# Neutronic Simulation of NRAD Reactor LEU Conversion Start-Up Tests

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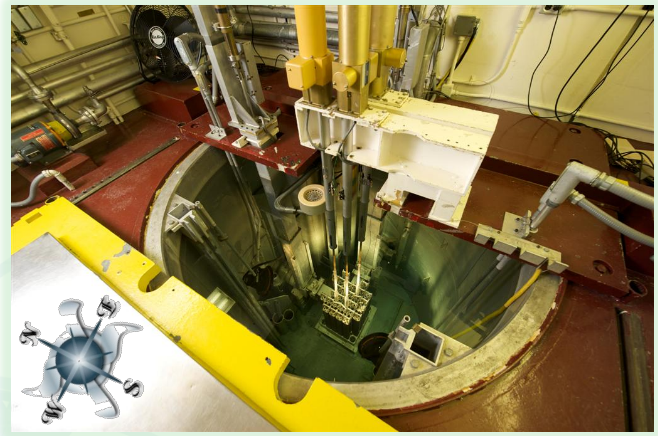
# Objective

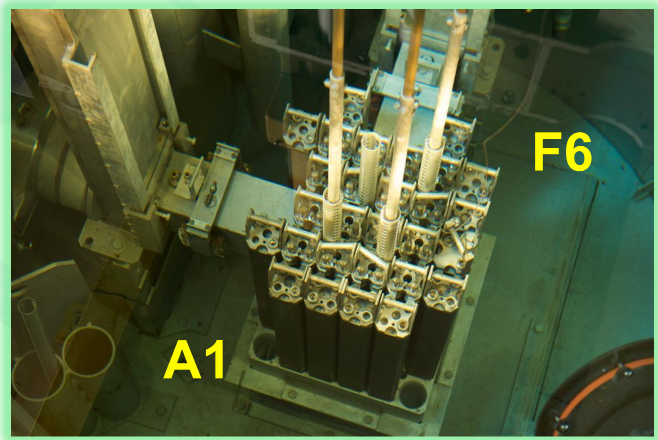
- **Neutronic benchmark development in support of evaluating the fresh-core reload of the NRAD TRIGA reactor with LEU-Er-Zr-H fuel.**


- **Acknowledgments**
  - **Idaho National Laboratory Staff**
  - **General Atomics**
  - **Collaborative support from GTRI, RERTR, TRIGA International, CERCA, IRPhEP**

# Neutron Radiography (NRAD) Reactor

- 250 kW TRIGA Mark II
- Conversion-type
- Located at INL
  - Former PRNC 2-MW reactor
- 60 U(30/20)-Er-Zr-H rods
- 12 graphite reflectors
- 3 control rods
- 2 neutron radiography beam lines
- Empty positions for in-core experimentation
  - Part of Hot Fuels Examination Facility (HFEF)



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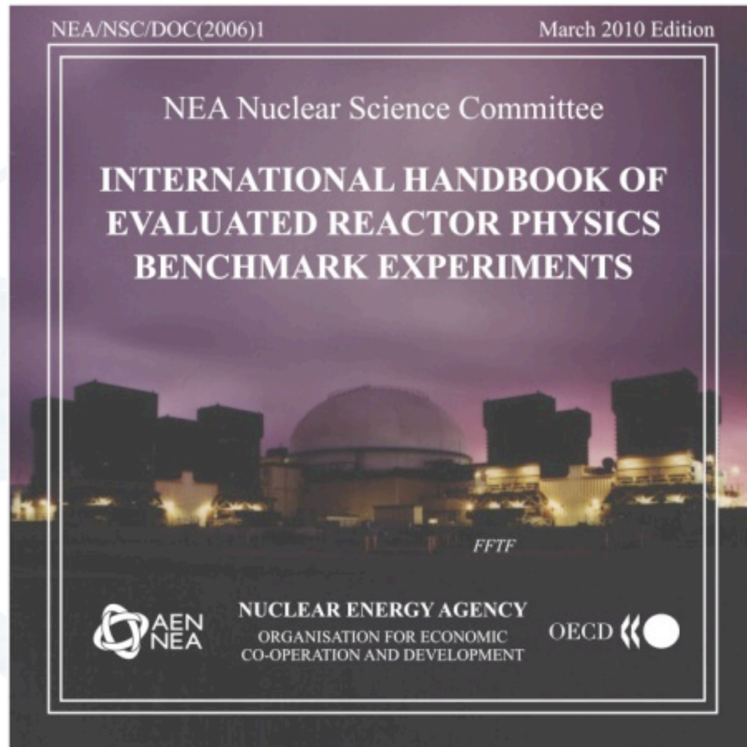
# NRAD LEU TRIGA Start-Up Tests

- March 9 – June 7, 2010
- Fuel loading approach to critical
- Initial critical
  - 56 fuel rods
  - Rod worths, ER, SDM
- Operational core
  - 60 fuel rods
  - Critical, rod worths, ER, SDM
- Calorimetric power calibrations
  - 100, 200, 250 kW
- Full power operation
  - ER
- Graphite reflector movements
- Radiography beam characterization performed after start-up tests were completed

# International Handbook of Evaluated Reactor Physics Benchmark Experiments

**March 2010 Edition**

- 15 Contributing Countries
- Data from 43 Experimental Series performed at 24 Reactor Facilities
- Data from 40 out of the 43 series are published as approved benchmarks
- Data from 3 out of the 43 series are published in DRAFT form
- Handbook available to OECD member countries, all contributing countries, and to others on a case-by-case basis

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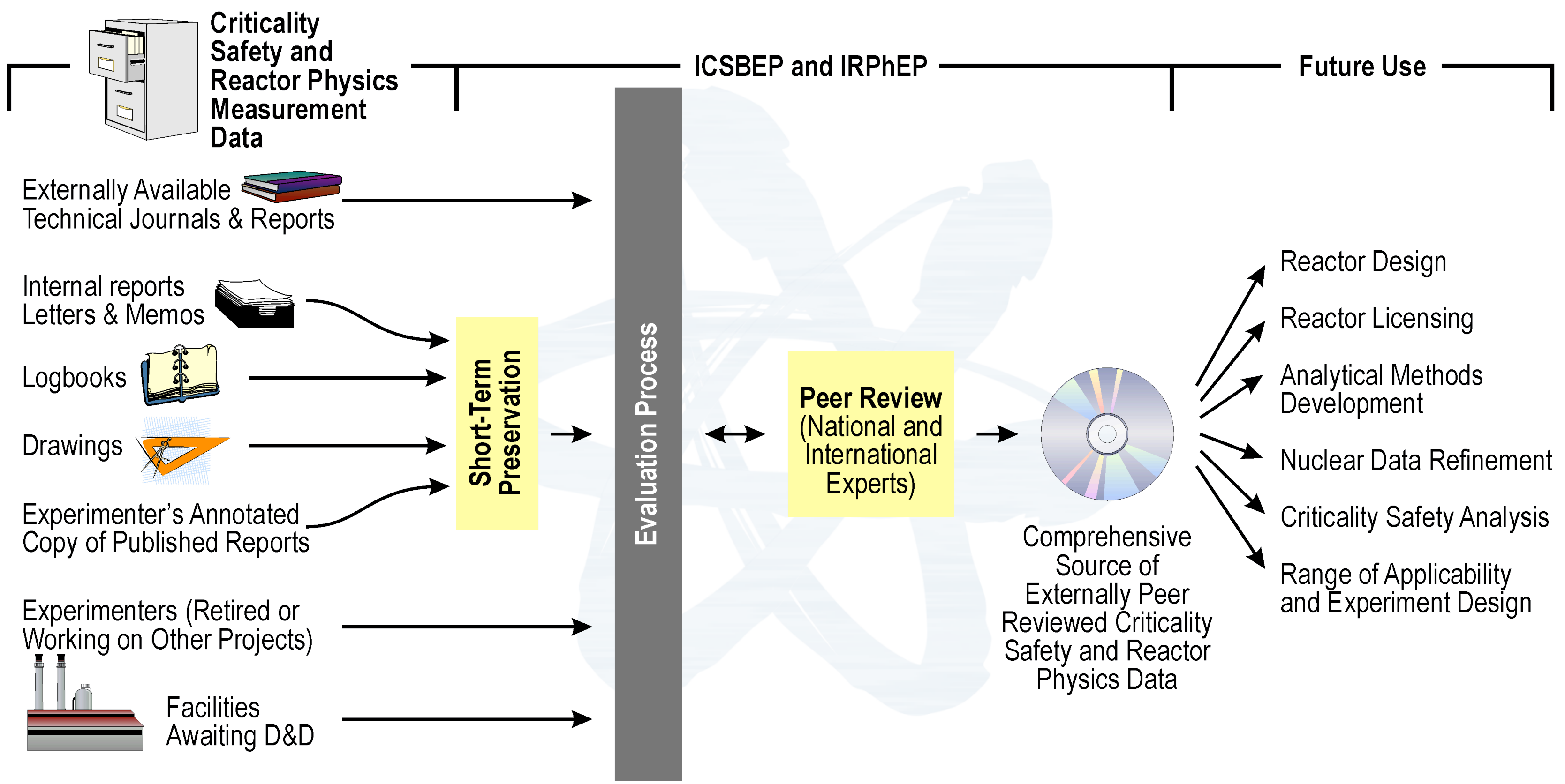
# Summary of Benchmarking Process

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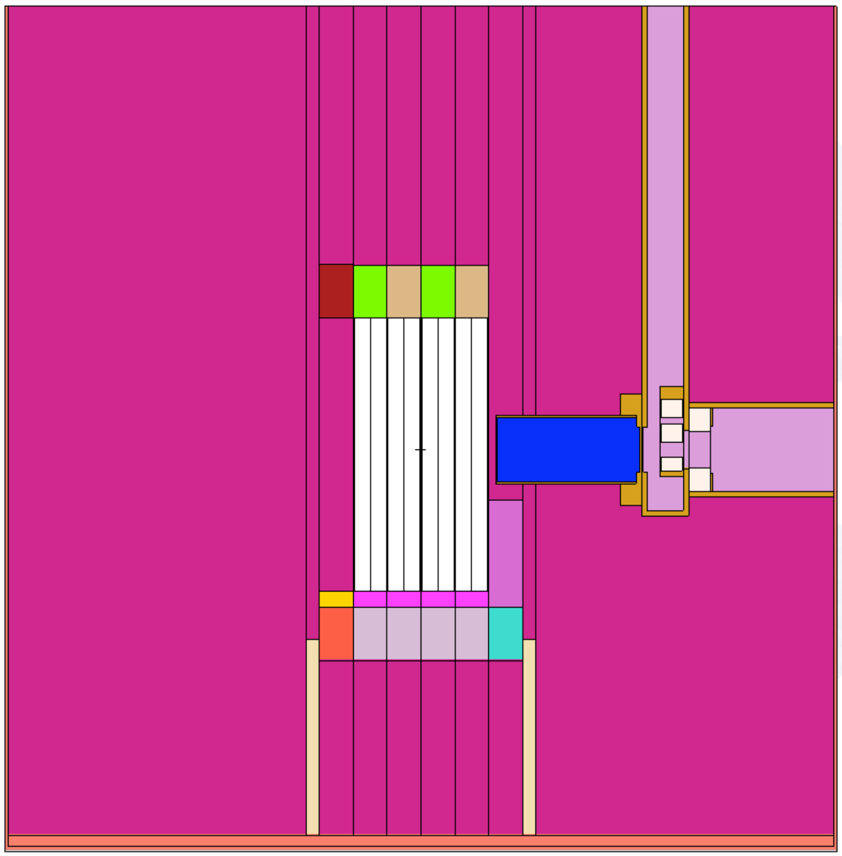
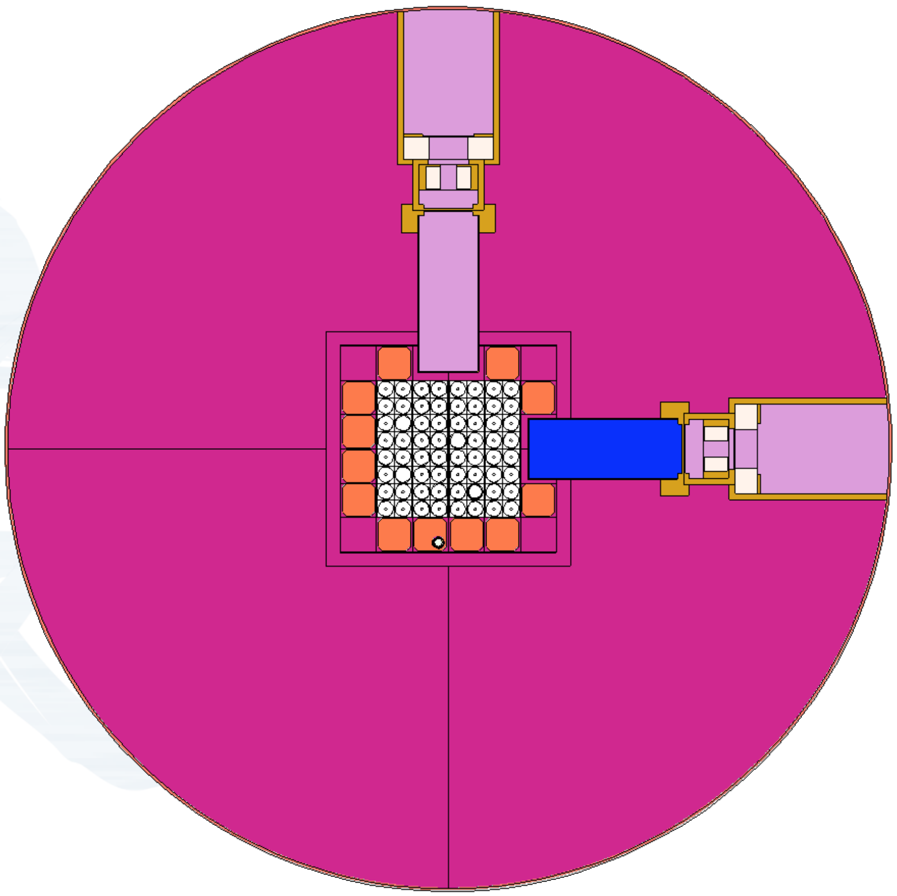
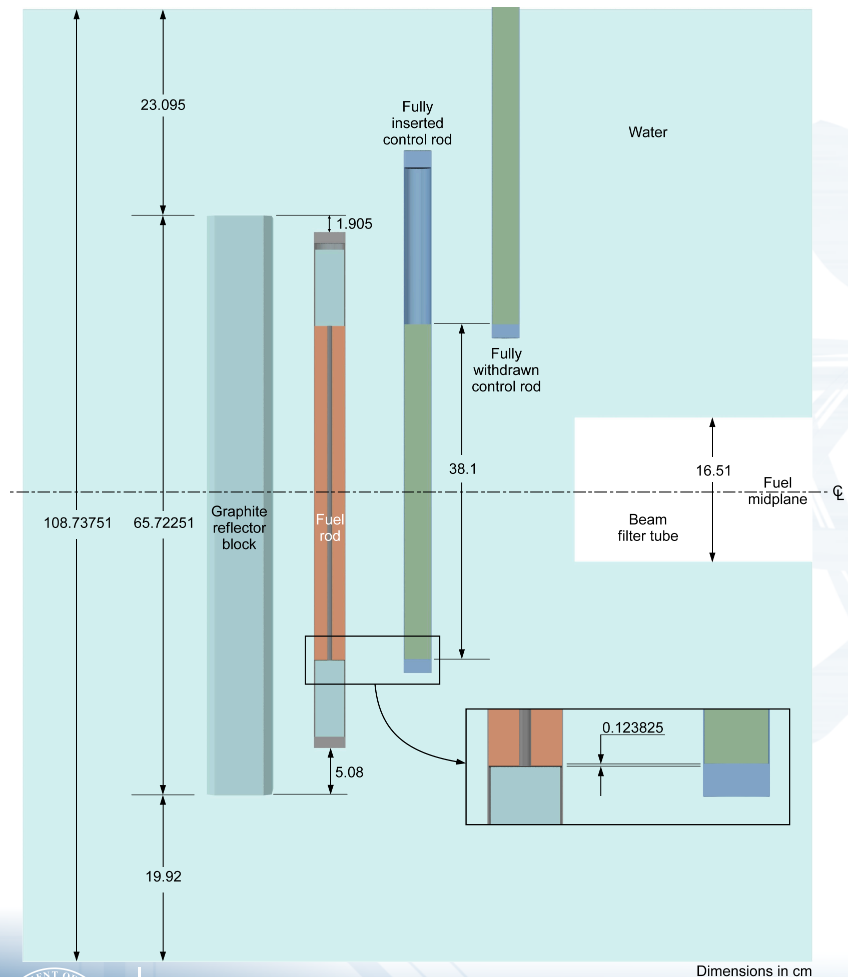
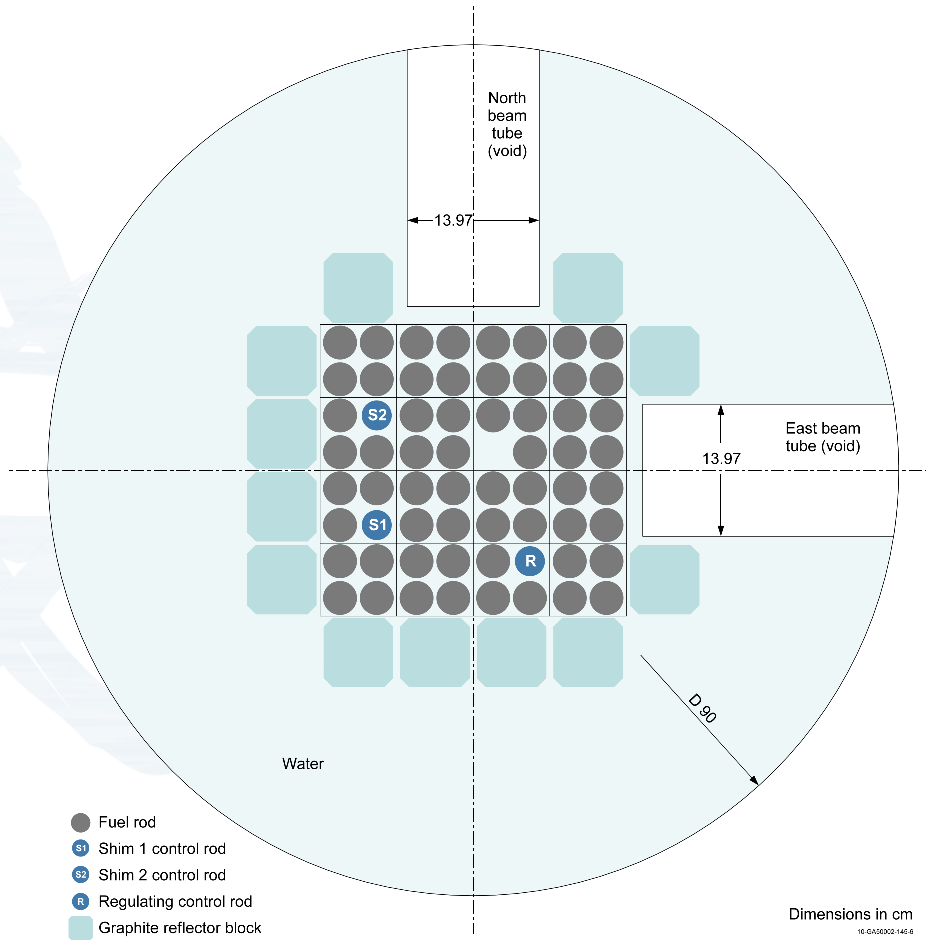
# Development of a Very Detailed Model





# Benchmark Model



# Primary Uncertainties

- Fuel Parameters
  - $^{234}U$ content
  - $^{236}U$ content
  - Hydride homogeneity
  - Erbium content
  - Hafnium content
- Stainless Steel Cladding
  - Composition
  - Impurities
- Water Saturation of Graphite Blocks
  - 30 vol.% theoretical saturation limit
  - Largest single contributor
- Total Experimental Uncertainty
  - ±0.0027 Δk (~0.3%)

# Criticality Calculation Results - I

- **Experiment $k_{eff}$ + Simplification Bias = Benchmark $k_{eff}$**

**1.0000 + 0.0013 = 1.0013 ± 0.0029**

| Analysis Code | Neutron Library | Calculated | | | $\frac{C-E}{E}(\%)$ |
|---|---|---|---|---|---|
| | | $k_{eff}$ | ± | σ | |
| MCNP5 | ENDF/B-VII.0 | 1.00996 | ± | 0.00007 | 0.86 |
| | JEFF-3.1 | 0.98541 | ± | 0.00007 | -1.59 |
| | JENDL-3.3 | 1.00734 | ± | 0.00007 | 0.60 |
| KENO-VI | ENDF/B-VII.0 (238-group) | 1.01278 | ± | 0.00007 | 1.15 |

# Criticality Calculation Results - II

- There is a computational bias of \$1.15 ± 0.02 using MCNP5 and ENDF/B-VII.0.
- Simplifications to the model provide only an additional \$0.17 ± 0.01.
- Analysis is most sensitive to the thermal scattering treatment, S(α,β), for hydrogen in ZrH.
  - Swap S(α,β) in JEFF-3.1 with ENDF/B-VII.0
    - \$3.03 ± 0.03
  - Remaining difference between neutron data
    - \$0.27 ± 0.03

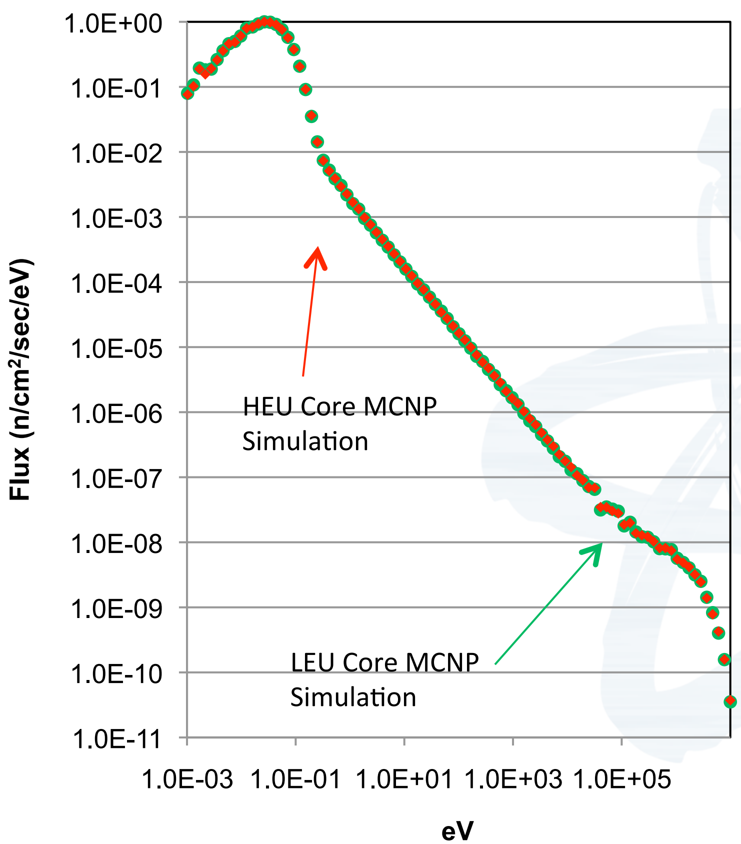
$\beta_{eff} \sim 0.0075$

# Reactor Physics Calculation Results

| Worth Measurement | Experimental ($) σ ≈ 5% (est.) | | | Detailed Model ($) | | | Simple Model ($) | | |
|---|---|---|---|---|---|---|---|---|---|
| Graphite Block C1 | -0.41 | ± | 0.02 | -0.39 | ± | 0.01 | -0.37 | ± | 0.01 |
| Graphite Block D1 | -0.44 | ± | 0.02 | -0.39 | ± | 0.01 | -0.41 | ± | 0.01 |
| Graphite Block F4 | -0.46 | ± | 0.02 | -0.33 | ± | 0.01 | -0.32 | ± | 0.01 |
| Graphite Block A5 | -0.17 | ± | 0.01 | -0.16 | ± | 0.01 | -0.14 | ± | 0.01 |
| *Fuel Cluster B5* | *-0.73* | *±* | *0.04* | *-1.22* | *±* | *0.02* | *-1.19* | *±* | *0.02* |
| Excess Reactivity | 1.18 | ± | 0.06 | 1.20 | ± | 0.02 | 1.20 | ± | 0.02 |
| Shutdown Margin | -7.06 | ± | 0.35 | -7.15 | ± | 0.09 | -7.17 | ± | 0.09 |
| Shim Rod 1 | -2.80 | ± | 0.14 | -2.70 | ± | 0.04 | -2.70 | ± | 0.04 |
| *Shim Rod 2* | *-2.85* | *±* | *0.14* | *-2.35* | *±* | *0.03* | *-2.40* | *±* | *0.03* |
| Reg Rod | -2.59 | ± | 0.13 | -2.47 | ± | 0.03 | -2.47 | ± | 0.04 |

$\beta_{eff} \sim 0.0071$ $\beta_{eff} \sim 0.0075$

# Beam Line Characterization




- **Evaluate quality of East radiography beam**
  - **Foil irradiations (±5%)**
- **Cd ratios with Au-Foils**
  - **HEU Core = 1.99**
  - **LEU Core = 1.81**
- **Cd ratios with In-Foils**
  - **Both Cores = 2.98**
- **Core conversion has not impacted radiography quality**

**Data courtesy of Chad Pope at INL**

# Lessons Learned

- Computational models are only as good as the data and physics you use
  - Need to evaluate cross section data
- Complete characterization of the fuel and reflectors is essential to quantifying their worth
  - You pay the price for accuracy
- Just because you can't model it perfectly, doesn't mean the reactor won't function
  - Computational analysis is a tool, not the solution

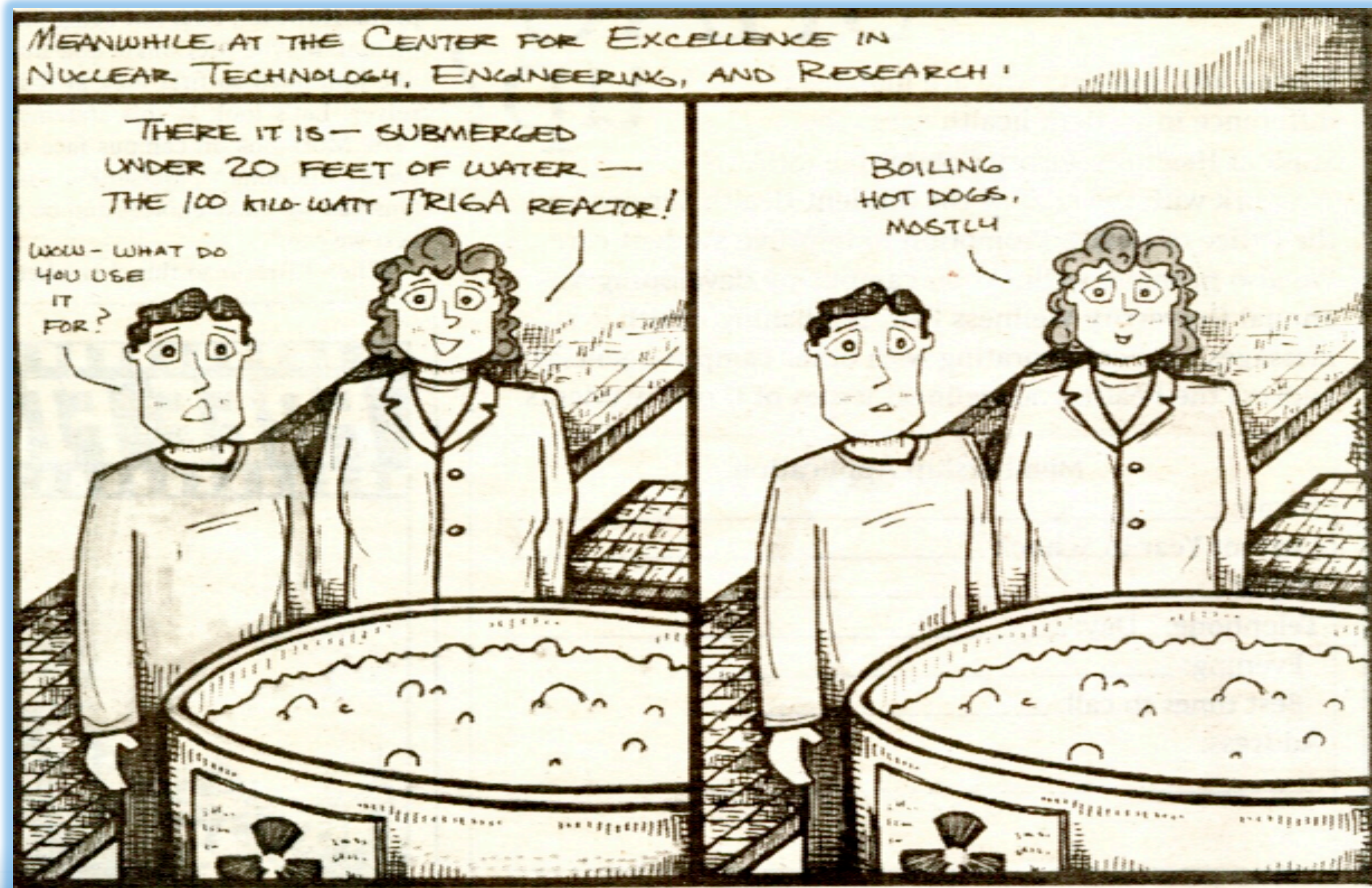
# Future Work

- **Experimental**
  - Determine water saturation in graphite
  - Perform additional reactor physics experiments
- **NRAD Operations**
  - Modify core with four new fuel elements and four graphite elements
  - Add pneumatic transfer experiment capabilities
- **Benchmark**
  - IRPhEP workgroup meeting in Oct 2010
    - March 2011 Handbook
  - Evaluate additional reactor physics experiments and modified core configurations

# Conclusions

- **Uncertainty**
  - Water saturation of graphite (to be determined)
  - Fuel element composition
- **Biases**
  - Simplification are negligible
  - There is an absolute computational bias in $k_{eff}$ but not $\rho$
- **Reactor Physics**
  - Good agreement between most measurements and calculations
- **Path Forward**
  - Additional experiments and analysis in support of an operational core
  - Additional ICSBEP/ IRPhEP evaluations

# Questions?



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# 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)"***

# 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

# International Reactor Physics Experiment Evaluation Project (IRPhEP)

- 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/

# Evaluation Included in IRPhEP Benchmarks

- Critical/Subcritical
- Buckling/Extrapolation
- Spectral Characteristics
- Reactivity Effects
- Reactivity Coefficients
- Kinetics Measurements
- Reaction-Rate Distributions
- Power Distributions
- Isotopic Composition
- Miscellaneous

- Extensive Peer Review
  - Evaluator(s)
  - Internal Review
  - Independent Review
  - International Workgroup Review

# Perturbation Analysis

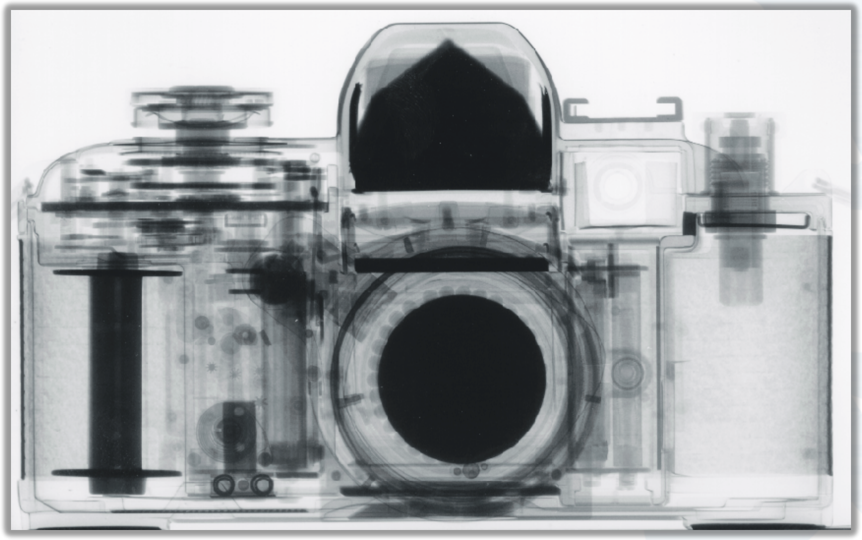
- Variation of parameters within published or assumed range of uncertainty
  - Manufacturing tolerances
  - Repeated measurements
  - Measurement limit
  - Bounding compositional requirements
- Sometimes the perturbation modeled is larger than the actual uncertainty, and is scaled back
  - Uncertainty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

# Bias Assessment

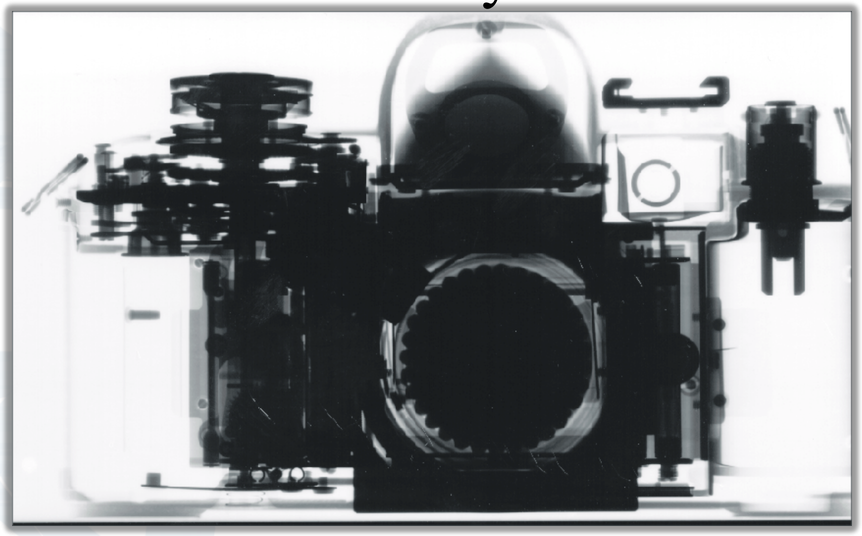
- The Effect of simplifying the model is assessed by comparison of the detailed model to the simple model
- Some simplifications are anti-correlated
  - Their effects must be modeled individually and as a whole to understand the complete result
- Sometimes the bias is smaller than the statistical uncertainty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

# Comparison of N-Ray and X-Ray Imaging

N-Ray

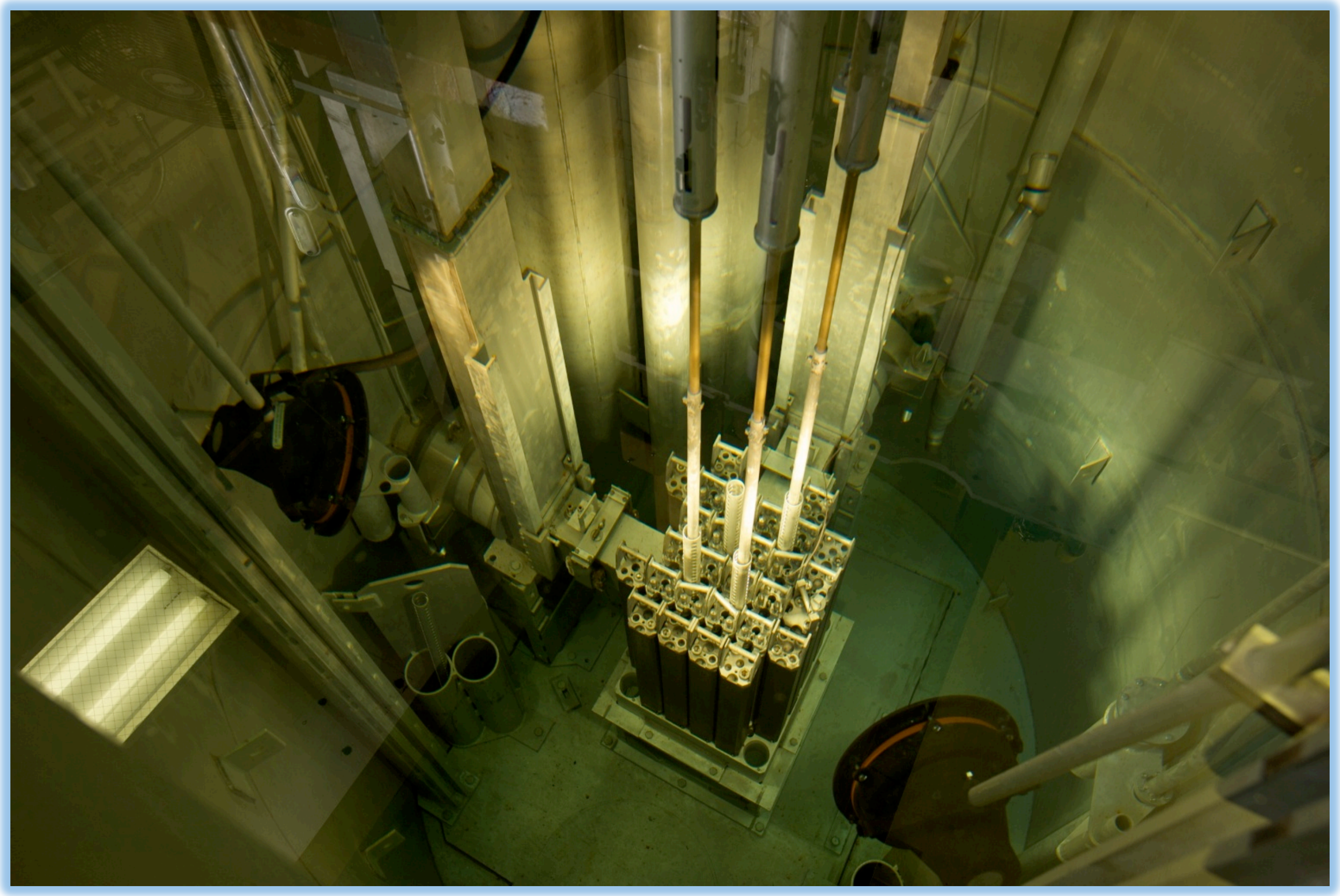


X-Ray

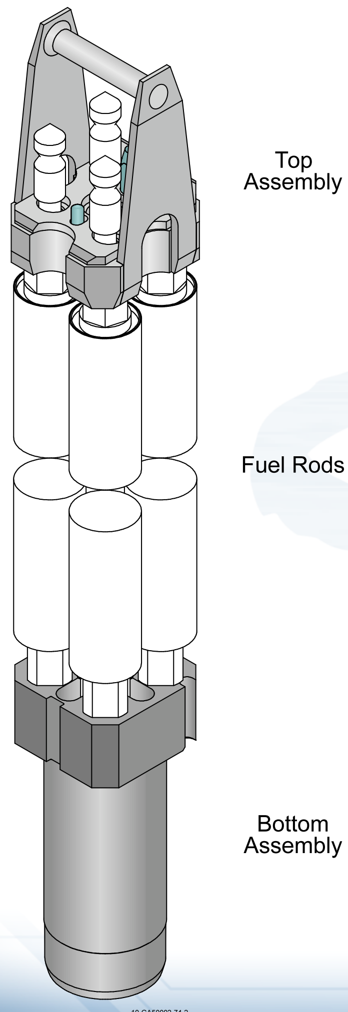


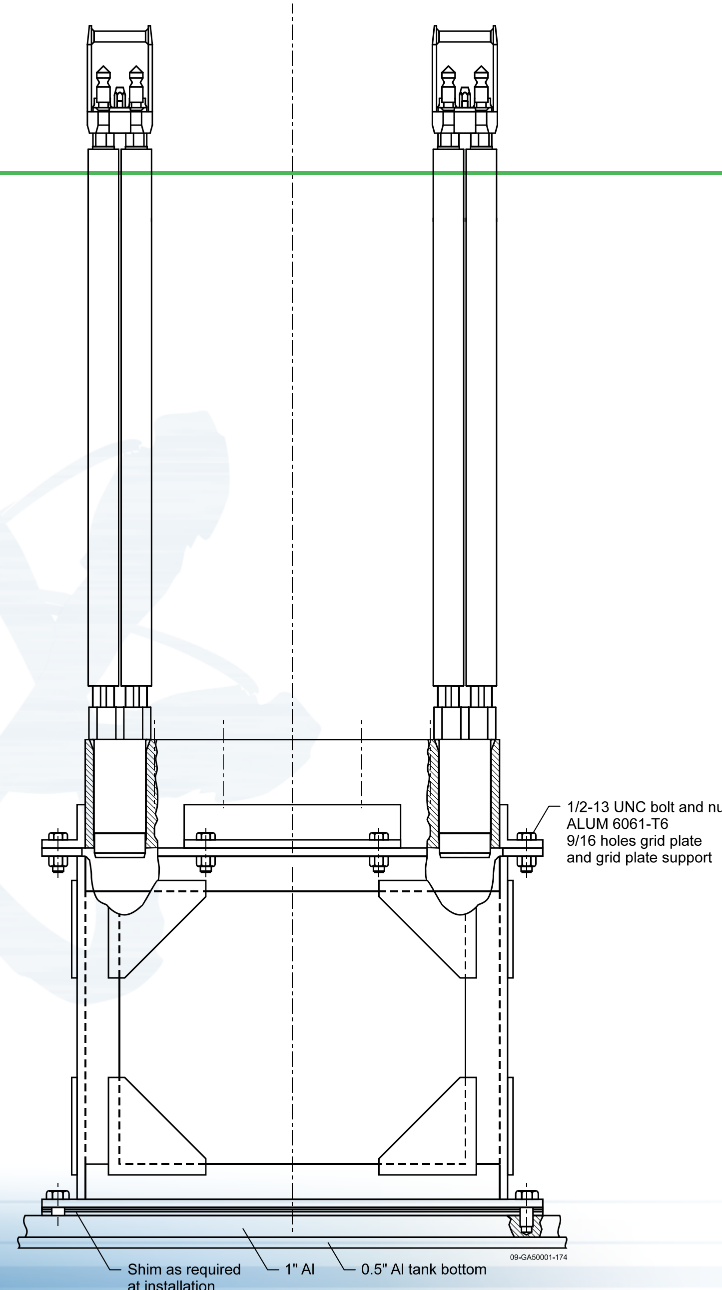
Atominstitute of the Austrian Universities, http://www.ati.ac.at/

# Photograph of NRAD Tank

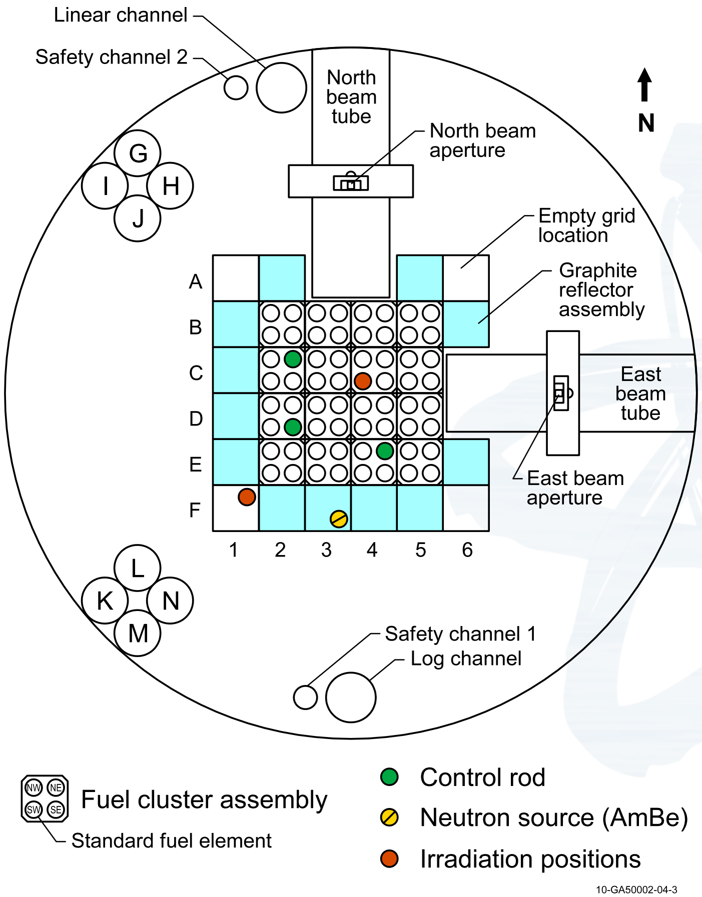


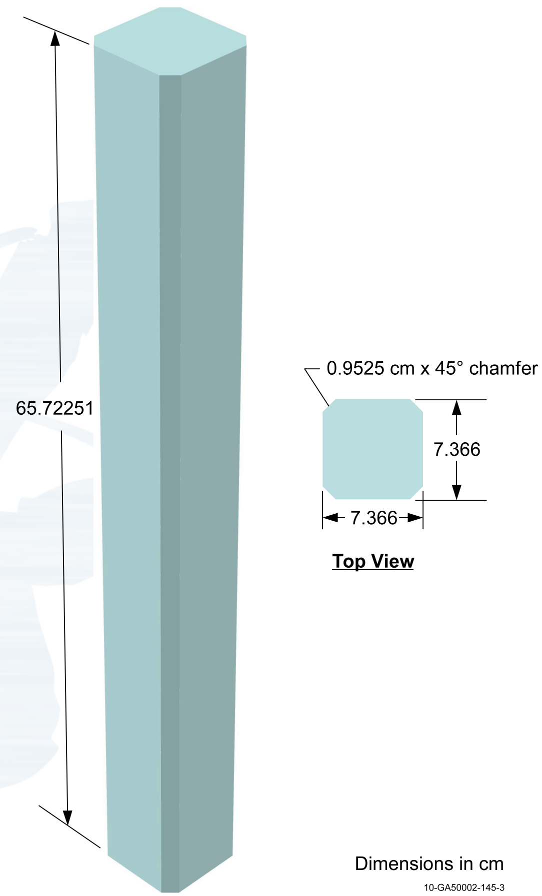
# Fuel Clusters



# Graphite Reflectors

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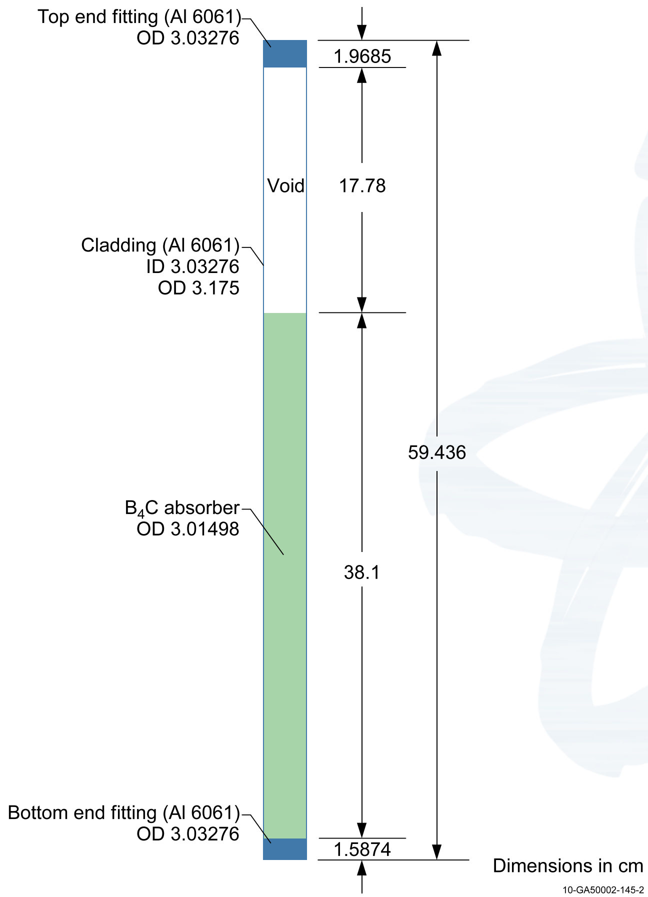
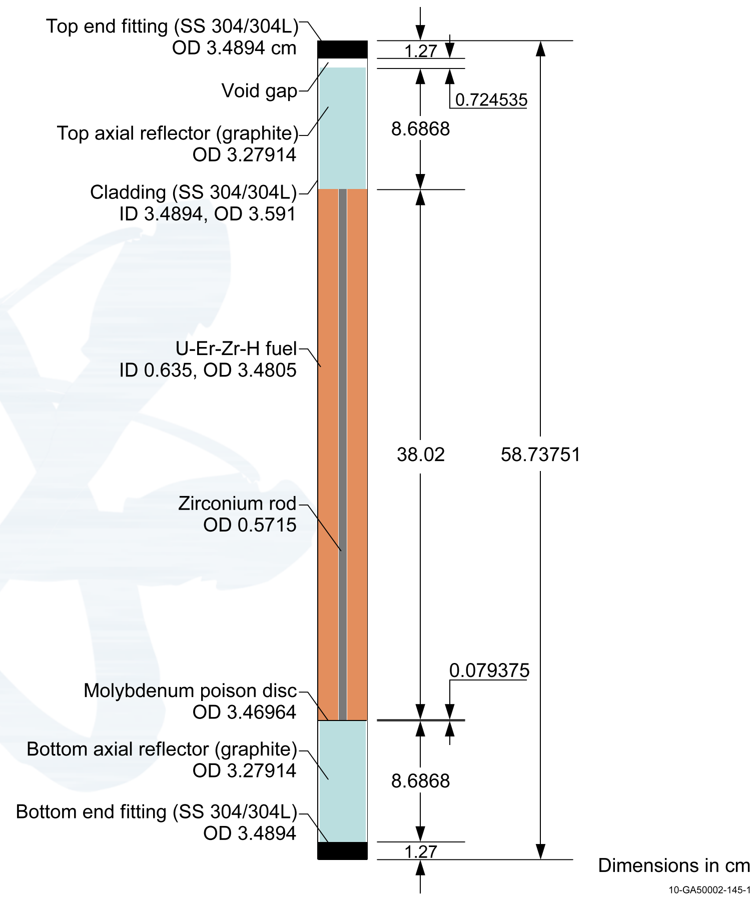
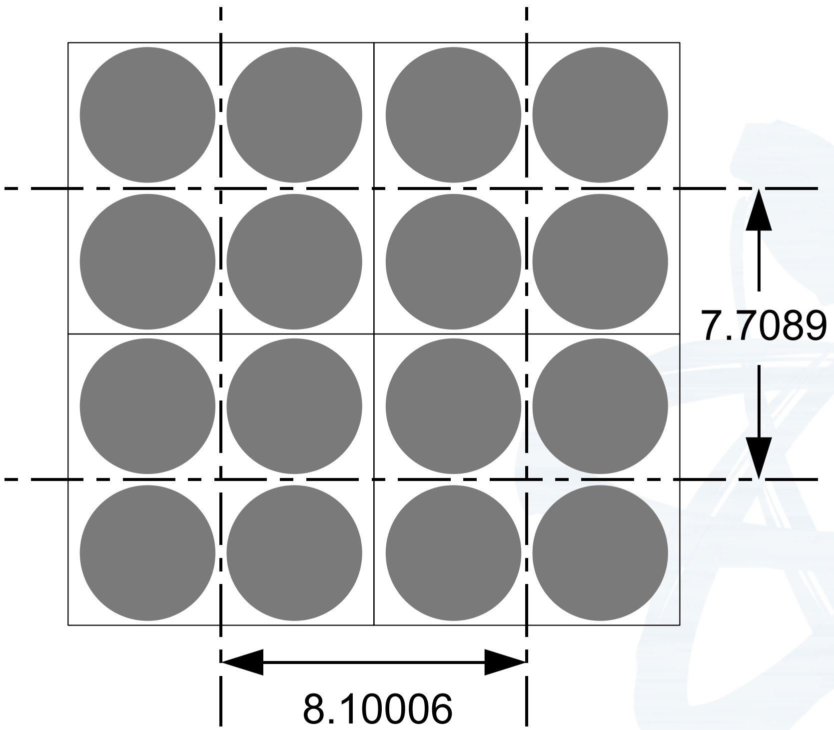
# Control and Fuel Rods

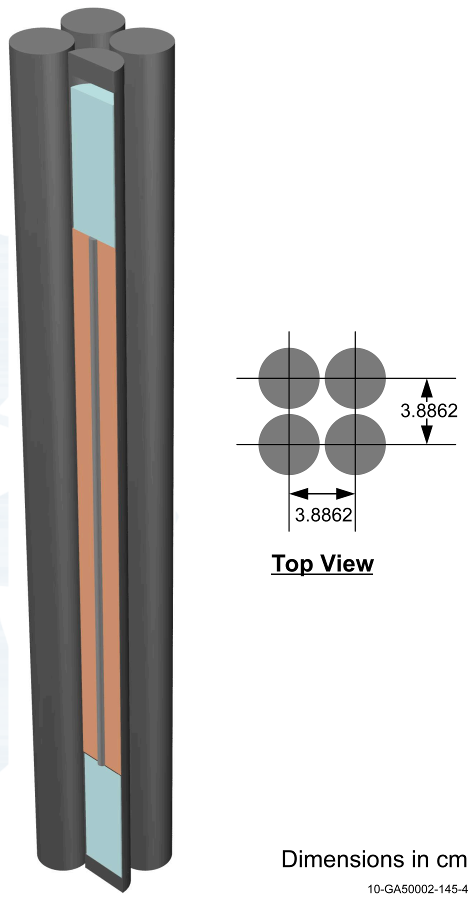


# Assembly and Fuel Pitches




Dimensions in cm
10-GA50002-145-5




Dimensions in cm
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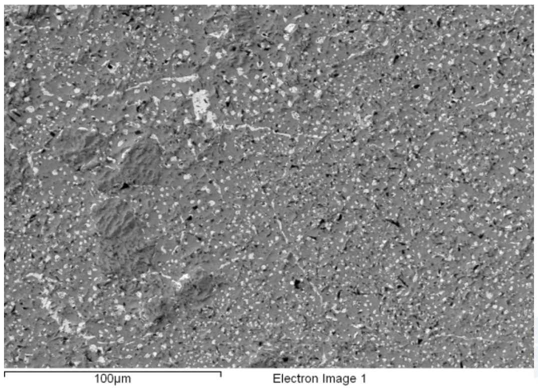
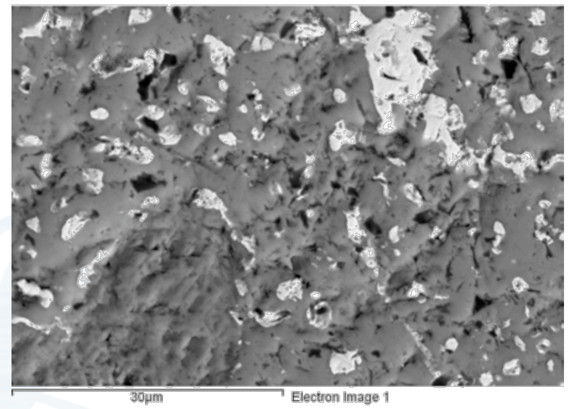
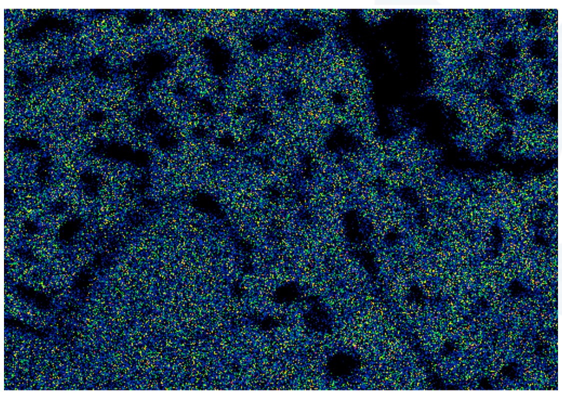
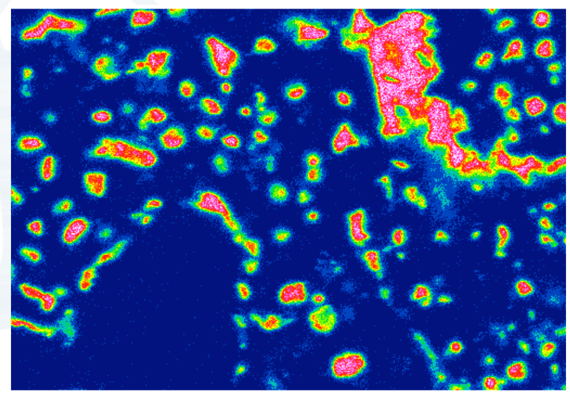
# “Typical” Fuel Micrographs



Zirconium_WD



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