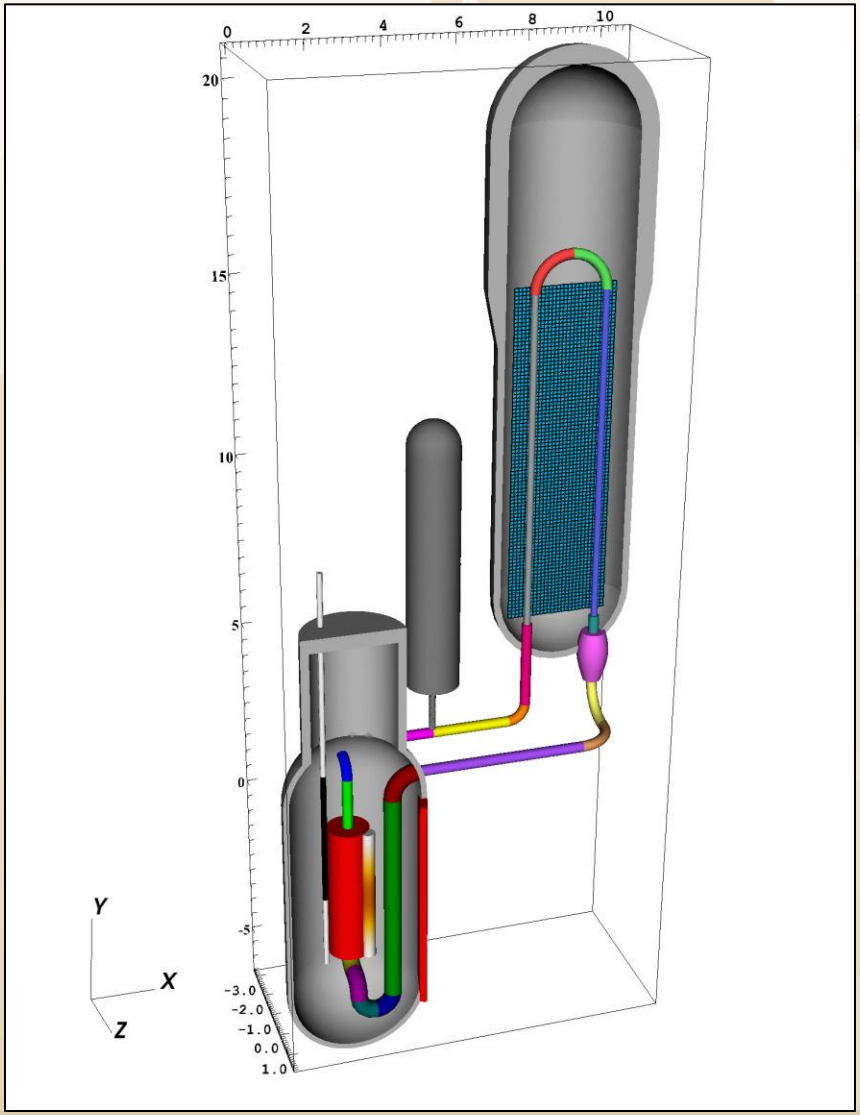
II. Overcooling Transients
(mild PTS/ageing accentuated)

PWR-I ("toy reactor")

PWR-I



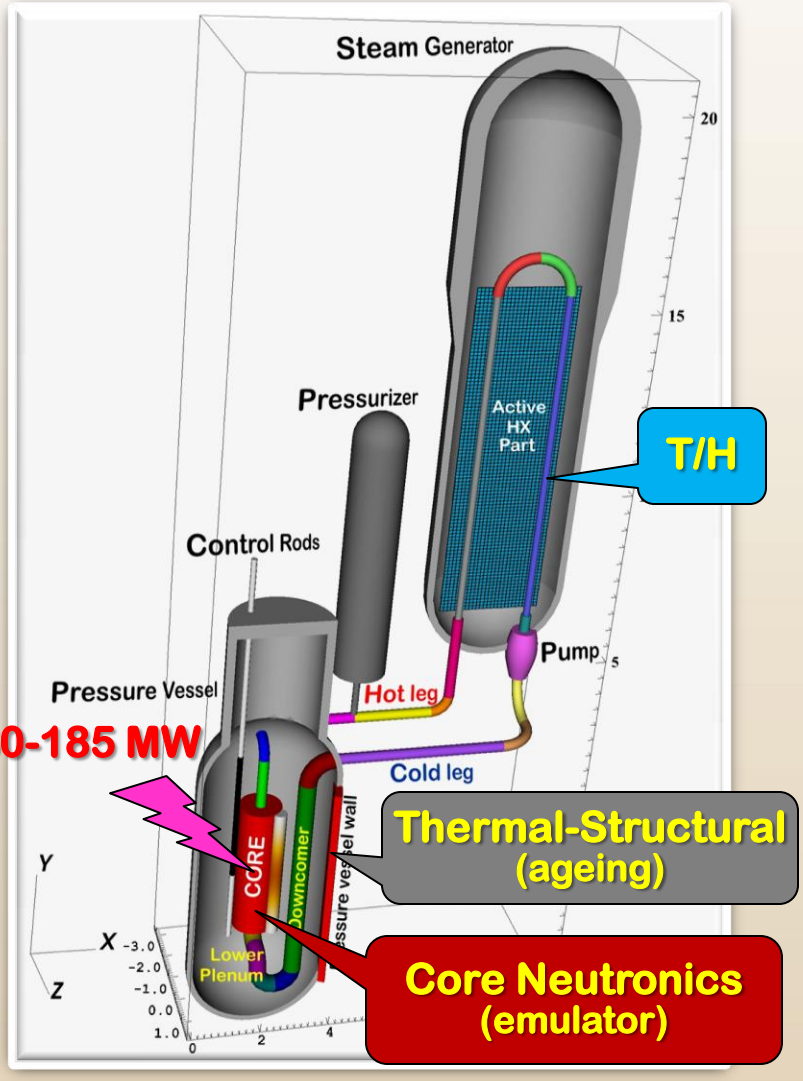
AP1000 reactor coolant system



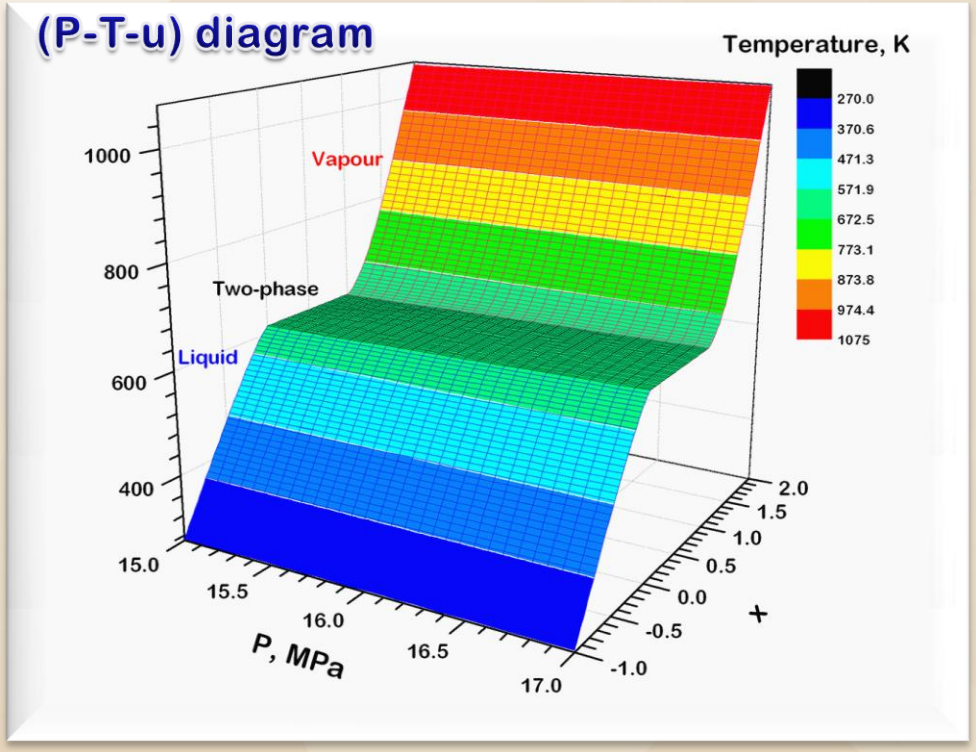
PWR-I

32 components

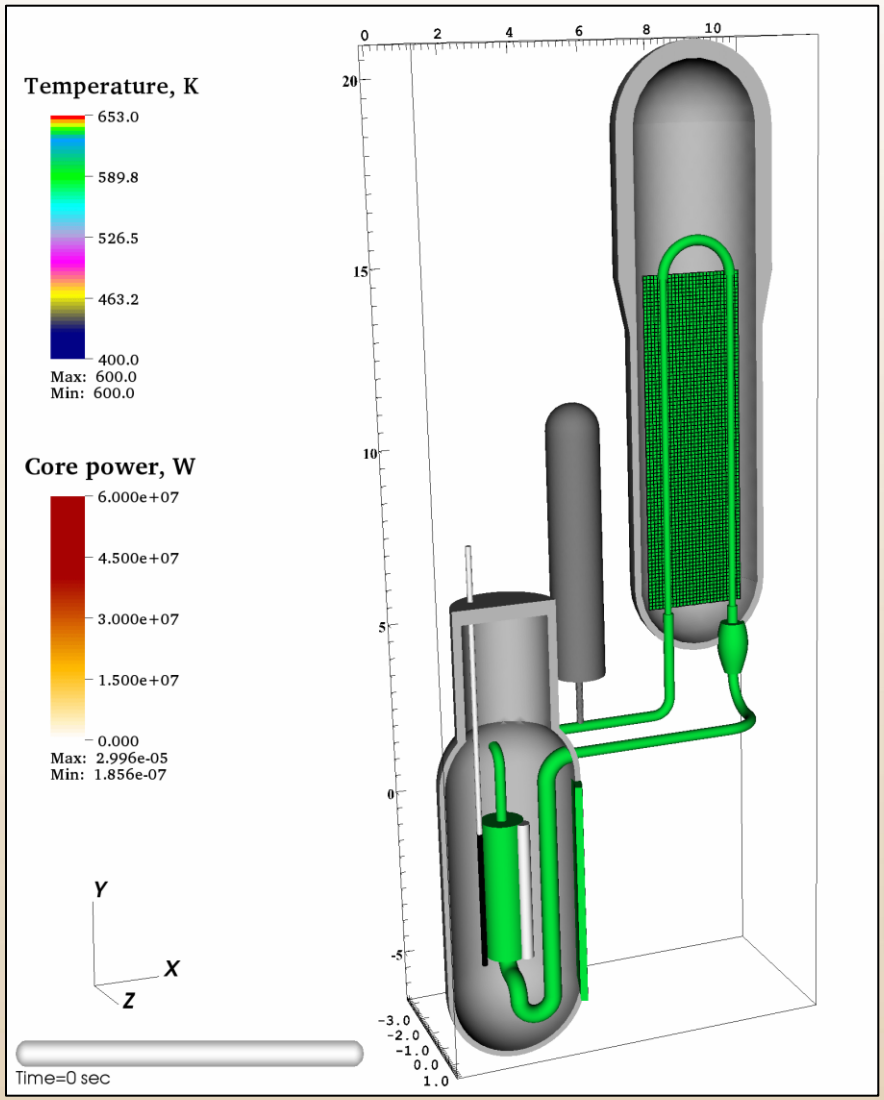
Tabulated water table:
Thermodynamically-consistent
Bi-cubic spline interpolation
Fast table search algorithms



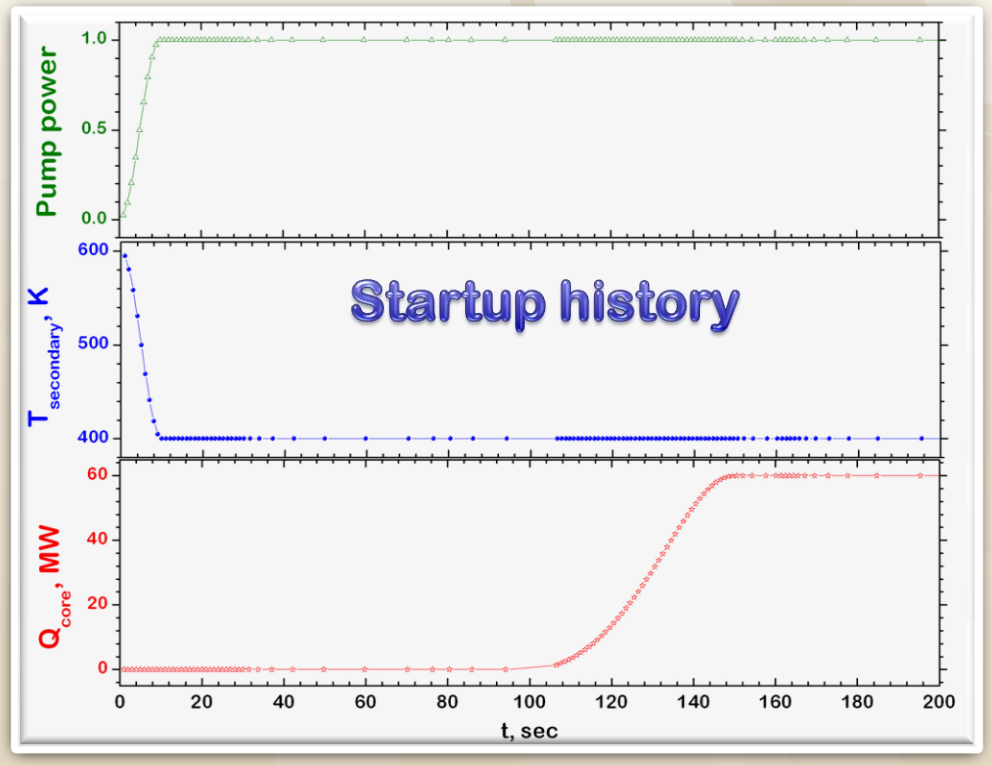
- **Nominal Power:** up to 185 MW
- **Coolant:** water (pressurized, with boiling)



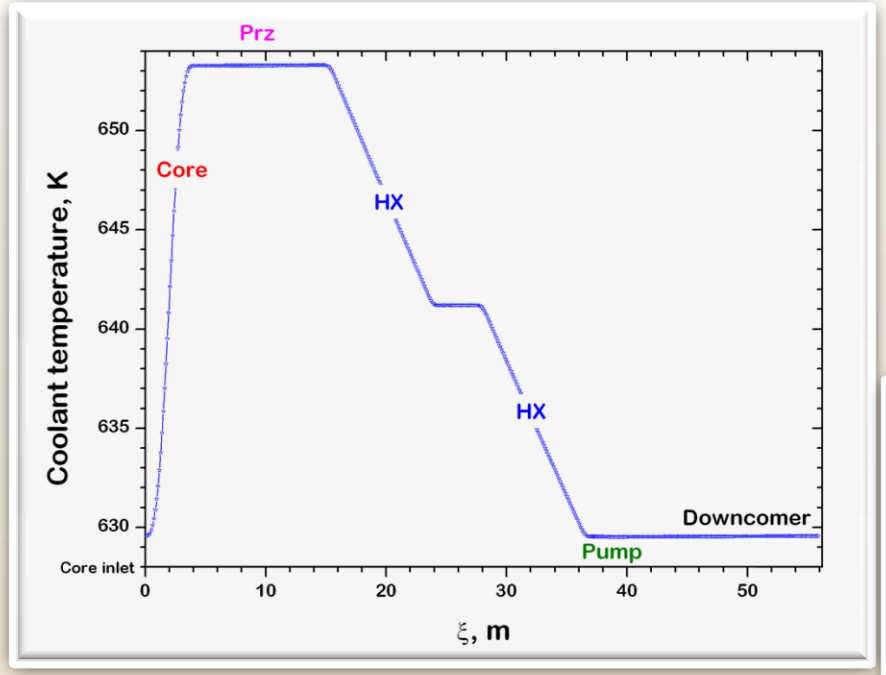
PWR-I: 1-phase tests

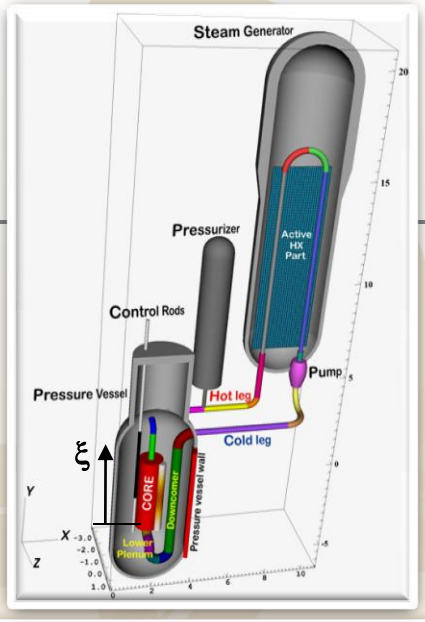


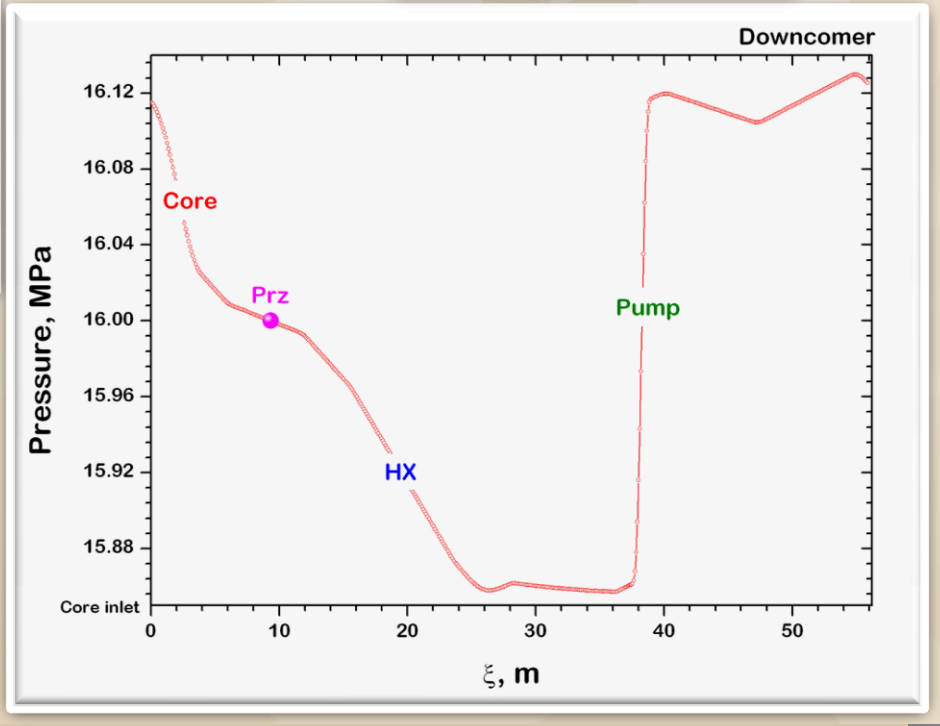
IC: 600 K, NULL state, no power



PWR-I: 1-phase tests

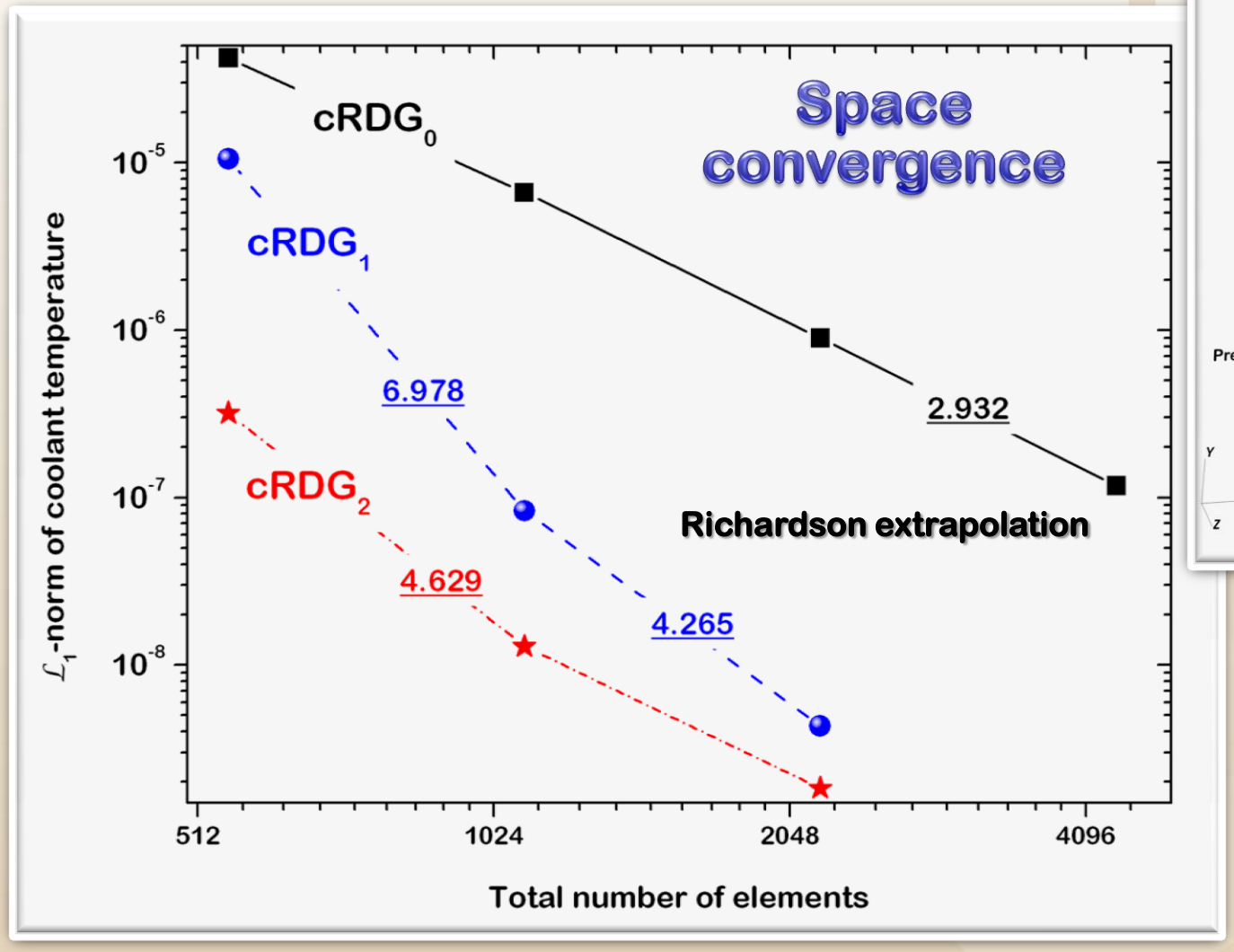


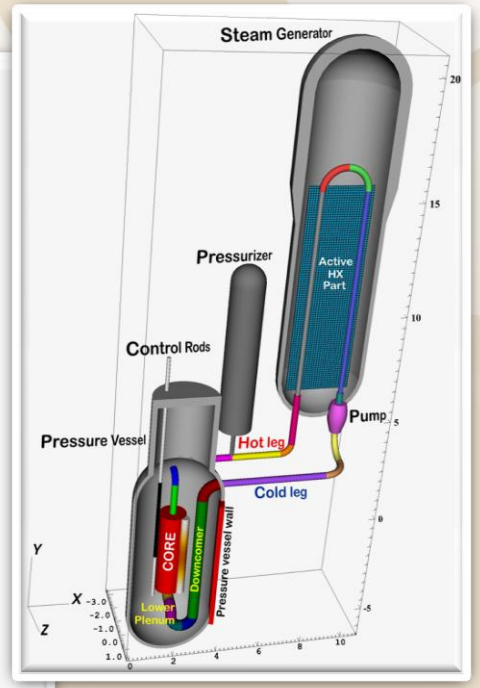




Steady-state solution

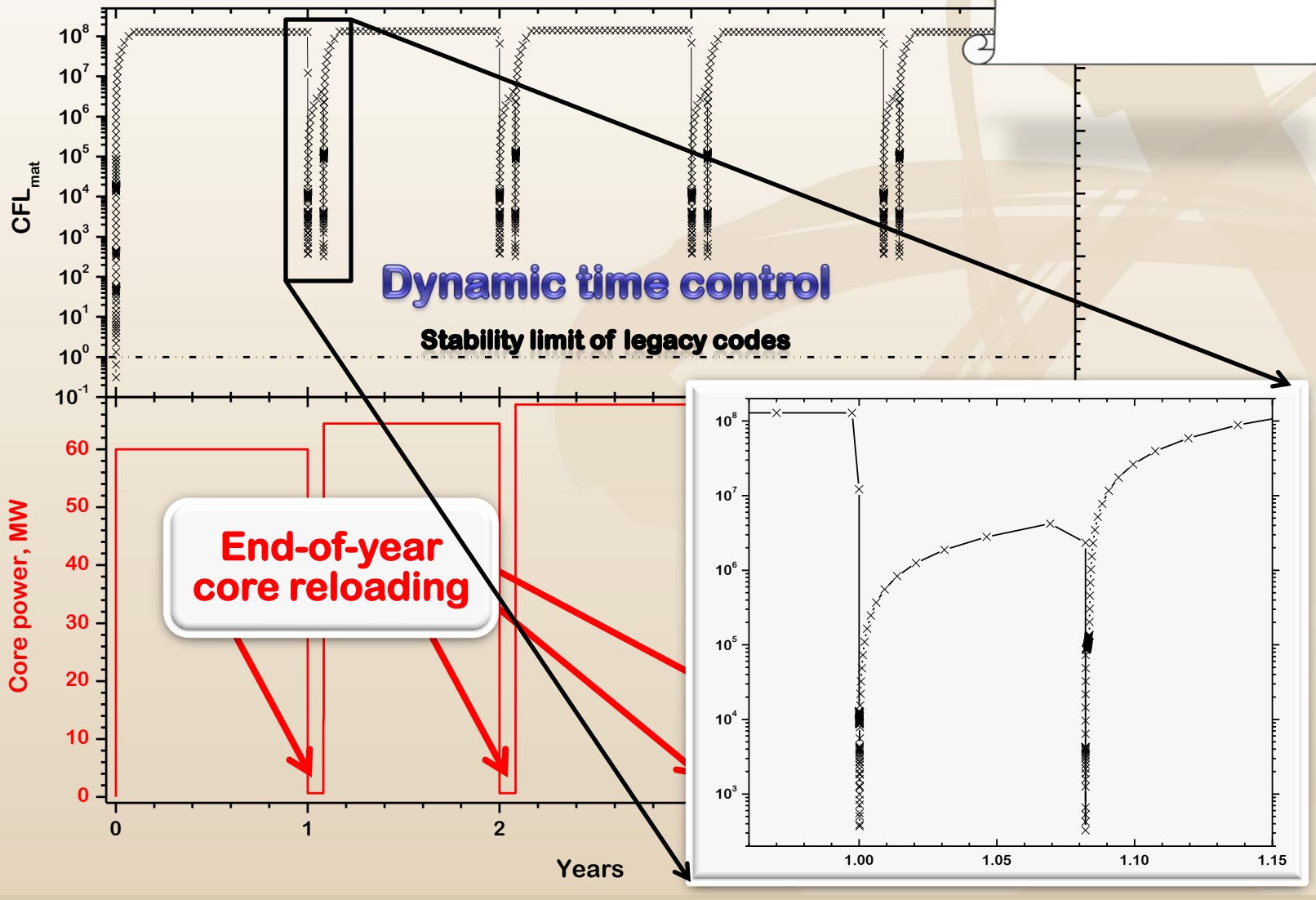
PWR-I: 1-phase tests



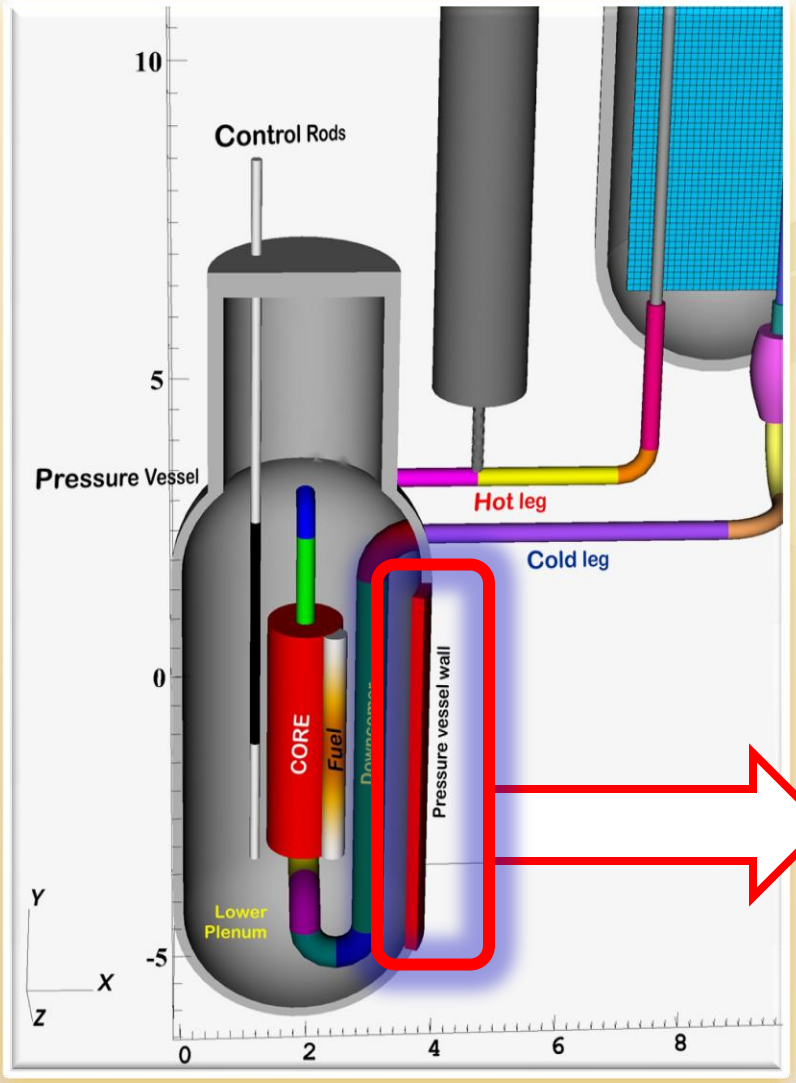


PWR-I: Ageing

5 min CPU time on 3.06 GHz Intel Core 2 Duo



PWR-I: Ageing



I. Corrosion products & chemicals transport

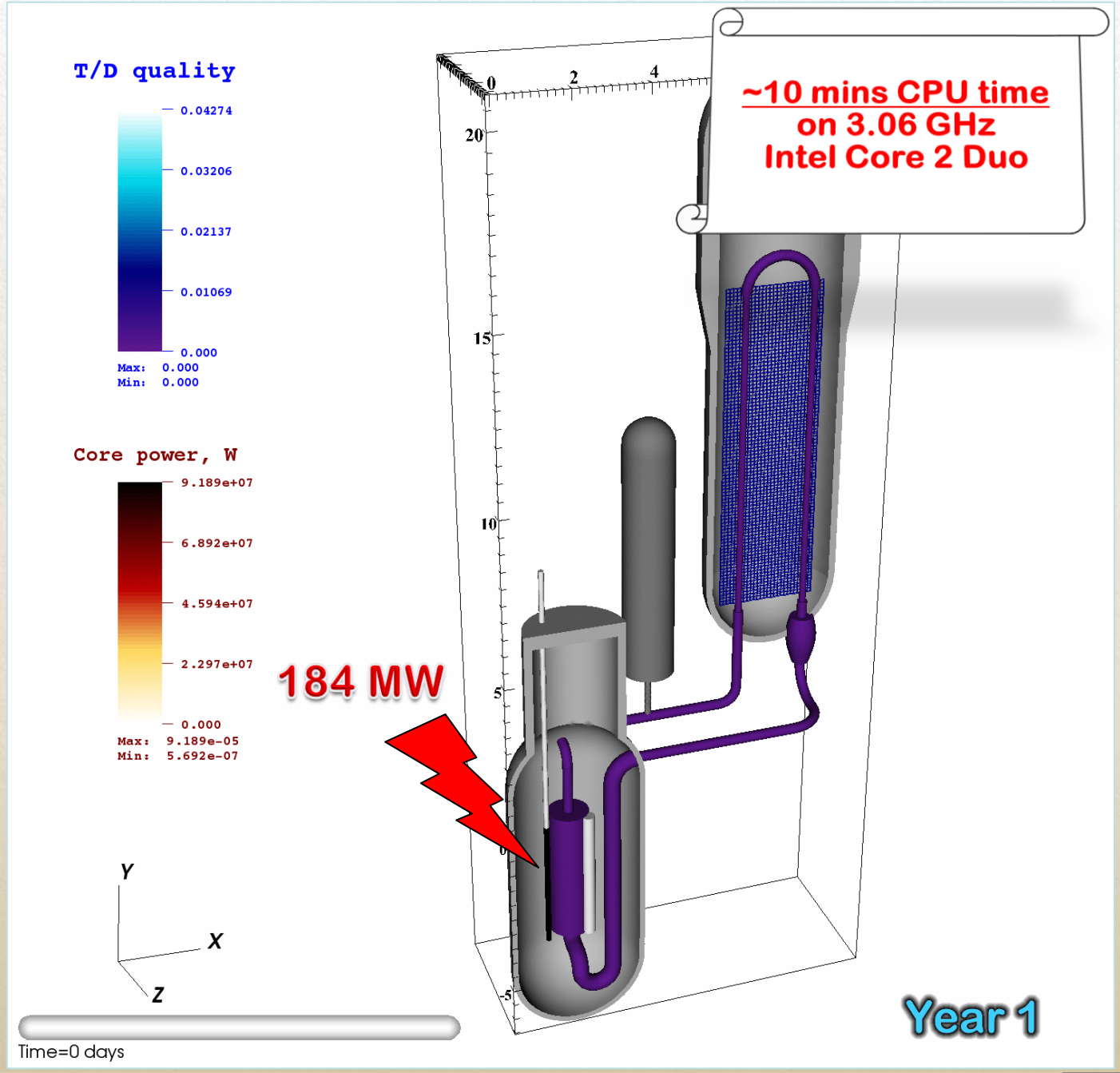
II. High-resolution (CFD-grade)

III. High-resolution neutronics (focus on fluence computation)

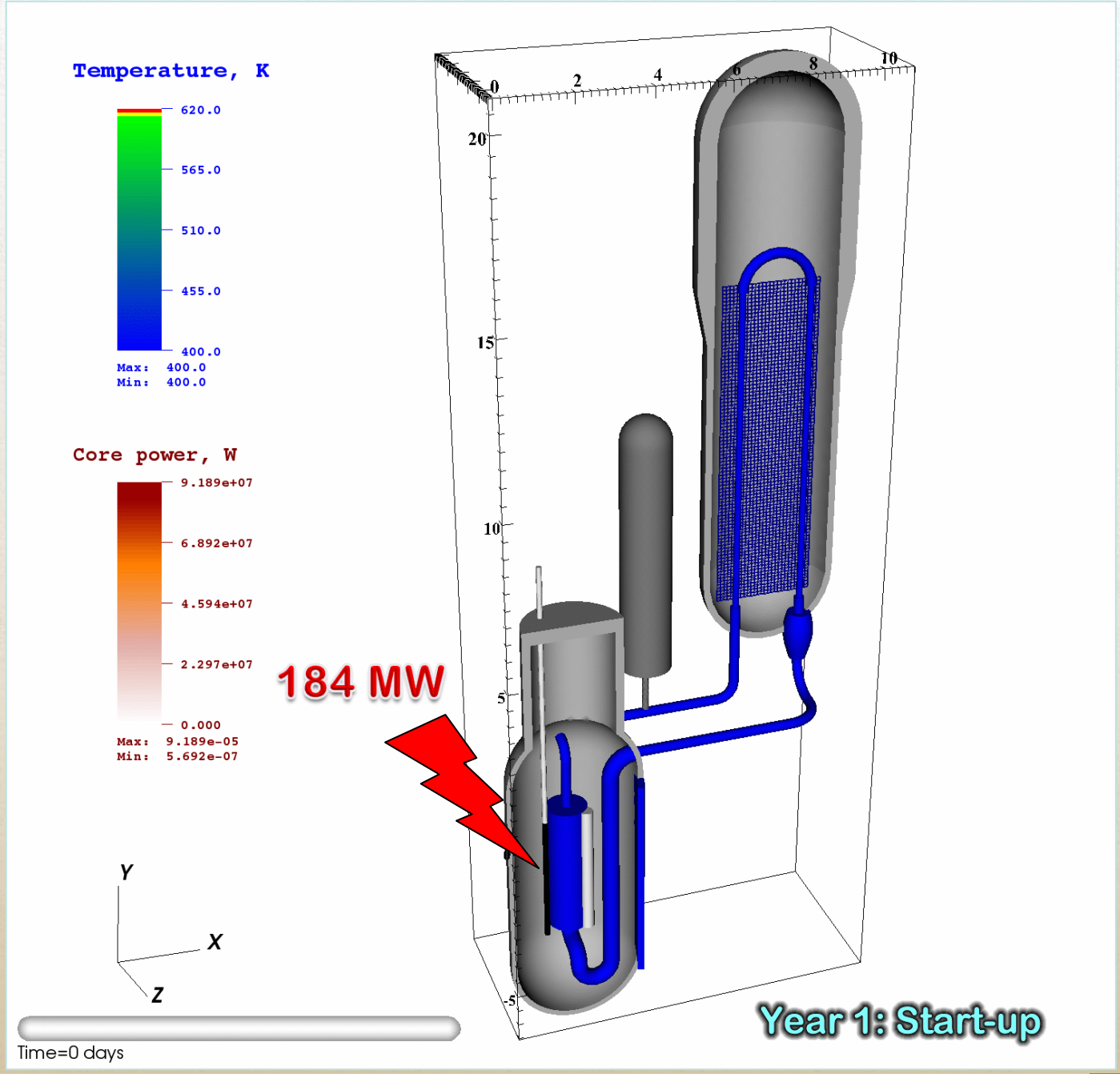
IV. Structural Mechanics + Material degradation/damage accumulation models

Ageing & Damage Accumulation

PWR-I:
2-phase tests



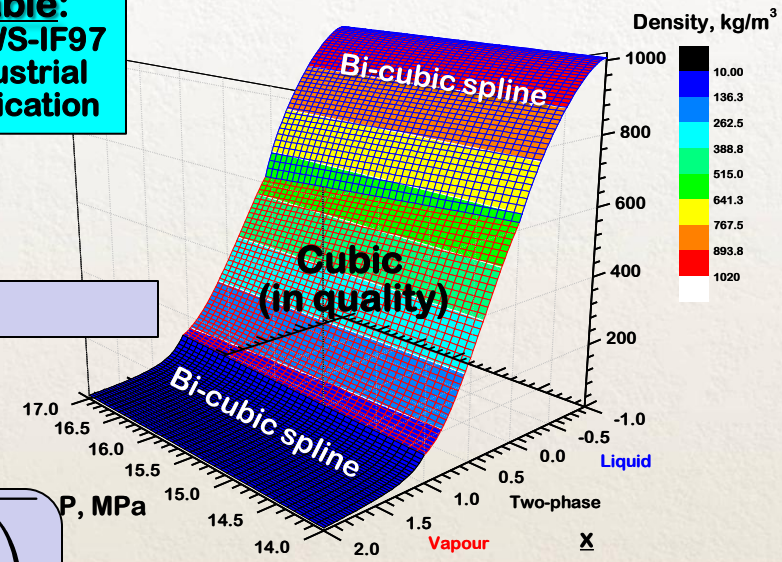
PWR-I:
2-phase tests



HEM+slip

$$\begin{bmatrix} P \\ u \\ i \end{bmatrix}$$

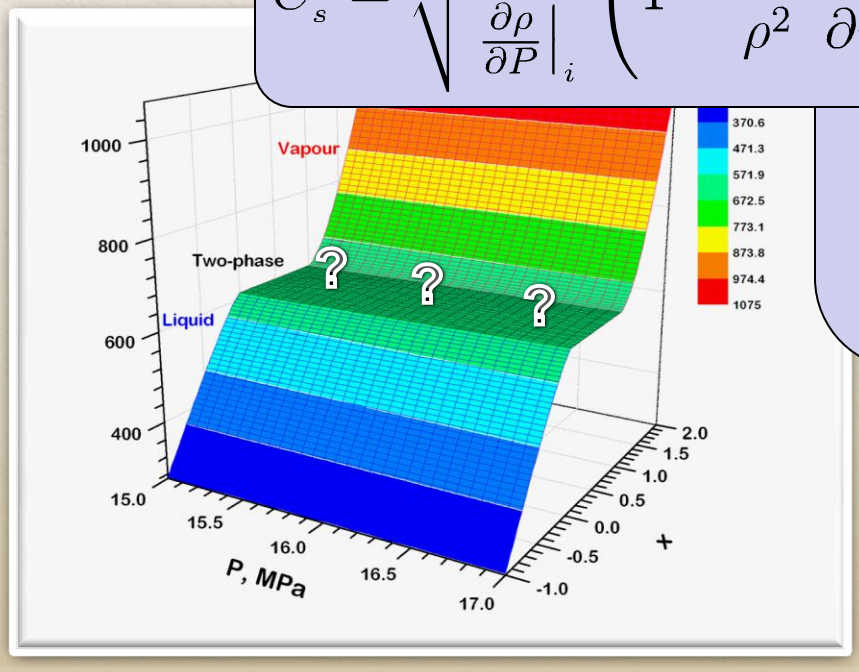
Table:
IAPWS-IF97 Industrial application

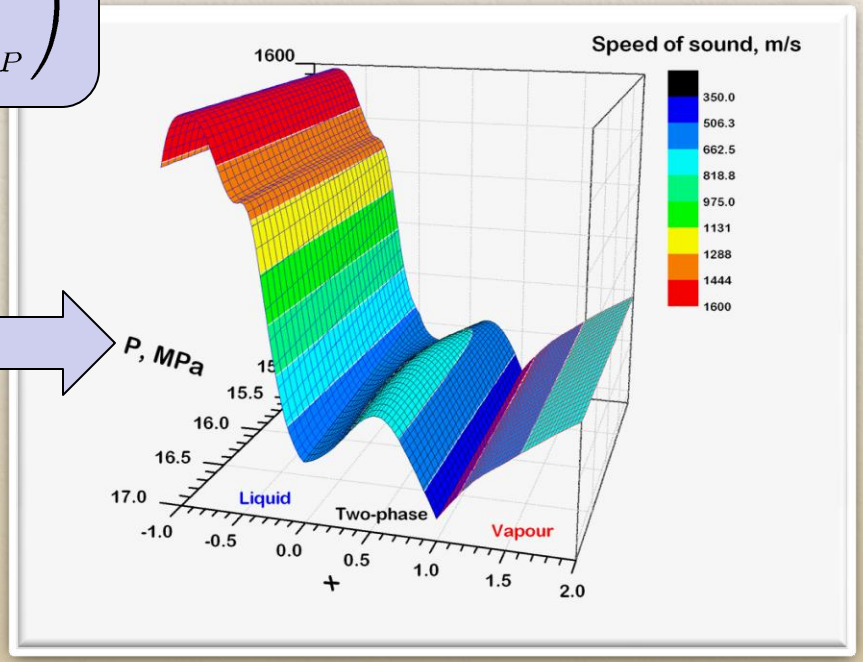


Conservation laws:

$$\begin{cases} \partial_t \rho + \partial_j \rho u_j = \mathcal{S}_\rho \\ \partial_t \rho u_i + \partial_j \left(\rho u_i u_j + P \right) = \mathcal{S}_{\rho u_i} \\ \partial_t E + \partial_j \left(u_j (E + P) \right) = \mathcal{S}_E \end{cases}$$

$$C_s = \sqrt{\frac{1}{\left.\frac{\partial \rho}{\partial P}\right|_i} \left(1 - \frac{P}{\rho^2} \left.\frac{\partial \rho}{\partial i}\right|_P \right)}$$





6-Equation model

Conservation laws:

$$
\begin{cases}
\partial_t \underline{\rho_L} + \partial_x \underline{m_L} = \mathcal{S}_{\underline{\rho}} \\
\partial_t \underline{m_L} + \partial_x \left(\dfrac{m_L^2}{\underline{\rho_L}} + \underline{P_L} \right) - P_I \partial_x \alpha_L = \mathcal{S}_{\underline{m}} + \underline{\rho_L} g_x \\
\partial_t \underline{E_L} + \partial_x \left(\dfrac{m_L}{\underline{\rho_L}} \left(\underline{E_L} + \underline{P_L} \right) \right) - \underline{P_L} \partial_t \alpha_L = \mathcal{S}_{\underline{E_L}} + \underline{m_L} g_x \\
\hline
\partial_t \underline{\rho_V} + \partial_x \underline{m_V} = -\mathcal{S}_{\underline{\rho}} \\
\partial_t \underline{m_V} + \partial_x \left(\dfrac{m_V^2}{\underline{\rho_V}} + \underline{P_V} \right) + P_I \partial_x \alpha_L = -\mathcal{S}_{\underline{m}} + \underline{\rho_V} g_x \\
\partial_t \underline{E_V} + \partial_x \left(\dfrac{m_V}{\underline{\rho_V}} \left(\underline{E_V} + \underline{P_V} \right) \right) - \underline{P_V} \partial_t \alpha_L = -\mathcal{S}_{\underline{E_V}} + \underline{m_V} g_x
\end{cases}
$$

$$
\underline{\rho_k} = \alpha_k \rho_k, \ \underline{m_k} = \alpha_k \rho_k u_k, \ \underline{E_k} = \alpha_k \rho_k e_k, \ \underline{P_k} = \alpha_k P_k, \ k = L, V
$$

6-Equation model

Stuhmiller, 1977
Prosperetti & Satrape, 1990
CATHARE

Conservation laws:

Single pressure, $P_L = P_V =$

$$P_I = \sigma \alpha_d \rho_c (u_d - u_c)^2$$

Closures

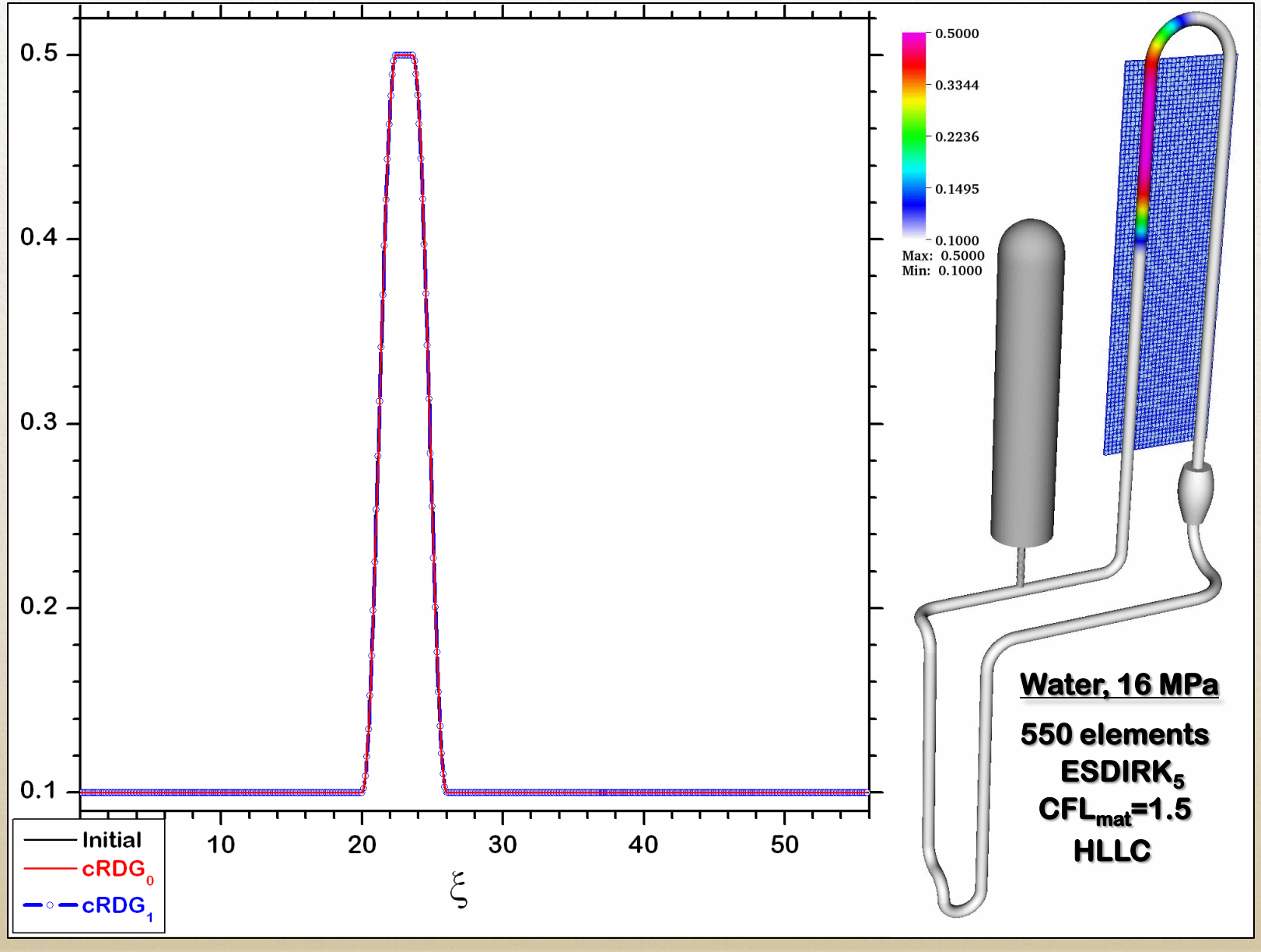
$$\left\{ \begin{array}{l}
\partial_t \underline{\rho_L} + \partial_x \underline{m_L} = \boxed{\mathcal{S}_{\underline{\rho}}} \\
\partial_t \underline{m_L} + \partial_x \left(\dfrac{m_L^2}{\underline{\rho_L}} + \underline{P} \right) - \boxed{P_I} \partial_x \alpha_L = \boxed{\mathcal{S}_{\underline{m}}} + \underline{\rho_L} g_x \\
\partial_t \underline{E_L} + \partial_x \left(\dfrac{m_L}{\underline{\rho_L}} \left(\underline{E_L} + \underline{P} \right) \right) - \underline{P} \partial_t \alpha_L = \boxed{\mathcal{S}_{\underline{E_L}}} + \underline{m_L} g_x \\
\hline
\partial_t \underline{\rho_V} + \partial_x \underline{m_V} = \boxed{-\mathcal{S}_{\underline{\rho}}} \\
\partial_t \underline{m_V} + \partial_x \left(\dfrac{m_V^2}{\underline{\rho_V}} + \underline{P} \right) + \boxed{P_I} \partial_x \alpha_L = \boxed{-\mathcal{S}_{\underline{m}}} + \underline{\rho_V} g_x \\
\partial_t \underline{E_V} + \partial_x \left(\dfrac{m_V}{\underline{\rho_V}} \left(\underline{E_V} + \underline{P} \right) \right) - \underline{P} \partial_t \alpha_L = \boxed{-\mathcal{S}_{\underline{E_V}}} + \underline{m_V} g_x
\end{array} \right.$$

$$\mathbf{V} = \begin{bmatrix} \alpha_c \\ P \\ u_L \\ u_V \\ i_L \\ i_V \end{bmatrix}$$

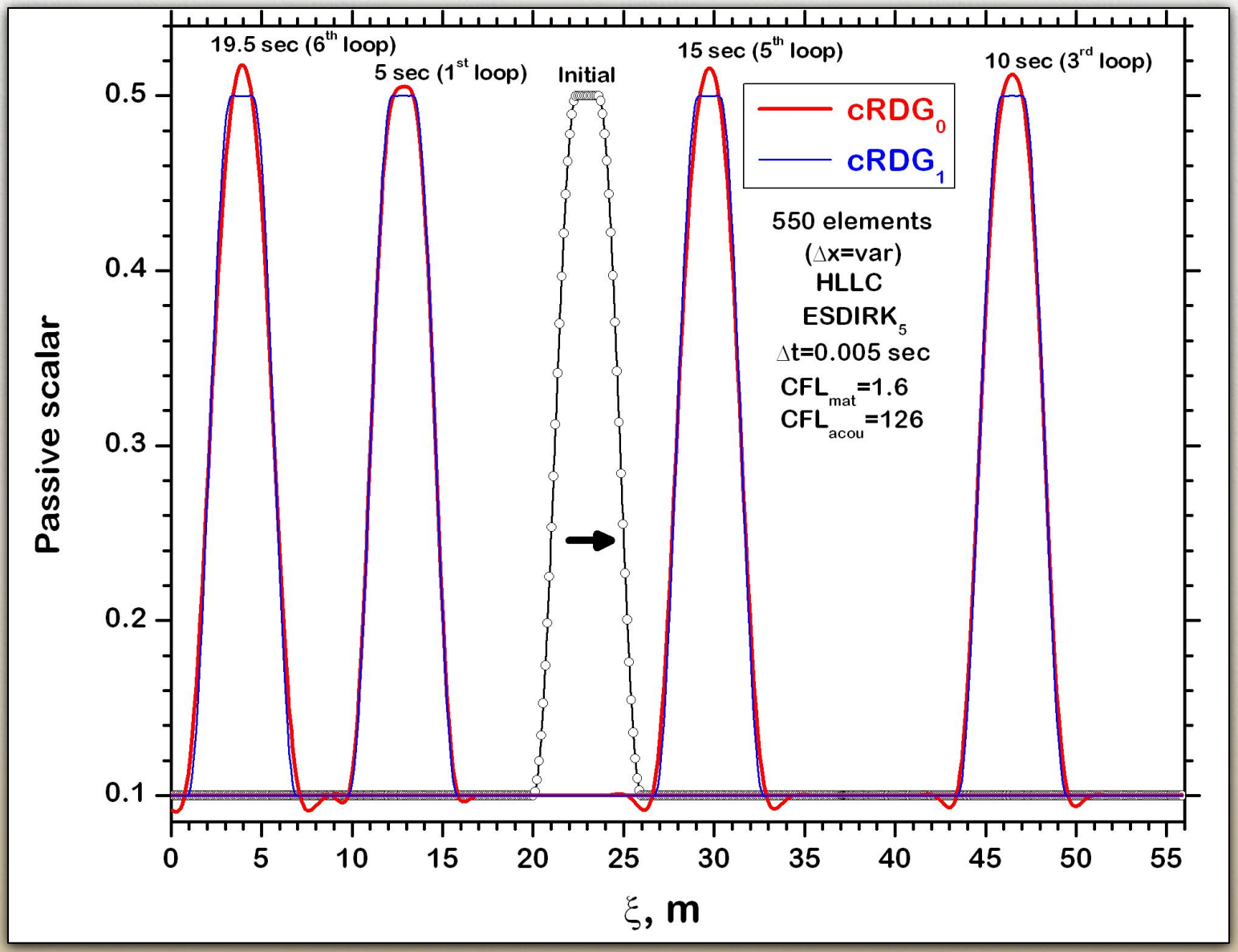
$$\boxed{P_I = \mathcal{F}(\mathbf{V})} \Rightarrow \text{Hyperbolic}$$

$$\underline{\rho_k} = \alpha_k \rho_k, \ \underline{m_k} = \alpha_k \rho_k u_k, \ \underline{E_k} = \alpha_k \rho_k e_k, \ \underline{P_k} = \alpha_k P, \ k = L, V$$

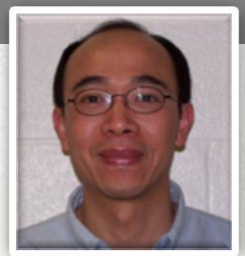
Transport of passive scalar



Transport of passive scalar

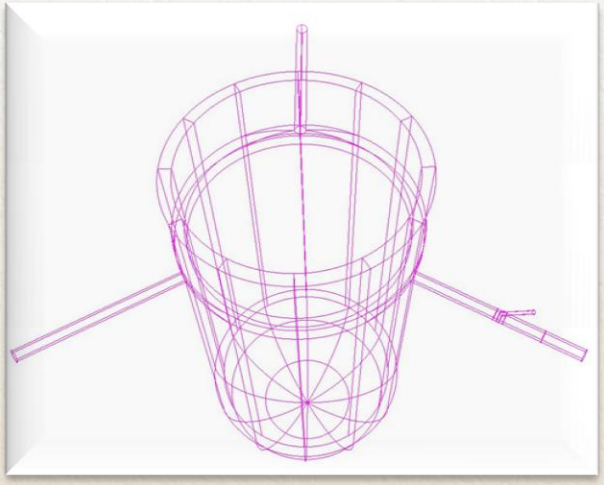


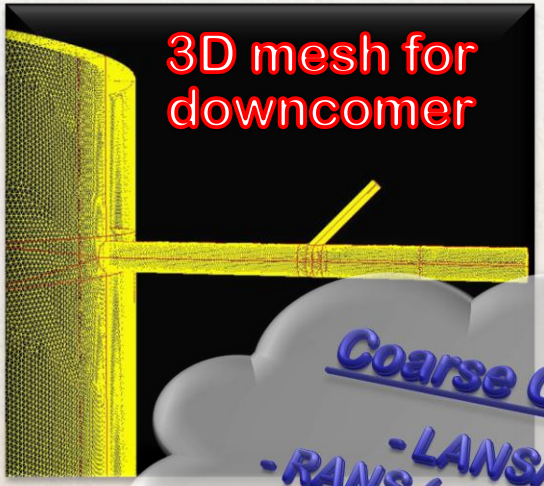
CFD/CG modeling



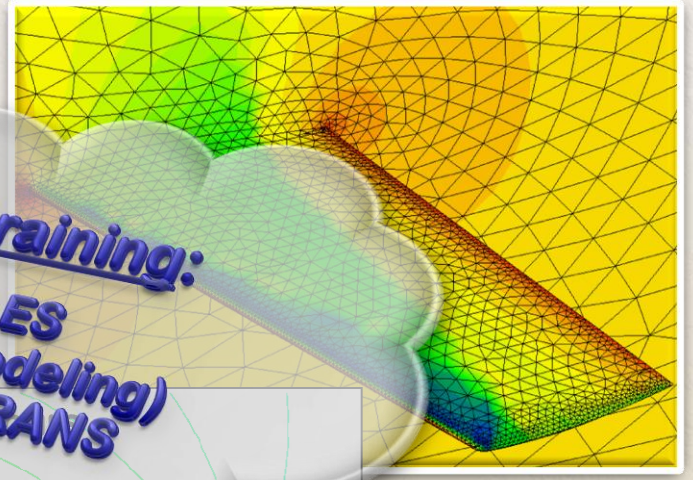
Hong Luo
NCSU

Steve Shkoller
UC Davis



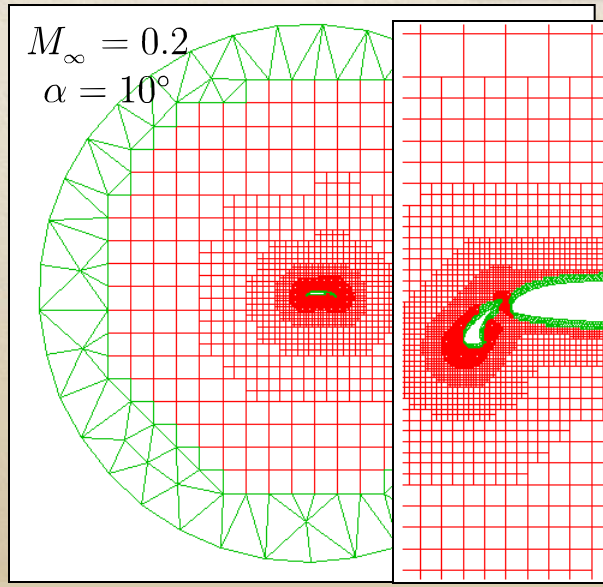


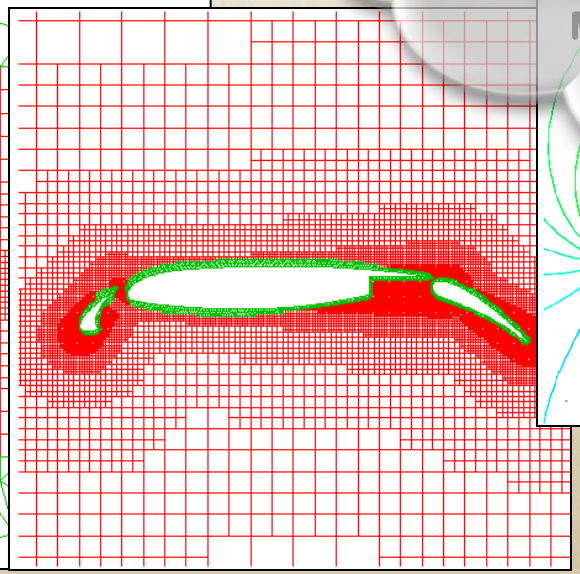
Transonic flow past a M6 wing configuration M_∞=0.84, α=3.06°

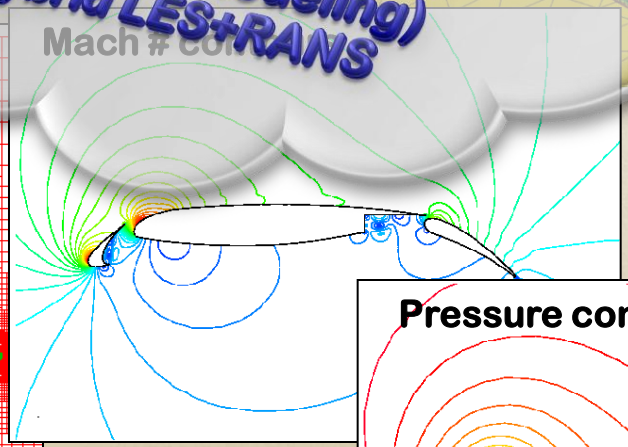


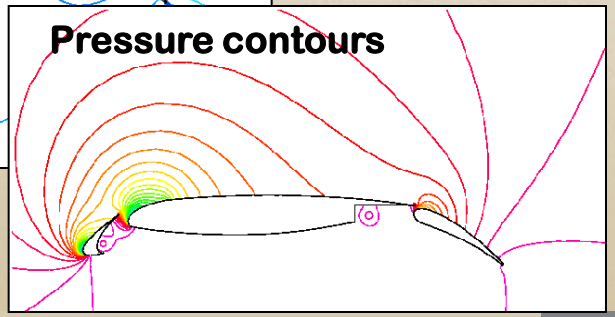
Coarse Graining:
- LANS/LES
- RANS (κ–ε modeling)
- Hybrid LES+RANS

3-element airfoil









Team

Bui Viet Anh
INL

Brandon Blackburn
INL

Samet Kadioglu
INL

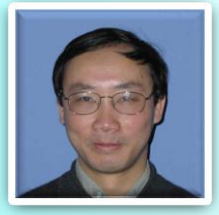
Ray Berry, INL

Hong Luo
NCSU

Steve Shkoller
UC Davis

Thermalhydraulics

Robert Nourgaliev
INL


Nam Dinh, INL

Abderrafi Ougouag
INL

Joshua Cogliati
INL

Hongbin Zhang
INL

Frederick Gleicher
INL

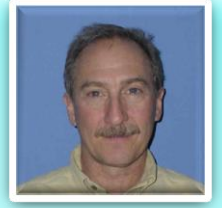
Pavel Medvedev
INL

Materials, Fuel, Neutronics

Ralph Nelson
LANL

Brian Williams
LANL

Laura Swiler
SNL


Mike Pernice
INL

Hany S. Abdel-Khalik
NCSU

UQ & SA

IT: CS, HPC, I/O, GUI support

Tami Grimmet
INL

Validation

Barton Smith
USU

Qiao Wu
OSU

Bob Youngblood
INL

Tunc Aldemir
OSU

Dana Kelly
INL

Risk analysis reliability