Qualification of the Reactor Physics Toolset for Current Reactors

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RP Code Validation Methodology

- **Follows the following steps:**
  - Review of the design basis accidents describing their progressions and the physical phenomena involved (The Technical Basis Document)
  - Definition of Reactor Physics Phenomena and ranking of their importance in the design basis accidents
  - Assembly of data sets for validation of the codes for the various phenomena (The Validation Matrix)
  - Validation of the codes against the selected data sets (Validation Reports)
  - Overall summary of the results of the validation (The Validation Manual)

The Reactor Physics Phenomena

- **Sixteen phenomena have been identified:**
- Coolant-Density-Change induced reactivity
- Coolant-Temperature-Change induced reactivity
- Moderator-Density-Change induced reactivity
- Moderator-Temperature-Change induced reactivity
- Moderator-Poison-Change induced reactivity
- Moderator-Purity-Change induced reactivity
- Fuel-Temperature-Change induced reactivity
- Fuel-Isotopic-Composition-Change induced reactivity
- Refueling induced reactivity
- Fuel-String-Relocation induced reactivity

RP Phenomena Cont.

- Device-Movement induced reactivity
- Prompt/Delayed neutron kinetics
- Flux-Detector response
- Flux and Power Distribution (Prompt/Decay Heat) in space and time
- Lattice-Geometry-Distortion reactivity effects
- Coolant-Purity-Change induced reactivity

Sources of Validation Data

- **Zero Energy Lattice Measurements (ZED-2)**
  - Provide data mainly for cell-code validation, but some for core-code
  - Measure lattice bucklings for reactivity, foil activation for flux/spectrum throughout the cell
  - Generally very accurate measurements, but for a limited range of state parameters, especially temperatures and fuel compositions
- **Measurements from Power Reactors**
  - Exclusively for core-code validation
  - Not generally as accurate as zero power measurements.

Sources of Validation Data, Cont.

- Code Intercomparisons (MCNP) used to:
  - Extend data-base of lattice parameter measurements to state parameter values (temperatures, compositions, etc.) found in power reactors in normal operation and upset conditions
  - To provide full core calculations for comparison with RFSP to confirm the applicability of 2-group diffusion theory as implemented in RFSP, eg methods used for representing reactivity control devices, coolant voiding in interlaced channels etc.

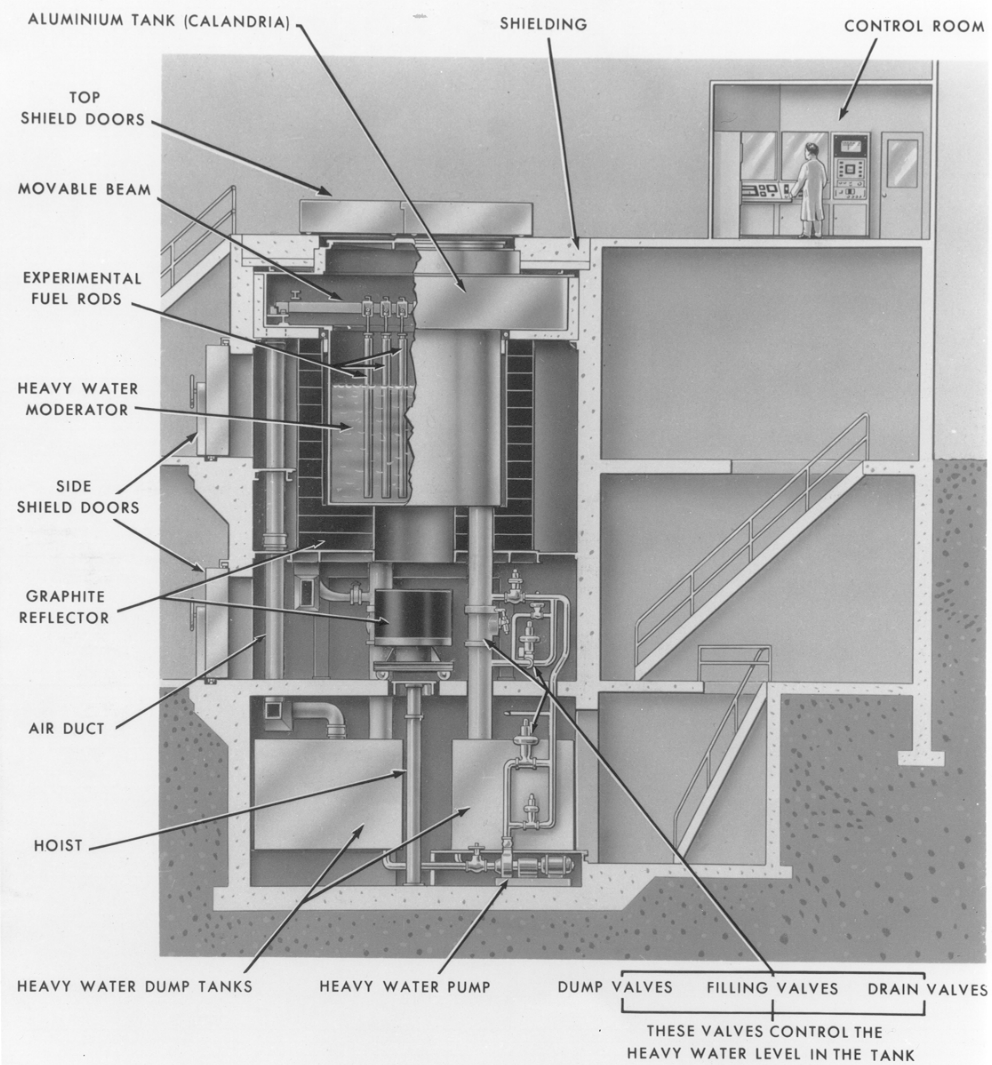
Validation for Phenomenon 01: Coolant density (void)

- This phenomenon is most important in a large loss of coolant accident (LLOCA)
  - Sudden major break in a PHT header leading to rapid voiding of a large fraction (25% in a C6) of the fuel channels in the core
  - Transient is modeled by the 3D kinetic module of RFSP, which includes the operation of the safety system, coupled with a thermalhydraulic code that models the coolant voiding
- Also a significant phenomenon in other accidents, eg loss of power to main PHT pumps.

PH01 Continued

- The greatest effort in validating for this phenomenon was put into validation of the cell code WIMS-IST
- This involved a long series of measurements in the zero energy facility ZED-2 in which the bucklings of lattices with and without coolant in the channel were measured.

ZED-2

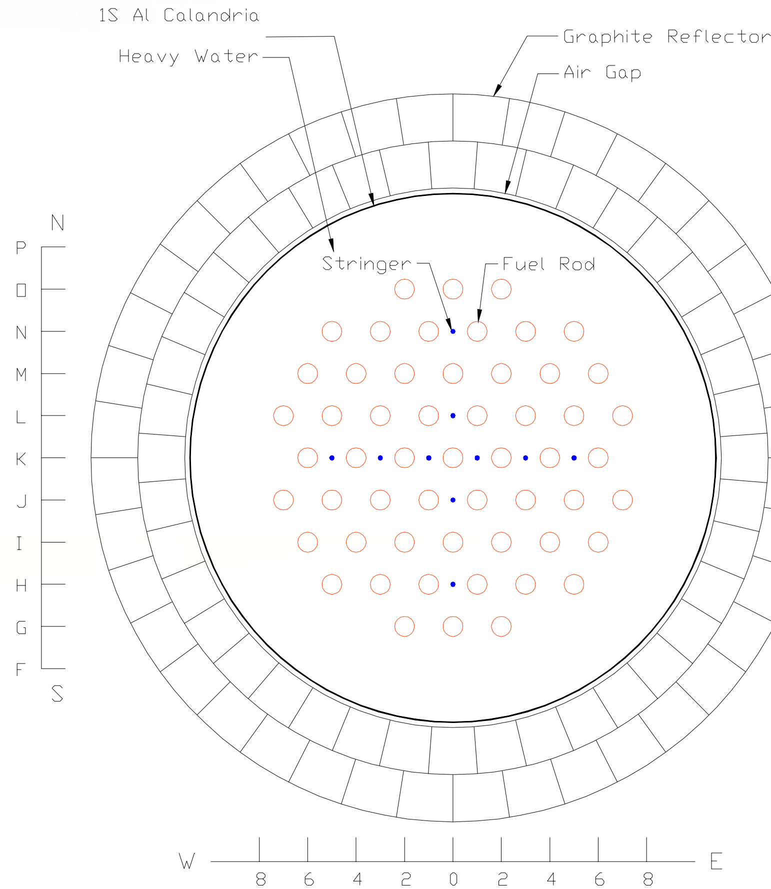


ZED-2 REACTOR

ATOMIC ENERGY OF CANADA LTD - RESEARCH CO.

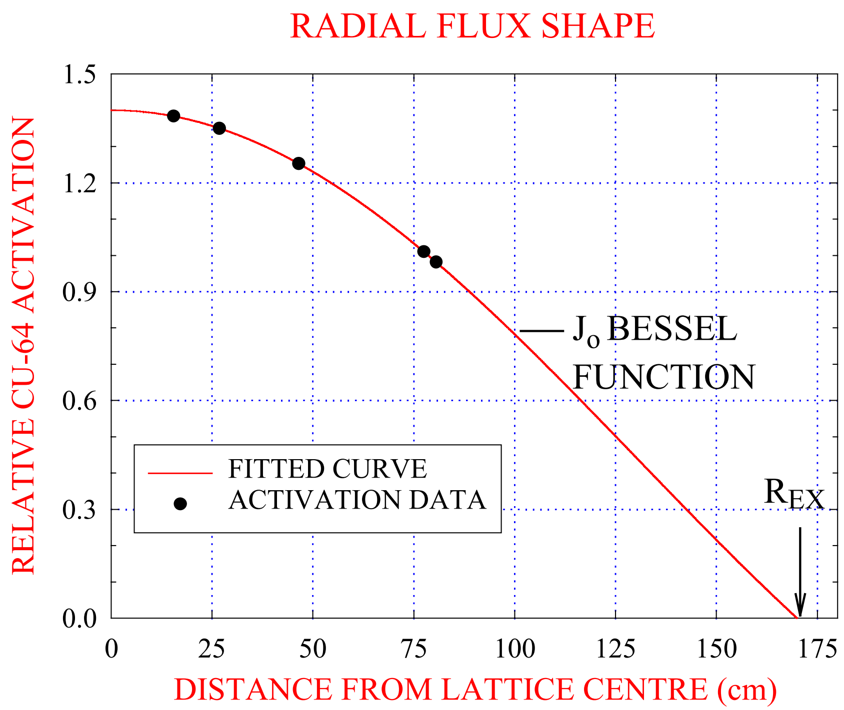
ZED-2

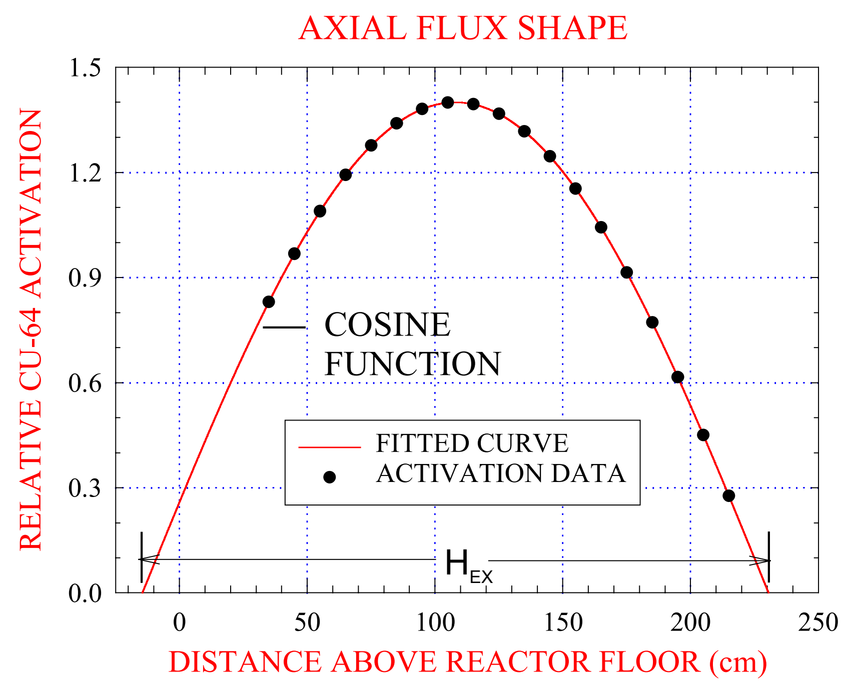
Flux-Map Buckling Measurement



Drawing is to scale

Flux-Map Buckling





$$\phi = \phi_0 \left(\cos(\alpha(z - z_0)) + J_0(\lambda r) \right)$$

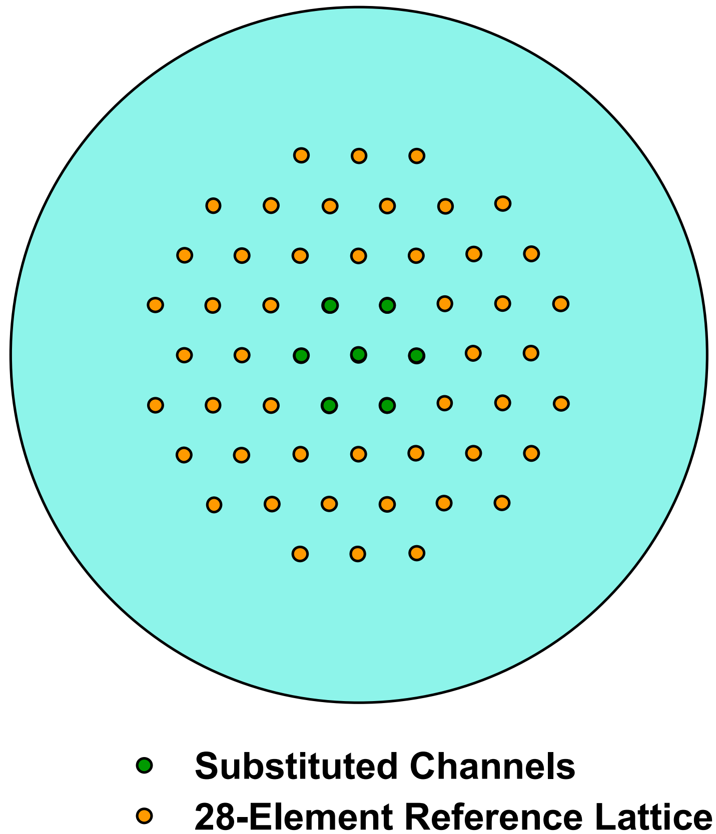
$$B^2 = \alpha^2 + \lambda^2$$

Measurement of Buckling by Substitution

- The general aim of these measurements was to measure data for conditions as close as possible to those found in operating power reactors, such as:
  - for burned up fuel
  - at high channel temperatures
  - for downgraded coolant
  - for poisoned moderator
  - for a range of coolant densities.
  - for radially crept pressure tubes
- Covering such a wide range of conditions necessitated the development of a method of measuring buckling using a smaller quantity of fuel: the substitution method.

SUBSTITUTION MEASUREMENTS IN ZED-2

- Requires only 35 bundles substituted in a reference lattice compared to about 275 bundles for a critical core
- Can measure void-reactivity and lattice reactivity for fuel/coolant temperatures in the range 25 to 300°C



Validation of the Substitution Method of Buckling Measurement.

- We had to find a way to show that the substitution method (a combination of in-reactor measurement and analysis) would work for the proposed MOX fuel.
- More than show the method "would work" we needed to be able to make a statement about the accuracy (uncertainty, precision) of the buckling values and BCV that would be obtained for the MOX fuel.
- The approach chosen was to compare substitution measurements of buckling and BCV with flux map values for the same lattices, for as wide a variety of test fuels and reference lattices as we could muster at reasonable cost.

Test Fuels and Reference Lattices

- Test Fuels
  - 7UO2
  - 19U
  - 28UO2
  - 28Pu Mix
  - 28UO2LB (Low Buckling)
  - 28UO2-H2O

- Reference Lattices
  - 28PuMix-D2O
  - 28UO2-Air
  - 28UO2-D2O
  - ZEEP
  - 28UO2-H2O
  - 28UO2LB-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 Method Validation

Measured Hc's and Flux Plots

BLACK BOX

Bucklings and BCV

Measured Flux Plots

Least Squares Fits

Bucklings and BCV

COMPARE

WIMS/MCNP Lattice Calculation Comparisons

- To extend the parameter space covered by ZED-2 measurements:
  - Higher fuel temperatures
  - More burnups
  - Higher moderator poison levels
  - Radially crept pressure tubes
  - Etc.

WIMS/RFSP MCNP Core Calculation Comparisons

- Comparisons made for a simplified C6 equilibrium core:
  - Eleven different fuel burnups
  - All 21 adjuster rods modeled, in and out
  - Zone controllers not modeled
  - Same coolant density and temperature throughout core
  - Same fuel temperature throughout core
  - Bundle end regions not modeled
  - CVR calculated for quarter core interlaced voiding, with and without adjuster rods inserted

Validation from Power Reactor measurements

- No validation data available
- Coolant density does change by about 20% as the reactor is heated up using pump heat after a long shutdown, but other reactivity effects interfere with a CVR measurement, eg fuel and coolant temperature, moderator temperature.
- In general it is hard to measure separate effects in a power reactor, but useful integral validation is possible.

Summary of Results of the Validation Exercise (All Phenomena)

- Summarized in the Validation Manual
- For four out of sixteen phenomena a bias larger than the uncertainty was identified
- Gaps in the data base of experiments or analyses were identified for ten phenomena
- The significance of the gaps is being assessed and for some of them additional measurements and analyses have been proposed

Review by an Independent Expert Panel

- Set up by the industry (Canadian utilities and AECL) and the regulator to help them to reach a conclusion regarding the appropriateness of: the bias and uncertainty proposed for CVR and Fuel Temperature Coefficient and the delayed neutron data proposed for use in LOCA transient analysis
- International panel: 3 from USA, 1 from Europe and 1 from Canada

Expert Panel Conclusions

- **Final report is not yet issued, but some conclusions are:**
  - **The ZED-2 measurements of buckling change on voiding are accurate to +/- 0.7 mk**
  - **Further WIMS/MCNP comparisons of lattice CVR would be desirable**
  - **Questions remain regarding the CVR of 28-element fuel**
  - **The bias and offset of the fuel temperature coefficient have not been convincingly supported.**
  - **The delayed neutron data proposed is appropriate**

Final Words

- The methodology adopted for validation of the reactor physics codes used for the analysis of existing CANDU reactors has been described
- Some of the ZED-2 measurements used in the validation have been described as have additional calculations used to extend the measurement validation to equilibrium power reactor cores at operating and upset conditions
- The same basic approach will be taken to validation for the ACR