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Integral Benchmarks Available Through the International Reactor Physics Experiment Evaluation Project and the International Criticality Safety Benchmark Evaluation Project

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Integral benchmarks available through the international reactor physics experiment evaluation project and the international criticality safety benchmark evaluation project

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Abstract

Interest in high-quality integral benchmark data is increasing as efforts to quantify and reduce calculational uncertainties accelerate to meet the demands of next generation reactor and advanced fuel cycle concepts. The International Reactor Physics Experiment Evaluation Project (IRPhEP) and the International Criticality Safety Benchmark Evaluation Project (ICSBEP) continue to expand their efforts and broaden their scope to identify, evaluate, and provide integral benchmark data for method and data validation. Benchmark model specifications provided by these two projects are used heavily by the international reactor physics, nuclear data, and criticality safety communities. Thus far, 14 countries have contributed to the IRPhEP, and 20 have contributed to the ICSBEP. The status of the IRPhEP and ICSBEP is discussed in this paper, and the future of the two projects is outlined and discussed. Selected benchmarks that have been added to the IRPhEP and ICSBEP handbooks since PHYSOR'06 are highlighted, and the future of the two projects is discussed.

1. Introduction

The International Reactor Physics Experiment Evaluation Project (IRPhEP) was first introduced at a Reactor Physics Conference during the International Conference on the Physics of Reactors, PHYSOR'06 (Briggs et. al., 2006). The work of the International Criticality Safety Benchmark Evaluation Project (ICSBEP) has never been formally presented at a reactor physics conference but has been referenced by many authors at such conferences. Since PHYSOR'06, both of these projects have continued to expand their efforts and broaden their scope. Accomplishments of each project are described in this paper and the data provided by both projects are characterized.

Numerous identifiers are used to categorize various benchmarks and experimental facilities throughout this paper. These identifiers are defined in Appendixes A.

1.1. IRPhEP

The work of the IRPhEP is documented in the *International Handbook of Evaluated Reactor Physics Benchmark Experiments (IRPhEP*

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Handbook). Since PHYSOR'06, two new editions of the *IRPhEP Handbook* have been published. The most recent edition contains data from 25 experimental series performed at 17 different reactor or experimental facilities. (Note: Certain experimental assemblies were constructed to simulate specific reactor types. Throughout this paper, these will be referred to as the reactor types for which they were intended to simulate.) This handbook includes evaluated data from the following reactor types:

- Seven liquid metal fast reactors (JOYO, BFS-1, BFS-2, ZPPR, ZEBRA, ZPR, and SNEAK)
- Two gas-cooled reactors (HTR-10 and ASTRA)
- One heavy-water reactor (DCA)
- Three light-water reactors (DIMPLE, CROCUS, and IPEN/MB-01)
- Two pressurized water reactors (VENUS and CREOLE)
- Two VVER reactors (ZR6 and PFACILITY).
-

Four fundamental physics evaluations of non-fast-reactor measurements performed on BFS-1 and BFS-2 are also included.

Twenty-one of the 25 evaluations contain approved benchmark data. The remaining four evaluations are published as draft documents only. Completion of the draft evaluations is planned for the 2009 edition, in addition to several new evaluations that are currently in progress.

Fourteen countries have contributed technical expertise and/or experimental data to the IRPhEP. Included are Belgium, Brazil, Canada, China, France, Germany, Hungary, Italy, Japan, Korea, the Russian Federation, Switzerland, the United Kingdom, and the United States.

1.2. ICSBEP

The work of the ICSBEP is documented in the *International Handbook of Evaluated Criticality Safety Benchmark Experiments* (*ICSBEP Handbook*). This handbook primarily contains evaluated integral benchmark data for critical and sub-critical systems. Criticality-alarm/shielding type benchmarks and relevant fundamental physics measurements are not only included in the scope of the ICSBEP, but benchmark data are now available in the latest version of the *ICSBEP Handbook.*

The 2008 edition of the *ICSBEP Handbook* will contain benchmark specifications for approximately 4,227 critical, near-critical, or subcritical configurations; 24 criticality alarm placement/shielding configurations with multiple dose points for each; and 145 configurations that have been categorized as fundamental physics measurements that are relevant to criticality safety applications. This edition is scheduled for publication in September of 2008.

Twenty countries have contributed technical expertise and/or experimental data to the ICSBEP. Included are Argentina, Brazil, Canada, China, the Czech Republic, France, Hungary, India, Israel, Japan, Kazakhstan, Korea, Poland, the Russian Federation, Serbia, Slovenia, Spain, Sweden, the United Kingdom, and the United States.

2. The 2008 Editions of the *IRPhEP* and *ICSBEP Handbooks*

The contents of the *IRPhEP* and *ICSBEP Handbooks* are characterised in the following two subsections.

2.1 IRPhEP Handbook

The 2008 Edition of the *IRPhEP Handbook* was published in March, 2008, (see Fig. 1) and is currently available only on DVD. The DVD version can be requested from the IRPhEP Internet site at <http://nuclear.inel.gov/irphep/>.

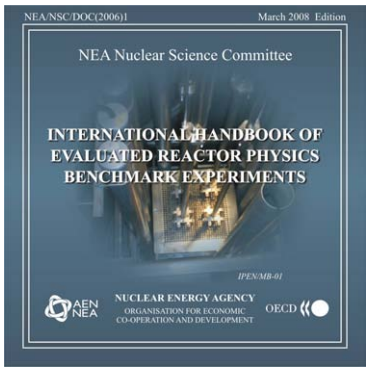

Fig. 1. March 2008 Edition of the *IRPhEP Handbook.*

The *IRPhEP Handbook* contains data and, in most cases, benchmark specifications for the following:

- One simulated PWR:

CREOLE-PWR-EXP-001 containing benchmark specifications for criticality, reactivity coefficients, reaction-rate distributions, and miscellaneous water expansion effects measurements.

- Two VVER reactors:
  PFACILITY-VVER-EXP-001 containing benchmark specifications for criticality and unevaluated data provided for reaction-rate distributions;

  ZR6-VVER-EXP-001 containing benchmark specifications for criticality, buckling measurements, spectral characteristics, reactivity effects, reactivity coefficients, and reaction-rate distributions.
- Seven liquid metal fast reactors:
  BFS1-LMFR-EXP-001 containing benchmark specifications for criticality, spectral characteristics, reactivity coefficients, kinetics measurements, and reaction-rate distributions;

  BFS2-LMFR-EXP-001 containing benchmark specifications for criticality, spectral characteristics, reactivity effects, and reaction-rate distributions;

  JOYO-LMFR-RESR-001 containing benchmark specifications for criticality, reactivity effects, and reactivity coefficients;

  ZPR-LMFR-EXP-001 containing benchmark specifications for criticality, spectral characteristics, reactivity effects, and reaction-rate distributions;

  ZEBRA-LMFR-EXP-001 containing CADENZA Cores, with benchmark specifications for criticality, spectral characteristics, reactivity effects, and reaction-rate distributions;

  ZEBRA-LMFR-EXP-002 (MOZART Part 1) containing benchmark specifications for criticality, buckling measurements, spectral characteristics, reactivity effects, and reaction-rate distributions;

  ZEBRA-LMFR-EXP-003 (MOZART Part 2) containing benchmark specifications for criticality, reactivity effects, and reaction-rate distributions.
- Two gas-cooled reactors:
  HTR10-GCR-RESR-001 containing benchmark specifications for criticality and unevaluated data for reactivity effects;

  ASTRA-GCR-EXP-001 containing benchmark specifications for criticality.
- Four light-water reactors:
  DIMPLE-LWR-EXP-001 containing benchmark specifications for criticality, buckling, spectral characteristics, and reaction-rate distributions; however, reactivity effects measurements were evaluated and determined to be unacceptable for use as benchmark data, and data for reactivity coefficients were evaluated and determined to be of benchmark quality but have not yet been developed into benchmark specifications;

  DIMPLE-LWR-EXP-002 containing benchmark specifications for criticality, buckling, spectral characteristics, and reaction-rate distributions, but data provided for reactivity coefficient measurements were evaluated and determined to be unacceptable for use as benchmark data;

  CROCUS-LWR-RESR-001 containing benchmark specifications for criticality and kinetics measurements;

  IPEN(MB01)-LWR-RESR-001 containing benchmark specifications for criticality, reactivity coefficient measurements, and kinetics measurements.
- One heavy-water moderated reactor:
  DCA-HWR-EXP-001 containing benchmark specifications for criticality, spectral characteristics, and reaction-rate distributions.
- Four fundamental physics assemblies:
  BFS1-FUND-EXP-001 containing benchmark specifications for criticality, spectral characteristics, and reaction-rate distribution measurements, but reactivity effects and kinetics measurements were not fully evaluated and are currently considered unacceptable for use as benchmark data;

  BFS1-FUND-EXP-002 containing benchmark specifications for spectral characteristics measurements and reaction-rate distributions, but measurements for criticality and reactivity effects were determined to be unacceptable for use as benchmark data;

  BFS1-FUND-EXP-003 containing benchmark specifications for spectral

characteristics measurements, but measurements for criticality were determined to be unacceptable for use as benchmark data;

BFS2-FUND-EXP-001 containing benchmark specifications for k_∞ and spectral characteristics measurements, but measurements for criticality and reactivity effects were determined to be unacceptable for use as benchmark data.

Evaluation of four experimental series, VENUS-PWR-EXP-001, VENUS-PWR-EXP-003, ZPPR-LMFR-EXP-001, and SNEAK-LMFR-EXP-001, are also included in the *IRPhEP Handbook* but are only in draft form.

2.2 ICSBEP Handbook

The 2008 Edition of the *ICSBEP Handbook* will be published in September of 2008 (see Fig. 2) and will be available on DVD and on the Internet. Both the DVD version and a password to access the online version can be requested from the ICSBEP Internet site at <http://icsbep.inl.gov>.

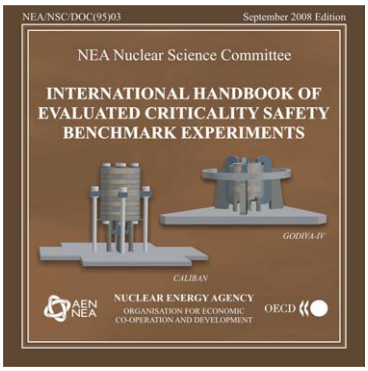

Fig. 1. September 2008 edition of the *ICSBEP Handbook*.

The 2008 Edition of the ICSBEP Handbook includes benchmark specifications for the following:

- 697 Pu experiments, of which 118 are metal (111 fast, 4 intermediate, 2 thermal, and 1 mixed), 544 solution (thermal), and 35 compound (6 fast, 1 intermediate, 21 thermal, and 7 mixed)
- 1,311 highly enriched U experiments, of which 541 are metal (354 fast, 14 intermediate, 138 thermal, and 35 mixed), 481 solution (3 intermediate and 478 thermal), 283 compound (8 fast, 14 intermediate, 216 thermal, and 45 mixed), 5 mixed metal/solution (thermal), and 2 compound/solution (thermal)
- 110 intermediate- and mixed-enrichment U experiments, of which 31 are metal (fast), 5 solution (thermal), and 74 compound (2 fast, 16 intermediate, 46 thermal, and 10 mixed)
- 1,356 low-enrichment U experiments, of which 70 are metal (thermal), 104 solution (thermal), 1,144 compound (thermal), and 38 mixed compound/solution (thermal)
- 262 ^{233}U experiments, of which 11 are metal (10 fast, 1 thermal), 246 solution (209 thermal, 29 intermediate, and 8 mixed), and 6 compound (thermal)
- 469 mixed Pu-U experiments, of which 48 are metal (45 fast, 2 intermediate, and 1 mixed), 72 solution (thermal), and 277 compound (2 fast, 3 intermediate, 255 thermal, and 17 mixed), 56 mixed compound/solution systems (thermal), and 16 mixed metal/compound (8 fast and 8 mixed)
- 20 special isotope experiments, all of which are metal (fast) (^{244}Cm, ^{238}Pu, ^{237}Np, and ^{242}Pu)
- Four criticality-alarm/shielding benchmarks containing 24 configurations with numerous dose points
- Five fundamental physics benchmarks, which includes 145 fission-rate and transmission measurements.

Reactor-physics-related benchmark data that have been added to the *ICSBEP Handbook* since PHYSOR'06 (2007 and 2008 editions) include:

- The mercury-cooled plutonium-metal fast reactor, BR-2 (IPPE—Russian Federation)
- The GODIVA-IV Prompt Burst Experiment (LANL—United States) and the French counterpart, CALIBAN (CEA Valduc—France)
- Additional configurations on the MB01 Reactor (IPEN—Brazil)
- ZPR-6 Assembly 7 sodium-cooled fast reactor assembly with high ^{240}Pu (ANL—United States)
- VVER-440 physics experiments (NRI—Czech Republic)
- ^{233}U solution reactors, PURNIMA-II (BARC—India) and ALECTO (CEA Saclay—France)

- STACY 5% enriched fuel rod lattices in 6% enriched uranyl nitrate solution with pseudo fission product elements (JAEA—Japan)
- The "Otto Hahn" PWR Nuclear Ship Program reactor
- Fast zero-power reactor, FR0 (Studsvik Sweden)
- Annular core ASTRA pebble bed assembly (RRC Kurchatov Institute—Russian Federation)
- RA-0 intermediate-enriched graphite-reflected, water-/graphite-moderated reactor (National University of Cordoba—Argentina)

Numerous other benchmarks that are relevant to criticality safety applications and nuclear data testing have also been added to the *ICSBEP Handbook* since PHYSOR'06.

A searchable **D**atabase for the **I**nternational Handbook of Evaluated **C**riticality Safety Benchmark **E**xperiments, DICE is included with the DVD version of the ICSBEP Handbook. DICE enables users to more effectively identify the experiments that are needed for their specific applications. The database also makes it easier to characterize the information generated by the ICSBEP and to identify gaps and inconsistencies in the data. The advanced search capabilities of DICE enable users to search, for example, for all experiments in which a desired minimum percentage of the fissions occur in the intermediate energy range or all experiments in which the fraction of capture in ^{238}U exceeds a user-specified percentage. Plotting capabilities have been implemented into DICE that allow users to view graphical representations of neutron flux and certain reaction rates [fission, capture, (n,2n), and neutron production] or sensitivity coefficients for major nuclides and nuclear processes. DICE also allows users to download data into a delimited file structure that enables users to generate separate plots of calculated k_{eff} values versus various other parameters in the database.

3. Future of the IRPhEP and ICSBEP

3.1 Future of the IRPhEP

Although the IRPhEP is a relatively new project, the 3rd edition of the *IRPhEP Handbook* was published in March of 2008, and approximately 300 copies are distributed annually. The number of contributing countries is expected to increase.

The 2009 Edition of the *IRPhEP Handbook* is expected to contain completed benchmarks of VENUS 3, ZPPR 10A, and SNEAK Cores 7A and 7B, all currently in draft form. Additional data are expected from the IPEN/MB01 Reactor and ZPR-6 Assembly 7 (high ^{240}Pu). Evaluation of several other reactor/experimental assemblies are planned or are in progress, some of which may be completed for the 2009 Edition of the *IRPhEP Handbook*. Included on the list of "in-progress" or "planned" evaluations are the PROTEUS reactor (GCR); FFTF (LMFR); ZPPR Assemblies 9, 13, and 17 (LMFR); VENUS Configurations 1, 7, 9, and 17 (PWR); VHTCR (GCR); HTTR (GCR); KRITZ (LWR); and TCA (LWR).

While benchmarks produced by the IRPhEP are of primary interest to the reactor physics community, many can be of significant value to the criticality safety and nuclear data communities as well. Benchmarks that support the Next Generation Nuclear Plant, for example, also support fuel manufacture, handling, transportation, and storage activities and could challenge current analytical methods.

3.2 Future of the ICSBEP

The ICSBEP provides high-quality criticality safety-related benchmark data from around the world, and the project continues to grow. The 14th publication of the *ICSBEP Handbook* is scheduled for September of 2008, and approximately 600 copies are distributed annually. The project has expanded to include criticality alarm/shielding benchmarks and relevant fundamental physics measurements. Critical excursion data may also be added in the future.

While benchmarks produced by the ICSBEP are of primary interest to the criticality safety community, many can be of significant value to the reactor physics and nuclear data communities as well. Improved cross section data benefit both reactor physics and criticality safety analysts, and many benchmarks can be used to reduce the uncertainties of specific adjusted nuclear data libraries.

3.3 Archival of Primary Documentation

Since the inception of the IRPhEP, the NEA has been collecting primary documentation and has been transforming those documents into electronic form to facilitate data retrieval and dissemination. An

archive of those documents has been established at the NEA. A summary of the types of data that are in the NEA archive are given in Appendix B.

4. Conclusions

The activities of the IRPhEP and ICSBEP systematically (1) consolidate and preserve the international reactor physics and criticality safety information base, (2) identify areas where more data are needed, (3) draw upon the resources of the international reactor physics/criticality safety communities to help fill those needs, and (4) identify discrepancies between calculations and experiments. The projects have already eliminated a large portion of the tedious and redundant research and processing of experimental data, and they have streamlined the validation process. Benchmarks produced by the IRPhEP and ICSBEP provide new dimension to validation efforts and greatly expand the collection of available integral benchmarks for nuclear data testing and uncertainty determination. The *IRPhEP* and *ICSBEP Handbooks* are expected to be valuable resources to the reactor physics, criticality safety, and nuclear data communities for decades.

Acknowledgements

The ICSBEP and IRPhEP are collaborative efforts that involve numerous scientists, engineers, administrative support personnel, and program sponsors from 22 different countries. The authors would like to acknowledge the efforts of all of these dedicated individuals without whom the ICSBEP and IRPhEP would not be possible.

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Appendix A. IRPhEP and ICSBEP Identifiers

A.1 IRPhEP Handbook

The IRPhEP Handbook is divided into 11 major sections, each representing 1 of 11 different reactor types. Each experimental series within the handbook is assigned a unique identifier that has two parts. The first part consists of the Reactor Name (RN), Reactor Type (RT), Facility Type (FT), and a three-digit Numerical Identifier (NID). The second part of the identifier generally begins on a separate line and includes the Measurement Type(s) (MT). Identifiers, therefore, take the following form:

(RN)-(RT)-(FT)-(NID) (MT).

The RN is unique to each reactor. The RT, FT, and MT are selected from the following three lists, respectively.

Reactor Type

Pressurized Water Reactor	PWR
VVER Reactor	VVER
Boiling Water Reactor	BWR
Liquid Metal Fast Reactor	LMFR
Gas-Cooled (Thermal) Reactor	GCR
Gas-Cooled (Fast) Reactor	GCFR
Light Water Moderated Reactor	LWR
Heavy Water-Moderated Reactor	HWR
Molten Salt Reactor	MSR
RBMK Reactor	RBMK
Fundamental	FUND

Facility Type

Experimental Facility	EXP
Power Reactor	POWER
Research Reactor	RESR

Measurement Type

Critical Configuration	CRIT
Subcritical Configuration	SUB
Buckling and Extrapolation Length	BUCK
Spectral Characteristics	SPEC
Reactivity Effects	REAC
Reactivity Coefficients	COEF
Kinetics Measurements	KIN
Reaction-Rate Distributions	RRATE
Power Distributions	POWDIS
Isotopic Composition	ISO
Other Miscellaneous Types of Measurements	MISC

Please note that experimental assemblies intended to represent a particular reactor type are assigned an RT identifier that is consistent with the desired reactor type.

A.2 ICSBEP Handbook

All evaluated critical and subcritical benchmark data are given in Volumes I through VII of the *ICSBEP Handbook*. Each of these volumes includes benchmark data representing one of seven different types of fissile-material systems. Volume VIII contains benchmark data from radiation-transport measurements that can be used to validate criticality-safety-related shielding or alarm-placement methodologies. Volume IX contains various types of fundamental physics measurements that are relevant to criticality safety applications. The titles of the nine volumes are as follows:

- Volume I: Plutonium Systems (PU)
- Volume II: Highly Enriched Uranium Systems (HEU)
- Volume III: Intermediate and Mixed Enrichment (IEU)
- Volume IV: Low-Enriched, Natural, or Depleted (LEU)
- Volume V: Uranium-233 Systems (U233)
- Volume VI: Mixed Plutonium-Uranium Systems (MIX)
- Volume VII: Special Isotope Systems (SPEC)
- Volume VIII: Criticality Alarm/Shielding Benchmarks
- Volume IX: Fundamental Physics Measurements.

Each of the first seven volumes is divided into four major sections, representing the physical form of the fissile material:

- Metal Systems
- Compound Systems
- Solution Systems
- Miscellaneous Systems.

Each of these four types of systems is subdivided into fast, intermediate, thermal, and mixed spectra systems, depending upon the neutron energy range where the majority of the fissions occur. In general, fast, intermediate, and mixed subdivisions are not applicable to solution systems; however, for certain solution systems (e.g., some heavy-water-moderated systems or highly concentrated solutions), the majority of the fissions occur above the thermal range.

In the *ICSBEP Handbook*, fast, intermediate, and thermal systems are defined as systems in which more than 50% of the fissions occur at energies greater than 100 keV, from 0.625 eV to 100 keV, and less than 0.625eV, respectively. Systems for which more than 50% of the fissions do not occur in any one of these three energy ranges are classified as "mixed" spectra systems.

Some experiment series contain data that can be categorized by more than one energy range. In these special cases, the data are assigned where they appear to fit best, with cross references from other applicable categories. Therefore, experimental data are presented only once.

Each ICSBEP experiment has a unique identifier that consists of the type of Fissile Material (FM), the Physical Form (PF) of the material, the Spectrum (SP), and a three-digit Numerical Identifier (NID). The identifier takes the following form:

(FM)-(PF)-(SP)-(NID).

Identifier elements and their meanings for critical and subcritical systems are given below. Criticality Alarm/Shielding Benchmarks (Volume VIII) and Fundamental Physics Measurements (Volume IX) have other identifier schemes that are not discussed in this paper.

Fissile Material

Plutonium	PU
Highly Enriched Uranium	HEU
Intermediate-Enriched Uranium	IEU
Low-Enriched Uranium	LEU
Uranium-233	U233
Mixed Plutonium - Uranium	MIX
Special Isotope	SPEC

Physical Form

Metal	MET
Compound	COMP
Solution	SOL
Miscellaneous	MISC

Spectrum	
Fast	FAST
Intermediate-Energy	INTER
Thermal	THERM
Mixed	MIXED

Appendix B. Contents of NEA Archives

Data under the following archival identifiers are available at the NEA.

- IRPHE/B&W-SS-LATTICE, Spectral Shift Reactor Lattice Experiments
- IRPHE/ZEBRA, AEEW Fast Reactor Experiments
- IRPHE/JOYO MK-II, Core Management and Characteristics Database
- IRPHE/JAPAN, Reactor Physics Experiments carried out in Japan
- IRPhE/HTR-ARCH-01, Archive of HTR Primary Documents
- IRPHE-SNEAK, KFK SNEAK Fast Reactor Experiments
- IRPhE/STEK, Experiments from Fast-Thermal Coupled Facility
- IRPhE-DRAGON-DPR, OECD High-Temperature Reactor Dragon Project
- IRPhE/RRR-SEG, Experiments from Fast-Thermal Coupled Facility
- Experiments in VENUS – Project on the Physics of Plutonium Recycling
- IRPHE/AVR, AVR – Experimental High Temperature Reactor
- IRPHE-KNK-II-ARCHIVE, KNK-II fast reactor documents, power history, and measured parameters
- IRPHE/BERENICE, effective delayed neutron fraction measurements
- IRPHE-TAPIRO-ARCHIVE, TAPIRO fast-neutron source reactor experiments.

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International Handbook of Evaluated Criticality Safety Benchmark Experiments (ICSBEP Handbook), NEA/NSC/DOC(95)03/I-IX, Organization for Economic Co-operation and Development-Nuclear Energy Agency (OECD-NEA), September 2008 Edition.

International Handbook of Evaluated Reactor Physics Benchmark Experiments (*IRPhEP Handbook)*, NEA/NSC/DOC(2006)1, Organization for Economic Co-operation and Development-Nuclear Energy Agency (OECD-NEA), March 2008 Edition.