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Availability of Neutronics Benchmarks in the ICSBEP and IRPhEP Handbooks for Computational Tools Testing

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Abstract - *The past few decades have seen a growth in activity to evaluate and retain historic experimental data as benchmarks for modern and future computational tools testing. Experiments have been performed worldwide to support reactor operations, measurements, design, and nuclear safety, representing an extensive investment in infrastructure, expertise, and cost. These valuable research activities represent valuable assets supporting the recording, development, and validation of our nuclear methods and integral nuclear data. Reproduction of these data present prohibitive costs. The International Criticality Safety Benchmark Evaluation Project (ICSBEP) and the International Reactor Physics Experiment Evaluation Project (IRPhEP) were established under the direction of the Organisation for Co-operation and Development Nuclear Energy Agency (OECD NEA) to address the challenges in data preservation accompanied with data evaluation to determine current and future merit in validation efforts. Handbooks are provided annually containing extensively peer-reviewed benchmark data provided by the many international participants. The experimental data are evaluated to ascertain quality, quantify biases and uncertainties, and establish benchmark models following a standardized handbook format. These handbooks and their accompanying databases are then made available internationally to OECD NEA member countries and facilities from non-member countries that actively contribute to their development. The 2016 edition of the* International Handbook of Evaluated Criticality Safety Benchmark Experiments *(ICSBEP Handbook) currently includes data for 570 evaluations containing benchmark specifications for 4,913 critical or subcritical configurations representing contributions from over 20 countries. There are also a total of 7 criticality-alarm-placement/shielding evaluations containing 45 benchmark configurations, and 8 fundamental physics benchmark evaluations containing 215 measurements relevant to criticality safety applications. The 2016 edition of the* International Handbook of Reactor Physics Benchmark Experiments *(IRPhEP Handbook) contains data from 151 experimental series representing 50 unique reactor facilities with contributions from over 20 countries. The contents of these handbooks are utilized worldwide in support of computational validation for models, simulations, and nuclear data. Both the ICSBEP and IRPhEP intend to continue to provide international preservation, evaluation, and dissemination of integral benchmark data.*

I. INTRODUCTION

In the past several decades, numerous experiments have been performed worldwide to support reactor operations, measurements, design, and nuclear safety. Those experiments represent an extensive international investment in infrastructure, expertise, and cost, representing significantly valuable resources of data supporting past, current, and future research activities. Those valuable assets represent the basis for recording, development, and validation of our nuclear methods and integral nuclear data [1]. The loss of these experimental data, which has occurred all too often in the recent years, is tragic. The high cost to repeat many of these measurements can be prohibitive, if not impossible, to surmount.

Two international projects were developed, and are under the direction of the Organisation for Co-operation and Development Nuclear Energy Agency (OECD NEA) to address the challenges of not just data preservation, but evaluation of the data to determine its merit for modern and future use. The International Criticality Safety Benchmark Evaluation Project (ICSBEP) was established to identify and verify comprehensive critical benchmark data sets; evaluate the data, including quantification of biases and uncertainties; compile the data and calculations in a standardized format; and formally document the effort into a single source of verified benchmark data [2]. Similarly, the International Reactor Physics Experiment Evaluation Project (IRPhEP) was established to preserve integral reactor physics experimental data, including separate or special effects data for nuclear energy and technology applications [3].

Annually, contributors from around the world continue to collaborate in the evaluation and review of select benchmark experiments for preservation and dissemination. The extensively peer-reviewed integral benchmark data can

then be utilized to support nuclear design and safety analysts to validate the analytical tools, methods, and data needed for next-generation reactor design, safety analysis requirements, and all other front- and back-end activities contributing to the overall nuclear fuel cycle where quality neutronics calculations are paramount.

II. DESCRIPTION OF THE ACTUAL WORK

The benchmark evaluation process typical to the ICSBEP and IRPhEP for preparation, evaluation, and distribution of benchmark experiment data is shown in Fig. 1. There are key steps involved for preparation of high-quality peer-reviewed international handbook data, which will be discussed in the following subsections.

1. Benchmark Experiment Data

The initial component of any benchmark evaluation based upon physical experimental data is the availability of experimental measurement data with sufficient supporting documentation for the preparation and evaluation of computational models of the experiments. While basic overviews of the experiment methodology, materials, and results are often compiled within technical journals and reports, the information provided is often concise and insufficient to support comprehensive benchmark analysis. Memos, logbooks, design drawings, material specifications, and direct access to experimenters and/or facilities is integral and priceless resources. In an aging nuclear workforce, often the most important information captured regarding an experiment becomes lost as experimenters retire or pass away, and the affiliated nuclear facilities are reacquisitioned or demolished.

2. Benchmark Evaluation Process

The benchmark evaluation process includes several key steps. The evaluation process itself is the most time and resource intensive of the benchmark process. Evaluators first identify experiments of interest, whether, for example, to support validation of computational models for a specific reactor or material type for simulation of a given process, or testing of integral nuclear data to identify sensitivities or investigate further nuclear data refinement.

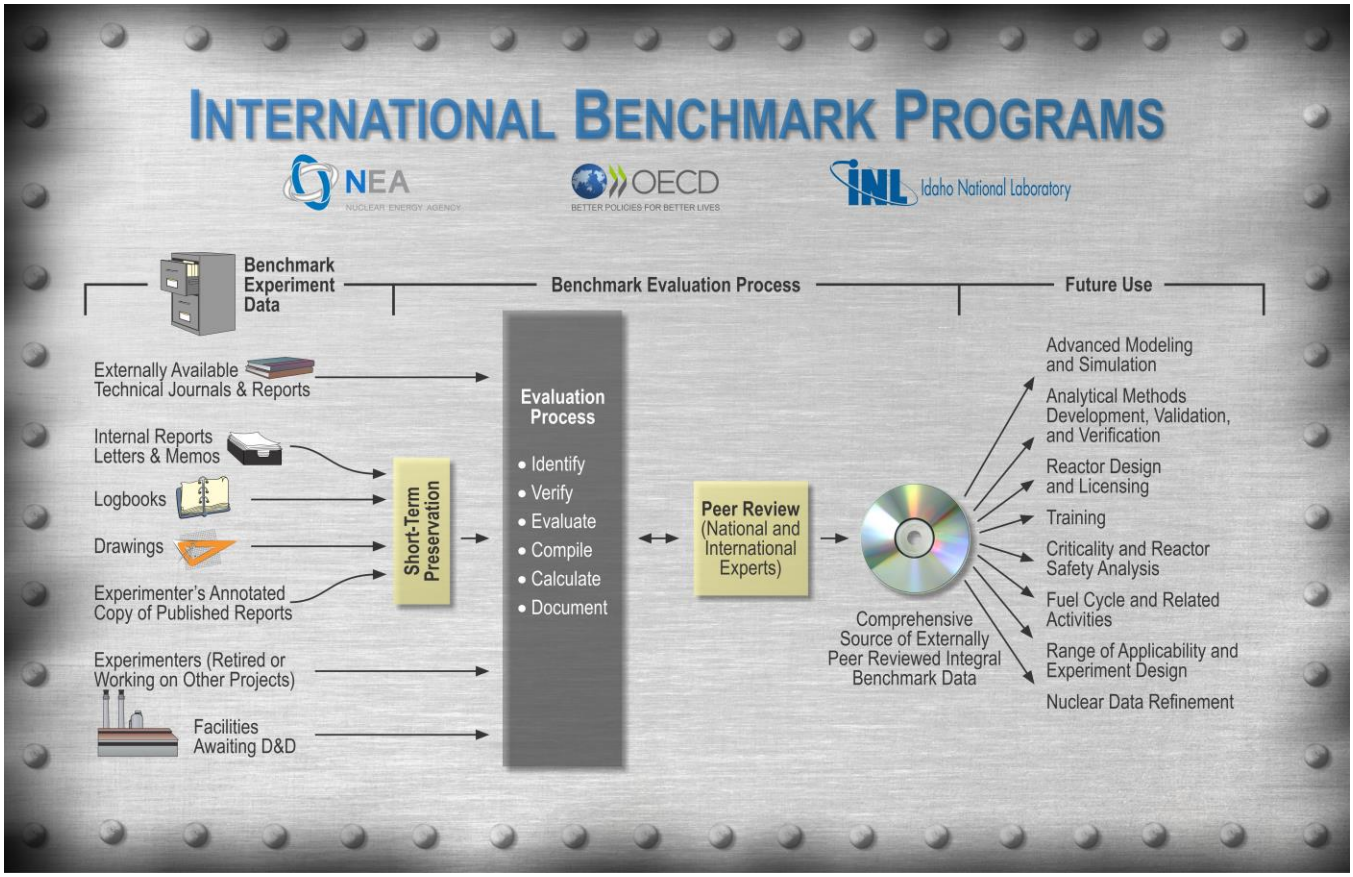

Fig. 1. Benchmark Evaluation Process for the ICSBEP and IRPhEP.

Upon identification of an experiment, or set of experiments to evaluate, the evaluator is expected to verify the accuracy of the available data and further investigate the availability of supporting information, as discussed in the previous subsection.

The evaluation of the experimental data includes addressing conflicting data and/or lack of data, and their impact on the accuracy of the benchmark results quantified. Computational models of the experiments are prepared and utilized to simulate the experimental measurements. Uncertainties in the measurements are accounted for, where possible, using available documented information. Uncertainties in material properties (compositions, densities, isotopic abundances, temperatures, etc.) and geometric properties (length, width, height, position, quantity, etc.) must also be addressed. Simulations of the impact of the uncertainty in experiment parameters, where possible are computed and compiled to prepare a total experimental uncertainty. Simplifications to the experiment to provide a benchmark model are also evaluated such that biases, with their respective uncertainties, are similarly tabulated.

Ultimately the benchmark evaluation effort is compiled into a document following a specific format whether for ICSBEP or IRPhEP. The end product provides preserved experimental data, evaluation of the experimental data, development and description of a benchmark model with benchmark experiment results (including biases and uncertainties), as well as sample calculations and input decks. All supporting information needed to supplement the benchmark evaluation report are provided in appendices or additional file resources with the handbooks.

A. Handbook Format

A key aspect of the benchmark project handbooks is the use of a specified format that is followed for the documentation of the evaluated benchmark experiment data. The application of a specific format facilitates familiarity with the benchmark evaluation process as well as ease of use from the user community. The basic handbook format includes five fixed sections and an appendix:

1. Detailed description of experimental measurements,
2. Evaluation of experimental data,
3. Benchmark specifications,
4. Results of sample calculations,
5. References, and

A. Typical input listings

Additional appendices containing supporting information and/or linked files can also be included with the benchmark evaluation.

3. International Peer-Review Process

Contributions to the benchmark handbooks undergo a more thorough review than most, if not all, professional publications. Once evaluators of the benchmark experiment data have completed their efforts, additional staff at their facility then typically review the report. These internal reviewers are expected to verify the accuracy of the experimental data, benchmark models, evaluation results, and adherence to the handbook format.

Once the internal review process has been resolved, the evaluation is provided to one or more independent reviewers. The independent reviewers are from other international facilities with interest and expertise in the benchmark evaluation process and of the subject matter for the evaluation. The independent reviewers repeat the review process except for verification of the accuracy of the experimental data from the original documentation.

Upon completion of the independent review process, the benchmark evaluation is ready to submit to the annual technical review meeting of the ICSBEP or IRPhEP. Annually international participants contribute their time and resources to individually review and discuss, page-by-page, each of the contributed evaluations. The conclusion of the technical review meeting results in a list of action items that must be resolved prior to final acceptance and publication in the international handbooks.

4. Distribution of Handbook Data

Completed and approved evaluations undergo final formatting and integration into the handbooks. Distributed handbook data includes the evaluation report, which is compiled into a PDF and integrated into the bookmark links and search features of the handbook structure. Additional data files are included that facilitate searching the handbook data to support specific validation or benchmark needs. The Database for the International Handbook of Evaluated Criticality Safety Benchmark Experiments (DICE) is utilized to sort through criticality safety handbook data [4]. Other files included on the handbooks might include calculated neutron flux/capture/fission spectrum data, neutron balance data, k_{eff} sensitivity data, sample input decks, preserved reference data, or auxiliary report information supporting the evaluation of the benchmark experiment data. The IRPhEP Database and Analysis Tool (IDAT) [5] was similarly deployed to facilitate searching of the data provided for reactor physics benchmark evaluations. Additional measurement data beyond criticality and subcriticality include buckling, spectral characteristics, reactivity effects, reactivity coefficients, kinetics, reaction rates, power distributions, and other miscellaneous types of measurements. The capabilities to do trending and comparison studies of the reactor physics data using IDAT is also available.

The completed handbooks are currently available in both DVD and online format. The DICE and IDAT software can be directly accessed online and used to perform searching regarding the handbooks without having actual access to the benchmark handbooks and detailed benchmark experiment models and measurements contained within. The handbooks are made available internationally to OECD NEA member countries and facilities from non-member countries that actively contribute to the ICSBEP and IRPhEP. Information regarding the ICSBEP and IRPhEP, and permission to access their respective handbook data can be found on the following websites: https://www.oecd-nea.org/science/wpncs/icsbep/ and https://www.oecd-nea.org/science/wprs/irphe/, respectively.

B. Handbook Revisions

Revisions to existing evaluations occur for two primary reasons: provision of additional data with supporting analyses, or, correction of errors identified by users of the handbooks. Often with IRPhEP benchmark evaluations, the initial evaluation of large reactor systems includes many more parameters and analyses than in a simple criticality safety benchmark. As such, the initial benchmark submissions typically focus solely upon evaluation of the critical core loadings. Once these configurations have been accepted as approved benchmark specifications into the handbook, then evaluation of additional reactor physics measurements are included as revisions to the original evaluation report. These additional measurements are subjected to the full review process. The advantage of this approach is that any significant problems or issues identified with the critical core benchmark analysis would not impact concurrent analysis of the other reactor physics measurements from that experimental series.

As users of the handbook identify errors or points of confusion in the handbook, they are invited to contact the current Chair of these projects. Minor corrections will be made to existing evaluations as necessary. Major concerns and errors will be addressed by the primary evaluators and/or reviewers, if available, for the evaluation in question. Resolution to the identified concern will then be addressed by the international technical review committee and the revised benchmark evaluation replaced in the next edition of the ICSBEP Handbook or IRPhEP Handbook.

III. RESULTS

The ICSBEP annually releases the *International Handbook of Evaluated Criticality Safety Benchmark Experiments* (ICSBEP Handbook) [6]. The 2016 edition of the ICSBEP Handbook (see Fig. 2) now includes data for 570 evaluations containing benchmark specifications for 4,913 critical or subcritical configurations, representing contributions from over 20 countries. There are a total of 7 criticality-alarm-placement/shielding evaluations containing a total of 45 benchmark configurations, and 8 fundamental physics benchmark evaluations containing a total of 215 measurements relevant to criticality safety applications. A general summary of the content of the 2016 edition of the ICSBEP Handbook is provided in Table I.

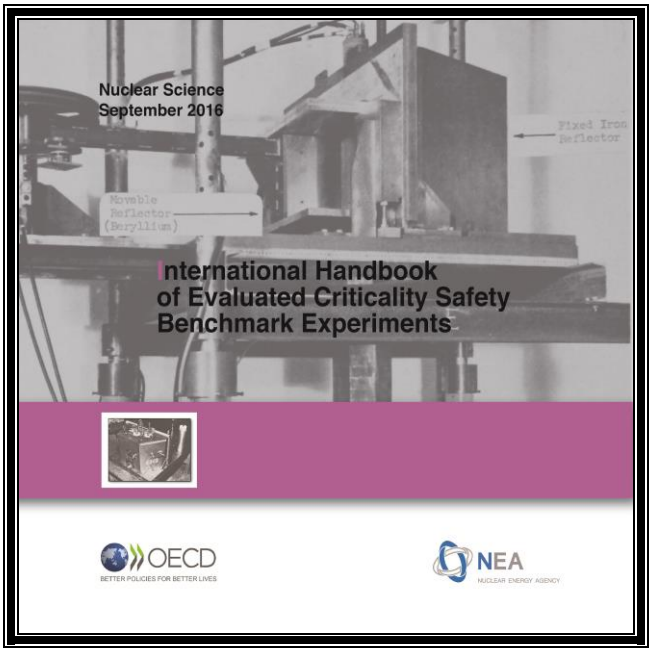

Fig. 2. Cover of the 2016 Edition of the ICSBEP Handbook.

Table I. Overview of Available Benchmark Data in the 2016 Edition of the ICSBEP Handbook.

Type	Quantity
Plutonium Experiments	748
Compound	36
Metal	123
Solution	589
Highly Enriched Uranium Experiments	1435
Compound	291
Metal	601
Solution	536
Mixed Compound/Solution	2
Mixed Metal/Solution	5
Intermediate- and Mixed-Enrichment Uranium Experiments	268
Compound	156
Metal	47
Solution	65
Low Enriched Uranium Experiments	1662
Compound	1398
Metal	87
Solution	117
Mixed Compound/Solution	60

Type	Quantity
^{233}U Experiments	244
Compound	6
Metal	11
Solution	227
Mixed Plutonium-Uranium Experiments	536
Compound	301
Metal	52
Solution	86
Mixed Compound/Solution	76
Mixed Metal/Compound	21
Special Isotope Experiments	20
Metal (^{237}Np, ^{238}Pu, ^{242}Pu, & ^{244}Cm)	20
Criticality-Alarm/Shielding Experiments	7
Unique Configurations with Multiple Data Points	45
Fundamental Physics Experiments	8
Unique Measurements such as Fission Rates, Transmission Measurements, Subcritical Neutron Multiplication	215

The IRPhEP annually releases the *International Handbook of Evaluated Reactor Physics Benchmark Experiments* (IRPhEP Handbook) [7]. The 2016 edition of the IRPhEP Handbook (see Fig. 3) now includes data from 151 experimental series (representing 50 reactor facilities) and represents contributions from over 20 countries. Of the 151 benchmarks, four are draft contributions to the handbook, and one is a draft benchmark pending final publication approval. Draft evaluations represent new information that has not been completely evaluated in time for handbook publication; however, there is a desire to preserve the experimental data and current evaluation information, making it available for public use. A general summary of the content of the 2016 edition of the IRPhEP Handbook is provided in Table II.

The contents of these handbooks are utilized worldwide to support computational validation of models, simulations, and nuclear data. As users of the handbook data identify errors or have questions regarding existing benchmark evaluations, the evaluations are discussed in the annual technical review meetings and revised as appropriate. Similarly, as newly evaluated data becomes available for existing benchmark reports, the additional data is peer-reviewed for inclusion as a revision to the original benchmark evaluation. Both the ICSBEP and IRPhEP intend to continue forward in the international preservation, evaluation, and dissemination of integral benchmark data.

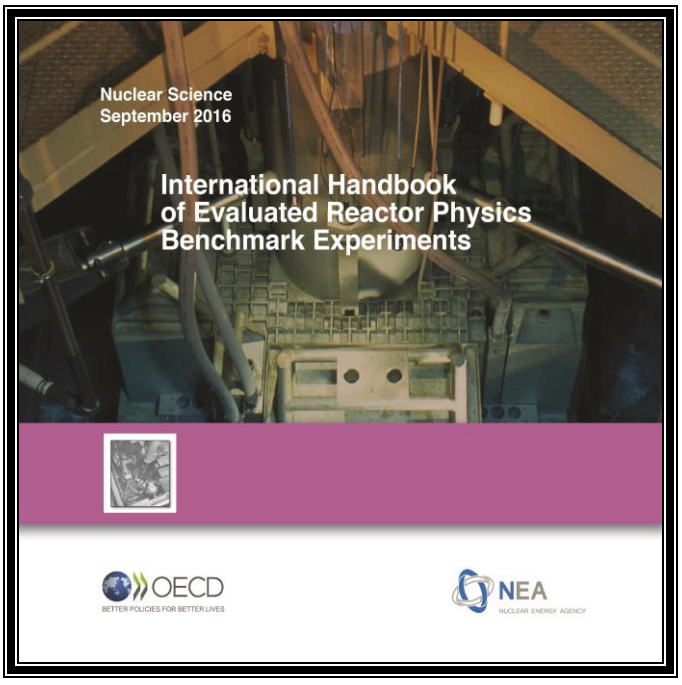

Fig. 3. Cover of the 2016 Edition of the IRPhEP Handbook.

Table II. Overview of Available Benchmark Data in the 2016 Edition of the IRPhEP Handbook.*

PWR (6)	SERIES (14)
DIMPLE	2 + 1 Draft
DUKE	1 Pending
EOLE	2
OTTOHAHN	1
SSCR	2
VENUS	2 + 3 Draft

VVER (3)	SERIES (5)
LR-0	3
P-Facility	1
ZR-6	1

BWR (0)	SERIES (0)

LMFR (9)	SERIES (25)
BFS-1	2
BFS-2	1
BR2	1
FFTF	1
JOYO	1
SNEAK	1
ZEBRA	3
ZPPR	11
ZPR	4

[1] Duplicate Facility

GCR (5)	SERIES (10)
ASTRA	1
HTR10	1
HTTR	3
PROTEUS	4
VHTRC	1

GCFR (1)	SERIES (1)
PROTEUS[1]	1

LWR (5)	SERIES (27)
CROCUS	1
DIMPLE[1]	2
IPEN(MB01)	18
KRITZ	3
TCA	3

HWR (3)	SERIES (5)
DCA	1
ETA	2
ZED2	2

MSR (0)	SERIES (0)

RBMK (1)	SERIES (1)
RBMK(CF)	1

Total Facilities	Total Series
50	151

SPACE (6)	SERIES (12)
ORCEF	1
SCCA	3
TOPAZ	2
UKS1M	1
ZPPR[1]	4
ZPR[1]	1

FUND (19)	SERIES (51)
ATR	1
BFS-1[1]	4
BFS-2[1]	1
CORAL(1)	1
FR0	3
HECTOR	2
IGR	1
KUCA	1
LAMPRE	1
MINERVE	1
NRAD	2
ORSPHERE	1
PBF	1
RA-6	1
RB	8
RHF	1
TRIGA	2
ZEBRA[1]	1
ZPR[1]	18

*PWR = Pressurized Water Reactor, VVER = Vodo-Vodynaoi Energetichesky Reactor,
BWR = Boiling Water Reactor, LMFR = Liquid Metal Fast Reactor, GCR = Gas Cooled (Thermal) Reactor,
GCFR = Gas Cooled (FAST) Reactor, LWR = Light Water Moderated Reactor,
HWR = Heavy Water Moderated Reactor, MSR = Molten Salt Reactor,
RBMK = Reaktor Bolshoy Moshchnosti Kanalniy, SPACE = Space Reactor,
and FUND = Fundamental Physics Measurements.

IV. CONCLUSIONS

The ICSBEP and IRPhEP actively provide international preservation, evaluation, and dissemination of integral benchmark data to support computational validation of models, simulations, and nuclear data in support of criticality safety and reactor physics applications. Annual contributions to their respective handbooks provides an ever-growing resource of evaluated benchmark experiment data that has assessed qualitatively and quantitatively to provide uncertainties, biases, and established benchmark models within a standardized handbook format. All benchmark evaluations undergo an intensive peer-review process with participants and contributions representing over 20 countries. Experiments were performed historically to support reactor operations, measurements, design, and nuclear safety. The extensive investments in infrastructure, expertise, and cost are not cheaply reproduced should the information from these legacy experiments become lost. The preservation and evaluation activities of the ICSBEP and IRPhEP provide a means to provide quality nuclear data for current and future needs in computational tools and nuclear data testing.

ACKNOWLEDGMENTS

The ICSBEP and IRPhEP is a collaborative effort that involves numerous scientists, engineers, and administrative support personnel from over 20 different countries. The authors would like to acknowledge the efforts of all of these dedicated individuals without whom this project would not be possible.

Countries that have contributed to the contents of the ICSBEP and/or IRPhEP Handbooks include the following:

- Argentina
- Belgium
- Brazil
- Canada
- People's Republic of China
- Czech Republic
- France
- Germany
- Hungary
- India
- Israel
- Italy
- Japan
- Kazakhstan
- Poland
- Republic of Korea
- Russia Federation
- Serbia
- Slovenia
- South Africa
- Spain
- Sweden
- Switzerland
- United Kingdom
- United States of America

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7. *International Handbook of Evaluated Reactor Physics Benchmark Experiments*, NEA/NSC/DOC(2006)1, OECD-NEA, Paris, France (2016).