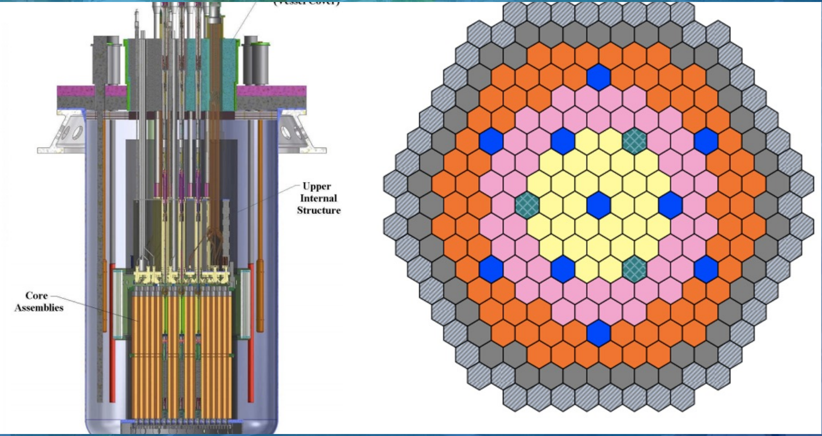
FAST REACTOR SAFETY



TANJU SOFU
Program Manager
Nuclear Science & Engineering Division
Argonne National Laboratory

U.S. DEPARTMENT OF ENERGY
Argonne National Laboratory is a U.S. Department of Energy laboratory managed by UChicago Argonne, LLC.

Argonne NATIONAL LABORATORY

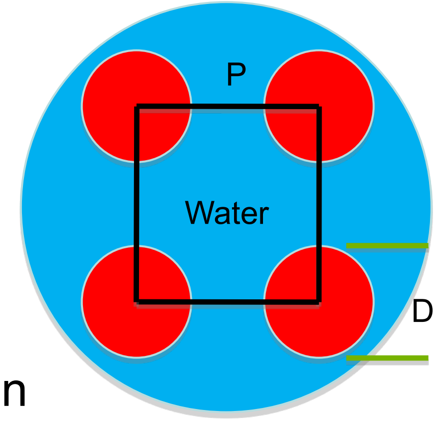
OUTLINE

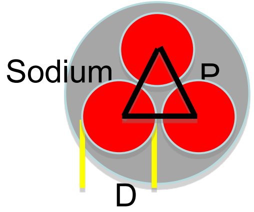
- Key features that impact safety
  - Reactor physics
  - Thermal-fluids
  - Fuel forms
- Safety approach
  - Defense-in-depth
  - Plant states considered in design
  - Approach for operational states and design basis accidents
  - Approach for design extension conditions and severe accidents
  - Source term assessments
- Summary

KEY SAFETY FEATURES

Thermal design considerations

- In WCR, water acts both as the coolant and moderator:
  - Optimal P/D ratio to assure
    - adequate moderation
    - sufficient cooling
- In a fast reactor with higher power density, only cooling function is needed
  - Lattice is more compact, stipulating a coolant with much better heat transfer capabilities (liquid metals)
  - Fuel pins can be packed much closer in a hexagonal lattice (triangular pitch)
    - Typically separated by a thin wire wrapped around each fuel pin to prevent pin-to-pin contact





KEY SAFETY FEATURES

Liquid sodium coolant

- ~100 times higher thermal conductivity compared to water
- Wide margin to boiling (>350°C)
- Compatible with structural components and metallic fuels
- High temperature operation (>500°C core outlet temperature)
  - Allows greater thermal efficiency (~40%) for energy conversion
- Low pressure primary and intermediate coolant system
  - No LOCA concern, no need for high-pressure coolant injection, low containment design pressure
  - Guard vessel (and guard pipes in loop type reactor) to "maintain" coolant inventory
- Dedicated systems for decay heat removal to an ultimate heat sink
  - Large core ΔT (150°C in an SFR vs. ~30°C in an LWR) facilitates reliance on passive systems driven by natural circulation for decay heat removal
- Simpler operation and accident management (long grace period for corrective action)
- Liquid sodium chemically reacts with air and water, and it is opaque

KEY SAFETY FEATURES

Reactor physics

- Need for a finer multi-group cross-section structure to resolve the fast spectrum
  - Neutrons are either absorbed or they leak before they get “thermalized”
  - Mid-energy resonances contribute to significant Doppler feedback
- Impact of energy spectrum on transmutation:
  - Fission/capture ratio is much higher in fast spectrum
  - Neutrons/fission is also greater in fast spectrum
  - Net result is more excess neutrons and less actinide generation
    - Greater flexibility for material selection
- Fast spectrum leads to ~10× longer neutron mean-free paths
  - Negligible spatial self-shielding
  - Greater sensitivity to neutron leakage from minor geometric changes
  - Reactivity perturbations impact the whole core, instead of locally as in thermal reactors

KEY SAFETY FEATURES

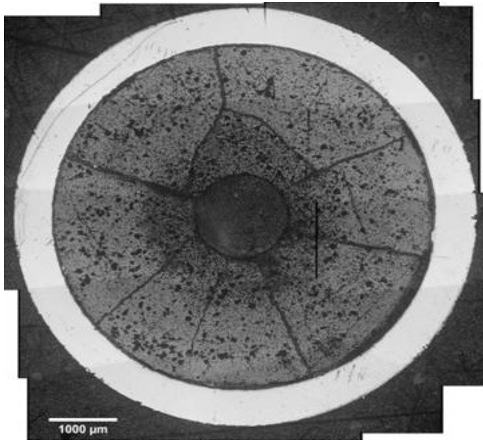
Reactor physics (cont.)

- High core power density (~5X in comparison to an LWR)
- Breeding or transmutation of transuranic waste products
  - Fast reactors are typically intended for closed fuel cycle
    - Uranium conversion leads to improved resource utilization and waste minimization
  - Long core life with breed-and-burn concepts
  - But higher enrichment is needed to achieve initial criticality (HALEU fuel)
- Inherent safety owing to “net” negative reactivity feedback during accidents with elevated core/coolant temperatures
  - For large cores, sodium void worth can be positive
- Shielding challenges unique to fast neutron spectrum

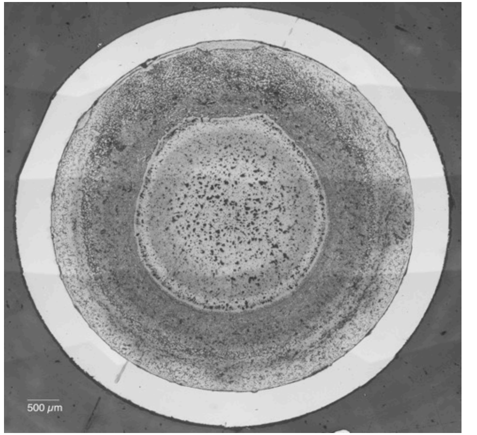
KEY SAFETY FEATURES

Fuels

- Design is expected to assure that
  - Fuel is not damaged during operational states
  - Fuel damage during postulated accidents does not propagate and core coolability is maintained
- Fast reactor fuels can reach higher burnup than LWR fuels with higher initial fissile loading and opportunity for “breed & burn”
- Fuel modeling capabilities should account for:
  - Fast neutron irradiation induced swelling (greater in a fast neutron spectrum)
  - Thermal and irradiation induced creep
  - Mechanical stresses from internal fission gas pressure
  - Thermal stresses from temperature gradients
  - Fuel-cladding chemical and mechanical interactions
  - Flow-induced vibration and fretting



High Burnup MOX Fuel



Metal Fuel with HT9 Clad

FUEL TYPES

Oxide vs. metallic fuel comparisons

	Metal (U-20Pu-10Zr)	Oxide (UO_2-20PuO_2)
Heavy Metal Density, g/cm^3	**14.1**	9.3
Melting Temperature, ^oK	1400	**3000**
Thermal Conductivity, W/cm-^oK	**0.16**	0.023
Operating Centerline Temp. (in ^oK) at 40 kW/m, and (T/T_{melt})	**1060 (0.76)**	**2360 (0.79)**
Fuel-Cladding Solidus, ^oK	1000 (eut. limit)	**1675**
Thermal Expansion, 1/^oK	**17×10^{-6}**	**12×10^{-6}**
Heat Capacity, J/g^oK	**0.17**	**0.34**

SAFETY APPROACH

Defense in depth

- Defense-in-depth is the key concept for fast reactor safety
- Fast reactor reliability and safety goals:
  - Excellence in operational safety and reliability ← simplified design
  - Low likelihood and degree of core damage ← inherent and passive safety
  - Smaller emergency planning zone ← reduced source term
- The traditional approach to demonstrating defense-in-depth compliance is deterministic, but a combination of deterministic and probabilistic approaches is increasingly recommended
  - Risk-informed safety approach considers both probability and consequences of postulated accidents
  - Accidents with large consequences are reduced in risk significance by requiring that their likelihood are acceptably small

SAFETY APPROACH

Plant states and their alignment with defense-in-depth

Defense-in-Depth Levels				
Level 1	Level 2	Level 3	Level 4	Level 5
Operational states		Accident conditions		EP&R
Normal Operation	Anticipated Operational Occurrences	Design Basis Accidents	Design Extension Conditions	Residual risk and practically eliminated accidents
			Severe accidents	Severe accidents

Plant states considered in design (Levels 1–4)

SAFETY APPROACH

Operational states and design basis accidents

- Like WCRs, fast reactor safety is first based on use of multiple, redundant engineered protection systems to lower the probability of accident occurrence and limit the consequences:
  - independent scram systems,
  - multiple coolant pumps and heat transport loops,
  - dedicated decay heat removal systems,
  - multiple barriers to release of radioactive materials.
- Unique LMR design features provide additional measures of protection:
  - High thermal conductivity of liquid metal coolants (70 W/m-K for sodium vs. 0.6 W/m-K for water).
  - Large margin to coolant boiling (~350°C in SFR and ~1150°C in LFR vs. ~20°C in PWR)
  - Minimal pressure loading on the coolant boundary: Reduced concern for coolant pipe breaks, no need for high-pressure coolant injection system
  - Large thermal inertia (especially with pool type reactors) with long grace period during accidents

SAFETY APPROACH

Design Extension Conditions

- Measures to prevent multiple-failure event sequences (including safety system failures) and mitigate their consequences are also considered in the design
  - Design features that enhance inherent safety (net negative reactivity feedback) and passive decay heat removal
- Independence and diversity of DEC design measures (from those relied on during design basis accidents)
  - Due consideration of potential for common cause failures
- A containment structure against external events and to prevent release of radioactivity to the environment as the last barrier
  - Sodium fires that may challenge containment integrity are specifically addressed
- DECs are analyzed using best estimate method, supported with a sensitivity analysis to identify and avoid cliff-edges

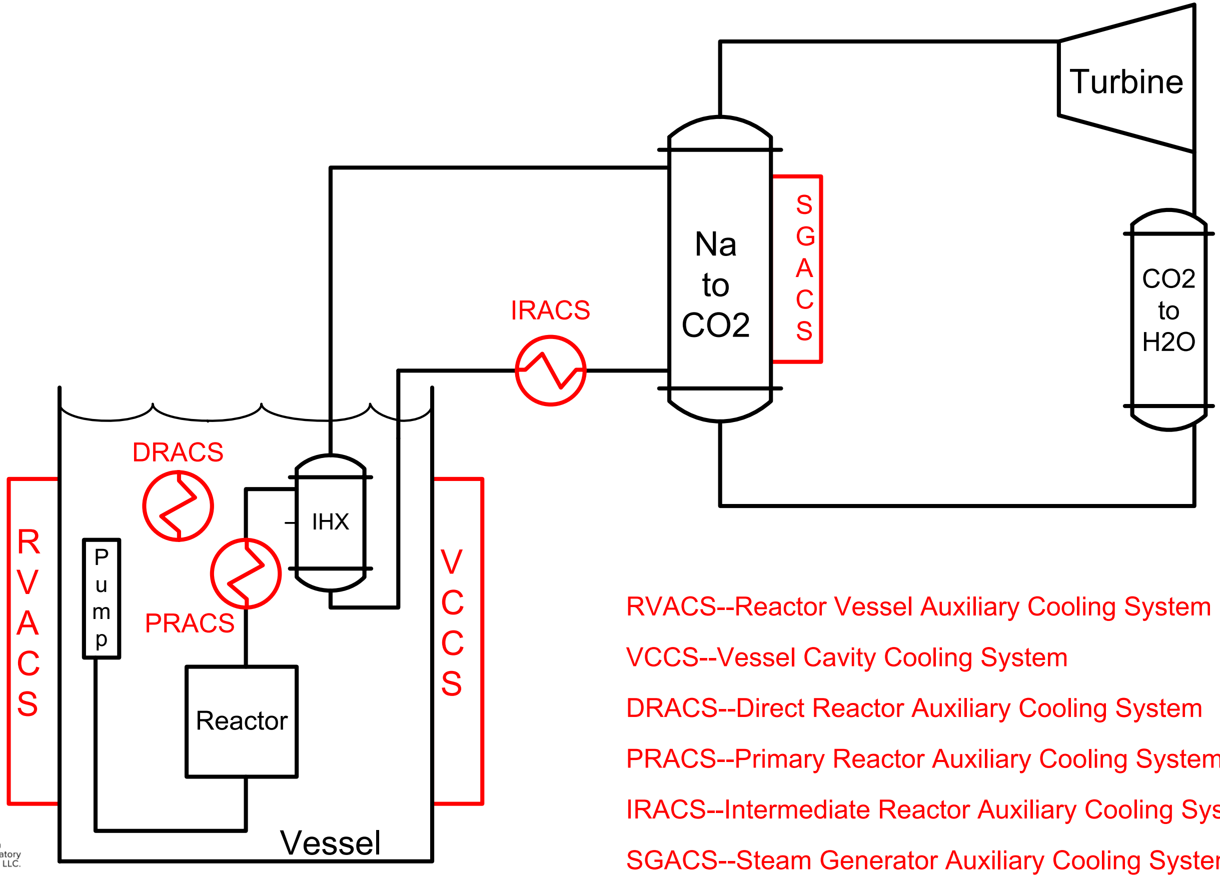
INHERENT SAFETY

Reactivity feedback mechanisms

- Doppler feedback: Effect of changes in neutron fission and absorption cross sections due to Doppler broadening
- Core radial expansion: Due to thermal expansion, irradiation-induced swelling, and irradiation-enhanced creep
- Fuel axial expansion: Effect of thermal expansion and transient swelling of especially the metallic fuels (and cladding)
- Coolant density and void worth: Can be positive (due to reduced Na moderation/absorption) or negative (due to enhanced neutron leakage) at elevated temperatures
- Control rod drive line expansion (relative to reactor vessel expansion): Due to difference in thermal expansion of control-ride driveline and reactor vessel

PASSIVE DECAY HEAT REMOVAL

Room for independent and diverse means for decay heat removal



RVACS--Reactor Vessel Auxiliary Cooling System

VCCS--Vessel Cavity Cooling System

DRACS--Direct Reactor Auxiliary Cooling System

PRACS--Primary Reactor Auxiliary Cooling System

IRACS--Intermediate Reactor Auxiliary Cooling System

SGACS--Steam Generator Auxiliary Cooling System

SAFETY APPROACH

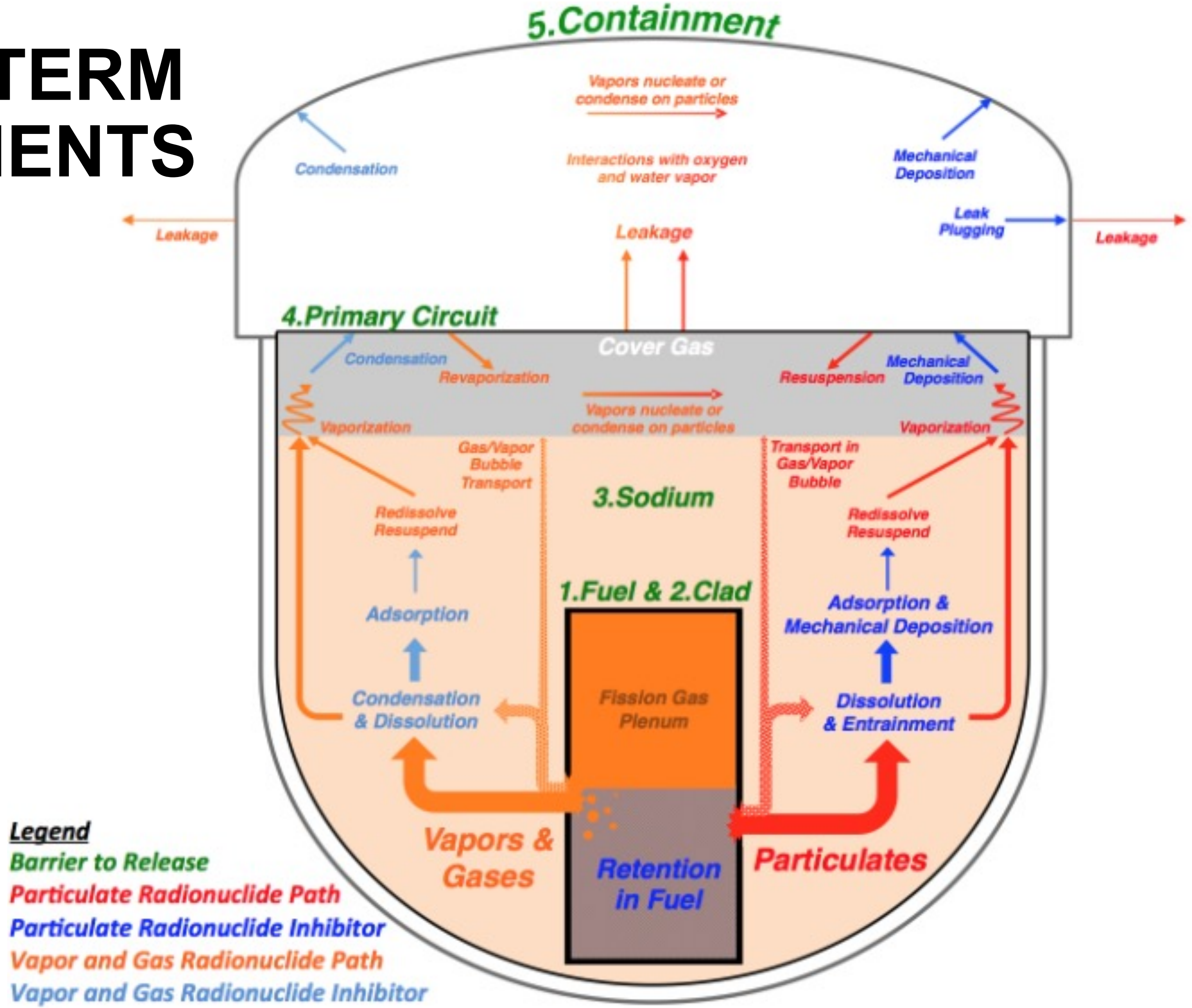
Severe accidents: Accidents leading to core damage

- Depending on design choices and characteristics, severe accidents can be pushed under the residual risk category (level 5)
  - Inherent/passive safety characteristics and choice of fuel
  - Complex reactivity feedback mechanisms for LMRs
  - Supplementary passive reactivity control devices, if needed
- If core damage cannot be prevented, assurance for in-vessel retention and core debris coolability is required to reduce impact on the containment function
- Severe accidents that could lead to a sudden or significant radioactivity release (beyond the regulatory limits) need to be practically eliminated:
  - Simultaneous failure of both the reactor and guard vessels
  - Complete loss of decay heat removal capability
  - Collapse of core support structure

SOURCE TERM ASSESSMENTS

- Risk-informed approach requires consequence analysis for all plant states considered in design through mechanistic source term assessments
- In fast reactors, only a small number of bounding accident conditions (with very low likelihood) are expected to contribute to significant source term:
  - Severe loss of decay heat removal capability
  - Severe loss-off-flow cases (multiple pump seizures)
  - Severe failures in spent fuel storage systems
- Source term development process:
  - Identification of radionuclide inventory and sources
  - Modeling of radionuclide transport pathways and phenomena
  - Evaluation of a class of bounding accidents

SOURCE TERM ASSESSMENTS



SUMMARY

- Rich legacy for fast reactor design, analysis and testing
- Defense-in-depth as the key reactor safety concept
- Plant states considered in design includes multiple failure events
  - Similar safety approaches for AOO and DBAs to LWRs
    - Unique safety features leading to significant design simplifications
  - Reliance on inherent safety and passive decay heat removal for DEC
  - Severe accidents (significant and sudden radioactivity release) are practically eliminated
  - Mechanistic source term assessments for residual risk events
- Unique reactor physics characteristics in fast spectrum
  - Complex reactivity feedback mechanisms
- Passive decay heat removal
  - Based on natural circulation or heat-pipe concepts
- Significant metallic and oxide fuel irradiation and transient testing base

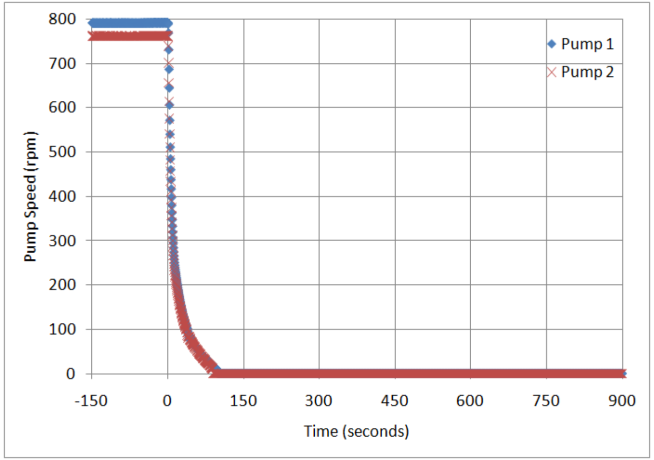
BACK-UP MATERIAL

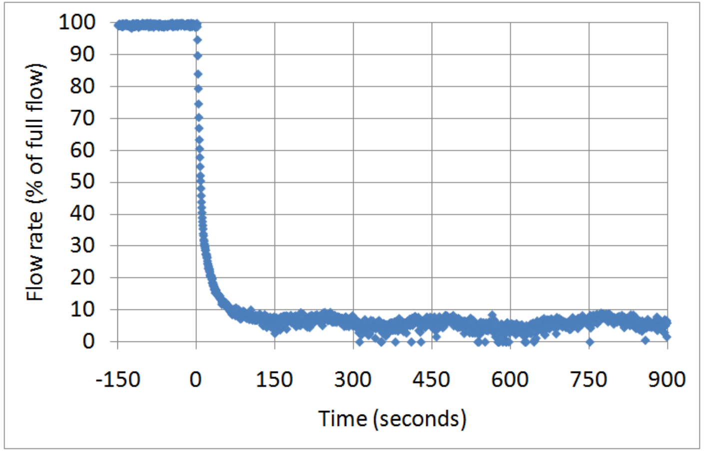
EBR-II INHERENT SAFETY DEMONSTRATION

- EBR-II's potential to survive severe accident initiators without core damage was demonstrated during the landmark inherent safety demonstration: Station blackout without scram (April 3, 1986)
  - From full power and full flow conditions
  - Simultaneous trip of all sodium pumps (primary and intermediate loop pumps)
    - Only auxiliary sodium coolant pump on battery power kept running
  - Reactor control system was manipulated to avoid scram
  - Decay heat removal system continued to operate at its rated capacity as a passive device

EBR-II INHERENT SAFETY DEMONSTRATION

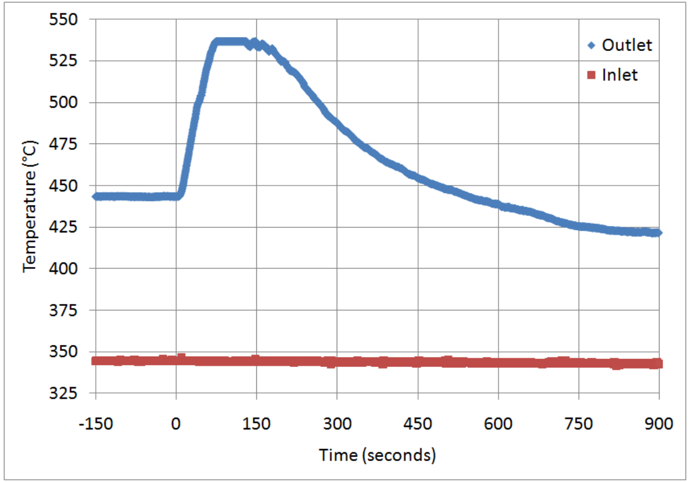
Pump coast-down without scram caused the reactor core temperatures to rise, introducing net negative reactivity and reducing reactor power to decay heat level.

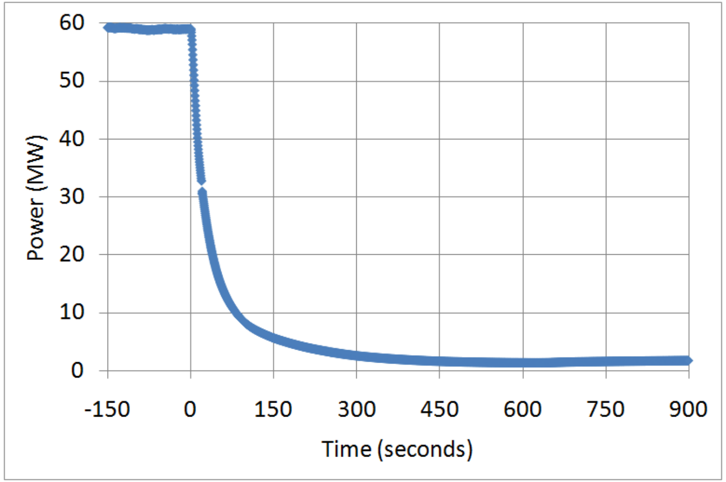




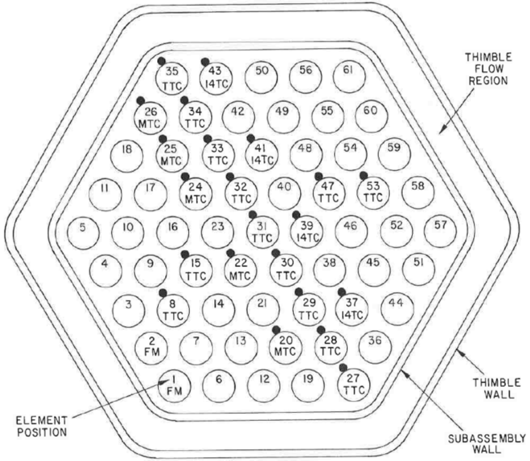
EBR-II INHERENT SAFETY DEMONSTRATION

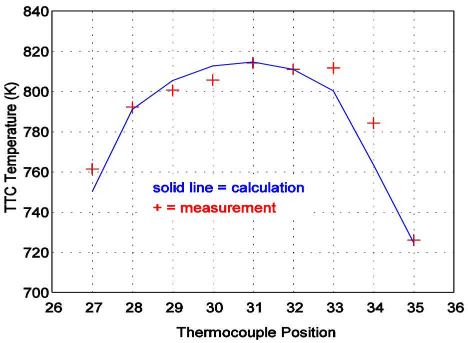
Pump coast-down without scram caused reactor core temperatures to rise, introducing net negative reactivity and reducing reactor power to decay heat level.

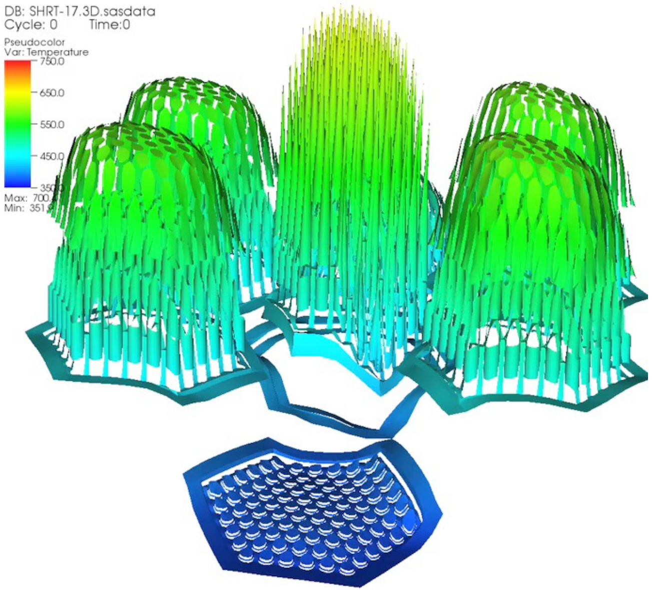




EBR-II INHERENT SAFETY DEMONSTRATION







Mesh represents sodium temp. distribution at top of the XX09 and surrounding assemblies (elevation and color represents temperature)