2 ZED-2 Physics Experiments in Support of ACR

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Presentation Objectives

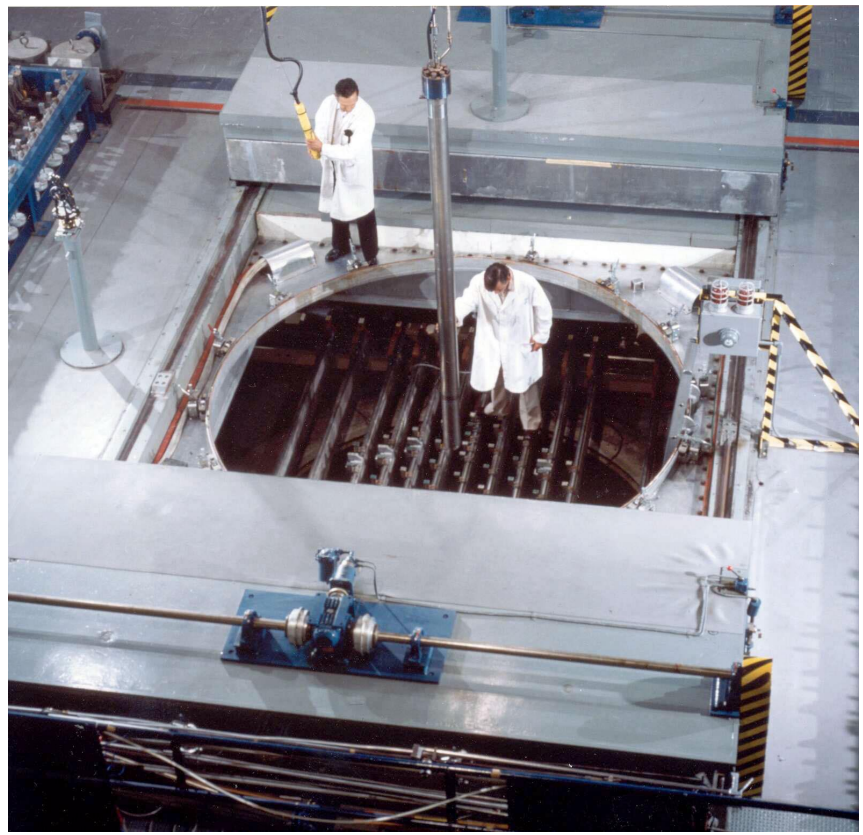
- Show that the ZED-2 experiments completed and planned will provide validation of ACR physics
  - methods & planned measurements used for ACR code qualification are the same as the methods for CANDU 6 physics code qualification
- State uncertainties for ZED-2 measurements and describe how these were determined
  - based on years of experience doing work in support of CANDU licensing
- Describe experiments done to date applicable to ACR physics
- Describe remaining experiments

Outline

- ZED-2 reactor description
- ACR description
- ZED-2 measurement techniques
  - buckling measurements
  - fine-structure measurements
  - absorber worth measurements
  - rod drop experiment
- Establishing measurement uncertainties
- Measurements done to date
- Reference fuel for ACR experiments
- Description of ACR experiments
- Summary

ZED-2 (Zero Energy Deuterium) Reactor at Chalk River Laboratories (CRL)

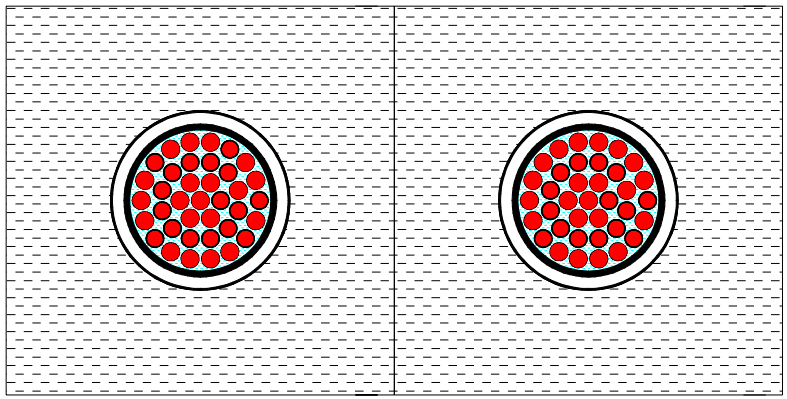
- Tank-type critical facility, 3.3 m in diameter & depth
  - moderator height adjusted to control reactor power
- Flexible facility
  - allows testing of a variety of fuels, different pitches (hex. or square), different coolants: D_2O, H_2O, air (voided)
- D_2O moderated; graphite radial & bottom reflector
- Typical lattice arrangement hexagonal, with 55 channels, each containing 5 fuel bundles
- Typical measurements are at room temperature, but 7 "hot sites" can be located in centre (10 MPa up to 300 ^oC)
- Shielding insufficient for measurements on irradiated fuel



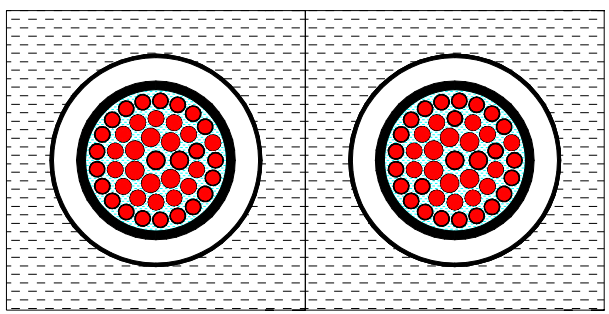
ACR Description

- light water coolant
- reduced lattice spacing
- modified fuel channels
- CANFLEX fuel bundles
- SEU fuel
- dysprosium poison

CANDU 6
Lattice Pitch = 28.58 cm

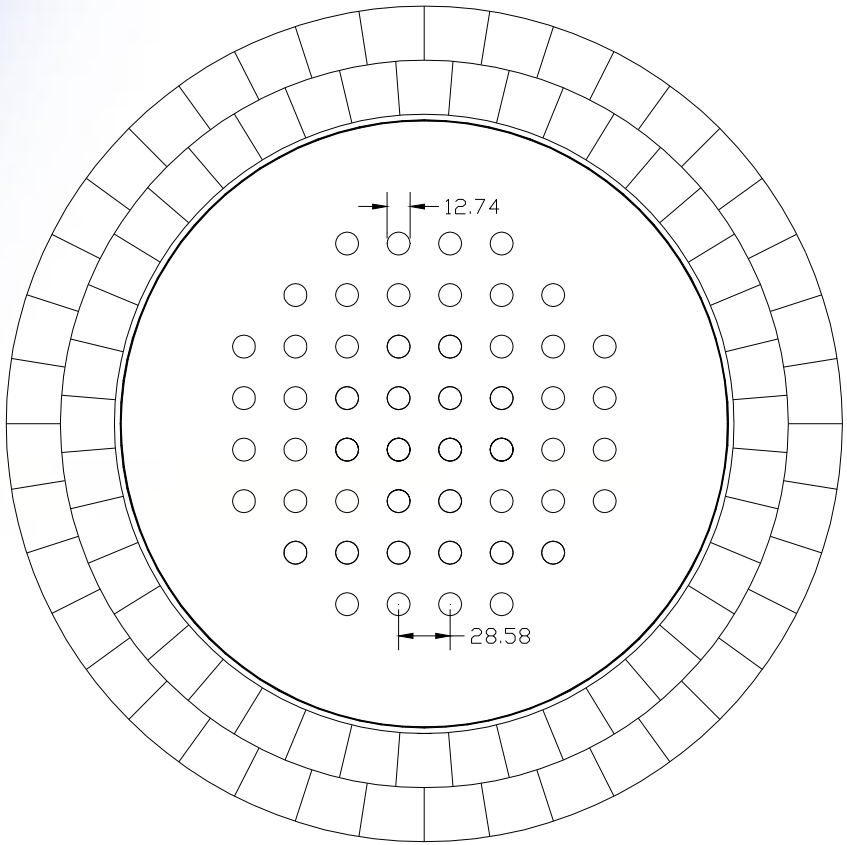


ACR
Lattice Pitch = 22 cm

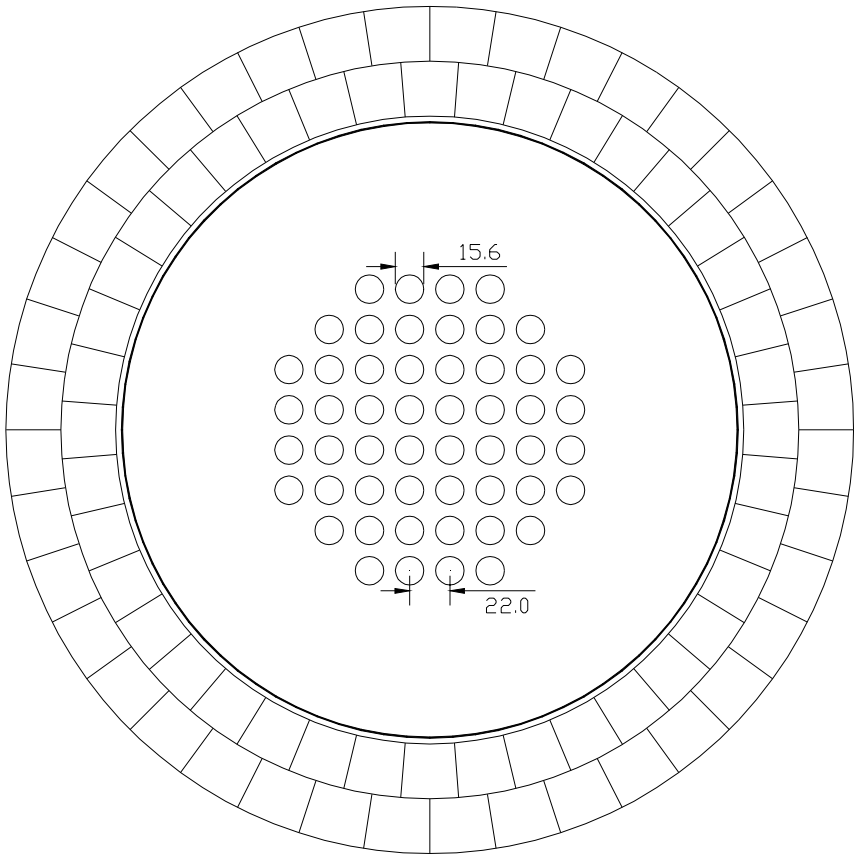


ACR Lattice in ZED-2

CANDU 6-Type Lattice



ACR-Type Lattice



- **ZED-2 ACR lattice captures the important physics in an ACR reactor**

ACR Fuel

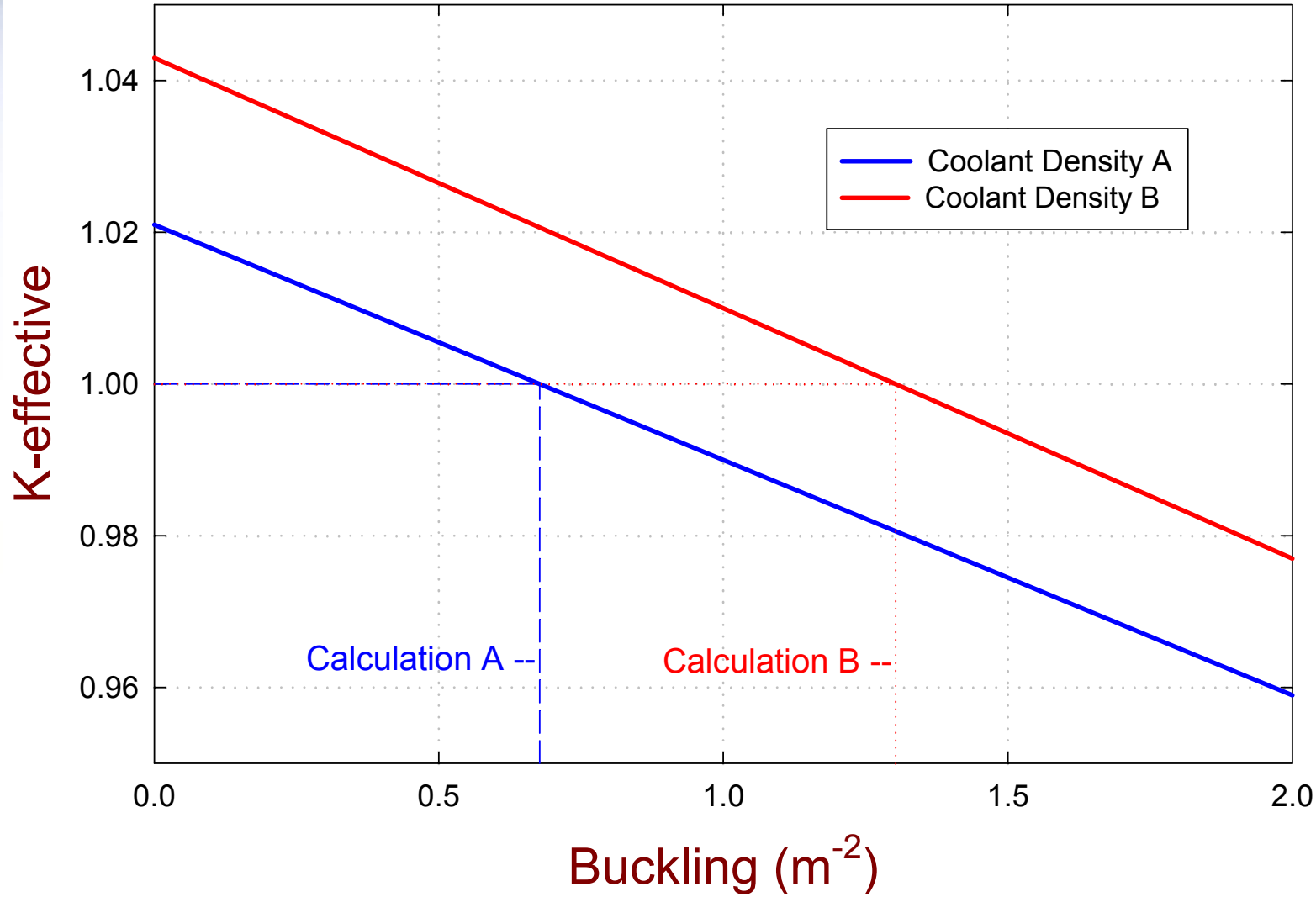
ZED-2 Measurements: General

- Material buckling (reactivity)
  - full core flux maps & substitution experiments
    - substitution method extensively validated
  - reactivity coefficients
    - void reactivity; fuel temperature; fuel/coolant temperature; moderator temperature, moderator purity, and moderator poison
- Reaction rates in foils
  - U-235, Pu-239, Dy-164, Cu-63, Mn-55, Au-197, In-115, Lu-176
  - reaction-rate ratios are sensitive indicators of the energy spectrum
  - for example In-115 has a large epithermal resonance at 1.457 eV and Cu-63 is ~ one-upon-v
  - In-115/Cu-63 capture is used to establish positions of asymptotic spectrum in a lattice
- Reactor period measurements (for neutron kinetics)
- Worth of reactivity devices (e.g., shutoff rod, zone controllers)

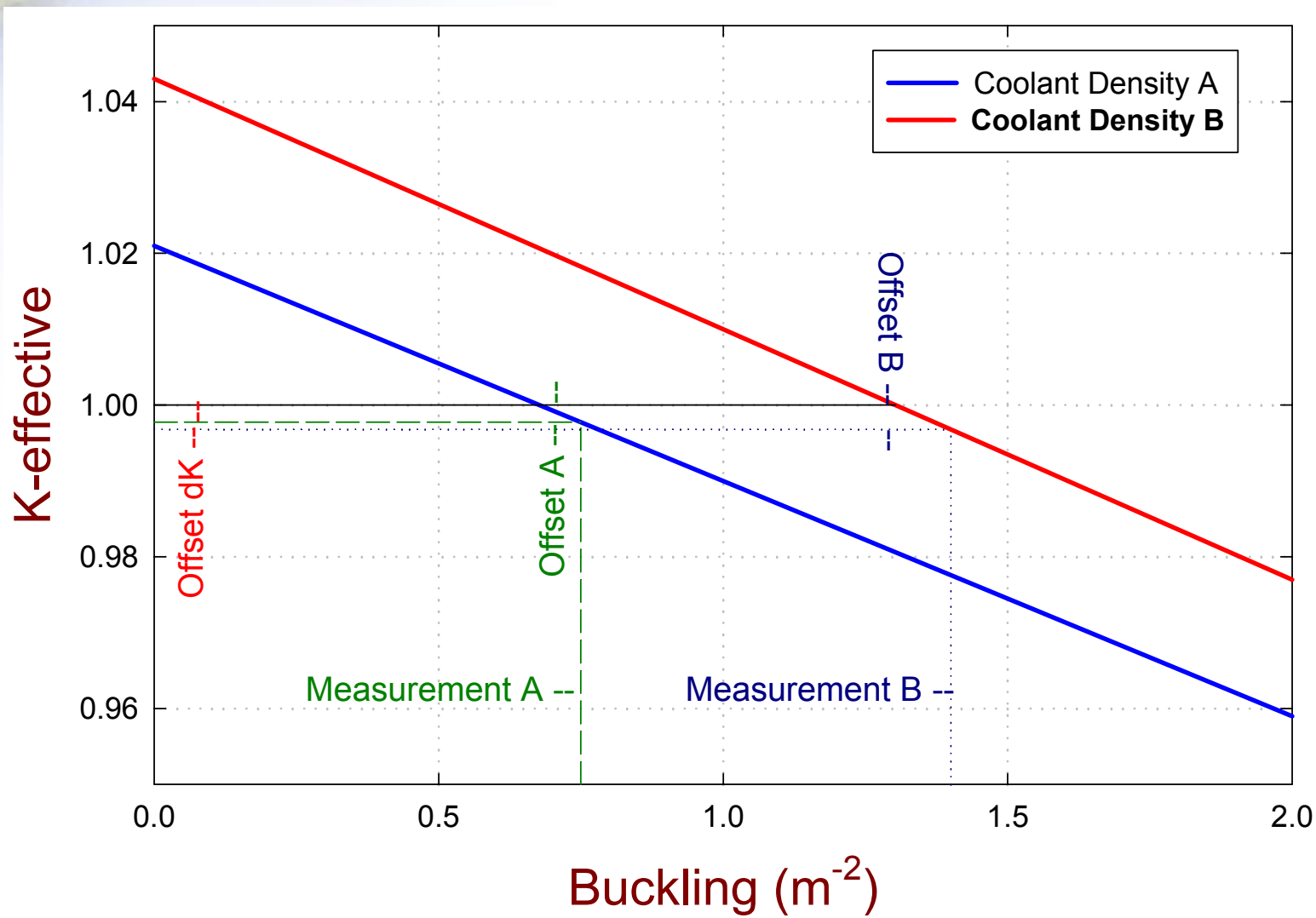
Buckling Data for Lattice Code Validation

- Buckling data are used to assess ability of lattice codes to calculate cell parameters and reactivity coefficients
- Bucklings are input to lattice calculation and deviation of the output k value from unity establishes offset
- For reactivity-coefficient calculations any deviation of the output delta-k value from zero establishes the offset
- Offsets depend on the lattice code and/or nuclear data library used for the analysis

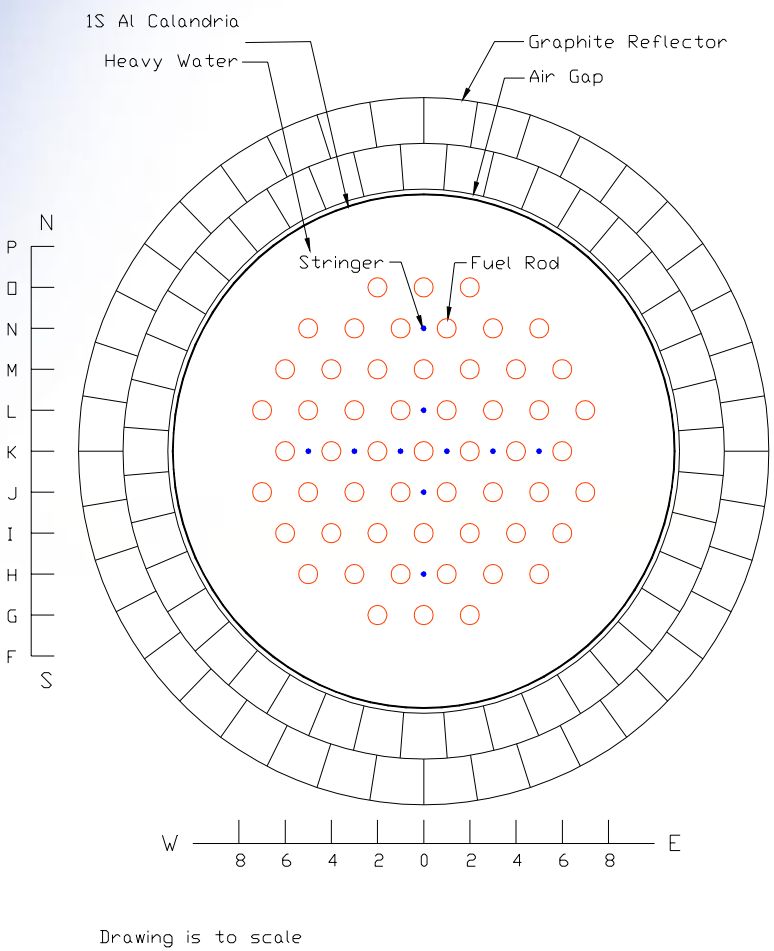
Code Prediction of Buckling

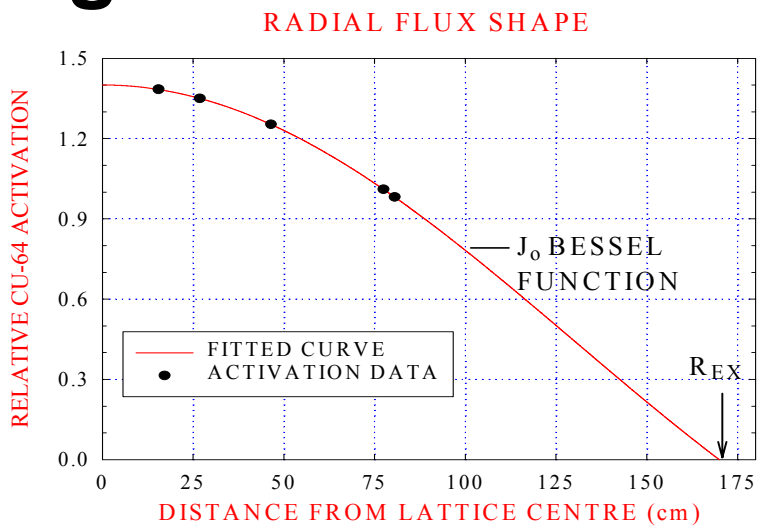


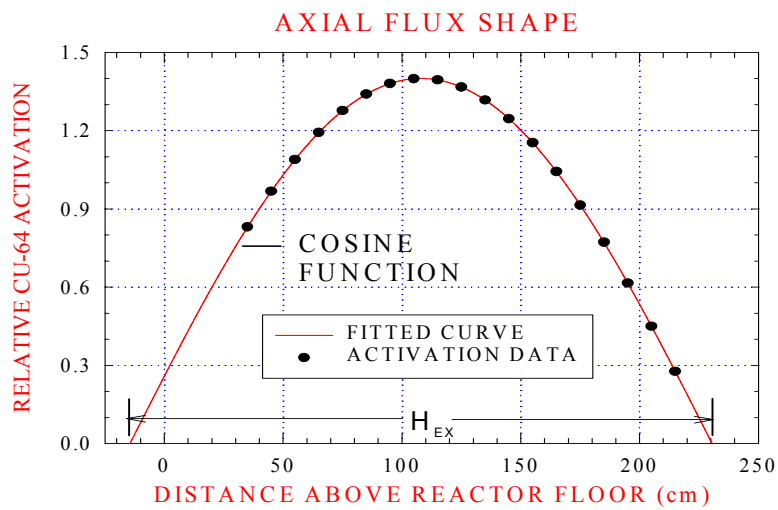
Establishing Code Offset



Flux-Map Buckling Measurement

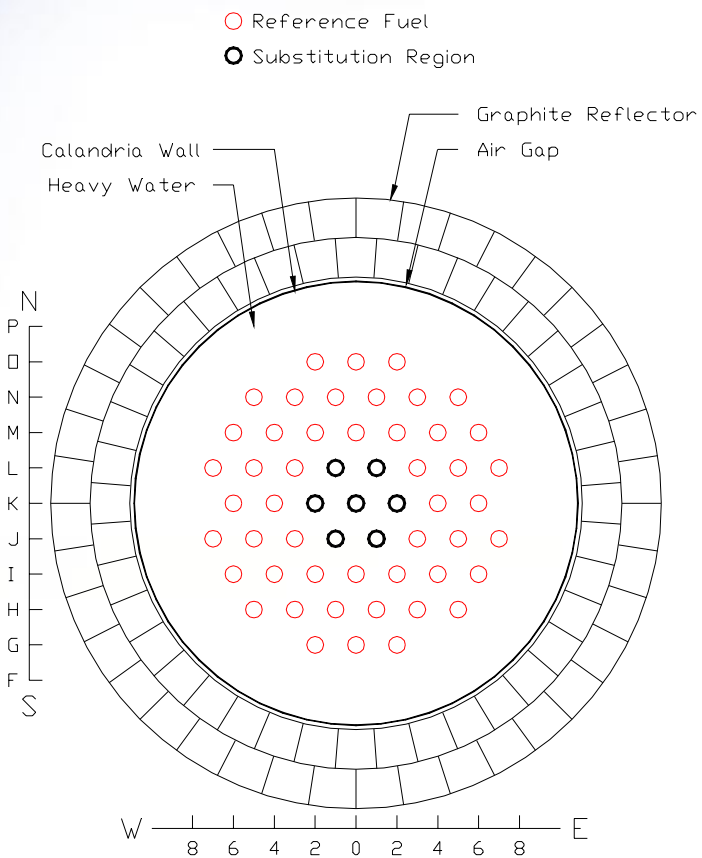


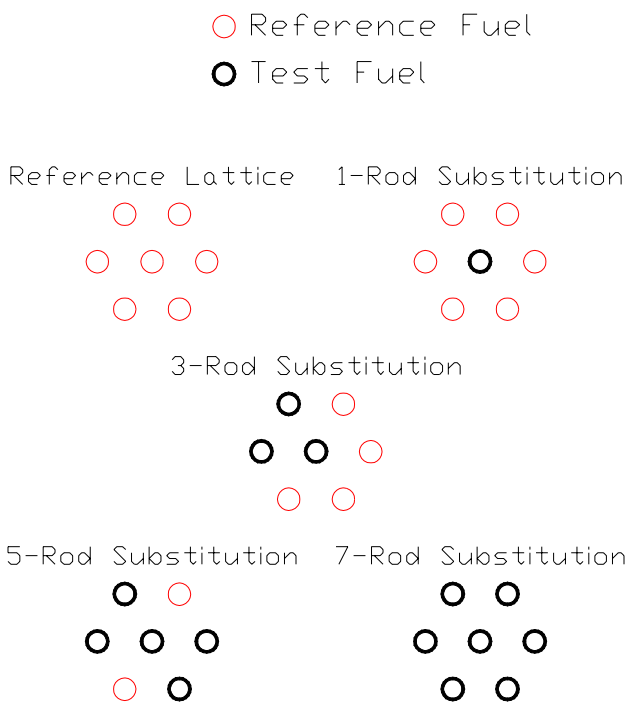




$$\text{Buckling} = (2.405/R_{EX})^2 + (\pi/H_{EX})^2$$

Substitution Experiments





Substitution Method

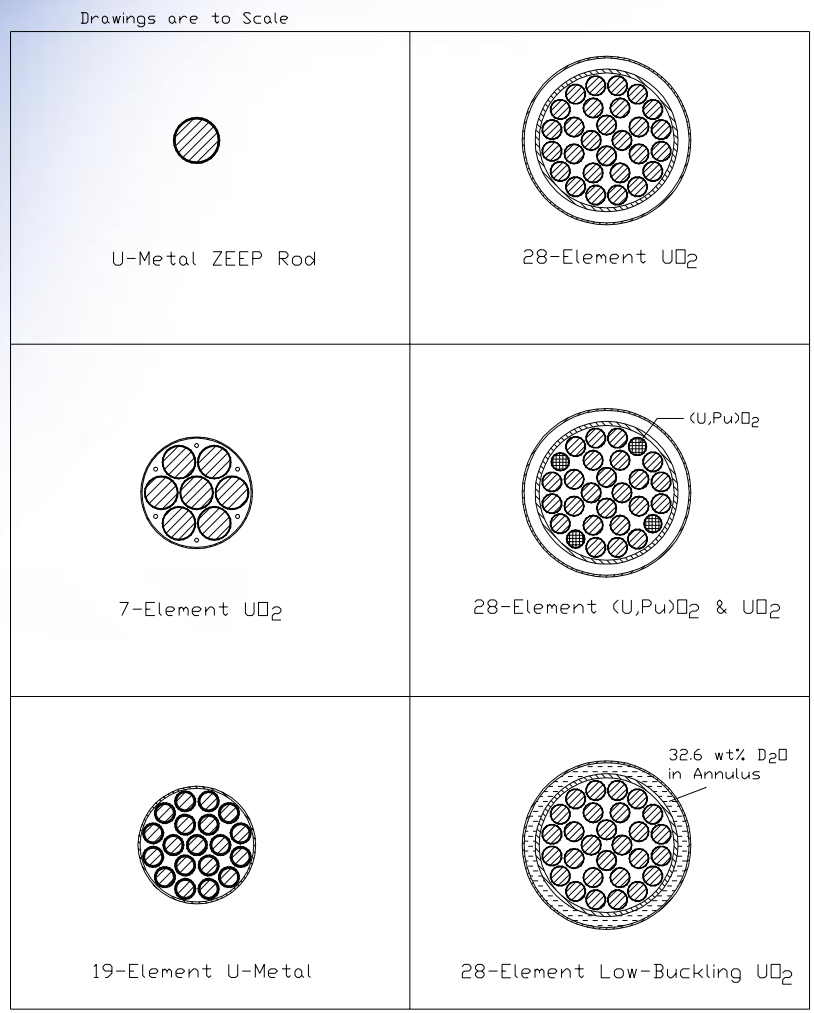
Substitution Analysis (con't)

Substitution Analysis (con't)

Substitution Method (conclusion)

Contamination Parameter

Validation of the Substitution Method



- Bucklings derived from full core flux maps are compared to bucklings derived using the substitution method.
- In a validation exercise extending over several years, measurements were made on 22 combinations of test and reference fuels in substitution experiments.
- Additional measurements have been performed and more are planned to expand the validation of the method into the ACR lattice regime

Substitution Method Validation

Measured Hc's and Flux Plots

Diffusion Theory Analysis

Bucklings and BCV*

Measured Flux Plots

Least Squares Fits

Bucklings and BCV

COMPARE

*BCV = Buckling change on voiding

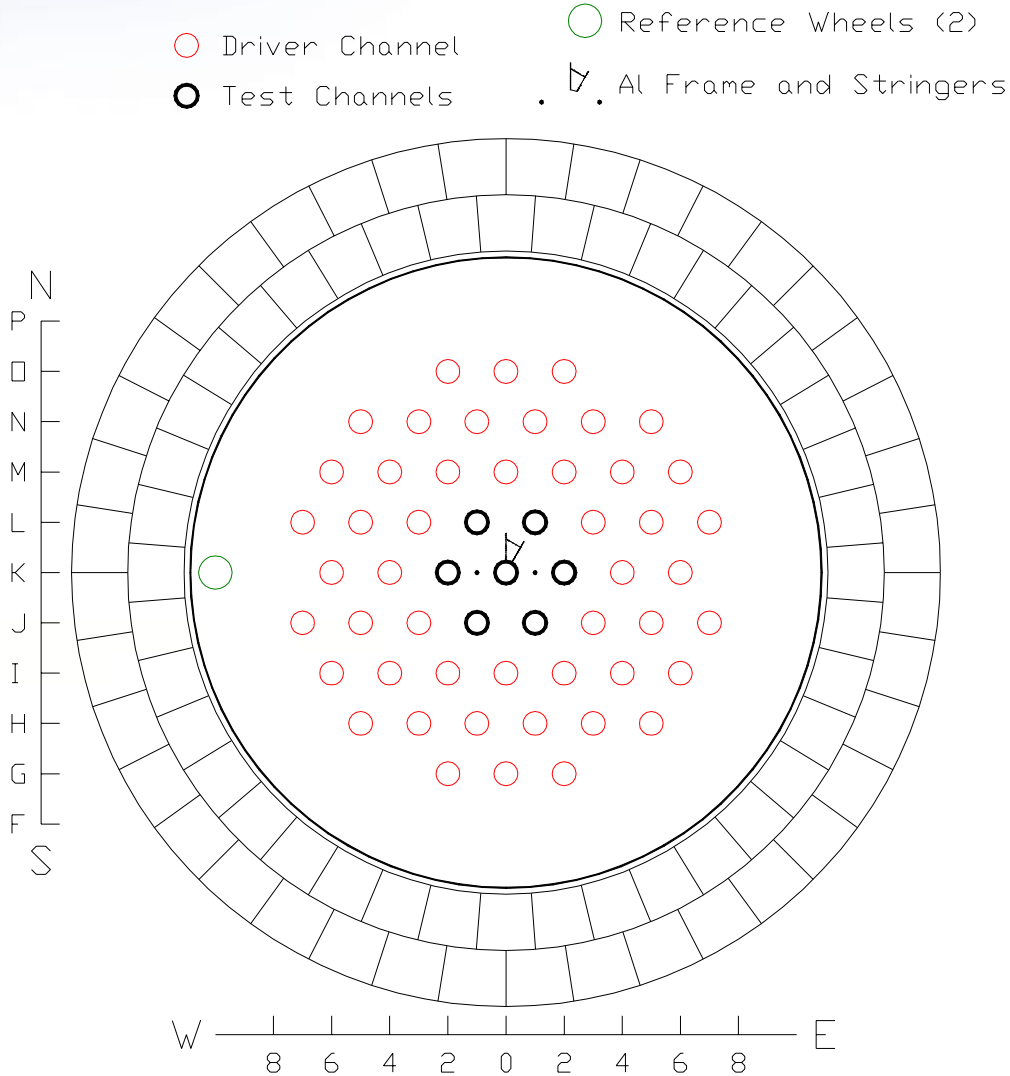
Substitution Method Validation

- Test Fuels
  - $7UO_2$
  - 19U
  - $28UO_2$
  - 28Pu Mix
  - $28UO_2$LB (Low Buckling)
  - $28UO_2$-H_2O
- Reference Lattices
  - 28PuMix-D_2O
  - $28UO_2$-Air
  - $28UO_2$-D_2O
  - ZEEP
  - $28UO_2$-H_2O
  - $28UO_2$LB-Air

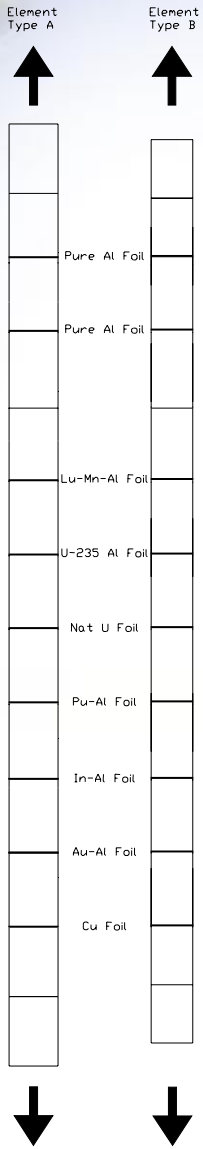
22 combinations of test fuel and reference lattice were measured and the bucklings and BCVs obtained compared with flux map values for the test fuels

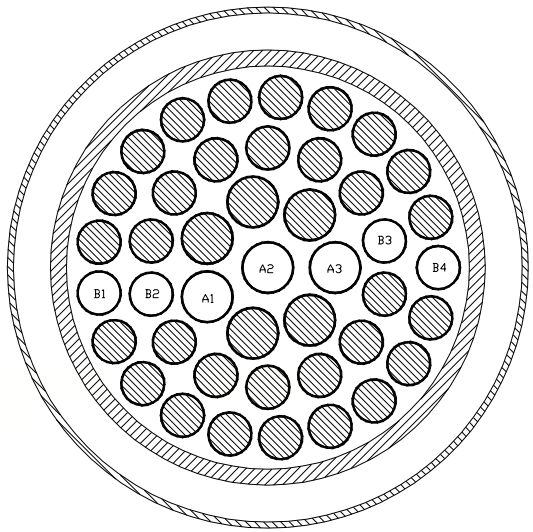
Substitution Validation

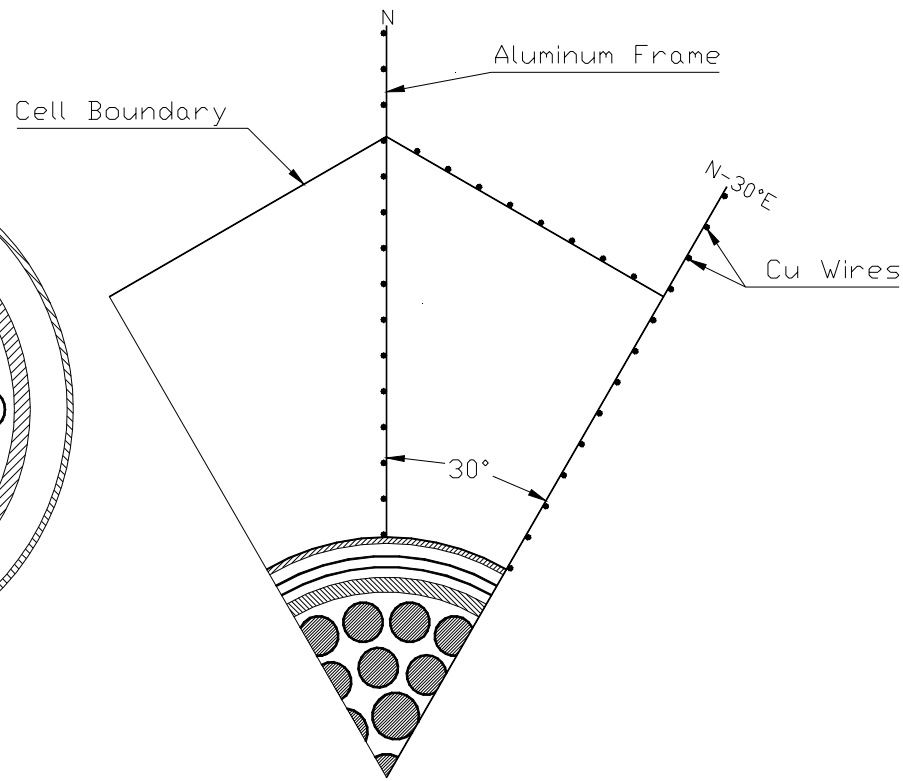
Fine Structure Including End Flux Peaking



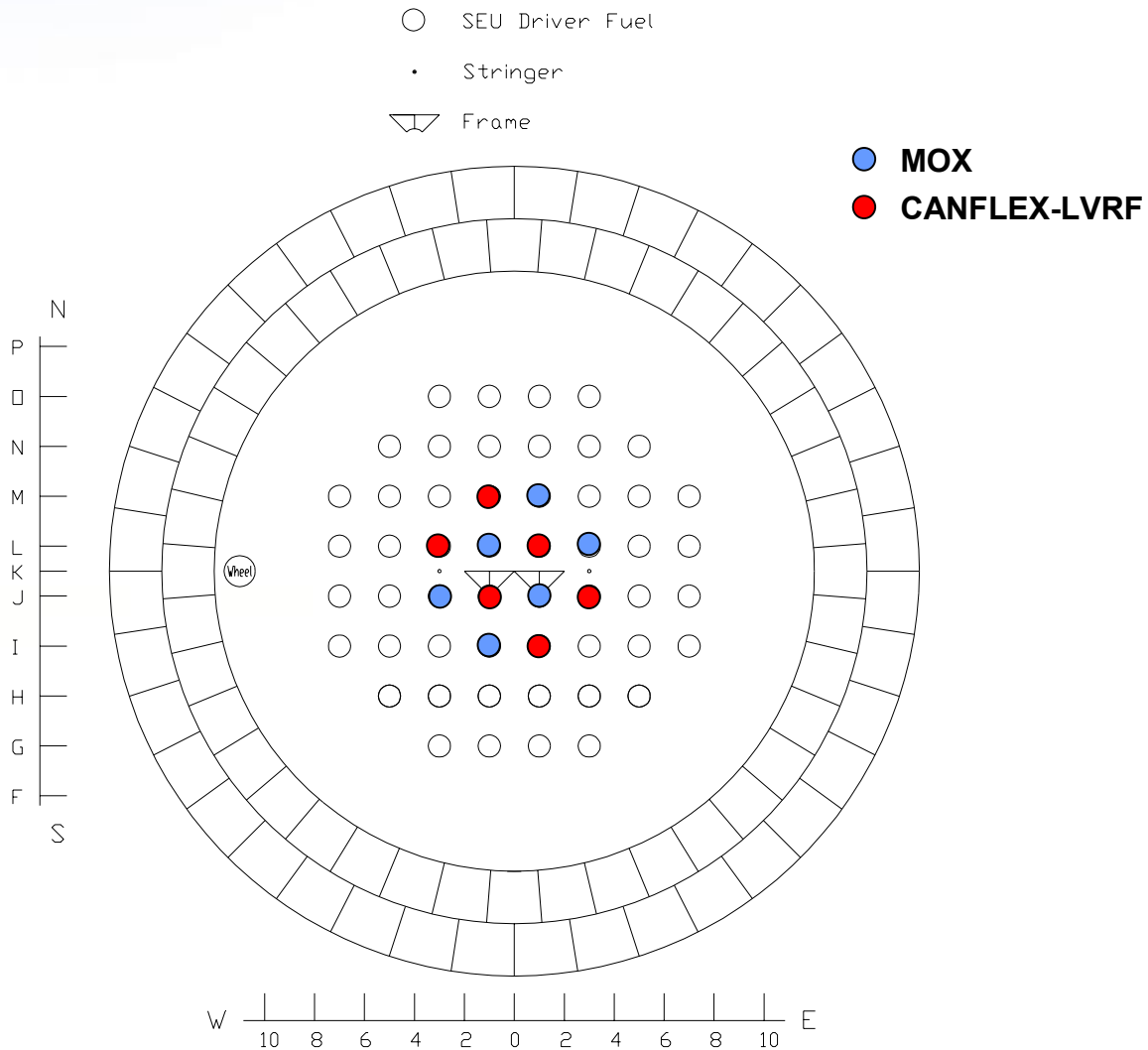
Demountable Bundle and Frame



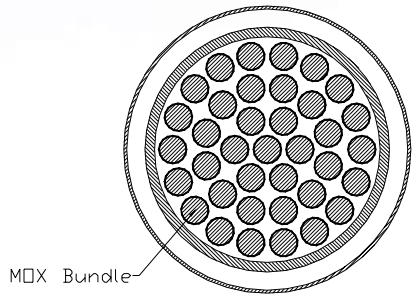


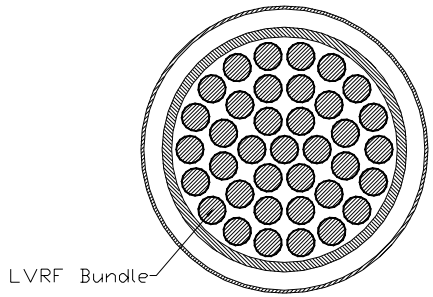


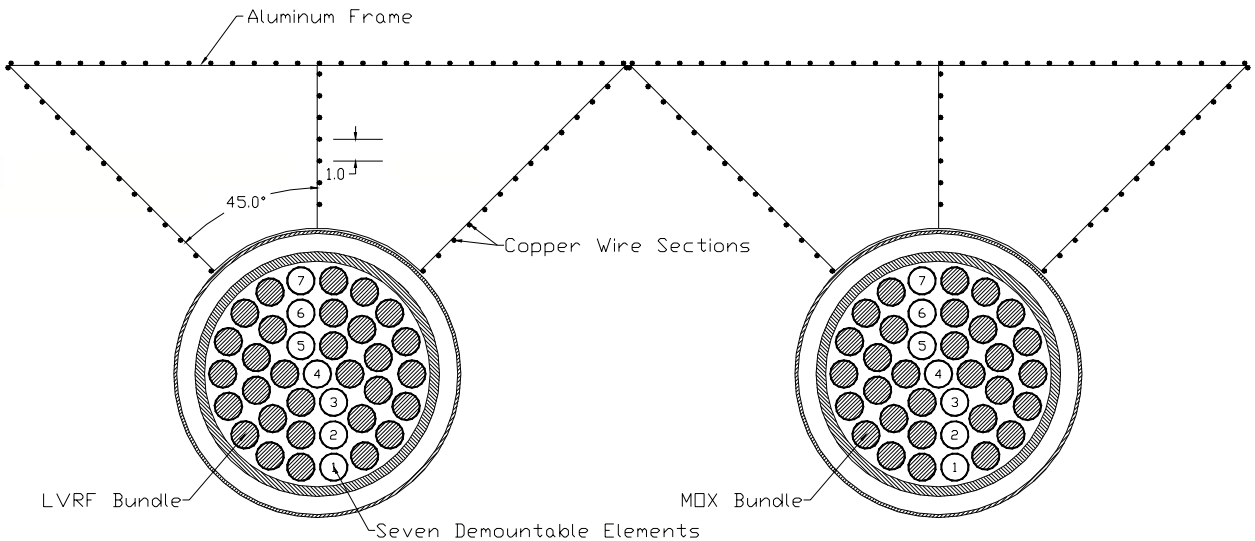
Square Lattice Fine Structure



Square Lattice Fine-Structure (con't)



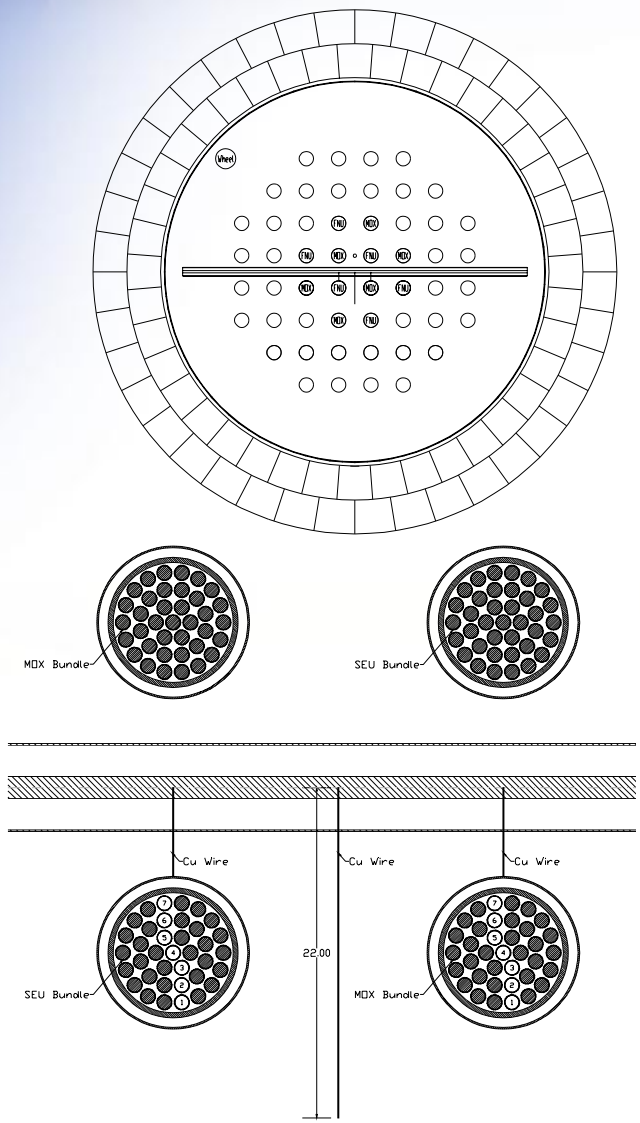




Fine Structure Analysis

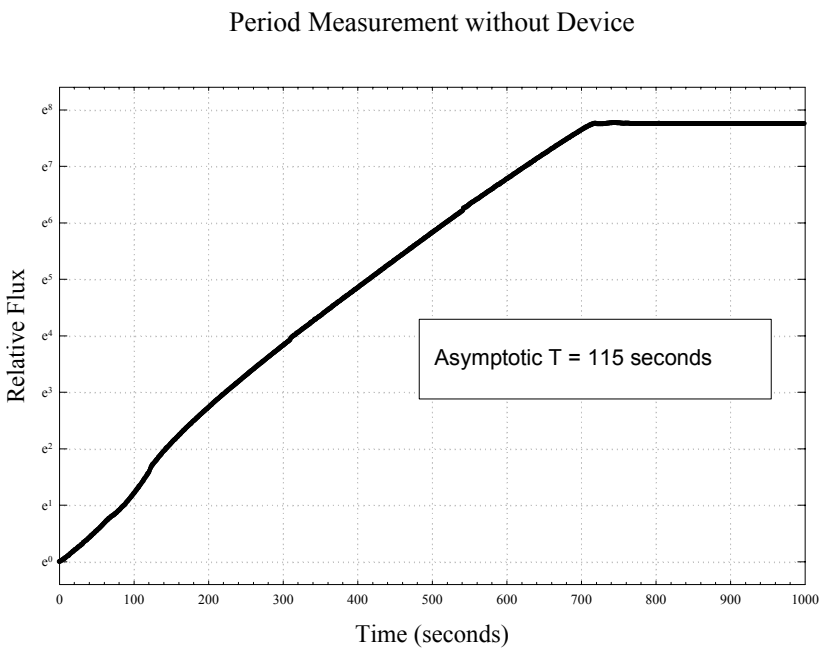
- U-235, Cu-63, and Mn-55 are approximately 1/v absorbers having only small resonance integrals
- Au-197 and In-115 have large resonances in the epithermal region at 4.916 eV &1.457 eV, respectively
- Pu-239, Lu-176 have large thermal resonances at 0.296 eV & 0.141 eV, respectively
- Reaction-rate ratios (normalized to the reference-wheel spectrum) are sensitive indicators of the energy spectra across the test cell
  - Pu-239/U-235 fission
  - Lu-176/Mn-55 capture
  - In-115/Cu-63 capture, etc.
- Activation data are compared directly to lattice cell predictions

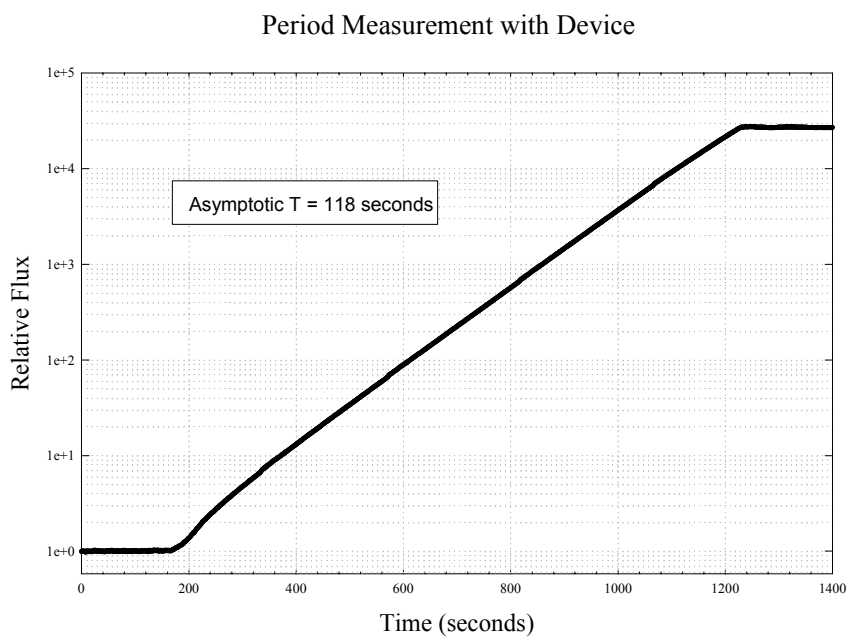
Absorber Worth Measurements



- **Absorber is suspended in the lattice and the following are measured**
  - **change in critical height on inserting absorber into lattice**
  - **global flux maps with and without absorber**
  - **fine-structure reaction rates in the fuel and moderator**
  - **data are suitable for validation of WIMS, RFSP, DRAGON & MCNP**
- **Alternatively reactor period is measured with and without the absorber to determine its worth**

Reactivity Worth of Adjuster or ACR-Type Shut-Off Device Using Kinetics





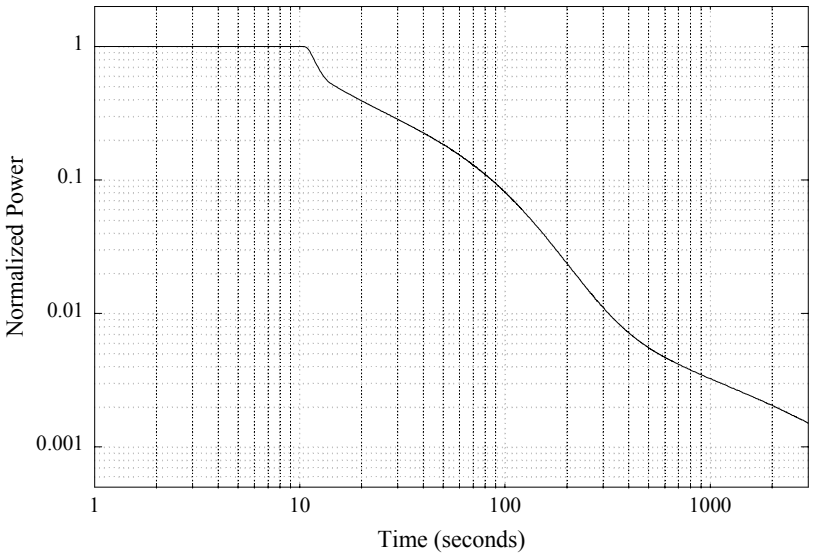
- **Reactor Period (T) is used to derive level-coefficient-of-reactivity through the in-hour equation**
- **level-coefficient-of-reactivity used to derive reactivity worth of a device through the difference in critical height with and without the device present in the reactor**

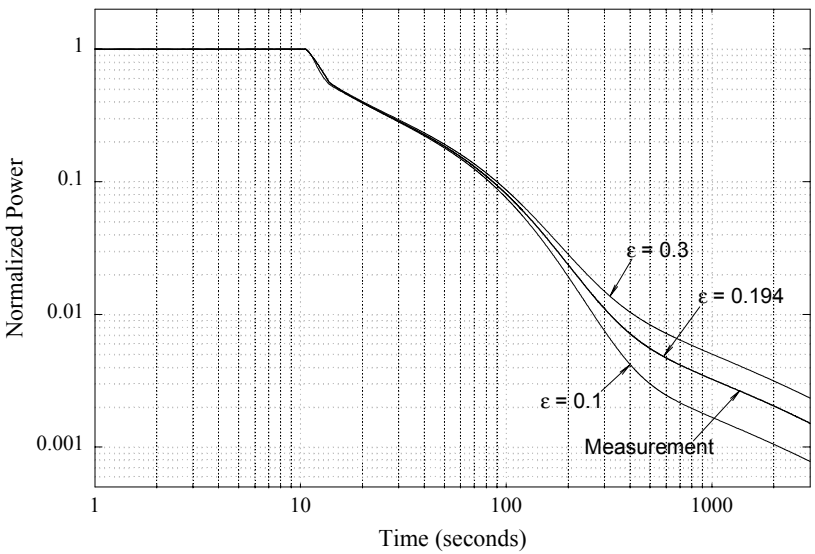
Requirements for Analyzing Period Measurements

Requirements for the analysis are:

- neutron yield per fission of ^{235}U
- effective delayed fraction and relative group yields and half-lives for ^{235}U direct delayed neutrons
- neutron yield per fission of ^{238}U
- relative numbers of fissions of ^{235}U and ^{238}U in the lattice
- effective delayed fraction and relative group yields and half-lives for ^{238}U direct delayed neutrons
- relative group yields and half-lives for delayed photo-neutrons
- relative yields of delayed photo-neutrons for ^{235}U and ^{238}U
- effective yield of delayed photo-neutrons for ^{235}U and ^{238}U (derived using a rod drop experiment)

Rod Drop Analysis to derive Photo-Neutron Component of Beta





- An absorber rod is dropped into the lattice and the resulting negative transient is measured (top curve)
- Methods of analysis used:
  1. inverse point kinetics
  2. direct point kinetics simulation of the transient
- In (1.) only the effective delayed photo-neutron fraction is allowed to vary so that a constant reactivity is achieved after the rod drop is complete (data from top curve provides input).
- In (2.) the same variation as in (1.) is allowed, but the reactivity worth of the rod is known (bottom curve).

Establishing Experimental Uncertainties

- For almost all measurements uncertainties are dominated by systematics
- Systematic uncertainties must be identified, quantified and corrected for
- Examples of systematics in ZED-2 measurements include
  - positioning of activation foils in a test lattice
  - self shielding in the foils
  - gap effects due to the difference in “fuel blackness” for fine-structure measurements
  - accuracy of core conditions (e.g. moderator purity)
  - thermal expansion of assemblies for high temperature work
  - stress and strain effects for high temperature work
- The approach is to “randomize” the various systematic errors

Establishing Uncertainties (con't)

Gap Effects

ZED-2 Measurements using Existing Fuel

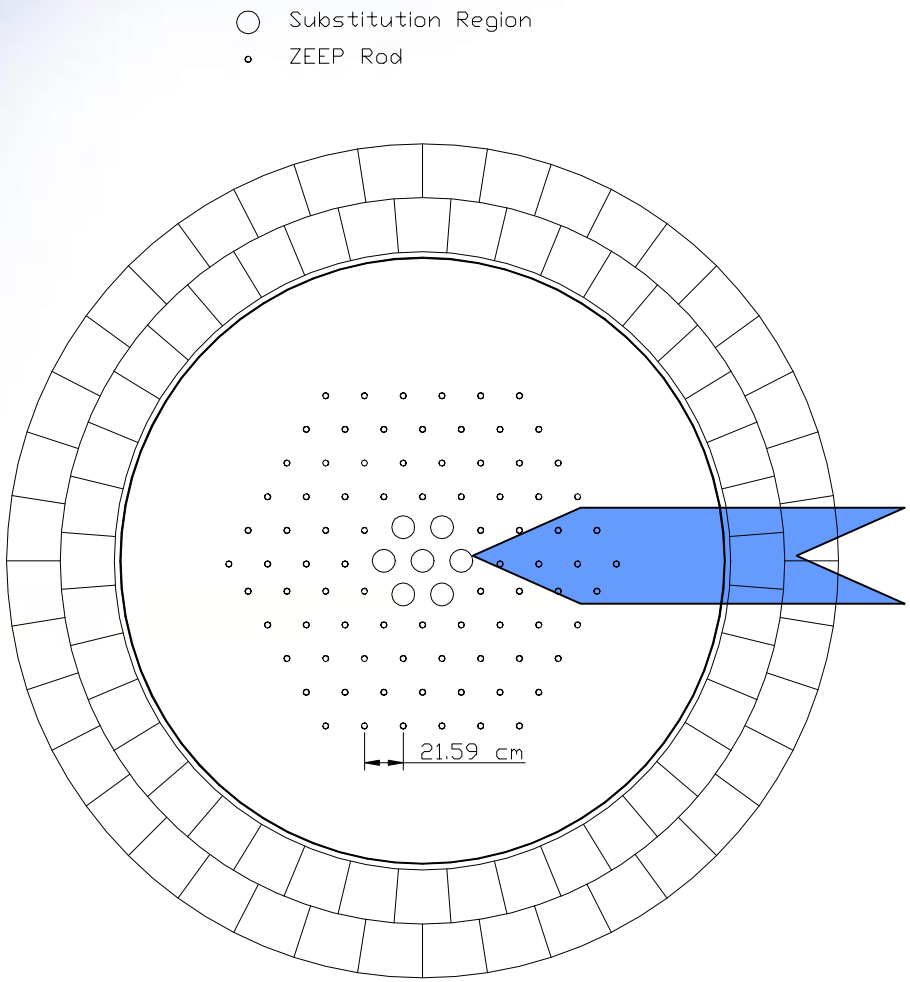
ZED-2 Measurements using Existing Fuel (con't)

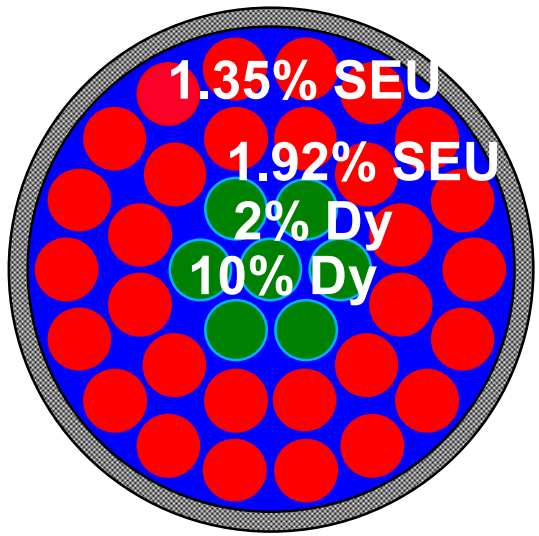
28-Element Flux Map Results

Sequence of Adding Light Water into a Voided 28-Element Reference Lattice

Analysis using ZED-2 MCNP Model

Substitutions of 37-Element LVRF



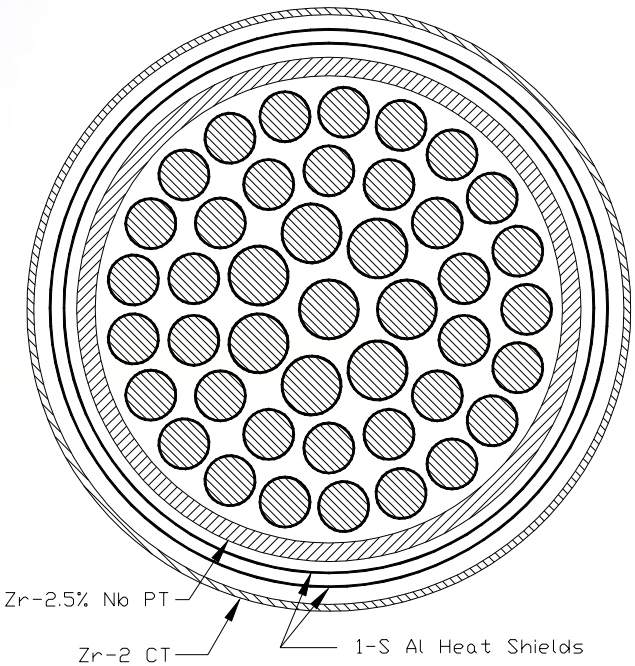


37-element LVRF

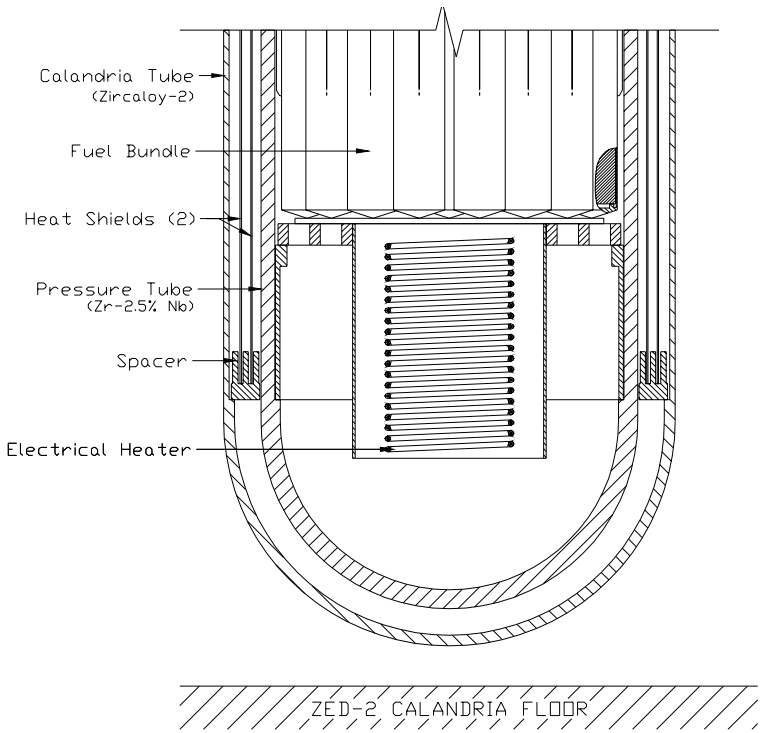
Substitution Analysis on 37-Element LVRF

High Temperature Measurements on LVRF

PLAN VIEW



BOTTOM SECTION



High Temperature Measurements on LVRF Results

CANFLEX SEU Reference Fuel for ACR Experiments

CANFLEX SEU Reference Fuel (con't)

Test Cells with a 7.1 Moderator-to-Fuel Ratio

Critical Height Predictions

Buckling Measurements using CANFLEX SEU Reference Fuel

Substitution Measurements using ACR-Type Fuel Channels

ACR-type Assemblies for ZED-2 Tests

Fine-Structure Measurements

Control Device Measurements

Summary

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