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CIELO Collaboration Summary Results: International Evaluations of Neutron Reactions on Uranium, Plutonium, Iron, Oxygen and Hydrogen

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The CIELO collaboration has studied neutron cross sections on nuclides that significantly impact criticality in nuclear technologies - ^{235,238}U, ^{239}Pu, ^{56}Fe, ^{16}O and ^{1}H - with the aim of improving the accuracy of the data and resolving previous discrepancies in our understanding. This multi-laboratory pilot project, coordinated via the OECD/NEA Working Party on Evaluation Cooperation (WPEC) Subgroup 40 with support also from the IAEA, has motivated experimental and theoretical work and led to suites of new evaluated libraries that accurately reflect measured data and also perform

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well in integral simulations of criticality. This report summarizes our results on cross sections and preliminary work on covariances, and outlines plans for the next phase of this collaboration.

CONTENTS

I. FOREWORD

The Nuclear Energy Agency (NEA) of the Organization for Economic Cooperation and Development (OECD) supports the need for high quality nuclear data for nuclear applications. These applications encompass not only energy production, but also handling of waste, radiological protection and medical isotope production. Several of these are still very demanding upon adequate and accurate nuclear data for design purposes and demonstration of safety.

For many years the NEA has supported international collaborative advances in evaluated cross-section nuclear databases via its Working Party on Evaluation Cooperation (WPEC). The work described in this article presents the CIELO project as an example of a recent important advance made by the international nuclear reaction data community, under WPEC Subgroup 40. Furthermore, it represents a continuing collaboration to take advantage of new cross section measurements, advances in theory, and information from integral experiments analyzed using various neutron transport and sensitivity computational tools. This article demonstrates the results of an intensive collaborative effort by more than 70 contributors over several years.

The future role of the NEA in this context will be to continue to assist the NEA member countries in their scientific development of modernised data, including new formats, visualization tools and software able to effectively manipulate the data on a large scale. In addition it can make a valuable contribution to the testing and validation of the nuclear data against its vast and unique collection of integral experiments.

Daniel Iracane,
Deputy Director-General and Chief Nuclear Officer of the Nuclear Energy Agency

II. INTRODUCTION

The Collaborative International Evaluation Library Organization (CIELO) project [1, 2], coordinated by the Nuclear Energy Agency (NEA) Working Party on Evaluation Cooperation (WPEC) NEA/WPEC Subgroup 40 since 2013, has stimulated advances to the neutron cross section evaluations of nuclides that significantly impact our nuclear technologies: hydrogen, oxygen, iron, and selected uranium and plutonium isotopes. The benefits of a CIELO-coordinated effort between experts in nuclear science from around the world has led to the advances described in this paper, which also represents the Summary Report of NEA WPEC Subgroup 40.

The primary motivation for the CIELO project was the desire to more-rapidly expedite improvements in these important cross sections. Improving the evaluated data for such nuclides is a major undertaking, desired by nuclear science and technology communities around the world. We felt that this could best be accomplished by establishing a more formal collaboration arrangement for experiments, and for theory and simulation components. The intention was to document open questions and issues that were resolved through the collaboration, and create evaluated data files that embody the advances. From the very beginning we have considered the collaboration process to be as important as the new evaluations being produced.

Since nuclear criticality applications are impacted by the integrated effects of neutron reactions on many nuclides, our goal was also to create data files that (neutronically) perform well together as a suite. This was summarized in an article developed at the beginning of the CIELO collaboration [1] in 2013. It was anticipated that

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the data files that we would produce would be available for adoption – in part or as a whole – by the major evaluated database efforts of ENDF, JEFF, JENDL, CENDL, and so on. And indeed, the CIELO-1 and CIELO-2 sets of cross section data described in this report have been adopted by the ENDF and JEFF communities, respectively. Other papers in this issue of *Nuclear Data Sheets* describe the CIELO efforts in more detail [3–8] and also describe the major ENDF/B-VIII.0 database release [9] that adopts CIELO-1 including the new standards [3].

Computational nuclear science and computing advances have played a key role in CIELO's progress. Fast computers have enabled large-scale nuclear criticality and transport simulations, mostly with the MCNP® version 6 code [10], to assess the performance of proposed evaluation changes, with a feedback loop leading to the optimization of the reaction model parameters and ultimately of the evaluated data files. These iterations took place in hours, instead of weeks/months as was the established tradition for previous evaluations.

Nuclear reaction theory and modeling codes for coupled channels, statistical reactions and fission, and R-matrix, continue to be refined. The community is also starting to understand the benefits, and use of, sensitivity tools such as the NEA's NDaST codes to help focus research efforts and to efficiently select relevant integral experiments for data testing. Also, various insights from the NEA/WPEC Subgroup 39 adjustment project have been useful.

Experimental work has always been the foundation of nuclear reaction data evaluations, and must remain so despite the costs and time involved in executing new measurement concepts to determine cross sections to unprecedented accuracy. The rallying of efforts behind CIELO has led to measurements over the course of this pilot project, most notably at JRC–Geel, CERN n_TOF, RPI, Los Alamos, and TUNL, see Table I.

TABLE I. Notable experimental contributions during the course of the CIELO project, since 2013. This tabulation does not include additional measurements impacting the new standards evaluation [3].

Laboratory	Measured data for CIELO
LANL	^{235,238}U, ^{239}Pu fission, PFNS and capture; iron inelastic gammas
RPI	^{235}U fission, capture; iron capture; ^{238}U and Fe semi-differential scattering; ^{16}O total cross section
TUNL	^{238}U$(n,2n)$
JRC–Geel	^{238}U capture; Fe inelastic scattering; ^{16}O(n,α) cross section
CERN n_TOF	^{235,238}U fission and capture

The CIELO project has worked with the IAEA standards project to stay abreast of standards cross section advances, and remain consistent with them. This pertains to recommendations on hydrogen, and actinide fission and capture cross sections. A new standards evaluation was released in 2017, and is also documented in this issue of *Nuclear Data Sheets* [3]. An IAEA Coordinated Research Project (CRP) on prompt fission neutron spectra (PFNS) [11] has also positively impacted CIELO.

III. CIELO EVALUATIONS CREATED

The CIELO pilot project has a goal of resolving some previous discrepancies in the evaluated data, via peer review interactions together with new experiments, theory, and simulation. But it is also recognized that – in some cases – differences of opinion will persist, reflecting open unsolved problems and uncertainties, as well as differences in evaluation methodology. In these cases the goal is to document the differences (see Refs. [1, 2, 12, 13]) and reflect them in alternate data evaluations. We account for this diversity by creating and archiving two sets of files, CIELO-1 and CIELO-2, with each set of files designed to work together as a suite in criticality applications. Many of the cross section updates have compensating impacts on criticality. For example, for CIELO-1, in thermal systems involving uranium and oxygen the increased criticality from the lower average-energy ^{235}U prompt fission neutron spectrum (PFNS) is compensated by the changes to ^{235}U capture (increase), ^{235}U resonance region prompt nubar (decrease), and oxygen that lower the criticality (increased (n,α) leads to more neutron absorption; and a lower scattering cross section leads to more leakage and less moderation).

In practice, CIELO-1 has been adopted by the ENDF community in ENDF/B-VIII.0, and CIELO-2 by the JEFF community in JEFF-3.3. These are illustrated in Table II.

TABLE II. Lead laboratories evaluating CIELO-1, -2 databases. CIELO-1 is being adopted by ENDF, CIELO-2 by JEFF. Many other labs contributed, including with data measurements. For each isotope we separately tabulate the work done on the resonance range and the fast region (*e.g.,* keV and above for actinides).

Isotope	CIELO-1	CIELO-2
^{1}H	LANL/IAEA	LANL/IAEA
^{16}O res.	LANL/JRC–Geel	IRSN/JRC–Geel
^{16}O fast	LANL	LANL
^{56}Fe res.	IAEA/BNL	IRSN
^{56}Fe fast	BNL/IAEA/CIAE	JEFF
^{235}U res.	ORNL/IAEA	IRSN/ORNL
^{235}U fast	IAEA+LANL PFNS	CEA
^{238}U res.	JRC–Geel	IRSN/CEA
^{238}U fast	IAEA+LANL PFNS	CEA
^{239}Pu res.	ORNL/CEA	ORNL/CEA
^{239}Pu fast	LANL	CEA

A. ^{235}U Neutron Reactions

Evaluation projects prior to CIELO have been strongly influenced by the ^{235}U resonance analyses performed at ORNL by Derrien and Leal and adopted by many of the world's various nuclear data libraries. Above the resolved resonance regime up to the fast neutron energy region, previous cross section evaluation work in the US was led by Young and Chadwick, and Madland for PFNS (LANL); in Europe by Romain, Morillon (CEA), and Vladuca and Tudora for PFNS, and in Japan by Iwamoto, Otuka, Chiba, Kawano, and Ohsawa for PFNS. The present CIELO evaluation work was performed by Capote, Trkov, Pigni, Leal, Sin, Talou, Rising, Neudecker, Morillon, Romain, Kahler. The CIELO-1 evaluation is described in detail by Capote *et al.* in Ref. [5] as well as in the main ENDF/B-VIII.0 paper [9], both in this issue of *Nuclear Data Sheets.*

A major challenge facing the CIELO team was the need to accommodate several important updates over the whole energy range: the inclusion of fission cross sections newly evaluated by the standards which are 0.4% higher in the fast region [3], a softer thermal PFNS spectrum [11, 14, 15], a new set of thermal constants [3, 16], and new accurate neutron capture measurement from Los Alamos and RPI with new data available up to tens of keV's. Additionally, the inelastic, $(n,2n)$, and other reaction channels were evaluated on the basis of new "modern" statistical model implemented in the latest reaction modeling codes that use a modern coupled-channel optical model formulation [17–19] to generate needed transmission coefficients. Since the previous ^{235}U and ^{238}U evaluations performed fairly well in many thermal, intermediate, and fast critical validation benchmarks [20], creating new evaluations with equal or even superior performance has been a challenge (and one that we feel we have met).

Within the CIELO project, two almost independent evaluations were produced. The CIELO-1 evaluation adopted the aforementioned new standards data; and achieved an excellent agreement with newly available capture data while both CIELO-1 and CIELO-2 allowed small modifications to the prompt fission neutron multiplicity to optimize matches to integral simulations of nuclear criticality. The CIELO-1 evaluation also adopted a resonating fission neutron multiplicity below 75 eV as reflected in measured data that have been neglected in previous ^{235}U evaluations.

In the early stages of the CIELO project, the resonance analysis developed by Leal, first at ORNL, and later at IRSN, accounted for new sets of capture data measured at LANL and RPI, as well as a better fit of the standards fission integral in the 7.8–11 eV range (the CIELO-2 file). Pigni (ORNL) in collaboration with the IAEA built on Leal's work with extensive modifications in the very important region below 100 eV for the CIELO-1 evaluation, as described below and in Ref. [5].

The ^{235}U resolved resonance CIELO-1 evaluation recently released within the ENDF/B-VIII.0 nuclear data library has also been developed on the basis of newly evaluated thermal neutron constants [16] as well as of new thermal Prompt Fission Neutron Spectra (PFNS) [11, 14, 15] and the new standards fission cross section [3].

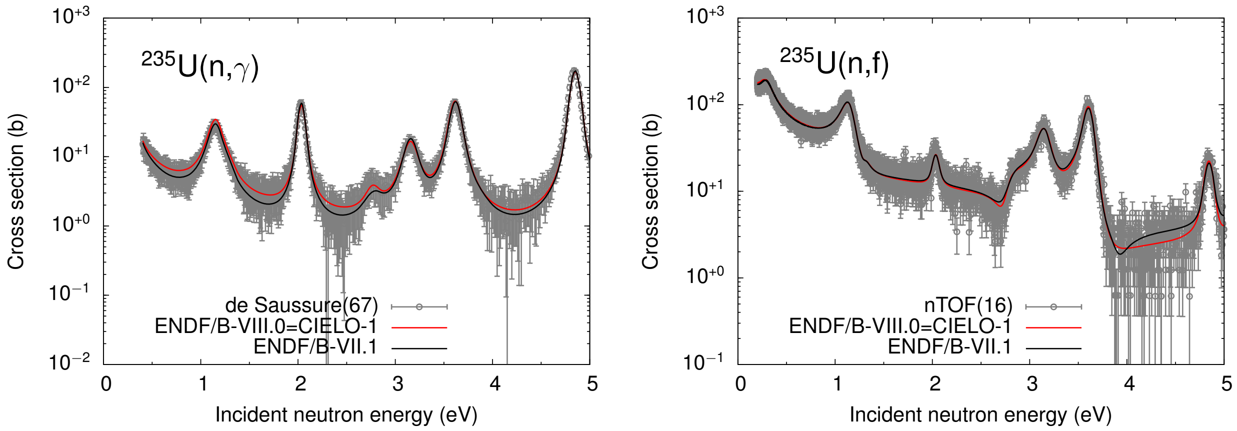
The softer thermal PFNS of the CIELO-1 evaluation (E_{av}= 2.00 MeV versus the earlier 2.03 MeV) increases the calculated thermal criticality k_{eff}, especially for high-leakage benchmarks. This introduces a strong positive slope for C/E (calculation/experiment) k_{eff} criticality as a function of increasing Above-Thermal-Leakage-Fraction (ATLF), for highly-enriched uranium solutions with thermal neutrons (HST) benchmarks, which needs to be removed (as described below).

For energies below 100 eV, this work restores benchmark performance for ^{235}U solutions by combining changes to the prompt resonance $\bar{\nu}$ and the resonance parameters. In achieving this, the present set of resonance parameters yields cross sections still in reasonable agreement with the suite of experimental data included in the previous resonance evaluations. Additionally, the set of η measurements performed by Brooks [21] in the mid-sixties at the Atomic Energy Research Establishment (Harwell) were analyzed and included in the fit for incident neutron energies up to 20 eV, and also new sets of data measured at CERN by the n_TOF collaboration [22, 23].

Our earlier CIELO summary paper, Refs. [2, 24], shows comparisons of SAMMY calculations with measurements by Brooks [21] in the incident neutron energy range up to 5 eV, and by Wartena and Weigmann [25] in the low energy range between 0.0015–0.45 eV. These studies and Ref. [5] address the value of including measured data on $\eta = \nu \cdot (1 + \alpha)^{-1}$ (ν being the average number of neutron per fission and $\alpha = \sigma_\gamma/\sigma_{\text{f}}$; by definition it is a quantity independent of any normalization factor in the cross sections). Despite the large uncertainties above 2 eV, the CIELO-1 η (decreased) values are on average in better agreement with the experimental data than ENDF/B-VII.1 values. By including this set of η measurements, the changes in the cross sections were evident in the valley of the resonances while keeping their peak values mostly unchanged, as seen in the resonance at E_{n}=2 eV. Fig. 1(a) shows the cross sections reconstructed from the resonance parameters of CIELO-1 and ENDF/B-VII.1 evaluations compared to De Saussure's capture data [26, 27] where the increased capture cross sections in the valleys are evident.

As shown in Fig. 4 of Ref. [2, 24], for neutron incident energies $\geq$ 4 eV, the result of an increased capture cross section is also evident in a decreased fission cross section, mainly in the valleys of the neighbour resonances. A similar effect is also shown in Fig. 1(b) that compares CIELO-1 with recent n_TOF fission data [22].

The use of a softer PFNS and the newly fitted thermal neutron constants (with higher thermal fission) compensated the decreased criticality that would result from a decreased neutron balance suggested by Brooks' data. Moreover, an additional constraint to the values of the resonance parameters was introduced by cross section integrals, *e.g.*, the fission integral in the incident energy



(a) n+^{235}U resonance capture below 5 eV. (b) n+^{235}U resonance fission below 5 eV.

FIG. 1. (Color online) n+^{235}U capture measurements of De Saussure [26, 27] and n_TOF fission measurements [22] compared to the ENDF/B-VII.1 and CIELO-1 (=ENDF/B-VIII.0) evaluations.

range between 7.8–11 eV,

$$I_f = \int_{7.8\text{ eV}}^{11\text{ eV}} \sigma_f(E)dE = 247.0 \text{ b·eV}, \tag{1}$$

which is close to the standard reference value, $I_f = 247.5(3.0)$ b·eV, recently adopted by Carlson [3] in the international evaluation of neutron cross section standards on the basis of an earlier recommendation by Wagemans [28]. Recently, the 2006 reference value of I_f was adopted as a normalization factor for the newly measured n_TOF fission cross section data [22].

The different prompt fission neutron average multiplicity evaluations are shown in Fig. 2 (bottom panel) for CIELO-1 (IAEA CIELO) and CIELO-2 (CEA CIELO). This $\overline{\nu}_p$ quantity remains one of the most influential parameters affecting nuclear criticality. It is typically known fairly accurately, to better than a percent, but the uncertainty range with which it is known still allows for different evaluation choices, and in practice it remains a widely-used "knob" that is adjusted (slightly) to optimize criticality simulations. The IAEA/ORNL evaluation for CIELO-1 has introduced $\overline{\nu}$-fluctuations in the low energy resonance region, as was also done for ^{239}Pu, see Fig. 2 (upper panel).

The CIELO-1 (=ENDF/B-VIII.0=IAEA CIELO) average ^{235}U capture cross section from 500 eV up to 3 keV is shown in Fig. 3 (lower panel). It follows recent Los Alamos (Jandel *et al.*) [30] and RPI (Danon *et al.*) [31] measurements, lying significantly (20–40%) below ENDF/B-VII.1 [32]. A good agreement with the RPI measured fission yield is observed in the upper panel of the same figure. The measured yield at RPI is the fraction of neutrons incident on a sample that produce a particular reaction (capture or fission). It includes reactions which occur in the first neutron interaction (primary yield) and those which occur after multiple scattering. The capture measurements observed the gamma-rays emitted using the RPI multiplicity detector [34]; fission events were separated from gamma events based on the gamma cascade total energy deposition and the multiplicity of the gamma cascade [31].

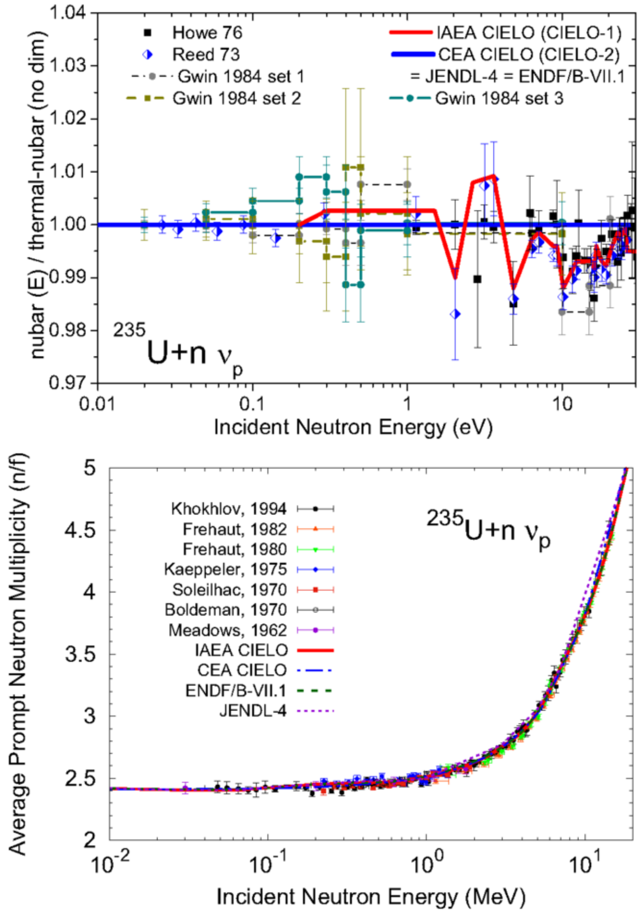


FIG. 2. (Color online) n+^{235}U prompt fission neutron multiplicity in CIELO-1 (IAEA CIELO) and CIELO-2 (CEA CIELO), in the resonance (upper panel) and the fast (bottom panel) energy ranges. Data taken from EXFOR [29].

The ^{235}U capture cross section from 3 to 80 keV is shown in Fig. 4; the new CIELO-1 evaluation lies above ENDF/B-VII.1 for energies from 3 to 20 keV closely following Los Alamos Jandel data [30]. The CIELO-2 (CEA

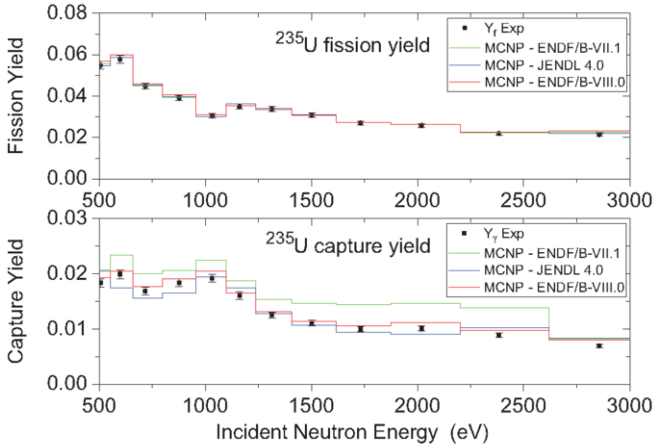


FIG. 3. (Color online) Average ^{235}U(n,f) and ^{235}U(n,γ) cross sections from ENDF/B-VII.1 [32], JENDL-4 [33] and CIELO-1 libraries are compared with RPI thick-target data [31] from 500 eV up to 3000 eV.

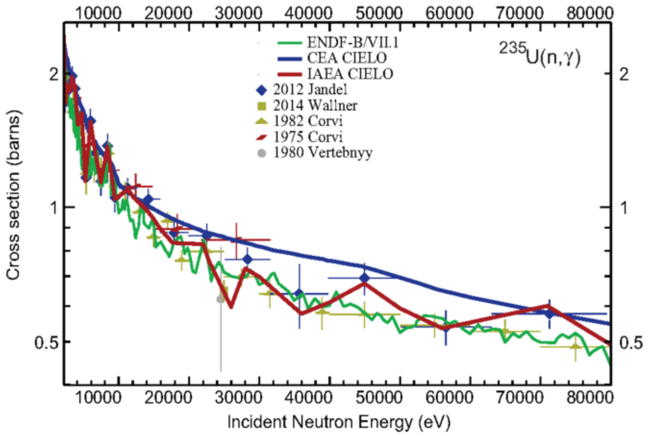


FIG. 4. (Color online) ^{235}U(n,γ) cross section comparing IAEA CIELO (CIELO-1=ENDF/B-VIII.0) and CEA CIELO (CIELO-2=JEFF-3.3) vs selected experimental data. The IAEA CIELO (CIELO-1=ENDF/B-VIII.0) follows the Los Alamos Jandel data.

CIELO) evaluation is significantly higher than CIELO-1 from 15 to 80 keV. A priority was also made in CIELO-1 to match the Wallner Accelerator Mass Spectrometry (AMS) measurements of capture [35], see Table III.

The inelastic scattering cross section has been reevaluated as part of a new optical [17, 19] and statistical model analysis of direct and compound reactions [5, 36, 37]. CIELO-1's total inelastic scattering is reduced compared to ENDF/B-VII.1, see Fig. 5; CIELO-2 features the highest inelastic scattering cross section below 500 keV, but then agrees pretty well with CIELO-1 cross section in the important range from 500 keV up to 2 MeV. CIELO-2 inelastic cross section becomes 10% lower than CIELO-1 at 5 MeV. Preequilibrium processes become important for incident energies above about 10 MeV. These, together with inelastic scattering reactions involving the excitation of collective states, are included in EMPIRE model calculations, allowing for the modeling of 14 MeV secondary neutron emission data measured by Kammerdiener at Livermore shown in Fig. 6. The ^{235}U($n,2n$) and ^{235}U($n,3n$) cross sections are shown in Fig. 7; IAEA CIELO-1 evaluation is in excellent agreement with Frehaut and Veeser measured data for (n,2n) and (n,3n) reactions, respectively. The CEA CIELO-2 evaluation is higher than Frehaut data at the (n,2n) threshold and lower above 11 MeV. The CEA CIELO-2 evaluation overestimates the (n,3n) Veeser data at 20 MeV.

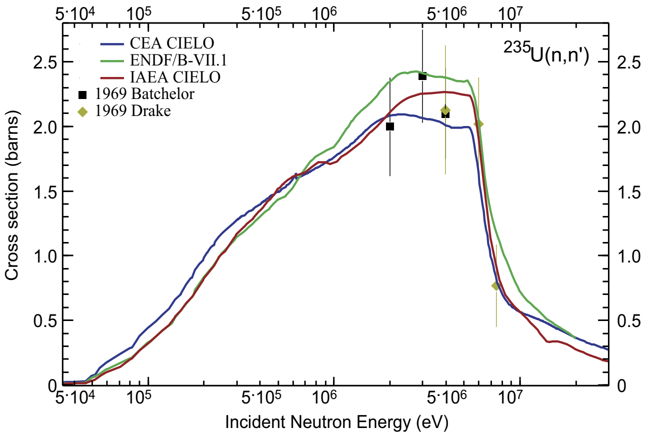


FIG. 5. (Color online) ^{235}U total inelastic cross sections in the IAEA CIELO-1 and CEA CIELO-2 evaluations.

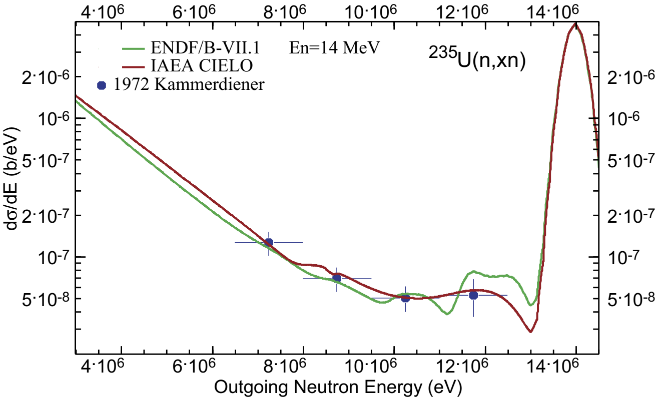


FIG. 6. (Color online) ^{235}U neutron emission spectra. IAEA CIELO-1's secondary neutron spectra, for 14 MeV incident energy, compared to measurements and to ENDF/B-VII.1. Fission neutrons are included.

The importance of the need for a better understanding of the prompt fission neutron spectra (PFNS) from actinides, owing to its large impact on criticality calculations, led to a multi-year IAEA Coordinated Research Project, the results of which are now documented in a major article [11]. An important conclusion was that the PFNS from thermal neutrons on ^{235}U should have a lower average energy, 2.00 MeV, versus the previous 2.03 MeV, based on an IAEA analysis of spectra and dosimetry activation measurements. This is a flashback to the past: Watt's seminal 1952 Physical Review paper, from the early days of Los Alamos, parameterized the data of the time with a functional form that had an average energy of 2.00 MeV! However, the evaluated PFNS is significantly

TABLE III. AMS data for ^{235}U and ^{238}U(n,γ) from Wallner [35]. The experimental data are compared to the spectrum-averaged data calculated for the IAEA CIELO-1=ENDF/B-VIII.0, and CEA CIELO-2, cross section values.

Energy	^{238}U(n,γ)	CIELO-1	CIELO-2	^{238}U(n,γ)/^{235}U(n,γ)	CIELO-1	CIELO-2
25 keV	0.391±0.017 b	0.399 b	0.380 b	0.60±0.03	0.59	0.49
426 keV	0.108±0.004 b	0.109 b	0.102 b	0.64±0.03	0.59	0.55

harder than spectra predicted by the Madland-Nix model (*e.g.*, ENDF/B-VII.0 PFNS) for outgoing neutron energies above 10 MeV. This behavior significantly improves agreement of calculated spectrum average cross sections with measured data for high-threshold reactions.

At higher incident neutron energies - 0.5 up to 20 MeV incident energy - CIELO adopts the calculated values by Neudecker [6] which were based on an extension of the Madland-Nix model, calibrated to measured data reported in this issue of *Nuclear Data Sheets*. This spectrum is seen to agree well with the NUEX data of Lestone and Shores in Fig. 8 for incident neutrons with an average energy of about 1.5 MeV. It is evident from the average PFNS energies shown in Fig. 9 that the trend of the Neudecker PFNS evaluations above 0.5 MeV incident energy matches the new IAEA spectrum average energy at thermal, and removes the previous ENDF/B-VII.1 unphysical kink in the neutron average energy near 3 MeV (which was based on matching one particular data set, that of Boykov [29]). Above 5 MeV the Neudecker evaluation is influenced by the new Los Alamos "Chi-nu" PFNS data [8], also described in this issue.

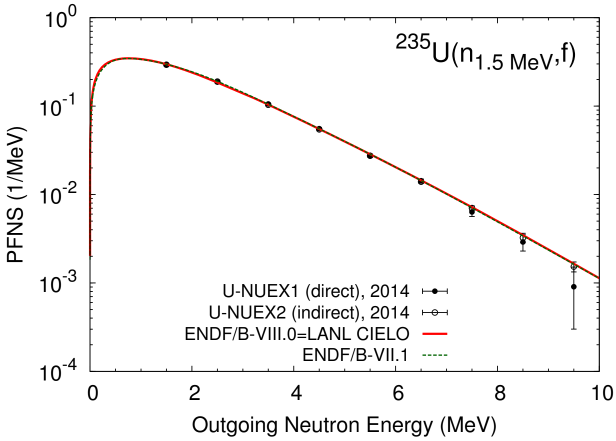


FIG. 8. (Color online) ^{235}U(n,PFNS). CIELO-1's prompt fission neutron spectra compared to NUEX data and to ENDF/B-VII.1, for 1.5 MeV incident energy.

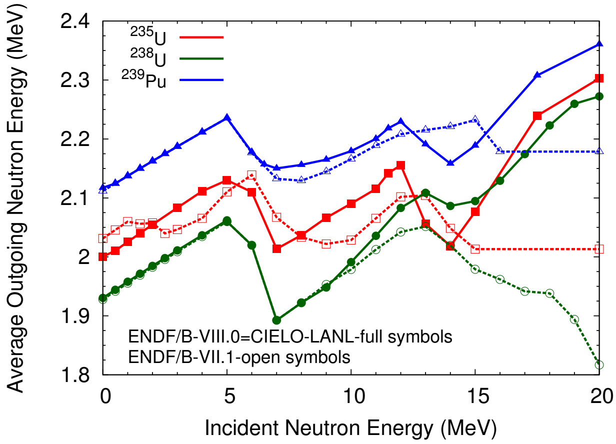


FIG. 9. (Color online) Major actinide averaged prompt fission neutron energy in CIELO-1 versus ENDF/B-VII.1.

B. ^{238}U Neutron Reactions

Prior to CIELO, evaluation projects have been strongly influenced by the ^{238}U resonance analyses by Derrien, Courcelle, Leal, and Larson in the resolved resonance region, and Fröhner in the unresolved resonance region, used in many of the world's various libraries. Previous higher energy neutron cross section evaluation work in the US was led by Young and Chadwick, and Madland for PFNS (LANL); in Europe by Romain, Morillon (CEA), and Vladuca and Tudora for PFNS, and in Japan by Iwamoto, Otuka, Chiba, Kawano, and Ohsawa for PFNS.

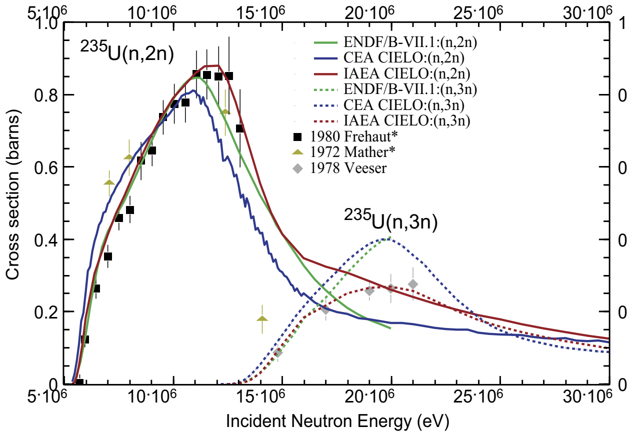


FIG. 7. (Color online) ^{235}U(n,2n) and (n,3n) comparing IAEA CIELO (CIELO-1=ENDF/B-VIII.0) and CEA CIELO (CIELO-2=JEFF-3.3). The asterisk indicates that the original published data values were modified by the evaluator.

The present CIELO evaluation work was done by Capote, Trkov, Sirakov, Schillebeeck, Kopecky, Kahler, Sin, Talou, Neudecker, Rising, Morillon, and Romain. It involves both a new resonance analysis that takes advantage of new measurements at Geel, and a new analysis of fast reactions using a coupled-channels optical model treatment, together with Hauser-Feshbach and preequilibrium modeling of compound and direct reaction processes and fission. The CIELO-1 evaluation is described in detail by Capote *et al.* in Ref [5] as well as in the main ENDF/B-VIII.0 paper [9], both in this issue of *Nuclear Data Sheets.*

The new evaluation for neutron induced reaction on

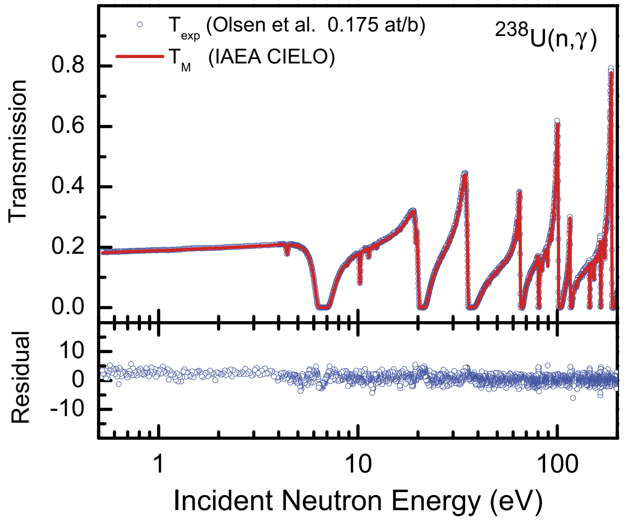


FIG. 10. (Color online) Resonance analysis of new ^{238}U data.

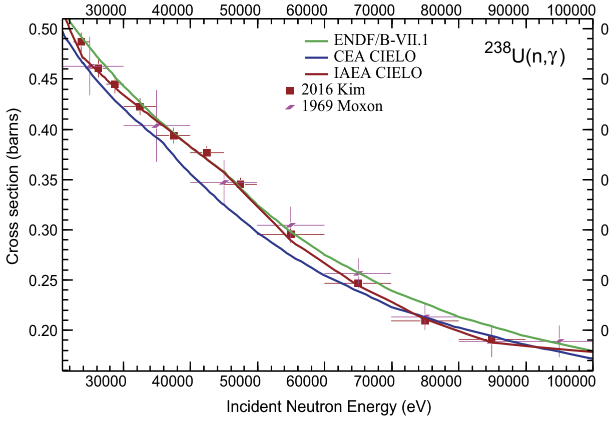


FIG. 11. (Color online) ^{238}U(n,γ) comparing IAEA CIELO-1 (=ENDF/B-VIII.0) and CEA CIELO-2 (=JEFF-3.3).

^{238}U in the resonance region was carried out considering well documented experimental data in the literature, and new measurements carried out at n_TOF, LANL, and Geel. Resonance parameters of individual resonances below 1200 eV were adjusted from a simultaneous resonance shape analysis of capture data obtained at GELINA [38] and transmission data obtained at a 42 m and 150 m station of ORELA [39, 40]. The contribution of the bound states was adjusted to produce a parameter file that is fully consistent with these data. This is illustrated in Fig. 10 which compares the experimental transmission T_{exp} and theoretical transmission T_M for the uranium sample with a 0.175 at/b areal density. Using the parameters of ENDF/B-VII.1, which are adopted from Derrien *et al.* [41], the theoretical and experimental transmission are not consistent. This suggests that Derrien *et al.* [41] applied a normalization correction to the experimental transmission to get a consistent fit.

In the unresolved resonance region average capture and total cross sections were derived from a least squares analysis of experimental data reported in the literature using the GMA code [42]. The generalised ENDF-6 model together with standard boundary conditions was used to parameterise these average cross sections in terms of average parameters following a procedure described in Refs. [43, 44]. The neutron strength functions and hard sphere scattering radius were adjusted to reproduce results of optical model calculations using the DCCOM potential of Quesada *et al.* [45, 46] and the inelastic neutron scattering data of Capote *et al.* [47–49], which include compound-direct interference effects [50], were adopted. The capture data in the 30–100 keV region are shown in Fig. 11 and compared with the capture cross section proposed by CIELO 1 (GMA analysis) and CIELO 2 (JEFF-3.3).

The prompt fission neutron average multiplicity evaluations is shown in Fig. 12 for CIELO-1. The fission cross section was taken from the recent standards evaluation update [3]. The prompt fission spectrum for CIELO-1 is taken from the analysis of Talou and Rising below 6 MeV, then ENDF/B-VII.1 to 8 MeV, and JENDL-4.0 at higher incident energies (see Fig. 9), and is described in more detail by Neudecker [6].

The ^{238}U inelastic scattering cross section has been a focus of attention in the CIELO collaboration, owing to its large impact on simulations of fast reactor criticality. The new evaluations shown in Figs. 13 and 14 are based on advanced nuclear reaction theory predictions, which include improved nuclear structure treatments [47–50] and fission competition modeling [37, 51, 52] (since accurate measurements of inelastic scattering are challenging). The role of theory is enhanced owing to the difficulty of accurately measuring scattering to the many excited states, although $(n, xn\gamma)$ data can be used to infer these reactions [53], and complementary semi-differential data, as measured at RPI, can be useful for validation [5, 47].

The CIELO-1 and CIELO-2 evaluated ^{238}U(n,2n) cross sections are shown in Fig. 15, compared to ENDF/B-VII.1 and to data. The earlier ENDF/B-VII.1 evaluation rose to higher values in the 6-8 MeV region above the threshold compared to some of the other evaluations (not shown in figure), and this same behavior is continued in the new CIELO-1 evaluation, informed in part by new Krishichayan measurements [54] from TUNL.

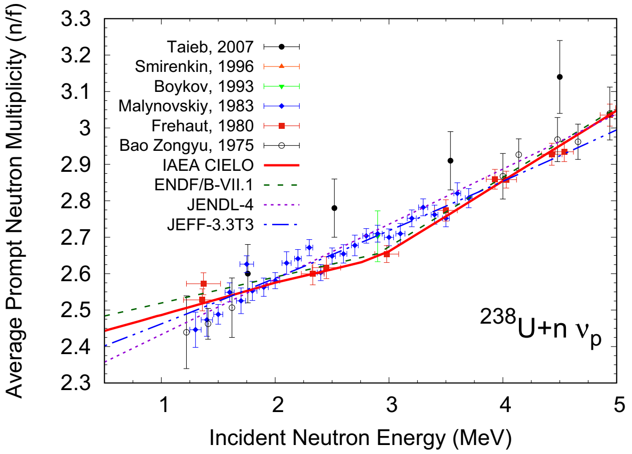


FIG. 12. (Color online) n+^{238}U prompt fission neutron multiplicity in IAEA CIELO-1 in the MeV-energy range.

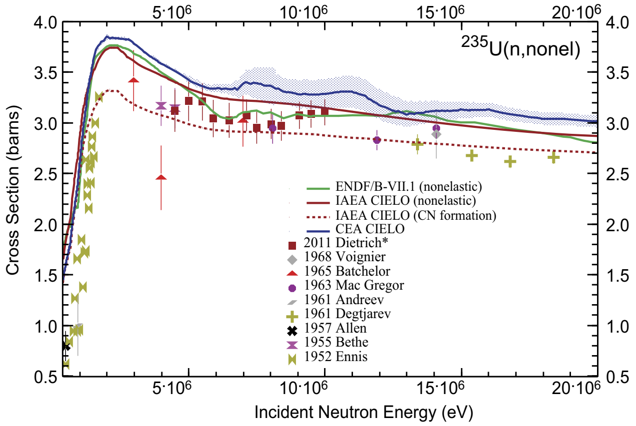


FIG. 13. (Color online) ^{238}U total nonelastic cross sections in the IAEA CIELO-1 and CEA CIELO-2 evaluations.

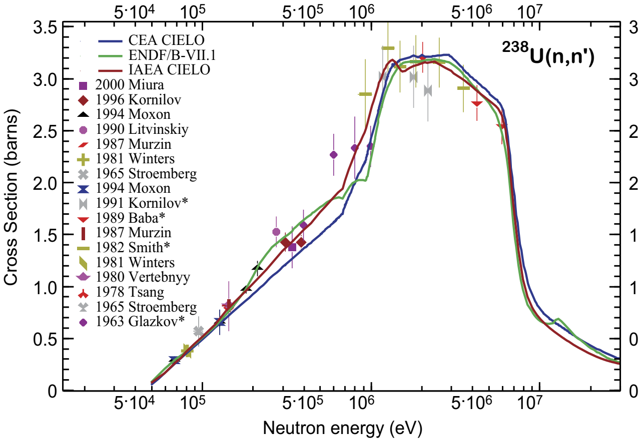


FIG. 14. (Color online) ^{238}U(n,n') cross sections in the IAEA CIELO-1 and CEA CIELO-2 evaluations.

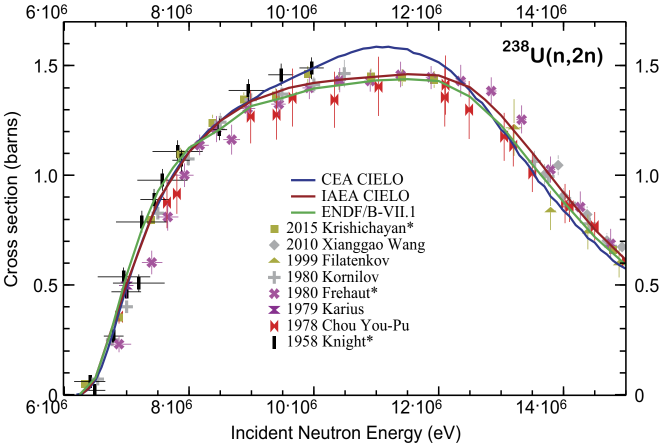


FIG. 15. (Color online) ^{238}U(n,2n) comparing IAEA CIELO (CIELO-1=ENDF/B-VIII.0) and CEA CIELO (CIELO-2=JEFF-3.3) with data, including recent TUNL measurements.

The previous ENDF/B-VII.1 evaluation was motivated by old LANL Knight data, together with integral measurements of $(n, 2n)$ reaction rates in critical assemblies (see Refs. [9, 32]), and this behavior is corroborated by the TUNL and other measurements, which guided the model calculations used in the present analysis. The new 14 MeV CIELO-1 evaluation is a little higher than the previous ENDF/B-VII.1's value.

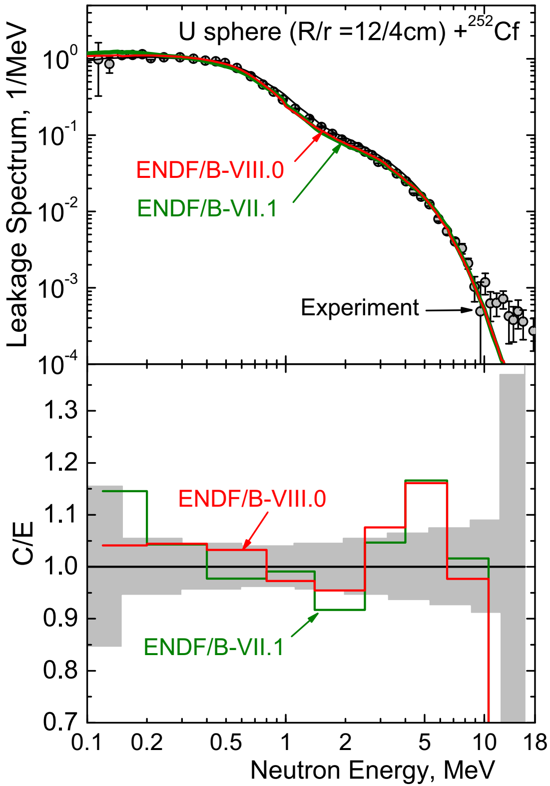


FIG. 16. (Color online) Integral neutron transmission through a depleted uranium sphere, for a Cf spontaneous fission neutron source, compared with simulations that use CIELO-1 data (ENDF/B-VIII.0).

Detailed discussions of integral data testing results of the uranium evaluations are given in Refs. [5, 9]. Here we show just one example: the neutron leakage spectra from a depleted uranium (0.2% of ^{235}U) sphere of diameter 24 cm (R=12, r=4 cm). These were measured by the ToF technique at IPPE, Russia with ^{252}Cf and D-T neutron sources, see Simakov *et al.* [55]. The californium spontaneous fission source result is shown in Fig. 16, and 14 MeV transmission data is shown in Capote's paper [5]. The measured and MCNP® version 6 simulated neutron spectra leaking from the outer surface of this sphere are shown in Fig. 16. It is evident that both CIELO-1 (ENDF/B-VIII.0) and ENDF/B-VII.1 reasonably reproduce the measured data, providing a useful validation of the evaluated data for neutron transport applications.

C. ^{239}Pu Neutron Reactions

Prior to CIELO, evaluation projects have been strongly influenced by the plutonium resonance analyses by Derrien, Leal, Larson, de Saussure, Fort, and Nakagawa. Higher energy neutron cross section plutonium evaluation work in the US was led by Young, Arthur, Chadwick, Talou, and MacFarlane, and Madland for PFNS (LANL); in Europe by Romain, Morillon, and Delaroche (CEA);

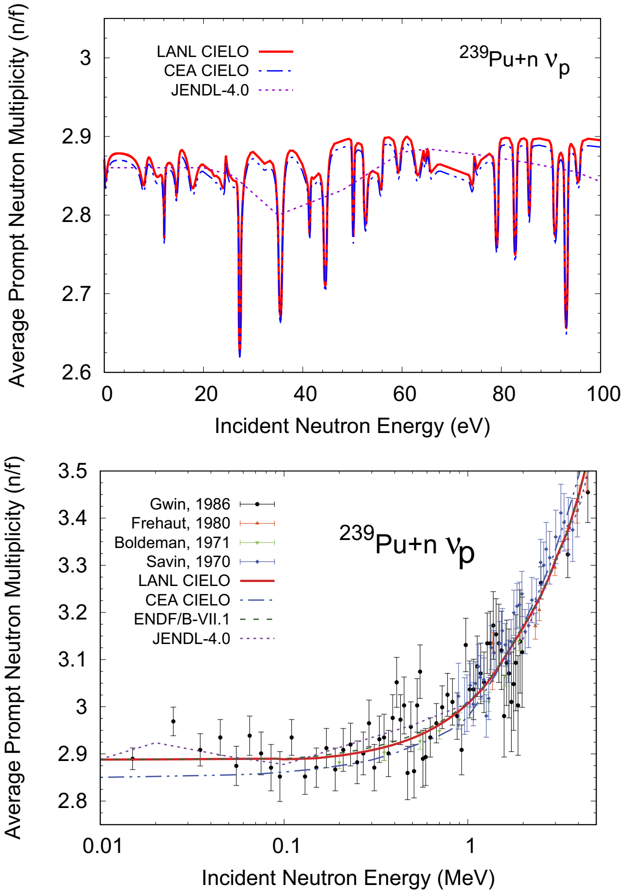


FIG. 17. (Color online) n+^{239}Pu prompt fission neutron multiplicity in CIELO-1 and CIELO-2, in the resonance and the fast range.

and in Japan by Iwamoto, Otuka, Chiba, and Kawano.

In the last three years the CIELO collaboration on ^{239}Pu adopted the earlier WPEC Subgroup 34 work on resonances by de Saint Jean, Noguere, Peneliau, Bernard, Serot, Leal, Derrien, Kahler, and McKnight, and updated the fast region fission, nubar, PFNS, and capture cross sections (work by Romain, Morillon, Chadwick, Talou, Neudecker, Kawano, Kahler, Capote, Trkov). CIELO-1 has adopted the recent new standards fission cross section [3], which increased the ^{239}Pu fission reference cross section by about 0.4% in the 0.1 keV to 1 MeV range relative to the earlier standards. The different prompt fission neutron average multiplicity evaluations for CIELO-1 and CIELO-2 are shown in Fig. 17. This $\overline{\nu}$ quantity remains one of the most influential parameters in affecting nuclear criticality. As for the evaluation for ^{235}U, it was adjusted (slightly) to optimize criticality simulations. The CEA evaluation for CIELO-2 has slightly renormalized the WPEC Subgroup 34 fluctuating values, see Fig. 17 (upper panel). The prompt fission spectrum for CIELO-1 is taken from ENDF/B-VII.1 below 6 MeV (though at thermal a very small modification was made, making it slightly harder), and at higher incident energies it is based on a recent analysis by Neudecker [6].

Earlier evaluations, such as ENDF/B-VII and JEFF-3.1, JENDL-4.0 suffer from a longstanding deficiency: an overprediction of plutonium solution criticality in transport simulations by approximately 500 pcm (0.5% in k-eff) [20]. The proposed resonance and prompt nubar updates by WPEC Subgroup 34 remove approximately half of this over-prediction. Further, the influence of our ^{16}O CIELO-1 evaluation and the new scattering kernels recommended by WPEC/Subgroup 42, now lead to much-improved thermal plutonium solution criticality predictions as discussed below in Sec. V.

Additional improvements must follow this pilot project. In the coming years we expect to see new plutonium prompt fission spectra (PFNS) and fission cross section data from the Los Alamos Chi-nu and TPC experiments and consideration of newly evaluated (softer) thermal PFNS from the IAEA CRP for ^{233}U and ^{239}Pu [11]; as an interim step we included the Neudecker PFNS spectrum for incident energies above 5 MeV, which provides an improved treatment of the effects of multi-chance fission and preequilibrium processes. Also, the recent Mosby *et al.* DANCE capture data should impact a future plutonium resonance analysis in the unresolved and resolved resonance regions, analogous to how DANCE data influenced the ^{235}U CIELO-1 evaluation described above. In the fast region above 30 keV, these data [7] motivated the capture cross section change shown in Fig. 18.

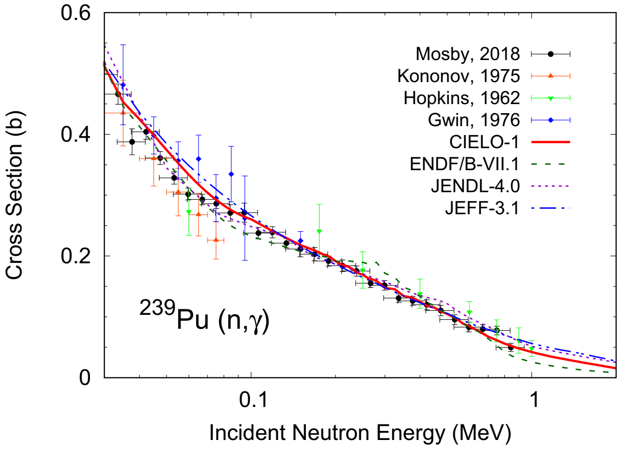


FIG. 18. (Color online) ^{239}Pu(n,γ) in CIELO-1 versus ENDF/B-VII.1, showing the influence of the new Mosby [7] Los Alamos DANCE detector data.

D. ^{56}Fe Neutron Reactions

A new effort by the CIELO collaboration to improve iron cross sections was deemed important based on sensitivity studies of nuclear criticality and shielding, and thermal and fast reactor design work. For example, uncertainty assessments performed by the WPEC Subgroup 26 for innovative reactor systems show that the knowledge of the inelastic scattering cross section of ^{56}Fe should be

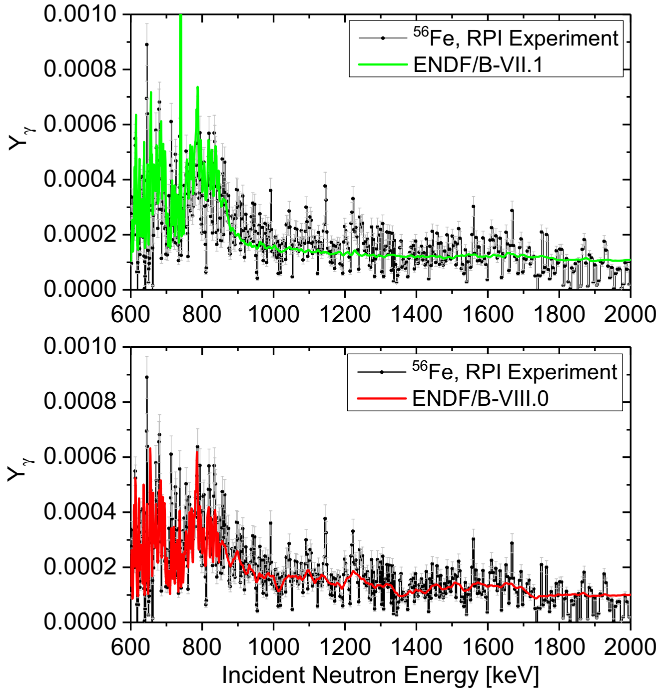


FIG. 19. (Color online) Photon yields (capture reactions per incident neutron) from the ^{56}Fe(n,γ) calculated with the CIELO-1 and ENDF/B-VII.1 cross section using MCNP® version 6 compared to RPI thick-target data.

improved to meet the target accuracy requirements for these systems.

The previous ^{56}Fe evaluations in the various libraries from different regions are largely independent, with some exceptions such as the resolved resonance parameters. They relied on the optical model and statistical model calculations, where the secondary particle energy and angular distributions play an important role in radiation shielding calculations. The evaluations can be separated into four energy ranges: (a) the resolved resonance region up to 850 keV, (b) from 850 keV to about 7 MeV where fluctuations still persist in the measured total cross section, (c) from about 7 MeV to 20 MeV, and (d) above 20 MeV. F. Perey and C. Perey of ORNL evaluated the resolved resonance parameters for ENDF/B-VI, and ENDF/B-VII.1 and CENDL have the same resonance parameter set. Other evaluations (JENDL, JEFF, and ROSFOND) adopt a modified version of the resolved resonances by Fröhner, performed for the JEF-2.2 evaluation.

The present CIELO-1 work was performed by Herman, Nobre, Brown, Arcilla, Trkov, Capote, Leal, Plompen, Danon, Qian, Ge, Liu, Hanlin, Ruan, Sin and Simakov, and is described in detail in this issue, in Ref. [4].

In the MeV energy region, the fluctuation behavior seen in the experimental total cross sections, which an optical model cannot reproduce, should be represented in the evaluated files as this can be important in neutron transport and shielding calculations. Usually the total cross sections in this energy region are obtained by tracing the experimental data available. For the other reaction channels, the Hauser-Feshbach model calculations are used for the evaluation, though the model codes employed are different.

The CIELO-1 evaluation in the resonance region essentially adopts JENDL with a correction of a typo for one resonance, deletion of one spurious resonance at 59.8 keV (pointed out by K. Guber), and modifications to the backgrounds below. Up to 4 MeV, the evaluated data for total, elastic cross sections and angular distributions, and inelastic scattering are based on measured data. At higher energies, EMPIRE nuclear model calculations played an important role, including the use of a soft-rotor optical model potential [56, 57].

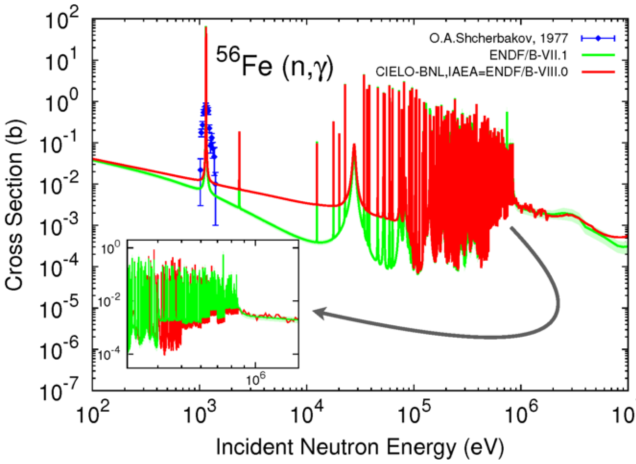


FIG. 20. (Color online) ^{56}Fe(n,γ) in CIELO-1 versus ENDF/B-VII.1.

The resolved resonance range extends up to the first inelastic scattering level (847 keV). Then, up to 2 MeV, capture cross sections were guided by the recent RPI experiment [58]. Fig. 19 shows comparisons of the γ-yields from the ^{56}Fe(n,γ) reaction (comparisons for ^{nat}Fe are given in Ref. [4]). The CIELO-1 representation matches the RPI data better than the earlier ENDF/B-VII.1 evaluation.

As in previous evaluations, "background" modifications to the cross sections above 400 keV were added by Trkov, to account for hypothesized missing p- and d-wave resonances and to avoid an unphysically-low neutron capture cross section. This background is, however, about 50% lower than in ENDF/B-VII.1 (see Fig. 20). In addition, a background was added in the 10 eV–100 keV region to extend the "1/v" dependence (see Fig. 20), and to better reproduce the measured ORELA capture data by Spencer *et al.* as seen in Fig. 21. This additional background was also motivated in part by a desire to better model the ZPR-34/9 critical assembly.

The inelastic scattering in CIELO-1 up to 4 MeV follows experimental data from Geel (Negret) and from Dupont (renormalized by Trkov); the latter data having a higher resolution. Above 4 MeV, EMPIRE model calculations are used, which were validated against the Negret and the Nelson (Los Alamos) measurements of

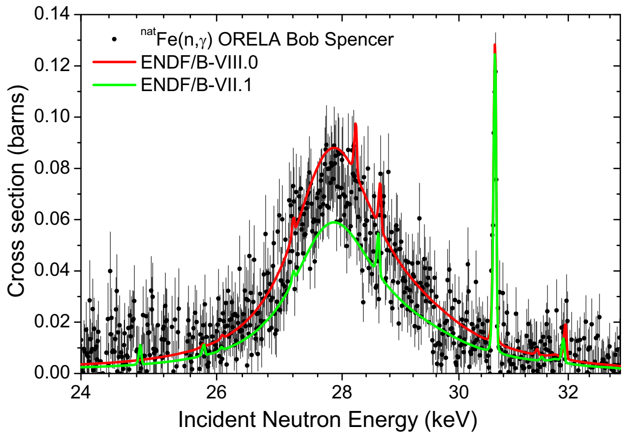


FIG. 21. (Color online) ^{56}Fe(n,γ) in CIELO-1 versus ENDF/B-VII.1, showing ORELA Spencer's data, near 28 keV resonance.

inelastic scattering followed by γ-ray emission. Compared to ENDF/B-VII.1, the inelastic scattering cross section in CIELO-1 is larger, for the energy range from threshold up to 14 MeV (Fig. 22).

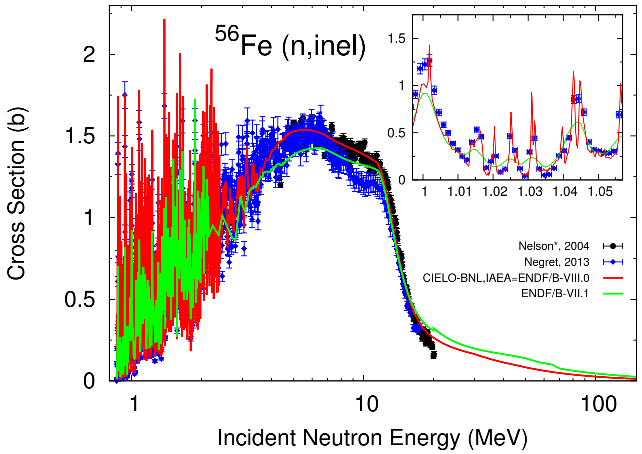


FIG. 22. (Color online) ^{56}Fe(n,inel) in CIELO-1 versus ENDF/B-VII.1. Region from 0.995 to 1.055 MeV is enlarged in the insert.

E. ^{16}O Neutron Reactions

The previous ENDF/B-VII.1 database comes from a merging of R-matrix analyses by Hale of LANL above 3.4 MeV, and by Lubitz and Caro of KAPL below 3.4 MeV, together with higher energy data from measurements and model calculations by Young and Chadwick. This evaluation has been adopted by (or at least strongly influenced) many other evaluation projects, for example JEFF-3.2, CENDL, and ROSFOND. But the CIELO-1 researchers recognized that some significant modifications are now warranted; for example, a previous renormalization of the (n,α) cross section downwards by 32% for ENDF/B-VII is now removed, as described below. We note that this conclusion differs from that summarized in our CIELO document at the beginning of the project three years ago [1] (our views changed). CIELO evaluation work for oxygen has been performed by Hale, Leal, Lubitz, Kunieda, Plompen, Kopecky, Kawano, Quaglioni and others. Two sets of evaluations were created for testing: Hale's (CIELO-1), and Leal's (CIELO-2), the latter having two options for the (n,α) cross section that can be studied.

^{16}O(n,α): The ^{16}O(n,α) reaction is important in nuclear criticality applications involving oxide fuels, and water, and its inverse – the ^{13}C(α,n) reaction – plays an essential role in nucleosynthesis studies, being a major source of neutrons in the s-process responsible for many of the elements produced above the iron peak.

Hale, Paris [59] and Kunieda [60] have been making the point, for over a decade, that R matrix calculations constrained by unitarity, together with ^{16}O total and elastic scattering data, point to the need for a significantly higher (n,α) cross section in the 3-6 MeV range. This view was adopted for the CIELO-1 evaluation, where the cross section was increased by $\sim 40\%$ over this range, with further increases as the incident energy extends to 9 MeV. Even though the Nuclear Energy Agency (NEA) NDaST sensitivity calculations of Hill show a very small sensitivity of the most-sensitive benchmarks to this cross section (about 3 pcm per % change in (n,α)), because of the very large 40% change in the cross section one finds significant changes in calculated criticality (over 100 pcm).

The (n,α) experimental data (and its inverse) supporting this change have been analyzed by Giorginis [61]. This (re-)analysis primarily concerned itself with, in the inverse reaction (α,n), the data of Bair and Haas [62] (BH73), Harissopulos [63] (Har05), Heil [64] (Heil08) and compared it to that of Giorginis [65](IRMM07) for the 'forward' (n,α) reaction.

The conclusion of this analysis indicates the following scale factors, assumed energy independent, should be applied to the data as given in the respective publications:

$$\sigma_{\rm corr}(\text{Har05}) \approx 1.36\ \sigma_{\rm orig}(\text{Har05}), \tag{2}$$
$$\approx 1.36 \times 0.70\ \sigma_{\rm orig}(\text{BH73}), \tag{3}$$
$$\approx 0.95\ \sigma_{\rm orig}(\text{BH73}). \tag{4}$$

Here, $\sigma_{\rm orig,corr}$ are the original and corrected (by energy-independent scalings shown here) data of the angle-integrated cross sections from the publications noted in parentheses. We discuss each of these factors and their physical origins.

The ratio $\sigma_{\rm corr}(\text{Har05})/\sigma_{\rm orig}(\text{Har05}) \approx 1.36$ was determined through a re-analysis by Giorginis [61] of the target thickness of the 99 ± 2%-enriched ^{13}C target employed. The evaluation of the target thickness by Har05 was accomplished by analyzing γ yield of 1,747 keV protons impinging on the enriched ^{13}C target and comparing to the known resonance in the ^{14}N system. Giorginis [61], however, notes that the absence of a plateau in the γ yield in Fig.(1) of Har05 indicates that the target thickness is comparable to the width of the energy resolution function and requires a deconvolution (via Voight profile) analysis in order to accurately determine the target thickness. The original target thickness calculation by Har05 employed the FWHM of the γ yield which mischaracterizes the target thickness. This correction results in a smaller ^{13}C surface density by roughly 30% and the corresponding scale factor of 1.36 in the cross section. The scale factor of 1.36 applied to the original Har05 cross section is in fairly good agreement with the scale of the data of Heil08, IRMM07 and, incidentally, with scale factors determined in unitary descriptions of data by Hale [59] and Kunieda [60].

Turning now to the topic of data reported in BH73, we discuss the origin of the factors (0.70×1.36) appearing in Eq.(3) for the corrected BH73 cross section:

$$\sigma_{\rm corr}({\rm BH73}) \approx 1.36 \times 0.70\ \sigma_{\rm orig}({\rm BH73}), \qquad (5)$$
$$\approx 0.95\ \sigma_{\rm orig}({\rm BH73}), \qquad (6)$$

which is approximately equal, for a range of energies, to the Har05 corrected data as indicated by Eqs.(2)–(4).

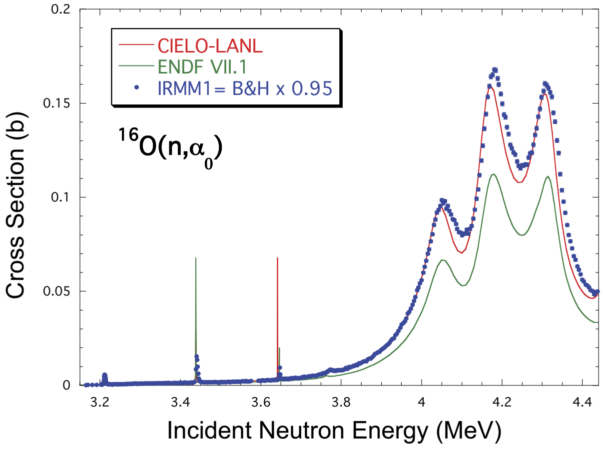


FIG. 23. (Color online) ^{16}O(n,α) in CIELO versus ENDF/B-VII.1, showing the higher cross section in the new evaluation. Hale's R-matrix calculation in the CIELO-1 evaluation, adopted by ENDF/B-VIII.0, agrees very well with Giorginis' recommendation based on a factor 0.95 times the original Bair and Haas published data.

The factor 1.36 discussed above is applied similarly to the thick-target yields of BH73 to transform them to thin-target cross sections as determined by Giorginis [61]. The factor 0.70 is the neutron efficiency correction determined in an analysis by Plompen [66].

The present discussion goes some way to addressing the discrepancy between the ENDF/B-VI.8 evaluation scale and that of ENDF/B-VII.1 and -VIII.0. Note, however, that the shape of the Har05 (α, n) cross section data remains inconsistent with the evaluation of Hale and has been removed from the evaluation.

Giorginis recommends renormalizing up his own Geel data, first published at the Nice ND2007 conference, to be consistent with the 0.95-normalized Bair and Haas data, though so far Giorginis has distributed Geel data only in the 6.3–9 MeV range. (We assume that the Khryachkov (IPPE, Obninsk) data remain in contradiction with the scale of the new recommendation).

Thus, progress has been made on clarifying what can only be said to be a messy state of affairs. But it is recognized that future experiments are needed to corroborate the large, approximately +40%, changes being made in CIELO-1 (Fig. 23). Indeed, new experimental efforts have been initiated by Los Alamos (Hye Young Lee *et al.*) using the LENZ detector, and by astrophysical groups pursuing low-background underground measurements (Wiescher *et al.*), and we look forward to the publication of these data.

^{16}*O(n,tot):* The total ^{16}O(n,tot) cross section plays an important role in our understanding of neutron reactions in oxygen, in part because of its influence on the (n,α) reaction via unitarity. Historically there have been questions at the 3-4% level regarding the absolute normalization of this cross section: for example the Cierjacks 1968 data being discrepant with the high-resolution Cierjacks 1980 data. Danon *et al.* [67, 68] have advanced our understanding here with a novel method in which the normalization of a measurement using a water target was made at 2.3 MeV, where the oxygen "window" (where the total cross section falls to almost zero owing to a destructive interference effect) allows the normalization to be made to the very well known hydrogen standard value. These new RPI data agree with Cierjacks 1968 to about 0.04%. These measurements were also treated as blind validation data, and Fig. 24 shows they largely support the new Hale evaluation, which was done *prior* to the measurement. The Hale evaluation [9] agrees with the Danon RPI total cross section data to better than 1% over the energy range from 0.2–9 MeV. It is now thought that the Cierjacks 1980 total cross section data need to be renormalized up by approximately 3.2-3.8%.

^{16}*O(n,elas):* The other important change for oxygen is the lower total elastic scattering cross section adopted, from thermal to 10s of keV energies. An assessment by Kopecky and Plompen led to a recommendation of a low-energy value of 3.765 b (CIELO-2); Hale's latest value of just un-

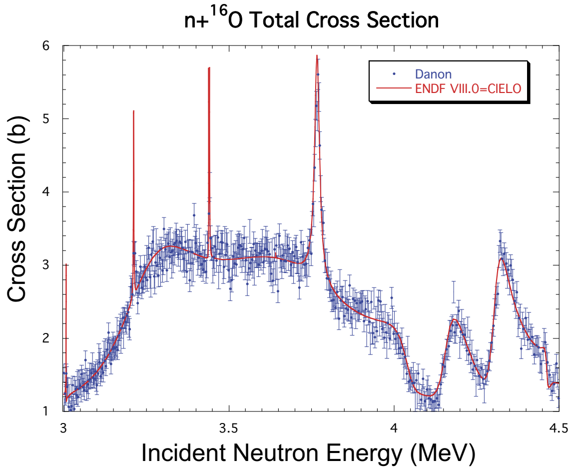


FIG. 24. (Color online) ^{16}O(n,tot) total cross section in CIELO-1 from Hale, calculated *prior* to the measured RPI data from Danon.

der 3.8 barns in the CIELO-1 file - which was influenced also by the Schneider (1976) measurement - is about 1.5% lower than the previous ENDF/B-VII.1 evaluation (3.852 b), Fig. 25. This seemingly-modest decrease has a significant impact on criticality applications (for example, the NDaST sensitivity tools indicate HST benchmarks are sensitive at the 100 pcm per % change in the elastic scattering cross section between 1 eV and 100 keV). Kozier, Roubtsov, Plompen and Kopecky [69] have noted that some heavy-water criticality benchmarks also suggest a lower thermal scattering cross section.

F. ^{1}H Neutron reactions

The *n–p* cross section is a primary standard in nuclear physics, featuring the lowest uncertainty of all measured cross sections. The *n–p* cross section plays an essential role in many neutronics simulations of transport and criticality for special nuclear materials (SNM) in solution systems and lattices, and is the ultimate standard for high-accuracy relative cross section measurements of neutron-induced reactions.

The R-matrix analysis for the *n–p* cross section was performed by G. Hale and M. Paris of LANL as part of the IAEA standards project [3], and it was adopted into the most recent ENDF/B-VIII.0 evaluation and also for CIELO-1 set. The earlier *n–p* standard [70], also from Hale, was previously adopted by ENDF/B-VII, JEFF, JENDL-4.0 and ROSFOND.

The changes in the *n–p* scattering cross section at energies below 20 MeV are quite small (and within the uncertainties of recent evaluations), resulting from including in the new evaluation nucleon-nucleon scattering data at energies up to 50 MeV. It should be noted that a common systematic uncertainty of 0.34% was added to the estimated R-matrix uncertainty of the fit. The additional uncertainty was estimated from the spread in fitted normalization of absolute measurements, and represents the "unknown" uncertainty of the method. This additional uncertainty increases the minimum uncertainty of the *n–p* standard scattering cross section up to about 0.5% [3].

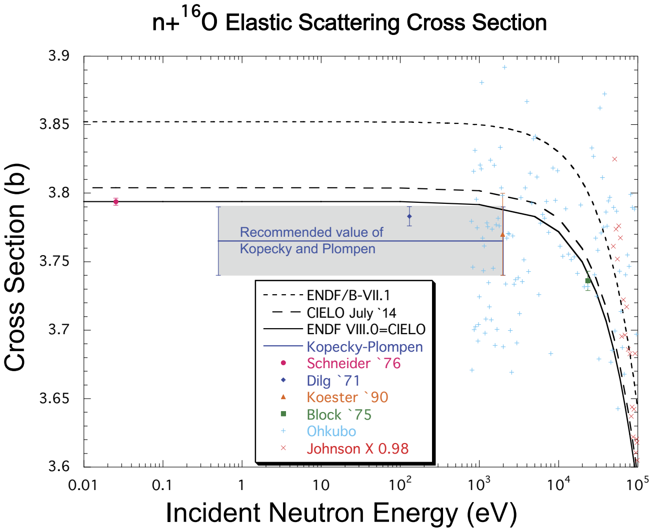


FIG. 25. (Color online) ^{16}O(n,elastic) elastic scattering cross section in CIELO-1 at low energies.

G. Thermal Scattering Law for Liquid Light and Heavy Water

New evaluations from the thermal scattering law (TSL) of neutrons scattered in liquid light and heavy water are very important in reactor applications. Significant efforts within the CIELO project addressed these data needs, coordinated by the Nuclear Energy Agency WPEC Subgroup 42, with a leading role played by the Argentinean group from the Centro Atómico Bariloche (CAB).

TSL evaluations for light and heavy water were generated by Márquez Damián, Granada and Cantargi at CAB, in collaboration with Roubtsov from the Canadian Nuclear Laboratories. Evaluations were based on the CAB Model for Light/Heavy Water [71] and were prepared using NJOY99.396 with updates to extend the calculation grids. Details of the model and its validation with experimental data can be found in Refs. [71, 72].

However, the TSL data in ENDF format are not easy to interpolate. A TSL Interpolator has been made available online at the IAEA/NDS webpage *www-nds.iaea.org/TSL-LibGen* that generates the TSL file in ENDF-6 format at the user-selected temperature from 273.15 up to 800^{0}K.

Compared with the ENDF/B-VII H-H$_2$O evaluation by Mattes and Keinert [73], many changes were introduced which are described in detail in the ENDF/B-VIII.0 paper [9]. These changes allowed an improved agreement with experimental neutron cross section data, and better represent the reduction in the total cross section on heavy water at sub-thermal energies (0.3 - 3.0 meV), which was already found in the ENDF/B-VII.1 evaluation [32]. They also reproduce a reduction of the experimental total cross section in the thermal range (10 - 50 meV) which was not possible with previous evaluations. This reduction in the total scattering cross section can be traced to the effects of coherent scattering in oxygen, which were not included in previous evaluations.

IV. COMPARISON WITH FEEDBACK FROM ADJUSTMENT PROJECT

The WPEC Subgroup 39 project develops methods and approaches to provide feedback from nuclear and covariance data adjustment considerations. The project has performed several cross section adjustments [74] based on a Bayesian approach. It uses available covariance data, sensitivity coefficients, and discrepancies between measurements and calculations, not only for criticality and reaction rate (spectral index) measurements but also for sample irradiations, reactivity and neutron transmission measurements. The Subgroup 39 researchers emphasize that past adjustments did not necessarily point to physically-correct nuclear data, owing to limitations in the method, including non-unique solutions, possible unappreciated systematic errors in the experiments, and compensating effects. In fact most of the activity of that Subgroup has been devoted to develop methods that help avoid compensating effects, to detect systematic errors in the experiments [75] and to select integral experiments that provide information on separated physics effects [74].

Here we briefly summarize some of the cross section changes made for CIELO-1, compared to insights provided by the WPEC Subgroup 39 Adjustment project.

- Fast reactor sodium worth reactivity measurement in Japan suggested a substantially (20-40%) reduced ^{235}U capture cross section in the 0.5–2 keV region, compared to ENDF/B-VII.1 (Fukushima *et al.* [76]). CIELO concurs with this, following corroborating cross section measurements at LANL/DANCE [30] and RPI [31]. CIELO-1 also adopts a higher capture cross section from 2.25-50 keV based on the Jandel DANCE data. This is partly consistent with the Japanese adjustment guidance, except for 6–20 keV where the adjustment goes in the opposite direction (however, we note that the sensitivity of the Japanese SWR measurements is almost negligible from 6–20 keV (Fukushima *et al.* [76]).
- ^{238}U inelastic is suggested to be lower than ENDF/B-VII.1 in the 2-5 MeV region, and in the 0.1–1 MeV region, according to Palmiotti [74]. This is partly consistent with the CIELO-1 changes; CIELO-1 is lower than ENDF/B-VII.1 from 0.2–0.6 MeV, but it is higher from 0.6–1 MeV. The values in the CIELO-1 file appear to be also consistent with the conclusions from Santamarina in a JEFF adjustment study [77]. We note though that changes in CIELO inelastic scattering were driven by fundamental improvements in nuclear reaction and structure modeling, not Subgroup 39 feedback.
- ^{239}Pu neutron capture is suggested to be higher in the 1–10 keV region, and in the region up to 100 keV, based on the impact of the PROFIL experiment. CIELO-1 has increased the capture in the fast region from 30–100 keV, consistent with this. But CIELO-1 has not yet addressed an upgrade of the unresolved resonance region up to 30 keV.
- ^{56}Fe. Palmiotti suggests a reduced inelastic scattering cross section just above its threshold, compared to ENDF/B-VII.1. But the CIELO-1 change near threshold goes in the opposite direction, an increase. We note JENDL-4 remains significantly higher than ENDF/B-VII.1 in the 0.9-3 MeV region.

Comparing the proposed changes by the Subgroup 39 (Adjustment Project) with the changes to ENDF/B-VII.1 that the evaluators made for CIELO-1 (and ENDF/B-VIII.0) one sees that they agree only for about half the cases. For the cases where the new CIELO evaluation choices disagree with the adjustment feedback, we are inclined to think that the CIELO changes are more likely to be correct, as they were generally guided by fundamental data measurements. This is not necessarily always true, but adjustment feedback often have suffered from the adjustment process having non-unique solutions, together with the deficiencies in the evaluated covariance data. For example, given the absence or the deficiency of covariance data for many angular and energy distributions in the evaluated data files, the adjustment process will tend to assume (incorrectly) that such distributions are perfectly known and thus not subject to change, and instead put the adjustments into other cross sections where covariance data are present.

Thus we conclude that integral data simulations can be used to guide the evaluation process, but should not replace it when better, more convincing evidence is presented. We also note that the production of "adjusted libraries" is a perfectly reasonable and warranted step beyond the creation of an evaluated data library, for applications that demand very high agreement with integral data, and especially where the application (*e.g.* a reactor) is neutronically similar to the critical assembly integral data that was used for the adjustment.

V. CRITICALITY VALIDATION TESTING

A. General

Validation testing of CIELO files was done throughout the evaluation process, providing feedback on the data libraries and how they perform, in concert together, for thousands of criticality and neutron transmission benchmarks (although this type of global test however can hide compensations [78]). The MCNP® version 6 transport code was used, after the data were processed by NJOY. Most of the testing was done by Kahler (Los Alamos), Trkov (IAEA), Hill (NEA), Brown and Arcilla (BNL), Noguere (CEA), Morillon (CEA), Kodeli (Ljubljana), Wu (CIAE) and Palmiotti (INL).

Owing to space limitations, we do not report here in detail on the results, but instead point the reader to companion papers in this issue, most notably the ENDF/B-VIII.0 data testing [5, 9], and the summary results from NRG/Petten below. Compared to ENDF/B-VII.1 the CIELO-1 files used in ENDF/B-VIII.0 perform as follows: For fast Pu and U critical assemblies, they perform equally well, with some improved performance for fast reflected assemblies; for intermediate and thermal energy assemblies the performance is also comparable, though for plutonium thermal solutions (PST) the previous large ($\sim$ 500 pcm) overprediction is largely removed in the CIELO-1 evaluations, as discussed further below. The CIELO ^{235}U evaluations also appear to fix the problems noted by Japanese researchers on modeling sodium void reactivity in fast critical assembly (FCA) experiments.

An example of the progress made by CIELO-1 is shown in Fig. 26, from an IAEA (Trkov) analysis. Over the suite of 119 benchmarks that have been systematically modeled by Los Alamos for many decades (*e.g.*, see Ref. [79]), and compared with measured k-eff criticality, the overall Chi-squared value is seen to have been cut by almost a factor of two from near 4 (in ENDF/B-VII.1) to near 2 (ENDF/B-VIII.0 with CIELO-1). As can be seen in the figure, notable improvements were obtained in the modeling of the Jemima and Zeus assemblies. The reason that the overall chi-squared is not unity is that this comparison of MCNP6® version 6 calculation versus measurement does not include any uncertainty in the calculated quantities, arising from nuclear cross section data uncertainties. Although such comparisons are valuable, one should remember that they can be strongly influenced by certain integral experiments where the quoted k-eff uncertainties are very small. We have simply adopted the recommended ICSBEP benchmark experiment uncertainties, even for cases where they are probably unrealistically small.

We have used the NEA's NDaST sensitivity tools to assess the impact of some of the CIELO-1 cross section changes, relative to ENDF/B-VII.1. Below we use the changes to ^{16}O (n,α) and (n,elastic) as an illustrative example. Ian Hill has analyzed over 3000 criticality benchmarks to characterize the effects.

The role of the increased CIELO-1 ^{16}O (n,α) reaction in absorbing neutrons and reducing criticality was found to be of order -100 pcm on LCT experiments, and about -50 pcm for HST experiments. The reduced low energy elastic scattering in CIELO-1, on the other hand, was found to be about -50 pcm on LCTs (but a higher value, -150-200 pcm on heavy water benchmarks), while for HST experiments the reduction is about -100 pcm for low-leakage systems (owing to reduced moderation), but as high as -300 pcm for high-leakage systems where reduced scattering increases the leakage. The overall effect is that simulations of HST highly-enriched solution thermal critical assemblies typically change by -100-200 pcm, whereas LCT low-enriched uranium thermal assemblies change by -150-200 pcm. Some heavy water benchmarks change by almost -300 pcm. As noted earlier, compared to ENDF/B-VII.1, these reductions in criticality are compensated (in part at least) by other changes to the ^{235}U resonance and nubar data and the thermal PFNS.

For plutonium solution thermal (PST) critical assemblies, previous ENDF/B-VII.1 and earlier JEFF and JENDL libraries largely overcalculated the criticality, by $\sim$ 500 pcm on average. The adoption of WPEC Subgroup 34's plutonium resonances and nubar in CIELO removed about one half of this discrepancy. The aforementioned changes to oxygen further reduced the overprediction by 100-200 pcm with an average effect of about 150 pcm (of which about 3/5 was due to the reduced elastic channel, and 2/5 to the increased (n,α). Further small reductions came from the adoption of the new scattering kernel for water, and from the use of a slightly harder thermal PFNS for plutonium.

Morillon and Bauge have done a useful study to identify the impact of remaining differences in CIELO-1 and

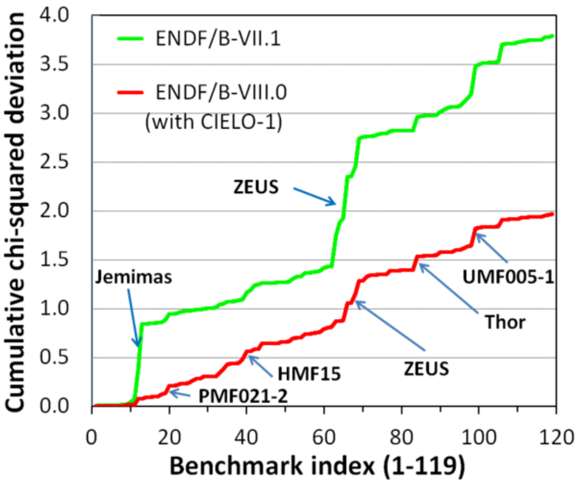


FIG. 26. (Color online) The cumulative chi-squared deviation for the new CIELO-1 (in ENDF/B-VIII.0) evaluation, versus ENDF/B-VII.1, for a suite of 119 assemblies defined by Mosteller *et al.* [79]. An overall factor of 2 improvement is seen for the full suite.

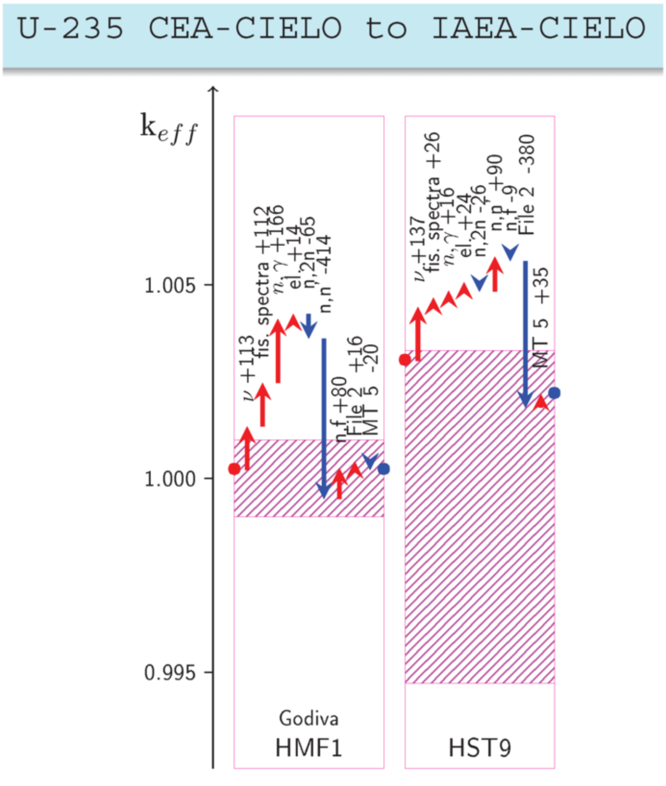


FIG. 27. (Color online) Simulations of criticality k-eff for ^{235}U for two critical assemblies: a fast assembly (Godiva, HMF-1), and a thermal assembly (HST-9). This figure shows that both IAEA CIELO-1 (ENDF/B-VIII.0) and CEA CIELO-2 (JEFF-3.3) predict similar k-eff values, but do so for very different reasons. The changes in criticality are evident when individual cross section channels are substituted between the two evaluations.

CIELO-2 files, on a variety of critical assemblies. They start with one set of files, their CEA evaluations in CIELO-2, and then make one-at-a-time substitutions of cross sections from CIELO-1 (ENDF/B-VIII.0), noting the change in calculated criticality, until the final file is essentially CIELO-1. This study helps identify where the big lever differences are, see Figs. 27, 28. We can observe that substantial differences, with important effects, are found between the CIELO-1 and CIELO-2 files: they both predict overall criticality well, but for very different reasons. One (or most likely, both) are deficient in a variety of ways.

For ^{235}U and ^{239}Pu fast assemblies one can observe that the largest effects are from differences in fission (especially the prompt neutron multiplicity and the PFNS spectrum) and inelastic and elastic scattering. Future work will be needed to make more progress on understanding such neutron reactions for fissile actinides.

B. Large-scale Testing from NRG Petten

As was done for the ENDF/B-VII.0 and ENDF/B-VII.1 releases of the library in 2006 and 2011, the new CIELO-1 data in ENDF/B-VIII.0 have been tested by performing calculations for a large number (2515) of criticality safety benchmark cases, taken from the International Handbook of Evaluated Criticality Safety Benchmark Experiments. Among the benchmark cases are ones for a variety of fuel types (leu, ieu, heu, mix, pu, u233); for many different physical forms of the fissile component (compound, metal, solution, miscellaneous); and for many types of neutron spectra (thermal, intermediate, fast, mixed).

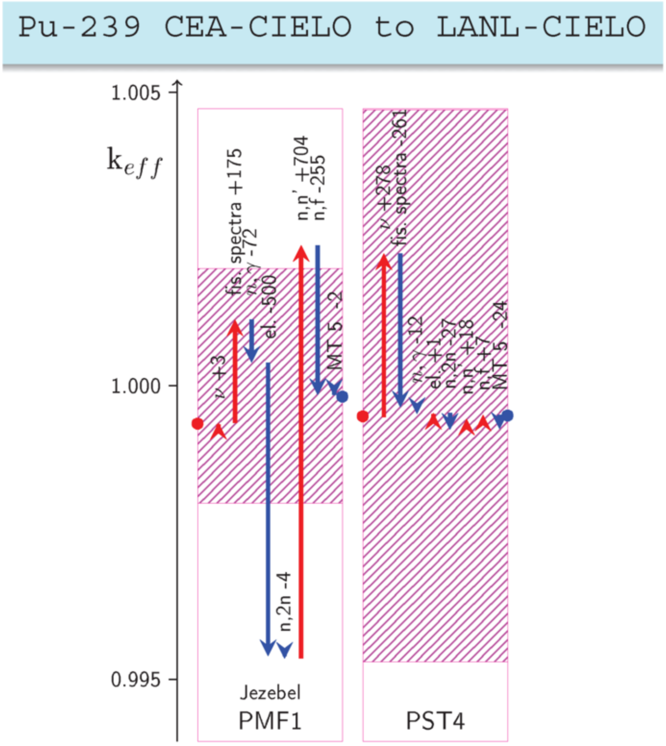


FIG. 28. (Color online) Simulations of criticality k-eff for ^{239}Pu for two critical assemblies: a fast assembly (Jezebel, PMF-1), and a thermal assembly (PST-4). This figure shows that both LANL CIELO-1 (ENDF/B-VIII.0) and CEA CIELO-2 (JEFF-3.3) predict similar k-eff values, but do so for very different reasons. The changes in criticality are evident when individual cross section channels are substituted between the two evaluations.

For the criticality safety calculations performed at NRG, the nuclear data (beta4 release of ENDF/B-VIII.0) were processed by NJOY-12.50, except for the thermal scattering data for H in ZrH, Be in Be, Be in BeO, graphite, and H in CH_2, which were processed by NJOY-99.364. The reason for using the older version of NJOY was a data pointer problem when using the NJOY-12.50 version for these thermal scattering data. All data were processed for room temperature (293.16 K), except for benchmark cases with elevated temperatures. For cases 2, 4, 6 of ieu-comp-therm-002 and for all cases of heu-sol-therm-039 the nuclear data were processed for the temperatures specified by the benchmark.

The criticality safety calculations were performed with MCNP® version 6.1.1. The average results for all these calculations are summarized in Tables IV–V, for each main category of the International Criticality Safety Benchmark Evaluation Project (ICSBEP). In these tables the results based on ENDF/B-VII.1 are also listed (for exactly the same benchmark cases), for easy comparison. All 2515 benchmark cases were calculated with both ENDF/B-VII.0 and ENDF/B-VII.1. The values for ENDF/B-VII.1 differ from those in Ref. [32], because many benchmark cases have been added since. The values in the tables are averages and standard deviations around the averages, and it is therefore hard to interpret the differences between the libraries, but in combination with figures (not shown) several observations can be made:

- Results for most of the compound cases with a thermal spectrum have decreased slightly, while the spread in the results is roughly the same, *e.g.* for the leu cases, the average $C/E-1$ has decreased from -77 to -144, while the standard deviation around it is virtually unchanged.

- The average for the leu-met-therm cases has improved, which is mainly due to the results for leu-met-therm-015 (2% enriched uranium in heavy water). The cases with 16 cm pitch are now within the experimental uncertainty band, which the 8 cm cases already were.

- The standard deviation for the heu-met-inter cases has improved because of a better performance for the varying C/^{235}U ratio in heu-met-inter-006 (Zeus, a graphite-heu core surrounded by a copper reflector), although the mean has increased.

- The average for pu-met-inter cases is much better due to the improved description of pu-met-inter-002 (ZPR-6, Assembly 10, a plutonium-carbon-stainless

TABLE IV. The average value of $C/E-1$ in pcm (100 pcm=0.1%) for CIELO-1 in ENDF/B-VIII.0 (beta4) per main ICSBEP category for compound and metal systems. Shown in *italics* are the values for the ENDF/B-VII.1 library.

	COMP				MET			
	therm	inter	fast	mixed	therm	inter	fast	mixed
LEU	−144 ± 473				−91 ± 204			
	− 77 ± 477				*395 ± 432*			
IEU	−391 ± 511	−367 ± 1396	−213				−5 ± 200	
	−219 ± 435	*−253 ± 1506*	*−50*				*120 ± 187*	
HEU	764 ± 1242	2693 ± 4355	−196 ± 219	−1063 ± 369	123 ± 694	126 ± 186	−85 ± 412	188 ± 573
	788 ± 1276	*2112 ± 5062*	*20 ± 118*	*−892 ± 413*	*143 ± 725*	*23 ± 424*	*31 ± 387*	*640 ± 696*
MIX	−346 ± 1080		−349 ± 198				229 ± 275	
	−141 ± 1148		*−39 ± 220*				*364 ± 363*	
PU		742		1979 ± 952		211 ± 787	158 ± 492	763 ± 438
		1119		*1910 ± 955*		*702 ± 1170*	*162 ± 516*	*921 ± 194*
^{233}U	−220 ± 144				−2806		−110 ± 133	
	23 ± 134				*−3466*		*−220 ± 162*	

TABLE V. The average value of $C/E-1$ in pcm (100 pcm=0.1%) for CIELO-1 in ENDF/B-VIII.0 (beta4) per main ICSBEP category for solution and miscellaneous systems. Shown in *italics* are the values for the ENDF/B-VII.1 library.

	SOL				MISC			
	therm	inter	fast	mixed	therm	inter	fast	mixed
LEU	133 ± 293							
	133 ± 270							
IEU	90 ± 505							
	53 ± 583							
HEU	22 ± 925							
	64 ± 914							
MIX	−545 ± 352				65 ± 599		−453 ± 260	
	−194 ± 365				*254 ± 576*		*−845 ± 539*	
PU	61 ± 535							
	454 ± 587							
^{233}U	285 ± 721	−1794 ± 833						
	540 ± 732	*−1544 ± 823*						

steel core with stainless steel and iron reflector), a benchmark for which all calculations so far were far too high (in fact, the calculated value for pu-met-inter-002 is still more than 1500 pcm too high).

- The averages and standard deviations for heu-met-fast and pu-met-fast cases have changed only slightly.
- The average for mix-met-fast cases has come down by 135 pcm, while at the same time the standard deviation around this average has decreased significantly. This is because the results for mix-met-fast-002 and -007, which are spherical cores with uranium and beryllium reflectors, are lower, while the result for mix-met-fast-008, which is a k-infinity benchmark, is higher.
- The average and standard deviation for u233-met-fast cases have both improved somewhat, as a result of higher results for the u233-met-fast-002, 003, 004, and 005 benchmarks, all of which are spherical cores (with different reflectors).
- The average for pu-met-mixed cases has gone down by 158 pcm, which is an improvement. This is due to better results for cases 1 and 2 of pu-met-mixed, while cases 3–6 have stayed the same, leading to an increase of the standard deviation.
- Most of the pu-sol-therm and u233-sol-therm cases have lower results than before, which is an improvement. The spread in the results is roughly unchanged, however.
- The mix-sol-therm cases also have lower results than before, which in this case is not an improvement.

The results of all criticality benchmark calculations are consolidated in Fig. 29. All the benchmark cases with *e.g.* a thermal spectrum are lumped together, and a normal distribution is fitted to the distribution of C/E values (expressed in units of a standard deviation). In case of "perfect" nuclear data (and "perfect" benchmark evaluations), the distribution of C/E would be the normal distribution with average zero and standard deviation one. The Figure shows that for thermal and fast spectrum cases, the distribution based on ENDF/B-VIII.0 is slightly more peaked than the one based on ENDF/B-VII.1, which is an improvement. For the intermediate and mixed spectrum cases, the statistics are too low for firm conclusions, but for these cases there appears to be a bias in the k_{eff} calculations that is roughly identical for ENDF/B-VIII.0 and

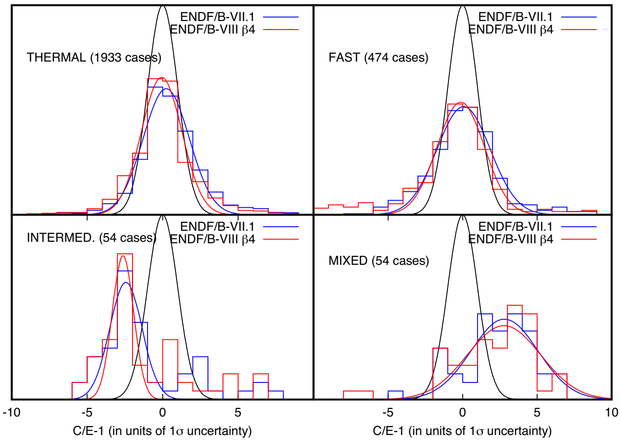


FIG. 29. (Color online) The distribution of C/E, in units of the combined benchmark and statistical uncertainty. The normal distribution (in black) would be the perfect situation.

ENDF/B-VII.1: for most of the intermediate spectrum cases the calculated value lies more than one standard deviation *below* the benchmark value, whereas for mixed spectrum cases most of the calculated value lie more than one standard deviation *above* the benchmark value.

VI. COVARIANCES

The CIELO covariance data need continued attention. In the ENDF community, ENDF/B-VII.1 [32] had a focused effort on providing covariances for a large range of isotopes and reactions. Nevertheless, numerous questions remain regarding the quest to represent "credible" uncertainties, especially following comparisons of ENDF/B-VII.1 uncertainty assessments with those in JENDL and JEFF files, and even when comparing uncertainties assessed in the resonance range versus those at energies slightly above the boundary for the fast range. The Nuclear Energy Agency WPEC Subgroup 39 has provided a valuable assessment of such questions and discrepancies, in a paper by Dr. Ishikawa [80]. This paper pointed out that – even for very important reactions such as major actinide fission, capture, and inelastic scattering – differences in uncertainties as large as an *order-of-magnitude* are not uncommon for certain energy regimes, and as we will see below this situation has not changed significantly. A cynic would note that this reflects the enduring difficulty in defining credible uncertainties in nuclear science (and other fields of research). The CIELO project includes work that will continue beyond this pilot project, with an aim of resolving some of these questions.

Although work on CIELO covariances is currently in-progress, we provide a summary of some of the uncertainty data choices made in CIELO-1, in the Beta-5 version of the ENDF/B-VIII.0 files. A focus here on ^{239}Pu and ^{235}U covariance data illuminates the current status of the work: the covariances for plutonium come from Talou and Neudecker (LANL), and for uranium isotopes come from Capote, Trkov, and Neudecker (IAEA, LANL), and also from the IAEA standards group for the fission cross sections. Examples of these uncertainties are given in Table VI for ^{239}Pu and Table VII for ^{235}U, for a typical neutron energy of 1 MeV for CIELO-1, ENDF/B-VII.1 and the latest JEFF and JENDL evaluations, together with their impact on the calculated criticality k-eff in Jezebel (PMF-1) (Table VIII) and Godiva (HMF-1) (Table IX). (A summary of the PFNS uncertainties is given in Ref. [9], showing how these have changed in the recent CIELO-1 work for ENDF/B-VIII.0). The criticality uncertainty results were obtained by Ian Hill and Oscar Cabellos (NEA) [81], using the NDaST and MCNP codes, and by Yokoyama and Ishikawa [82]. Of course the various uncertainty data are used for all the appropriate incident neutron energies in the calculations; we tabulate here only the 1 MeV values owing to space limitations.

TABLE VI. ^{239}Pu cross section uncertainties at 1 MeV incident neutron energy, 1-sigma. Values are given for CIELO-1 (ENDF/B-VIII.0beta5), ENDF/B-VII.1, JEFF-3.3 (derived from CIELO-2, in version JEFF-3.3) and JENDL-4.0u1. The full uncertainty information – values at all incident energies, and correlations – can be obtained from the numerical files. Comparisons at 1 MeV are useful to illuminate the large differences between the different evaluations, which impact different Jezebel calculated criticality uncertainties (Table VIII).

	CIELO-1 Unc. (%)	B-VII.1 Unc. (%)	JEFF-3.3 Unc. (%)	JENDL-4.0 Unc. (%)
fission	1.3	0.6	0.3	0.9
nubar	0.3	0.3	0.4	0.3
PFNS E_{av}	1.7(37keV)	1.7(37keV)	4.38(93keV)	2.7(57keV)
elastic	13	12	1.4	3.7
inelastic	28	28	4.6	5.3
capture	18	20	8.6	12

TABLE VII. ^{235}U cross section uncertainties at 1 MeV incident neutron energy, 1-sigma, see Table VI caption (note that the CIELO-1 uncertainty of the PFNS average energy of 1.8% replaces the ENDF/B-VIII.0beta5 value of 0.9% in anticipation of a forthcoming change). Comparisons at 1 MeV are useful to illuminate the large differences between the different evaluations, which impact different calculated Godiva criticality uncertainties (Table IX). The CIELO-1 total inelastic uncertainty MT4 is estimated here as MT51 + MT851.

	CIELO-1 Unc. (%)	B-VII.1 Unc. (%)	JEFF-3.3 Unc. (%)	JENDL-4.0 Unc. (%)
fission	1.3	0.5	1.8	0.8
nubar	0.4	0.5	0.5	0.5
PFNS E_{av}	1.8(35keV)	3.6(75keV)	4.84(98keV)	3.0(61keV)
elastic	3.4	4.0	2.1	3.0
inelastic	10 (est.)	7.0	10	7.5
capture	14	16	11	33

We can make the following observations on covariances, based on the results shown in Tables VI, VII, after which

TABLE VIII. Jezebel (PMF1) criticality k-eff uncertainty, based on NDaST and MCNP simulations that use the ^{239}Pu covariance uncertainty data, for CIELO-1 (ENDF/B-VIII.0beta5), ENDF/B-VII.1, JEFF-3.3 (derived from CIELO-2, in version JEFF-3.3) and JENDL-4.0u1. Units are in "pcm", where 1000 pcm is 1% in k-eff. The summed value is less than the summed individual values in quadrature owing to correlations between the various channels. The experimental k-eff value is shown below the calculated (Summed) value for comparison, and below that is given the absolute difference between the calculated k-eff and the measured k-eff, C-E.

	CIELO-1	B-VII.1	JEFF-3.3	JENDL-4.0u1
	Jezebel	Jezebel	Jezebel	Jezebel
	k-eff Unc.	k-eff Unc.	k-eff Unc.	k-eff Unc
	(pcm)	(pcm)	(pcm)	(pcm)
fission	903	331	305	434
nubar	241	81	413	209
PFNS E_{av}	185	186	443	286
elastic	463	438	90	198
inelastic	797	797	150	250
capture	67	74	30	59
Summed	**1025**	**562**	**645**	**648**
Exp. unc.	110	110	110	110
$\|C\text{-}E\|$	15	12	68	185

TABLE IX. Godiva (HMF1-1) criticality k-eff uncertainty, based on NDaST and MCNP simulations that use the ^{235}U covariance uncertainty data, see Table VIII caption.

	CIELO-1	B-VII.1	JEFF-3.3	JENDL-4.0u1
	Godiva	Godiva	Godiva	Godiva
	k-eff Unc.	k-eff Unc.	k-eff Unc.	k-eff Unc.
	(pcm)	(pcm)	(pcm)	(pcm)
fission	788	269	648	320
nubar	540	545	510	274
PFNS E_{av}	132	276	364	176
elastic	276	294	109	426
inelastic	698 (est.)	616	698	681
capture	281	873	375	269
Summed	**1039 (est.)**	**1220**	**1342**	**962**
Exp. unc.	100	100	100	100
$\|C\text{-}E\|$	6	8	16	167

we will comment on the calculated resulting k-eff uncertainties in fast critical assemblies:

1. In comparing different evaluator's assessments of uncertainties, see Tables VI, VII, one is struck by how much they vary, often differing by factors of 2–5 or more! Given that the various covariance evaluators are recognized experts in their fields, that they have access to the same world-wide measured data, and that they use somewhat similar modeling and evaluation computational tools, this seems surprising. We must conclude that defining credible uncertainties – those that are neither unrealistically large nor small, remains a challenging problem. This partly reflects the fact that uncertainties are not physical quantities but instead represent assessments of our knowledge, and such assessments can be subjective.

2. The fission cross section and nubar uncertainties have increased substantially in CIELO-1 owing to recent considerations by the IAEA standards group, who include an assessment of "unrecognized systematic uncertainties" (USU), that in some cases double the previous assessments. Yet the JEFF fission uncertainty for ^{239}Pu (but not for ^{235}U) is much reduced, in contradiction to this.

3. The ^{235}U neutron capture uncertainty is significantly smaller in CIELO-1, owing to IAEA evaluation considerations that include an improved understanding following various measurements (including LANSCE/DANCE, RPI, and AMS measurements). The ^{239}Pu neutron capture uncertainty is also reduced, but to a lesser degree as the experiment at DANCE was not as accurate as that employed for the ^{235}U target. (This is actually more evident in the k-eff results in Tables VIII, IX, since capture occurs mostly at lower energies, below 1 MeV.)

4. The CIELO-1 uncertainty assessments for elastic and inelastic scattering have not changed substantially. For ^{239}Pu, CIELO-1 data were just carried over from ENDF/B-VII.1, and the uncertainties are seen to be much larger than those in the JEFF and JENDL files.

5. The CIELO-1 PFNS evaluation uncertainty for ^{235}U is substantially reduced, owing to the improved evaluation methodology aided by Starostov, Kornilov, Vorobyev and Chi-Nu new data sets and an improved uncertainty quantification of experimental data and model values; No change was made to plutonium in the fast range between ENDF/B-VII.1 [83] and CIELO-1. Tabulations of the new CIELO-1 PFNS covariances, versus ENDF/B-VII.1, are given in Ref. [9].

We now comment on the implications that these uncertainty data have on calulated k-eff uncertainties for integral fast critical assemblies, see Jezebel (Table VIII) and Godiva (Table IX):

1. The total "Summed" calculated k-eff uncertainties, which often exceed 1000 pcm (1% in k-eff), are very large. This reflects the uncertainties in our nuclear physics understanding, and is the reason for continued nuclear science (and CIELO!) research. They are unacceptably large for many applications in nuclear technology, but fortunately much more accurate measurements of integral criticality are available where k-eff is measured to better than a few hundred pcm uncertainty, see the "Exp. unc." in the

tables. In practice the evaluated libraries are either calibrated to match such integral data (the $C - E$ values are small) via a nubar tweak (*e.g.* CIELO-1), and/or are adjusted in a post-evaluation process to match such data (WPEC Subgroup 39).

2. Because of the aforementioned calibration process, the calculated summed k-eff uncertainty for the Jezebel and Godiva assemblies are "discrepant" with the measured (much smaller) difference in C-E in comparison with the k-eff integral data. This situation is understood. One could avoid the calibration, obtain a worse C-E value, which would now be *consistent* with the above calculated summed criticality uncertainty, and only remedy the worse performance through subsequent "adjustment" to the accurate integral data using Bayesian methodologies. The CIELO-1 researchers will pursue the merits of this approach in the coming years, with Subgroup 39, but at the present time it was not adopted owing to the lack of a widely-available adjustment capability in all relevant nuclear technology applications communities.

VII. MAIN CONCLUSIONS & FINDINGS

Here we briefly tabulate our main conclusions and findings from this CIELO pilot project:

- **How did the collaboration work?** Our initial goal of obtaining one consensus CIELO evaluation for each nucleus proved to be unachievable at this first stage of the collaboration, and instead we created two sets of evaluations, CIELO-1 and -2, that spanned the different opinions. This was also a consequence of the (very reasonable) view that different evaluation communities desired to maintain inhouse capabilities and control of their evaluated data. But we still feel major accomplishments were made in the evaluations and in the related data that were measured.
- **Use of standards.** Adopting the new IAEA standards cross sections without modification, while maintaining good integral performance in criticality simulations, is not easy when there is limited time to work through the various issues in a project with a completion deadline. Still, we showed this to be possible in CIELO. The CIELO-2 evaluation adopted fission cross sections consistent with previous 2006 standards, which are close to the current ones.
- **Experiment versus theory?** Both CIELO-1 and -2 evaluators used a combination of theory and modeling, and experiment, in making evaluated decisions. But one can see something of a difference in emphasis. The CIELO-2 evaluators from France emphasize the elegance of evaluations being generated consistently by modeling codes that provide a global match to data with emphasis on integral data performance; while the CIELO-1 evaluators tended to be motivated by the desire to represent each individual measured data set while still achieving the best possible integral performance. This perhaps reflect Gallic (theory) versus Anglo Saxon (empirical) sensibilities, although the CIELO-1 evaluation community was truly international!
- **Searching for "minima"**. When creating a new CIELO evaluation, it is important to include studies across the breadth of reaction channels involved (fission, PFNS, nubar, capture, scattering, and so on), since they all contribute in concert, in criticality applications. Only in this way can new, and hopefully more accurate, minima be found in a Chi-squared assessment (calculation versus experiment) of the accuracy of the evaluations.
- **^{235}U, ^{239}Pu fission cross section**. Recent standards work has *doubled* the fission uncertainties owing to assessments of large (1.2%) unrecognized systematic uncertainties in previous experiments, and we included this in CIELO-1. Future studies, as well as the publication of new measurements such as those from the LLNL-LANL TPC detector, will contribute to continued assessments of these uncertainties, which have a substantial impact on our applications.
- **^{235}U PFNS**. There is a compelling case that the thermal PFNS in ^{235}U should be softer than in earlier evaluations such as ENDF/B-VII.1; likewise, at fast energies near 1 MeV, the PFNS is softer than in earlier evaluations.
- **^{235}U capture**. The capture should be lower in the 1 keV region than in earlier evaluations such as ENDF/B-VII.1; In the 10s of keV region, although there are indications from some data (LANL/DANCE) that the capture should be higher versus earlier evaluations, more accurate measurements are needed for a definitive understanding.
- **^{235}U scattering**. Uncertainties remain in elastic and inelastic cross sections and angular distributions, in the fast region (100s keV to MeVs), which will need new measurements for their resolution. The semi-differential scattering type of measurement, pioneered at RPI, is a useful technique to pursue.
- **^{235}U and ^{239}Pu nubar**. Nubar is a parameter that evaluators adjust to optimize agreement with criticality measurements. Criticality depends so very sensitively on nubar that, even though it is often known to better than a percent, it can be adjusted based on integral data and remain consistent with the fundamental measurements. Perhaps this is no bad thing. There is little optimism that super-high-accuracy fundamental nubar measurements will become feasible any time soon.

- ^{238}**U capture**. Three new experiments have been carried out for this very important reaction confirming cross section values derived within the IAEA Neutron Standard project (2006 and 2017). An excellent agreement is also achieved by CIELO-1 evaluation with pioneering AMS experiments by Wallner *et al.*. CIELO-1 evaluation adopted reference cross sections from Standards, which agree with latest measurements. However, the CIELO-2 evaluation is about 5% lower around 20–30 keV.

- ^{238}**U inelastic**. Advances have been made to scattering, through theory work together with the recent semi-differential RPI measurements, but work is still needed to understand and resolve differences between CIELO-1 and CIELO-2 evaluations.

- ^{239}**Pu,** ^{235}**U PFNS**. New data from the Chi-nu LANL-LLNL experiment is now being published, that should better constrain the various evaluations (which presently show significant differences in the mean values and in their covariances).

- ^{239}**Pu inelastic**. Advances have been made to scattering by CIELO-2 (JEFF-3.3), though this represents future work for CIELO-1. Work is still needed to understand and resolve differences between CIELO-1 (unchanged from ENDF/B-VII.1) and CIELO-2 evaluations, including the very different (factor of 5) covariance assessments. Future work will benefit from semi-differential RPI-type measurements.

- ^{56}**Fe reactions**. Developing an improved evaluation for isotopes of iron has proved to be a challenge. A detailed representation of the resonating cross sections is important to quite high incident energies, as is a proper accounting of neutron capture and scattering processes, and we conclude that large uncertainties in existing measurements result in inadequately-constrained evaluated data. This allows various evaluation choices, with a consequence that great attention is needed to optimally match integral criticality and transport data. Our final CIELO-1 evaluation in ENDF/B-VIII.0 performs fairly well for criticality applications, but future work on elastic and inelastic scattering cross sections and angular distributions is needed to improve simulations of neutron transmission through macroscopic quantities of iron.

- ^{16}**O reactions**. A consensus was established for the correct value for the low energy neutron elastic scattering cross section, and for the magnitude of the total cross section up to the many-MeVs of incident neutron energy range. This was accomplished through analyses that integrate careful studies of experimental data with theoretical R-matrix analyses. While such analyses also support the CIELO-1 larger (by $\sim 40\%$) (n,α) cross section in the few-MeV region, future experimental work is still needed to corroborate this result.

VIII. FUTURE WORK

This CIELO pilot project is ending in 2018. Ongoing work on covariances for the CIELO data will be included into the final files.

There are additional details regarding the evaluated data for CIELO nuclides that have intentionally not been addressed in the CIELO collaboration, owing to time and scope limitations. Fission product yields were not studied, although another NEA WPEC subgroup (Subgroup 37) led by R.W. Mills has made progress here. The IAEA is coordinating studies on fission product data. Another topic is inelastic scattering. It has been central to the ^{235,238}U CIELO advances, but we were limited in the amount of time available for subject matter experts to work collaboratively across different laboratories to resolve differences for ^{239}Pu. The challenges were laid out in a useful IAEA document by Plompen *et al.* [13]. There remain open questions on the magnitude of the inelastic cross sections, as well as the merits of different treatments for angular distributions in both the MeV and the 10s-of MeV preequilibrium regions, ranging from quantum to semiclassical approaches [50, 84, 85].

We feel that our CIELO collaboration has stimulated much progress in nuclear experiments, theory, evaluation, and simulation. Many of the results have been adopted by regional evaluation efforts, such as ENDF and JEFF. In the long term, the community will continue CIELO collaborative efforts in nuclear science, under the auspices of both the IAEA and NEA, the IAEA focusing on advancing the underlying cross section data in the CIELO evaluations, and the NEA focusing on sensitivity studies and integral validation testing and feedback.

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