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Overview of Experiments for Physics of Fast Reactors from the International Handbooks of Evaluated Criticality Safety Benchmark Experiments and Evaluated Reactor Physics Benchmark Experiments

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Abstract. Specialists involved in the process of validation and verification of codes and cross sections for the physics of fast reactors traditionally used the benchmarks presented in the “Cross Section Evaluation Working Group Benchmark Specifications” BNL-19302 (ENDF-202) handbook first issued in 1974 and last updated in 1991. This handbook presents simplified homogeneous models of experiments with appropriate corrections of the experimental data. This approach was relevant to the codes and computational possibilities existed during the design of the first generations of fast reactors.

The Nuclear Energy Agency (NEA) of the Organisation for Economic Cooperation and Development (OECD) coordinates the activities of two international projects on the collection, evaluation and documentation of experimental data - the International Criticality Safety Benchmark Evaluation Project (ICSBEP) (since 1995) and the International Reactor Physics Experiment Evaluation Project (IRPhEP) (since 2003). The result of the activities of these projects are, every year updated, the International Handbooks of critical (ICSBEP Handbook) and reactor physics (IRPhEP Handbook) benchmark experiments. The handbooks present detailed models of experiments with minimal corrections and comprehensive analysis of their uncertainties. Such models are of particular interest in terms of implementation of possibilities of the modern calculational codes and systems of automated prediction of the uncertainties of the design parameters and margins.

The handbooks contain a large number of experiments that are suitable for the study of physics of fast reactors. Many of these experiments were performed at specialized critical facilities, such as BFS (Russia), ZPR and ZPPR (USA), ZEBRA (UK), or the experimental reactors, JOYO (Japan) and FFTF (USA). Other experiments, such as compact metal assemblies, are also of interest in terms of the physics of fast reactors, were performed at the multipurpose critical facilities in Russia (VNIITF and VNIIEF) and the US (LANL, LLNL, and others.).

This paper provides an overview of various key experiments and includes the results of calculations with modern cross sections in comparison with the evaluated benchmark data.

Key Words: Benchmark, Fast Reactor, Handbooks, Reactor Physics.

1. Introduction

Verification is a constant support necessary for validation of calculational methods and computational data for fast reactors, and is always carried out on the basis of experiments in critical assemblies [1]. Several countries have performed extensive studies regarding the development of established fast reactor critical test stands. A summary of the better-known test stands is as follows:

- France
  - MASURCA
- Germany
  - SNEAK
- Japan
  - Fast Critical Assembly (FCA)
- Russian Federation
  - BFS
- United Kingdom
  - ZEBRA
- United States of America
  - Zero Power Reactor (ZPR)
  - Zero Power Physics Reactor (ZPPR)

Many of the experiments performed on these critical test stands were assessed by specialized experts and then offered as benchmarks. The benchmarks are then available for testing models of national nuclear data and calculation tools supporting the development of a variety of design solutions. The first most comprehensive and accessible information on the estimated criticality had been compiled as the BNL-19302 (ENDF-202) "Cross Section Evaluation Working Group Benchmark Specifications" (CSEWG) Handbook [2] and an article in the Nuclear Science and Engineering [3], both published in 1974 and 1975, respectively. A summary of the benchmark models available from both works is further discussed below. This benchmark information was used to verify the national libraries of nuclear data (ENDF/B, ABBN, etc.) together with other experimental data available up until the year 1994. This handbook presents simplified homogeneous models of experiments with appropriate corrections of the experimental data, which was a relevant approach to the codes and computational possibilities existing during the design of the first generations of fast reactors.

In 1994, via the Organisation for Economic Co-operation and Development Nuclear Energy Agency (OECD NEA), the International Criticality Safety Benchmark Evaluation Project (ICSBEP) was formed as a result of the common criticality safety efforts of various cooperating countries [4] and the first *International Handbook of Evaluated Criticality Safety Benchmark Experiments* (ICSBEP Handbook) was prepared [5]. In recent years, professionals associated with maintaining constancy and validation of the computational software for reactor facilities and of various aspects of the fuel cycle began to use evaluated data from the ICSBEP Handbook as benchmark experiments. In the 2016 edition of this handbook, the collection of criticality safety benchmark experiments contained in the ICSBEP Handbook is summarized below:

- Data from 22 contributing countries
- ~69,000 pages
- 570 evaluations containing a total of 4,913 critical, near-critical, or subcritical configurations
- 7 evaluations containing a total of 45 criticality-alarm-placement/shielding configurations
- 8 evaluations containing a total of 215 fundamental physics measurements pertaining to criticality safety
- 829 unacceptable experiment configurations

The ICSBEP handbook presents detailed models of experiments with minimal corrections and comprehensive evaluation of their uncertainties. Such models are of particular interest in terms of implementation of possibilities of the modern calculational codes and systems of automated prediction of the uncertainties of the design parameters and margins.

2. Primary Nuclear Fuel Materials

Verification of the constants describing the main reactor fissile nuclides in the hard energy component of the neutron spectrum used spherical metal assemblies with highly enriched uranium (GODIVA, FLATTOP-25) and plutonium (JEZEBEL, FLATTOP-Pu). Assemblies are designed as either a bare system or a system comprised with the metal sphere surrounded by a depleted uranium metal reflector. TABLE I summarizes the characteristics of compact critical assemblies of metallic fuel without diluents and a hard neutron spectrum, for which there are an estimated benchmark model in [2] and [5].

TABLE I: Compact Metal Fast-Neutron Benchmark Characteristics.

Experiment Name	**Benchmark Identification**		**Fuel**	**Configuration**
	CSWEG [2]	**ICSBEP [5]**		
GODIVA	FR-05	HMF-003	U (92 % ^{235}U/U)	Bare Sphere
FLATTOP-25	FR-22	HMF-028	U (98 % ^{235}U/U)	Sphere with U Reflector
JEZEBEL	FR-01	PMF-001	Pu	Bare Sphere
FLATTOP-Pu	FR-23	PMF-006	Pu	Sphere with U Reflector
BIG TEN	FR-20	IMF-007	U (10 % ^{235}U/U)	Cylinder with U Reflector
SCHERZO 556	[6,7]	MMF-008	U (5.56 % ^{235}U/U)	k_∞

FIGURE 1 shows the results of calculations comparing the C/E-1 (%) values for the critical assemblies listed in TABLE I, where C represents the calculated eigenvalue and E represents the recorded benchmark experiment eigenvalue. Calculations of these criticality benchmark models were conducted using Monte Carlo N-Particle (MCNP) version 6.1 [8]. The upper part of FIG. 1 presents the C/E-1 values computed with ENDF/B-VII.1 nuclear data libraries (the designation E-71 below is also used) for models from the ICSBEP Handbook [5] and ENDF-202 CSEWG [2]. The comparison in FIG. 1 shows that the experimental differences are consistent with each other within 2**σ**. The lower part of FIG. 1 shows the C/E-1 values obtained via calculations performed using different nuclear data libraries: E-71, JEFF-3.2 (JF32), RUSFOND-2010 (RF10). FIGURE 1 also shows the values of C/E-1 obtained using the MMK-KENO Monte-Carlo criticality code group using the ABBN-93 nuclear data library only as a comparison.

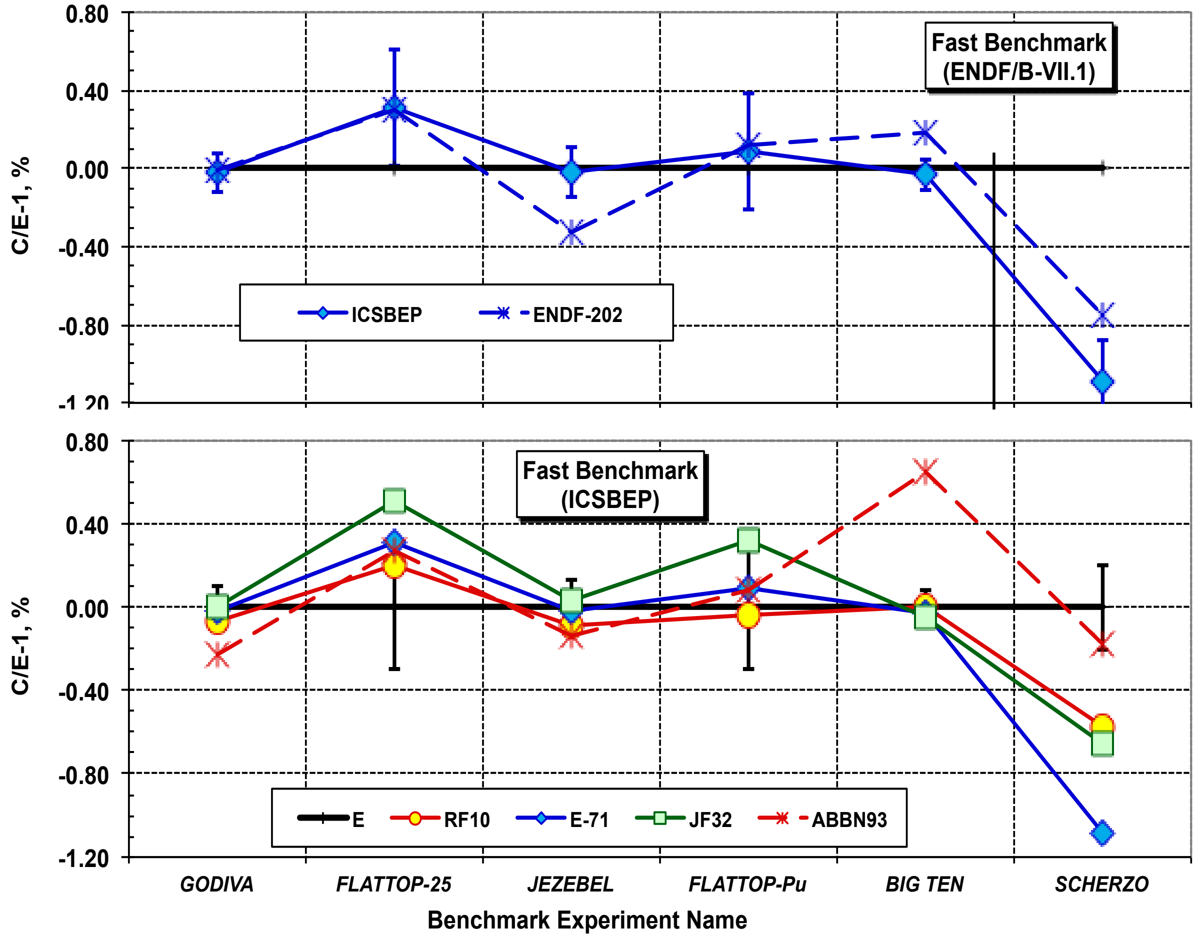

FIG. 1. Comparison of Computational and Experimental Differences for Rigid Assemblies.

The above comparison in FIG. 1 shows that the calculations are generally in good agreement with the estimated values, except for the SCHERZO 556 assembly. It should be noted, however, that the sharing of the evaluation of k_∞ and the ratio f8/f5 for SCHERZO 556 allowed for the accurate evaluation of one of the most important characteristics of a critical assembly – removal cross sections under the fission threshold of ^{238}U with inelastic scattering. The results of this assessment are provided in more detail elsewhere [9].

3. Critical Assemblies Related to Fast Reactors

The subsequent step in the verification and validation of nuclear data and computational software supporting fast reactors used more sophisticated critical model with design characteristics more similar to the actual reactor plants. Some such benchmarks were initially presented in CSEWG [2] and the ICSBEP Handbook [5], with additional complex assemblies evaluated in the newer *International Handbook for Evaluated Reactor Physics Benchmark*

Experiments (IRPhEP Handbook) [10]. The International Reactor Physics Experiment Evaluation Project (IRPhEP) was established in 2003 to preserve integral reactor physics experimental data, including separate or special effects data for nuclear energy and technology applications [11]. The 2016 edition of the IRPhEP Handbook contains the following contributions:

- Data from 21 contributing countries
- 151 experimental series
  - 147 approved evaluations
  - 4 draft evaluations
- 50 unique reactor facilities

The list of critical assemblies, for which there are an estimated benchmark model in [2] and an evaluated benchmark model in [5 or 10] is provided in TABLE II. TABLE II, along with the name of the assembly, includes such characteristics as fuel, the volume of the core, the ratio of ^{238}U nuclei among the nuclear fuel, and quantity of nuclear fissile materials or other constituents, where available.

TABLE II: Fast Reactor Assembly Benchmark Characteristics.

Experiment Name	Benchmark Identification		Fuel	Volume, L	N_{U8}/N_{fis}	Material Fractions*
	CSWEG [2]	ICSBEP [5] or IRPhEP [10]				
ZPR-3/6F	FR-07	IMF-015	U	50	1.13	FM (32), Al (45), SST (23)
ZPR-3/53	[3]	MMI-004	Pu	198	1.57	FM (6), C (79), SST (15)
ZPR-3/54	[3]	MMI-003	Pu	227	1.57	FM (6), C (79), SST (15)
SNEAK-7A	FR-16	SNEAK-001	Pu	--	--	--
ZPR-3/12	FR-09	ICF-004	U	101	3.71	FM (38), C (48), SST (14)
ZPR-3/48	FR-03	MCF-003	Pu	391	4.36	FM (18), C (41), Na (12), SST (28)
ZPR-3/56B	FR-13	MCF-004	Pu	615	4.65	FM (15), C (2), O (30), Na (17), SST (36)
SNEAK-7B	FR-17	SNEAK-001	Pu	--	--	--
ZPR-3/11	FR-08	IMF-016	U	138	7.55	FM (83), SST (17)
ZPR-9/31	FR-18	MCF-005	U	1004	7.37	FM (24), C (23), Na (19), SST (33)
ZPR-6/6A	FR-15	ICI-005	U	3990	5.06	FM (14), O (29), Na (19), SST (37)
ZPR-6/7	FR-12	MCF-001	Pu	3120	6.55	FM (14), O (30), Na (19), SST (36)
ZPPR-2	FR-11	MCF-006	Pu	2406	5.08	FM (14), O (28), Na (20), SST (37)

*Al=Aluminum, C=Carbon, FM=Fissile Materials, Na=Sodium, O=Oxygen, & SST=Stainless Steel.

FIGURE 2 shows the results of calculations comparing the C/E-1 (%) values for criticality calculations of the fast reactor assemblies listed in TABLE. In the upper portion of this figure is presented the results for E-71 nuclear data and models from the ICSBEP Handbook [5], IRPhEP Handbook [10] and ENDF-202 CSEWG [2]. In the lower part of the FIG. 2 the ICSBEP/IRPhEP results are provided for different nuclear data systems: E-71, JF32 and RF10. FIGURE 2 also shows the values of C/E-1 obtained using the MMK-KENO Monte-Carlo criticality code group using the ABBN-93 nuclear data library only as a comparison.

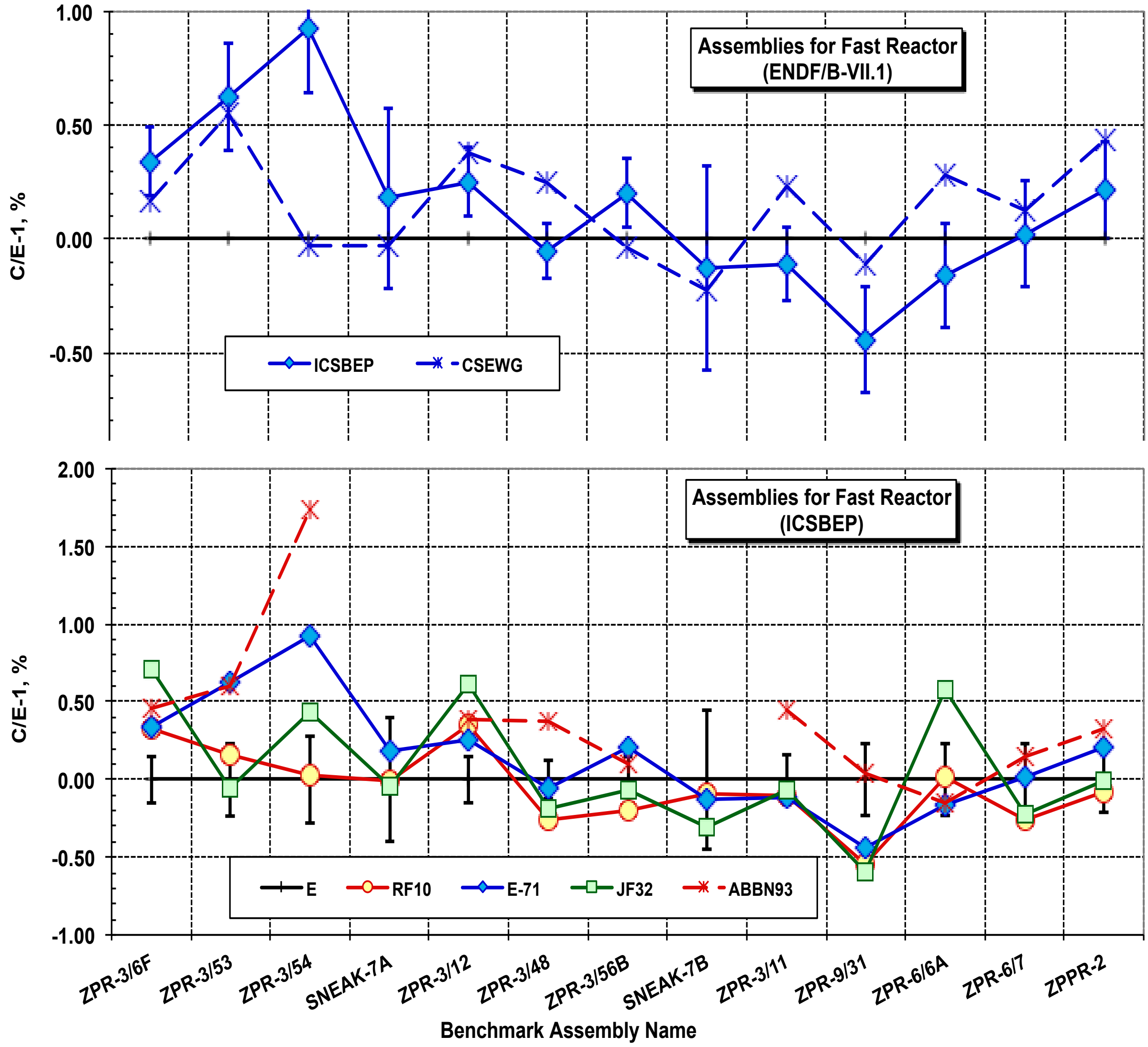

FIG. 2. Comparison of Computational and Experimental Differences for Fast Reactor Assemblies.

From the comparison shown in FIG. 2 depicts that the experimental differences are consistent with each other within 2σ except for the ZPR-3/54 assembly. In [3], the ZPR-3/54 model was incorrectly assessed with a correction for heterogeneity, which was taken to be the value of an amendment to the estimated model of assembly ZPR-3/53. These assemblies are of the same material in the core composition, but different reflector material. In the case of assembly ZPR-3/53, the reflector was uranium; to construct assembly ZPR-3/54, a steel reflector was used. A comparison of these two assemblies calculated differences allows for verification of the reflective properties of the steel.

Among the collection of benchmark models on the ICSBEP Handbook are those that simulate an infinite medium. There is a series of KBR assemblies constructed in Russia at the Institute of Physics and Power Engineering (IPPE), which studied the absorption characteristics of the structural materials of neutrons in steel components (Fe, Cr, Ni, Mn, and Mo) and Zr metal. A series of five benchmark models for these experiments [5] received the ICSBEP identification HCI-005 and have been evaluated previously in some detail [12].

FIGURE 3 shows a comparison of the C/E-1 (%) values computing using the following nuclear data libraries: E-71, JF32, JL40 (JENDL-4.0), and RF10. It can be seen that the value differences C/E-1 for chromium and zirconium assemblies reaches ~10 %. In [12] it is shown that there are new experimental, microscopic data for primarily for the reevaluation of the capture cross sections for chromium and zirconium isotopes. If the nuclear data information is revised and used in the RF10 (indicated in FIG. 3 as RF10+), then the value of computational and experimental discrepancies for this series of decreasing to within 1 %. FIGURE 3 also shows the values of C/E-1 obtained using the MMK-KENO Monte-Carlo criticality code group using the ABBN-93 nuclear data library only as a comparison. As can be seen from FIG. 3, with the use of benchmark models from the ICSBEP Handbook it is possible to increase both reliability and accuracy of nuclear data that are used in the design of the actual reactor plants.

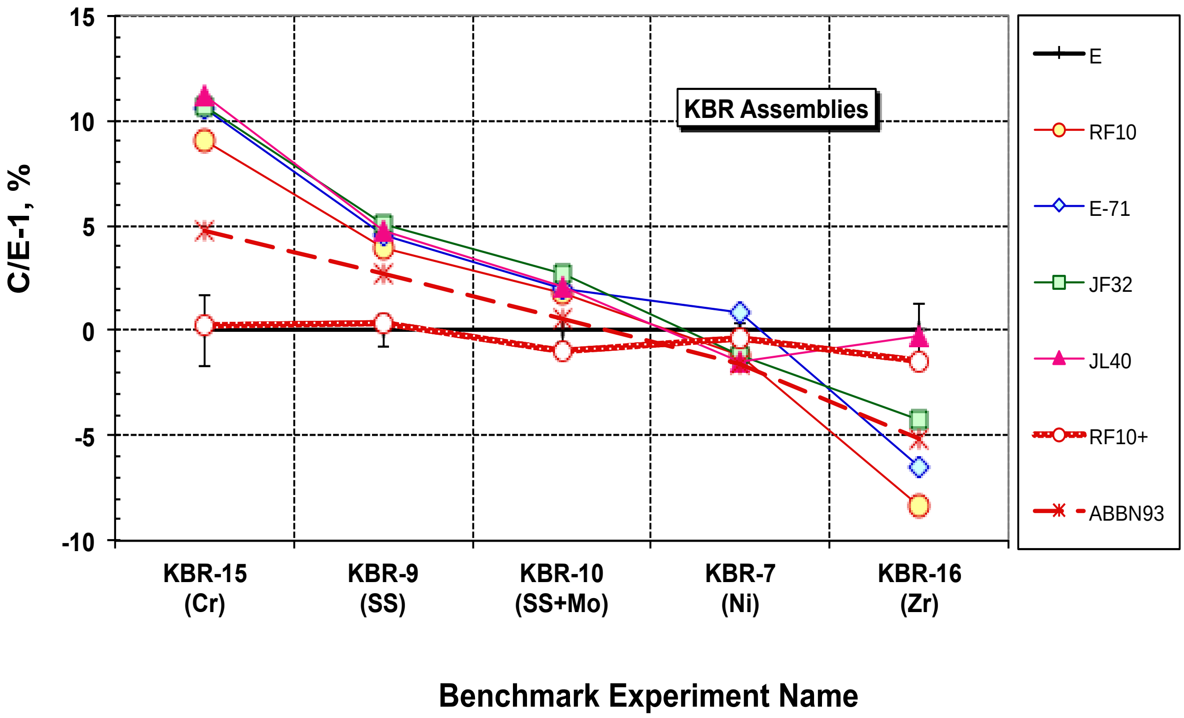

FIG. 3. Comparison of Computational and Experimental Differences for KBR (HCI005) Assemblies.

4. Additional Fast Reactor Content in the IRPhEP Handbook

The IRPhEP Handbook [10] contains a growing selection of fast reactor assembly benchmarks, as summarized in TABLE III for the 2016 edition of the handbook. Contributions to the liquid metal fast reactor section of this handbook include complex critical assemblies supporting physics measurements and fast reactor mockups. Benchmark evaluations of experimental test reactors currently include FFTF and JOYO. As listed in TABLE III, benchmark contributions include critical configuration specifications, as well as benchmark specifications for measurements of spectral characteristics, reactivity effects, reactivity coefficients, reaction-rate distributions, and other miscellaneous types of measurements. Extensive sample computations of the data found without these benchmark evaluations are too numerous to discuss in detail. Readers are encouraged to delve into individual benchmark reports to develop personalized validation suites appropriate for testing their fast reactor nuclear data, modeling, and simulation needs.

TABLE III: Fast Reactor Assembly Benchmark Characteristics [10].*

Facility	**Identifier**	**1**	**3**	**4**	**5**	**6**	**7**	**10**	**Key Features**
BR-2	BR2-001	+							Mercury Coolant
BFS-61	BFS1-002	+	+				+		Lead Coolant
BFS-73/1	BFS1-001	+	+		+	+	+		Metal Fuel
ZPR-3/48+48B	ZPR-003	+							Metal Fuel
ZPR-3/56B	ZPR-004	+							FFTF Design
ZPR-6/7	ZPR-001	+	+	+			+		Physics Measurements
ZPR-6/7	ZPR-002	+		+			+		Physics Measurements
BFS-62/3A	BFS2-001	+	+	+			+		BN-600
SNEAK-7A/-7B	SNEAK-001	+	+		+	+	+		Physics Measurements
ZEBRA-22~-25	ZEBRA-001	+	+	+					CADENZA
ZEBRA-11/-12	ZEBRA-002	+	+	+			+		MOZART-1
ZEBRA-12/4+5	ZEBRA-003			+			+		MOZART-2
ZPPR-2	ZPPR-011	+	+	+					500 MWe
ZPPR-12	ZPPR-010	+		+					400 MWe CRBR
ZPPR-9	ZPPR-002	+	+	+			+		650 MWe JUPITER
ZPPR-10A	ZPPR-001	+	+	+			+		650 MWe JUPITER
ZPPR-10B	ZPPR-005	+	+	+			+		650 MWe JUPITER
ZPPR-13A	ZPPR-007	+	+	+			+		650 MWe JUPITER
ZPPR-17A	ZPPR-009	+	+	+			+		650 MWe JUPITER
ZPPR-10C	ZPPR-006	+	+	+			+		800 MWe JUPITER
ZPPR-18A	ZPPR-003	+	+	+			+		1,000 MWe JUPITER
ZPPR-18C	ZPPR-008	+	+				+		1,000 MWe JUPITER
ZPPR-19B	ZPPR-004	+	+	+			+		1,000 MWe JUPITER
JOYO	JOYO-001	+		+	+				JOYO MK-I
FFTF	FFTF-001	+	+	+	+			+	LMFBR

*Benchmark Specifications Available for the Following Measurements:
1=Criticality, 3=Spectral Characteristics, 4=Reactivity Effects, 5=Reactivity Coefficients, 7=Reaction-Rate Distributions, and 10=Miscellaneous

Current contributions to the IRPhEP Handbook represent only a fraction of the international contingent of critical experiments, test reactors, and power reactors. For example, of the ZPR/ZPPR series of critical assemblies, there were a total of 63 assemblies for ZPR-3, nine for ZPR-6, 35 for ZPR-9, and 21 for ZPPR [13]. Many of these unique assemblies included various different loadings and measurements. Similarly, over 100 unique assemblies have been created for the BFS assemblies [14]. Efforts to fund the continued evaluation of these legacy data serve to preserve the historic experimental measurements utilized in fast reactor design.

Further evaluation of measurements from international prototype, test, research, and power reactors such as EBR-II, Phenix, Superphenix, CEFR, and the BN series would represent the next stage in advanced computational methods and nuclear data validation. Efforts to coordinate simulation of neutronics, thermalhydraulics, and materials effects into a single multiphysics platform will require more comprehensive benchmark development, enabling future verification and validation of next generation fast reactor systems.

5. Conclusions

The availability of benchmarks to support the validation and verification of codes and cross sections supporting the physics of fast reactors has evolved since the initial CSEWG compilation found in ENDF-202 containing simplified models of corrected experimental data. At that time, this approach was relevant to the computational capabilities that existed to support first generation fast reactors. Modern collection, evaluation, and documentation of experiment data in the ICSBEP Handbook and IRPhEP Handbook provide detailed benchmark models with minimal corrections and comprehensive uncertainty analysis. These modern resources serve to test modern calculational codes and systems supporting fast reactor design parameters, margins, and uncertainties. These handbooks contain a large number of internationally contributed data from rigid critical assemblies testing parameters defining fissile materials, complex assemblies providing physics testing and mockup reactor design, and measurements from experimental test reactors. Comparative results computed with modern cross sections for many key benchmark experiments have been provided and discussed in this paper.

6. Acknowledgments

The IRPhEP and ICSBEP represent collaborative efforts that involve numerous international scientists, engineers, and administrative support. The authors would like to acknowledge the efforts of all of those dedicated individuals without whom these projects would not be possible

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