Providing Nuclear Criticality Safety Analysis Education through Benchmark Experiment Evaluation

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ICSBEP/IRPhEP

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Educating the Next Generation of Nuclear Criticality Safety Professionals

- **Challenge of a New Nuclear Criticality Safety Workforce:**
  - **Provide assessment of nuclear systems and establish safety guidelines without significant experience or hands-on training prior to graduation**

- **Benchmark Analysis Participation in the ICSBEP/IRPhEP:**
  - **ICSBEP – International Criticality Safety Benchmark Evaluation Project**
  - **IRPhEP – International Reactor Physics Experiment Evaluation Project**
  - **Provide students and young professionals with the opportunity to gain experience and enhance critical engineering skills.**

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Why Do We Have Nuclear Benchmarks?

- Criticality Safety
  - Plant Operations
  - Transportation
  - Waste Disposal
  - Experimentation
  - Accident Analysis
  - Standards Development
- Materials
  - Testing
  - Physics Validation
  - Interrogation
- Research and Development
  - New Reactor Designs
  - Design Validation
- Computational Methods
  - Cross-Section Data
  - Code Verification
    - Fundamental Physics
  - Model Validation

How Does Benchmark Design Apply to You?

International Criticality Safety Benchmark Evaluation Project (ICSBEP)

- Purpose:
  - Identify and verify comprehensive sets of critical benchmark data by reviewing documentation and talking with experimenters
  - Evaluate the data and quantify the overall uncertainty via sensitivity analyses
  - Compile the data into a standardized format
  - Perform calculations of each experiment with standard criticality safety codes
  - Formally document work into a single source
- http://icsbep.inel.gov

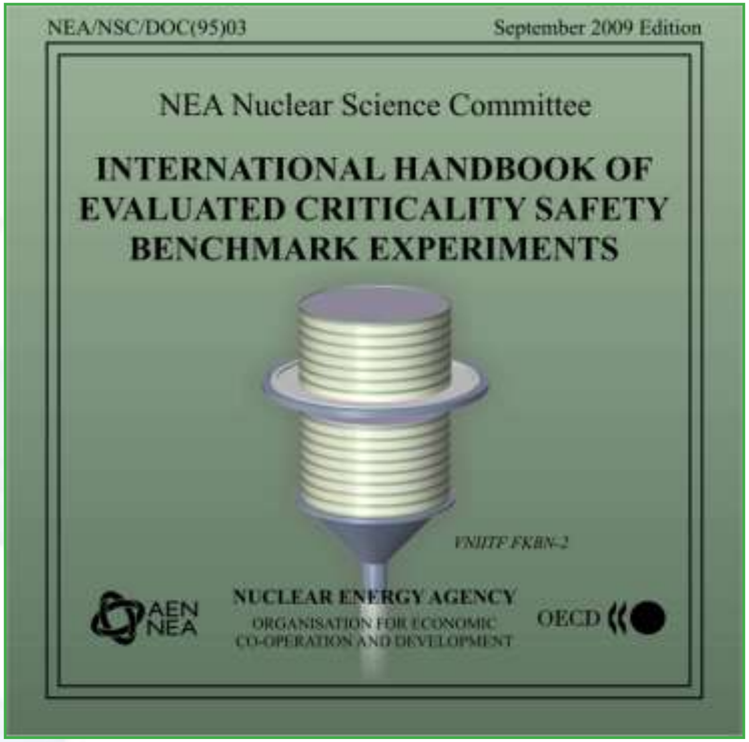
International Handbook of Evaluated Criticality Safety Benchmark Experiments (ICSBEP)

The ICSBEP was initiated in Oct. 1992 by DOE and the former INL to systematically evaluate and archive data required for validation of Criticality Safety Analyses.

The Program is operated under OECD NEA sanction, managed by the INL, with US participation and leadership sponsored by DOE NNSA's Nuclear Criticality Safety Program.

September 2009 Edition

- 20 Contributing Countries
- Spans over 51,000 Pages
- 4,283 Critical or Subcritical Configurations
- Four Criticality-Alarm/ Shielding Benchmarks – 24 Configurations – numerous dose points
- Five Fundamental Physics Benchmarks – 155 fission rate and transmission measurements and reaction rate ratios for 45 different key materials



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International Reactor Physics Experiment Evaluation Project (IRPhEP)

- Similar to the ICSBEP
- Focus to collect data regarding the numerous experiments in support of nuclear energy and technology performed at research laboratories
- Experiments represent significant investments of time, infrastructure, expertise, and cost that might not have received adequate documentation
- Measurements also include data regarding reactivity measurements, reaction rates, buckling, burnup, etc., that are of significant worth for current and future research and development efforts
- http://irphep.inl.gov/

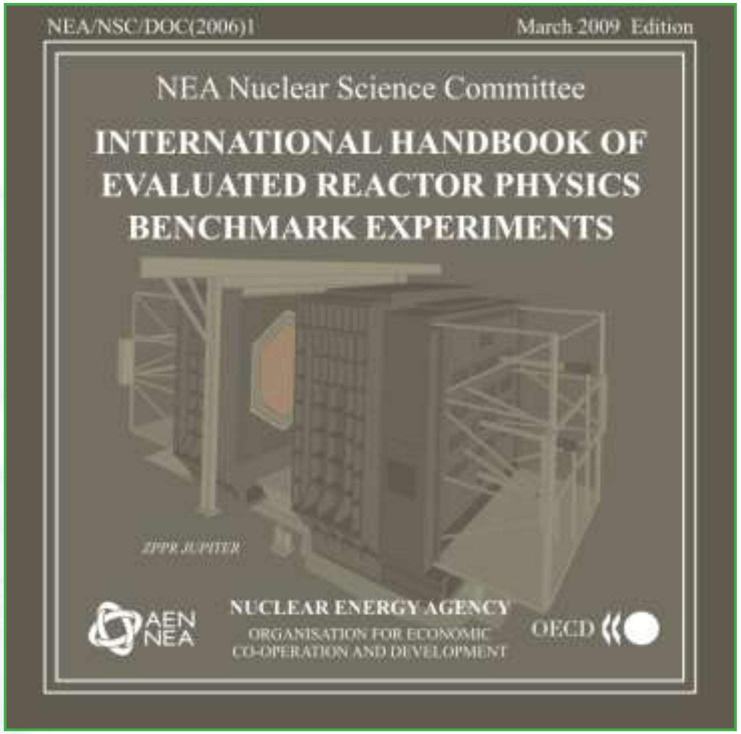
International Handbook of Evaluated Reactor Physics Benchmark Experiments (IRPhEP)

The IRPhEP is a more recent effort that synergistically complements the ICSBEP to achieve the same goal for in-core reactor physics integral experiments.

The INL manages the technical review and publication aspects of this program for the OECD NEA as well.

March 2009 Edition

- 15 Contributing Countries
- Data from 36 Experimental Series performed at 21 Reactor Facilities



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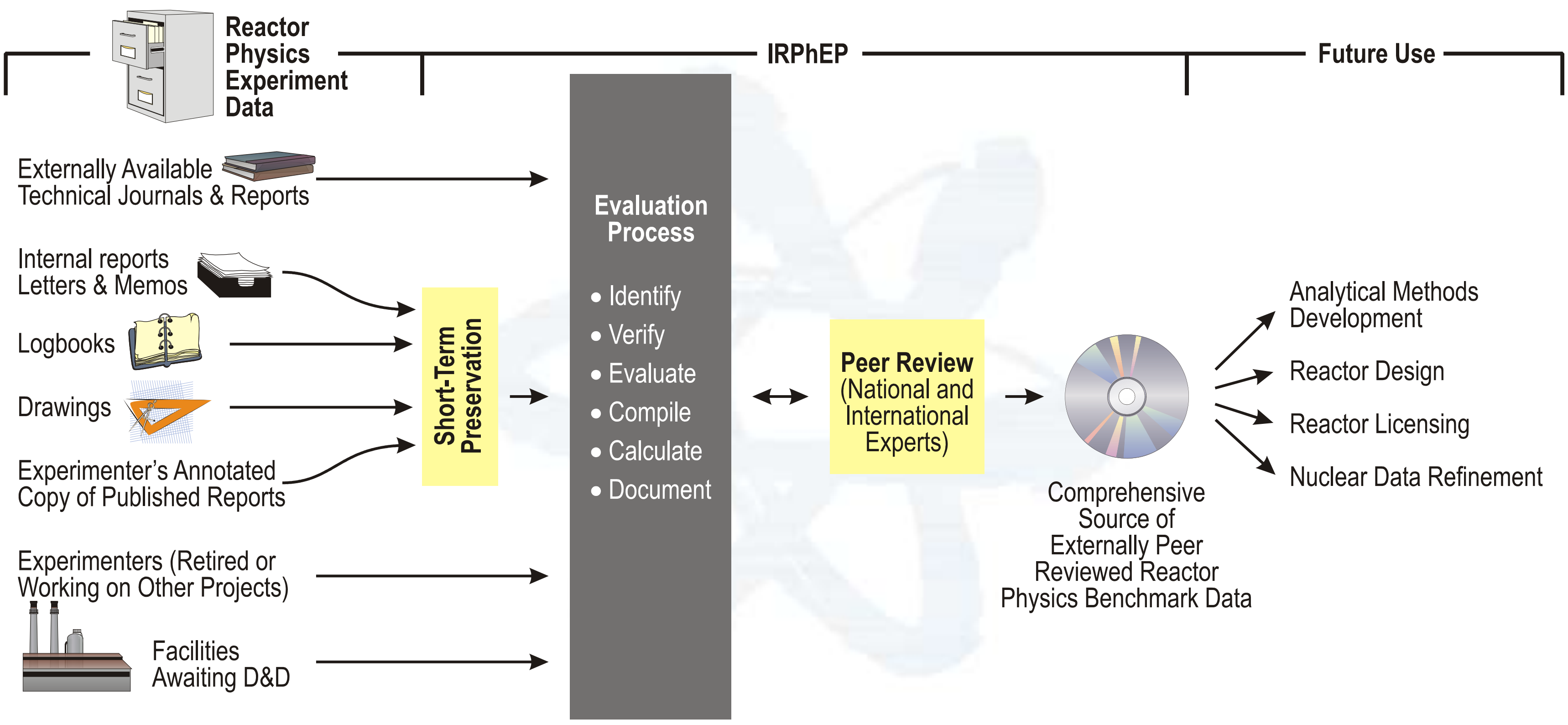
Additional Benchmark Material

- The IRPhEP benchmark report follows the same general guidelines as for the ICSBEP Handbook, but includes additional material:
  - Critical/Subcritical
  - Buckling/Extrapolation Length
  - Spectral Characteristics
  - Reactivity Effects
  - Reactivity Coefficient Data
  - Kinetics Measurements Data
  - Reaction-Rate Distributions
  - Power Distribution Data
  - Isotopic Measurements
  - Miscellaneous

Summary of Benchmarking Process



Student Investigation Breeds Comprehension

- Benchmark procedures require investigation into
  - History and background
    - Purpose of experiment?
  - Experimental design and methods
  - Analytical capabilities and procedures
  - Experimental results
- Often experiments were performed with the intent to provide data for criticality safety assessments
  - Many are utilized to develop criticality safety standards

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Culturing Good Engineering Judgment

- Often experimental information is incomplete or misleading
  – Contact original experimenters (if available)
  – Interact with professionals from the ICSBEP/IRPhEP community
  – Establish a personal network for the young professional engineer

"Do, or do not.
There is no 'try'"
- Jedi Master Yoda

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Developing an Analytical Skill and Tool Set

- **Evaluators develop analytical and computational capabilities throughout the evaluation process**
  - **Utility of conventional computational codes and neutron cross section data libraries**
    - **Monte Carlo or Diffusion methods**
    - **MCNP and KENO are the most common in the US**
  - **Application of perturbation theory and statistical analyses**
    - **Uncertainty evaluation**
    - **Bias assessment**
  - **Technical report writing**
  - **Understanding acceptability of results**

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Extensive International Review Process

- ICSBEP and IRPhEP benchmarks are subject to extensive review.
  - Evaluator(s) – primary assessment of the benchmark.
  - Internal Reviewer(s) – in-house verification of the analysis and adherence to procedure.
  - Independent Reviewer(s) – external (often foreign) verification of the analysis.
  - Technical Workgroup Meeting – annual international effort to review all benchmarks prior to inclusion in the handbook.
    - Sometimes a subgroup is assigned to assess any final workgroup comments and revisions prior to publication.
  - Benchmarks are determined to be acceptable or unacceptable for use depending on availability of data, which translates into uncertainty in results.
    - All approved benchmarks are retained in the handbook.

Opportunities for Involvement

- Each year the ICSBEP hosts one or two Summer Interns at the Idaho National Laboratory
- INL has also funded benchmark development via the CSNR Next Degree Program
- Students have participated in the projects as subcontractors through various universities and laboratories
- Benchmark development represents excellent work for collaborative Senior Design Projects, Master of Engineering Project, or Master of Science Thesis Topic
- Further information can be Obtained by contacting the ICSBEP Program Director
  - J. Blair Briggs, J.Briggs@inl.gov

Past and Present Student Involvement

- **Since 1995, approximately 30 students have participated in the ICSBEP and/or IRPhEP**
- **Students have authored or coauthored 51 ICSBEP or IRPhEP evaluations**
- **They have also submitted technical papers to various conferences and journals**

Some Benchmark Activities at the INL

- ICSBEP
  - Slabs of Enriched Uranium Oxyfluoride
  - Concrete-Reflected Enriched Uranium Metal Cylinders
  - Polyethylene-Reflected Array of HEU Separated by Vermiculite
  - Nickel-Reflected Plutonium Metal Sphere Subcritical Noise Measurements
  - HEU Cylinders Reflected by Beryllium
  - Critical Pin Arrangements with Fuel from the Fast Flux Test Facility in Water
- IRPhEP
  - High Temperature Engineering Test Reactor
  - Fast Flux Test Facility
  - Power Burst Facility
  - Nuclear Radiography Reactor

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Slabs of HEU-O_2F_2

- Critical experiments performed at the Oak Ridge Critical Experiments Facility in the mid-1950's
- Different slab thicknesses of uranium oxyfluoride solution were performed to determine a minimum thickness for an infinite slab

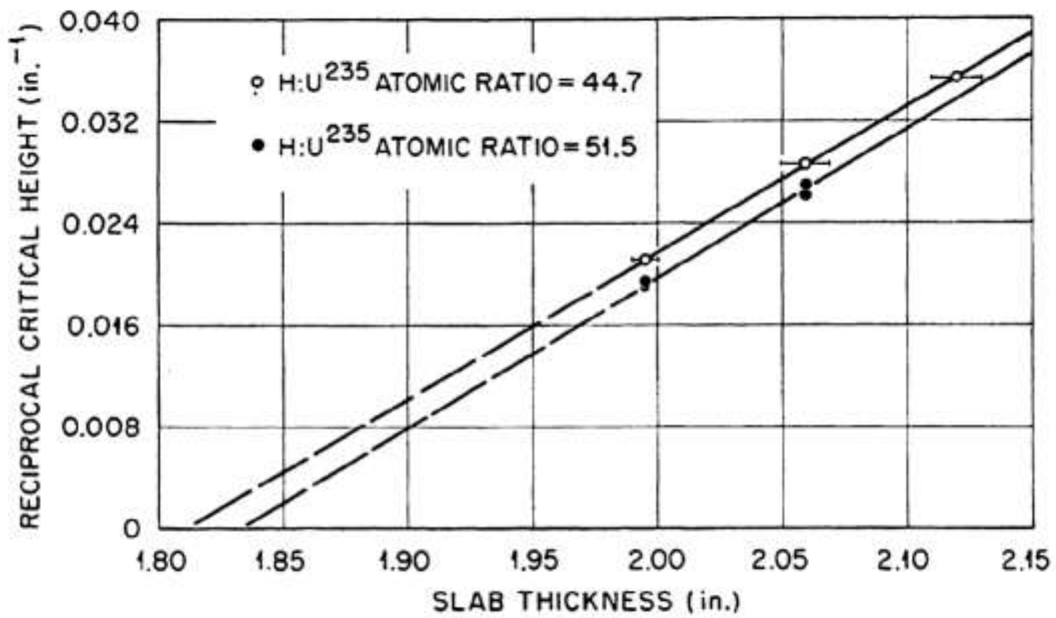
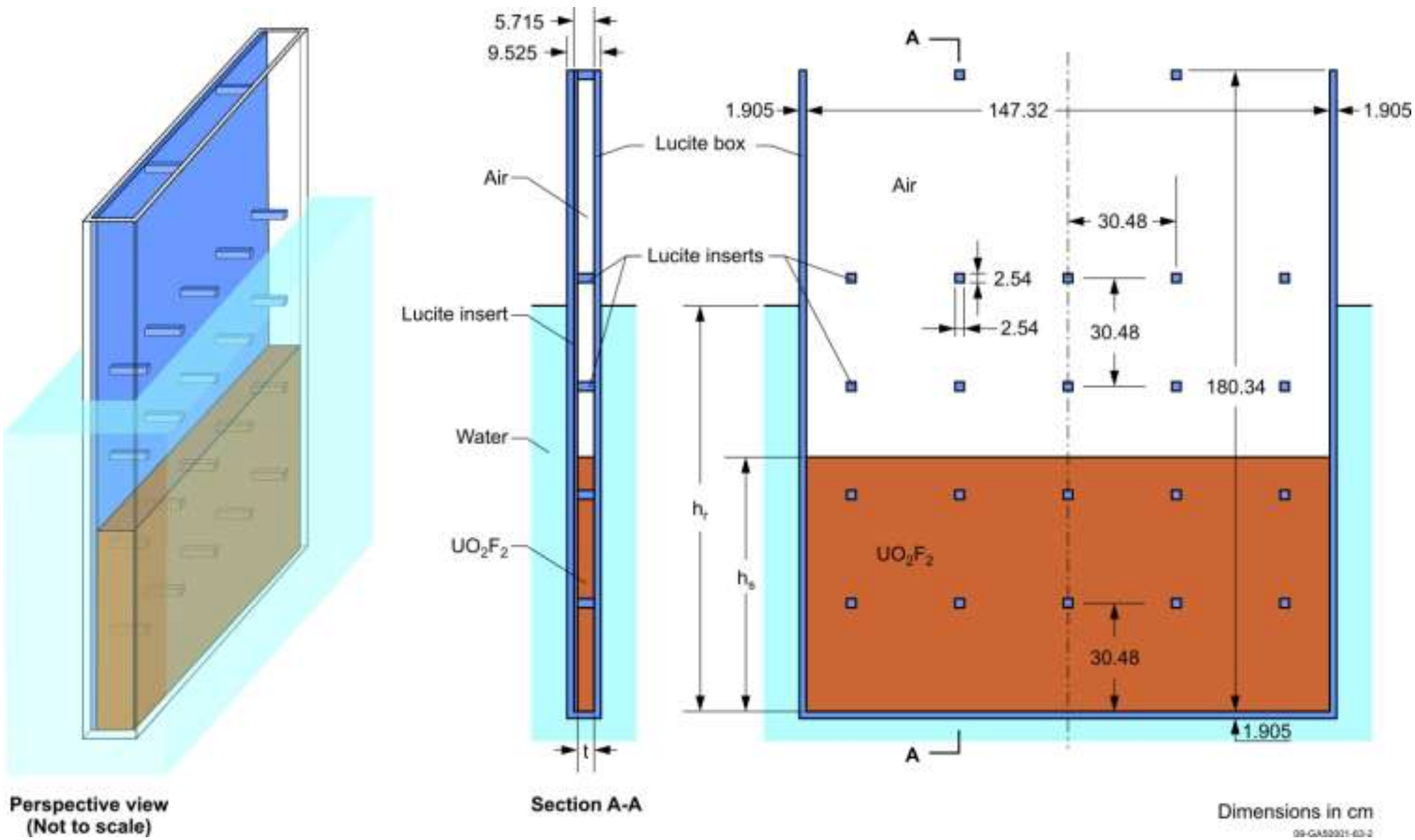


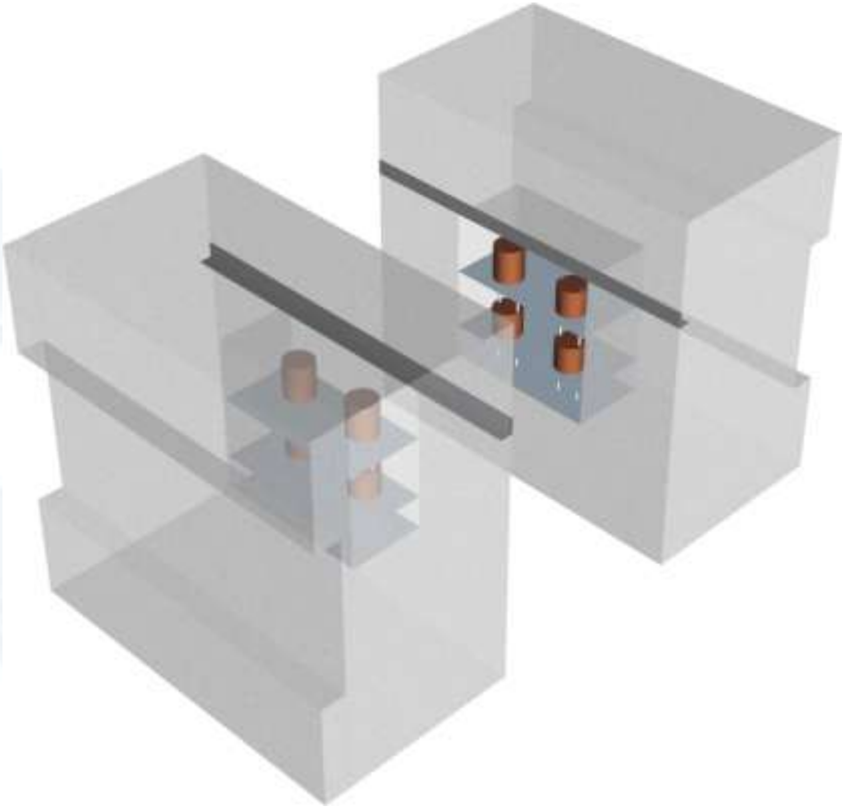
FIG. 1. Reciprocal critical height of a slab of enriched U^{235} solution as a function of the thickness of the slab.

Detailed Model for Slabs of HEU-O_2F_2



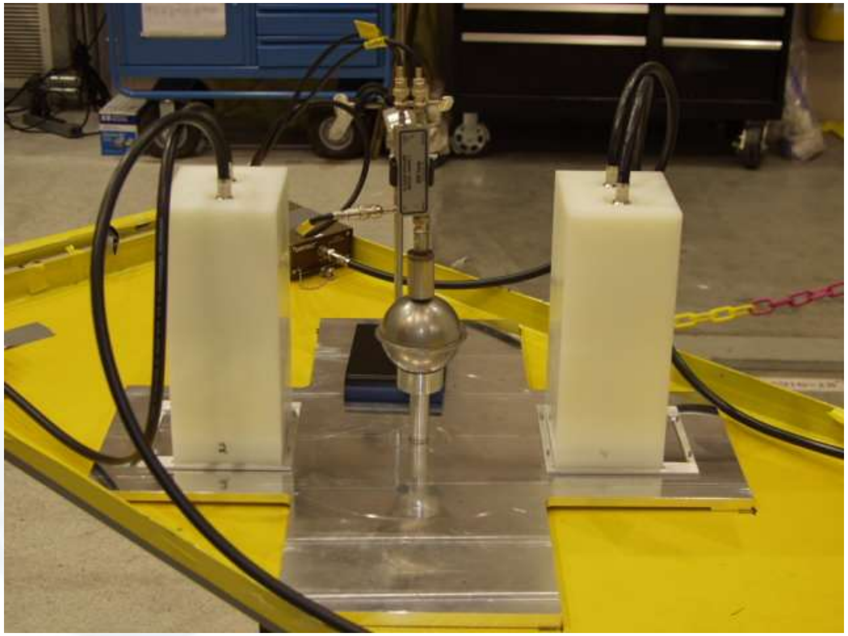
Concrete-Reflected HEU-Metal Cylinders

- Part of an extensive program at the Oak Ridge Critical Experiments Facility
  - Part IV in early 1970’s
  - Magnuson concrete
- In support of nuclear safety in transportation and storage of subcritical units of fissile material
  - Most storage vaults have concrete floors and walls



Subcritical Nickel-Reflected Plutonium Spheres

- **Modern experiments at the Device Assembly Facility in Nevada**
- **Uses Californium Source-Driven Noise Analysis (CSDNA) methods**
- **Currently modeled using MCNP and MCNP-DSP**
- **Part of a series of experiments: polyethylene, acrylic, tungsten, copper, lead, manganese**



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Fast Flux Test Facility (FFTF)

- 400 MWt, sodium-cooled, fast-neutron reactor
- Prototypic Liquid Metal Fast Breeder Reactor
- Extensive characterization
- Provided over 10 years of operation
  - Nuclear power plant operations and maintenance protocols
  - Advanced nuclear fuels
  - Materials and components
  - Reactor safety design
  - Radioisotope production

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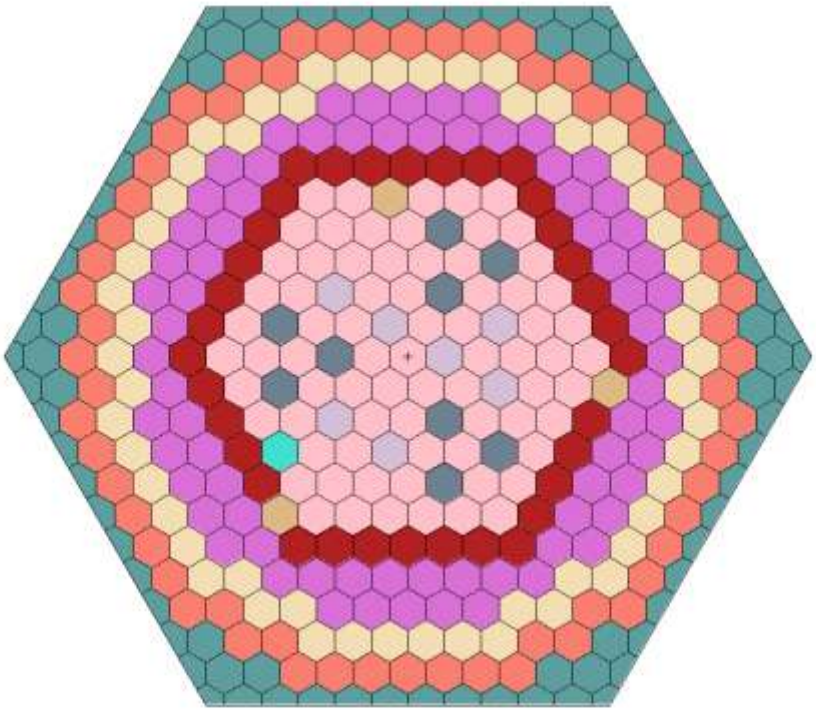
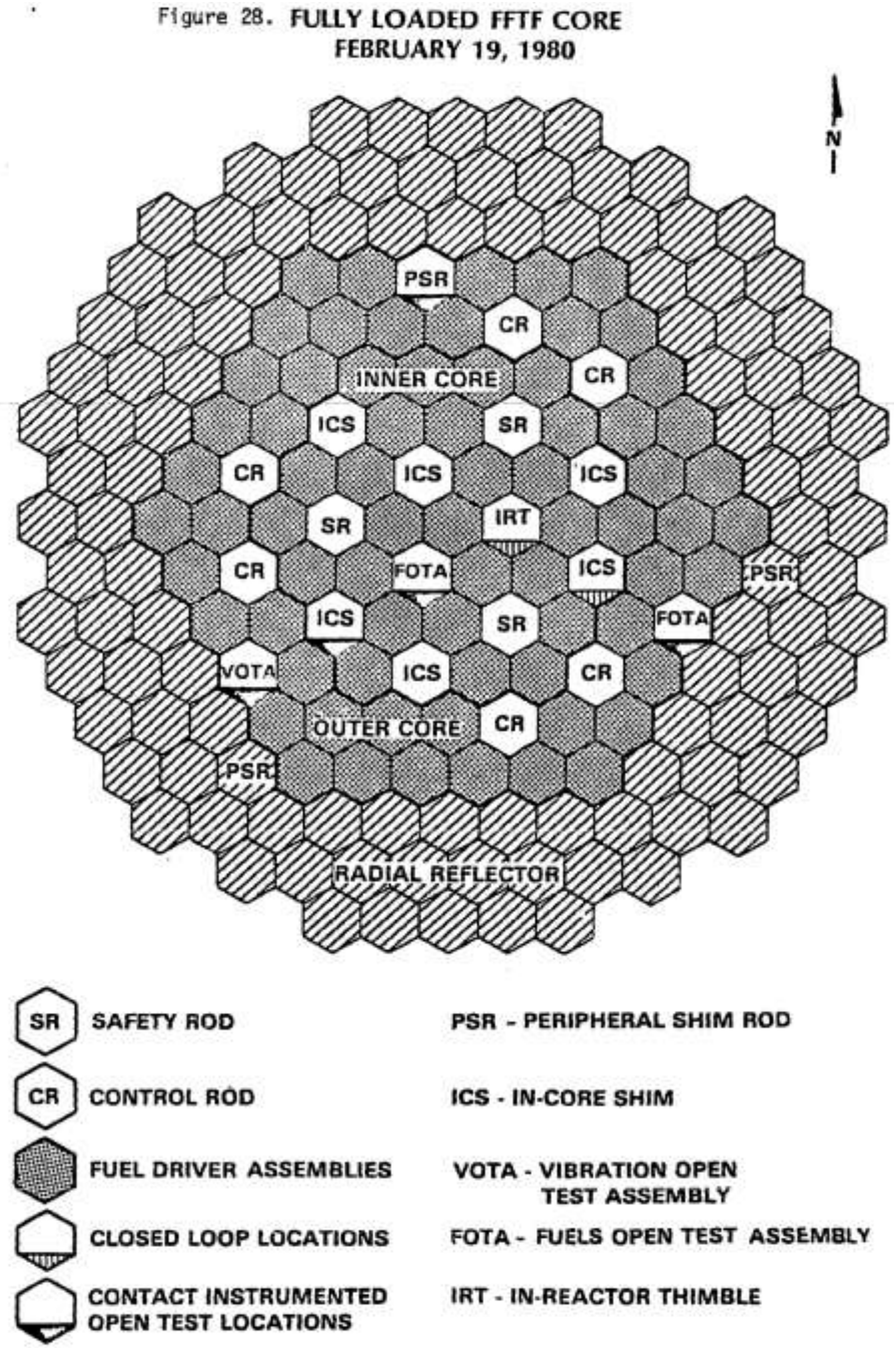
HEX-Z Homogenized FFTF Model in MCNP





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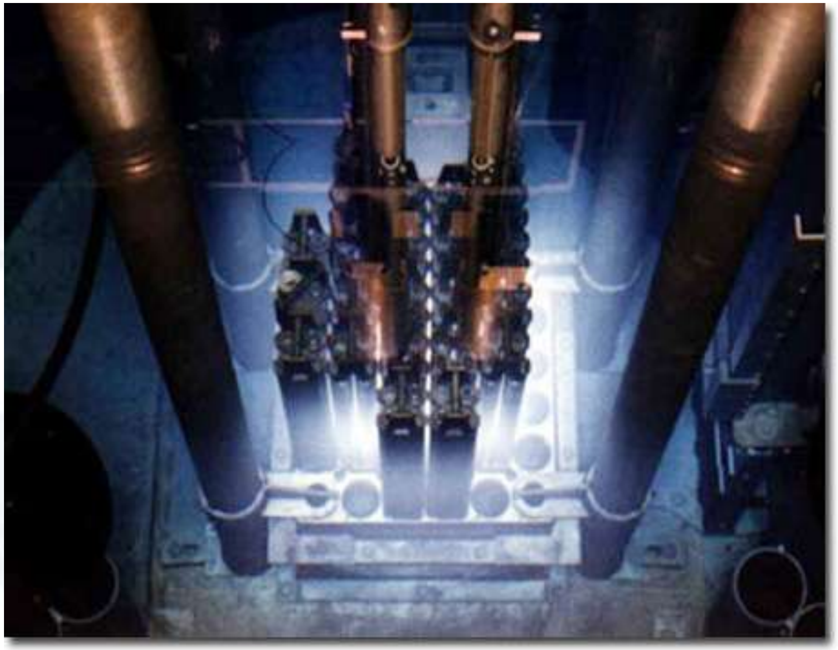
Nuclear Radiography (NRAD) Reactor

- The NRAD is being refueled with LEU (<20% U^{235})
- Neutron radiography allows for the non-destructive testing of objects
- Full-core benchmark is being developed
  - ICSBEP
  - Experiment planning
  - Future benchmarking activities



Conclusion

- **Benchmarks represent an important means for developing and assessing a collection of nuclear experimental data**
  - **Application to criticality safety**
  - **Validation of nuclear activities**
- **Participation in the benchmark evaluation process can be of significant benefit to young professionals and their ultimate location of employment**
- **There exist many ongoing benchmarking activities through the ICSBEP and IRPhEP**

Questions?


MEANWHILE AT THE CENTER FOR EXCELLENCE IN NUCLEAR TECHNOLOGY, ENGINEERING, AND RESEARCH:
THERE IT IS— SUBMERGED UNDER 20 FEET OF WATER — THE 100 KILO-WATT TRIGA REACTOR!
WOW - WHAT DO YOU USE IT FOR?
BOILING HOT DOGS, MOSTLY

Extra Slides

What is a Benchmark?

- **Merriam-Webster**
- ***"a point of reference from which measurements may be made"***
- ***"something that serves as a standard by which others are measured or judged"***
- ***"a standardized problem or test that serves as a basis for evaluation or comparison (as of computer system performance)"***

Criticality Safety Engineer Specialist

- **American Nuclear Society Nuclear Criticality Safety Division Education Committee Definition of a Criticality Safety Engineer**
  - **"***One who applies engineering principles to the understanding of the properties of fissile materials such that they are controlled in a practicable manner in systems and processes while protecting from the consequences of a criticality accident, preferably by prevention of the accident."*

The Benchmark Approach

- An ICSBEP Benchmark Report has Four Major Sections
  - 1.0 Detailed Description
    - Compilation of All Known Available Data Regarding the Experiment
    - Try to Provide a Clear Idea of the Experiment Purpose and Procedure
    - Note Any Inconsistencies in Available Data
    - Essentially this Section Acts as a Means of Preserving Pertinent Available Data for the Experiment

The Benchmark Approach

- An ICSBEP Benchmark Report has Four Major Sections
  - 2.0 Evaluation of Experimental Data
    - Uncertainty Assessment of Experiment Parameters
      - Experimental Measurements
        - Temperature, Position
      - Geometrical Properties
        - Shape, Amount
      - Compositional Variations
        - Density, Material Abundance
    - Use Best Engineering Judgment and Practices to Account for Unknown Experiment Parameters
    - An Overall Uncertainty is Quantified

The Benchmark Approach

- **An ICSBEP Benchmark Report has Four Major Sections**
  - **3.0 Benchmark Specifications**
    - **Provide Sufficient Information to Justify and Construct a Calculational Model that Best Represents the Experiment**
    - **Justify and Quantify Simplifications in the Model Compared to the Physical Experiment**
      - **Bias or Correction Factor**
    - **Provide Expected Eigenvalue for the Benchmark**
      - **Typically k_{eff} = 1.0000**
    - **Another User Should Be Able to Model the Benchmark Completely without Any Other Section!**

The Benchmark Approach

- An ICSBEP Benchmark Report has Four Major Sections
  - 4.0 Results of Sample Calculations
    - Summary of Calculated Results for Different Computer Codes and Cross-Section Data using the Benchmark Model(s)
  - Appendices
    - Any Additional Information Pertinent to the Benchmark
      - Input Decks for Computer Codes
      - Calculations
      - Photos or Scanned Documentation

Perturbation Analysis

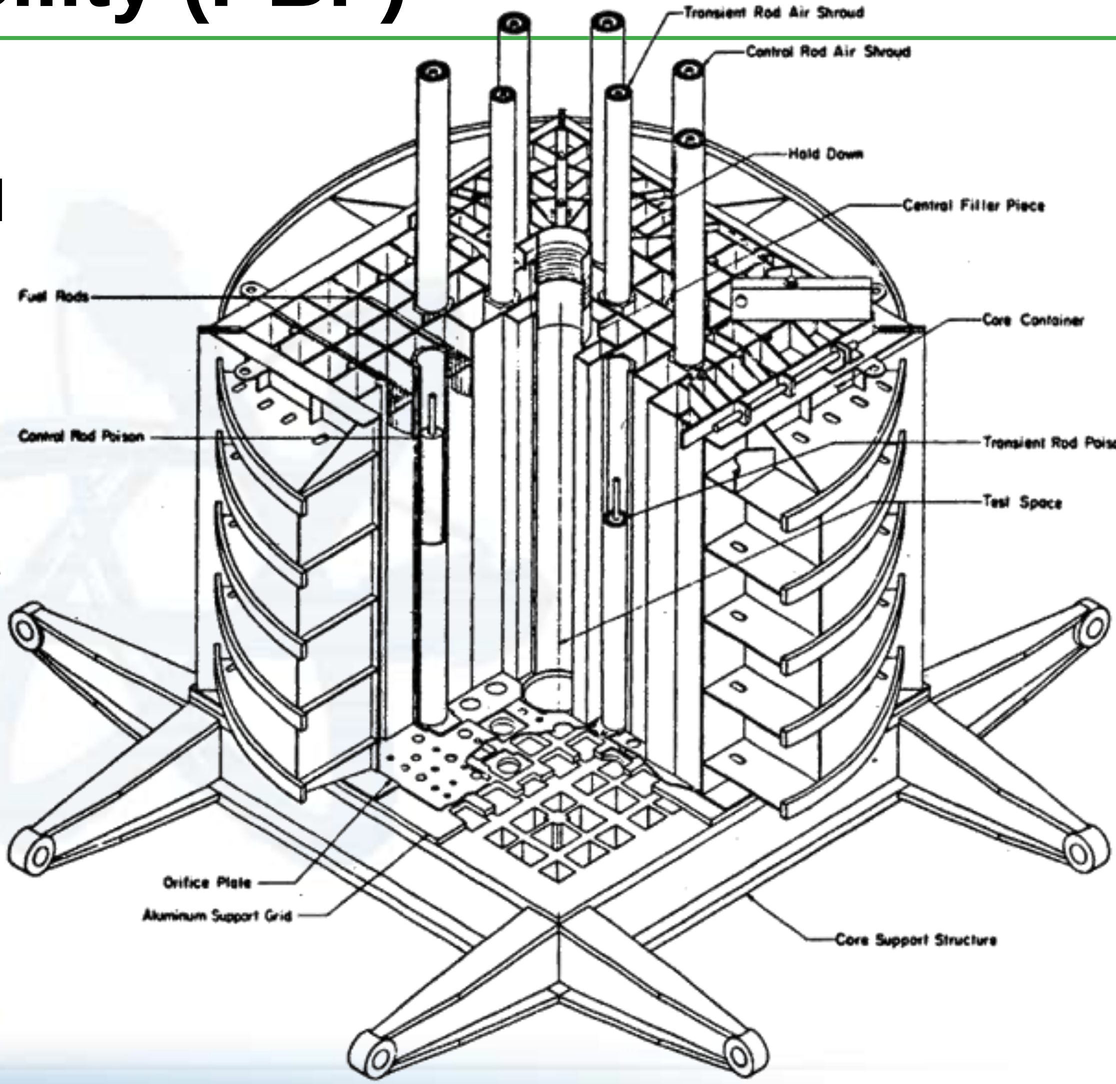
- Variation of parameters within published or assumed range of uncertainty
  - Manufacturing tolerances
  - Repeated measurements
  - Measurement limit
  - Bounding compositional requirements
- Sometimes the perturbation modeled is larger than the actual uncertainty, and is scaled back
  - Uncertainty is on the same order of magnitude as the statistical uncertainty in the computation

Bias Assessment

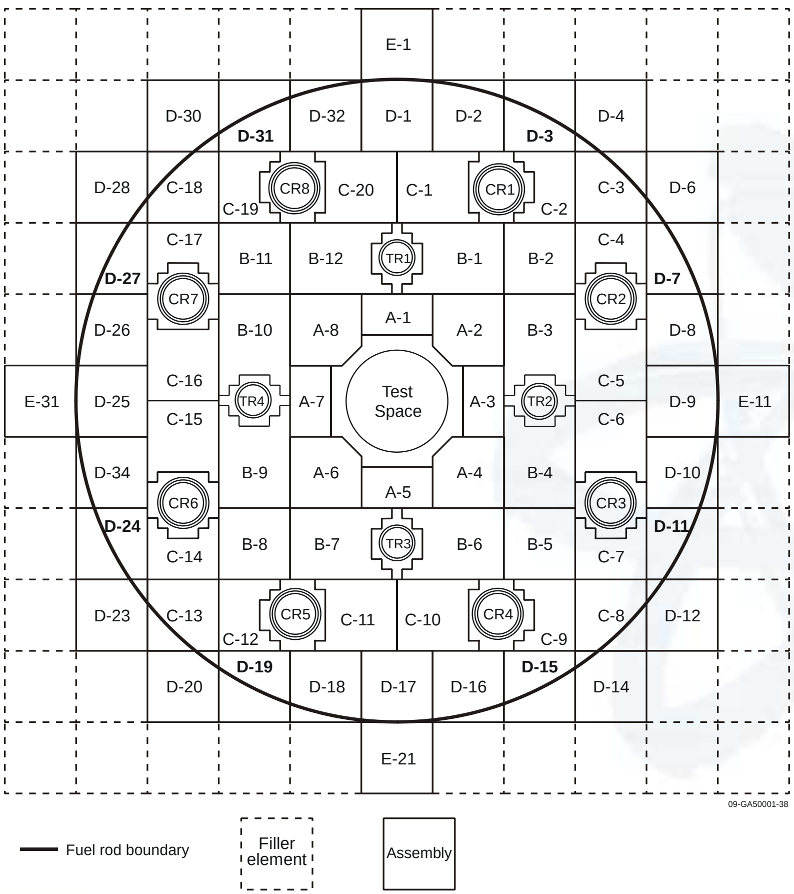
- The Effect of simplifying the model is assessed by comparison of the detailed model to the simple model
- Some simplifications are anti-correlated
  - Their effects must be modeled individually and as a whole to understand the complete result
- Sometimes the bias is smaller than the statistical uncertainty
  - The bias is assumed negligible
  - The uncertainty is included in the overall uncertainty of the benchmark model

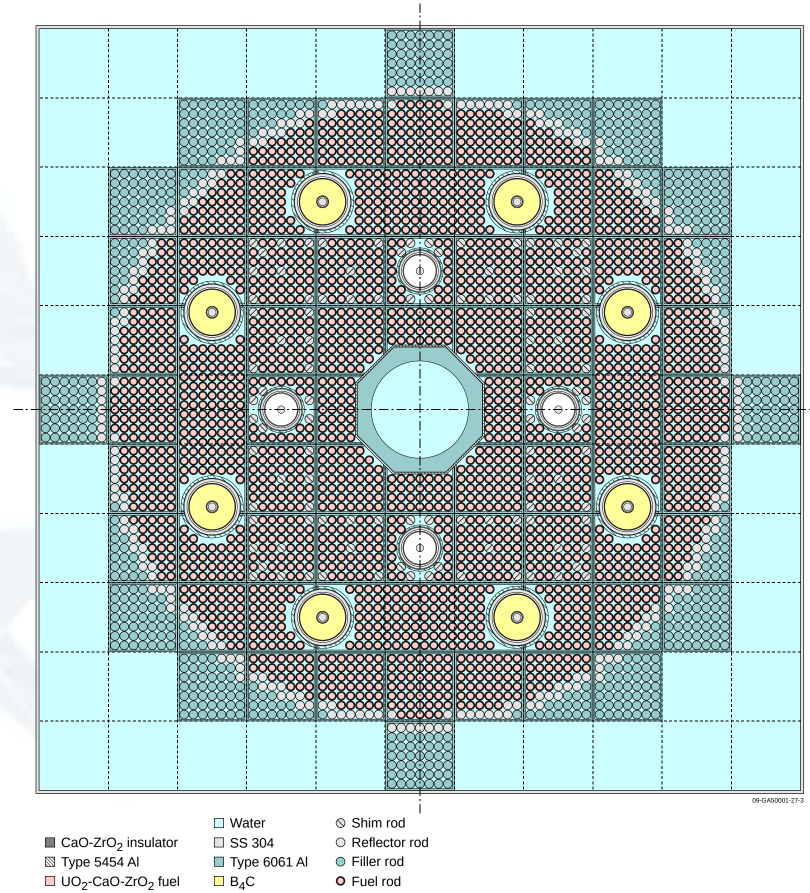
Power Burst Facility (PBF)

- 1972-1985 at the INL
- Provide Experimental Data for Postulated Accident Failure Conditions
- Unique "Inert-Matrix" Fuel
  - $U(18)O_2$-CaO-ZrO_2 Ternary Ceramic
  - Of Interest for the Generation-IV Reactor Program

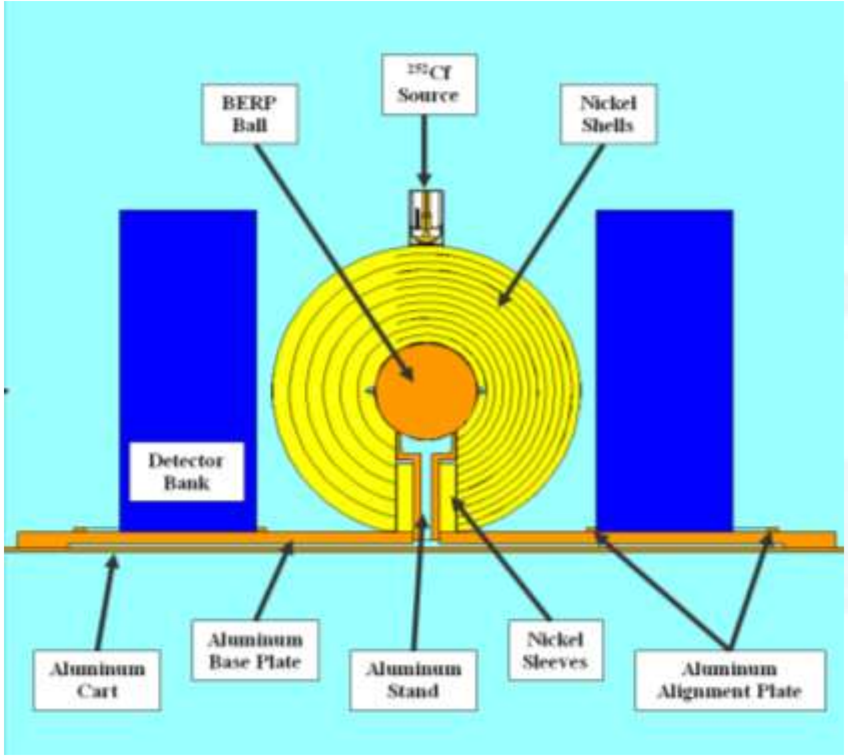


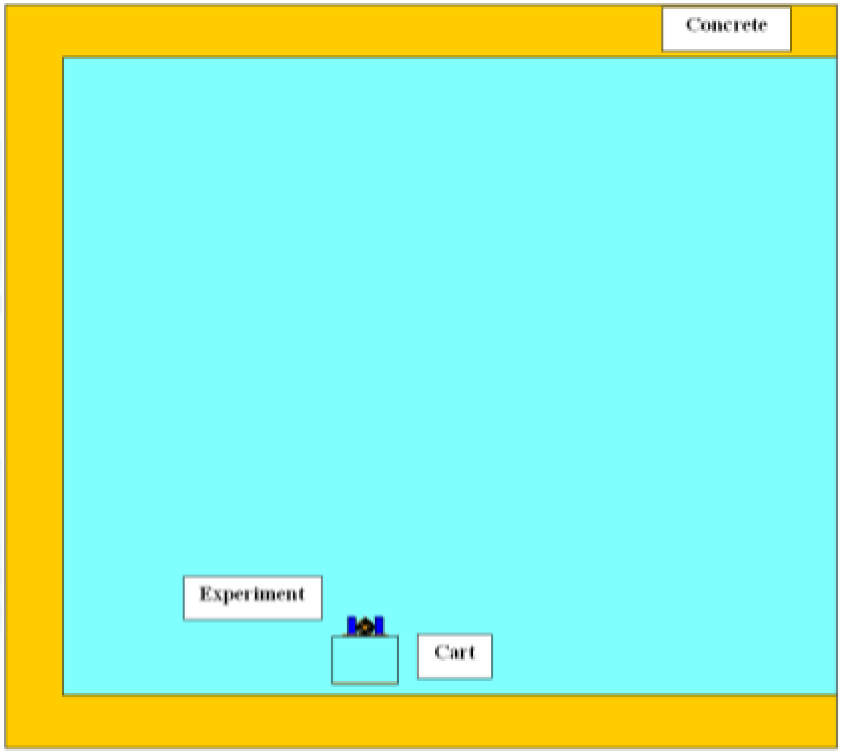
Power Burst Facility (PBF)





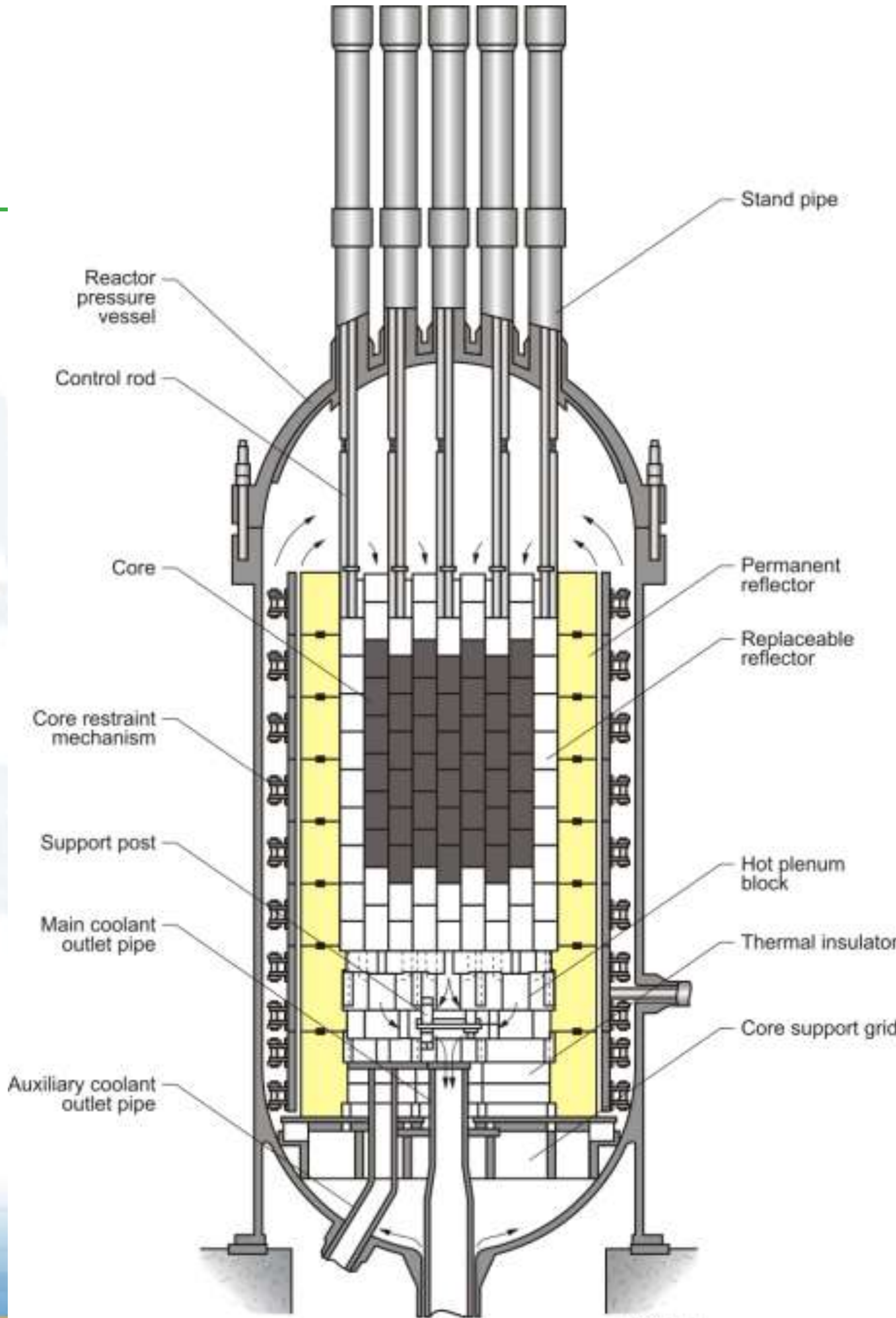
Subcritical Nickel-Reflected Plutonium Spheres – MCNP Visual Editor



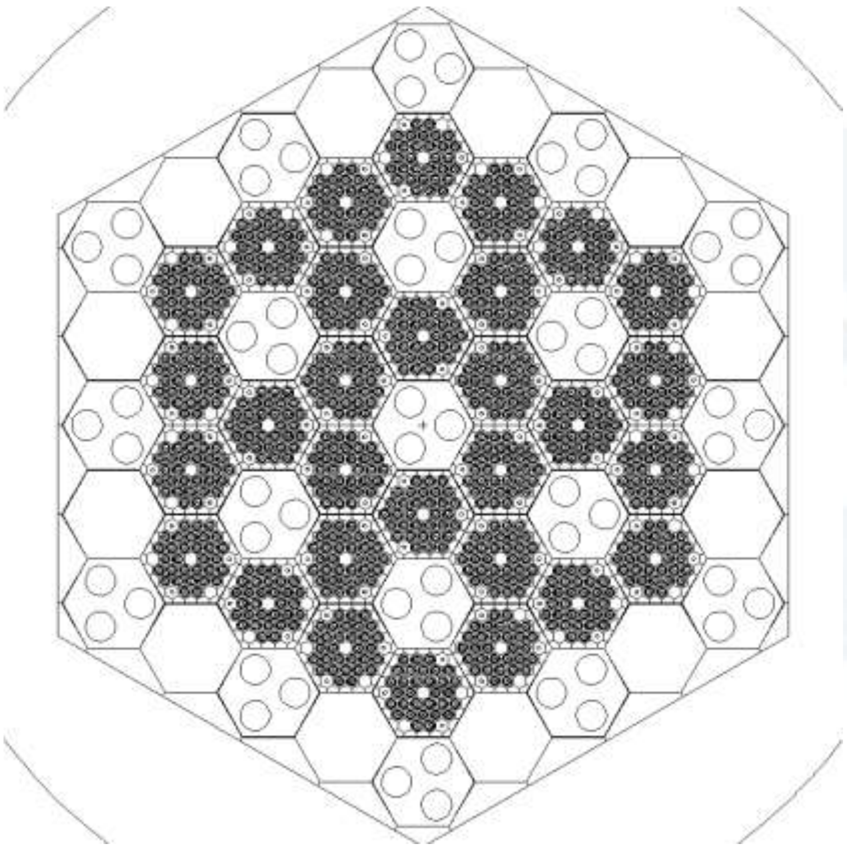


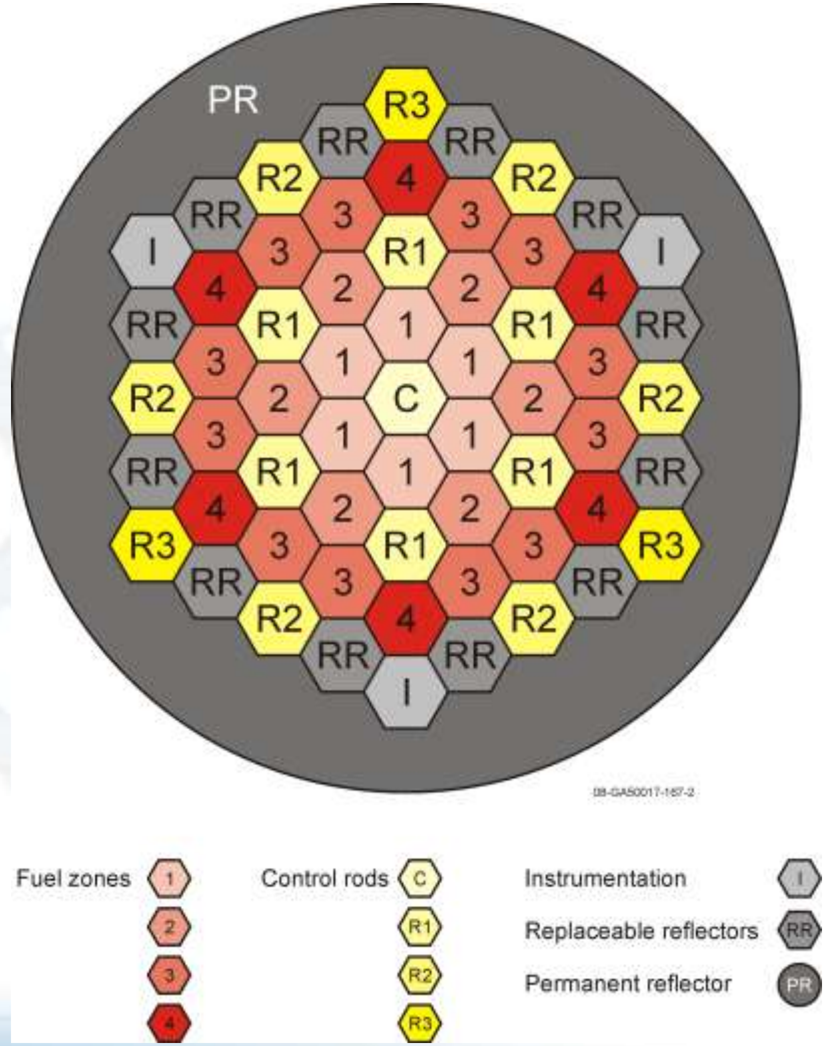
High Temperature Engineering Test Reactor (HTTR)

- Japanese 30 MWt, Graphite-Moderated, Helium-Cooled Reactor
- Currently Operational
- Research Reactor to Assess Future High Temperature Gas Reactors
- High Priority Benchmark for the Next Generation Nuclear Plant (NGNP) Project

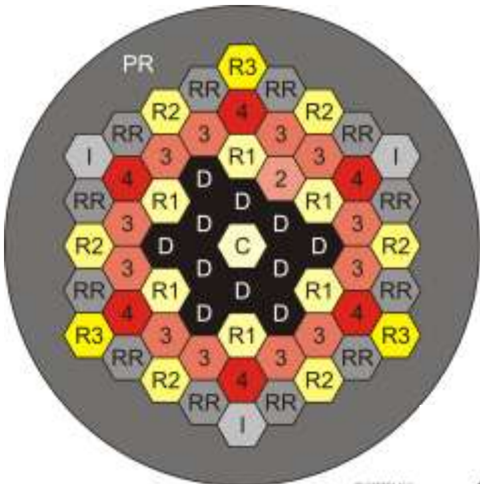


Fully-Loaded Core Description of the HTTR





Annular HTTR Core Configurations



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Initial Critical

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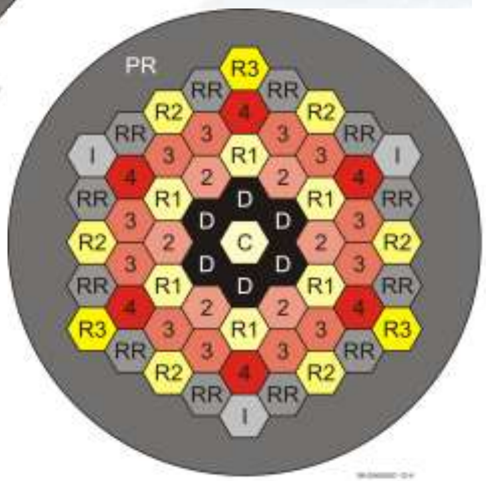

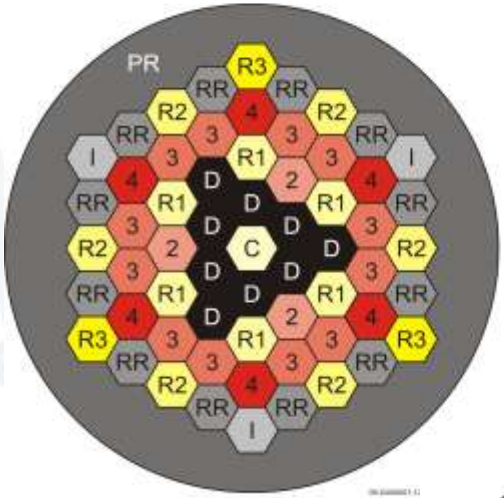

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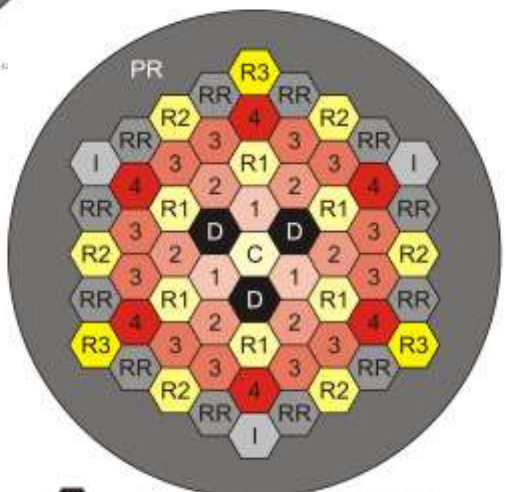
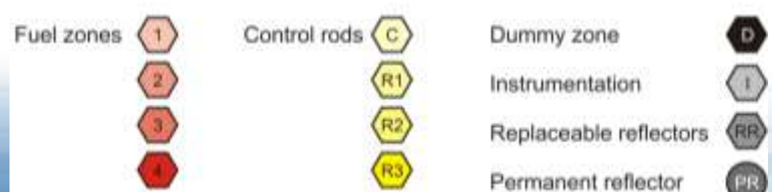
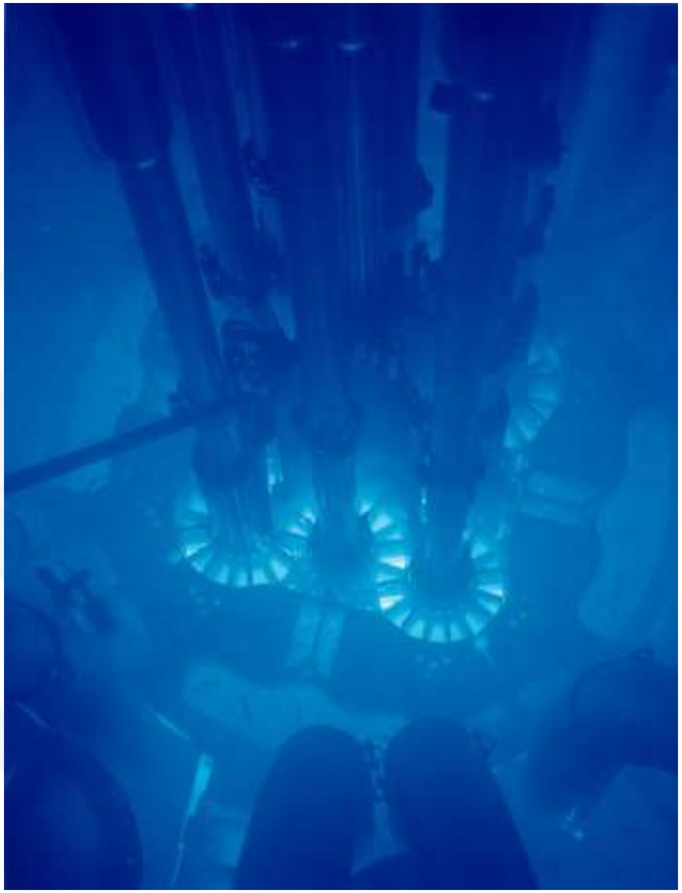




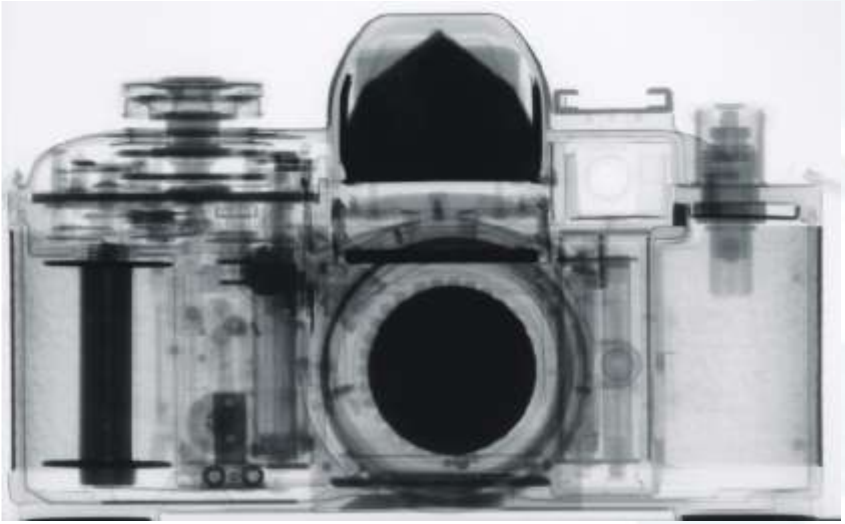
Advanced Test Reactor and ATR-C

- **250 MW "Four Leaf Clover" Thermal Reactor**
- **Materials Irradiation**
- **National Science User Facility**
- **ATR-C is a Critical Experiments Facility**
- **Full-Core Characterization is to be Performed and Benchmarked on Both Reactors**
  - **Currently a Critical Benchmark Exists for the ATR**

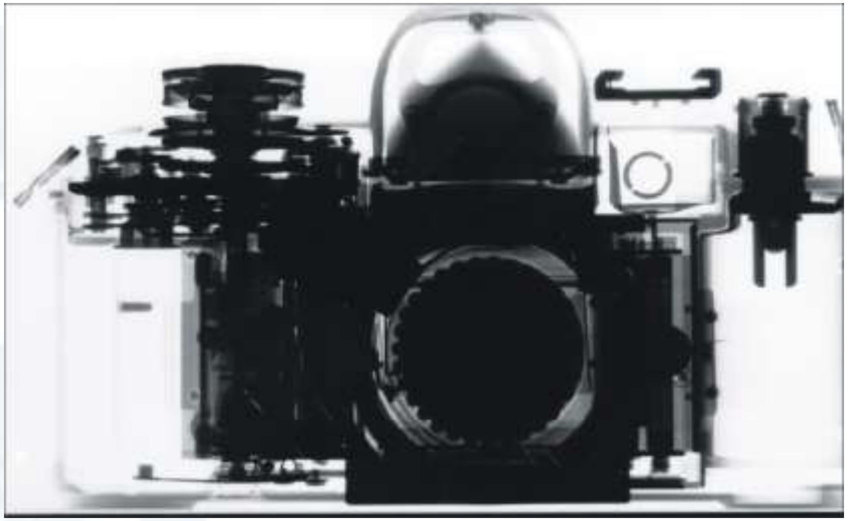


Comparison of N-Ray and X-Ray Imaging

N-Ray



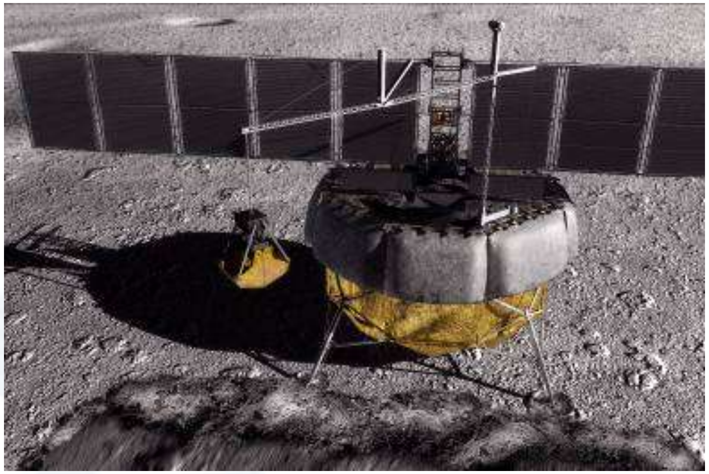
X-Ray

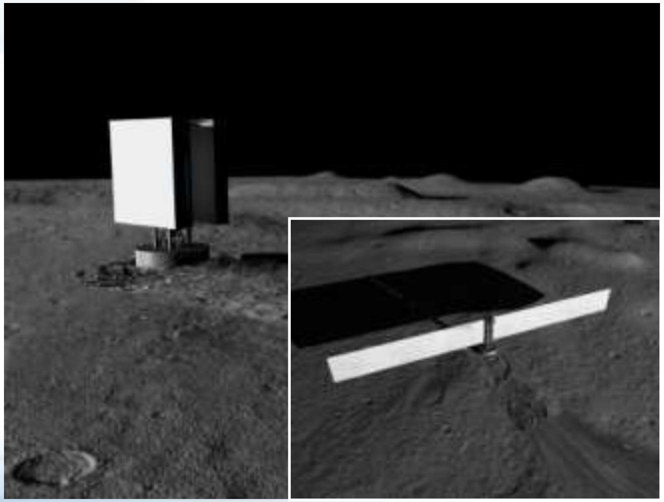


Atominstitute of the Austrian Universities, http://www.ati.ac.at/

Lunar Fission Surface Power (FSP) System

- **Inter-Laboratory Collaboration**
- **40 kWe, Fast-Fission, NaK-Cooled, HEU, SS316-Clad Reactor**
- **Utilized Current Benchmark Data to Evaluate Necessity for a Cold-Critical Experiment with the FSP**
- **TSUNAMI - Tools for Sensitivity and Uncertainty Analysis Methodology Implementation in Three Dimensions (SCALE/KENO)**





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