NRIC National Reactor Innovation Center

Startup Physics Testing of Advanced Reactors

A Survey of Historical Practices

Samuel E. Bays

6/28/2024

Scope

- Document the startup physics testing from initial fuel loading to ascension to full power for historical advanced reactor programs.
    - What was measured?
    - Why was it measured?
    - How was it measured?
    - How well did measurements agree with predictions?

- Provide broad coverage over advanced reactor types:
    - System for Nuclear Auxiliary Power (SNAP10A)
    - Molten Salt Reactor Experiment (MSRE)
    - Ft. St Vrain (FSV)
    - High Temperature engineering Test Reactor (HTTR)
    - Experimental Breeder Reactor – II (EBR-II)
    - Superphénix

Notable observations from NRIC historical review.

- https://www.osti.gov/biblio/2284092

- All reactors studied (except Fort St. Vrain) used the 1/M method to measure critical mass with all control rods withdrawn.
- All reactors used super-critical methods for measuring control rod/drum worths. Augmented by subcritical measurements.
- All reactors evaluated control rod resonance interference.
- All reactors measured flux/power distribution using in-core activation dosimeters or neutron flux detectors.

What is startup physics testing?

- Startup physics testing is a set of measurements made prior to normal operation of all reactors. It is a typical part of reactor commissioning.
- These tests verify that the as-built reactor will operate as it was designed, including important safety and hazard mitigation features.
- Systems, structures, and components (SSC) are tested when the reactor is at a power level sufficiently low that reactor safety is not reliant on the SSC to perform its safety function.
- The startup physics test plan is organized into a series of hold points of increasing power, temperature, and pressure.

Hold Points (Before initial crit.)

1. Hot Functional Tests – non-nuclear performance checks
   Rod drop times, no hot spots in biological shielding, no coolant leaks.
2. Fuel Loading and Inverse Multiplication Approach to Critical
   - Measure shutdown margin.

   We will go critical where we say we will.

Hold Points (Initial Criticality)

3. Zero Power Criticality
   - Critical control element position

     We went critical where we said we would.
   - Control element worth **(S-Curves)**
   - Isothermal Temperature Coefficient (ITC)

     Linear Response.
   - Radial/Axial Peaking Factor (by activation analysis)

     Hot Channel Factors.

     Useful to calibrate startup detector to flux magnitude.
   - Kinetics Parameters

     Important to characterize reactivity with molten salt fuel flowing versus not flowing.

Hold Points (Low Power)

4. Low Power **(e.g., <30% Power)**
   - Flux symmetry.

     Fuel is loaded symmetrically because rod/drum worths are symmetric.
   - 2D Power Measurements.

     In-Core self-powered flux Detectors, thermocouples, instrument trees, etc.
   - Transition to natural circulation tests.

     Done at modestly low power but with prototypic power/flow ratio.

Hold Points (Intermediate Power)

5. Intermediate Power Tests **(e.g., 30-100% Power)**
   - Power Coefficient

     Non-linear temperature response.
   - HZP to HFP reactivity

     Power defect.
   - Pump halving time, bypass flow, pressure drop, etc.

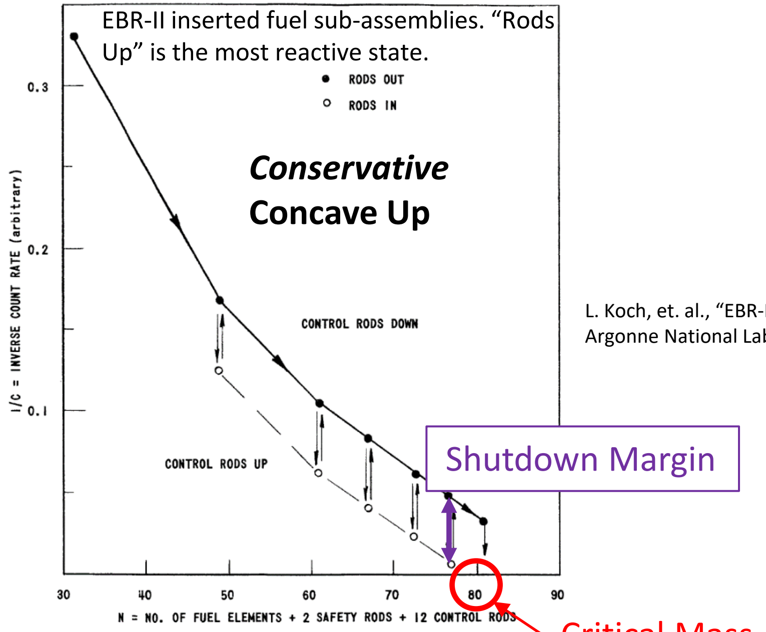
     Verifies assumptions made in safety analysis.
   - Reactor stability and noise analysis

     Assesses potential flow-instability and vibration.

     Useful for high dominance ratio, high power/flow scenarios.

Initial loading to critical

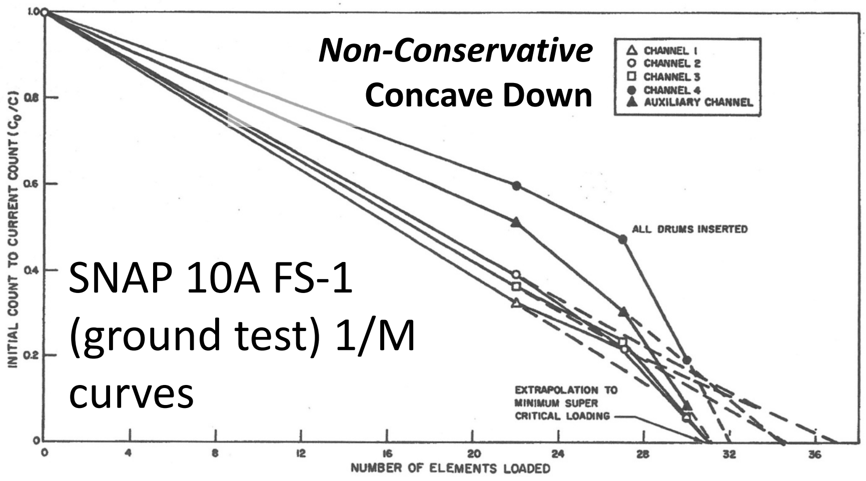
- The 1/M approach to critical process ensures the correctness of: modeling and simulation, the fuels and materials manufacturing, the reactor configuration, and the instrumentation and control (I&C).



EBR-II 1/M curves with and without control rods inserted.

L. Koch, et. al., "EBR-II Dry Critical Experiments", Argonne National Laboratory, ANL-6299, (1961)

- Concave up conservatively predicts critical mass.
- Concave down can result from too large of fuel addition or poor field of view between source and detector.



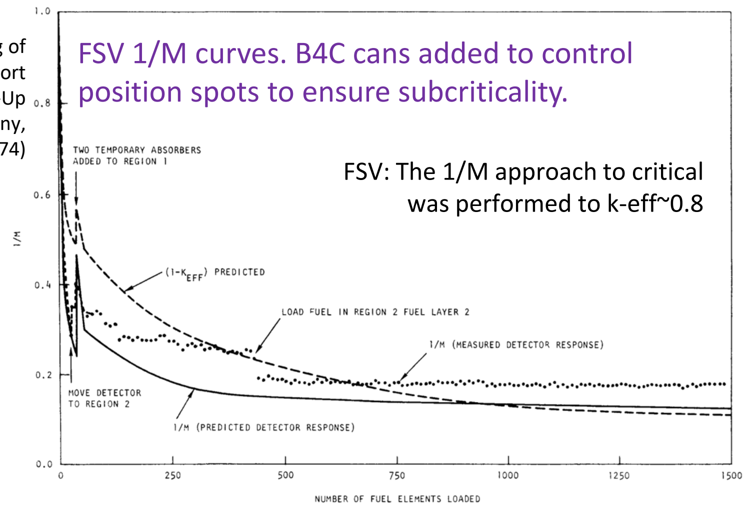
R. Gimera and R. Johnshon, "SNAP10A Reactor Quarterly Progress Report", Atomics International, NAA-SR-9594, (1964).

NRIC National Reactor Innovation Center

Ex-core detector miscalibration

- FSV: A 2nd 1/M measurement with the core fully loaded was performed. Inverse multiplication measured as a function of control rod position revealed an ex-core detector “de-calibration” effect.
  - Later attributed to the power in outer core fuel columns being suppressed by control rod motion disproportionately to the average reactor power. Most of the flux entering ex-core detectors originates only in outer core fuel columns.

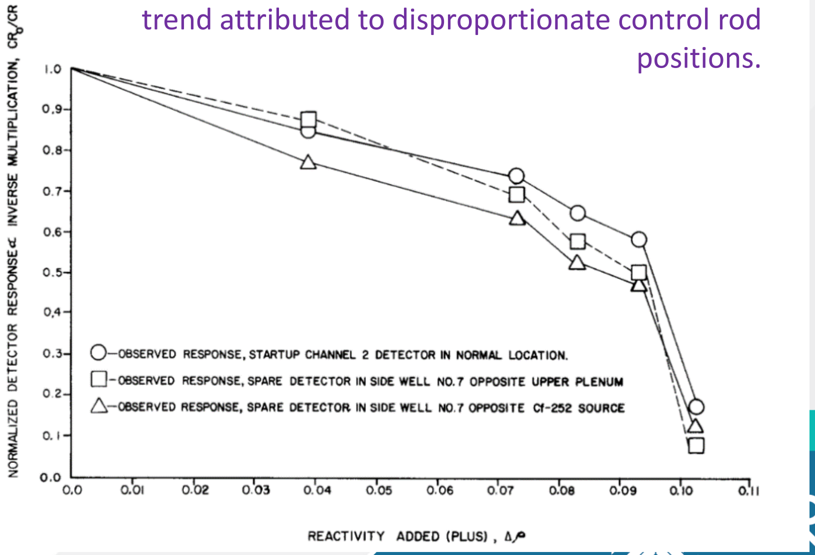
A. Marshal and J. Brown, “Loading of Fuel and Reflector Elements in the Fort St. Vrain Initial Core (Results of Start-Up Test A-1)”, General Atomic Company, GA-A13101, (1974)



FSV 1/M curves. B4C cans added to control position spots to ensure subcriticality.

FSV: The 1/M approach to critical was performed to k-eff~0.8

FSV 1/M curves from a fully loaded core. Concave down trend attributed to disproportionate control rod positions.



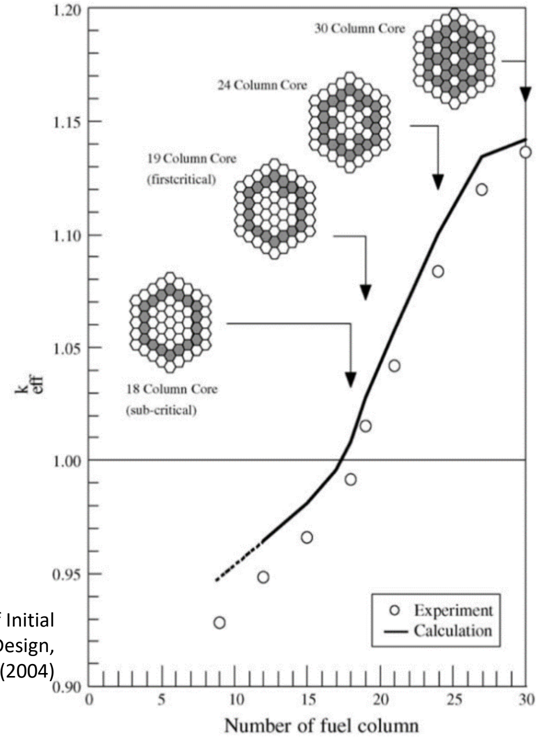
H. Olson et. al., “The Fort St. Vrain High Temperature Gas-cooled Reactor: IX. Rise-to-Power Physics Tests”, Nuclear Engineering and Design, vol. 76, pp 71-77, (1983)

Miss-prediction of critical mass

- HTTR: The 1/M approach to critical revealed a different critical mass than predicted by both nodal diffusion and Monte Carlo codes.
  - Later attributed to poorly characterized nitrogen impurities in the graphite blocks and boron impurities in the graphite dummy blocks.

- Critical number of fuel columns was initially predicted to be 16±1 by both deterministic and Monte Carlo codes.

- The actual number of columns needed for criticality was 19.



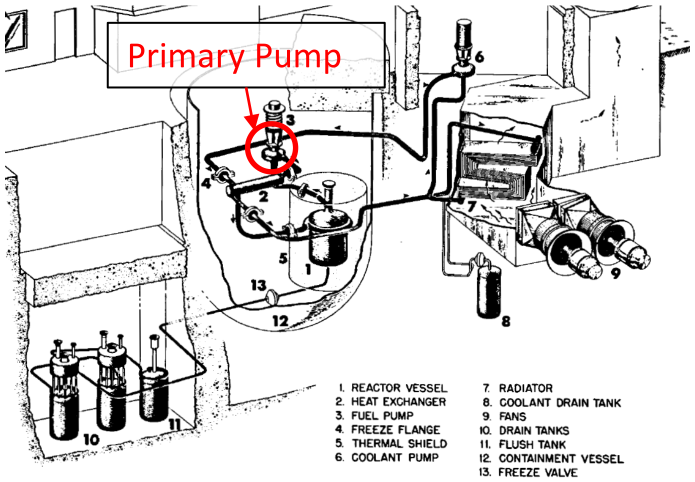
N. Nojiri, et. al., "Characteristic Test of Initial HTTR Core", Nuclear Engineering and Design, vol. 233, pp 283-290, (2004)

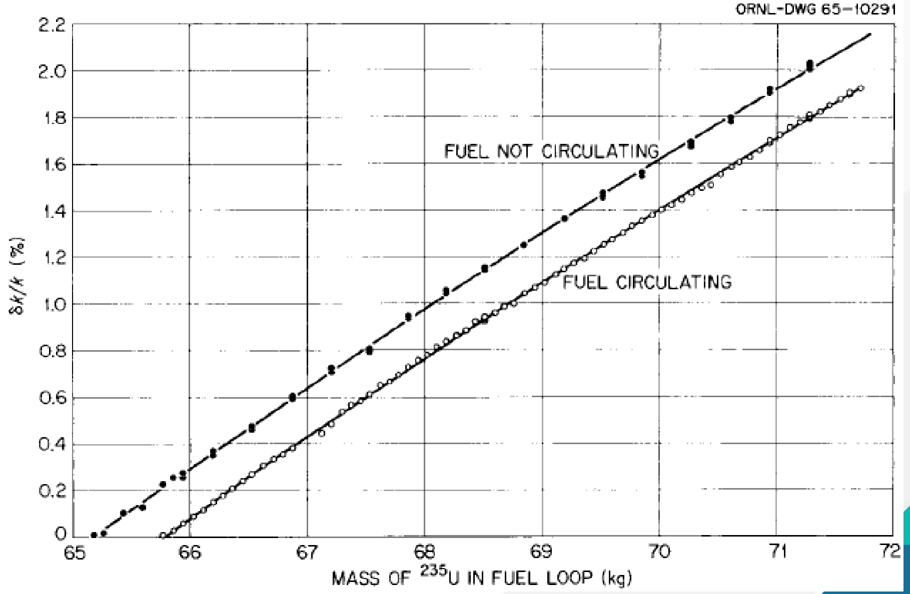
- Reevaluation of the nitrogen content of the graphite, the boron impurity in the graphite dummy blocks, the nuclear data library, and coated fuel particle heterogeneity treatment in the design codes resulted in an updated predicted value of 18 ± 1 columns.

NRIC National Reactor Innovation Center

The role of delayed neutron precursors in molten salt reactors

- The MSRE critical control rod position was measured with the pump on and off after every 4th fuel capsule addition.
- The difference in core reactivity is due to the delayed neutron precursors, which would normally contribute to buffering prompt neutron changes in the core, decay outside of the core as the fuel salt carries them through the primary coolant piping.



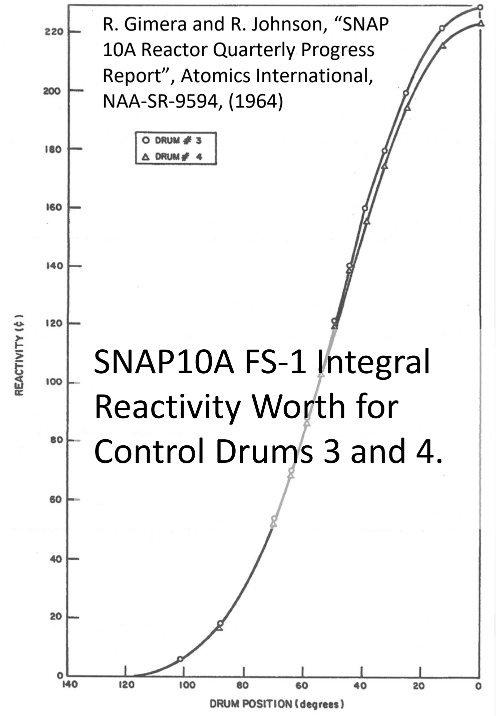


B. Prince, et. al., "Zero-Power Physics Experiments on the Molten-Salt Reactor Experiment", Oak Ridge National Laboratory, ORNL-4233, (1968)

NRIC National Reactor Innovation Center

Control element worth

- These measured worths are typically used in routine plant operation rather than the calculated worth curves.
- All reactors measured worth starting from a critical configuration and inserting control rod/drum in step increments to make the reactor super-critical.
  - Step insertions of control rod create a stable period that then can be converted to a reactivity using the in-hour equation.
    - i.e, the rod bump method.
  - Accurate values for prompt neutron lifetime and delayed neutron fractions needs to be available. The FSV measured these parameters at low power.

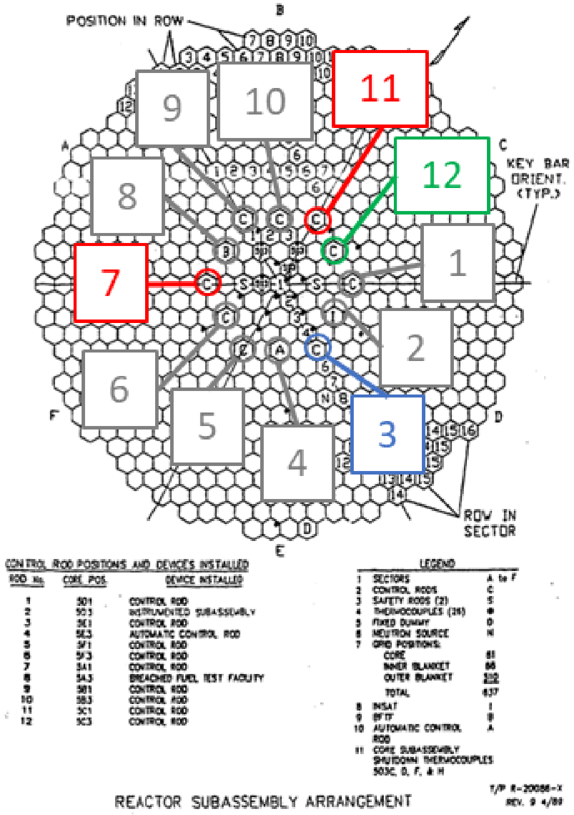


$$\rho = \frac{l^*}{T_P} + \sum_{i=1}^{6} \frac{\beta_i}{1 + \lambda_i T_P}$$

Where ρ is reactivity, l* is the mean neutron generation time. Tp is the stable period. βi is the ith delayed neutron fraction, λi is the decay constant for the ith delayed neutron precursor group.

Control rod interference effects

- Rod-shadowing can change the reactivity of the control rod. Shadowing effects are brought on by the flux depression and/or neutron spectrum influence of neighboring control rods.



ROD SHADOWING EFFECT

Rod Positions (in.)			Count Rates (counts/min)	Δk (Ih)
No. 12	No. 7	No. 11		
0	14	14	Critical	0
0	0	14	6924	128
0	14	0	7338	120

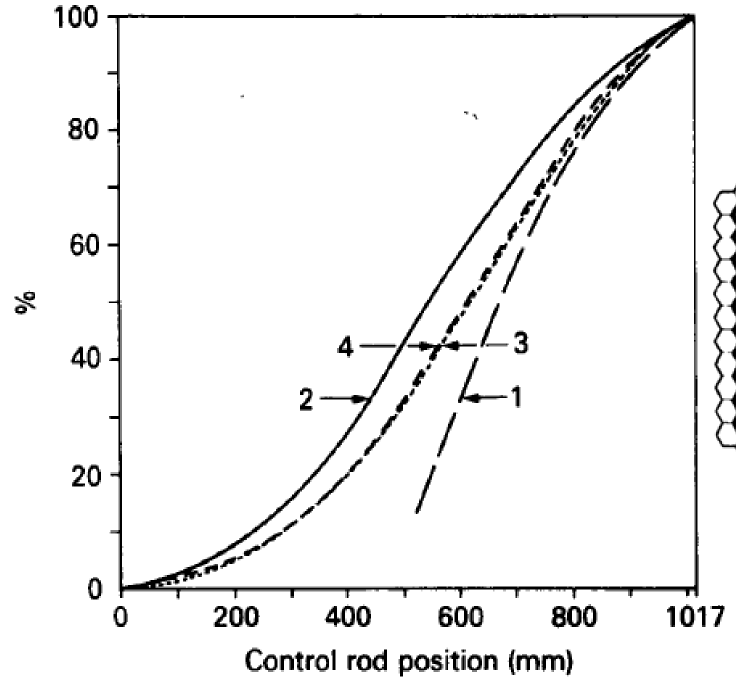
In EBR-II the control elements were fueled sub-assemblies that would be inserted into the core. A position of 0-inch is fuel not-inserted or negative reactivity. A position of 14-inch is fuel inserted or positive reactivity.

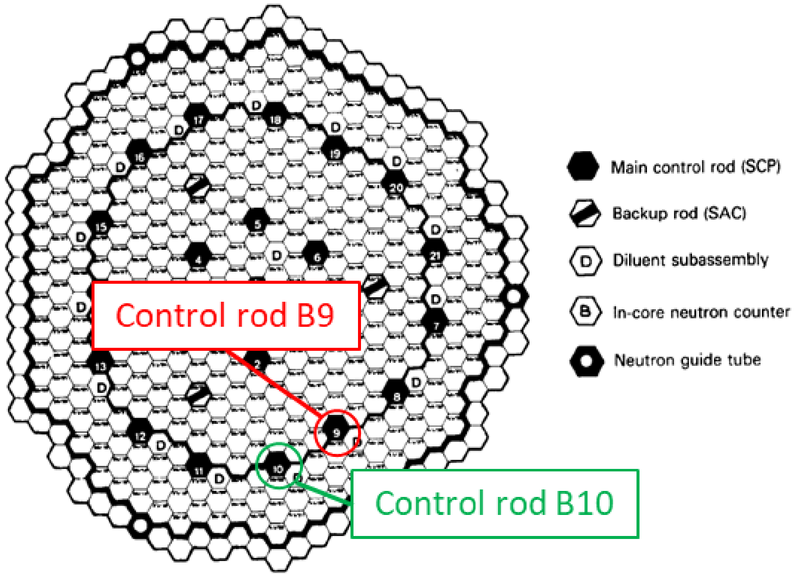
F. Kirn, et. al., “EBR-II Wet Critical Experiments”, Argonne National Laboratory, ANL-68684, (1964)

The worth of two EBR-II control rods was worth 6% less when they were withdrawn adjacent to each other.

Super-critical versus sub-critical measurements

- Control rod/drum worth measurements should be made as close the critical state as possible to mitigate flux distortion effects, e.g., the FSV ex-core detector de-calibration issue.
- Sub-critical methods can provide supporting information but are generally not as sensitive to rod interference effects.



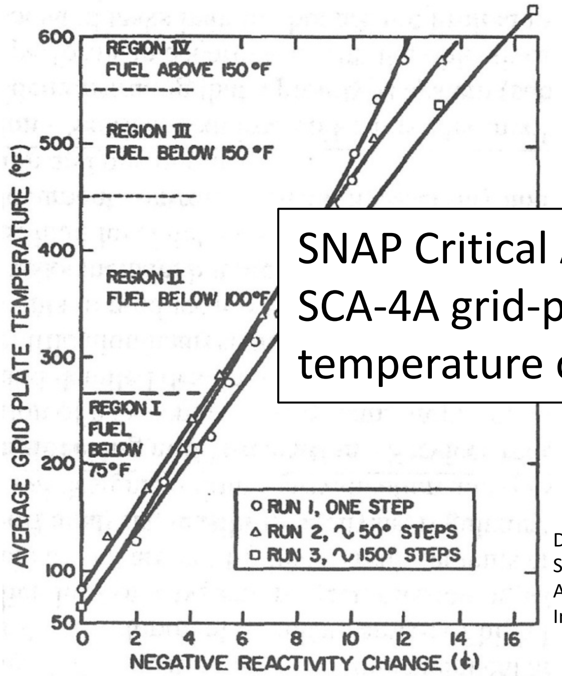


Reactivity worth of Superphénix control element B9 when balanced against B10 as measured by: half-balancing (1), full-balancing (2), MSM (3), temperature compensation (4).

J. Gauthier, et. al., “Measurement and Predictions of Control Rod Worth”, Nuclear Science and Engineering, vol. 106, pp 18-29, (1990)

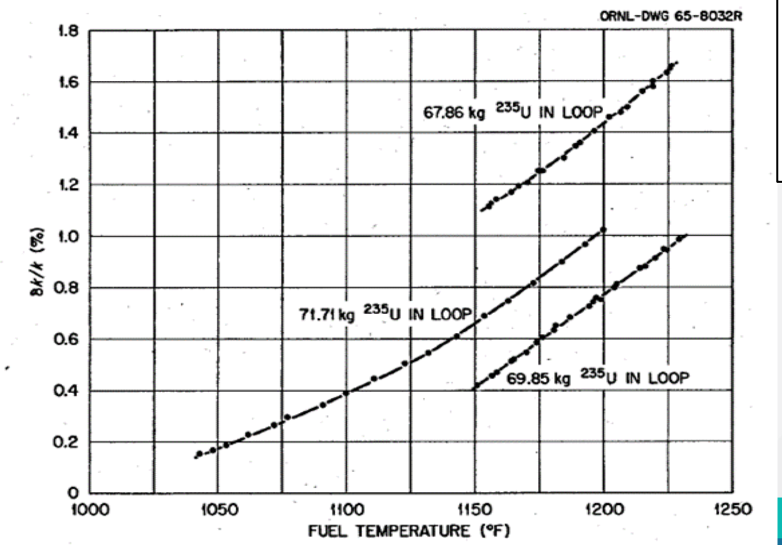
Isothermal temperature coefficients

- The ITC measurement should be conducted in a way that exercises all relevant Doppler, coolant density, and thermal expansion effects in core, coolant, and structures.
- The ITC should be made below the point of added heat, i.e., reactor power is equivalent to energy lost to ambient.



SNAP Critical Assembly, SCA-4A grid-plate temperature coefficient.

D. Clifford, "Final Report on the SNAP10A Prototype Critical Assembly Studies", Atomics International, NAA-SR8613, (1964)



MSRE reactivity as a function of fuel salt temperature.

B. Prince, et. al., "Zero-Power Physics Experiments on the Molten-Salt Reactor Experiment", Oak Ridge National Laboratory, ORNL-4233, (1968)

Transient response

- Reactors with self-regulating, inherent, or passive temperature feedback safety features were tested for design basis transients.
- These are transients at low power. Power-to-flow ratio is controlled to produce similar temperature response as at full-power but not temperatures high enough to challenge safety limits.

Self-stabilization test at zero power in Superphénix.

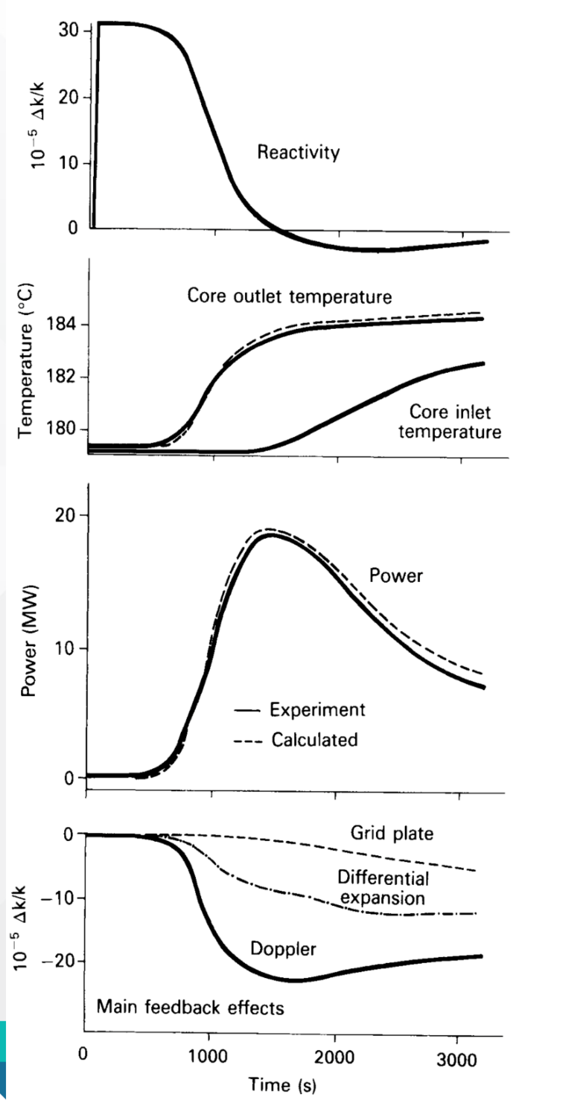
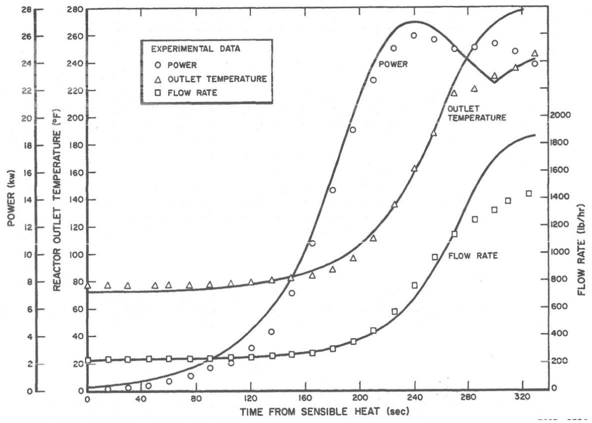
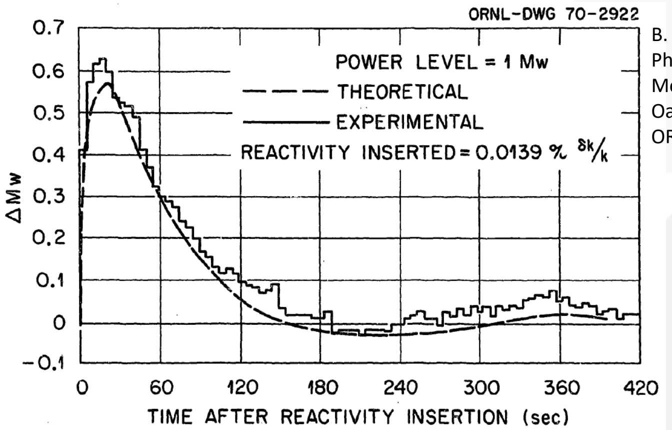


Fig. 3. Self-stabilization test (control rod raised by 30 × 10^{-5} $\Delta k/k$ at zero power).

R. Johnson, "SNAPTRAN 10A/2 Kinetics Testing and Destruct Reactor Experiments" Atomics International, NAA-SR-11906, (1966)



SNAP10A FS-3 Startup Transients

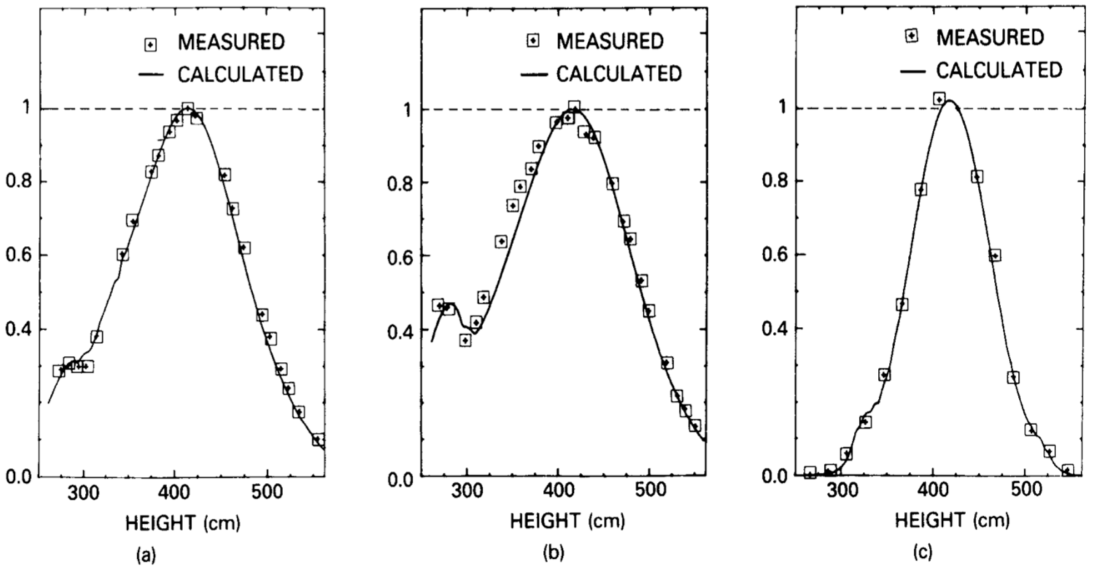


MSRE step reactivity insertion at 1 MWth.

B. Prince, et. al., "Zero-Power Physics Experiments on the Molten-Salt Reactor Experiment", Oak Ridge National Laboratory, ORNL-4233, (1968)

Flux (power) mapping

- Radial and axial flux (or power) distribution measurements assess the predictions of the hot-channel in the core physics calculations.
  - This was done using activation wires (or foils), by in-core flux detector traverses, or removing the fuel after irradiation for ex-core gamma scanning.



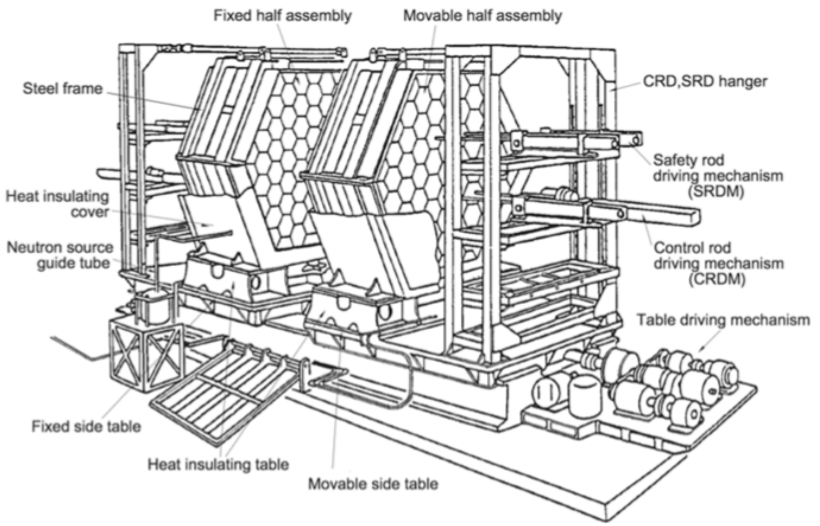
J. Cabrillat and M. Martini, "Power and Neutron Flux Distributions in the Core and Shielding", Nuclear Science and Engineering, vol. 106, pp 37-44, (1990)

Axial profiles in the radial shields of Superphénix: (a) fission of U-235 in row 18, (b) capture of gold in row 20, and (c) Ni(n,p) reaction in row 14 .

The role of zero power critical assemblies (ZPCA)

- SNAP10A, EBR-II, and HTTR benefited from extensive zero power critical assembly tests which were prototypic of the actual reactor.
- Though not actually part of reactor commissioning, ZPCAs sometimes provided direct predictions of the startup physics measurement.

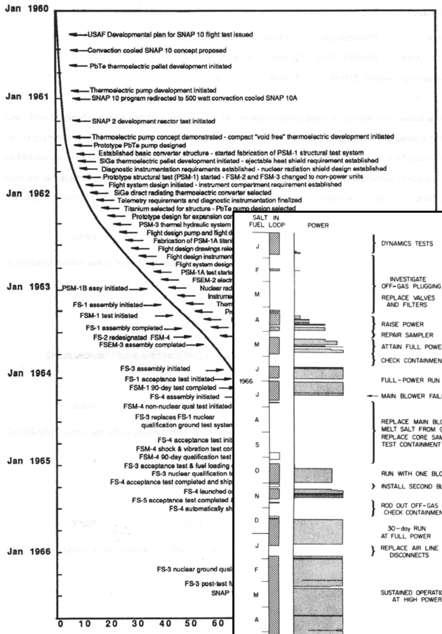
- ZPCAs have high accessibility.
    - Less occupational exposure hazards.
    - No expensive vessel penetrations.
    - Can directly attach electrical heaters.
    - Can use many more activation dosimeters.



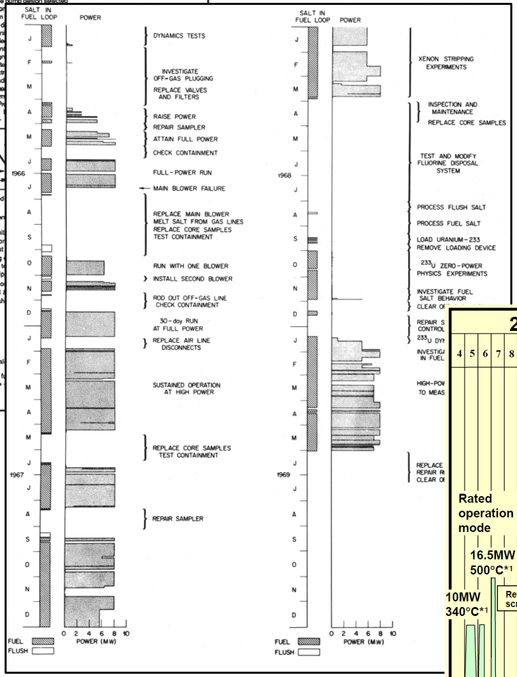
Very High Temperature Reactor Critical (VHTRC) supported HTTR

H. Yasuda, et. al., “Construction of VHTRC”, Japanese Atomic Energy Institute, JAERI-1305, (1987)

Questions?

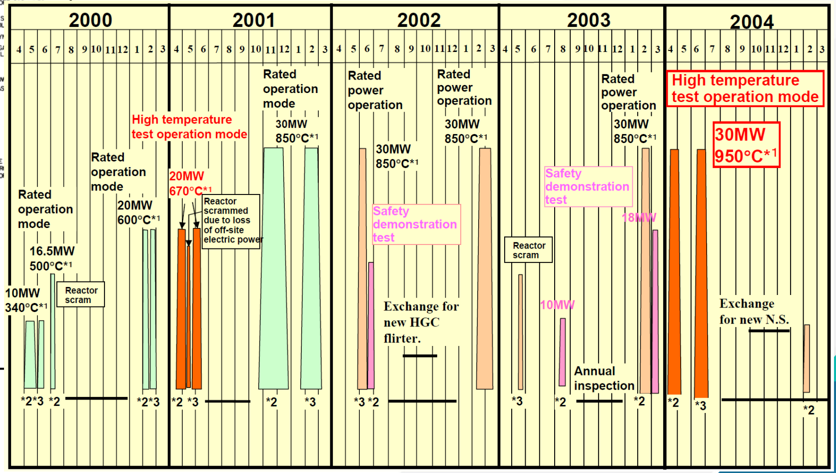


SNAP10A Test Program



MSRE Test Program

HTTR Test Program



National Reactor Innovation Center

Startup physics testing satisfies requirements set by regulations.

- 10 CFR 50.43(e)(1),
  - the applicant's license will be approved if performance of each safety feature of the design has been demonstrated through either analysis, appropriate **test** programs, experience, or a combination thereof
- 10 CFR 52.47(b)(1),
  - The proposed inspections, **tests**, analyses, and acceptance criteria that are necessary and sufficient to provide reasonable assurance that, … that incorporates the design certification has been constructed and will be operated in conformity with the design certification
- 10 CFR 830.3 [definitions: surveillance requirements],
  - requirements relating to **test**, calibration, or inspection to ensure that the necessary operability and quality of safety SSCs and their support systems required for safe operations are maintained …

Measurements common to all advanced reactors studied

- Inverse multiplication (1/M)
  - Typically going critical at the critical mass.

- Quantification of control rod (or drum) reactivities.
- Reactor power [and distribution] using in-core / ex-core detectors.
- Temperature and power coefficients of reactivity.
- Power and temperature response to changes in coolant flow.

ANS-19.13. Initial Startup of Advanced Reactors – Working Group (ISARWG)

- Approximately 30 reactor physics experts
  - National Labs: INL, LANL, NNL
  - Industry: GEH, BWXT, X-Energy, UltraSafe, KairosPower, TerraPower, Radiant, eVinci, Flibe Energy, J. Foster Assoc.
  - Universities: NC-State, UC-Berkley, Colorado Mines, Purdue
  - Multiple retired or semi-retired: EBR-II, FFTF, HTTR, SNAP, etc.
  - NRC representative, INL Nuclear Safety Rep.

ANS-19.13 Test Prioritization

- Parameters required to demonstrate safety *shall* be measured. **These are needed to verify the safety analysis…. Shall measure.**

- Parameters required to quantify margin *should* be measured. **These typically are identified from biases in software validation test cases, i.e., SQA.**

- Parameters used for code benchmarking or Nth-of-a-kind characterizations *may* be measured.

NRIC National Reactor Innovation Center

7/9/2024

www.nric.inl.gov