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Startup Physics Testing of Advanced Reactors

A Survey of Historical Practices

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Scope

- Define startup physics testing

- Critical assemblies and startup physics testing

- A new critical assembly capability: SPARC

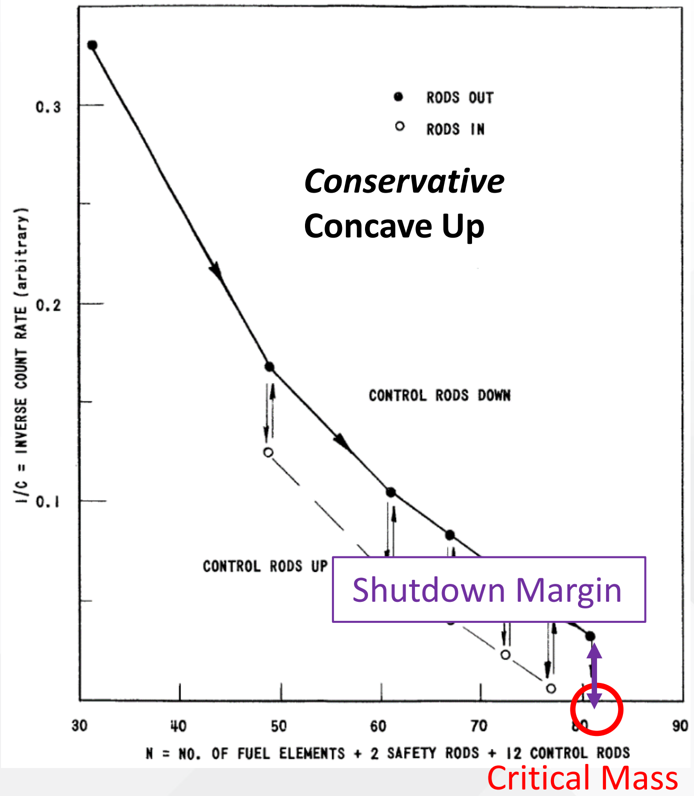
What is startup physics testing?

- Startup physics testing is a set of measurements made prior to normal operation of all reactors… 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.
  - **Final check against all hardware and software quality programs.**
- 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.

Measurements common to all advanced reactors studied

- Inverse multiplication (1/M)
  - Verifying the "dry" critical mass.
  - **Verify shutdown margin prior to critical of fully-loaded core.**
- Quantification of control element 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.

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



EBR-II inserted fuel sub-assemblies. "Rods Up" is the most reactive state.

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

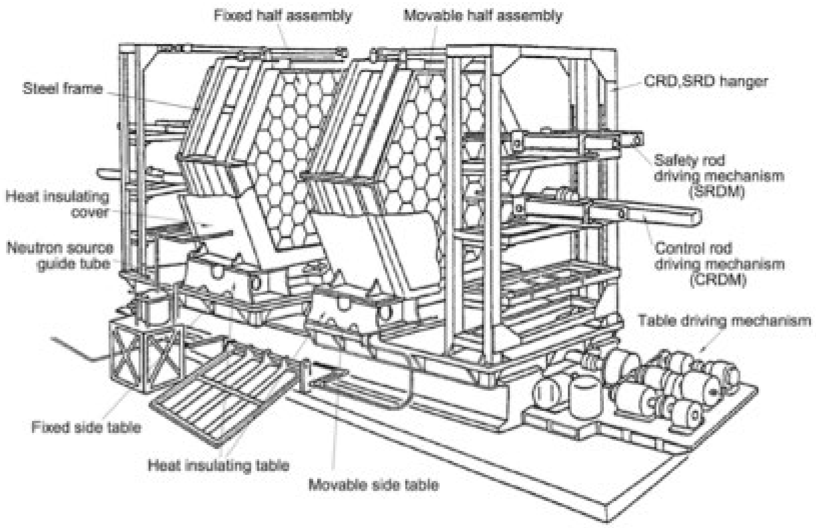
What are critical assemblies?

- Used to measure parameters important to the safety and performance of the actual reactor.
  - Reactivity of important components (fuel, reflector) & configurations (immersion, flooding, compactions).
  - Temperature effects (i.e., electrically heated)
  - Kinetics parameters.
  - Power/flux distribution and neutron.
  - Ex-core detector calibration/characterization.
- Validate (or correct) computational models.
  - **Informs the acceptance bands for startup measurements.**

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 can provide 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)

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SNAP8-Experimental Reactor (S8ER)

- September 17, 1962 - S8ER Critical Assembly [NAA-SR-9642]
  - **1/M method used to find minimum critical mass**
  - Found reactivity worth of SmO/GdO poison splines

- SNAP Critical Assemblies (SCA-4B)

  [NAA-SR-9871]
  - **Max Hypothetical Accident**: Water reflected, and water flooded core
  - 1/M method: minimum critical mass, bare core, poison splines, transport collar, etc.
  - Pulsed neutron method - large uncertainties due to sub-criticality of "dry core configuration"
  - **Fully loaded (211 fuel rods) - just critical at 75 poison rods**

S8ER Critical Assembly

D. Crouter, "SNAP 8 Experimental Reactor Critical Assembly", Atomics International, NA-SR-9642, (1964)

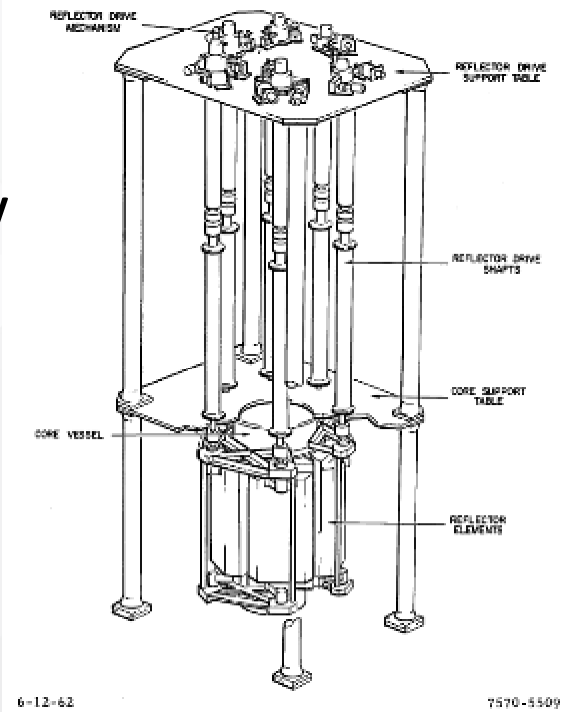
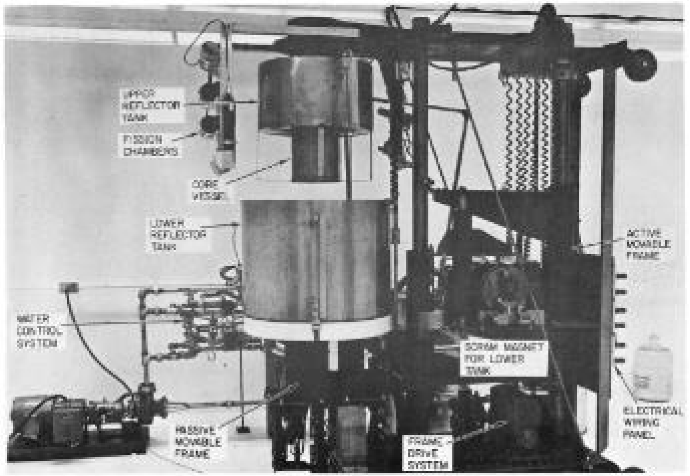


Figure 2. Critical Machine

S8ER (Cont.)

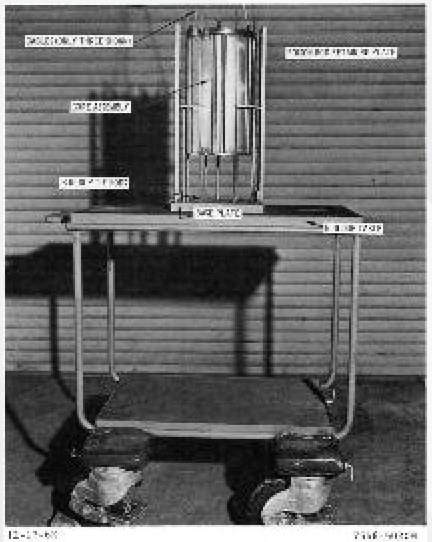
- Unitized Core Package [NAA-SR-8692]
  - 150 poison rods & 211 fuel rods loaded simultaneously
  - 1/M confirm subcriticality during loading
  - Confirmed dry subcriticality: with “poison splines” without control elements
- May 19, 1963 – S8ER First Dry Critical [NAA-SR-9862]
  - Two control elements to their most reactive position
  - Several dry subcriticality measurements to confirm shutdown with poison rods
  - **1/M used as poison rods removed**



SCA-3B Critical Assembly

S. Yee, “SNAP Critical Assembly – 4B Phase III Water Immersion Experiments”, Atomics International, NAA-SR-9871, (1964)

S8ER Unitized Core Package



C. E. Johnson, “SNAP 8 Quarterly Progress Report, April – June 1963”, Atomics International, NAA-SR-86902, (1963)

Testing Needs

- Large-scale critical experiments are crucially needed.
  - Enhance criticality safety with new intermediate neutron energy benchmark experiments
  - Support LEU+ fuel current fleet & HALEU advanced reactors

- DOE's DNCSH and NCSP programs solidified need for a configurable split table type "zero-power reactor".
- DNCSH supported INL in assessed candidate locations to develop a plan for deployment.
  - PBF-613 (former SPERT-IV reactor building) identified

- System Physics Advanced Reactor Critical facility (SPARC)
  - Will commission facility in 2028 with a basic experiment (~5% enriched UO_2 in polyethylene blocks)
  - **Seeking input and collaborative opportunities for reactor physics experiments that will immediately follow***

Historic ZPPR split table (now gone)

*contact Nicolas.Woolstenhulme@inl.gov

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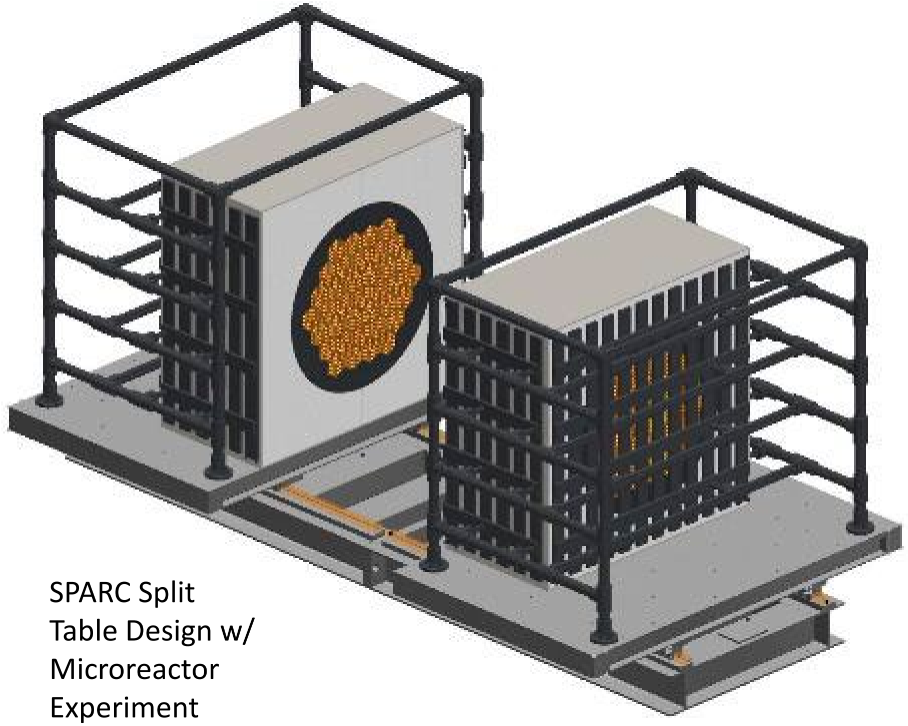
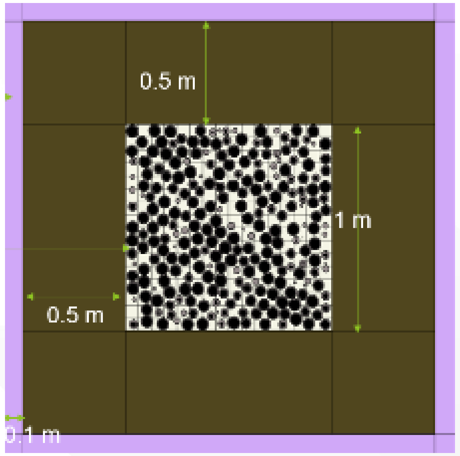
SPARC Capability

- Designing table for a ~2m cube core (when assembled) and 24,000 kg weight capacity
  - Size adequate for large graphite moderated/reflected tests
  - Weight adequate for fast and epithermal tests
  - Enables elevated temperature tests
  - Large enough to study spatial/spectra effects in moderator and control element schemes

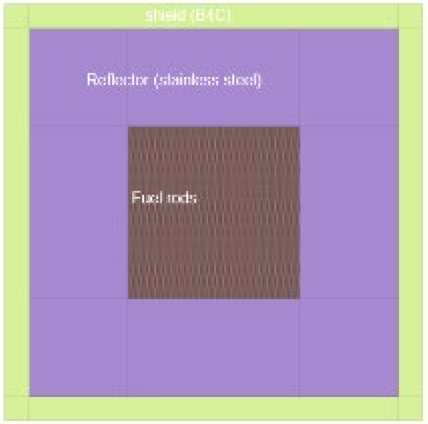


SPARC Split Table Design w/ Microreactor Experiment

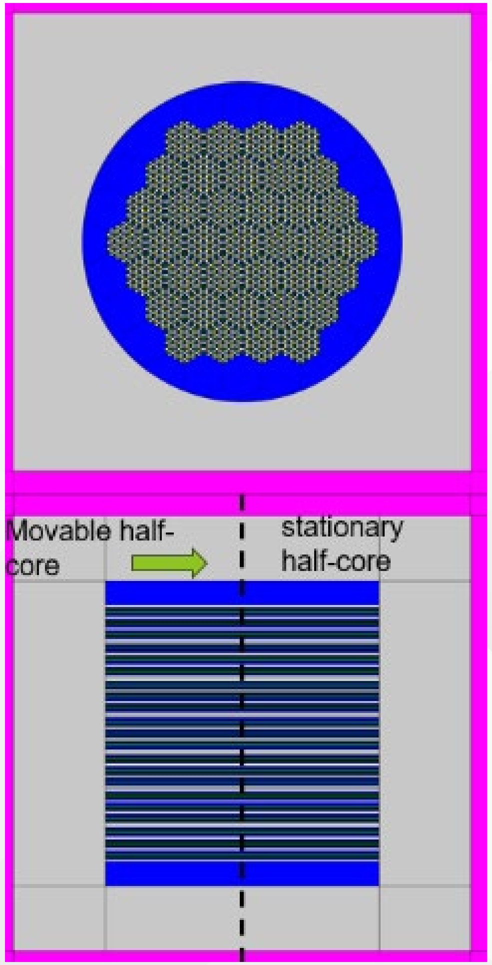
SPARC Closing the Gap



TRISO Pebble Bed



Metallic Fuel Fast Spectrum

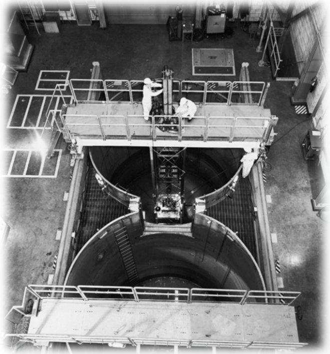


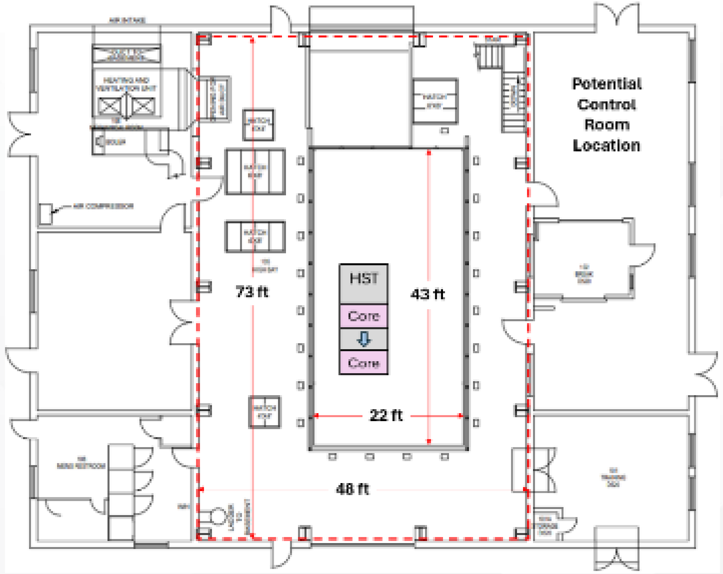
Metal Hydride Heat Pipe Microreactor

Neutronic models to help determine size, weight capability, and facility shielding requirements for various SPARC configs

SPARC Facility

PBF-613 once housed the legendary SPERT-IV tests!

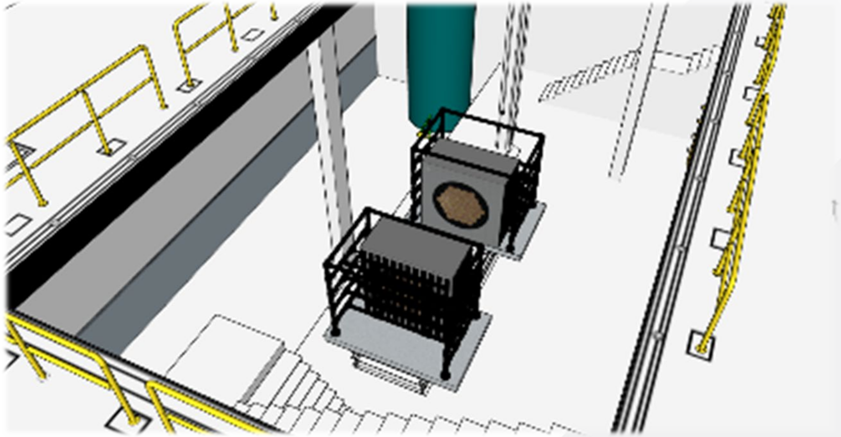




SPARC in PBF-613 (SPERT-IV Building)

- Large basement (46’ wide X 22’ tall X 73’ long) low neutron room return
- 12 ton over head crane and sturdy concrete slab basement floor
- Side wings for reactor control room, office space
- Lower level/sump area mitigates risk of criticality through flooding

Control Console



Split Table View from Main Floor

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Applicable Standards to both Critical Assemblies and Startup Testing

- ANSI/ANS-1-2000 [Conduct of Critical Experiments]
  - *"Manual operations that result in reactivity additions to a critical assembly should be limited to a predicted keff of 0.90 for unknown configurations."*
  - *"Additions of reactivity to a critical assembly beyond those permitted by [above] shall be made by remote operation."*
- ANSI/ANS-8.1-2014 [Nuclear Criticality Safety in Operations with Fissionable Materials Outside Reactors]
  - *"Validation shall be performed by comparison to critical and exponential experiments, and the area of applicability for the validation should be established from this comparison."*
- ANSI/ANS-8.10-2015 [Nuclear Criticality Safety Controls in Operations with Shielding and Confinement]
  - *"The shielding and confinement system of a facility shall be designed to limit the dose resulting from exposure to direct radiation and to radionuclides generated by the criticality accident and released…"*
- ANSI/ANS-19.13-2024 [Initial Fuel Loading and Startup Physics Tests for FOAK Advanced Reactors]
  - *"If the parameter being evaluated is an input to the safety analysis and its error could reduce the safety margin, the parameter shall be measured."*

S/U Hold Points (Before initial crit.)

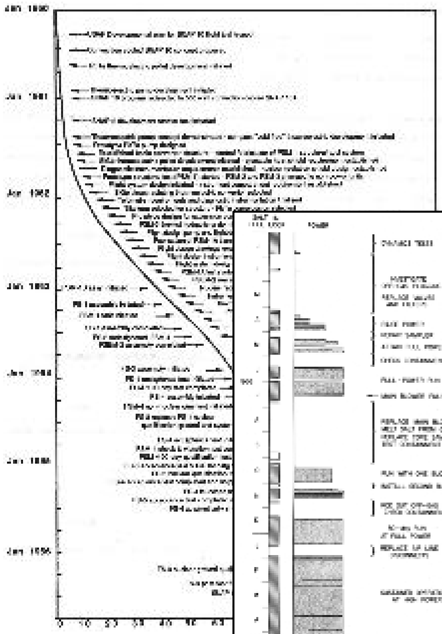
1. Hot Functional Tests – non-nuclear performance checks
   Rod drop times, no hot spots in biological shielding, no coolant leaks.
2. Fuel Loading and Inverse Multiplication Approach to Critical
   - Measure shutdown margin.

   We will not go critical before the safety rods are removed.

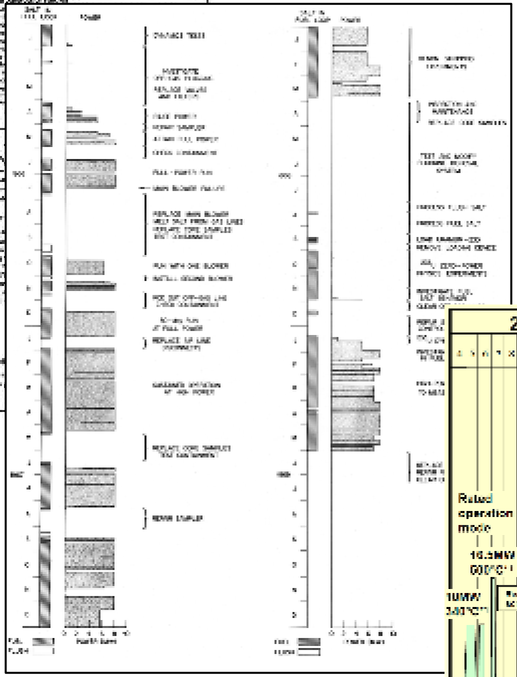
   - Alternative Loading Methods (like a factory) are subject to ANSI/ANS subcriticality standards like ANSI/ANS-1, 8.1, 8.10, etc.
   - **Future Standards Needs: How to validate predicted multiplication (i.e., after fuel loading) with measurement (i.e., with the startup detector) prior to approach to criticality. E.g., rod-drop method or pulsed neutron method, etc.**

- More hold points discussed in supplementary slides

Questions?

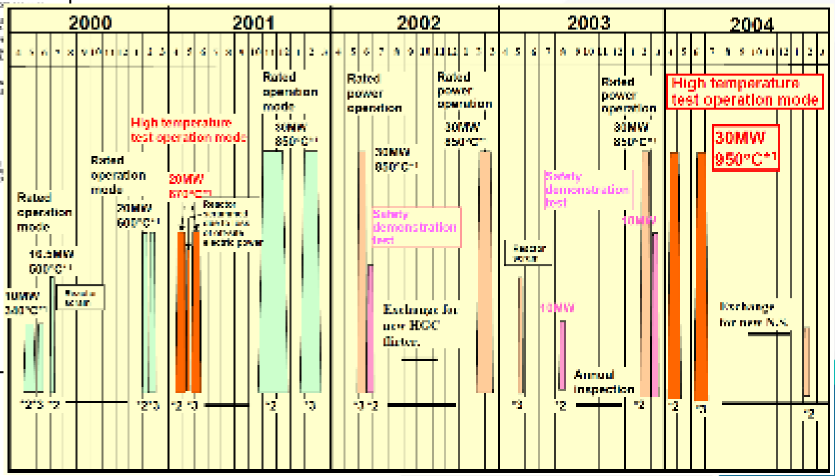


SNAP10A Test Program



MSRE Test Program

HTTR Test Program



S/U 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.

S/U 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.

S/U 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.

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 …

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.

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.

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