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.

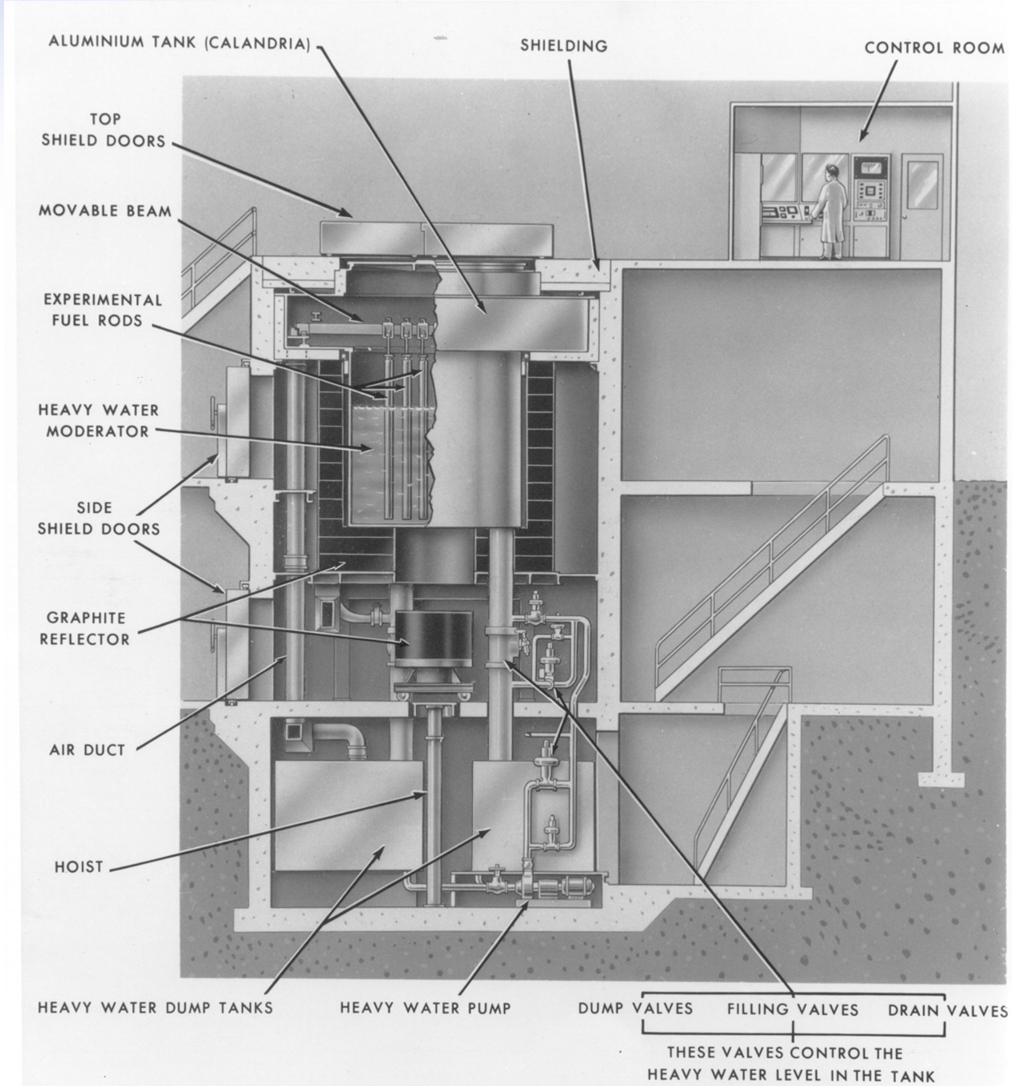
Validation for Phenomenon 01: Coolant density (void)

- 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

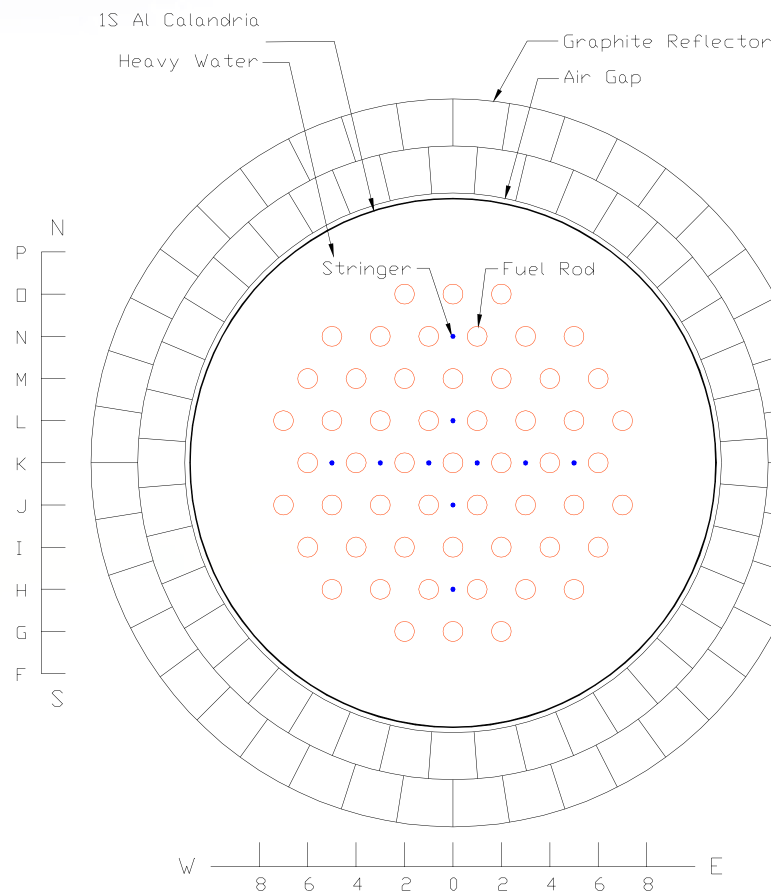


ZED-2 REACTOR

ATOMIC ENERGY OF CANADA LTD - RESEARCH CO.

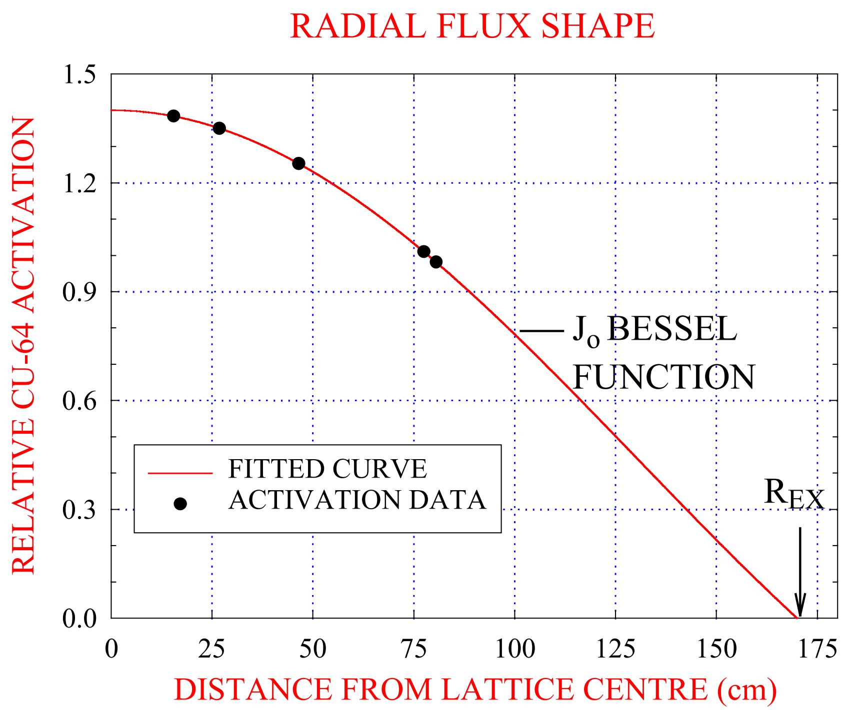
ZED-2

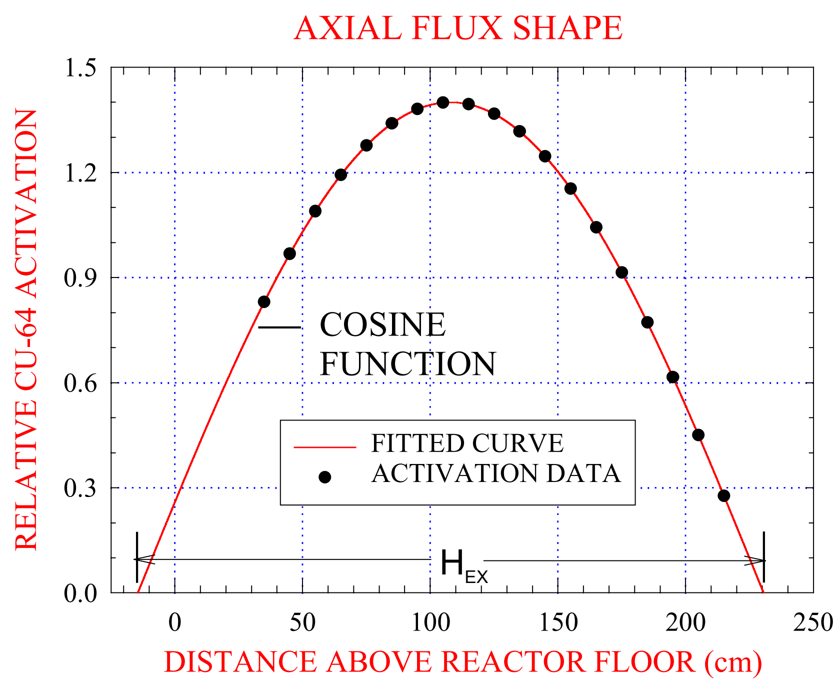
Flux-Map Buckling Measurement



Drawing is to scale

Flux-Map Buckling





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

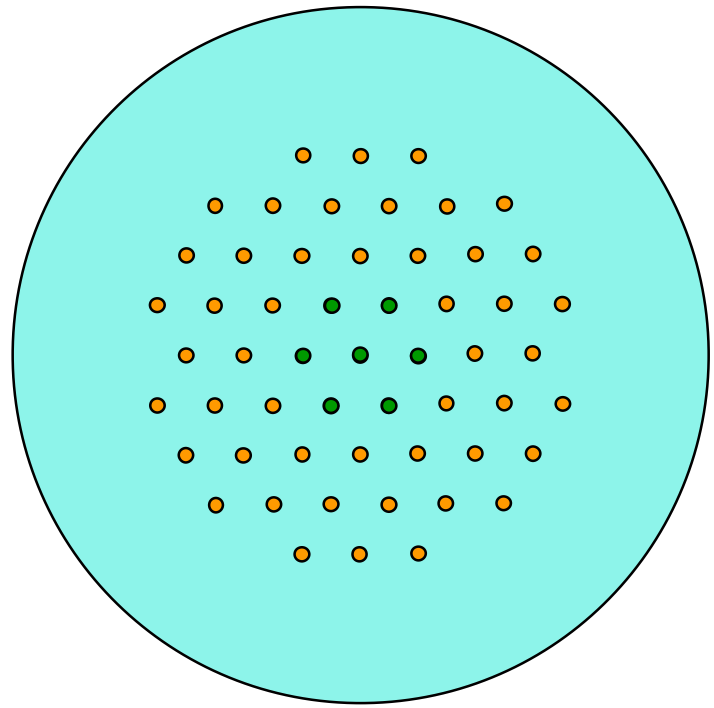
$$B^2 = \alpha^2 + \lambda^2$$

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



- Substituted Channels
- 28-Element Reference Lattice

Validation of the Substitution Method of Buckling Measurement.

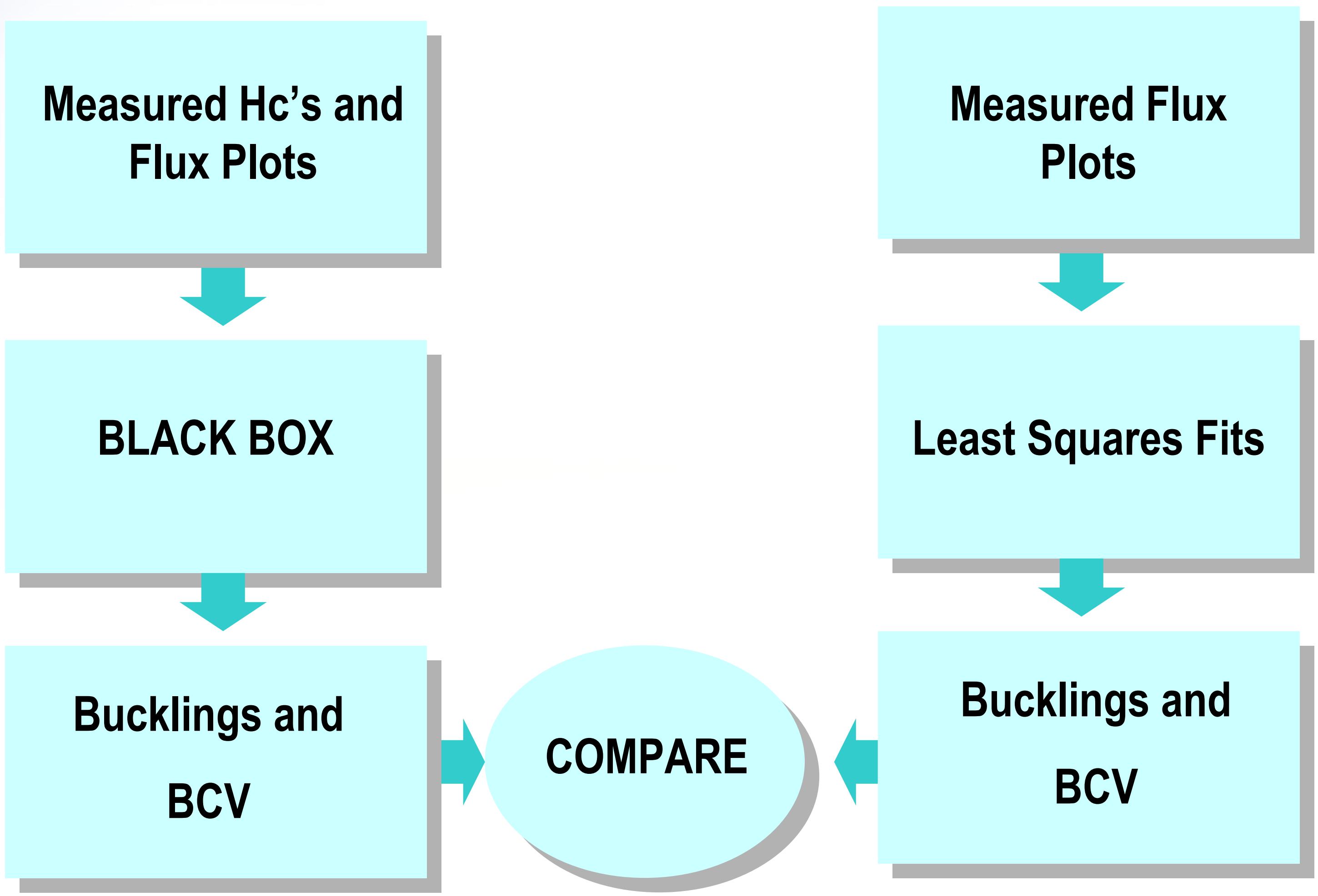
- We had to find a way to show that the substitution method (a combination of in-reactor measurement and analysis) would work for the proposed MOX fuel.
- More than show the method “would work” we needed to be able to make a statement about the accuracy (uncertainty, precision) of the buckling values 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



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