Status of Cross Section Progress for $^{235,8}\text{U}$, $^{239}\text{Pu}$, $^{56}\text{Fe}$, $^{16}\text{O}$

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LANL

(with CIELO collaboration)

Abstract

Progress is described for nuclear cross section evaluations, calculations, and experimental measurements at Los Alamos and other laboratories, on 235,8U, 239Pu, 16O and 1H, for the CIELO project at the Nuclear Energy Agency/WPEC. This includes first data from the LANSCE Chi-nu project, providing insights into the energy spectrum of fission neutrons. The net effect of various nuclear data updates is a suite of CIELO files that models criticality well, but feature an improved agreement with differential data (prompt-fission neutron spectra, time of flight experiments in the resonance region, resonance fission neutron multiplicity, quasi-differential neutron scattering data)
Overview comments on CIELO progress

Progress on our understanding of $^1H$, $^{16}O$, $^{56}Fe$, $^{235}U$, $^{238}U$, and $^{239}Pu$ neutron reactions:

- a variety of different teams and approaches
- experiments & theory advanced

A set of starter files has been created via a USA-Europe-IAEA collaboration

- this suite of (ENDF/B-VIII.beta1) files, taken together (with a new H2O scattering kernel), appears to model integral criticality fairly well. Validation testing ongoing (including SG39 support); future refinements planned
- other CIELO collaborations will provide alternative options, e.g. a European JEFF3.3-testing suite (including CEA/BIII+IRSN files) coming.
- Add/refine covariances
- These analyses will be documented in the coming year, including journal articles in Elsevier’s Nuclear data Sheets (January 2018)
Examples of convergence of opinion
(1) Oxygen-16 (n, alpha)

Hale increases (n, a) by ~40% compared to B-VII

Leal “high and low” options, high similar to Hale, low still > B/VII

Hale file is in accordance with IRMM (Georginis et al.) conclusions

Future “confirmatory” experiments beginning at various labs, including Los Alamos
Examples of convergence

Oxygen-16 low-energy elastic scattering

Leal adopts 3.765b at OK

Hale’s somewhat higher, but both much lower than B-VII.1

Note insights from Chalk River too
Examples of convergence

Oxygen-16 total cross section, normalization determined from RPI experiment

RPI measurement made after evaluation completed

Agrees to <1%

Resolves 3-4% normalization uncertainties
Examples of convergence U235

Capture cross section reduction
near 1 keV reduction

Thermal PFNS – IAEA/LANL and CEA/BIII evaluations ~ agree

Thermal 235U eav=2.00 MeV
Thermal 239Pu eav~2.10 MeV
(tentative, until we obtain new data)
Examples where open questions remain
- These differences of opinion will be documented

Magnitude of actinide inelastic scattering

Actinide capture
- 238U uncertainties further reduced, largely confirming standard
- 235U significant differences remain in the 10s-100s of keV
- 239Pu new DANCE capture data, but will largely influence a future evaluation (more time needed to include in res analysis)

Various questions in resonance evaluation of 56Fe
DANCE Capture Data Test

- Mosby's data Oct. 2015
  - from URR to 1 MeV
  - URR parameters slightly adjusted
  - CoH3 calculation given to the high energy part
    - Soukhovitskii 2005 potential
    - fission adjusted
    - M1 scissors mode included
- CIELO file issue
  - Inelastic scattering exists in URR, but total does not have it
  - Cross section fixed from 9 to 30 keV
Conclusions on CIELO collaboration

CIELO has stimulated healthy collaborations

Enabled significant progress on these evaluations

- enabled large changes to new regional evaluation files, ENDF, JEFF, ...

We welcome feedback from:

- Integral validation data testers
- Adjustment SG39 project insights
- Sensitivity tools like NEA’s NDaST
CIELO progress:
Scattering (Elastic & Inelastic) for Actinides and Iron

New RPI semi-integral approach has had a large impact on validating and improving inelastic and elastic scattering on 238U and 56Fe

- longer term work on 239Pu and 235U planned at LANSCE

Modern inelastic scattering advances made from theory with insights from measured data:

- 238,5U work from the IAEA
- 235U from BRC
- 239Pu work from LANL
- 56Fe work from BNL, IAEA

Note SG39 strong sens. to 238U inelastic
CIELO progress: Actinide Capture

239Pu: New LANSCE data “first” for many decades (Mosby, Jandel)

- tend to support ENDF; only modest changes needed, including above 1 keV where we need a SAMMY analysis, as for 235U n,g

235U was a major advance, from 0.5-2 keV (lower capture)

- In tens of keV suggests a small increase to ENDF (but contradicted by Wallner AMS measurement at 25 keV)

238U capture from Schbx

tends to support standards view
CIELO progress: Actinide PFNS - Impacts everything

IAEA Standards 235U PFNS advances suggest a softer spectrum (2.00 MeV versus 2.03 average energy), but not as soft as Kornilov’s 1.97

- concurrent changes to 235U nubar (lowered) being discussed

New LANSCE PFNS from 235U supports “ENDF” Madland-Nix PFNS in the fast range near 2 MeV, as do LANL/NUEX measurements

- This challenges other studies, where softer PFNS are explored

- Leading to a view to not change fast PFNS (much, at least) for 235U and 239Pu, where Chatillon BRC/LANSCE data also ~ supports ENDF. Chinnu will measure 239Pu in ~ 1 years. New CIELO file uses Talou-Rising eval. For 235U
\(^{235}\)U: LANL PFNS Experimental Work in Fast Range (0.5-6 MeV) Suggests ENDF PFNS is Accurate

- Lestone data was released last year for \(^{235}\)U as well as \(^{239}\)Pu PFNS (Published in ND2013 proceedings)
  - \(E_{\text{inc}}\) average \(\sim 1.5\) MeV
  - \(E_{\text{emission}} > 1.5\) MeV
- New preliminary data from LANSCE/Chi-nu
  - \(E_{\text{inc}}\) average – various “monoenergetic” and average energy cuts possible, including 1.5 and 2 MeV
  - \(E_{\text{emission}} < 1\) MeV in first phase of Chi-nu
$^{235}\text{U}$ : LANL PFNS Experimental Work in Fast Range (0.5-6 MeV) Suggests ENDF PFNS is Accurate

Below 0.1 MeV, backgrounds very high (6:1 ratio) and data less reliable

\[
\begin{align*}
\text{\textbf{235 U PFNS}}
\end{align*}
\]

- Chi-Nu, $E_{\text{inc,avg}} = 2.0$ \((0.7 < E_{\text{inc}} < 6)\) MeV
- Chi-Nu, $E_{\text{inc,avg}} = 1.5$ \((0.7 < E_{\text{inc}} < 3)\) MeV
- ENDF/B-VII.1, $E_{\text{inc,avg}} = 2.0$ \((0.7 < E_{\text{inc}} < 6)\) MeV
- ENDF/B-VII.1, $E_{\text{inc,avg}} = 1.5$ \((0.7 < E_{\text{inc}} < 3)\) MeV
- IAEA, $E_{\text{inc}} = 2.0$ MeV
$^{235}\text{U}$: 2 LANL Experiments cover the whole emission energy range – Chi-nu (LANSCE) and NUEX (Lestone-Shores)

\[\text{E}_{\text{out}} < 1 \text{ MeV}\]

\[\text{E}_{\text{out}} > 1 \text{ MeV}\]

FIG. 3. The emission probabilities listed in Tables III and IV, and the corresponding 1.5-MeV n + $^{239}\text{Pu}$ and $^{235}\text{U}$ Los Alamos fission model fission-neutron energy spectra (curves).
239Pu: Some Particular Challenges

- Build on the excellent WPEC subgroup 34 work from CEA & ORNL
- Capture discrepancies. *We’re waiting for final DANCE data; preliminary results obtained*
- New PFNS results coming (IAEA CRP etc), Chi-nu
- Inelastic scattering discrepancies between evaluations
- Use of new IAEA Standards, including fission (TPC)
- Other new data that will impact the evaluation – new PFGS data from DANCE; New FPY data from TUNL (impact esp at 14 MeV)
Pu-239 Status. Version-0 performs like SG34 at low energies, ENDF/BII.1 at higher energies as expected (See Kahler talk)

- **Contents of the Pu239 file CIELO/B -**
  - Based on ENDF/B-VII.1 cross sections
  - SG34 resolved resonance parameters
  - Prompt nu-bar in JEFF-3.2, up to 650 eV
  - Total nu-bar re-calculated
  - Base file uses ENDF/B-VII.1 chi< 5 MeV; Romano tweak at thermal: Neudecker>5 MeV
    [Until we see Chi-nu 239Pu data, we are hesitant to deviate from ENDF in fast range]
  - Variants: Other PFNS calculations from Neudecker et al.
  - Huge section of delayed gamma-ray spectra removed

- **Some issues planned to be resolved in this and next years**
  - Unresolved resonance range, consider use of ISSF = 1 option
  - Revise inelastic scattering, in collaboration with CEA/DAM, IAEA, and JAEA
  - New gamma-ray production cross section, use of FILE6, and resolve inconsistent fission gamma-ray production
  - Upgrade capture cross sections which considers new DANCE data
Improvements in the new LANL evaluation – Neudecker work

**Experiment:**
- Recently published data of Chatillon et al. and Lestone et al. included (+ Granier corrections)
- Improved uncertainty estimate of exp. data (including Chi-Nu studies)

**Modeling:**
- Einc-dependent parametrization of \( <\text{TKE}> \) and \( <\text{Er}> \) by Lestone et al. & Madland was used (constant for ENDF/B-VII.1)
- Pre-equilibrium component of the PFNS considered via CoH
- Only neutrons coming from the fission process are counted

**Evaluated output:**
- Given for Einc= thermal – 30 MeV
- Evaluated covariances are given for all Einc and also between different Einc
239Pu PFNS at all given Einc, Compared to Neudecker’s Current Evaluation

Romano tweak almost invisible
PFNS Average Energy – CIELO file for testing (ENDF <5 MeV except for a tweak at thermal by Romano, and Neudecker > 5 MeV)
$^{239}$Pu PFNS at E$_{\text{inc}}$ = 1.5 MeV
$^{239}$Pu PFNS at $E_{\text{inc}} = 5.5-6$ MeV (opening of second chance fission)
\( ^{239}\text{Pu} \) PFNS at \( E_{\text{inc}} = 11.5 \text{ MeV} \) and \( E_{\text{inc}} = 14 \text{ MeV} \)
Determining the Prompt Fission Neutron Spectrum (Chi): One of Our Highest Priorities & an IAEA CRP. Chi-nu PFNS delayed till next year (235U measured recently)

Large uncertainties below 1 MeV and above 5 MeV impact criticality calculations and (n,2n) transmutations

Lestone’s talk: accurate underground NUEX data released by Los Alamos:

![Graph showing neutron spectrum](image)

E_{out}>1.5 \text{ MeV}
Ongoing work on PFNS by Talou, Reisner, Neudecker
(red = cielo.0 ; green = cielo.1)

Black = snapshot of ongoing work. Will be updated to include Lestone, Chatillon, etc
Ongoing work on PFNS – Reisner result for thermal, in file cielo.1 for testing
Plutonium Capture: Improvements Are Needed

Existing uncertainties >15%

- SG33 & PROFIL (PHENIX)  
  239Pu(n,g) integral testing suggests B-VII is ~ 10% low over this fast reactor spectrum. Also, Ishikawa’s ADJ work suggests JENDL should be raised 5-10%

- DANCE measurements now being analyzed

239Pu(n,\gamma) Cross Section

Cross Section (b)

Neutron Energy (MeV)

& Ben Diven
Preliminary Results for $^{239}$Pu from DANCE

Investigating structures in keV region
Plan: complete analysis by end of this FY
What will be the impact on criticality calculations?
How could we improve?

Fission and scattered neutron background strong above 10 keV (left)

Neutron detector inside DANCE (right) could reject much of this

Prototype detector run in January – optimizations are needed
Inelastic Scattering Discrepancy

- IAEA Technical Meeting on Model Calculation for Major Actinides
  - Summary report published: INDC(NDS)-0597, R. Capote, et al.

These two files equally work for Jezebel keff prediction.

Probably, the difference in the inelastic scattering comes from the optical potential parameters adopted in each library
  - CEA total cross section is higher than ENDF in the 30keV - 500keV range
  - total and absorption cross sections anti-correlated
Pu-239 Inelastic Scattering - Kawano and collaborators

- Correct treatment of compound cross section
  - Full Engelbrecht-Weidenmueller (EW) transformation performed
  - Fission channel has not yet optimized
    - higher than evaluations
  - Difference between the EW and Hauser-Feshbach-Moldauer cases seems to be small
Reaction Rates in Fast Critical Assemblies Provide Integral Test of Prompt Fission Neutron Spectrum & (n,2n) Cross Sections - *Plutonium-239 PFNS Data*

239Pu

With NUEX data added (Lestone)

Selected Spectral Index Data for the Central Region of Jezebel or Flattop-Pu (with ENDF/B-VII.1 Cross Sections)

NUEX insights ~ contradict our dosimetry (n,2n) data feedback

More work is needed, see new IAEA CRP on dosimetry data validation

"Closed" data points are from Jezebel; "open" data points are from Flattop-Pu.
New $^{16}\text{O}$ Evaluation Based on R-Matrix Analysis of the $^{17}\text{O}$ System

G. M. Hale and M. W. Paris, T2
Major advances for $^{16}$O

- Higher \((n,a)\) cross sections informed by both Georginis re-analysis of older data, and by constraints from scattering theory

- Lower total/elastic low-energy cross section
  - not quite as low as Kopecky-Plompen analysis, but lower than B-VII

- Total cross section validated through recent RPI measurement
  - Confirmation data, obtained after evaluation was completed, agrees to 1%
Outline

- Reminder of R-matrix properties, EDA code
- Status of the $^{17}\text{O}$ system analysis and $^{16}\text{O}$ evaluation
  - Low-energy scattering cross sections
  - $^{13}\text{C}(\alpha,n)$ and $^{16}\text{O}(n,\alpha_0)$ cross sections
  - Fits, data renormalizations, etc.
  - Extension of the evaluation to higher energies
- Summary and conclusions
R-matrix Formalism

**INTERIOR (Many-Body) REGION**
(Microscopic Calculations)

\[ H + \mathcal{L}_B \]
compact, hermitian operator with real, discrete spectrum; eigenfunctions in Hilbert space

\[ |\psi^+\rangle = (H + \mathcal{L}_B - E)^{-1} \mathcal{L}_B |\psi^+\rangle \]

**ASYMPOTIC REGION**
(S-matrix, phase shifts, etc.)

\[ \langle r_{c'} | \psi_c^+ \rangle = -I_{c'}(r_{c'}) \delta_{c'c} + O_{c'}(r_{c'}) S_{c'c} \]
or equivalently,

\[ \langle r_{c'} | \psi_c^+ \rangle = F_{c'}(r_{c'}) \delta_{c'c} + O_{c'}(r_{c'}) T_{c'c} \]

Measurements

\[ \mathcal{L}_B = \sum_c |\alpha_c\rangle \left( \frac{\partial}{\partial r_c} r_c - B_c \right) \]

\[ \langle r_c | c \rangle = \frac{\hbar}{\sqrt{2 \mu_c a_c}} \frac{\delta(r_c - a_c)}{r_c} \left[ \phi_{s_1}^{\mu_1} \phi_{s_2}^{\mu_2} \bigotimes Y_l^m(\hat{r}_c) \right]_J^M \]

\[ R_{c'c} = \langle c' | (H + \mathcal{L}_B - E)^{-1} | c \rangle = \sum_\lambda \frac{\langle c' | \lambda \rangle \langle \lambda | c \rangle}{E_\lambda - E} \]

WPEC meeting, NEA/OECD, Paris, May 9, 2016
R-Matrix Analysis of Reactions in the $^{17}$O System

<table>
<thead>
<tr>
<th>channel</th>
<th>$a_c$ (fm)</th>
<th>$l_{\text{max}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n^{16}$O</td>
<td>4.4</td>
<td>4</td>
</tr>
<tr>
<td>$\alpha^{13}$C</td>
<td>5.4</td>
<td>5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Energies (MeV)</th>
<th># data points</th>
<th>Data types</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{16}$O(n,n)$^{16}$O</td>
<td>$E_n = 0 – 7$</td>
<td>2540</td>
<td>$\sigma_T, \sigma(\theta), P_n(\theta)$</td>
</tr>
<tr>
<td>$^{16}$O(n,$\alpha$)$^{13}$C</td>
<td>$E_n = 2.35 – 5$</td>
<td>672</td>
<td>$\sigma_{\text{int}}, \sigma(\theta), A_n(\theta)$</td>
</tr>
<tr>
<td>$^{13}$C($\alpha$,n)$^{16}$O</td>
<td>$E_{\alpha} = 0 – 5.4$</td>
<td>870</td>
<td>$\sigma_{\text{int}}$</td>
</tr>
<tr>
<td>$^{13}$C($\alpha$,$\alpha$)$^{13}$C</td>
<td>$E_{\alpha} = 2 – 5.7$</td>
<td>1168</td>
<td>$\sigma(\theta)$</td>
</tr>
<tr>
<td>total</td>
<td></td>
<td>5250</td>
<td>8</td>
</tr>
</tbody>
</table>

$\chi^2$ per degree of freedom = 1.68
## Total Cross Section Data

<table>
<thead>
<tr>
<th>Authors (n,n):</th>
<th>Energy Range</th>
<th>Energy Shift</th>
<th>Normalization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Schneider</td>
<td>0.0253 eV</td>
<td>0</td>
<td>1.0 (fixed)</td>
</tr>
<tr>
<td>Dilg, Koester, Block</td>
<td>0.13 – 23.5 keV</td>
<td>0</td>
<td>1.0 (fixed)</td>
</tr>
<tr>
<td>Ohkubo (corr. for H)</td>
<td>0.8 – 935 keV</td>
<td>0</td>
<td>0.9989</td>
</tr>
<tr>
<td>Johnson &amp;</td>
<td>49 – 3139 keV</td>
<td>0</td>
<td>0.9799</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Authors (α,n):</th>
<th>Energy Range</th>
<th>Energy Shift</th>
<th>Normalization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drotleff et al.</td>
<td>346 – 1389 keV</td>
<td>0</td>
<td>1.0 (fixed)</td>
</tr>
<tr>
<td>Heil et al.</td>
<td>416–899 keV</td>
<td>0</td>
<td>1.0 (fixed)</td>
</tr>
<tr>
<td>Kellogg</td>
<td>445–1045 keV</td>
<td>0</td>
<td>1.506</td>
</tr>
<tr>
<td>Bair and Haas</td>
<td>0.997–5.402 MeV</td>
<td>4 keV</td>
<td>0.9410</td>
</tr>
</tbody>
</table>
Integrated (total) Cross Sections

\[ ^{13}\text{C}(\alpha,\text{n}) \]

\[ \sigma_T (\text{b}) \]

\[ E_\alpha (\text{MeV}) \]

\[ E_n (\text{MeV}) \]
n$^{16}$O Total Cross Section

$\sigma_T (b)$

$E_n$ (MeV)

WPEC meeting, NEA/OECD, Paris, May 9, 2016
$n^{16}O$ Elastic Scattering Cross Section

WPEC meeting, NEA/OECD, Paris, May 9, 2016
Giorginis’ Analysis of \((\alpha, n)\) Measurements

- Considered two measurements, Bair and Haas (B&H73) and Harissopulos et al. (Har05).

- Determined a preliminary cross-section scale for B&H73 based on the integral of the thick-target yield over the narrow resonance at 1.056 MeV that agrees with the published scale of Har05.

- Then applied a correction common to both data sets related to characterization of the \(^{13}\text{C}\) target that gives the cross-section scales \(0.95\times\text{B&H73}\) and \(~1.42\times\text{Har05}\).

- Considers the relative shape of the B&H73 measurement to be the most accurate since it had the thinnest target.
$^{13}\text{C}(\alpha,n)^{16}\text{O}$ Cross Section

![Graph showing the $^{13}\text{C}(\alpha,n)^{16}\text{O}$ cross section with different data points and curves.]

- **Legend**:
  - red line: calc
  - blue circles: B&H73 x 0.94
  - green plus signs: Har05 x 1.42

- **Axes**:
  - $\sigma_{\alpha,n}$ (b) on the y-axis
  - $E_\alpha$ (MeV) on the x-axis

- **Data Points**:
  - (3, 0.25) for B&H73 x 0.94
  - (4, 0.3) for Har05 x 1.42

**Note:**
- The graph compares the calculated cross section with experimental data from different sources.
- The energy range is from 1 to 5 MeV.

**WPEC meeting, NEA/OECD, Paris, May 9, 2016**
$^{16}$O(n, $\alpha_0$)$^{13}$C Cross Section
n$^{16}$O Elastic Cross Section
$n^{16}O$ Total Cross Section

![Graph of $\sigma_T$ vs $E_n$ (MeV)]

- Cielo 3/16
- ENDF/B-VII.1

![Graph of $\sigma_S$ vs $E_n$ (MeV)]

- Cielo 3/16
- ENDF/B-VII.1

WPEC meeting, NEA/OECD, Paris, May 9, 2016
n+^{16}\text{O} \text{ Total Cross Section – Comparison to RPI: Integral in 3.2-6 MeV region, C/E=1.005 +/- 0.003. (Confirmatory data, not included in Hale’s analysis),}

**Hale estimate of his evaluated uncertainties:**

- 0.5 - 2.0 MeV: 1.99 %
- 2.0 - 3.2 MeV: 3.03 %
- 3.2 - 6.0 MeV: 2.60 %
- 6.0 - 9.0 MeV: 7.59 %
Comparison to RP1 Total Cross Section – Data after evaluation

0.5 - 2.0 MeV, C/E = 0.996

2.0 - 3.2 MeV, C/E = 0.988-0.990

3.2 - 6.0 MeV, C/E = 1.004-1.005
Comparison, cont.  

6.0 - 9.0 MeV, C/E = 0.992
Capture Cross Section

\[ \sigma_{n,\gamma} \] (b) vs. \[ E_n \text{ (MeV)} \]

- Cielo 3/16
- ENDF/B VII.1

WPEC meeting, NEA/OECD, Paris, May 9, 2016
Summary and Conclusions

- R-matrix descriptions are constrained by fundamental properties (unitarity, causality, TRI) of nuclear reaction theory.
- EDA analysis of the $^{17}$O system includes data from all possible reactions, giving results that are highly constrained by the properties above (especially unitarity).
- The low-energy n+$^{16}$O scattering cross sections are now in better agreement with high-precision measurements, and the (n,$\alpha_0$) cross section agrees with the data of B&H73, IRMM07 (Giorginis).
- The evaluated $^{16}$O file Cielo 3/16 extends to 150 MeV, and is the same as ENDF/B VII.1 above 9 MeV (except for capture).
56Fe iron evaluation advances - BNL, IAEA, ORNL, IRNS

- New evaluation makes use of most precise and most recent experimental data between resonance region and 4 MeV (Berthold data for total, new Geel (Negret, Plompen) data for inelastic, and old but not used before data by Dupont for inelastic, Kinney data for elastic angular distributions)

- It uses IRDFF file for the dosimetry reaction \((n,p)\) (calculations agree with IRDFF within uncertainties except of low incident energies)

- Employs dispersive, Lane-consistent optical model above 4 MeV

- Uses consistent modeling up to 150 MeV

- Is informed by the semi-integral data from RPI (neutron emission and capture)

- Provides better reproduction of inelastic (low energies by construction, higher energies by improved modeling)
56Fe iron evaluation advances - BNL, IAEA, ORNL, IRNS

- Reproduces experimental neutron spectra better than in VII.1

- Improves agreement for the criticality benchmarks by adjusting angular distributions in the resonance region and adding background to capture to simulate the effect of lost d-wave resonances (we’ll work on resonance region to remove backgrounds and angular distribution tweaks while maintain benchmark results)
nat-Fe: Total, Elastic, Inelastic 900-950 keV
Elastic angular distributions

Kinney data are the most extensive and detailed above the inelastic threshold.

JEF-2.2=>JEFF-3.2 ang. distr. are fitted to the Kinney data

Whenever low energy-resolution experimental data are available they are closer to EMPIRE than to Kinney

However, RPI semi-integral experiment favors JEF(F)s so we adopted it between 846 keV and 4 MeV

RPI broad-average data compared with EMPIRE and broad-averaged evaluations
Elastic angular distributions – Kinney data

![Graph showing elastic angular distributions for 26-Fe-56(n,el) Ei1.20E+6](EMPIRE)

- Evaluation Ei1.20E+6
- JEFF-3.2 Ei1.20E+6
- JENDL-4.0 Ei1.20E+6
- 1976 Kinney
- 1966 Cox

**26-Fe-56(n,el) Ei1.20E+6**

**EMPIRE**
235U iron evaluation advances - IAEA, ORNL, IRNS, LANL & Performance in Criticality Simulations – Low energy RR

- fit of Thermal Neutron Constants (TNC) based on microscopic experiments results in a higher thermal fission (~587 barns) and capture (~100 barns) cross sections, and lower total nubar (2.4216 vs 2.4368)

- new resonance parameters fitted to the new TNC and resonance integrals recommended by the Neutron Standard committee, and tuned on integral data

- new evaluation of PFNS that agrees well with microscopic measurements and corresponds to a lower 235U thermal PFNS average energy (now 2.00 MeV, before - 2.03 MeV) that increases criticality
235U iron evaluation advances - IAEA, ORNL, IRNS, LANL & Performance in Criticality Simulations – Low energy

- the higher 16On,a cross sections leads to more neutron absorption and reduces criticality of epithermal assemblies
- new TSL on hydrogen slightly increases criticality of thermal solutions
- strong energy dependence of resonance nubar based on measured data from 0.3 eV up to 60 eV reduces criticality of epithermal assemblies
- decrease of neutron capture around 1 keV and above that increases criticality for intermediate assemblies (still to be compensated)
235U iron evaluation advances - IAEA, ORNL, IRNS, LANL & Performance in Criticality Simulations – Fast energies

- Optical model for fission describes Neutron Standard fission cross sections on U-235 and U-238 within 3% using double and triple humped barriers with absorption. Such accuracy allows for a better prediction of elastic and inelastic neutron scattering.

- Interference of direct and compound mechanisms leads to the increase of inelastic cross sections from ~50 up to 500 keV on U-238.

- Neutron scattering to collective states in the continuum is important to describe observed neutron emission spectra for incident neutron energies above 1 MeV.

- Increased inelastic scattering on U-238 above 500 keV up to 2 MeV, slightly decreased below.
CIELO progress:
(1) Resonance Region, extended to higher energies

Leal, Schillebeeckx, Noguerre, … have made significant advances in representing our understanding of

- **235U** resonances, notably (n,g) near 1 keV, based on recent consistent data between RPI and LANSCE/DANCE
  - updates may be needed in 10s of KeV region too
- **238U** Geel measurements, which are leading to a new evaluation that is only a small perturbation compared to previous ENDF. Up to 20 keV.
  - The new (n,g) is leading to an update to the standards (similar result)
- **239Pu** resonances from SG34
- **56Fe** resonances up to 2 MeV with more rigorous angular distribution treatment
CIELO progress:
(2) 16O

Various files for testing, including R-matrix analyses from Hale and from Leal

- it appears that acceptable integral performance may be maintainable, following small updates to 235U nubar, and thermal PFNS

Questions remain on the magnitude of 16O(n,α), with discrepancies of order 30-50%, which have ~ 100 cpm impacts on criticality.

- new measurement is planned at LANL, in Fall-2015

Low-energy thermal elastic/total - consensus reached (3.765 barns)

A new total cross section has been obtained in the few-MeV region from RPI: “Game changer” (Lubitz).

<table>
<thead>
<tr>
<th>3.2 MeV &lt; E &lt; 6 MeV</th>
<th>C/E</th>
<th>C/E Statistics</th>
</tr>
</thead>
<tbody>
<tr>
<td>ENDF/B-VII.1</td>
<td>0.988</td>
<td>±0.002</td>
</tr>
<tr>
<td>Leal 1</td>
<td>1.030</td>
<td>±0.002</td>
</tr>
<tr>
<td>Leal 2</td>
<td>1.006</td>
<td>±0.002</td>
</tr>
<tr>
<td>Hale</td>
<td>1.012</td>
<td>±0.002</td>
</tr>
<tr>
<td>Cierjacks 80</td>
<td>0.968</td>
<td>±0.002</td>
</tr>
</tbody>
</table>

Normalization uncertainty:
\[
\frac{\sigma_{\text{exp}}^H}{\sigma_{\text{ENDF}}^H} = 0.996 \pm 0.003^*\]

*Statistical
CIELO progress:
(3) 56Fe - using advanced EMPIRE modeling, & SAMMY to 2 MeV

New 56Fe evaluation produced as a “starter file”, BNL, IAEA, … taking into account recent data from Geel & LANSCE on inelastic scattering, & RPI

- Geel data below 6 MeV accurate and consistent with new evals

Performance in iron benchmarks ~ acceptable/good (“no worse!”)

Independent evaluation studies from China tend to corroborate conclusions
56Fe: Advances Needed in Inelastic Scattering

New measurements (IRMM) & SAMMY analyses in resonance region; new Hauser-Feshbach analyses at higher energies
Prompt Neutron Multiplicity

- From IAEA’s latest file:
  - “Prompt nu-bar evaluated by V. Pronyaev, based on Reed data from C00-3058-39, normalized to thermal value of 2.41161. Simon data were measured rel. to 252Cf(sf) normalized at 10-27 eV on Reed’s data (10-Jan-2016). The dip in the data around 30 eV was suppressed. Thermal value was increased by 0.0046 below 0.2 eV.”
DANCE Capture Data Test

- Mosby's data Oct. 2015
  - from URR to 1 MeV
  - URR parameters slightly adjusted
  - CoH3 calculation given to the high energy part
    - Soukhovitskii 2005 potential
    - fission adjusted
    - M1 scissors mode included
- CIELO file issue
  - Inelastic scattering exists in URR, but total does not have it
  - Cross section fixed from 9 to 30 keV
Summary …

CIELO collaboration is making progress in resolving open questions
Starter files created – being tested
Documentation to be completed in next year.
Possible CIELO papers – NDS 2018?

- Chadwick - short overview of CIELO SG40 objectives and accomplishments
- Hale et al - 16O evaluation?
- Hale, Kunieda, Livermore collaborators, ...
- Broader O16 collaboration conclusions on magnitude of n,a based on unitarity
- Georginis, Plompen et al - conclusions on 16O (n,a) corrections on historic data
- Plompen et al, the low energy 16O total elastic cross section
- Leal? - his R-matrix 16O evaluation (not in B-VIII)
- Herman et al - BNL staff - more details on 56Fe in fast region?
- Trkov et al - resonance region of 56Fe
- Leal et al - new resonance analysis of 56Fe
- Chinese work on 56Fe - eg inelastic scattering evaluation
Possible CIELO papers – NDS 2018?

- Romain, Morillon, Bauge et al - CEA fast actinide evaluations
- Chinese work on 235U
- M.Pigni et al (Trkov) resonance analysis of 235U
- R. Capote et al, fast 235U and 238U analysis
- L. Leal resonance analysis of 235U
- Schillebeeckx et al., new Geel 238U resonance analysis - MBC notes not yet in B-VIII-beta1
- Kawano - 238U and LANSCE capture theory and moel calculations
- Neudecker - PFNS evaluations of actinides - incl those that did not make it into B-VIII, eg thermal 239Pu
- Talou - multiplicity dependent fission neutrons and gamma-rays
- Kawano, Capote, Romain, et al, latest conclusions on actinide inelastic cross sections
Neutron reaction on XXX under the CIELO Collaboration

author¹,*
¹Lab address
(Dated: April 29, 2016)

Abstract.
Note we do not yet know page restrictions for these individual CIELO papers, but plan for somewhere between 4-10 pages each. (The same ND2018 issue will have a large 100+ paper on ENDF/B-VIII, and a large 30+ page paper on new standards). Thus we expect perhaps 150 pages reserved for separate CIELO papers.

I. INTRODUCTION

The paper should be journal quality; it will be peer reviewed.

Give background, e.g. - The CIELO pilot project was commissioned by the OECD’s Nuclear Energy Agency WPEC (Working Party on International Nuclear Data Evaluation Co-operation) during a meeting held in May 2012. The goal has been to identify deficiencies and discrepancies in our current understanding of neutron reactions on high priority nuclides ¹H, ¹⁶O, ⁵⁶Fe, ²³⁵U, ²³⁸U and ²³⁹Pu, and to develop proposed solutions and improvements in our understanding. The goals of CIELO are documented in Ref. [? ]. This reference, together with other papers such as Refs. [? ? ? ] document some of the questions being addressed.

Explain clearly which isotope and cross sections or energy/angle distributions will be addressed.

Explain the background as to why our previous understanding was inadequate. Why - a lack of accurate experimental data? Insufficiently reliable model predictions? What were the assessed uncertainties prior to the present work?

Possibly summarize the applications that have motivated the work.

II. RESULTS

Explain the basis for your new conclusions - new experiments made, theory, new analyses?

What are your new proposed uncertainties?

Proposed or recommended evaluations should (a) provide a ENDF-formatted file that can be archived on the NEA CIELO web site; and (b) be documented in this paper, with illustrative figures that compare the recommendation against the main evaluated data libraries, such a ENDF/B-VII.1 [? ? ], JEFF-3.1 [? ? ], JENDL-4.0 [? ], BROND/ROSFOND [? ], and CENDL-3.1 [? ].

What are remaining open questions that remain unsolved?
Cecil Lubitz:

“After several “preliminary” months on CIELO it’s clear that we have bitten off a big chunk. Get ready to chew.”
LANL plans to measure new cross sections on $^{16}\text{O}(n,\langle \rangle)$

- Use a newly developed instrument LENZ with a large solid angle and low alpha detection threshold
- Use a white neutron source at WNR/LANSCE in Fall 2015
- Relative measurement to $^6\text{Li}(n,a)$ reaction to reduce systematic uncertainty
- First goal is to measure cross sections at the energies between 3 and 5 MeV

![Picture of LENZ chamber]

*Neutron energy resolution, assuming 5 ns of timing resolution, which is subject to be improved*
LENZ : Twin Frisch-grid Ionization Chamber + Silicon Strip Detectors

- The multiple target system allows to have a oxygen and a Li reference target at the same time.
- Solid oxygen target is made by anodizing highly-enriched water on tantalum backing.
- At forward angles, the silicon strip detector measures angles and charged particles energy deposit.
- Digitizers provide wavelet information for post processing of improvement of signal-to-noise ratio with no dead time.
Hale comments on new (n,tot) RPI data:

Comments about LANL n+16O Cielo evaluation:

The evaluation we submitted in June of last year is similar in many ways to ENDF/B VI.8. For that reason, since the total cross section was preserved in the evaluation that finally became ENDF/B VII.1, it is not surprising that the agreement with the new RPI measurement of the total cross section looks similar for VII.1 and the LANL Cielo file. Our latest evaluation is somewhat better in the "window", and somewhat worse at energies above about 4.5 MeV. Adding these total cross section data to the analysis would likely decrease the total cross section somewhat in the 2.5-3.5 MeV region, which because of the often-noted anti-correlation effect of unitarity in this region, would tend to raise the fitted (n,alpha) cross section at these energies. This would make the disagreement even worse with experiments that favor the lower normalization scale for the reaction cross section.

We are anxious to add these measurements (not the binned data) to our analysis to see what their effect might be, but we are gratified that the initial comparison does not seem to indicate any major problems with the evaluation. Hopefully, we will have additional (n,alpha) data coming from Los Alamos in the next year or so. In the meantime, we are working on extending the existing LANL file above 6 MeV, and including the Geel (n,alpha) data in our analysis, following Giorginis' recommendations about normalizations, etc.
General
Intercompare evaluations, and identify goals for a new evaluation

JENDL is a new work (though adopts ENDF n,a); ENDF (JEFF uses ENDF) is a hybird of KAPL work < 3.2 MeV, LANL (Hale et al) > 3.2 MeV - assess value of.
The 2005 ORNL work generated a resonance analysis for 16O, full R-matrix. Included angular distributions, n, alpha, and it has never been tested. Needed L

Total, Elastic and inelastic scattering
Compare existing evaluations and R-matrix analysis, and define path forward

At low energies, assess whether evaluations of elastic scattering indeed need to be lowered by ~3%, as proposed by Plompen, Lubitz, Roubtsov etc
covariances for mubar: Need reliable anisotopic 16O scattering uncertainties. Palmiotti thinks Gerry's present uncertainties are too small on mubar.

Capture
ENDF adopted JENDL's capture cross section to include resonance contribution - establish consensus to use this

(n,a)
Review different evaluations (all largely same as ENDF)
Review previous data, and agee on scales - eg Bair & Haas had renorm their original data down by ~20%; Are Johnson data the same as these?

Review new data - Georfinis (Geel), Khryachkov (IPPE) - contact physicists working on 13C(a,n) for astrophysics
The above new data confirm ENDF below 6 MeV but point to changes above
Intercompare R-matrix calcs (Hale, Kunieda, Leal)
Seek to understand why the above R-matrix evaluations, influenced by total cross sec data, suggest ~30% higher (n,a) than most measurements
Define an evaluation strategy... If theory contradicts these data, do we use data instead? Or do we conclude theory is right and measurements had a scale error?
Assess whether evaluations (all now based on ENDF) above ~ 6 MeV need changing, if it is concluded new Geel data are more accurate than old Davis data

Integral
Establish suite of integral validation tests, including k-eff, transmission, etc
2 benchmarks sensitive to oxygen data (+11 more benchmarks with water) are available in the SINBAD database
Broomstick experiment
Following WPEC SG7, With the existing (n,a) evaluations perform well, for the most part, on LEU solutions, Can the new eval perform well too
(n,a) impact at higher energies: Does this higher energy >6 MeV region impact any applications significantly (maybe medical applications)? Carlson notes M check astrophysics constraints on 13C(a,n) reaction rate
1H & Other Standards: Hale’s Summary and Outlook

- NN analysis progressing; more p-p elastic scattering data needed in the 30-50 MeV range. Low-energy parameters retain their earlier (correct) values. Need to extend analysis above 200 MeV.

- New data for n+^6^Li fit in well with the existing data set, and cause no problems with the R-matrix fitting.

- n+^{12,13}C analyses in good shape below 2 MeV. Could produce a natural C standards file in this energy region now. More work is needed on both evaluations at higher energies, however.

- Problem with unrealistically small uncertainties on standards cross sections may be solved by using parameter confidence intervals.
The uncertainties in the n-p scattering cross sections that were put into VII.1 (as described in my CW 2008 paper) are fairly realistic (maximum of 1% at around 10 MeV). The uncertainties on the capture cross section are probably too large, due to the kludge I had to make to compensate for Lubitz's insistence that the thermal value be a certain number. All of this should be better in the next release, since we will use confidence intervals in place of standard deviations (which has the effect of scaling up the standard deviation by a known amount).
n-p Differential Cross Sections

n-p Scattering Cross Section at 10.04 MeV

\[ \frac{d\sigma}{d\Omega} (b/\text{sr}) \]

\[ \theta_{\text{c.m.}} \text{ (degrees)} \]

\[ 0.072 \rightarrow 0.075 \]

\[ 0 \rightarrow 180 \]

Calc

PhaseFormula 102
n-p Polarizations

![Graph showing n-p Polarization at 10.03 MeV](image)
$^{11}$H recent data added to analysis

n-p Total Cross Section

n-p Differential Cross Section at 14.9 MeV
<table>
<thead>
<tr>
<th>CIELO: Summary of tasks to address:</th>
</tr>
</thead>
</table>

### Actinides: 239Pu, 235U, and 238U - specific issues for each nuclide are noted

#### Fast Region (keVs and above to 20 MeV) - fission listed separately

1. **Inelastic and elastic scattering - below a few MeV (eg 7)**
   - Review existing discrepancies between evaluations
   - Collect all available experimental data
   - Review various theoretical approaches, as embodied in codes (including HF, Coupled Channels, KKM, ...)
   - Discuss and review optical model options

2. 238U: dispersive coupled-channels OM developed at IAEA

3. Seek consensus on best evaluated representation of data

4. 238U: 238U Elastic and inelastic scattering data from RPI. Quasi differential available (mainly inelastic) from RPI from from 0.5 MeV up to 20 MeV.

5. 235U: New (n,xng) data to be published in PRC by Kerveno et al. (IPHC, Strasbourg (F)) could be useful to model inelastic scattering on first levels, see

6. Understand implications from integral data testing on changes in inelastic scattering - especially k-eff and reaction rates (spectral indices for 85/5f etc)

7. Assess covariances and implement in ENDF format

8. Create ENDF formatted files

#### Inelastic and elastic scattering - 7-20 MeV

1. Review existing discrepancies between evaluations, data, and models (including preequilibrium)

2. Collect all available experimental data - including Kammerdiener's data and Baba's (U8) data

3. Review various theoretical approaches, as embodied in codes (including preeq, HF, Coupled Channels, KKM, PFNS background, ...)

4. Discuss and review optical model options

5. Seek consensus on best evaluated representation of data - including possible continued use of pseudostates

6. Understand implications from integral data testing on changes in inelastic scattering - especially 14 MeV pulsed spheres/transmission data

7. Assess covariances and implement in ENDF format

8. Create ENDF formatted files

#### Neutron Capture

1. 239Pu: Review discrepancies between evaluations, which exceed 10% at the higher energies

2. 235U: Review discrepancies between evaluations, which exceed 25% near 1 KeV (Japan's 'higher result') and 10% at the higher energies

3. 238U: Consider adopting 238U capture from standards - ENDF/B-VII used this, but with some small differences. Study implications from data testing of

   - Monitor Standards results for any changes, based on new measurements from DANCE, nTOF, Geel

4. 239Pu: Review data (very few measurements, especially above 100 keV there is just the LANL Hopkins data); See if DANCE data is available in time

5. 235U: Review new DANCE data and RPI data, that appear to corroborate JENDL changes near 1 keV, but point to higher energy changes too

6. Review guidance from integral PROFIL data (suggests Pu9 and (maybe) US from ENDF should be higher), and Wallner AMS data at 25 keV and 420 keV

7. Assess model calculations predictions (consistent with above inelastic scattering HF/CC/OM calculations)

8. Seek consensus on best evaluated representation of data

9. Understand implications from integral data testing on changes in capture - especially k-eff and reaction rates (spectral indices for 85/5f etc)

10. Assess covariances and implement in ENDF format

11. Create ENDF formatted files

#### n2n

1. Discuss data, including discrepancies in rise from threshold, and differences near 14 MeV

2. Review existing evaluations (including "GEANIE evaluation" for 239Pu), data, and calculation predictions

3. 235U: New (n,xng) data to be published in PRC by Kerveno et al. (IPHC, Strasbourg (F)) could be useful to model n2n scattering, see prelim results in

4. 239Pu: Carefully note insights on n2n making 238Pu from LANL, and discuss contradictory feedback from PROFIL

5. Validate any changes against n,2n reaction rates in critical assemblies, eg Fig 57 in NDS112,(2012) ENDF

6. Create ENDF file and covariances
### Fission (all energies), cross sections, nubar and spectra for n,g

**Review Overall Goals**, as embodied in this document and in LAUR CIELO document

#### Fission Cross Section

- Seek consensus that we adopt the fission cross section standard from the IAEA group
- Assess implications of adopting standard fission cross section on integral testing
- If IAEA standards team updates their value, use it; this would include any recent/forthcoming fission measurements, eg nTOF, RPI, TPC
- Modeling of fission would occur as part of the above inelastic/capture/n2n activities, but seek consensus that we do not use calculations in the final cross section

**Prompt nubar**

- 238U: Subthreshold fission for 238U – discrepancies between different evaluations. Lead spectrometer measurements near 70 keV suggest a peak

**PFNS**

- Review work of IAEA CRP on PFNS
  - Aim to adopt the CRP’s recommendation
- Seek consensus on using LANL high-accuracy NUEX Pu9 and U5 data, as published in Dec NDS2011 to help define high-energy spectrum
- Use new PFNS measurements, especially below MeV, coming from LANSCE/Chi-nu in the coming years
- Use guidance on high energy tail of spectrum from dosimetry reactions (new IAEA IRDFF CRP), eg from LANL crits, Russian fast reactor, & CERF
- As part of IAEA CRP, advance our theoretical models, and use incorporate other data (new and existing)
- Understand implications from integral data testing on changes in nubar - especially k-eff
- Create ENDF formatted files, including covariances

**PFGS**

- Review existing evaluations and experimental data, and various theoretical approaches
- Represent fission gammas separately at all energies, including above 1.09 MeV for U5 and Pu9 (an ENDF drawback), & use new data available
- Update PFGS spectra to use modern measurements from DANCE, as well as multiplicity distribution if possible
- Create ENDF formatted files, including covariances

**Delayed data**

- Review differences in present evaluations
- Develop plan for work needed

**Energy Release**

- Compare energy release data in evaluations, for prompt n, g, fission fragments; and delayed energy release
- Update as necessary - eg ~ MeV level changes are implied for 239Pu from Jandel’s DANCE data for 239Pu (but 235U looks good)
- Consider updating energy release incident-energy-dependence based on Lestone’s work
Integral Data Testing and Validation

Review Overall Goals, as embodied in this document and in LAUR CIELO document

Define suite of critical assembly, reactor, transmission, etc experiments to use in validation assessments, and observables (k-eff, rates, spectral indices)

238U: selection of 12 ICSBEP criticality benchmarks sensitive to elastic scattering is available from JSI/IAEA (Trkov, Capote)

Seek to ensure good performance in data testing, which includes:

Fast, Intermediate, and thermal assemblies, k-eff

239Pu: Aim for (Partial?) improvement of longstanding overprediction of thermal Pu solutions

Modeling spectral indices well in various systems (incl fast), 8f/5f, 9f,5f, 237np-f/5f, 233u-f/5f etc, see Table XXXVIII in VII.1 NDS 2011 paper

Modeling of post irradiation experiments (PIE) such as PROFIL (CEA) and MANTRA (INL)

Modeling MOX experiments for mock up of LWR, eg in EOLE, Cadarache

See if PFNS improvements give improved n2n detector responses in fast crits, eg through a softer PFNS spec aove 10 MeV

nubar validation using multiplication subcritical measurements

LLNL pulsed spheres

Can we obtain improved predictions of intermediate assemblies, eg ZPR at Argonne

Aim to maintain good prediction of crits, including new as-built high-resolution 3D MCNP Jezebel model?

Use sensitivity methodologies for assessing changes/improvements by reaction and energy range
56Fe

General
Review differences in evaluations. In ENDF/B-VII.1 RR extend up to 850 keV, but pointwise fluctuations extend up to almost 10 MeV.
Get insights from previous evaluators on tasks to work on. For example, Trkov, Koning, Vonach, Tagesen were involved in the last European Jeff evaluation.
Optical model and other key modeling parameters

Fast Region
Inelastic and elastic
Review new data: RPI has high-res transmission up to 2 MeV, and scattering data ("quasi differential data"), that needs an MCNP calc to compare.
Review new data: Arjan Plompen (Geel) has inelastic data (actually, gamma-production) too measured this year, from 800 keV to 5 MeV.
Review new data: Schillebeeckx and Trkov’s postdoc have made some new measurements, and reviewed existing measurements...
Review new data: Ron Nelson (LANL) has gamma-production data for iron.
Review new data: The Grimes et al. Ohio work should be looked at too – it is suggesting a big change for nonelastic, but that our total cross section. IAEA coupled-channel OM work going on for iron.
Pronyaev – also doing work on inelastic gamma production. At one point this was being considered as a standard (now more likely to use Ti).

Charged-particle production
Review data, evaluations, and model predictions for (n, alpha) etc.
Data above 20 MeV may be needed too, eg for fusion applications, using new gas-production data from Haight.

Activation xs
Review/Include activation data needed for fission/fusion

DPA
Take advantage of insights from new IAEA CRP on damage and DPA

Resonance Region, Resolved and UnResolved Parameters (hundred of keV's and below)

RRR & UR
Review latest evaluation from Luiz Leal

Integral validation
Define suite of integral tests - critical assemblies, transmission/shielding, reactor experiments, etc.
17 benchmarks with iron as shielding material (+8 more with stainless steel) are available in the SINBAD database.
Compile feedback from recent testing - eg SG33, fast reactor COMARA experience, etc, Steven VDM's NDS 2012 benchmarking paper (which notes...)
Andrej Trkov has shielding benchmarks that are relevant too. The euracos benchmark for sinbad.
Pay attention to Fe-reflected fast critical benchmarks (+ thermal bench from CEA, e.g. PERLE experiments in EOLE)
Use ZPR3-54, ZPR9-34, ZPR6-10 and possibly CIRANO with reaction rate distributions
Use sensitivity methodologies for assessing changes/improvements by reaction and energy range
Pu-SOL-THERM Benchmarks – II. Prelim LANL testing of new Subgroup 34 resonance results

- A set of seven Pu-SOL-THERM benchmarks have been extracted from the larger set.
  - PST1.4 & PST12.13 span the ATLF space;
  - PST12.10 & PST34.15 span the ATFF space;
  - PST4.1 & PST18.6 span the $^{239}$Pu atom percent space;
  - PST12.10 & PST34.4 span the g Pu per liter space.

- All benchmark experiments are performed in simple geometry
  - PST1.4 & PST4.1 are a water-reflected spheres;
  - PST18.6, PST34.4 & PST34.15 are water-reflected cylinders;
  - PST12.10 & PST12.13 are a water-reflected slabs;
Pu-SOL-THERM Benchmarks – III. Prelim LANL testing of new Subgroup 34 resonance results

The E71 1.00576 \( k_{\text{calc}} \) average demonstrates that the 7 benchmark subset reflects the larger population.

Data revisions in the “Leal7a” \(^{239}\text{Pu}\) evaluated file have eliminated \(~50\%\) of the long-standing \( k_{\text{calc}} \) bias.

### Calculated Eigenvalues\(^{(a)}\) for a Selection of PST Assemblies Using Various \(^{239}\text{Pu}\) Cross Sections

<table>
<thead>
<tr>
<th>Assembly</th>
<th>ENDF/B-VII.1</th>
<th>JEFF-3.1.2 (^{(b)})</th>
<th>JENDL-4.0 (^{(b)})</th>
<th>Leal7a (^{(c)}) + e71</th>
<th>Leal7a (RR, nu, pfns only) + e71</th>
</tr>
</thead>
<tbody>
<tr>
<td>PST1.4</td>
<td>1.00448</td>
<td>1.00127</td>
<td>1.00588</td>
<td>1.00199</td>
<td>1.00202</td>
</tr>
<tr>
<td>PST4.1</td>
<td>1.00383</td>
<td>0.99907</td>
<td>1.00482</td>
<td>1.00044</td>
<td>1.00044</td>
</tr>
<tr>
<td>PST9</td>
<td>1.01939</td>
<td>1.01367</td>
<td>1.02510</td>
<td>1.01543</td>
<td>1.01546</td>
</tr>
<tr>
<td>PST12.10</td>
<td>1.00412</td>
<td>0.99973</td>
<td>1.00498</td>
<td>1.00083</td>
<td>1.00080</td>
</tr>
<tr>
<td>PST12.13</td>
<td>1.00955</td>
<td>1.00468</td>
<td>1.01069</td>
<td>1.00611</td>
<td>1.00620</td>
</tr>
<tr>
<td>PST18.6</td>
<td>1.00472</td>
<td>1.00153</td>
<td>1.00557</td>
<td>1.00202</td>
<td>1.00208</td>
</tr>
<tr>
<td>PST34.4</td>
<td>1.00258</td>
<td>0.99999</td>
<td>1.00417</td>
<td>0.99922</td>
<td>0.99937</td>
</tr>
<tr>
<td>PST34.15</td>
<td>0.99742</td>
<td>0.99563</td>
<td>0.99844</td>
<td>0.99679</td>
<td>0.99707</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td><strong>1.00576</strong></td>
<td><strong>1.00195</strong></td>
<td><strong>1.00746</strong></td>
<td><strong>1.00285</strong></td>
<td><strong>1.00293</strong></td>
</tr>
</tbody>
</table>

\(^{(a)}\) MCNP calculations are for 250M histories; stochastic uncertainty is \(~5\) pcm.

\(^{(b)}\) JEFF-3.1.2 and JENDL-4.0 \(^{239}\text{Pu}\) only; remaining nuclides are ENDF/B-VII.1

\(^{(c)}\) “LEAL7a” evaluation provides revised resolved resonance parameters coupled to a joint ORNL/CEA evaluated \(^{239}\text{Pu}\) file; the “LEAL7a (RR,nu,pfns)” file couples just these data to the existing ENDF/B-VII.1 \(^{239}\text{Pu}\) file.
Time-line

May 2013: CIELO WPEC Subgroup initiated
- Teams identified

Nov 2013: NEMEA7-CIELO: Main collaboration kick-off
- Refine scope of work, collaborators who will work on tasks
- Will result in detailed work plans, time line goals, for each nucleus

Next 2014-2016 Years:
- Various collaboration meetings, continual email collaborative exchanges
- Engagement with validation data testers continually
- Start incorporating new IAEA standards results (fission, capture, scattering, …)
- Explore interdependencies on criticality from the 6 CIELO nuclides

May 2016:
- Document conclusions from CIELO collaborations in WPEC report (& NDS paper, 2018)
- Create formatted files that embody CIELO’s initial conclusions