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ADDITIONS TO THE ICSBEP AND IRPHEP HANDBOOKS SINCE NCSD 2009

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ABSTRACT

High-quality integral benchmark experiments have always been a priority for criticality safety. However, interest in integral benchmark data is increasing as efforts to quantify and reduce calculational uncertainties accelerate to meet the demands of future criticality safety needs to support next generation reactor and advanced fuel cycle concepts. The importance of drawing upon existing benchmark data is becoming more apparent because of dwindling availability of critical facilities worldwide and the high cost of performing new experiments. Integral benchmark data from the International Handbook of Evaluated Criticality Safety Benchmark Experiments and the International Handbook of Reactor Physics Benchmark Experiments are widely used. Significant Benchmark data have been added to those two handbooks since the last Nuclear Criticality Safety Division Topical Meeting in Richland, Washington (September 2009). This paper highlights those additions.

Key Words: Benchmark, Criticality Safety, ICSBEP, IRPhEP, Reactor Physics

1 INTRODUCTION

Since the last Nuclear Criticality Safety Division (NCSD) topical meeting in Richland, Washington (September 2009), the International Criticality Safety Benchmark Evaluation Project (ICSBEP) and the International Reactor Physics Evaluation Project (IRPhEP) have continued to provide quality integral benchmark data to the international criticality safety, nuclear data, and reactor physics communities. Integral benchmark data from the *International Handbook of Evaluated Criticality Safety Benchmark Experiments (ICSBEP) Handbook*[1] and the *International Handbook of Reactor Physics Benchmark Experiments (IRPhEP) Handbook*[2] are widely used and are among the most frequently referenced documents in the Nuclear Industry. Those two handbooks are published annually in September and March, respectively. Information concerning those handbooks and the associated projects that produce them is well known and has been the topic of numerous technical papers.

Since the last NCSD topical meeting, four new editions of each handbook have been published, each of which contains numerous new types of benchmark data. The contents of the ICSBEP handbook have increased from 501 evaluations (over 50,000 pages) containing benchmark specifications for 4,283 critical or subcritical configurations and 13 criticality alarm placement/shielding configurations to 570 evaluations (over 68,000 pages) containing benchmark specifications for 4802 critical or subcritical configurations, 24 criticality-alarm-placement/shielding configurations, and 200 configurations categorized as fundamental-physics measurements that are relevant to criticality-safety applications (including estimated contents of the September 2013 edition of the ICSBEP handbook).

The IRPhEP focus is 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 types of measurements in addition to the critical configuration. The contents of the IRPhEP handbook have increased from 36 experimental series performed at 21 different nuclear facilities to 65 experimental series performed at 34 different nuclear facilities. Significant additions of reactor-physics measurement data have also been made to previously published IRPhEP evaluations and additional reactor data have been copied from the ICSBEP Handbook to the IRPhEP Handbook to consolidate reactor physics data. With those additions, the 2013 edition of the IRPhEP Handbook will contain data from 131 different experimental series that were performed at 47 different nuclear facilities. Included is a DRAFT evaluation of a DUKE Power Depletion Reactivity Benchmark that is expected to be finalized for the 2014 edition of the IRPhEP Handbook. As of 2013, the IRPhEP handbook contains the IRPhE Database and Analysis Tool (IDAT), which facilitates searching and trending handbook contents.

2 BENCHMARKS ADDED TO ICSBEP AND IRPHEP HANDBOOKS SINCE 2009

Hundreds of new benchmarks have been added to the ICSBEP and IRPhEP Handbooks since 2009. Those benchmarks are summarized below by the categorization assigned in the respective handbook in which they appear.

2.1 New ICSBEP Benchmarks

Since the last NCSD Topical Meeting, 519 critical or subcritical benchmark configurations from 72 experimental programs have been added to the ICSBEP Handbook. Included are 37 plutonium benchmarks, 85 high-enriched uranium benchmarks, 150 intermediate-enriched uranium benchmarks, 191 low-enriched or natural uranium benchmarks, 1 uranium-233 benchmark, and 55 mixed uranium/plutonium benchmarks. There have been no benchmarks for special isotope systems, criticality alarm systems, or fundamental physics measurements, added to the ICSBEP Handbook since publication of the 2009 edition. Newly added benchmarks are summarized in the following subsections.

2.1.1 Plutonium Benchmarks

Benchmark specifications for plutonium systems that have been added to the ICSBEP Handbook since publication of the 2009 edition include a major revision of the Jezebel benchmark experiment performed at Los Alamos National Laboratory (LANL) in the United States and newly evaluated experiments performed at the Valduc Nuclear Center in France and the Bhaba Atomic Research Centre (BARC) in India. Newly added plutonium benchmarks are summarized in Table I.

TABLE I. Plutonium Benchmarks Added to the ICSBEP Handbook Since Publication of the 2009 Edition

ICSBEP Identifier	Facility	Benchmark Descriptive Title
PU-MET-FAST-001 (Major Revsion)	LANL	Bare Sphere of Plutonium-239 Metal (4.5 at.% 240Pu, 1.02 wt.% Ga)
PU-SOL-THERM-031	Valduc	Plutonium (19% ^{240}Pu) Nitrate Solution in a Water-Reflected Parallelepiped Tank (50x50 cm Side) Poisoned by an Array of Hafnium Plates
PU-SOL-THERM-038	Valduc	Plutonium Temperature Effect Program - Low Concentrated (20 or 15 G/L) Plutonium Nitrate Solutions At Room Temperature
PU-SOL-THERM-039	Valduc	Plutonium Temperature Effect Program - Low Concentrated (20, 15 or 14.3 g/l) Plutonium Nitrate Solutions at Temperatures Varying from 28°C to 40°C
PU-COMP-FAST-004	BARC	PURNIMA-I: A Plutonium Oxide Fast Reactor with Axial Molybdenum and Radial Copper and Mild Steel Reflectors

2.1.2 High Enriched Uranium Benchmarks

Benchmark specifications for high enriched uranium systems that have been added to the ICSBEP Handbook since publication of the 2009 edition include experiments from LANL, Oak Ridge National Laboratory (ORNL), and Bettis Atomic Power Laboratory (BAPL) in the United States and Russian Federal Nuclear Center Institute of Technical Physics (VNIITF) in the Russian Federation. Newly added high enriched uranium benchmarks are summarized in Table II.

TABLE II. High Enriched Uranium Benchmarks Added to the ICSBEP Handbook Since Publication of the 2009 Edition

ICSBEP Identifier	Facility	Benchmark Descriptive Title
HEU-MET-THERM-032	LANL	One Dimensional Array of Highly Enriched Uranium, Moderated and Reflected by Polyethylene
HEU-MET-THERM-033	LANL	2 X 2 Polyethylene Reflected and Moderated Highly Enriched Uranium System with Rhenium
HEU-MET-THERM-034	LANL	2 X 2 X 13 Array of Highly Enriched Uranium with Ni-Cr-Mo-Gd Alloy, Moderated and Reflected by Polyethylene
HEU-MET-FAST-056	ORNL	Polyethylene-Reflected Arrays of HEU(93.2) Metal Units Separated by Vermiculite
HEU-MET-FAST-059	ORNL	Oralloy (93.15 ^{235}U) Metal Annuli With Beryllium Core
HEU-MET-FAST-069	ORNL	Oralloy (93.2 ^{235}U) Metal Cylinder With Beryllium Top Reflector
HEU-MET-FAST-081	ORNL	Grotesque: Complex Geometric Arrangement of Unreflected HEU(93.15) Metal Pieces
HEU-MET-FAST-100	ORNL	Delayed Critical ORNL Unreflected Uranium (93.2) Metal Spheres
HEU-SOL-THERM-034	ORNL	Water-Moderated and -Reflected Slabs of Uranium Oxyfluoride
HEU-SOL-THERM-047	ORNL	Interaction of Unreflected Aluminum Cylinders in a Hexagonal Array Containing Uranyl Fluoride Solution
HEU-SOL-THERM-048	ORNL	Critical Parameters of Enriched ^{235}U Solutions in Reflected, Interacting Arrays of Aluminum Cylinders
HEU-SOL-THERM-051	ORNL	Critical Parameters of Enriched 235U Solutions in Annular Geometry
HEU-COMP-FAST-001	ORNL	Critical Configuration and Physics Measurements for Graphite Reflected Assemblies of U(93.15)O_2 Fuel Rods (1.27-cm Pitch)
HEU-COMP-FAST-002	ORNL	Critical Configuration for a Graphite Reflected Assembly of U(93.15)O_2 Fuel Rods (1.506-cm Pitch)
HEU-COMP-FAST-004	ORNL	Critical Configuration for Beryllium Reflected Assemblies of U(93.15)O_2 Fuel Rods (1.506-cm Pitch and 7-Tube Clusters)

HEU-COMP-THERM-018	BAPL	ETA-I: D_2O Moderated Lattice of UO_2-ThO_2
HEU-MET-FAST-043	VNIITF	HEU Cylinders Axially Reflected by Steel
HEU-MET-FAST-044	VNIITF	HEU Cylinders Axially Reflected by Aluminum
HEU-MET-FAST-087	VNIITF	Heterogeneous Iron-Diluted HEU Cylinder
HEU-MET-FAST-088	VNIITF	Two Heterogeneous Cylinders of Highly Enriched Uranium, Polyethylene, and Steel with Polyethylene Reflector
HEU-MET-FAST-089	VNIITF	Heterogeneous Aluminum-Diluted HEU Cylinder
HEU-MET-FAST-090	VNIITF	Two Heterogeneous Cylinders of Highly Enriched Uranium, Polyethylene, and Aluminum with Polyethylene Reflector
HEU-MET-FAST-091	VNIITF	Highly Enriched Uranium Cylinder Reflected by Polyethylene
HEU-MET-FAST-092	VNIITF	Four Molybdenum-Reflected HEU Cylinders
HEU-MET-FAST-093	VNIITF	Heterogeneous Molybdenum Diluted HEU Cylinder
HEU-MET-FAST-094	VNIITF	Two Heterogeneous Cylinders of Highly Enriched Uranium and Molybdenum with Beryllium Moderator and Depleted-Uranium Reflector
HEU-MET-MIXED-018	VNIITF	Two Heterogeneous Cylinders of Highly Enriched Uranium, Polyethylene, and Steel with Polyethylene Reflector
HEU-MET-MIXED-019	VNIITF	Two Heterogeneous Cylinders of Highly Enriched Uranium, Polyethylene, and Aluminum with Polyethylene Reflector
HEU-MET-MIXED-020	VNIITF	Two Heterogeneous Cylinders of Highly Enriched Uranium, Polyethylene, and Molybdenum with Polyethylene Reflector

2.1.3 Intermediate and Mixed Enrichment Uranium Benchmarks

Benchmark specifications for intermediate and mixed enrichment uranium systems that have been added to the ICSBEP Handbook since publication of the 2009 edition include experiments from Idaho National Laboratory (INL) and Argonne National Laboratory-West (ANL-W) in the United States; Dounreay and Aldermaston Atomic Weapons Establishment (AWE) in the United Kingdom; Institute of Physics and Power Engineering (IPPE) in the Russian Federation; Studsvik Facilities in Sweden; and Centro Atómico Bariloche in Argentina. Newly added intermediate and mixed enrichment uranium benchmarks are summarized in Table III.

TABLE III. Intermediate and Mixed Enrichment Uranium Benchmarks Added to the ICSBEP Handbook Since Publication of the 2009 Edition

ICSBEP Identifier	Facility	Benchmark Descriptive Title
IEU-COMP-THERM-013	INL	Fresh-Core Reload of the Neutron Radiography (NRAD) Reactor with Uranium(20)-Erbium-Zirconium-Hydride Fuel
IEU-MET-FAST-015	ANL-W	ZPR-3 Assembly 6F: A Spherical Assembly of Highly Enriched Uranium, Depleted Uranium, Aluminum and Steel with an Average ^{235}U Enrichment of 47 Atom %
IEU-MET-FAST-016	ANL-W	ZPR-3 Assembly 11: A Cylindrical Assembly of Highly Enriched Uranium and Depleted Uranium with an Average ^{235}U Enrichment of 12 Atom % and a Depleted Uranium Reflector
IEU-COMP-FAST-004	ANL-W	ZPR-3 Assembly 12: A Cylindrical Assembly of Highly Enriched Uranium, Depleted Uranium and Graphite with an Average ^{235}U Enrichment of 21 Atom %
IEU-SOL-THERM-002	Dounreay	Bare and Water-Reflected Spheres and Hemispheres of Aqueous Uranyl Fluoride Solutions (30.45% ^{235}U)
IEU-SOL-THERM-003	Dounreay	Bare and Water Reflected Cylinders of Aqueous Uranyl Fluoride Solutions (30.3% ^{235}U)
IEU-COMP-INTER-006	Aldermaston	Single Cores of 30.14% ^{235}U Enriched UO_2 / Wax Mixtures – Bare and with Single Reflector Materials
IEU-COMP-THERM-015	Aldermaston	Single Cores of 30.14% ^{235}U Enriched UO_2 / Wax Mixtures – Bare and with Single

		Reflector Materials
IEU-COMP-THERM-016	Aldermaston	Single Cores of 30.14% ^{235}U Enriched UO_2 / Wax Mixtures with Composite Reflectors
IEU-COMP-MIXED-004	Aldermaston	Single Cores of 30.14% ^{235}U Enriched UO_2 / Wax Mixtures – Bare and with Single Reflector Materials
IEU-MISC-FAST-001	IPPE	BFS-85 Assemblies : Model of Fast Reactor with Central Zone of Lead or Lead-Bismuth
IEU-MET-FAST-022	Studsvik	The FR0 Experiments with Diluted 20%-Enriched "Cylindrical" Uranium Metal Reflected by Copper
IEU-MET-INTER-001	Studsvik	The FR0 Experiments with Diluted 20%-Enriched "Cylindrical" Uranium Metal Reflected by Copper
IEU-COMP-THERM-014	Centro Atómico Bariloche	RA-6 Reactor: Water Reflected, Water Moderated $U(19.77)_3Si_2$-Al Fuel Plates

2.1.4 Low Enriched or Natural Uranium Benchmarks

Benchmark specifications for low enriched or natural uranium systems that have been added to the ICSBEP Handbook since publication of the 2009 edition include experiments from ORNL and Sandia National Laboratories (SNL) in the United States; Atomic Energy of Canada Limited (AECL) Chalk River Laboratories in Canada; Institute de Pesquisas Energeticas e Nucleares (IPEN) in Brazil; Valduc Nuclear Center in France; Japan Atomic Energy Agency (JAEA) and Kyoto University in Japan; and RRC KI in the Russian Federation. Newly added low enriched or natural uranium benchmarks are summarized in Table IV.

TABLE IV. Low Enriched or Natural Uranium Benchmarks Added to the ICSBEP Handbook Since Publication of the 2009 Edition

ICSBEP Identifier	Facility	Benchmark Descriptive Title
LEU-MET-THERM-004	ORNL	Triangular Lattices of 2.49 cm Diameter LEU (4.948) Rods in Water
LEU-MET-THERM-007	ORNL	Water-Moderated and Water-Reflected 0.30 in. Diameter U(4.95) Metal Rods in Square-Pitched Arrays
LEU-COMP-THERM-078	SNL	Water-Moderated Square-Pitched $U(6.90)O_2$ Fuel Rod Lattices with 0.52 Fuel-To-Water Volume Ratio
LEU-COMP-THERM-080	SNL	Water-Moderated Square-Pitched $U(6.90)O_2$ Fuel Rod Lattices with 0.67 Fuel-To-Water Volume Ratio
LEU-MET-THERM-003	AECL	ZED-2 Reactor: Natural-Uranium Metal Fuel Assemblies in Heavy-Water
LEU-COMP-THERM-046	IPEN	Critical Loading Configurations of the IPEN/MB-01 Reactor Considering Temperature Variation from 14°C To 85°C
LEU-COMP-THERM-058	IPEN	Critical Loading Configurations of the IPEN/MB-01 Reactor with Large Void in the Reflector
LEU-COMP-THERM-088	IPEN	Critical Loading Configurations of the IPEN/MB-01 Reactor with Heavy Reflectors Composed of Carbon Steel and Nickel
LEU-COMP-THERM-092	IPEN	Critical Loading Configurations of the IPEN/MB-01 Reactor with Soluble Boron
LEU-COMP-THERM-057	Valduc	4.738-Wt.%-Enriched Uranium Dioxide Fuel Rod Arrays Reflected by Water in a Dry Storage Configuration
LEU-COMP-THERM-074	Valduc	MIRTE Program: Four 4.738-Wt.%-Enriched Uranium Dioxide Fuel Rod Arrays in Water Separated by a Cross Shaped Screen of Titanium (5-mm And 10-mm Thick)
LEU-MISC-THERM-007	JAEA	STACY: A 60-Cm-Diameter Tank Containing 5%-Enriched UO_2 Fuel Rods (2.5-cm Square Lattice Pitch) in 6%-Enriched Uranyl Nitrate Solutions, Unreflected and Water-Reflected

LEU-MET-THERM-005	Kyoto University	Evaluation of the Kyoto University Critical Assembly Erbium Oxide Experiments
LEU-COMP-THERM-030	RRC KI	VVER Physics Experiments: Regular Hexagonal (1.27-cm Pitch) Lattices of Low-Enriched U(3.5 Wt.% ^{235}U)O_2 Fuel Rods in Light Water at Different Core Critical Dimensions
LEU-COMP-THERM-064	RRC KI	VVER Physics Experiments: Regular Hexagonal (1.27 cm Pitch) Lattices of Low-Enriched U(2.4 Wt.% U-235)O_2 Fuel Rods in Light Water at Different Core Critical Dimensions

2.1.5 Uranium-233 Benchmarks

Benchmark specifications for uranium-233 systems that have been added to the ICSBEP Handbook since publication of the 2009 edition include only one configuration from BAPL in the United States. Newly added uranium-233 benchmarks are summarized in Table V.

TABLE V. Uranium-233 Benchmarks Added to the ICSBEP Handbook Since Publication of the 2009 Edition

ICSBEP Identifier	Facility	Benchmark Descriptive Title
U233-COMP-THERM-004	BAPL	D_2O Moderated Lattice of $^{233}UO_2$-$^{232}ThO_2$

2.1.6 Mixed Plutonium/Uranium Benchmarks

Benchmark specifications for mixed plutonium/uranium systems that have been added to the ICSBEP Handbook since publication of the 2009 edition include experiments from ANL and ANL-W in the United States, IPPE in the Russian Federation, and Valduc Nuclear Center in France. Newly added mixed plutonium/uranium benchmarks are summarized in Table VI.

TABLE VI. Mixed Plutonium/Uranium Benchmarks Added to the ICSBEP Handbook Since Publication of the 2009 Edition

ICSBEP Identifier	Facility	Benchmark Descriptive Title
MIX-COMP-FAST-005	ANL	ZPR-9 Assembly 31: A Cylindrical Assembly with Mixed (Pu,U)-Carbide Fuel and Depleted Uranium Carbide Blanket
MIX-MET-INTER-003	ANL-W	ZPR-3 Assembly 54: A Cylindrical Assembly of Plutonium Metal, Depleted Uranium, and Graphite with a Thick Iron Reflector
MIX-MET-INTER-004	ANL-W	ZPR-3 Assembly 53: A Cylindrical Assembly of Plutonium Metal, Depleted Uranium and Graphite with a Thick Depleted Uranium Reflector
MIX-COMP-FAST-006	ANL-W	ZPPR-2: A Cylindrical Assembly with Mixed (Pu,U)-Oxide Fuel and Sodium Reflected by Depleted Uranium, Sodium and Steel
MIX-MET-FAST-006	IPPE	BFS-61 Assemblies: Critical Experiments of Mixed Plutonium, Depleted Uranium, Graphite and Lead with Different Reflectors
MIX-MET-FAST-014	IPPE	BFS-87 Assemblies: Model of Fast Reactor with Lead or Lead-Bismuth Reflector
MIX-MISC-FAST-004	IPPE	BFS-97, -99 Assemblies, Part II: Critical Experiments With Heterogeneous Compositions Of Plutonium, Depleted-Uranium Dioxide, And Polyethylene
MIX-COMP-THERM-017	Valduc	Water-Moderated and Water-Reflected PHENIX Pin (UO_2-PuO_2; Pu/(U+Pu)=26%, 240Pu=16%) Arrays
MIX-MISC-THERM-006	Valduc	Arrays of UO_2-PuO_2 PHENIX Pins Containing 26% of Plutonium (^{240}Pu/Pu=16%) in a Mixed Uranium-Plutonium (Pu/(U+Pu)=29.7%, ^{240}Pu/Pu=19%) Nitrate Solution

2.2 New IRPhEP Benchmarks

Most IRPhEP evaluations include a critical configuration; however, the main focus of that project is other reactor physics-type measurements, many of which can be used to test specific nuclear cross section data and enable refinement of those data. Such refinements can be of great importance to the criticality safety community.

Since the last NCSD Topical Meeting, data from 29 experimental programs conducted at 13 different nuclear facilities have been added to the IRPhEP Handbook. Included are data from two simulated Pressurized Water Reactors (PWR) plus DRAFT data derived from operating commercial PWRs, one Voda-Vodyanoi Energetichesky Reaktor (VVER), nine Liquid Metal Fast Reactors (LMFR), seven Gas Cooled Reactors (GCR), one Light Water Reactor (LWR), one Heavy Water Reactor (HWR), three Space Reactors, and four Fundamental Physics Reactors. There have been no Boiling Water Reactor (BWR), Gas Cool Fast Reactor (GCFR), Molten Salt Reactor (MSR), or Reaktor Bolshoy Moshchnosti Kanalniy (RBMK) benchmark data added to the IRPhEP Handbook since 2009; however, criticality measurements from one RBMK evaluation were copied from the ICSBEP Handbook to the IRPhPE Handbook. Newly added reactor physics measurements are summarized in the following subsections.

2.2.1 PWR Reactor Benchmarks

Benchmark specifications from two experimental series that simulate PWRs have been added to the IRPhEP Handbook since 2009 plus DRAFT specifications from actual power plant data. Included are data from the B&W Spectral Shift Facility in Lynchburg, Virginia, United States and the VENUS facility at Centre d'étude de l'Energie Nucléaire / Studiecentrum voor Kernenergie (CEN/SCK) in Belgium. DRAFT specifications are also included for Depletion Reactivity data that were derived from fission rate data taken from actual Power Reactors operated by DUKE Power in the United States. A short summary of those benchmark specifications is given in Table IX.

TABLE IX. Simulated PWR Reactor Benchmarks Added to the IRPhEP Handbook Since 2009

IRPhEP Identifier	Facility	Benchmark Descriptive Title
SSCR-PWR-EXP-001	Lynchburg	B&W Spectral Shift Reactor Lattice Experiment: A 484 Uranium Rods Critical Experiment with Infinite Radial Reflector (Includes Benchmark Specifications for Critical and Spectral Characteristics Measurements)
VENUS-PWR-EXP-005	CEN/SCK	VENUS-PRP Configurations No. 9 and 9/1 (Includes Benchmark Specifications for Power Distribution Measurements)
DUKE-PWR-POWER-001	DUKE	PWR Fuel Assembly Depletion Reactivity Determination Using PWR Fission Rate Measurements (Includes **DRAFT** Reactivity Effects Measurements)

2.2.2 VVER Reactors Benchmarks

Benchmark specifications from experiments performed at only one VVER facility have been added to the IRPhEP Handbook since 2009. Those experiments were performed at the Nuclear Research Institute, Řež plc (NRI) facility in the Czech Republic. A short summary of those benchmark specifications is given in Table X.

TABLE X. Simulated VVER Reactor Benchmarks Included in the IRPhEP Handbook Since 2009

IRPhEP Identifier	Facility	Benchmark Descriptive Title
LR(0)-VVER-RESR-001	NRI	VVER Physics Experiments: Hexagonal Lattices of Low-Enriched U(2.0 – 3.3 wt.% $^{235}U)O_2$ Fuel Assemblies in Light Water with Central Control-Assembly Mockup (Includes Critical and Reaction Rate Distribution Measurements)

2.2.3 Liquid Metal Fast Reactor Benchmarks

Benchmark specifications from nine LMFR experimental series have been added to the IRPhEP Handbook since 2009. Included are data from IPPE's BFS1 facilities in the Russian Federation, JAEA's JOYO reactor facility in Japan, and Hanford's Fast Flux Test Facility (FFTF) and ANL-W's ZPPR at facility in the United States. A short summary of those benchmark specifications is given in Table XI.

TABLE XI. Simulated Fast Reactor Benchmarks Added to the IRPhEP Handbook Since 2009

IRPhEP Identifier	Facility	Benchmark Descriptive Title
BFS1-LMFR-EXP-002	IPPE	BFS-61 Assemblies: Experimental Model of Lead-Cooled Fast Reactor with Core of Metal Plutonium-Depleted Uranium Fuel and Different Reflectors (Includes Critical, Spectral Characteristics, and Reaction Rate Distribution Measurements)
JOYO-LMFR-RESR-001	JAEA	Japan's Experimental Fast Reactor JOYO MK-I Core: Sodium-Cooled Uranium-Plutonium Mixed Oxide Fueled Fast Core Surrounded by UO_2 Blanket (Critical and Reactivity Coefficient Measurements were available in the 2009 edition of the Handbook. Reactivity Effects (Burnup reactivity) measurements were added in 2010)
FFTF-LMFR-RESR-001	Hanford	Evaluation of the Initial Isothermal Physics Measurements at the Fast Flux Test Facility, a Prototypic Liquid Metal Fast Breeder Reactor (Includes Critical, Spectral Characteristics, Reactivity Effects, Reactivity Coefficient, and Miscellaneous Measurements)
ZPPR-LMFR-EXP-005	ANL-W	ZPPR-10B Experiment: A 650 MWe-Class Sodium-Cooled MOX-Fueled FBR Homogeneous Core Mock-Up Critical Experiment with Two Enrichment Zones, Seven Control Rods and Twelve Control Rod Positions (Includes Critical, Spectral Characteristics, Reactivity Effects, and Reaction Rate Distribution Measurements)
ZPPR-LMFR-EXP-006	ANL-W	ZPPR-10C Experiment: A 800 MWe-Class Sodium-Cooled MOX-Fueled FBR Homogeneous Core Mock-Up Critical Experiment with Two Enrichment Zones and Nineteen Control Rod Positions (Includes Critical, Spectral Characteristics, Reactivity Effects, and Reaction Rate Distribution Measurements)
ZPPR-LMFR-EXP-007	ANL-W	ZPPR-13A Experiment: A 650 MWe-Class Sodium-Cooled MOX-Fueled FBR Radial Heterogeneous Core Mock-Up Critical Experiment with Central Blanket Zone and Two Internal Blanket Rings (Includes Critical, Spectral Characteristics, Reactivity Effects, and Reaction Rate Distribution Measurements)
ZPPR-LMFR-EXP-008	ANL-W	ZPPR-18C Experiment: A 1,000 MWe-Class Sodium-Cooled MOX-Fueled FBR Homogeneous Core Mock-Up Critical Experiment in the State of Removal of One of Eighteen Half-Inserted Control Rods, Where Enriched Uranium is Used with the Shape of A Sector in the Outer Core (Includes Critical, Spectral Characteristics, Reactivity Effects, and Reaction Rate Distribution Measurements)
ZPPR-LMFR-EXP-009	ANL-W	ZPPR-17A Experiment: A 650 MWe-Class Sodium-Cooled MOX-Fueled FBR Axial Heterogeneous Core Mock-Up Critical Experiment with Central Internal Blanket Zone (Includes Critical, Spectral Characteristics, Reactivity Effects, and Reaction Rate Distribution Measurements)
ZPPR-LMFR-EXP-010	ANL-W	ZPPR-12: Mockup of the 400 MWe Sodium-Cooled Clinch River Breeder Reactor (Includes Critical and Reactivity Effects Measurements)
ZPPR-LMFR-EXP-011	ANL-W	ZPPR-2: A Cylindrical Assembly with Mixed (Pu,U)-Oxide Fuel and Sodium Reflected by DU, Sodium and Steel (Includes Critical Measurements)

2.2.4 Gas-Cooled Reactor Benchmarks

Benchmark specifications from seven GCR experimental series have been added to the IRPhEP Handbook since 2009. Included are data from JAEA's High Temperature Engineering Test Reactor (HTTR) and Very High Temperature Reactor Critical Assembly (VHTRC) in Japan and Paul Scherrer Institute's (PSI) HTR PROTEUS facility in Switzerland. A short summary of those benchmark specifications is given in Table XII.

TABLE XII. Simulated GCR Reactor Benchmarks Added to the IRPhEP Handbook Since 2009

IRPhEP Identifier	Facility	Benchmark Descriptive Title
HTTR-GCR-RESR-001	JAEA	Evaluation of the Start-Up Core Physics Tests At Japan's High Temperature Engineering Test Reactor (Fully-Loaded Core) (Critical configurations were available in the 2009 edition of the Handbook. Subcritical, Reactivity Effects, and Reaction Rate Distribution Measurements were added in 2010)
HTTR-GCR-RESR-002	JAEA	Evaluation of the Start-Up Core Physics Tests at Japan's High Temperature Engineering Test Reactor (Annular Core Loadings) (Includes Critical and Reaction Rate Distribution Measurements)
HTTR-GCR-RESR-003	JAEA	Evaluation of Zero-Power, Elevated-Temperature Measurements at Japan's High Temperature Engineering Test Reactor (Includes Critical and Reactivity Coefficient Measurements)
VHTRC-GCR-EXP-001	JAEA	Temperature Effect on Reactivity in VHTRC-1 Core (Includes Critical and Reactivity Coefficient Measurements)
PROTEUS-GCR-EXP-001	PSI	HTR-PROTEUS Pebble Bed Experimental Program Cores 1, 1A, 2, and 3: Hexagonal Close Packing with a 1:2 Moderator-To-Fuel Pebble Ratio (Includes Critical Measurements)
PROTEUS-GCR-EXP-002	PSI	HTR-PROTEUS Pebble Bed Experimental Program Core 4: Random Packing with a 1:1 Moderator-To-Fuel Pebble Ratio (Includes Critical Measurements)
PROTEUS-GCR-EXP-003	PSI	HTR-PROTEUS Pebble Bed Experimental Program Cores 5, 6, 7, & 8: Columnar Hexagonal Point-On-Point Packing with a 1:2 Moderator-To-Fuel Pebble Ratio (Includes Critical Measurements)
PROTEUS-GCR-EXP-004	PSI	HTR-PROTEUS Pebble Bed Experimental Program Cores 9 & 10: Columnar Hexagonal Point-On-Point Packing with a 1:1 Moderator-To-Fuel Pebble Ratio (Includes Critical Measurements)

2.2.5 Light-Water Reactor Benchmarks

Benchmark specifications from two LWR facility have been added to the IRPhEP Handbook since 2009. Those experiments were performed at JAEA's Tank Critical Assembly (TCA) in Japan and Institute de Pesquisas Energeticas e Nucleares (IPEN) in Brazil. A short summary of those benchmark specifications is given in Table XIII.

TABLE XIII. Simulated LWR Reactor Benchmarks Added to the IRPhEP Handbook Since 2009

IRPhEP Identifier	Facility	Benchmark Descriptive Title
TCA-LWR-EXP-001	JAERI	Temperature Effects on Reactivity in Light Water Moderated UO_2 Core with Soluble Poisons at TCA (Includes Reactivity Coefficient Measurements)
IPEN(MB01)-LWR-RESR-001	IPEN	Reactor Physics Experiments in the IPEN/MB-01 Research Reactor Facility (Critical, Kinetics and Reaction Rate Distributions were available in the 2009 edition of the Handbook. Spectral Characteristics, Reactivity Effects, Reactivity Coefficients, and Power Distribution Measurements have been added since 2009)

2.2.6 Heavy-Water Reactor Benchmarks

Benchmark specifications from only one HWR facility have been added to the IRPhEP handbook since 2009. Those experiments were performed at Atomic Energy of Canada, LLC (AECL) Zero Energy Deuterium Facility (ZED-2) in Canada. A short summary of those benchmark specifications is given in Table XIV.

TABLE XIV. Heavy-Water Reactor Benchmarks Added to the IRPhEP Handbook Since 2009

IRPhEP Identifier	Facility	Benchmark Descriptive Title
ZED2-HWR-EXP-001	AECL	28-Element Natural UO_2 Fuel Assemblies In ZED-2 (Includes Critical Measurements)

2.2.7 Space Reactor Benchmarks

A category for Space Reactors was added in 2013. Benchmark specifications from three series of Space Reactor experiments have been added to the IRPhEP Handbook since 2009. Those experiments were performed on ORNL's Small Compact Critical Assembly (SCCA) in the United States. A short summary of those benchmark specifications is given in Table XV.

TABLE XV. Space Reactor Benchmarks Added to the IRPhEP Handbook Since 2009

IRPhEP Identifier	Facility	Benchmark Descriptive Title
SCCA-SPACE-EXP-001	ORNL	Critical Configuration and Physics Measurements for Graphite Reflected Assemblies of $U(93.15)O_2$ Fuel Rods (Includes Critical, Spectral Characteristics, Reactivity Effects, and Reaction Rate Distribution Measurements)
SCCA-SPACE-EXP-002	ORNL	Critical Configuration and Physics Measurements for Graphite Reflected Assemblies of $U(93.15)O_2$ Fuel Rods (1.506-cm Pitch) (Includes Critical, Spectral Characteristics, Reactivity Effects, and Reaction Rate Distribution Measurements)
SCCA-SPACE-EXP-003	ORNL	Critical Configuration for Beryllium Reflected Assemblies of $U(93.15)O_2$ Fuel Rods (1.506-cm Pitch and 7-Tube Clusters) (Includes Critical Measurements)

2.2.8 Fundamental Physics Assembly Benchmarks

Benchmark specifications from four series of Fundamental Physics experiments have been added to the IRPhEP Handbook since 2009. Those experiments were performed on INL's Neutron Radiography (NRAD) Reactor in the United States, Vinča's RB reactor in Serbia, and Winfrith's **Z**ero **E**nergy **B**reeder **R**eactor **A**ssembly (ZEBRA) in the United Kingdom. A short summary of those benchmark specifications is given in Table XVI.

TABLE XVI. Fundamental Physics Benchmarks Added to the IRPhEP Handbook Since 2009

IRPhEP Identifier	Facility	Benchmark Descriptive Title
NRAD-FUND-RESR-001	INL	Fresh-Core Reload of the Neutron Radiography (NRAD) Reactor With Uranium(20)-Erbium-Zirconium-Hydride Fuel (Includes Critical and Reactivity Effects Measurements)
RB-FUND-EXP-001	Vinča	Rb Reactor: Natural Uranium Metal Rods And 2 % Enriched Uranium Metal Fuel Elements In Lattice Of Heavy Water - Core Rb5/1973 (Includes Critical Measurements)
RB-FUND-EXP-002	Vinča	Rb Reactor: Natural Uranium Metal Rods And 2 % Enriched Uranium Metal Fuel Elements In Lattice Of Heavy Water - Core Rb39/1978 (Includes Critical Measurements)
ZEBRA-FUND-RESR-001	Winfrith	K-Infinity Measurements In Zebra Core 8 (Includes Critical and Spectral Effects Measurements)

3 CONCLUSIONS

Over 400 scientists from 24 different countries have combined their efforts to produce the ICSBEP and IRPhEP Handbooks. Those two handbooks continue to grow and provide high-quality integral benchmark data that will be of use to the criticality safety, nuclear data, and reactor physics communities for future decades.

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5 REFERENCES

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 2013 Edition.
2. *International Handbook of Reactor Physics Benchmark Experiments*, NEA/NSC/DOC(2006)1, Organization for Economic Co-operation and Development-Nuclear Energy Agency (OECD-NEA), March 2013 Edition, ISBN 978-92-64-99208-5