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Growth and Expansion of the International Criticality Safety Benchmark Evaluation Project and the Newly Organized International Reactor Physics Experiment Evaluation Project

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GROWTH AND EXPANSION OF THE INTERNATIONAL CRITICALITY SAFETY BENCHMARK EVALUATION PROJECT AND THE NEWLY ORGANIZED INTERNATIONAL REACTOR PHYSICS EXPERIMENT EVALUATION PROJECT

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1.0 Introduction

Since ICNC 2003, the International Criticality Safety Benchmark Evaluation Project (ICSBEP) has continued to expand its efforts and broaden its scope. Criticality-alarm / shielding type benchmarks and fundamental physics measurements relevant to criticality safety applications are not only included in the scope of the project, but benchmark data are also available in the latest version of the *International Handbook of Evaluated Criticality Safety Benchmark Experiments* (ICSBEP Handbook) [1]. A considerable number of improvements have been made to the searchable database, DICE, and the criticality-alarm / shielding benchmarks and fundamental physics measurements are included. Twelve countries participated in the ICSBEP in 2003. That number has increased to 18 with recent contributions of data and/or resources from Brazil, Czech Republic, Poland, India, Canada, and China. South Africa, Germany, Argentina, Australia, and Sweden have also been invited to participate.

Since ICNC 2003, the number of evaluations included in the ICSBEP Handbook have increased from 350 (28,000 pages) containing benchmark specifications for 3,070 critical or subcritical configurations to 442 (over 38,000 pages) containing benchmark specifications for 3,955 critical or subcritical configurations, 23 criticality-alarm-placement / shielding configurations with multiple dose points for each, and 20 configurations categorized as fundamental physics measurements that are relevant to criticality safety applications in the 2006 Edition of the ICSBEP Handbook. Approximately 30 new evaluations and 250 additional configurations are expected to be added to the 2007 Edition of the ICSBEP Handbook.

Since ICNC 2003, a reactor physics counterpart to the ICSBEP, the International Reactor Physics Experiment Evaluation Project (IRPhEP) was initiated. Beginning in 1999, the IRPhEP was conducted as a pilot activity by the Organization of Economic Cooperation and Development (OECD) Nuclear Energy Agency (NEA) Nuclear Science Committee (NSC). The project was endorsed as an official activity of the NSC in June of 2003. The IRPhEP is patterned after the ICSBEP, but focuses on other integral measurements, such as buckling, spectral characteristics, reactivity effects, reactivity coefficients, kinetics measurements, reaction-rate and power distributions, nuclide compositions, and other miscellaneous-type measurements in addition to the critical configuration. The two projects are closely coordinated to avoid duplication of effort and to leverage limited resources to achieve a common goal.

The purpose of the IRPhEP is to provide an extensively peer-reviewed set of reactor physics-related integral benchmark data that can be used by reactor designers and safety analysts to validate the analytical tools used to design next generation reactors and establish the safety basis for operation of these reactors. While coordination and administration of the IRPhEP takes place at an international level, each participating country is responsible for the administration, technical direction, and priorities of the project within their respective countries.

The work of the IRPhEP is documented in an OECD NEA Handbook entitled, *International Handbook of Evaluated Reactor Physics Benchmark Experiments* (IRPhEP Handbook) [2]. The second edition of the IRPhEP Handbook, the March 2007 Edition, spans nearly 5,000 pages and contains data from 21 experimental series performed at 13 reactor facilities. Also included are evaluated data from five liquid metal fast reactors (JOYO, BFS-1, BFS-2, ZPPR, and ZEBRA), one gas-cooled reactor (HTR-10), one heavy water reactor (DCA), three light water reactors (DIMPLE, CROCUS, and IPEN MB-01), one pressurized water reactor (VENUS), and 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.

Seventeen of the 21 evaluations are published as approved benchmarks. The remaining four evaluations are published as DRAFT documents only. Completion of the DRAFT evaluations is planned for the 2008 Edition.

2.0 The 2006 ICSBEP and 2007 IRPhEP Handbooks

ICSBEP Handbook – The 2006 Edition of the *International Handbook of Evaluated Criticality Safety Benchmark Experiments* (ICSBEP Handbook) [1] was published in September of 2006 (Fig. 1). The ICSBEP Handbook is available on DVD or 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>.

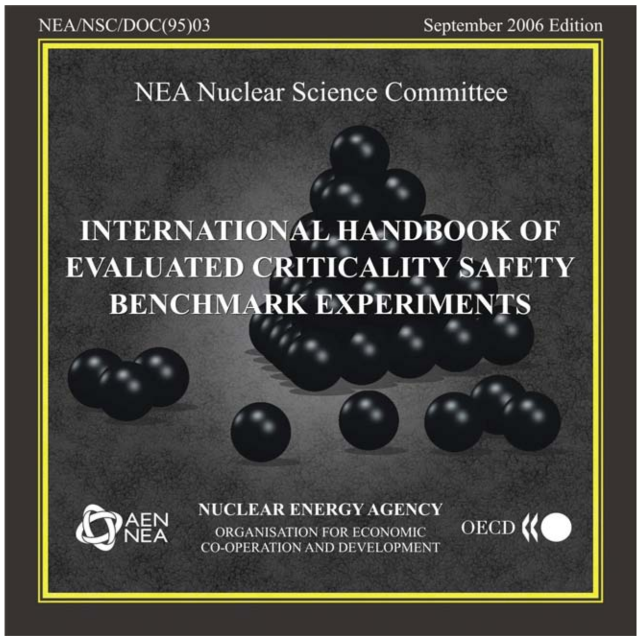

Figure 1. September 2006 Edition of the ICSBEP Handbook

The 2006 Edition of the ICSBEP Handbook includes benchmark specifications for the following:

- 658 plutonium experiments, of which 94 are Metal (87 Fast, 4 Intermediate, 2 Thermal, and 1 Mixed), 529 Solution (Thermal), and 35 Compound (6 Fast, 1 Intermediate, 21 Thermal, and 7 Mixed);
- 1,233 high enrichment uranium experiments, of which 477 are Metal (304 Fast, 14 Intermediate, 127 Thermal, and 32 Mixed), 466 Solution (3 Intermediate and 463 Thermal), 283 Compound (8 Fast, 14 Intermediate, 216 Thermal, and 45 Mixed), 5 mixed Metal / Solution (Thermal), and 2 Compound / Solution (Thermal);
- 85 intermediate and mixed enrichment uranium experiments, of which 20 are Metal (Fast), 5 Solution (Thermal), and 60 Compound (2 Fast, 14 Intermediate, 41 Thermal, and 3 Mixed)
- 1,246 low enrichment uranium experiments, of which 65 are Metal (Thermal), 104 Solution (Thermal), 1066 Compound (Thermal), and 11 Mixed Compound / Solution (Thermal)
- 245 ^{233}U experiments, of which 11 are Metal (10 Fast, 1 Thermal), 229 Solution (192 Thermal, 29 Intermediate, and 8 Mixed), and 5 Compound (Thermal)
- 468 mixed plutonium-uranium experiments, of which 48 are Metal (45 Fast, 2 Intermediate, and 1 Mixed), 72 Solution (Thermal), and 276 Compound (1 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];

- Three criticality-alarm / shielding benchmarks containing 21 configurations with numerous dose points;
- One fundamental physics benchmark, which includes 20 fission rate measurements.

IRPhEP Handbook – The 2007 Edition of the *International Handbook of Evaluated Reactor Physics Benchmark Experiments* (IRPhEP Handbook) [2] was published in March of 2007 (Fig. 2). The IRPhEP Handbook is currently available only on DVD. The DVD version of the IRPhEP Handbook can be requested from the IRPhEP Internet site at <http://nuclear.inel.gov/irphep/>.

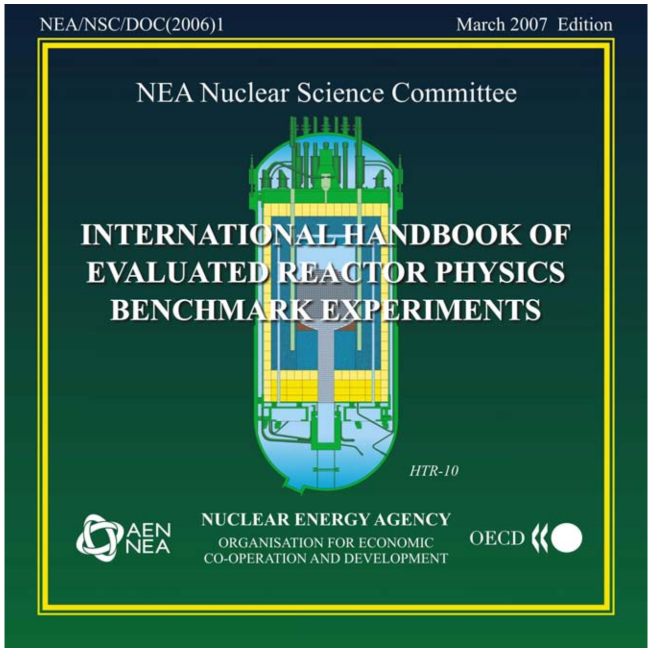

Figure 2. March 2007 Edition of the IRPhEP Handbook.

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

- Two VVER Reactors PFacility-VVER-EXP-001 contains benchmark specifications for criticality, but the data provided for the reaction rates have not yet been evaluated. ZPR6-VVER-EXP-001 contains benchmark specifications for criticality, buckling measurements, spectral characteristics, reactivity effects, reactivity coefficients, and reaction-rate distributions.
- Four Liquid Metal Fast Reactors BFS1-LMFR-EXP-001 contains benchmark specifications for criticality, spectral characteristics, reactivity coefficients, kinetics measurements, and reaction-rate distributions. BFS2-LMFR-EXP-001 contains benchmark specifications for criticality, spectral characteristics, reactivity effects, and reaction-rate distributions. JOYO-LMFR-RESR-001 contains benchmark specifications for criticality, reactivity effects, and reactivity coefficients. ZEBRA-LMFR-EXP-001 contains benchmark specifications for criticality, spectral characteristics, and reactivity effects. Data are provided for reaction-rate distributions, but those data have not been fully evaluated.
- One Gas-Cooled Reactor HTR10-GCR-RESR-001 contains benchmark specifications for criticality, but the data provided for reactivity effects have not been evaluated.
- Four Light Water Reactors DIMPLE-LWR-EXP-001 contains benchmark specifications for criticality, buckling, spectral characteristics, and reaction rate distributions, but data provided for reactivity effects measurements were evaluated and determined to be unacceptable for use as benchmark data. Data provided for reactivity coefficients were evaluated and determined to be of benchmark quality but have not been developed into

benchmark specifications. DIMPLE-LWR-EXP-002 also contains 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 contains benchmark specifications for criticality and kinetics measurements. IPEN(MB01)-LWR-RESR-001 contains benchmark specifications for criticality and reactivity coefficient measurements.

- <u>One Heavy Water Moderated Reactor</u> DCA-HWR-EXP-001 contains benchmark specifications for criticality, spectral characteristics, and reaction rate distributions.
- <u>Three Fundamental Physics Assemblies</u> BFS1-FUND-EXP-001 contains benchmark specifications for criticality, spectral characteristics, and reaction rate distribution measurements, but reactivity effects and kinetics measurements have not yet been fully evaluated. BFS1-FUND-EXP-002 contains 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. BFS2-FUND-EXP-001 contains 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.

Draft data are available for two pressurized water reactors (VENUS 1 and 2), three liquid metal fast reactors (two ZEBRA Mozart Evaluations and ZPPR-10A), and one fundamental physics assembly (BFS-1).

3.0 New Types of Benchmarks Available in the ICSBEP and IRPhEP Handbooks

The first criticality alarm and shielding benchmarks were published in 2005, and fundamental physics measurements were introduced in 2006. Examples of these types of ICSBEP benchmarks are highlighted in Figures 3 through 5.

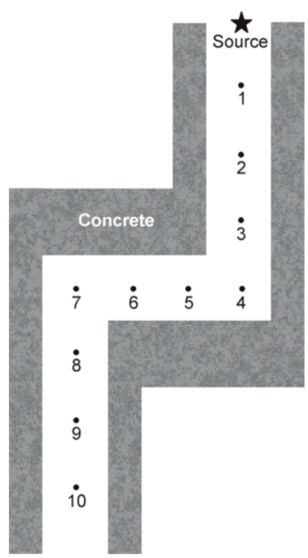

Figure 3. ICSBEP Volume VIII: ALARM-CF-AIR-LAB-001, NEUTRON Fields in Three-Section Concrete Labyrinth from Cf-252 Source, *Mark Nikolaev, Natalia Prokhorova, and Tatiana Ivanova* **[1]** *(Institute of Physics and Power Engineering – Russian Federation)*.

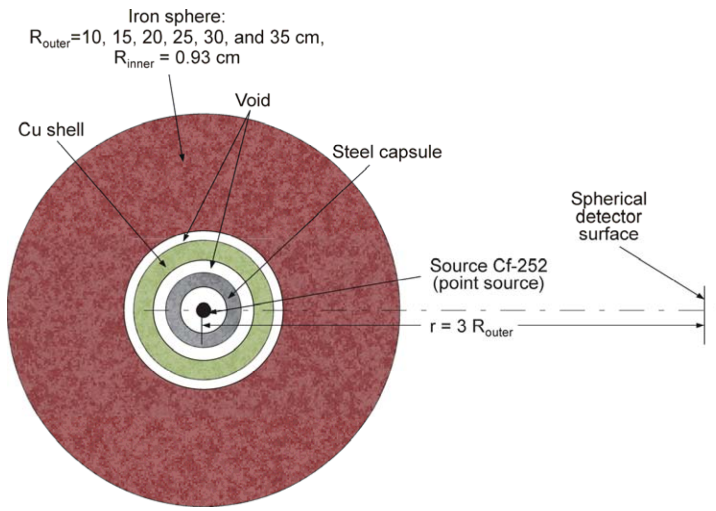

Figure 4. ICSBEP Volume VIII: ALARM-CF-FE-SHIELD-001, Neutron and Photon Leakage Spectra from Cf-252 Source at Centers of Six Iron Spheres of Different Diameters, *Gennady Manturov, Yevgeniy Rozhikhin, and Lev Trykov* **[1]** *(Institute of Physics and Power Engineering – Russian Federation)*.

Figure 5. ICSBEP Volume IX: FUND-NIST-CF-MULT-FISS-001, NIST Sphere Experiments for ^{235}U, ^{239}Pu, ^{238}U, and ^{237}Np Fission Rates, *Soon Sam Kim and Robert W. Schaefer* **[1]** *(Idaho National Laboratory – United States of America)*.

Several types of IRPhEP-evaluated measurement data are also relevant to criticality safety applications. These data are classified by reactor type or as fundamental physics assemblies with several possible types of measurements. Examples of IRPhEP Benchmarks are given in Figures 6 and 7.

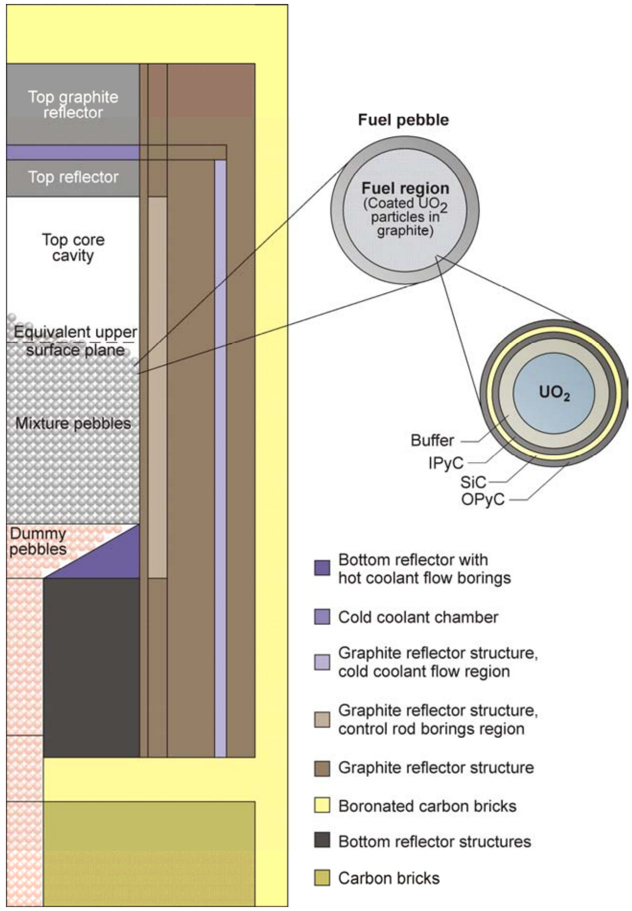

Figure 6. IRPhEP GCR: HTR10-GCR-RESR-001, Evaluation of the Initial Critical Configuration of the HTR-10 Pebble-Bed Reactor, *William K Terry et. al.,* **[1, 2]** *(Idaho National Laboratory – United States of America) and Yuliang Sun (Institute of Nuclear and New Energy Technology – China)*.

Model of Central Cell for Spectral Characteristics Benchmark Specifications

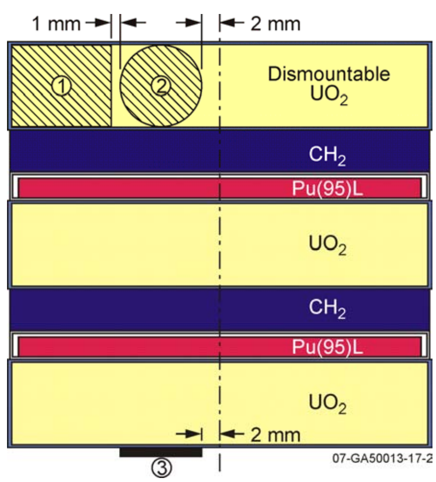

Figure 7. IRPhEP FUND: BFS1-FUND-EXP-001, BFS-97, -99, -101 Assemblies: Experimental Program on Critical Assemblies with Heterogeneous Compositions of Plutonium, Depleted-Uranium Dioxide, and Polyethylene, *Anatoly Kochetkov et. al.,* **[2]** *(Institute of Physics and Power Engineering – Russian Federation)*.

The three-bend labyrinth benchmark shown in Figure 3 is just one of 11 such benchmark configurations. Six cases have an unshielded californium source with various types of shielding/absorbing material fastened to selected walls or various obstructions positioned in the labyrinth. Five similar cases have a polyethylene shield around the californium source.

Figure 4 shows one of six configurations in which a californium source is surrounded by various thicknesses of iron. Three similar configurations are available using various thicknesses of lead shielding. An unshielded reference configuration is also available.

Figure 5 shows one of 20 configurations in which a ^{252}Cf source is positioned inside a spherical region that is either void (dry) or filled with water (wet). Fission rates for ^{235}U, ^{238}U, ^{239}Pu, and ^{237}Np are measured just outside the spherical region. Measurements were made on three different sized spherical regions (3-, 4-, and 5-inch-diameter).

The benchmark depicted in Figure 6 is an IRPhEP benchmark of the Chinese HTR-10 pebble bed research reactor. This benchmark is of particular interest to the criticality safety community because of the double heterogeneity in the core and because there are no control rods. The benchmark is very much like a large tank containing pebble bed fuel that might be encountered in fuel fabrication facilities and transportation or storage applications. Similar pebble bed ASTRA data will be provided in the 2007 Edition of the ICSBEP Handbook, but the configurations included in that series of experiments include control rods just outside the core.

Finally, Figure 7 shows a model of the central cell for spectral characteristics benchmark measurements performed on the BFS-1 experimental reactor assembly. BFS-1 is a fast-reactor assembly; however, it is a very flexible assembly that can easily be reconfigured to represent numerous other types of reactor designs. The configuration depicted in Figure 7 is one of several configurations of heterogeneous plutonium, depleted-uranium dioxide, and polyethylene that were assembled in order to represent damp MOX powders. For this reason these assemblies have been categorized as Fundamental Physics Assemblies. The following spectral ratios were measured:

$\sigma_f^{U\text{-}238}/\sigma_f^{U\text{-}235}$
$\sigma_f^{Pu\text{-}239}/\sigma_f^{U\text{-}235}$
$\sigma_f^{Np\text{-}237}/\sigma_f^{Pu\text{-}239}$
$\sigma_f^{Pu\text{-}240}/\sigma_f^{Pu\text{-}239}$
$\sigma_f^{Am\text{-}241}/\sigma_f^{Pu\text{-}239}$
$\sigma_f^{Am\text{-}243}/\sigma_f^{Pu\text{-}239}$
$\sigma_f^{Cm\text{-}244}/\sigma_f^{Pu\text{-}239}$
$\sigma_f^{Cm\text{-}245}/\sigma_f^{Pu\text{-}239}$

4.0 Future Work

There are four general types of experimental measurements that have relevance to criticality safety: (1) measurement of critical assemblies, (2) measurement of subcritical assemblies, (3) criticality alarm and shielding measurements, and (4) fundamental physics measurements, such as integral measurements of neutron leakage, scattering, and absorption (e.g., National Institute of Standards and Technology [NIST] iron and water spheres or Lawrence Livermore National Laboratory [LLNL] pulsed sphere measurements). The ICSBEP has focused primarily on critical and subcritical assemblies of fissile material. The future focus of the ICSBEP includes evaluation of all four types of experiments. The ICSBEP expects to publish approximately 30 new evaluations (200 to 300 Configurations) each year. The 2007 Edition of the ICSBEP Handbook will include benchmark data for additional NIST Sphere measurements (Fig. 5) with cadmium on the outside of the spheres, Baikal-1 Skyshine measurements, neutron transmission measurements through ^{235}U, ^{238}U, ^{239}Pu, Fe, Cr, and Ni, and critical / subcritical measurements from numerous fissile material systems. Annual publication of the ICSBEP Handbook is scheduled for September.

The IRPhEP expects to add approximately seven new evaluations to the IRPhEP Handbook each year. Annual publication of the IRPhEP Handbook is scheduled for March.

Both the ICSBEP and the IRPhEP continue to encourage users to develop their own computer input directly from the benchmark specifications. Direct use of computer input files without proper checking is strongly discouraged.

Conclusions

The ICSBEP continues to provide high quality criticality safety-related benchmark data from around the world, and the project continues to grow. Eighteen countries have contributed in the past or are currently contributing to the project, and five additional countries have been invited to contribute. Approximately 500 copies of the ICSBEP Handbook are distributed annually. The project has expanded to include criticality alarm/shielding benchmarks and fundamental physics measurements.

Although the IRPhEP is a relatively new project, over 300 copies of the first edition of the IRPhEP Handbook have been distributed and the second edition is now available. Eleven countries have directly contributed to this project. 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. Benchmarks that support the Next Generation Nuclear Plant (NGNP), for example, also support fuel manufacture, handling, transportation, and storage activities and could challenge current analytical methods.

Criticality alarm/shielding benchmarks and fundamental physics measurements provided by the ICSBEP and benchmarks produced by the IRPhEP add new dimension to criticality safety benchmarking efforts and expand the collection of available integral benchmarks for nuclear data testing.

Acknowledgements

The ICSBEP and IRPhEP are collaborative efforts that involve numerous scientists, engineers and administrative support personnel from 20 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. The authors would especially like to acknowledge the evaluators and reviewers of the benchmark data that were recently published in the 2006 Edition of the ICSBEP Handbook and the 2007 Edition of the IRPhEP Handbook, which are highlighted in this paper.

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1. *International Handbook of Evaluated Criticality Safety Benchmark Experiments*, NEA/NSC/DOC(95)03/I-IX, Organization for Economic Co-operation and Development - Nuclear Energy Agency (OECD-NEA), September 2006 Edition.

2. *International Handbook of Evaluated Reactor Physics Benchmark Experiments*, NEA/NSC/DOC(2006)1, Organization for Economic Co-operation and Development - Nuclear Energy Agency (OECD-NEA), March 2007 Edition.