The Problem with the Nuclear Data for Deuterium-Uranium Systems

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2005 November

AECL

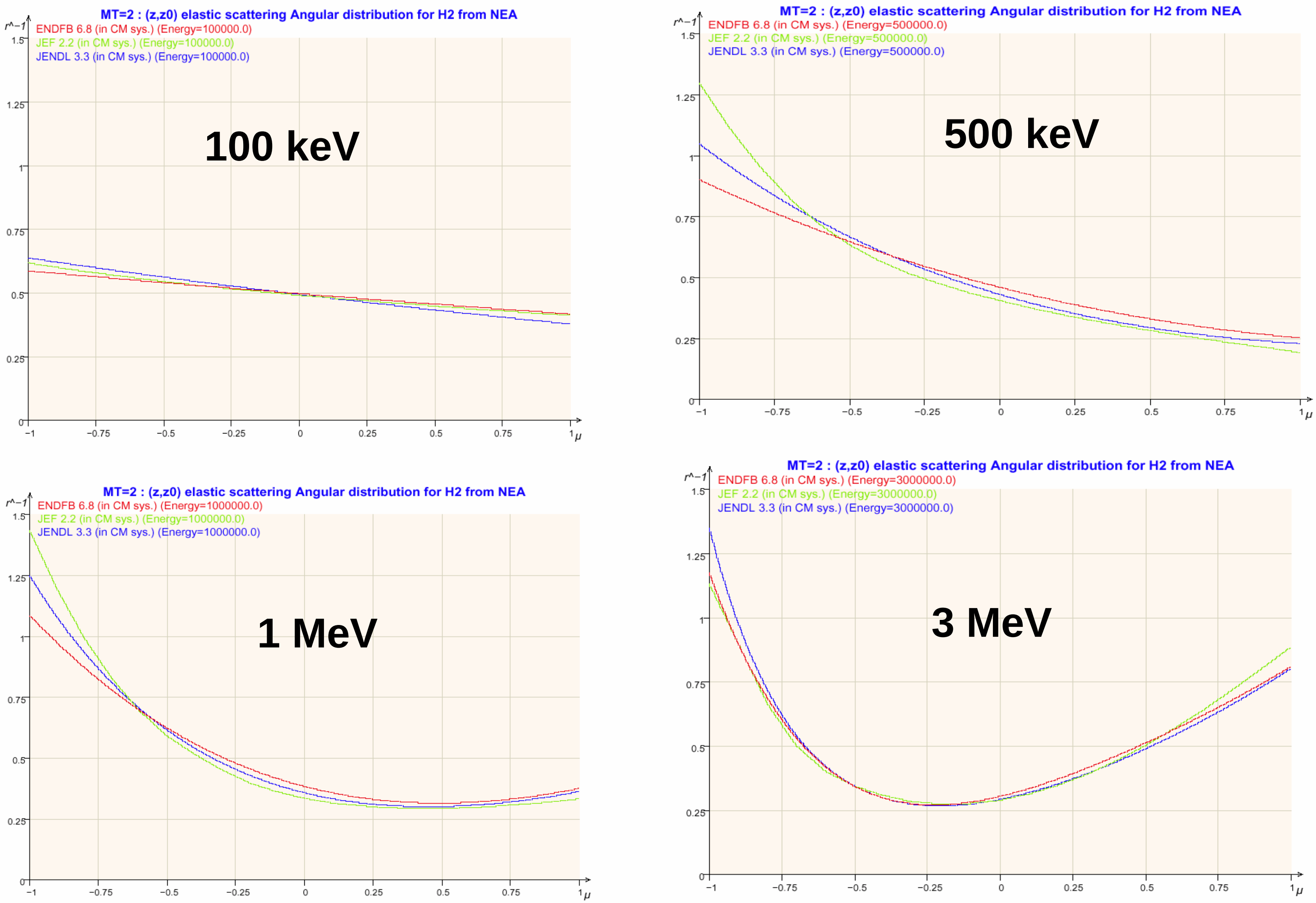
Outline

- International Criticality Safety Benchmark Evaluation Project (ICSBEP) HEU D_2O Solution Thermal critical experiments (HST-004 & -020)
- AECL Chalk River Laboratories (CRL) ZED-2 (Zero Energy Deuterium) critical experiments
  - Existing: NU (Natural Uranium) in hexagonal lattices; D_2O & air 'cooled' fuel channels
  - Recent: SEU (Slightly Enriched Uranium) CANFLEX bundles in square lattices; H_2O & air cooled
- Numerical benchmark studies
  - CANDU-SCWR (CANada Deuterium Uranium - Supercritical Water Reactor) lattice
  - ^{2}H-reflected U-metal sphere
- Summary/Conclusions

Background:
Changes to ENDF/B-VI ^{2}H cross-section data

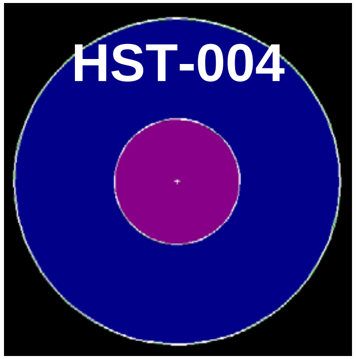
- ENDF/B-VI.4 [MCNP ZAID=1002.60c & .64c processed by LANL]
- ENDF/B-VI.5 (through ENDF/B-VI.8) [ZAID=1002.66c]
  - data range extended from 100 to 150 MeV
  - (n,2n), elastic & inelastic cross sections revised slightly above 10 MeV to match experimental data better
  - angular distributions for elastic scattering revised slightly >20 MeV & <3.2 MeV to improve agreement with measurement
  - *Surprisingly large reactivity change* (~9.7 mk) observed by LANL & KAPL for HEU D_2O solution benchmarks HEU-SOL-THERM (HST-004 & 020)
- Questions raised:
  - What is the impact for other D_2O critical systems?
  - Which is better: ENDF/B-VI.4 [1002.60c,.64c] or -VI.5 [1002.66c]?
  - Are there indications of additional problems with ^{2}H data?

Comparison of ^2H angular scattering distributions

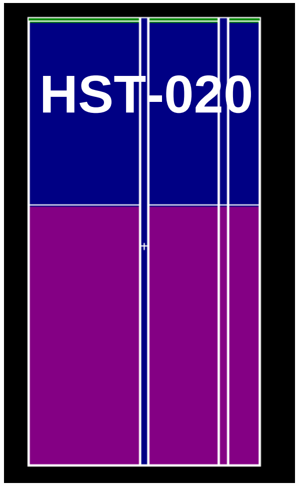


<u>Limited ^{2}H data</u>: HST-004 & -020 ICSBEP benchmarks

- **High leakage (~40%); HEU; homogeneous uranyl fluoride solutions in D_2O; large experimental uncertainties for k; thermal fission fraction 38-97%**
- **HST-004**
  - 6 expts. with inner sphere of HEU uranyl fluoride in D_2O reflected by outer annulus of D_2O
  - LANL believes HST-004 results are more reliable than HST-020

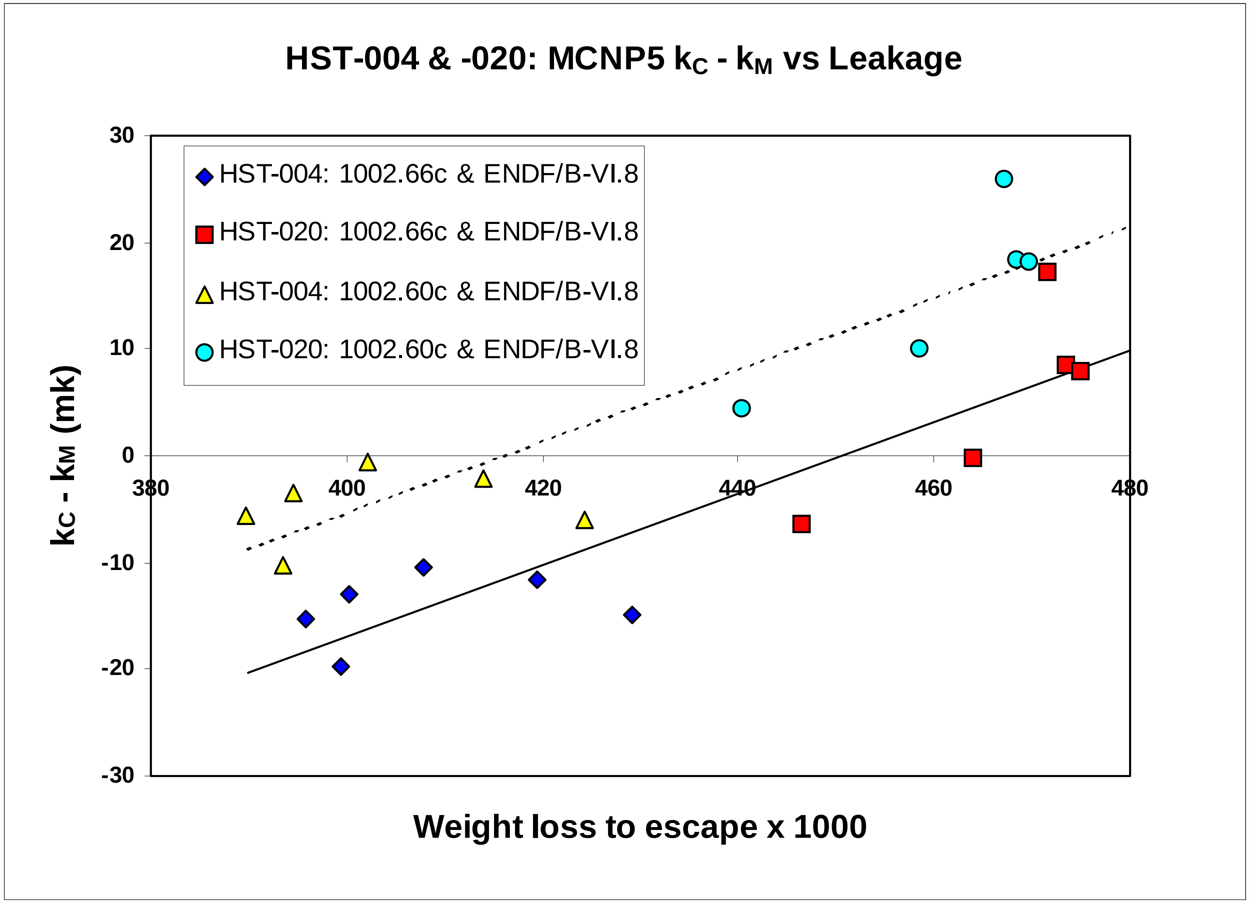


- **HST-020**
  - 5 expts. with unreflected cylinders of HEU uranyl fluoride in D_2O
  - have reactivity biases of approximately –4 mk, due to the *<u>calculated</u>* omission of room return



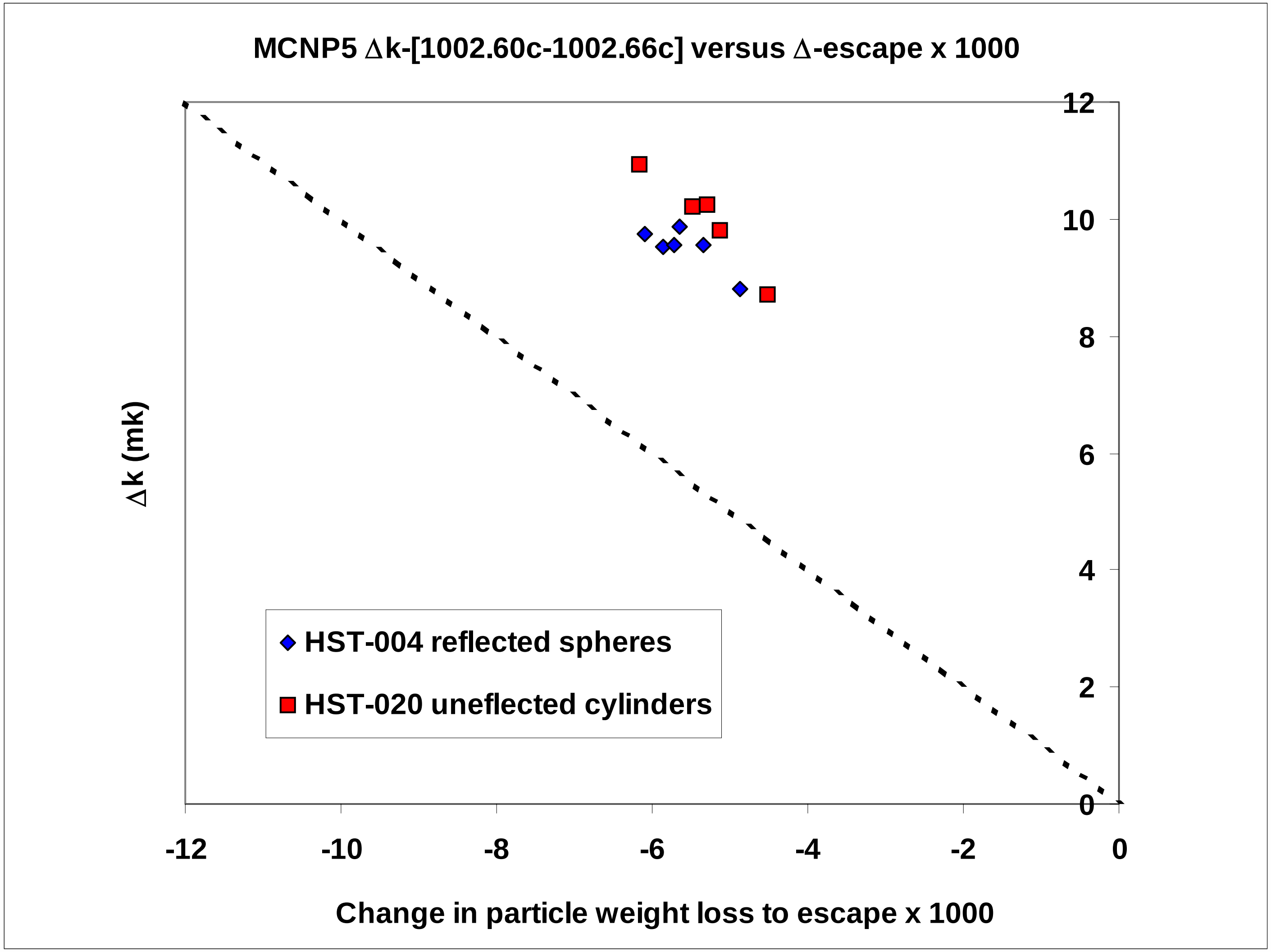
CRL HST MCNP5 results

- $k_{Calc.} - k_{Meas.}$ **shows a large spread of ~37 mk & rising trend with calculated leakage**
- **Using ENDF/B-IV [1002.60c] increases** ***k*** **by ~9.7 mk**

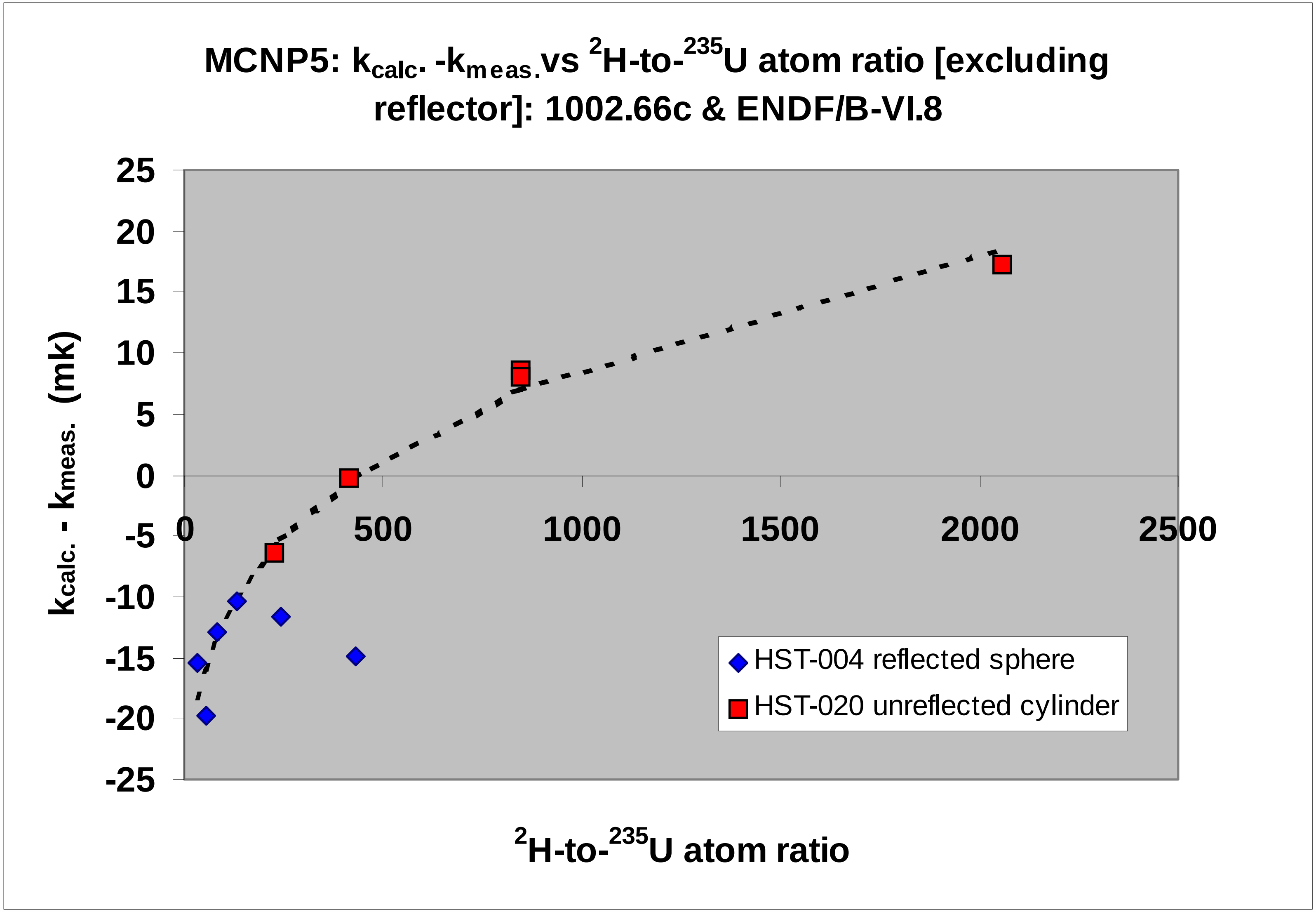


CRL HST MCNP5 results

- Δk [1002.60c – 1002.66c] depends on change in calculated leakage



CRL HST results: dependence on ^{2}H-to-^{235}U atom ratio



Comparison of HST & ZED-2 critical experiments

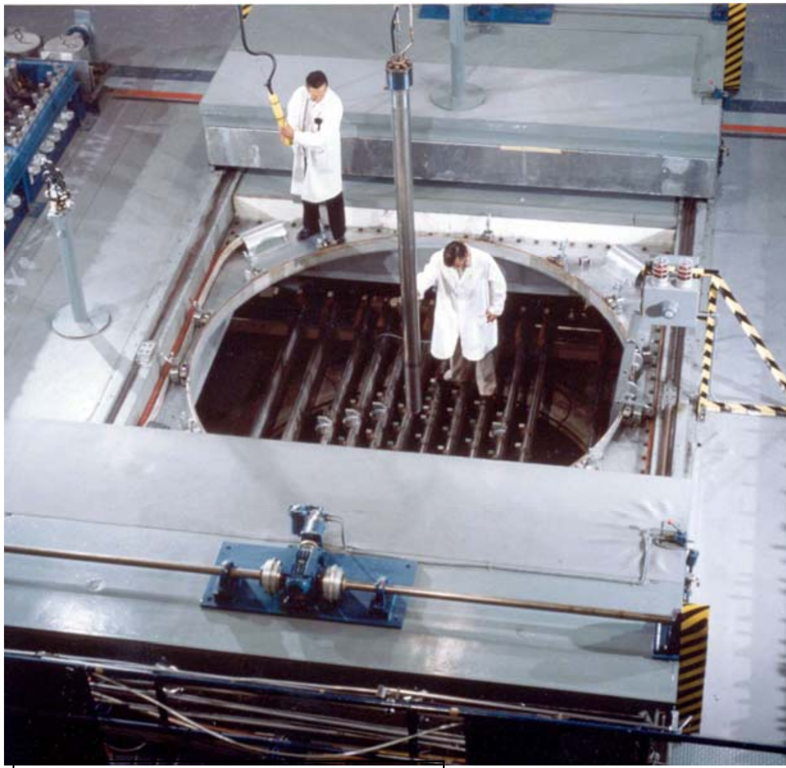
- HST & ZED-2 experiments are complementary

Characteristic		
Neutron leakage	Low (~11% from D_2O moderator surface)	High (~40%)
Enrichment	Natural Uranium (NU; 0.7% ^{235}U)	HEU (> 90% ^{235}U)
Physical form	Heterogeneous rod lattices	Homogeneous solutions

- HST experiments feature simple geometry & materials
- ZED-2 results potentially more directly relevant to existing reactor applications

ZED-2 Reactor at Chalk River Laboratories

- Tank-type critical facility, 3.3 m in diameter & depth
  - D_2O moderator height increased to bring critical; some fuel protrudes above
  - runs at a few Watts; first criticality 1960
- Flexible facility that 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 is 31-cm hexagonal pitch, with 55 channels, each containing 5 fuel bundles
- Mainly used for CANDU reactor physics validation experiments, e.g., coolant void reactivity (CVR)
- Hope to include some results in IRPhEP (AECL/Canada now involved)



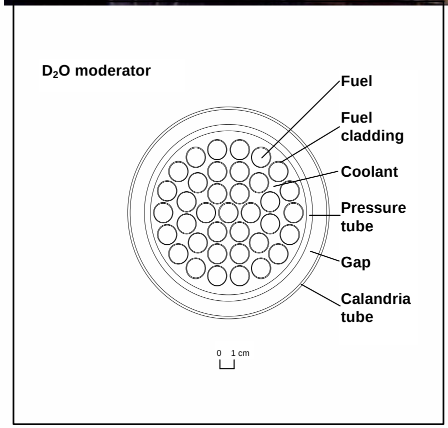


Figure 1. Cross section of a 37-element CANDU fuel lattice cell

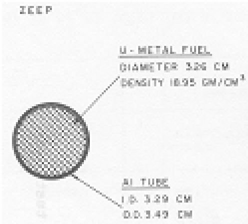
CANDU fuel lattice cell

ZED-2 MCNP5 hex. reference-lattice simulations

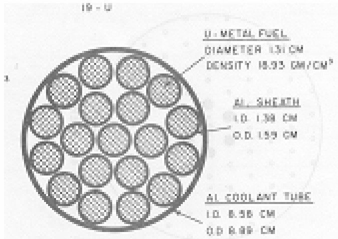
In order of increasing ^{238}U capture:

1. 91 ZEEP U-metal rods; lattice pitch = 22.86 cm
2. 91 ZEEP U-metal rods; lattice pitch = 21.59 cm
3. 91 ZEEP U-metal rods; lattice pitch = 20.00 cm
4. 55 ***air-cooled*** (i.e., voided) 28-element UO_2 assemblies (i.e., 5 Pickering-type bundles each) plus 30 ZEEP U-metal rods; lattice pitch = 31.00 cm
5. 55 ***air-cooled*** 28-element UO_2 assemblies plus 30 19-element U-metal assemblies; lattice pitch = 31.00 cm
6. 55 ***heavy-water-cooled*** 28-element UO_2 assemblies plus 30 ZEEP U-metal rods; lattice pitch = 31.00 cm
7. 55 ***heavy-water-cooled*** 28-element UO_2 assemblies plus 30 19-element U-metal assemblies; lattice pitch = 31.00 cm

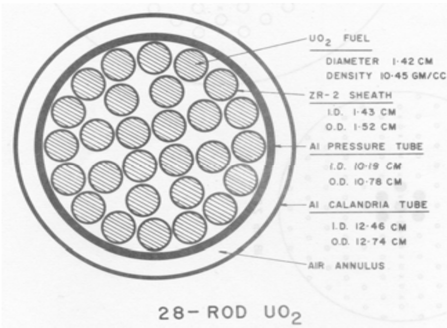
Critical heights ranged from 155.8 to 213.3 cm (14% to 9% calculated leakage from D_2O surfaces)



ZEEP (1945)



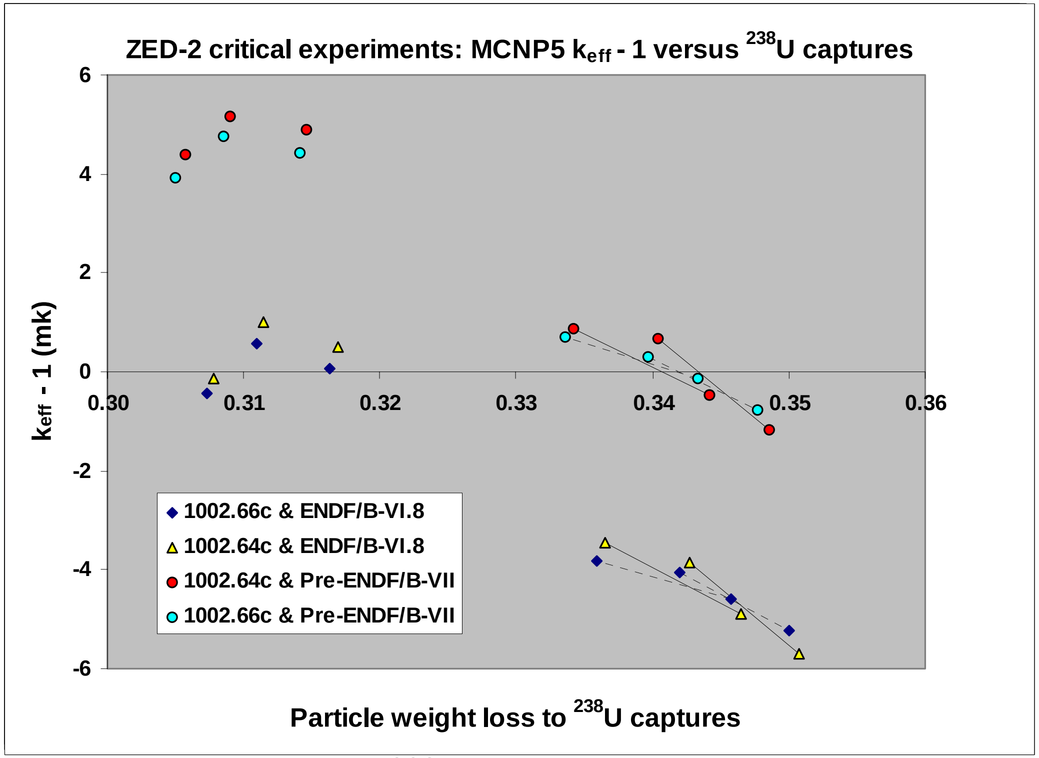
19-el. U-metal



28-el. UO_2

Dependence of MCNP5 ZED-2 k_{eff} on nuclear data

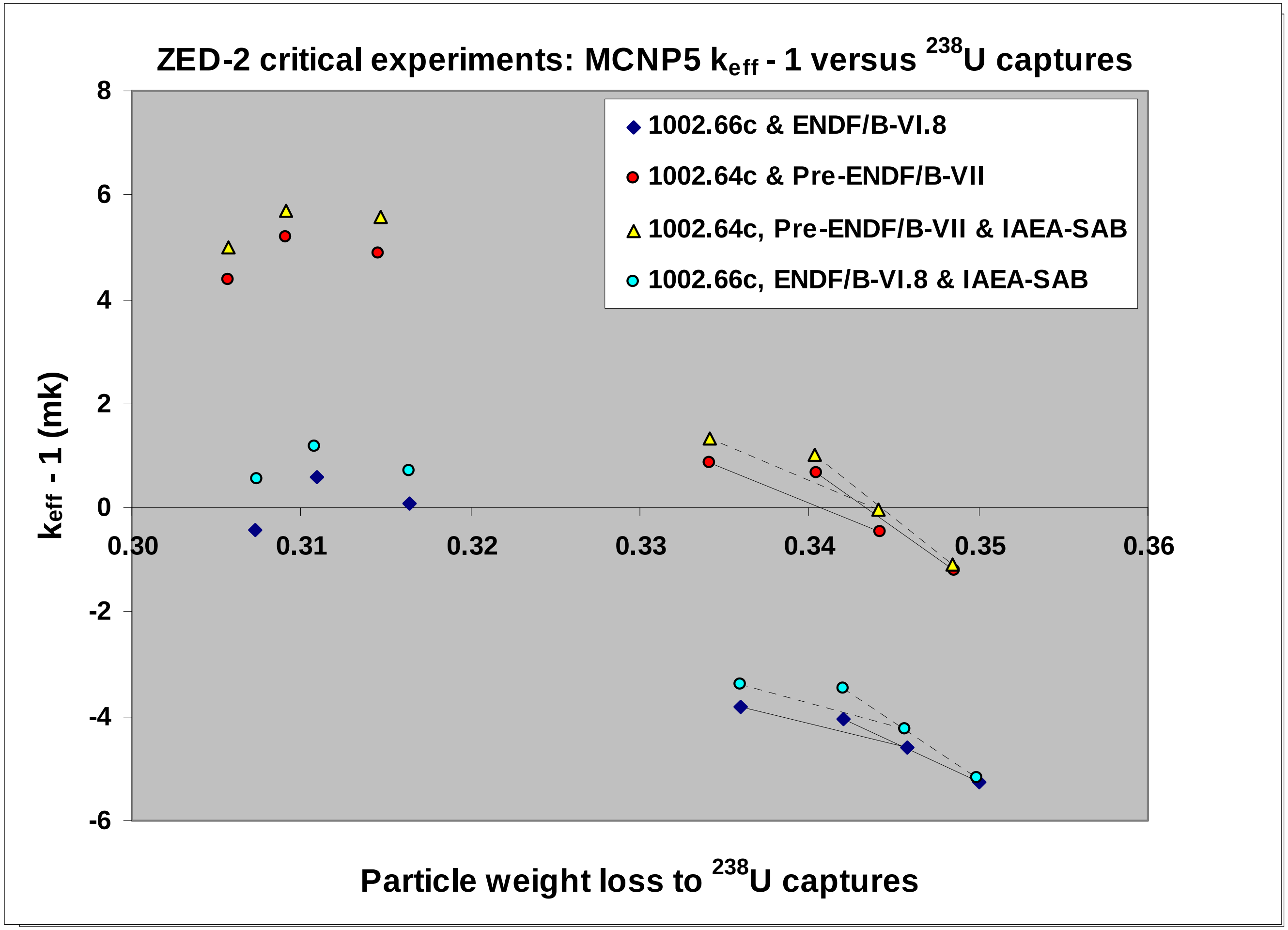
- **4 data sets:**
  - **Deuterium from ENDF/B-VI.8 (1002.66c) & ENDF/B-VI.4 (1002.64c)**
  - **Uranium from ENDF/B-VI.8 & Pre-ENDF/B-VII**



- **Decreasing trend with increasing ^{238}U captures**
- **Small reactivity impact (<1 mk) due to different ^{2}H data; CVR bias worse with 1002.64c**
- **Behaviour of D_2O-cooled cases differs from air-cooled cases**
- **Main impact is a gain of ~4 mk due to pre-ENDF/B-VII ^{238}U,^{235}U**

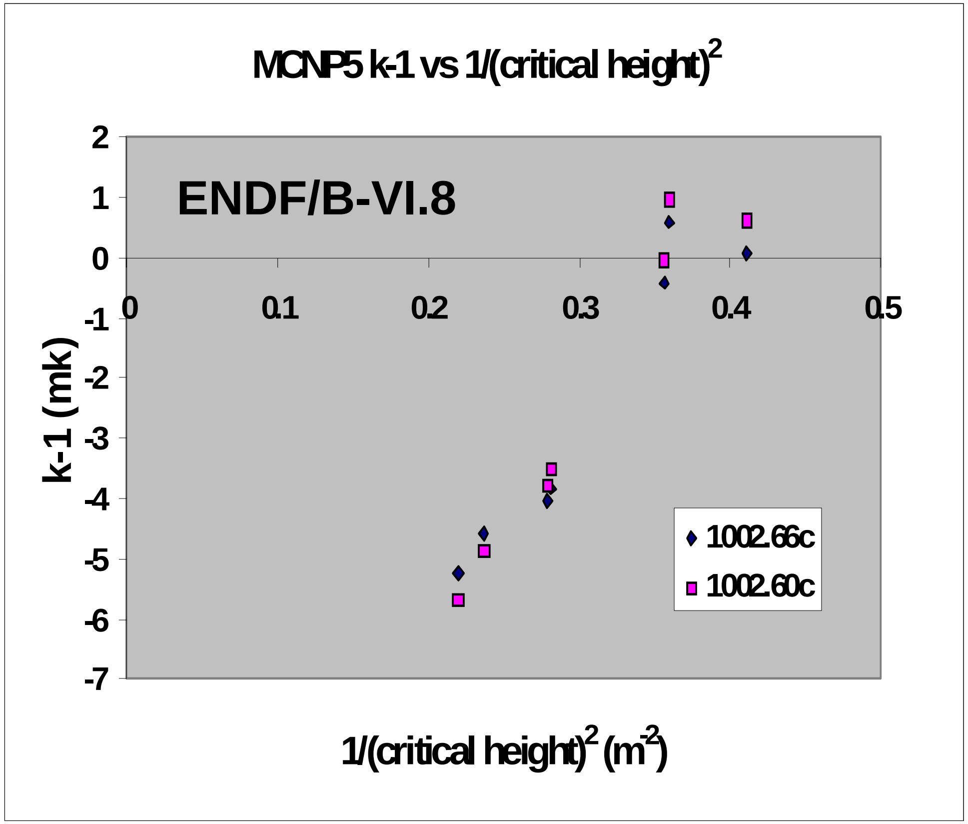
<u>ZED-2 MCNP5 simulations</u>: IAEA-S(α,β) for D_2O

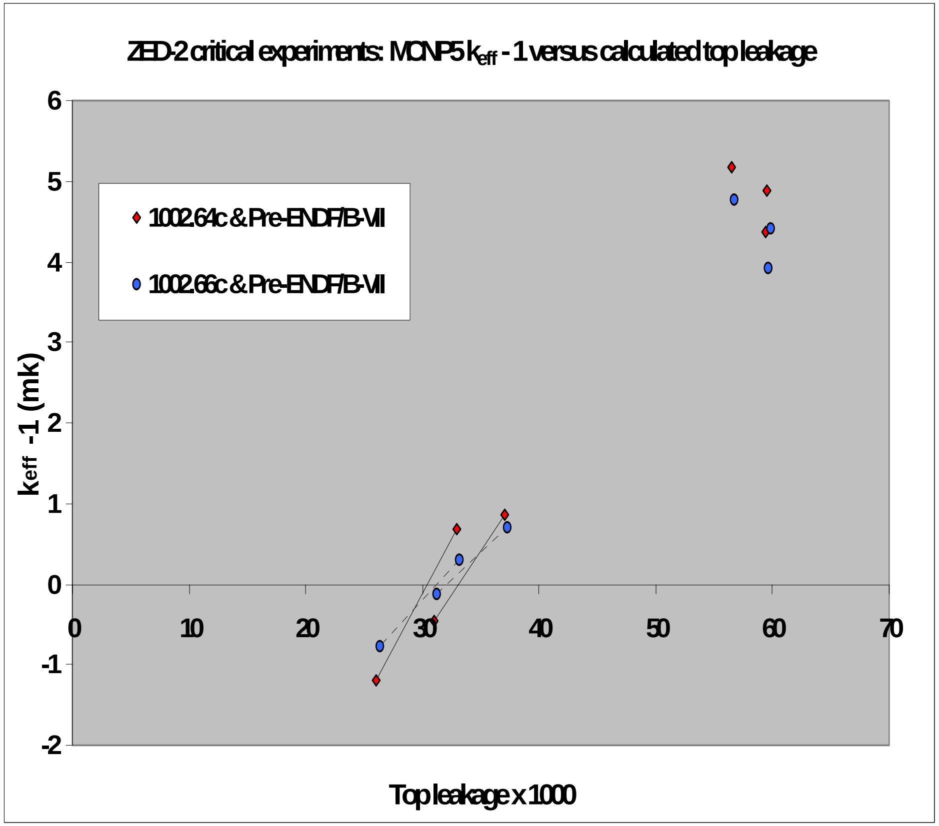
- Small increase in k (<1 mk)
- CVR bias slightly worse (~0.2mk)



ZED-2 MCNP5 k_{eff} *also* increases with neutron leakage

- Neutron leakage from D_2O moderator is predominantly thermal (~87% <0.625 eV)
- Small net in-leakage of fast neutrons (>0.1 MeV) at top moderator surface due to fissions in exposed fuel above
- Axial leakage ~1/(critical height)^2



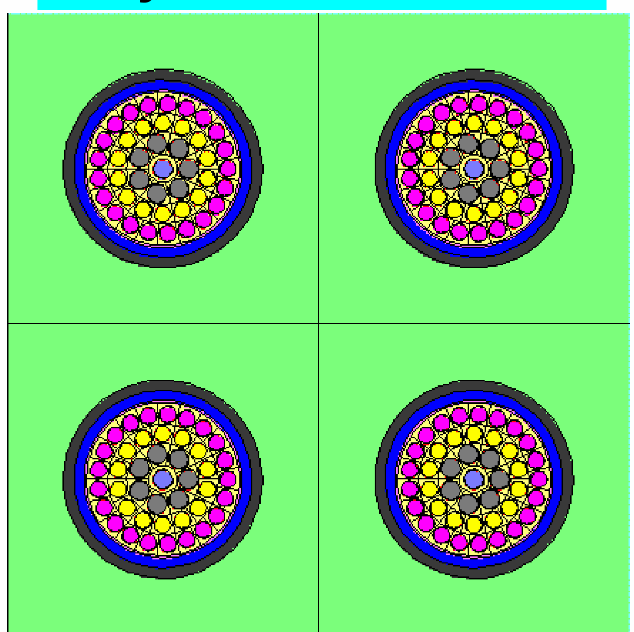


MCNP5 CANDU-SCWR (Supercritical Water Reactor) benchmark

(*Proc. Int. Workshop on Nucl. Data Needs for Generation-IV Nucl. Energy Systems*, Antwerp, 2005}

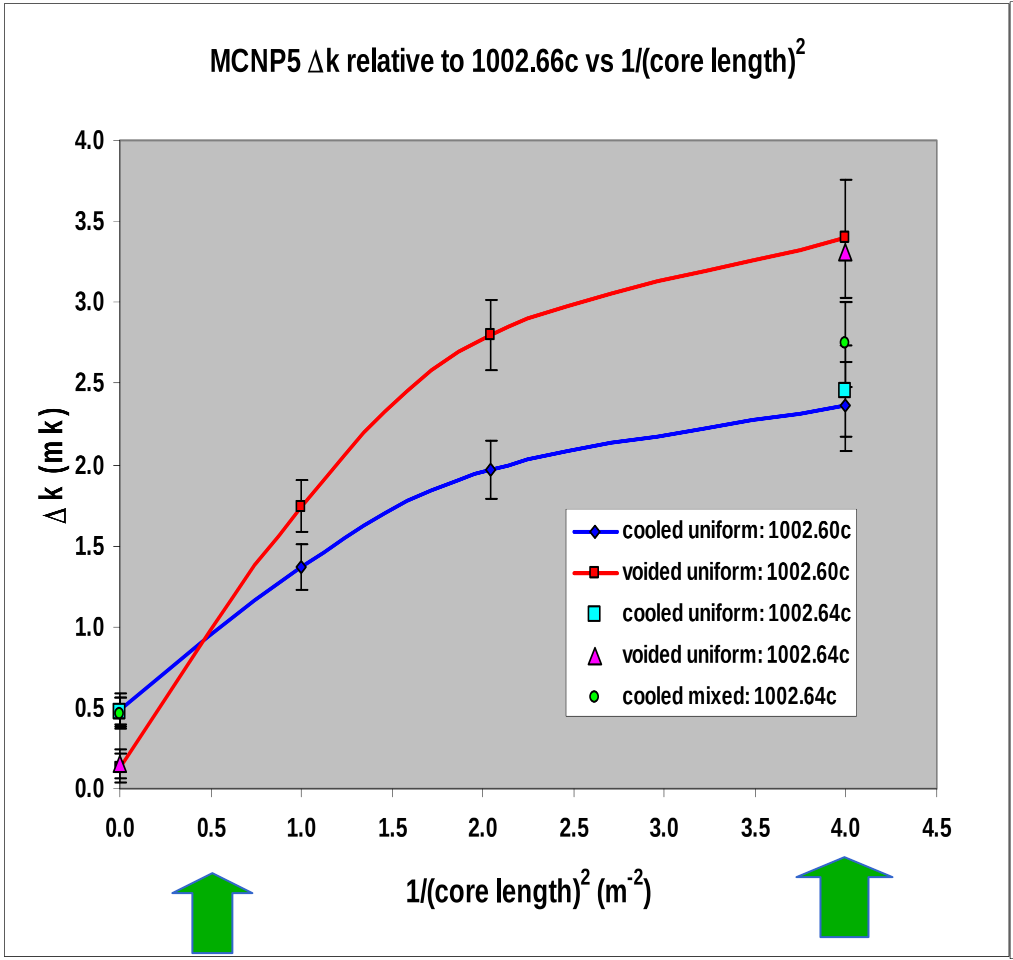
- 21-cm square lattice pitch; 4.25 wt% ^{235}U
- Uniform lattice of mid-life (22.3 MWd/kgU) fuel [composition from WIMS-AECL] & "mixed" lattice (0.2 & 44.2 MWd/kgU)
- H_2O cooled [inlet density = 0.44 g/cm^3] & voided configurations
- Nuclear data at 294 or 300 K
- Reactivity sensitivity to ^2H data calculated as a function of axial-neutron-leakage (i.e., finite core length with a vacuum boundary)

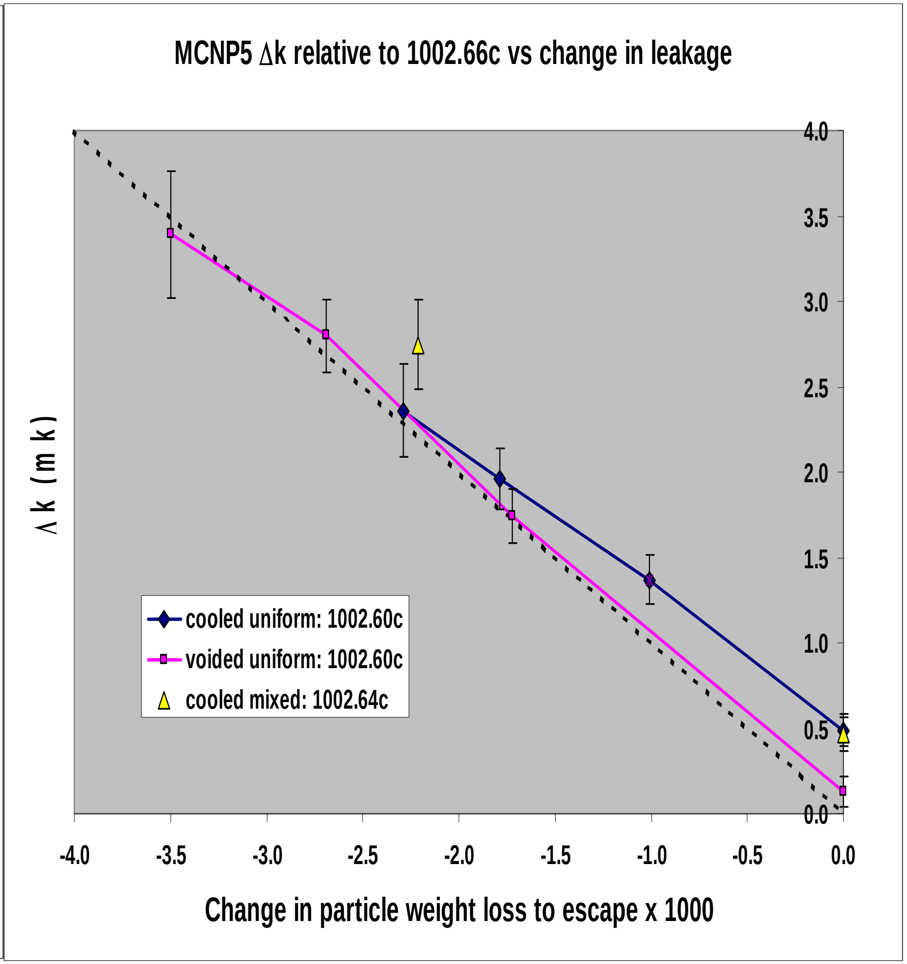
2-by-2 MCNP5 model



Sensitivity of CANDU-SCWR numerical benchmark to ^{2}H data

- Δk-[1002.64c – 1002.66c] increases with axial leakage & depends on coolant state
- Essentially a 1:1 correspondence between Δk & the change in calculated leakage





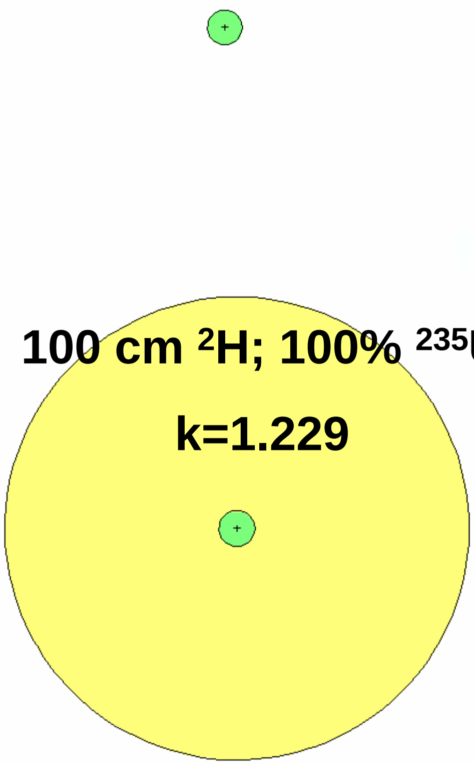
ZED-2

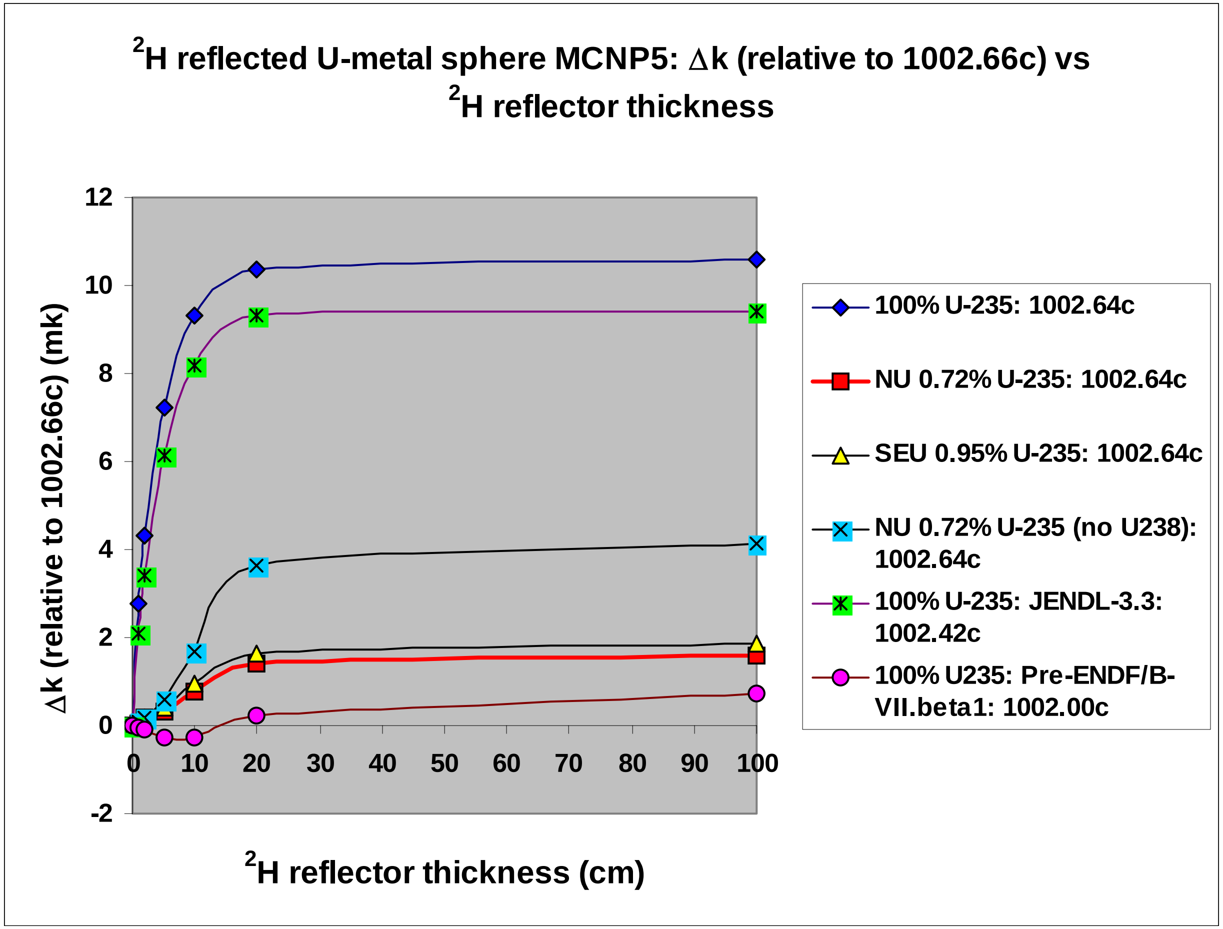
~HST-004,020 leakage

Simplified ^2H benchmark to highlight reactivity impact of angular scattering

- ^2H-(at D_2O # density)reflected 8.4-cm radius U-metal sphere; no S(α,β)

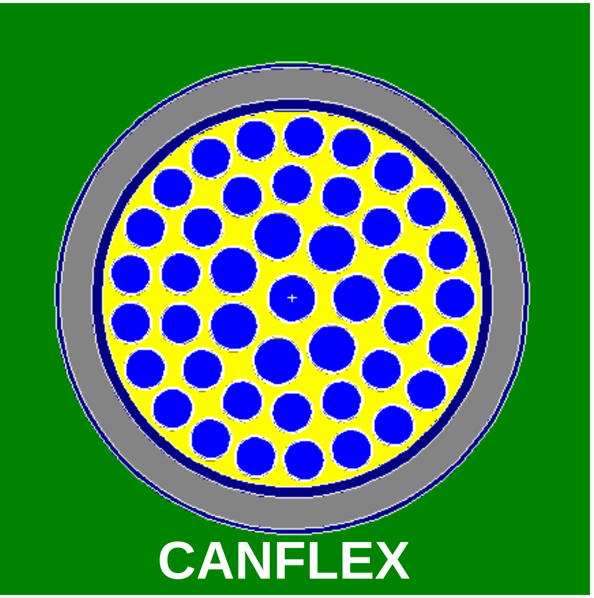
0 cm ^2H; 100% ^{235}U
k=0.997

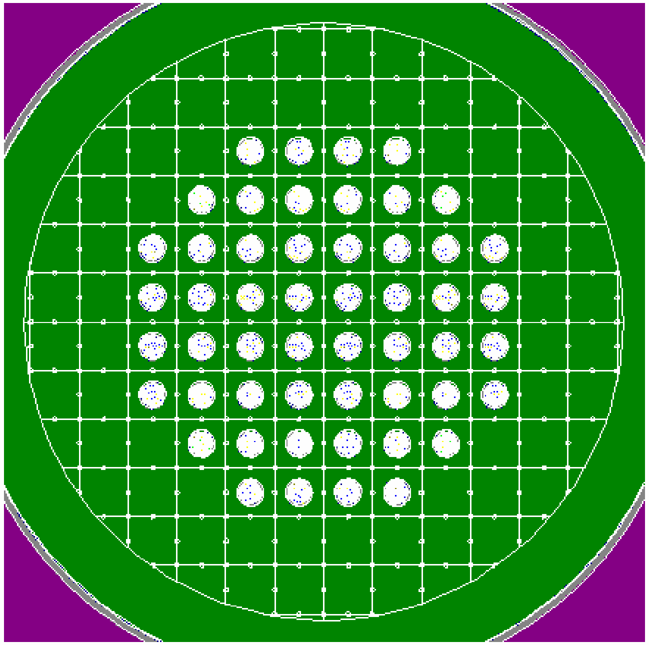


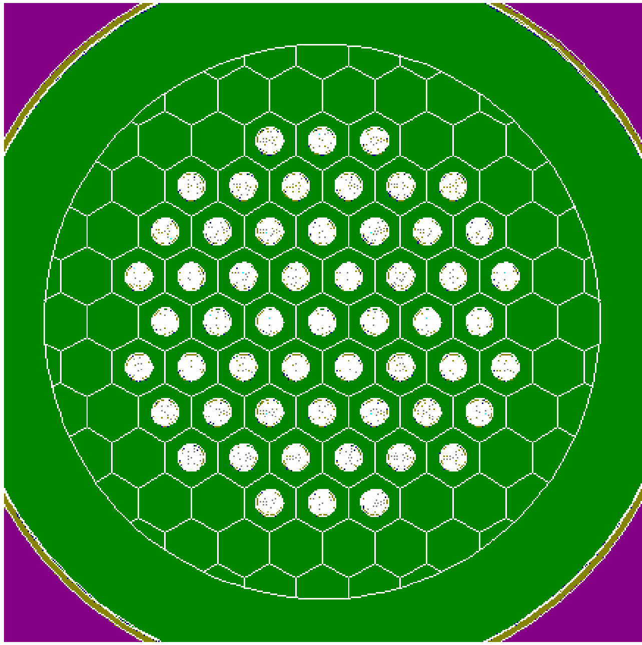


Recent ZED-2 results

- Slightly Enriched Uranium (SEU): 0.95 wt% ^{235}U
- 43-element CANFLEX fuel geometry (greater subdivision)
- Square vs. hexagonal lattices; pitch = 20 to 24.5 cm
- H_2O & air ‘coolant’



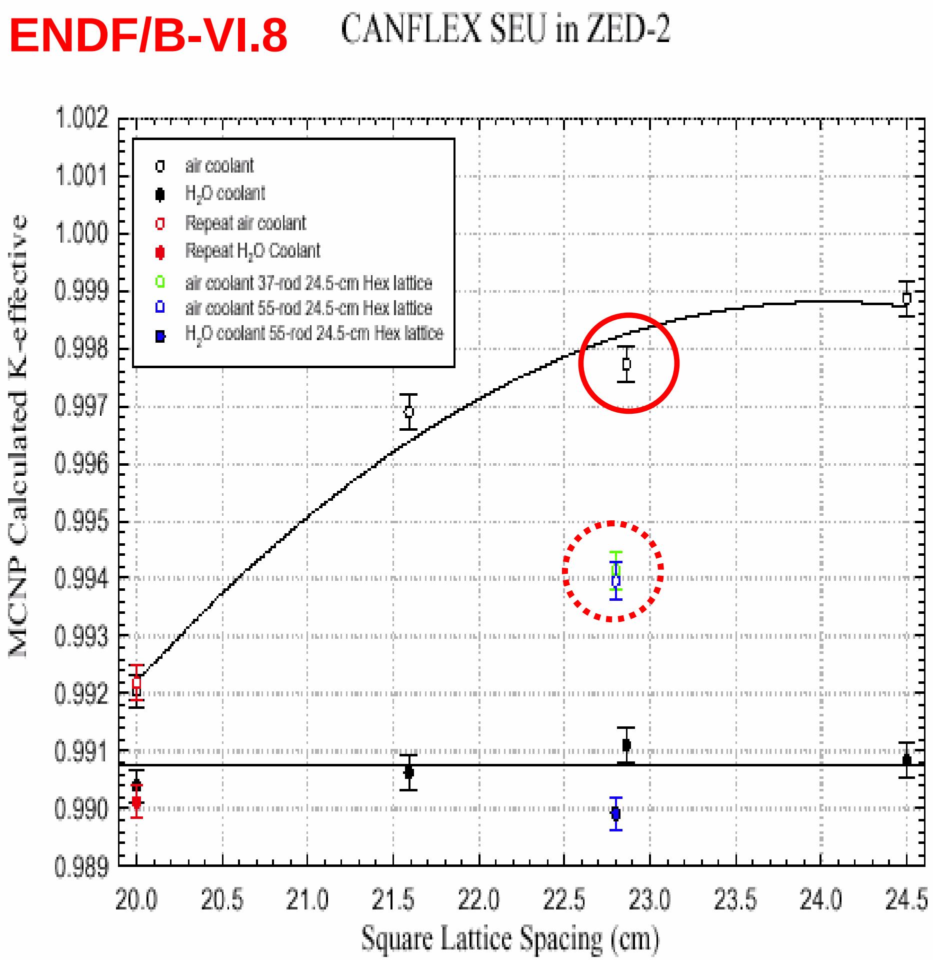


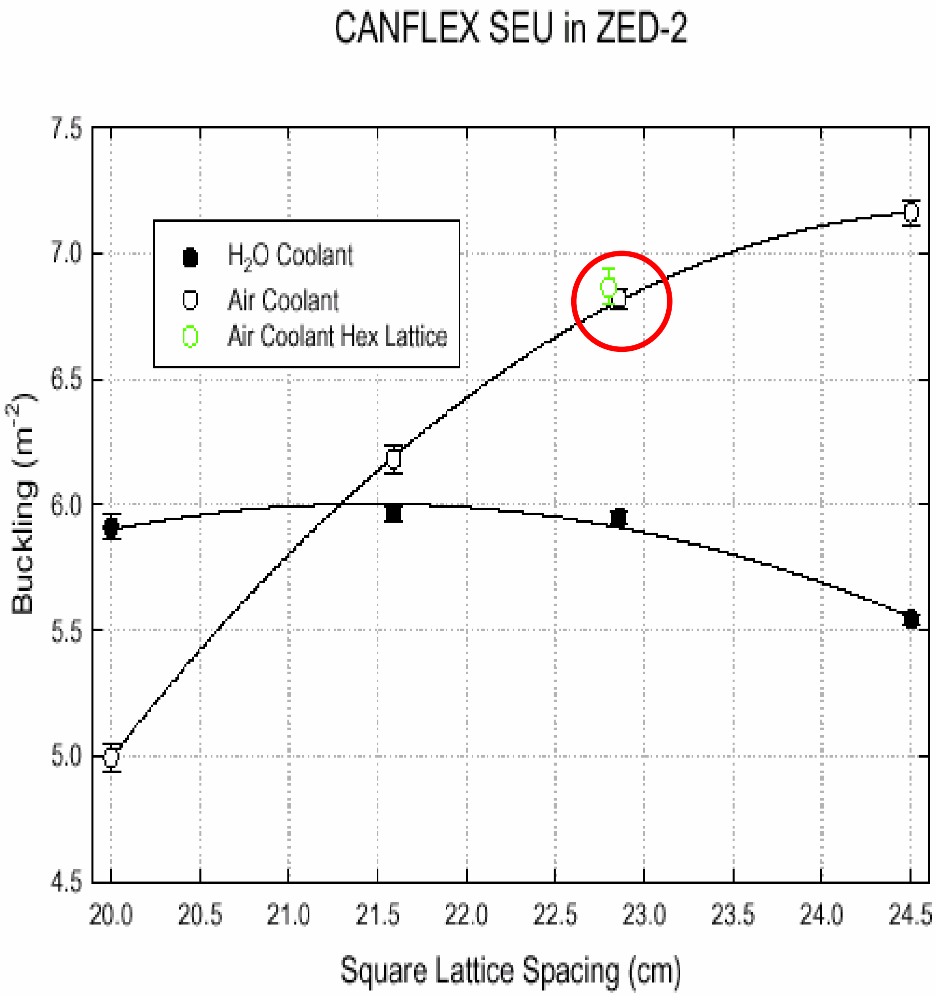


Recent ZED-2 H_2O CVR results for SEU CANFLEX fuel

- MCNP5 H_2O CVR bias increases to ~+8 mk with square lattice pitch
- Hexagonal-pitch data plotted at equivalent square lattice pitch
- MCNP5 shows different hex & sq. results, but expt. critical bucklings the same

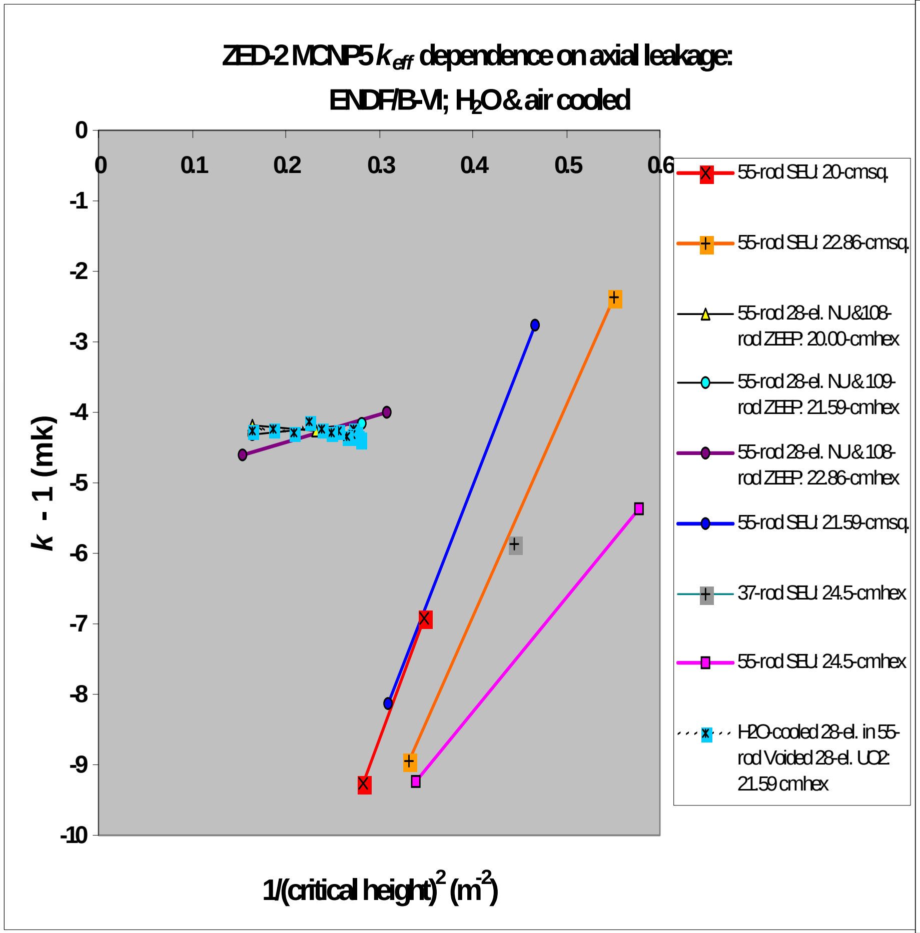
ENDF/B-VI.8

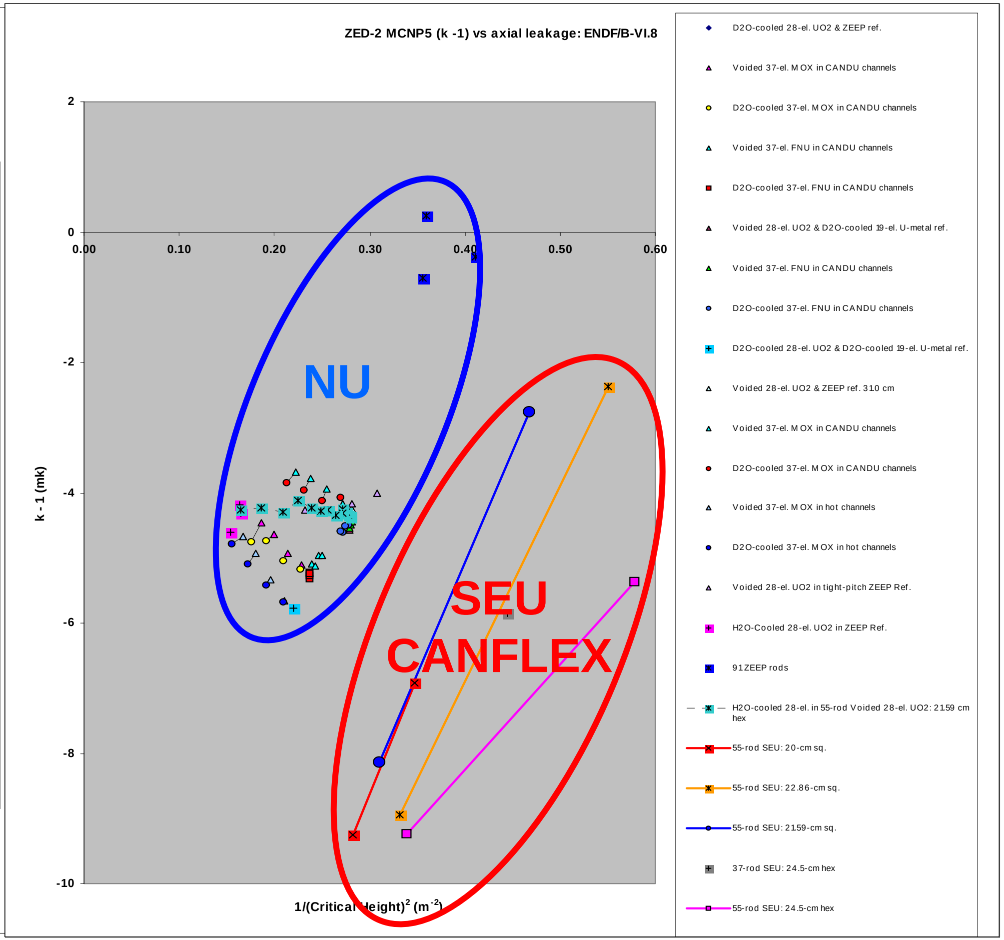




Dependence of ZED-2 MCNP5 k_{eff} on axial leakage

- New SEU ZED-2 H_2O CVR measurements involve relatively large changes in axial leakage
- MCNP5 k_{eff} increases with axial leakage, as before





Summary/Conclusions

- **Big difference in reactivity sensitivity of HST (~10 mk) & ZED-2 (<1 mk) NU results to ENDF/B-VI.5 & VI.4 ^{2}H data**
- **ZED-2 results show lower D_2O CVR bias (by ~0.6 mk) with newer ENDF/B-VI.5 ^{2}H data relative to ENDF/B-VI.4**
- ***But*, still a significant rising trend of (k_{eff} –1) with leakage for both ZED-2 & HST criticals**
- **Numerical benchmarks with different ^{2}H data show**
  - **CANDU-SCWR: reactivity sensitivity depends on leakage & presence/absence of low-density H_2O coolant**
  - **^{2}H-reflected U-metal sphere: reactivity sensitivity depends on ^{235}U enrichment (^{235}U # density & offset due to ^{238}U captures) & reflector thickness (reduced leakage)**
- **MCNP5 results for new SEU CANFLEX ZED-2 measurements show a large (up to ~+8 mk) H_2O CVR bias that depends on lattice pitch & arrangement (square vs. hexagonal)**
- **New ^{2}H evaluation &/or angular scattering measurements needed?**

Acknowledgments

- ***Russ Mosteller*** **(LANL) provided pre-ENDF/B-VII for U & 1002.64c data in ACE format**
- ***Andre Trkov*** **(IAEA) provided new S(α,β) for D_2O & H_2O**
- ***Radoslav Zajac*** **(BNL-NNDC) provided pre-ENDF/B-VIIbeta1 1002.00c data**
- **CRL ZED-2 experiment & analysis crew, particularly, Mike Zeller, Benoit Arsenault & Bruce Wilkin**

Reminder .....

- ***PHYSOR-2006*** **is 10 months away:** ***Sept. 10-14, Vancouver, BC, Canada***
- **Key dates:**
  - **Jan. 7, 2006, 1000-word reduced-length paper due**
  - **June 15, 2006, full-length papers due**
- **See http://www.cns-snc.ca/physor2006**
- **Technical Program includes:**
  - **Plenary: Advances in Nuclear Data Libraries**
  - **Covariance Data Generation for Nuclear Applications (Luiz Leal, ORNL)**
  - **Nuclear Safety Validation & Performance of ENDF/B-VII (Richard McKnight, ANL)**
  - **Nuclear Data (Mike Dunn, ORNL)**
  - **The International Reactor Physics Experiment Evaluation Project (IRPhEP) (J. Blair Briggs, INL; Ibrahim Attieh, AECL)**

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