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# *Comparison of Recent Hafnium Isotope Evaluations*

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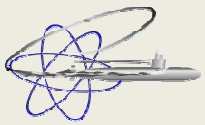
# Evaluations Considered

- ENDF/B-VII.1 (ORNL, 2009)
  - $^{174,176,178,180}$Hf revised starting from JEFF-3.1
    - JENDL-3.3 + new evaluation using RPI resonance measurements (Trbovich, 2004).
  - $^{177,179}$Hf revised starting from JENDL-3.3
- JEFF-3.1.2 (SERCO – Winfrith, IRMM Geel, 2011)
  - Resolved resonance range based on new measurements (Ware, 2010).
  - RRR extended, URR parameters from JENDL-3.3
  - JEFF-3.2 (2014) uses the same RRR and URR.
- JENDL-4.0 (JAEA, 2009)
  - $^{178}$Hf RRR unchanged from JENDL-3.3
  - $^{174,176,177,179,180}$Hf JENDL-3.3 + new evaluation using RPI measurement
  - New URR parameters.
  - New elastic scattering angular distributions (ESADs).



# Thermal Cross Sections & Resonance Integral Comparisons

## Isotopic Comparisons

**HF174 (0.16%)**

| | ENDF/B-VII.1 | | JEFF-3.1.2 | | | | JENDL-4.0 | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 2200 m/s | Res. Int. | 2200 m/s | Rel. Dif. | Res. Int. | Rel. Dif. | 2200 m/s | Rel. Dif. | Res. Int. | Rel. Dif. |
| Total | 597.53 | 1157.68 | 666.22 | 11% | 1002.77 | -13% | 577.21 | -3% | 792.51 | -32% |
| Elas. Scat. | 48.13 | 701.45 | 14.89 | -69% | 539.88 | -23% | 15.02 | -69% | 397.57 | -43% |
| Rad. Capt. | 549.40 | 445.83 | 651.34 | 19% | 452.49 | 1% | 562.18 | 2% | 383.80 | -14% |

**HF176 (5.26%)**

| | ENDF/B-VII.1 | | JEFF-3.1.2 | | | | JENDL-4.0 | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 2200 m/s | Res. Int. | 2200 m/s | Rel. Dif. | Res. Int. | Rel. Dif. | 2200 m/s | Rel. Dif. | Res. Int. | Rel. Dif. |
| Total | 26.94 | 1152.84 | 22.15 | -18% | 1079.09 | -6% | 27.96 | 4% | 1163.02 | 1% |
| Elas. Scat. | 5.56 | 447.61 | 5.30 | -5% | 434.58 | -3% | 5.83 | 5% | 452.58 | 1% |
| Rad. Capt. | 21.38 | 694.29 | 16.85 | -21% | 633.58 | -9% | 22.13 | 4% | 698.98 | 1% |

**HF177 (18.6%)**

| | ENDF/B-VII.1 | | JEFF-3.1.2 | | | | JENDL-4.0 | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 2200 m/s | Res. Int. | 2200 m/s | Rel. Dif. | Res. Int. | Rel. Dif. | 2200 m/s | Rel. Dif. | Res. Int. | Rel. Dif. |
| Total | 373.80 | 8037.86 | 371.27 | -1% | 7971.99 | -1% | 372.10 | 0% | 8004.45 | 0% |
| Elas. Scat. | 0.21 | 814.40 | 0.04 | -81% | 796.20 | -2% | 0.22 | 2% | 782.27 | -4% |
| Rad. Capt. | 373.59 | 7213.08 | 371.23 | -1% | 7165.41 | -1% | 371.89 | 0% | 7210.87 | 0% |

**HF178 (27.28%)**

| | ENDF/B-VII.1 | | JEFF-3.1.2 | | | | JENDL-4.0 | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 2200 m/s | Res. Int. | 2200 m/s | Rel. Dif. | Res. Int. | Rel. Dif. | 2200 m/s | Rel. Dif. | Res. Int. | Rel. Dif. |
| Total | 90.53 | 3966.66 | 87.37 | -3% | 3969.96 | 0% | 88.51 | -2% | 3695.96 | -7% |
| Elas. Scat | 6.61 | 2084.34 | 4.55 | -31% | 2160.86 | 4% | 4.47 | -32% | 1769.53 | -15% |
| Rad. Capt | 83.92 | 1871.44 | 82.82 | -1% | 1798.22 | -4% | 84.04 | 0% | 1914.84 | 2% |

**HF179 (13.62%)**

| | ENDF/B-VII.1 | | JEFF-3.1.2 | | | | JENDL-4.0 | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 2200 m/s | Res. Int. | 2200 m/s | Rel. Dif. | Res. Int. | Rel. Dif. | 2200 m/s | Rel. Dif. | Res. Int. | Rel. Dif. |
| Total | 49.57 | 832.44 | 47.66 | -4% | 824.39 | -1% | 47.50 | -4% | 779.96 | -6% |
| Elas. Scat | 6.78 | 298.22 | 7.79 | 15% | 283.73 | -5% | 7.00 | 3% | 261.42 | -12% |
| Rad. Capt | 42.79 | 523.80 | 39.87 | -7% | 530.24 | 1% | 40.49 | -5% | 507.21 | -3% |

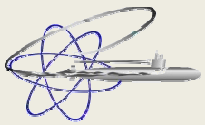
**HF180 (35.08%)**

| | ENDF/B-VII.1 | | JEFF-3.1.2 | | | | JENDL-4.0 | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 2200 m/s | Res. Int. | 2200 m/s | Rel. Dif. | Res. Int. | Rel. Dif. | 2200 m/s | Rel. Dif. | Res. Int. | Rel. Dif. |
| Total | 35.44 | 317.08 | 38.61 | 9% | 340.31 | 7% | 34.13 | -4% | 309.55 | -2% |
| Elas. Scat | 22.37 | 276.59 | 25.56 | 14% | 291.71 | 5% | 21.21 | -5% | 268.01 | -3% |
| Rad. Capt | 13.07 | 29.26 | 13.05 | 0% | 37.36 | 28% | 12.92 | -1% | 29.34 | 0% |

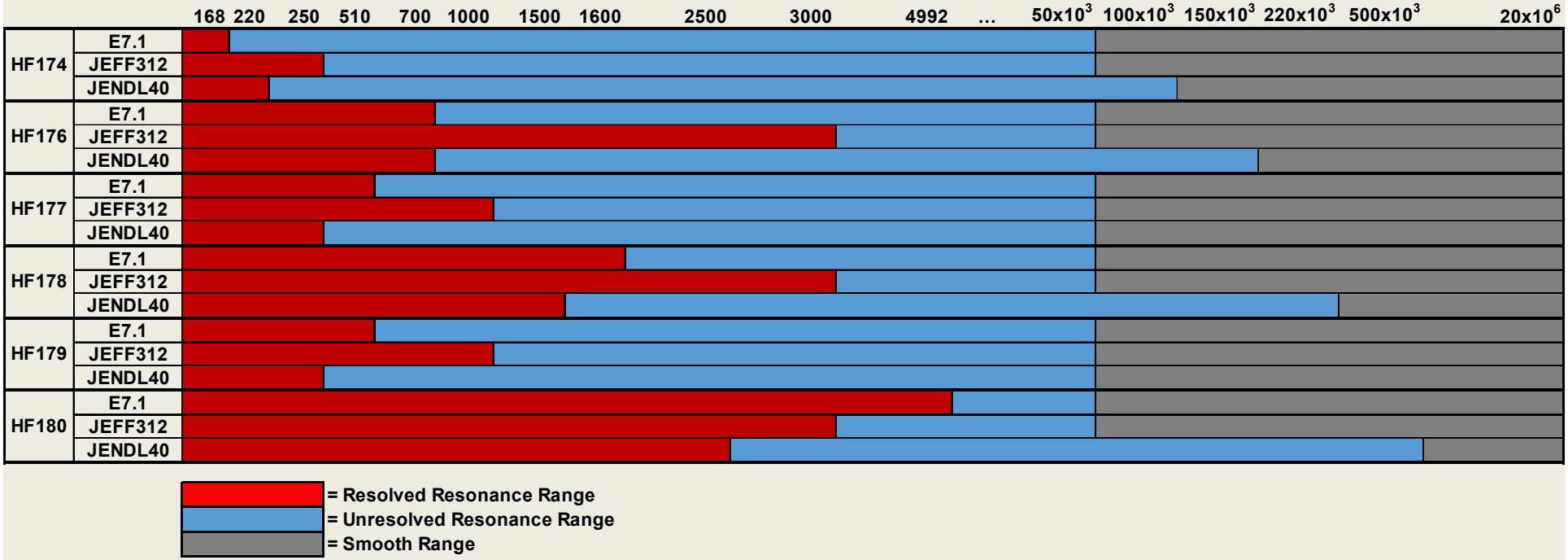
## Abundance-Weighted (Elemental) Comparisons

**HF Elem.**

| | ENDF/B-VII.1 | | JEFF-3.1.2 | | | | JENDL-4.0 | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 2200 m/s | Res. Int. | 2200 m/s | Rel. Dif. | Res. Int. | Rel. Dif. | 2200 m/s | Rel. Dif. | Res. Int. | Rel. Dif. |
| Total | 115.78 | 2864.25 | 115.16 | -1% | 2855.82 | 0% | 114.19 | -1% | 2774.35 | -3% |
| Elas. Scat. | 10.98 | 882.40 | 11.58 | 5% | 902.27 | 2% | 9.98 | -9% | 782.30 | -11% |
| Rad. Capt. | 104.80 | 1971.00 | 103.58 | -1% | 1942.70 | -1% | 104.21 | -1% | 1980.34 | 0% |



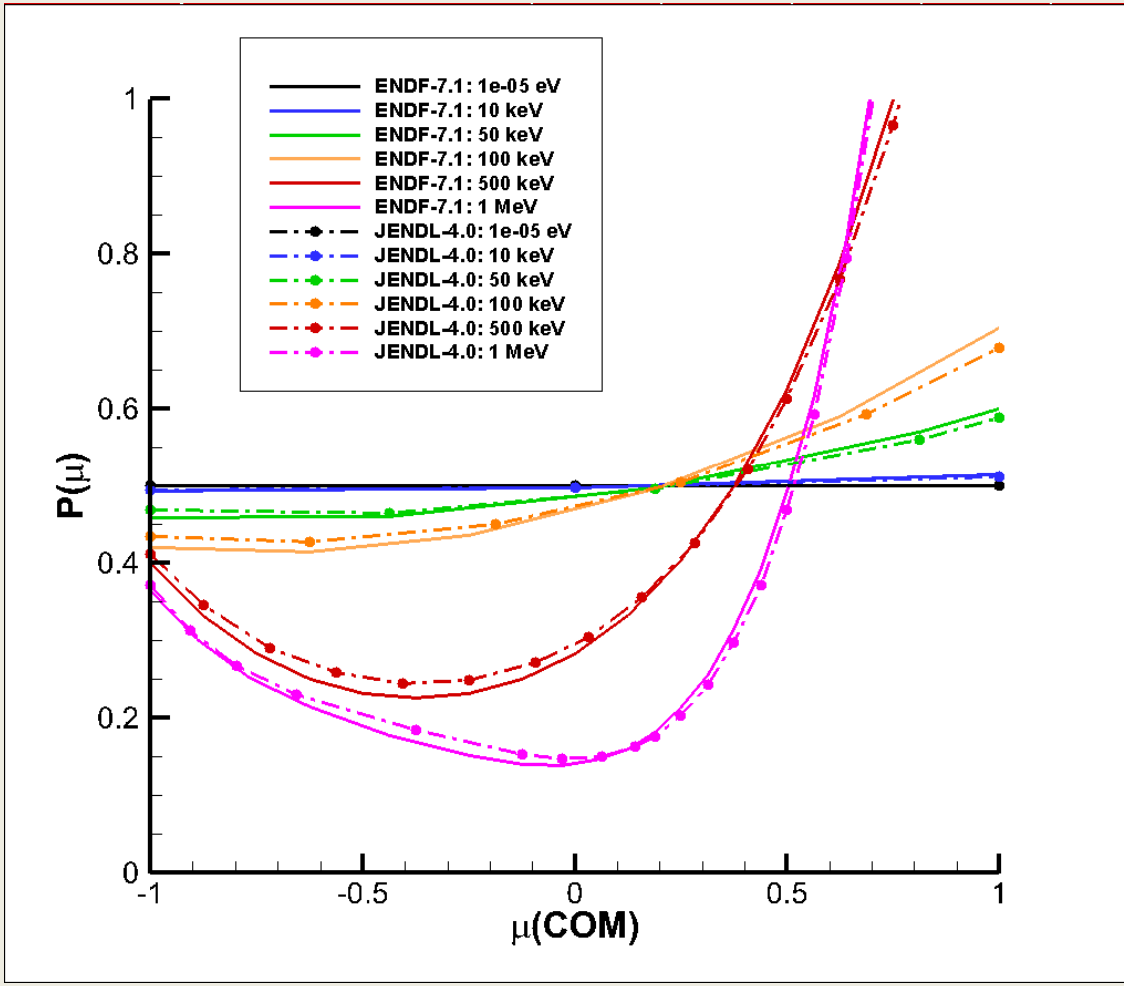
# Resolved and Unresolved Resonance Energy Range Comparisons




1. JEFF-3.1.2 (for all but Hf-180) extends RRR to higher energies than ENDF/B-VII.1 and JENDL-4.0.
2. JENDL-4.0 extends URR to higher energies than ENDF/B-VII.1 and JEFF-3.1.2 for all but HF-177 and HF-179.

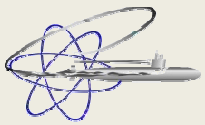
# ESAD Comparisons

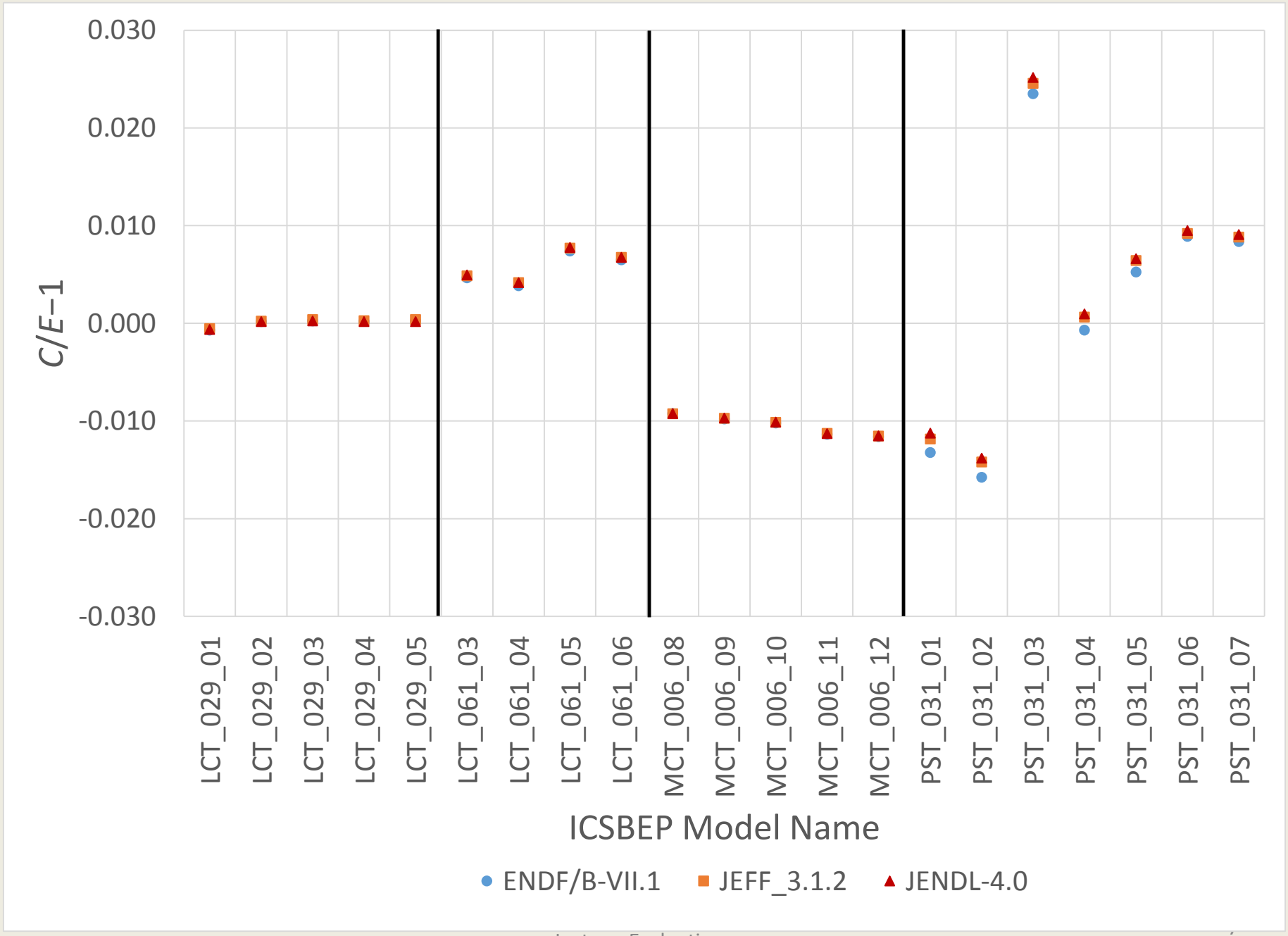
- ENDF/B-VII.1 and JEFF-3.1.2 use identical ESADs.
- JENDL-4.0 is all new:
  - Contains much more low-energy detail
    - 48 vs. 13 ESADs from 0.00001 eV – 1.0 MeV
  - Appears to be less forward-peaked.
- Example below is for Hf-178:

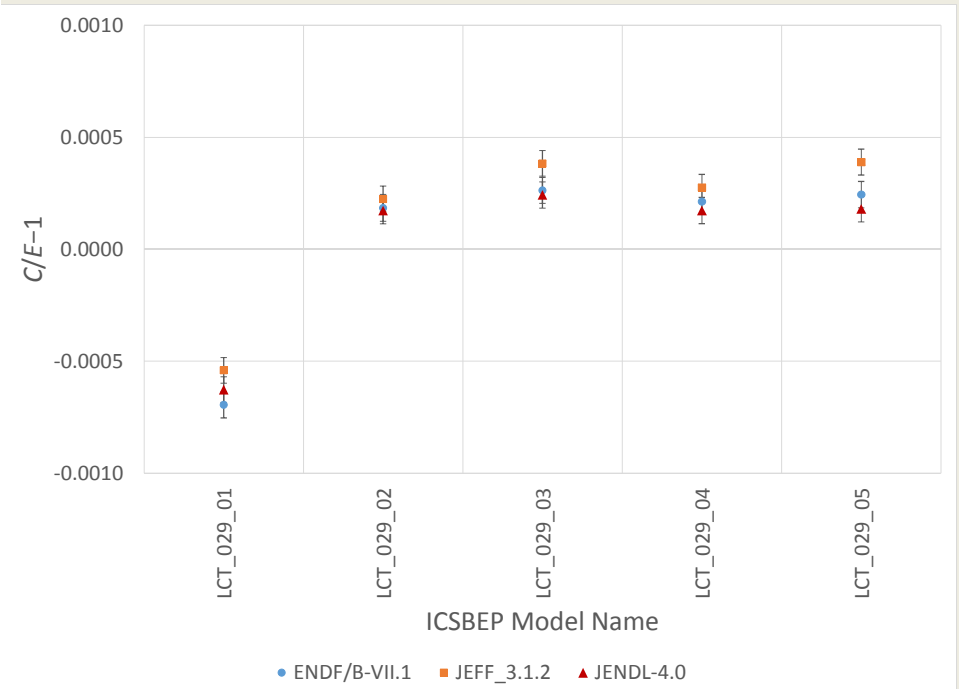


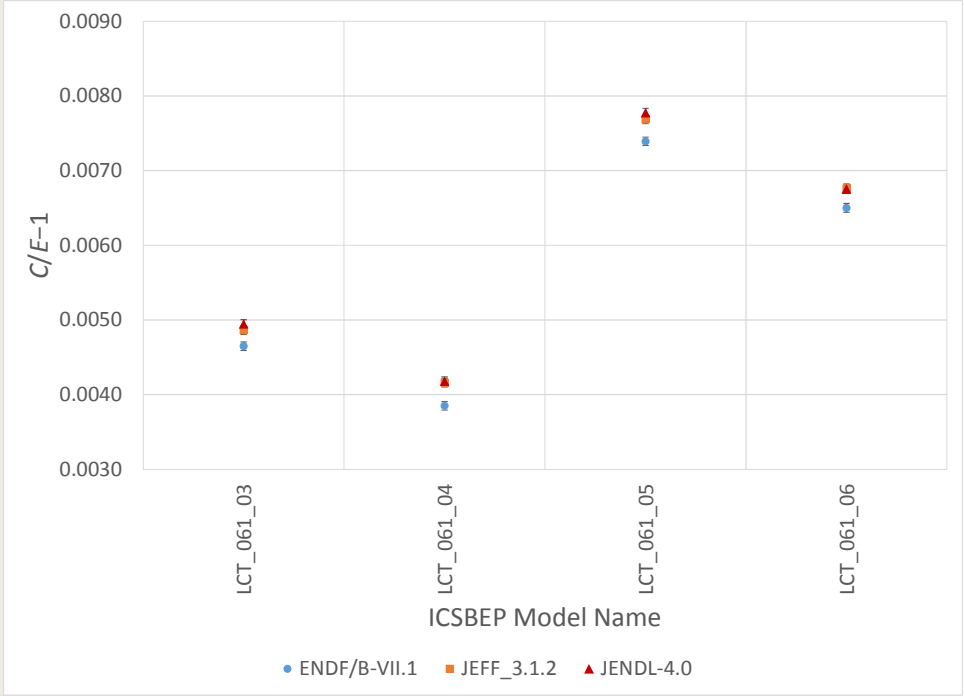
# Performance in Benchmarks

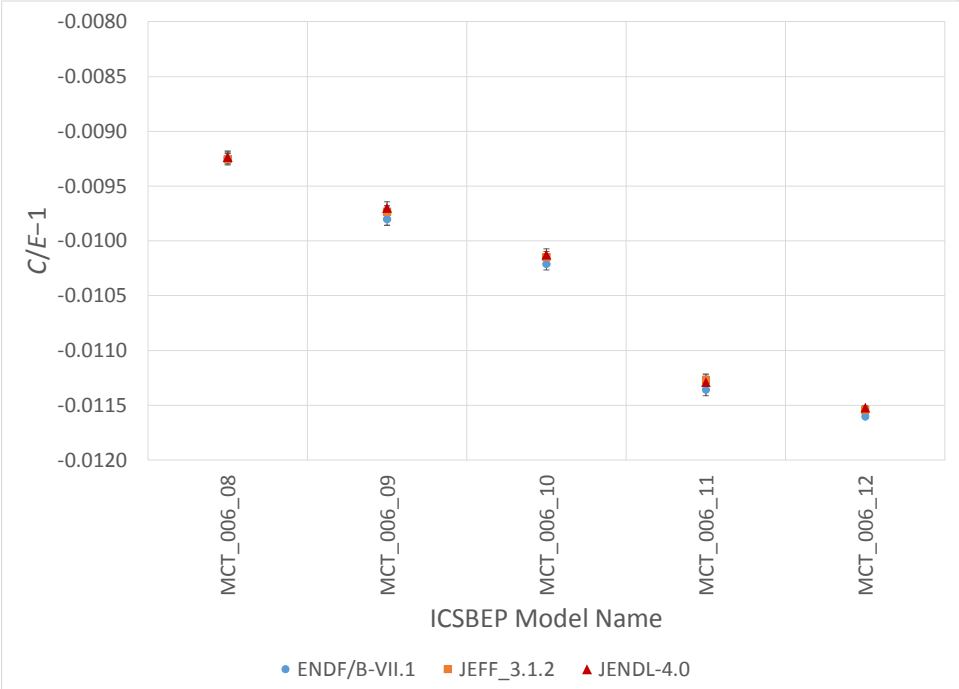
- The following models were analyzed using the three different sets of hafnium isotopes. All other cross sections were taken from ENDF/B-VII.1.
  - LCT-029: Cases 1–5
    - Water-Moderated and Water-Reflected 4.738 Wt.% Enriched $UO_2$ Rod Arrays Surrounded by Hafnium Plates.
  - LCT-061: Cases 3–6
    - Hexagonal (1.27-cm Pitch) Lattices of 4.4 Wt.% Enriched $UO_2$ VVER Fuel Rods in Light Water Perturbed by Hafnium Absorber Rods.
  - MCT-006, Cases 8–12
    - Water-Moderated Mixed Oxide Hexagonal Lattices – 1.0 Wt.% $PuO_2$, 8% $^{240}Pu$, Natural Uranium
  - PST-031, Cases 1–7
    - Plutonium (19% $^{240}Pu$) Nitrate Solution in a Water-Reflected Parallelepiped Tank (50 x 50 cm side) Poisoned by an Array of Hafnium Plates.
- Cross sections generated using NJOY2012 + NDEX and results generated using the MC21 continuous energy Monte Carlo code.
  - Running strategy chosen to reduce *k*-eff 95% CIs to < 10 pcm.

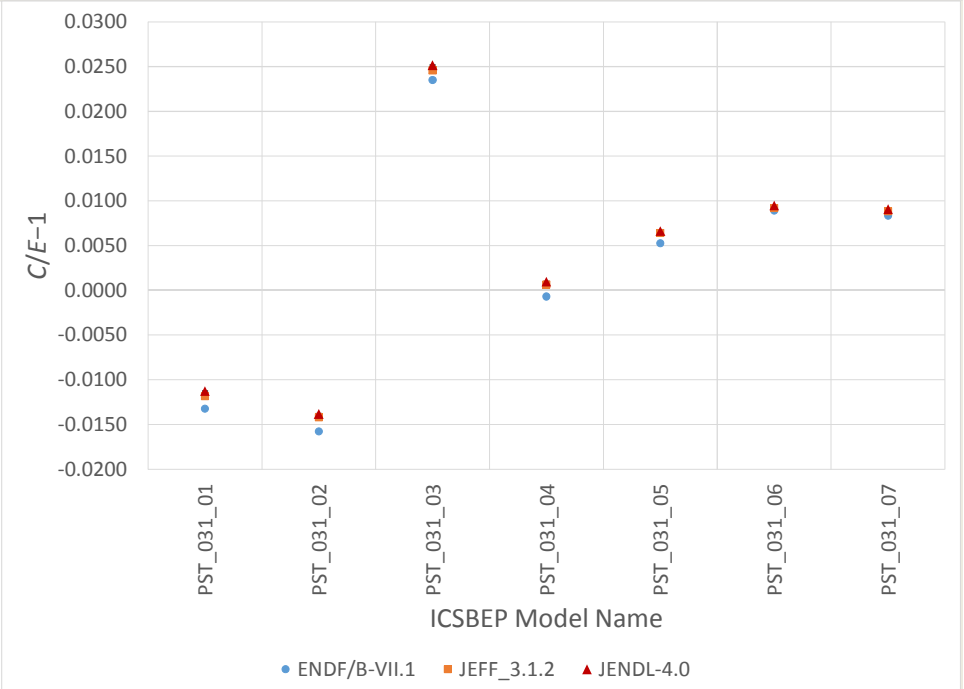



0.030
0.020
0.010
0.000
-0.010
-0.020
-0.030
C/E–1
LCT_029_01
LCT_029_02
LCT_029_03
LCT_029_04
LCT_029_05
LCT_061_03
LCT_061_04
LCT_061_05
LCT_061_06
MCT_006_08
MCT_006_09
MCT_006_10
MCT_006_11
MCT_006_12
PST_031_01
PST_031_02
PST_031_03
PST_031_04
PST_031_05
PST_031_06
PST_031_07
ICSBEP Model Name
ENDF/B-VII.1
JEFF_3.1.2
JENDL-4.0



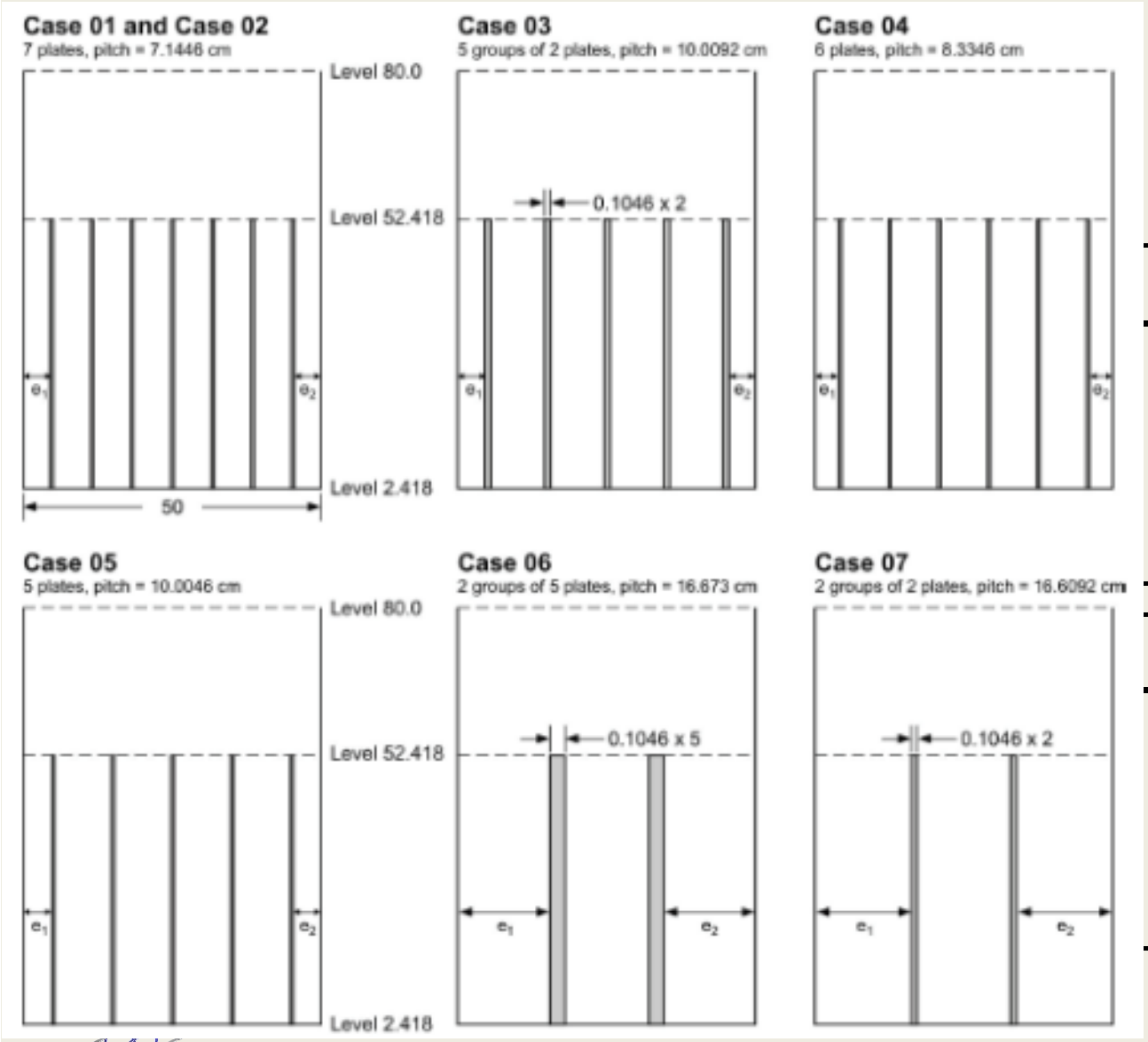




Isotope Evaluations

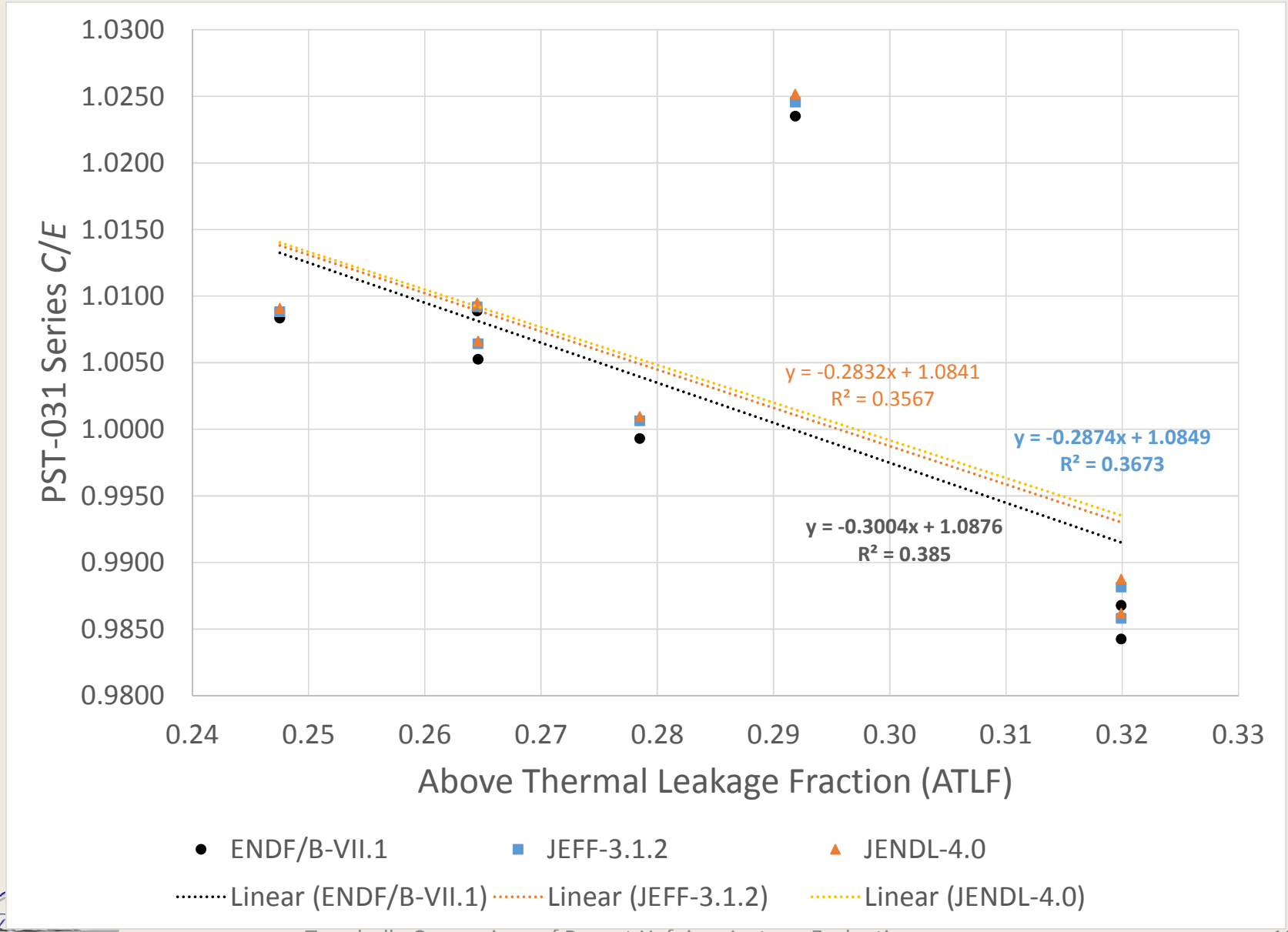
# PST-031 Analysis




| | ΔC/E (pcm) | |
|---|---|---|
| PST-031 | JEFF-ENDF | JENDL-ENDF |
| Case 1 | 138 | 197 |
| Case 2 | 156 | 195 |
| Case 3 | 105 | 165 |
| Case 4 | 133 | 165 |
| Case 5 | 118 | 137 |
| Case 6 | 30 | 58 |
| Case 7 | 48 | 72 |

| | Spectral Parameters | | |
|---|---|---|---|
| PST-031 | ATFF | ATLF | EALF |
| Case 1 | 0.10 | 0.32 | 0.15 |
| Case 2 | 0.08 | 0.32 | 0.11 |
| Case 3 | 0.10 | 0.29 | 0.14 |
| Case 4 | 0.07 | 0.28 | 0.09 |
| Case 5 | 0.06 | 0.26 | 0.08 |
| Case 6 | 0.04 | 0.26 | 0.07 |
| Case 7 | 0.04 | 0.25 | 0.06 |

# PST-031 Above Thermal Leakage Plot



# URR Probability Table and Resonance Scattering Effects

## PST-031 Case 1

| | Effect of URR Tables: | | | |
|---|---|---|---|---|
| | With | Without | $\Delta C/E$ | 95% CI |
| E71 | 0.98678 | 0.98658 | -0.00020 | 0.00008 |
| JEFF | 0.98816 | 0.98813 | -0.00003 | 0.00008 |
| JENDL | 0.98875 | 0.98829 | -0.00046 | 0.00008 |

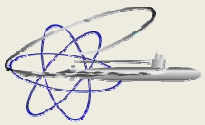
| | Effect of Res. Scattering: | | | |
|---|---|---|---|---|
| | None | DBRC | $\Delta C/E$ | 95% CI |
| E71 | 0.98678 | 0.98639 | -0.00039 | 0.00008 |
| JEFF | 0.98816 | 0.98779 | -0.00037 | 0.00008 |
| JENDL | 0.98875 | 0.98826 | -0.00049 | 0.00008 |

The effects of PTs in the URR generally follow expectations:

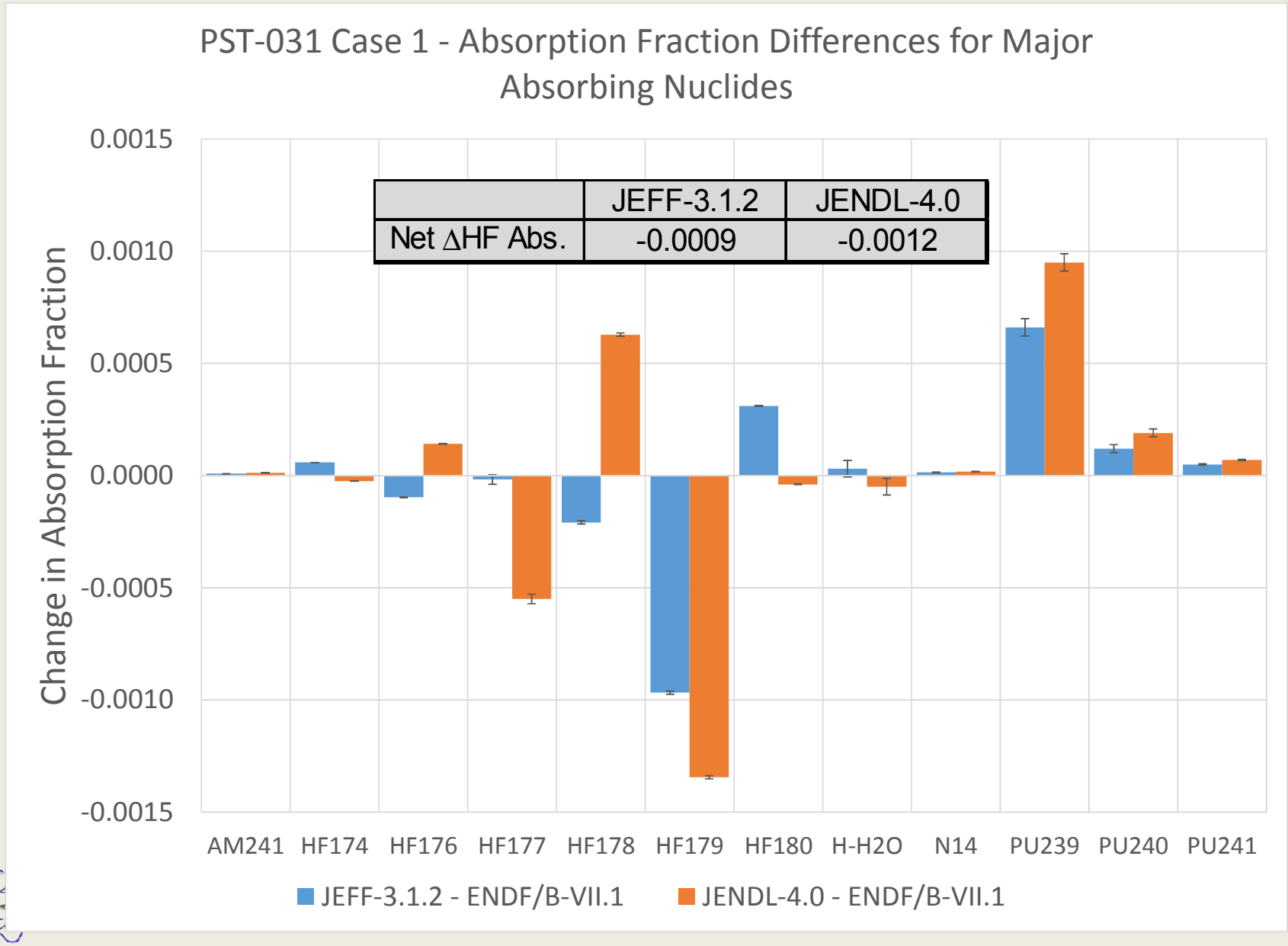
- Largest impact on JENDL-4.0, since it extends the URR higher in energy for most of the Hf isotopes.
- Lowest impact on JEFF-3.1.2, since it extends the RRR higher in energy for most of the Hf isotopes.

The effects of resonance scattering treatments are on the same order for all the data sets, perhaps a little higher for the JENDL-4.0 evaluation.

- Primarily driven by the 7.8 eV resonance in Hf-178.



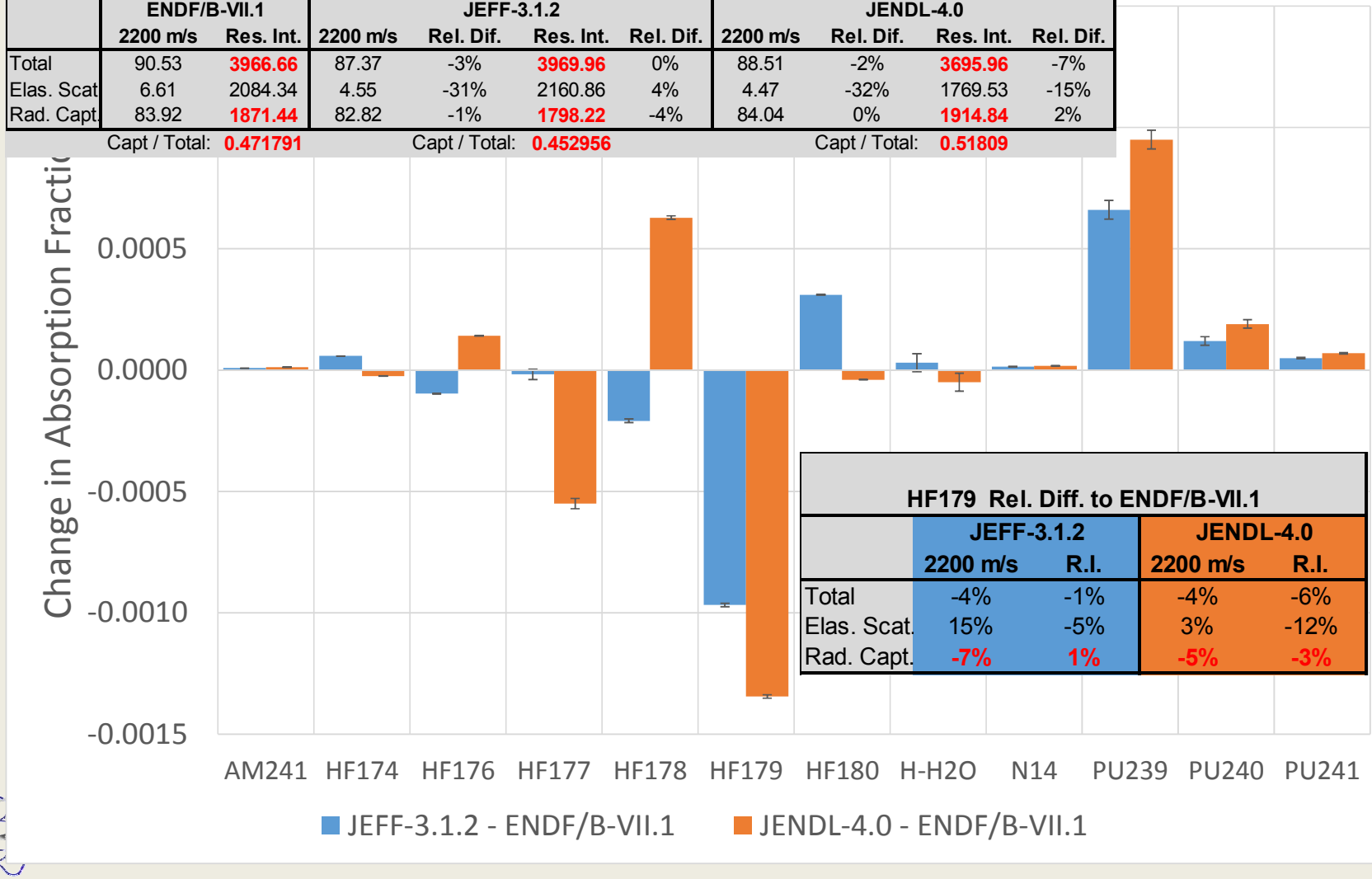
# Absorption Fraction Differences



# Absorption Fraction Differences

PST-031 Case 1 - Absorption Fraction Differences for Major Absorbing Nuclides

| HF178 (27.28%) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | ENDF/B-VII.1 | | JEFF-3.1.2 | | | | JENDL-4.0 | | | |
| | 2200 m/s | Res. Int. | 2200 m/s | Rel. Dif. | Res. Int. | Rel. Dif. | 2200 m/s | Rel. Dif. | Res. Int. | Rel. Dif. |
| Total | 90.53 | 3966.66 | 87.37 | -3% | 3969.96 | 0% | 88.51 | -2% | 3695.96 | -7% |
| Elas. Scat | 6.61 | 2084.34 | 4.55 | -31% | 2160.86 | 4% | 4.47 | -32% | 1769.53 | -15% |
| Rad. Capt. | 83.92 | 1871.44 | 82.82 | -1% | 1798.22 | -4% | 84.04 | 0% | 1914.84 | 2% |
| | Capt / Total: | 0.471791 | | Capt / Total: | 0.452956 | | | Capt / Total: | 0.51809 | |




| HF179 Rel. Diff. to ENDF/B-VII.1 | | | | |
|---|---|---|---|---|
| | JEFF-3.1.2 | | JENDL-4.0 | |
| | 2200 m/s | R.I. | 2200 m/s | R.I. |
| Total | -4% | -1% | -4% | -6% |
| Elas. Scat. | 15% | -5% | 3% | -12% |
| Rad. Capt. | -7% | 1% | -5% | -3% |

# Conclusions

- Differences between ENDF/B-VII.1, JEFF-3.1.2, and JENDL-4.0 Hafnium:
  - Use of RPI (Trbovich) or Geel (Ware) measurements to inform RRR parameters,
  - JEFF-3.1.2 extends RRR to higher energies,
  - JENDL-4.0 extends some of the URR ranges to higher energies.
- Benchmarks available for testing have large swings in C/E, making qualitative judgements difficult:
  - No compelling reason to adopt JEFF-3.1.2 or JENDL-4.0 or change ENDF/B-VII.1:

| | Model Average C/E | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | LCT-029 | | LCT-061 | | MCT-006 | | PST-031 | |
| Hafnium Eval. | Avg. | Std. Dev. | Avg. | Std. Dev. | Avg. | Std. Dev. | Avg. | Std. Dev. |
| ENDF/B-VII.1 | 1.00004 | 0.00041 | 1.00560 | 0.00163 | 0.98956 | 0.00101 | 1.00234 | 0.01363 |
| JEFF-3.1.2 | 1.00015 | 0.00039 | 1.00587 | 0.00164 | 0.98961 | 0.00099 | 1.00338 | 0.01335 |
| JENDL-4.0 | 1.00003 | 0.00037 | 1.00592 | 0.00164 | 0.98963 | 0.00100 | 1.00375 | 0.01335 |