An Algorithm to Correct for Control Rod Cusping in the NESTLE Multidimensional Neutronics Module of RELAP5-3D

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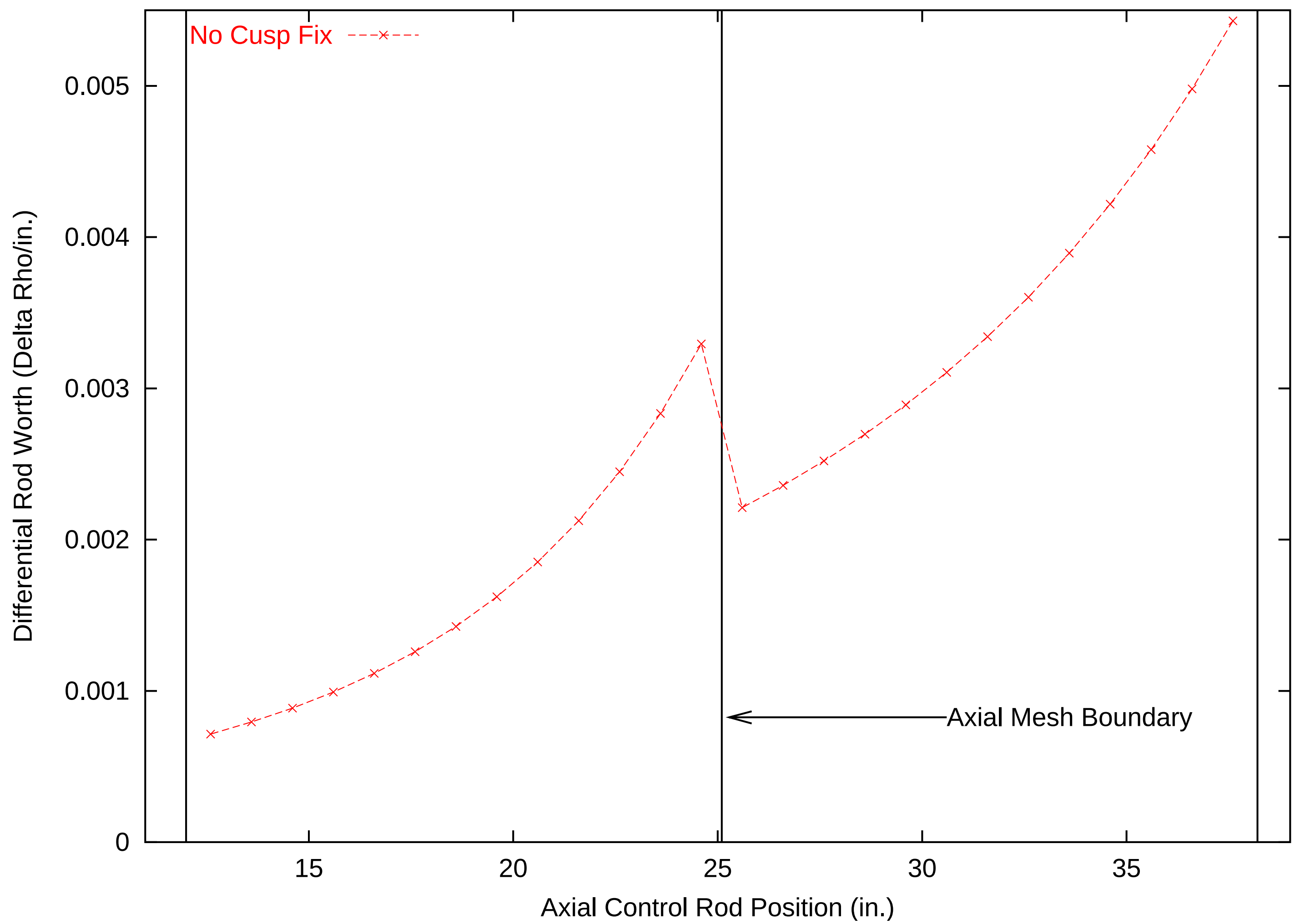
Presentation Overview

- Introduction
- Overview of the NESTLE NEM Solution Technique
- Overview of Several Control Rod Cusping Correction Techniques
- Description of the Finite-Volume Correction Technique
- Assessment of the Correction in Steady-State and Transient Analyses
- Conclusions

Introduction

- Some transients involving control rod motion in operating reactors present the need for multidimensional neutronics simulation.
- Control Rod Cusping, which causes the core reactivity level and power distribution to be inaccurately predicted, occurs when rod tips lie at axial positions which do not correspond to node boundaries.
- Control Rod Cusping is the result of not using flux * volume weighted cross sections in homogenized partially rodded nodes.
- Auxiliary 1-D axial diffusion-theory calculations which incorporate explicit rod-out and rod-in cross-sections can be used to obtain flux * volume weighted cross-sections in partially rodded nodes.
- Use of these adjusted cross sections have been shown to reduce the Control Rod Cusping effect on reactivity in both the transient and steady-state analysis of a 3-D PWR test problem.

Differential Control Rod Worths for a Westinghouse PWR Without Control Rod Cusping Correction



Overview of the NEM Technique as Implemented in NESTLE

- The main neutronics solution algorithm is a simple coarse-mesh finite-difference (CMFD) method (only unknowns are node-average fluxes) with adjustable connectivity between adjacent nodes.
- Node connectivity is adjusted at every N-th user-specified source iteration using the results of higher-order 1-D NEM 2-node auxiliary calculations.
- The 4th-order Nodal Expansion Method (NEM) algorithm employed by NESTLE expands the spatial dependence of the 1-D intranodal flux profiles in a series of polynomials ranging from 1st through 4th order.
- The coefficients of these polynomials are obtained from boundary conditions, continuity of flux and current at node interfaces as well as weighted-residual constraints within a given node.
- The resulting NEM intranodal flux solutions from the 2-node problems are then used to update the connectivity between adjacent nodes in the next source iteration of the main CMFD solution.

Description of the Control Rod Cusping Correction Techniques

Properties of all methods tested:

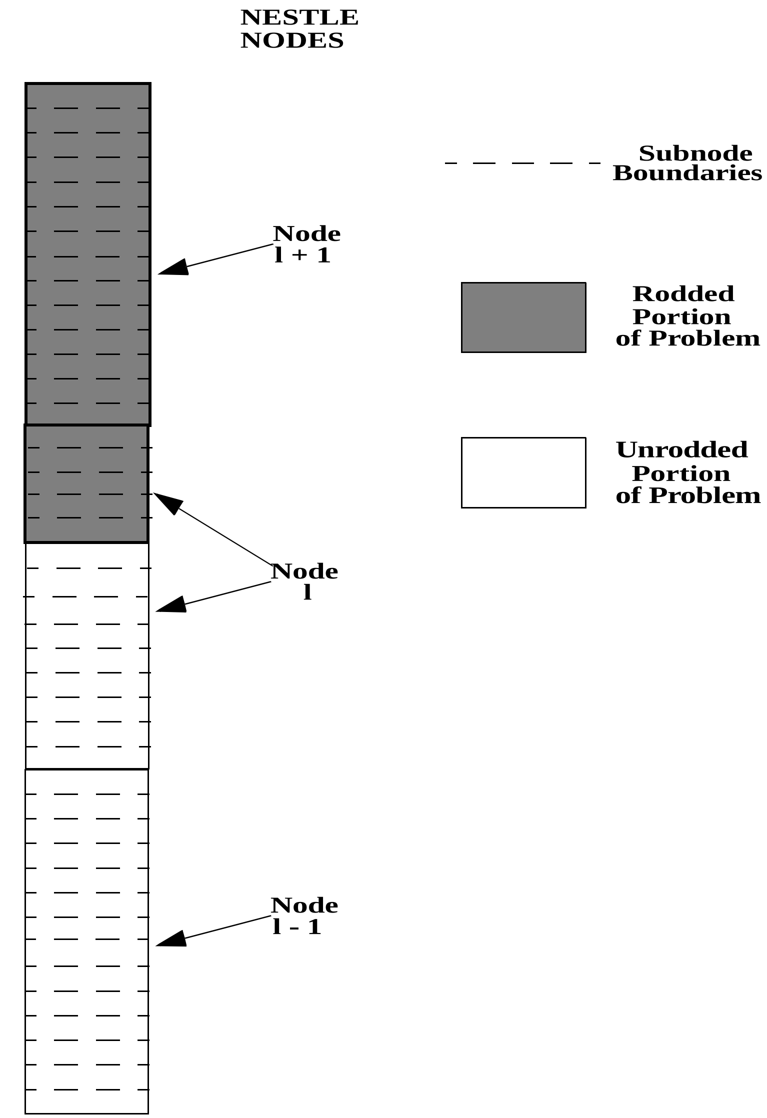
- Employ explicit auxiliary axial models of the rodded and unrodded regions (accounting for the position of the rod tip) of each partially rodded node as well as the fully rodded and unrodded nodes axially adjacent to these nodes (if available).
- Employ the most up-to-date cross-sections in all 4 portions of the problem solution space.
- Preserve the most recently calculated average fluxes in fully rodded and unrodded axial neighbor nodes.
- Approximate the transverse leakage source from radially adjacent nodes as quadratic functions of axial position.
- Calculate new weighting factors and update energy-group dependent cross-sections in all partially rodded nodes after completion of NEM update to CMFD solution (same for LSOR and Krylov solution tecniques).

Description of the Control Rod Cusping Correction Techniques (Cont)

Attributes/Deficiencies of Various Control Rod Cusping Correction Techniques:

- 4 Node 4th-Order NEM (same method as used in NESTLE NEM updates)
  - Method worked well except when rod very near axial node boundary (<2% or >98% inserted). **Extreme aspect ratios**
- Multi-Node 2nd-Order NEM (simply derived from 4th order NEM)
  - Method worked well when many subnodes used in partially rodded and axial neighbor nodes (nodes apportioned to rodded/ unrodded regions to achieve near equal node sizes).
  - 3 unknowns per node per energy group. **Slow**
- Multi-Node Finite-Volume Technique
  - Method again worked well when many subnodes used.
  - Single unknown per node per energy group.
  - Lower order solution than 2nd-Order NEM. **Need More Subnodes**

Auxiliary Fine-Mesh Finite-Volume Problem



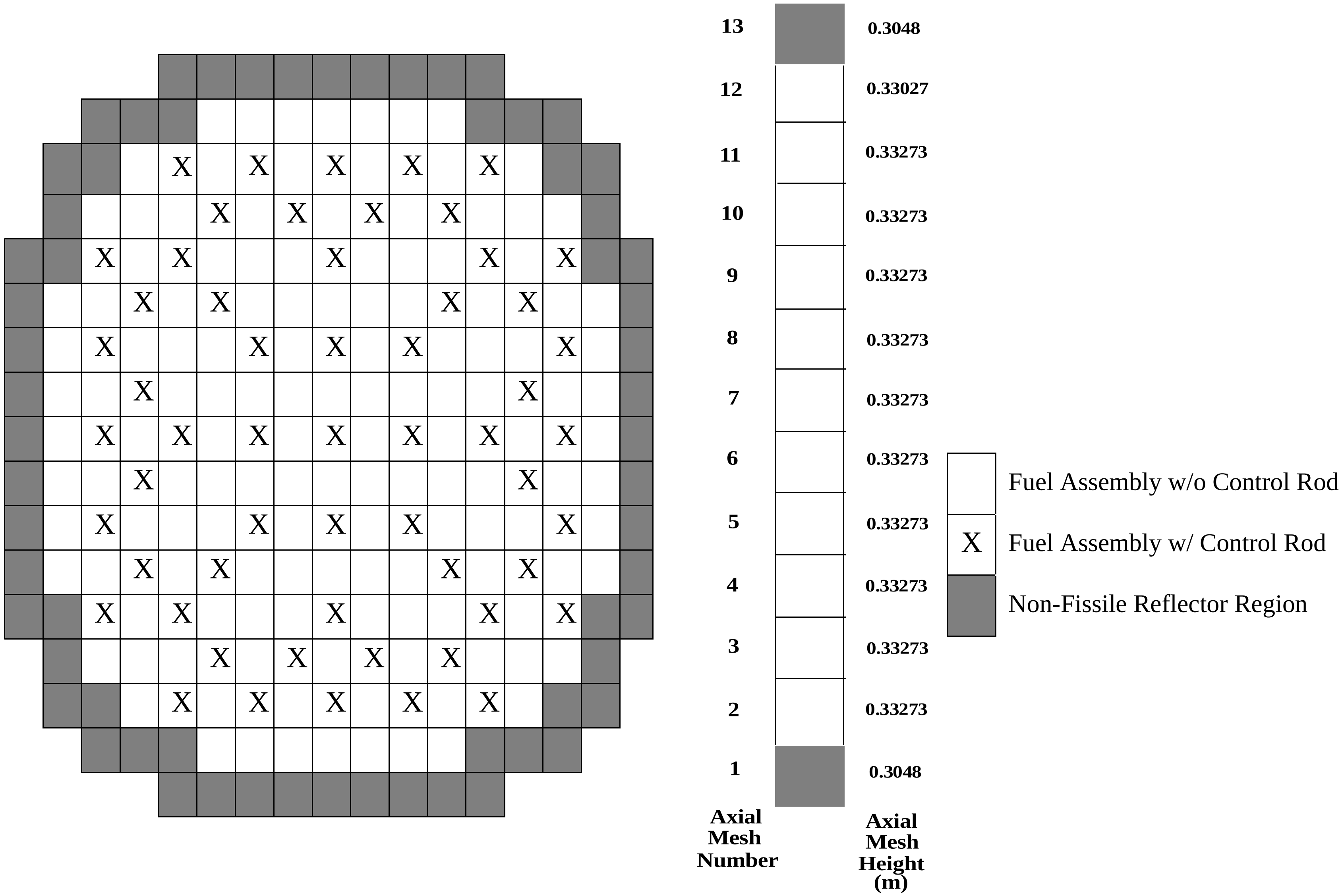
Fine-Mesh Finite-Volume Technique

- Finite-Volume Method enforces group-dependent nodal balance over each subnode.
- Fick's Law of Diffusion used to connect a given subnode to its axial neighbors.
- Latest values of transverse leakages (fit quadratically) and if applicable, non-implicit portion of transient and/or fixed sources terms make up Right Hand Sides of nodal balance equations.
- Known NESTLE fluxes in nodes above and below partially rodded node provide additional equations needed for closure.
- Resulting equations for the subnode neutron fluxes can be placed in matrix format and solved by direct means. (in this case the SuperLU algorithm)
- Same number of subnodes used at all rod tip locations.
  (A single matrix structure)

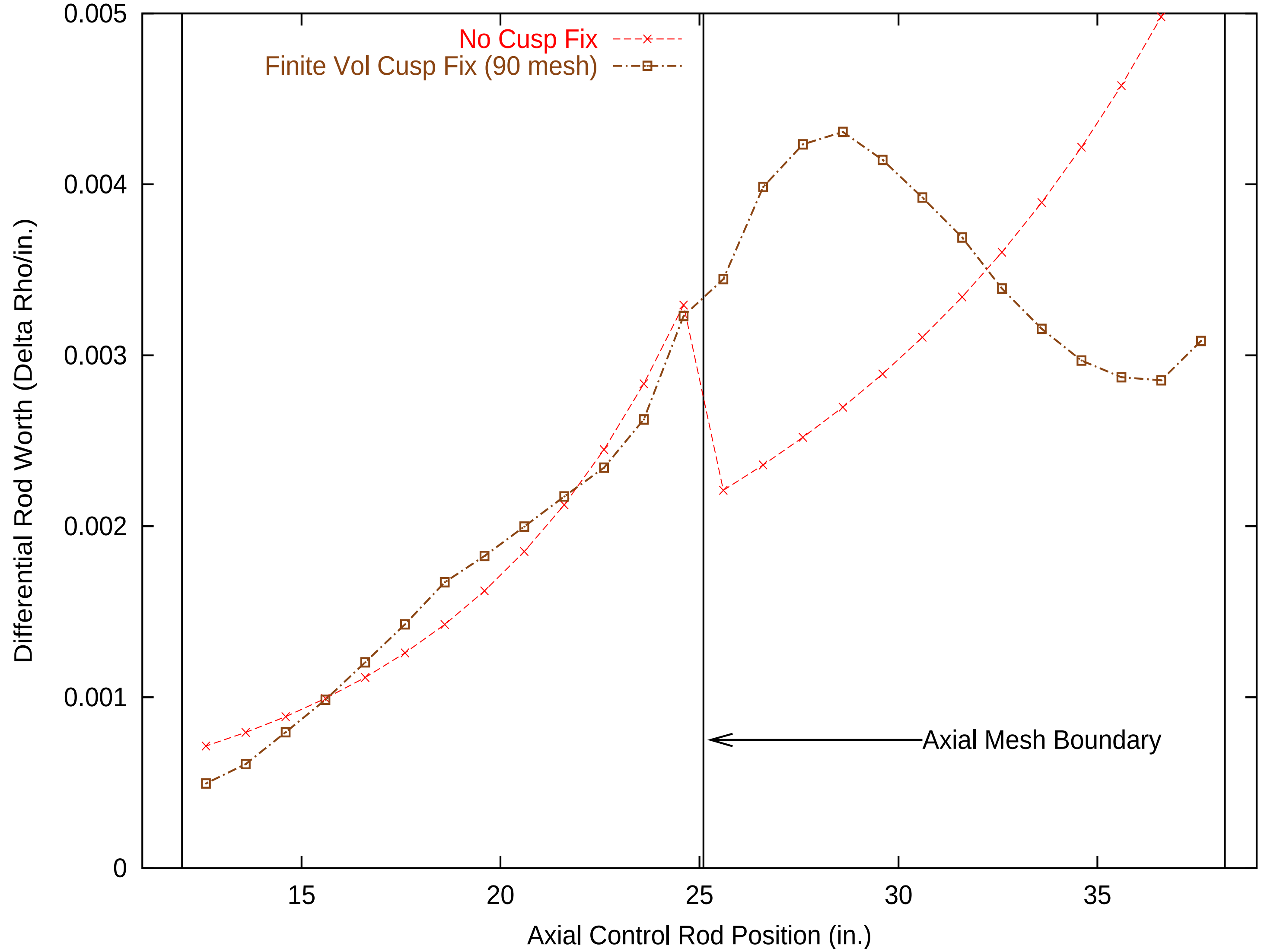
Westinghouse PWR Assessment Problem

- Test problem is INEEL modification of "Typical PWR" test verification suite problem.
- NESTLE multi-D nodal kinetics replaces point kinetics in problem.
- 2-group cross-sections obtained from NEACRP 3-D LWR benchmark. (dependence of cross-sections on T/H conditions ignored)
- Core consists of 193 PWR fuel assemblies, 57 of which contain control rods.
- 64 non-fueled assembly-sized regions represent radial reflector.
- Model divided axially into 13 ~1ft. tall nodes, 11 of which are in active core.
- In cases studied all 57 rods are moved as a single bank to magnify effects of Control Rod Cusping.
- Reactivity loss during Transient End State calculations obtained from immediate control rod insertion followed by ~30 sec. wait period.

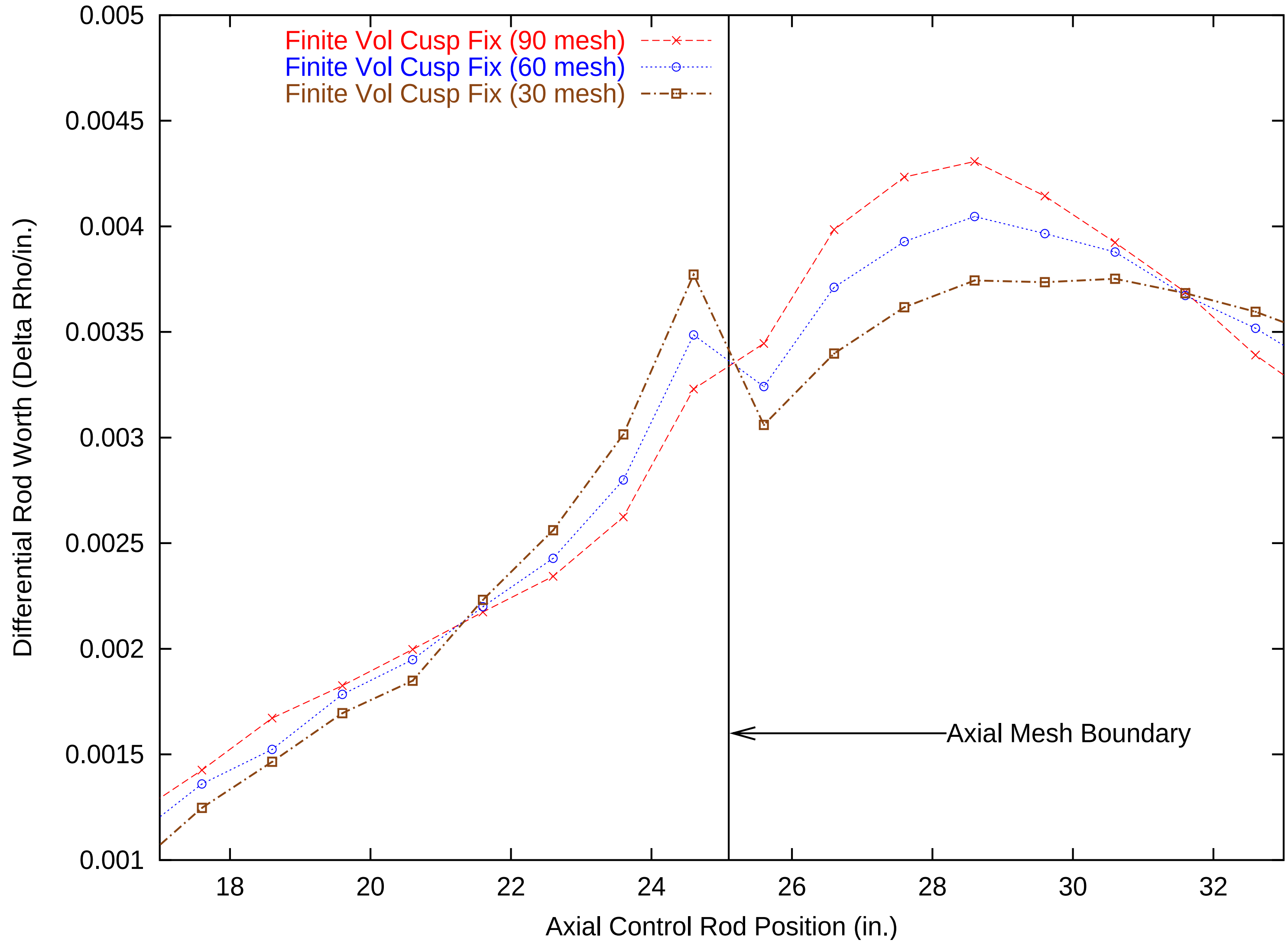
Geometric Description of PWR Assessment Problem



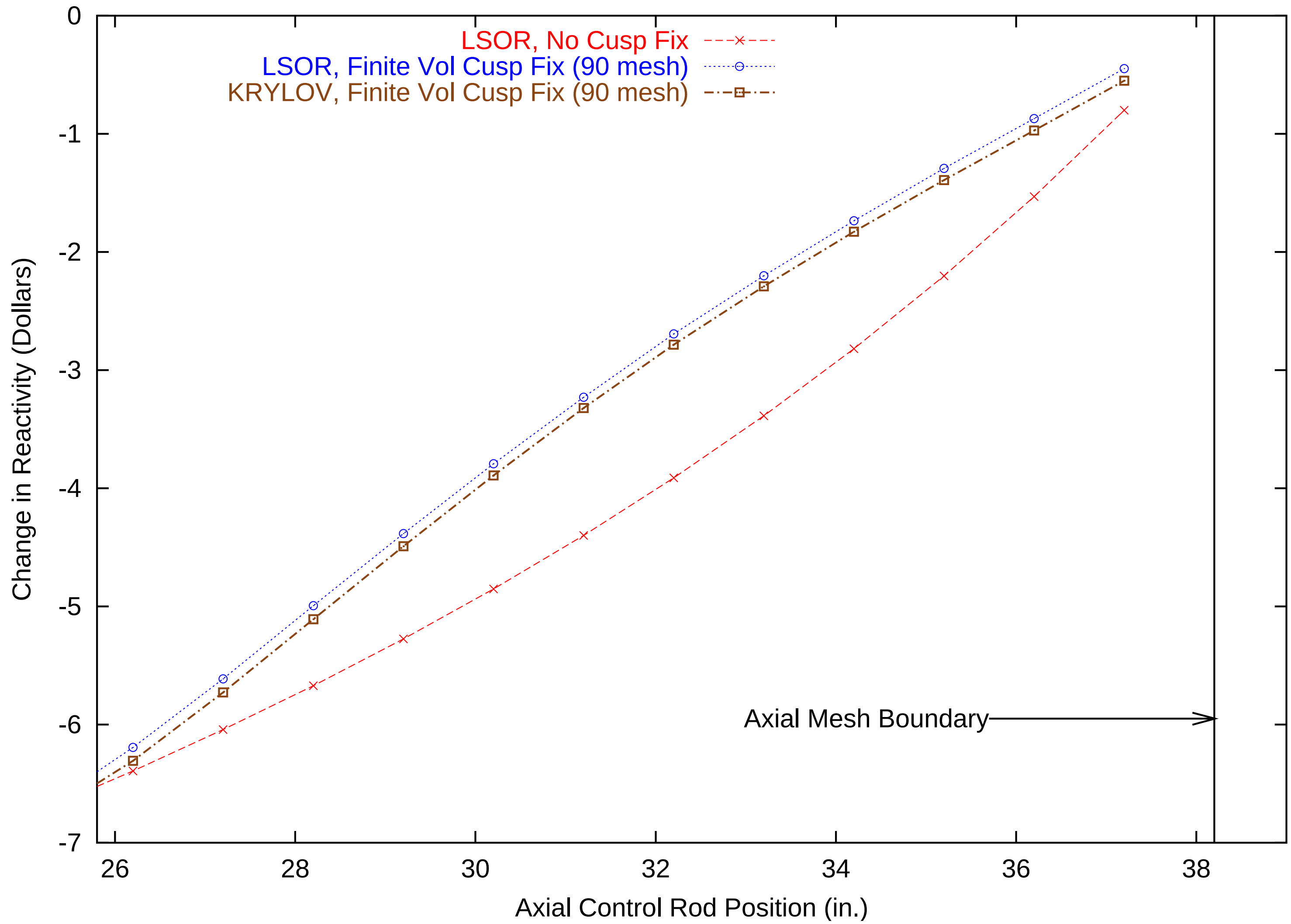
Differential Control Rod Worths w/ and w/o Cusp Fix



Differential Rod Worths w/ Varying Subnoding



Reactivity Loss at Transient End State w/ and w/o Cusp Fix



Conclusions

- Several methods have been developed to correct for the reactivity and power distribution effects of Control Rod Cusping.
- Control Rod Cusping occurs in steady-state and transient NESTLE calculations where control rods are partially inserted into axial nodes.
- New algorithms explicitly calculate the neutron flux in the rodded and unrodded portions of partially rodded nodes such that homogenized cross-sections can be obtained by flux * volume weighting.
- The most efficient algorithm tested was a finite-volume method with multiple subnodes.
- This method was shown to greatly reduce the Control Rod Cusping effect on reactivity in a 3-D PWR test problem.
- In this particular test problem use of 30, 60, and 90 subnodes at each control rod tip incurred run-time penalties of 25%, 54%, and 104%, respectively.
- Further development may be needed to correctly adjust discontinuity factors at the axial boundaries of the partially rodded nodes.