Contributions to integral nuclear data in ICSBEP and IRPhEP since ND2013

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Abstract. The status of the International Criticality Safety Benchmark Evaluation Project (ICSBEP) and the International Reactor Physics Experiment Evaluation Project (IRPhEP) was last discussed directly with the international nuclear data community at ND2013. Since ND2013, integral benchmark data that are available for nuclear data testing has continued to increase. The status of the international benchmark efforts and the latest contributions to integral nuclear data for testing is discussed. Measurements found in the IRPhEP Handbook offer additional means to support integral nuclear data validation. Select benchmark configurations that have been added to the ICSBEP and IRPhEP Handbooks since ND2013 are highlighted.

1. Introduction

The status of the International Criticality Safety Benchmark Evaluation Project (ICSBEP) [1] and the International Reactor Physics Experiment Evaluation Project (IRPhEP) [2] was last discussed directly with the international nuclear data community at ND2013. Since ND2013, integral benchmark data that are available for nuclear data testing have increased. The contents of the 2015 edition of the *International Handbook of Evaluated Criticality Safety Benchmark Experiments (ICSBEP Handbook)* [3] have increased from 549 evaluations containing benchmark specifications for 4708 configurations in 2012 to 567 evaluations with 4874 critical, near-critical, or subcritical configurations. The number of criticality-alarm-placement/shielding configurations has increased from 24 to 31, and there are now 207 configurations (200 in 2012) that have been categorized as fundamental physics measurements that are relevant to criticality safety applications.

Since ND2013, the contents of the *International Handbook for Evaluated Reactor Physics Benchmark Experiments (IRPhEP Handbook)* [4] have increased from 56 experimental series at 32 unique nuclear facilities in 2012 to 143 different experimental series that were performed at 50 different nuclear facilities in the 2015 edition. Of these 143 evaluations, 139 are published as approved benchmarks with the remaining four evaluations published in draft format only. Measurements available in the IRPhEP Handbook include criticality, buckling and extrapolation length, spectral characteristics, reactivity effects, reactivity coefficients, kinetics, reaction-rate distributions, power distributions, isotopic compositions, and/or other miscellaneous types of measurements for various types of reactor systems. The variety in measurements beyond criticality offer additional means to support validation of computational simulations and integral nuclear data [3].

Twenty-five countries have contributed to these two projects: 22 to the ICSBEP and 20 to the IRPhEP. Contributing countries include the following: Argentina, Belgium, Brazil, Canada, People's Republic of China, Czech Republic, France, Germany, Hungary, India, Israel, Italy, Japan, Kazakhstan, Poland, Republic of Korea, Russian Federation, Serbia, Slovenia, South Africa, Spain, Sweden, Switzerland, United Kingdom, and the United States of America.

A primary purpose of the ICSBEP and the IRPhEP is to provide extensively peer-reviewed integral benchmark data that can be utilized by the international nuclear data community for testing and improvement of nuclear data files. These handbooks also support the international reactor physics, criticality safety, and math and computation communities for validation of analytical methodologies used in reactor physics, fuel cycle, nuclear facility safety analysis and design, and advanced modelling and simulation.

2. The 2015 editions of the ICSBEP and IRPhEP handbooks

2.1. The ICSBEP handbook

The September 2015 edition of the ICSBEP Handbook [3] is available on DVD (see Fig. 1) or downloaded directly from the internet. The DVD or online access can be requested using the following website: `https://www.oecd-nea.org/science/wpncs/icsbep/`.

The 2015 edition of the ICSBEP Handbook includes benchmark specifications for the following:

- 748 plutonium experiments
  - 36 compound
  - 123 metal
  - 589 solution

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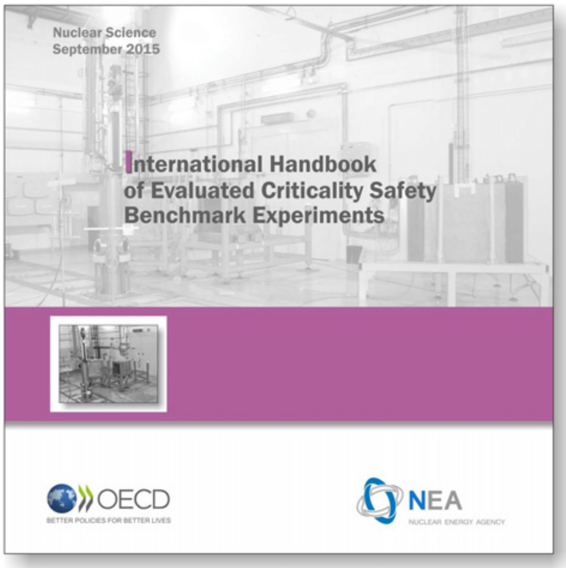

Figure 1. September 2015 cover of the ICSBEP Handbook.

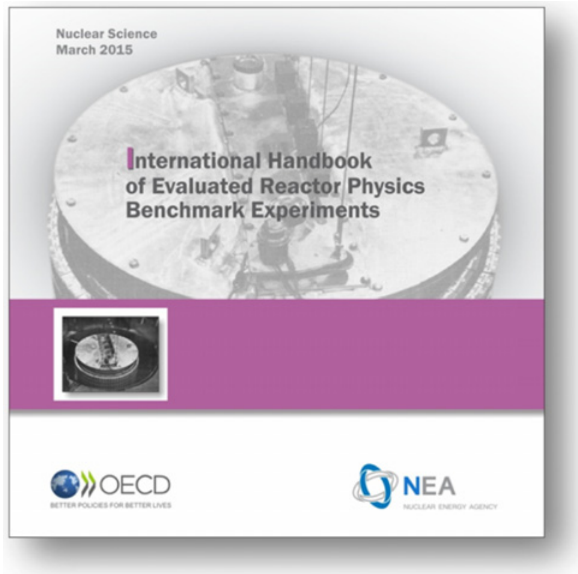

Figure 2. March 2015 cover of the IRPhEP Handbook.

- 1420 highly enriched uranium experiments
  - 291 compound
  - 586 metal
  - 536 solution
  - 2 mixed compound/solution
  - 5 mixed metal/solution
- 268 intermediate- and mixed-enrichment uranium experiments
  - 156 compound
  - 47 metal
  - 65 solution
- 1641 low enriched uranium experiments
  - 1377 compound
  - 87 metal
  - 117 solution
  - 60 mixed compound/solution
- 244 ^{233}U experiments
  - 6 compound
  - 11 metal
  - 227 solution
- 536 mixed plutonium-uranium experiments
  - 301 compound
  - 52 metal
  - 86 solution
  - 76 mixed compound/solution
  - 21 mixed metal/compound
- 20 special isotope experiments
  - metal (^{237}Np, ^{238}Pu, ^{242}Pu, & ^{244}Cm)
- 7 criticality-alarm/shielding experiments
  - 31 unique configurations with numerous dose points
- 7 fundamental physics experiments
  - 207 unique measurements such as fission rates, transmission measurements, and subcritical neutron multiplication measurements.

2.2. The IRPhEP handbook

The March 2015 edition of the IRPhEP Handbook [4] is also available on DVD (see Fig. 2) or downloaded directly from the internet. The DVD or online access can be requested using the following website: `https://www.oecd-nea.org/science/wprs/irphe/irphe-handbook/`.

The 2015 edition of the IRPhEP Handbook includes benchmark specifications for the following nuclear reactors or assemblies that simulate certain reactor characteristics:

- 6 Pressurized Water Reactor (PWR)
  - DIMPLE, DUKE, EOLE, OTTOHAHN, SSCR, VENUS
- 3 Vodo-Vodynaoi Energetichesky Reactor (VVER)
  - LR-0, P-Facility, ZR-6
- 0 Boiling Water Reactor (BWR)
- 9 Liquid Metal Fast Reactor (LMFR)
  - BFS-1, BFS-2, BR2, FFTF, JOYO, SNEAK, ZEBRA, ZPPR, ZPR
- 5 Gas Cooled (Thermal) Reactor (GCR)
  - ASTRA, HTR10, HTTR, PROTEUS, VHTRC
- 0 Gas Cooled Fast Reactor (GCFR)
- 5 Light Water Reactor (LWR)
  - CROCUS, DIMPLE, IPEN(MB01), KRITZ, TCA
- 3 Heavy Water Reactor (HWR)
  - DCA, ETA, ZED2
- 0 Molten Salt Reactor (MSR)
- 1 Reaktor Bolshoy Moshchnosti Kanalniy (RBMK)
  - RBMK(CF)
- 6 Space Reactor (SPACE)
  - ORCEF, SCCA, TOPAZ, UKS1M, ZPPR, ZPR
- 19 Fundamental Physics Reactor Measurements (FUND)
  - ATR, BFS-1, BFS-2, CORAL(1), FR0, HECTOR, IGR, KUCA, LAMPRE, MINERVE, NRAD, ORSPHERE, PBF, RA-6, RB, RHF, TRIGA, ZEBRA, ZPR

3. Selected benchmark specifications (since ND2013) of interest for nuclear data testing

As indicated in Sect. 1, benchmark specifications for over 200 experimental configurations have been added to the

ICSBEP and IRPhEP Handbooks since ND2013. Many of those experiments can be useful for nuclear data testing and are highlighted in this section.

3.1. Plutonium data

The Institut de Radioprotection et de Sûreté Nucléaire (IRSN) and Commissariat à l'énergie atomique et aux énergies alternatives (CEA) had previously investigated low concentrated (14–20 g/l) plutonium nitrate solution at room temperature in [PU-SOL-THERM-038] as part of the IRSN Plutonium Temperature Effect Program. Additional data from that program (28 °C–40 °C) were then performed and evaluated in [PU-SOL-THERM-039]. These experiments were conducted to investigate, confirm, and validate theoretical studies that have shown a positive temperature effect for highly diluted plutonium solutions.

Two ZPR-3 fast-neutron physics benchmarks were performed and then later evaluated by Argonne National Laboratory (ANL) to test plutonium with a slightly softened spectrum with thick depleted uranium or lead reflectors [PU-MET-INTER-003, ZPR-FUND-EXP-017 and PU-MET-INTER-004, ZPR-FUND-EXP-018, respectively]. The configurations were originally constructed to study a discrepancy between calculated and measured central reactivity measurements and comprised ^{239}Pu-Al metal and graphite plates within a stainless steel matrix. The primary difference between the two assemblies is the thick reflector surrounding the experiment and separating it from room return effects. Replacing the depleted uranium with lead effectively eliminated ^{238}U delayed neutron data as a possible source of error when evaluating this discrepancy.

3.2. Highly enriched uranium data

An evaluation of the Oak Ridge National Laboratory (ORNL) Oralloy (Oak Ridge Alloy) Sphere [HEU-MET-FAST-100, ORSPHERE-FUND-EXP-001] was completed. Oralloy is a highly enriched uranium (HEU) metal alloy, approximately 93.2 wt.% ^{235}U, manufactured for use at ORNL. ORSphere was a very precisely measured, HEU alloy spherical assembly. Benchmark specifications are provided for two critical configurations, worth measurements, delayed neutron fraction, surface material worth coefficient, prompt neutron decay constant, relative fission density, and relative neutron importance measurements. The experiments had been performed to recreate GODIVA I experiments with greater accuracy.

The third in a series of ORNL space reactor mock-ups (see Fig. 3) was evaluated [HEU-COMP-FAST-004, SCCA-SPACE-EXP-003]. This experiment consisted of beryllium-reflected arrays of UO_2 (93.15 wt.% ^{235}U) fuel pins, stainless-steel-clad, to support the validation of reactor physics methods and calculations for the Medium-Power Reactor Experiments (MPRE) space power reactor design. Evaluated experimental data for the graphite-reflected configuration includes two critical configurations, spectral characteristics, various material worth measurements, axial/radial fission rate measurements and cadmium measurements. Only two critical configurations have been currently evaluated for the beryllium-reflected series. Ongoing efforts to evaluate potassium metal worth, as the simulated reactor coolant, are underway for inclusion in future editions of the ICSBEP and IRPhEP Handbooks.

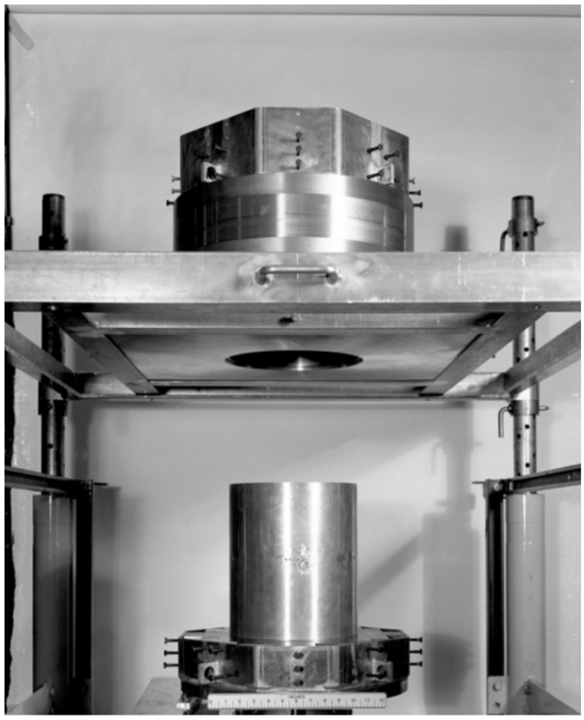

Figure 3. ORNL beryllium-reflected space reactor mock-up.

3.3. Intermediate enriched uranium data

The quantity of intermediate enriched uranium (IEU) benchmark experiments is rather paltry compared against the plethora of available HEU and low enriched uranium (LEU) experiments. The critical conditions for an unreflected, 37 wt.% enriched ^{235}U, 69.2-cm-diameter sphere of UO_2F_2 was evaluated and reported in [IEU-SOL-THERM-005]. This experiment is similar to one of $U(93.2\%)O_2(NO_3)_2$ solution inside the same sphere [HEU-SOL-THERM-013] and another with $^{233}UO_2(NO_3)_2$ solution [U233-SOL-THERM-001] that were previously evaluated. Calculations with ENDF/B-VII.0 and -VII.1 nuclear data libraries of the IEU benchmark are approximately 0.5% low but within the 1σ benchmark uncertainty of $\pm$ 0.0065 Δk.

The prior evaluation of the Idaho National Laboratory (INL) Neutron Radiography (NRAD) Reactor when it was converted from HEU to 20 wt.% enriched ^{235}U [IEU-COMP-THERM-013, NRAD-FUND-RESR-001] has since been followed by a second evaluation of the reactor with the addition of four fuel elements and four graphite rods [NRAD-FUND-RESR-002]. The NRAD reactor is a 250 kW TRIGA® (Training, Research, Isotopes, General Atomics) Mark II tank-type research reactor with water-moderated, graphite-reflected, stainless-steel-clad UErZrH fuel. Benchmark specifications are available for the critical configurations and reactivity effects measurements. The 1σ uncertainty for k_{eff} is $\pm$ 0.0015 Δk yet Monte Carlo calculations of the benchmark models are between approximately 0.8% and 1.4% greater, much greater than the 1σ uncertainty.

3.4. 7% enriched uranium data

The Sandia Pulsed Reactor Facility at Sandia National Laboratories in New Mexico is the home of the Seven Percent Critical Experiment (7uPCX). This facility was designed and constructed to investigate critical systems containing light water reactor (LWR) fuel with enrichments above 5% ^{235}U. The 7uPCX assembly is water moderated and contains adjustable arrays of aluminum-clad, square-pitched UO_2 fuel rods enriched to 6.90%. Two benchmark evaluations [LEU-COMP-THERM-078 and LEU-COMP-THERM-096] have been contributed to the ICSBEP Handbook with a total of 34 critical configurations with lattice arrangements of varying number of fuel rods, water holes, and water-filled gaps. These high-precision experiments are evaluated to have very low benchmark k_{eff} uncertainties of ± 0.0010 Δk, making them very valuable for the validation of PWR and BWR designs with higher enrichments.

3.5. Thorium in heavy water data

A second evaluation of the Babcock & Wilcox Company's Spectral Shift Control Reactor (SSCR) series [SSCR-PWR-EXP-002] was added to the IRPhEP Handbook. This particular series of SSCR experiments comprise large lattices of aluminium-clad UO_2/ThO_2 fuel rods moderated and cooled by a D_2O/H_2O mixture. The fuel contains 93 wt.% enriched ^{235}U with a N_{Th}/N_U ratio of 15; the D_2O concentration was 60.40 mol.%. Benchmark specifications are currently available for a critical configuration and the thermal disadvantage factor, which is defined as the ratio of the average thermal neutron flux in the moderator to that in the fuel of a unit cell.

3.6. Molybdenum data

Following the prior completion of four HEU (95.98 wt.% ^{235}U) cylinders reflected by varying thicknesses of molybdenum axial reflectors [HEU-MET-FAST-092] experiments were performed at the Russian Federal Nuclear Center – VNIITF as part of a series to test the neutronics properties of various test materials on the FKBN-2 vertical lift machine. Test materials were used as a reflector (various thicknesses), diluent, and diluent mixed with either beryllium or polyethylene to adjust the spectra; experiments typically have either fast or mixed spectra. An HEU cylinder diluted and axially reflected by molybdenum (see Fig. 4) [HEU-MET-FAST-093]; two cylinders of HEU, beryllium, beryllium-oxide, and molybdenum reflected by depleted uranium [HEU-MET-FAST-094], and two cylinders of HEU, polyethylene, and molybdenum reflected by polyethylene [HEU-MET-MIXED-020] are now available in the ICSBEP Handbook. The benchmark models are simple with 1σ uncertainties between ± 0.0005 and ± 0.0014 Δk.

The IPEN/MB-01 reactor (zero power critical facility used to simulate light water reactor conditions) in São Paulo, Brazil, has an extensive selection of benchmark experiment data contributed to the ICSBEP and IRPhEP Handbooks. One of the latest evaluations [LEU-COMP-THERM-067] includes four core configurations containing varying arrangements of solid molybdenum metal rods: 20, 24, 28, and 30. There is good agreement between calculated and benchmark experiment eigenvalues, approximately within the benchmark 1σ uncertainty of ±0.0005 Δk.

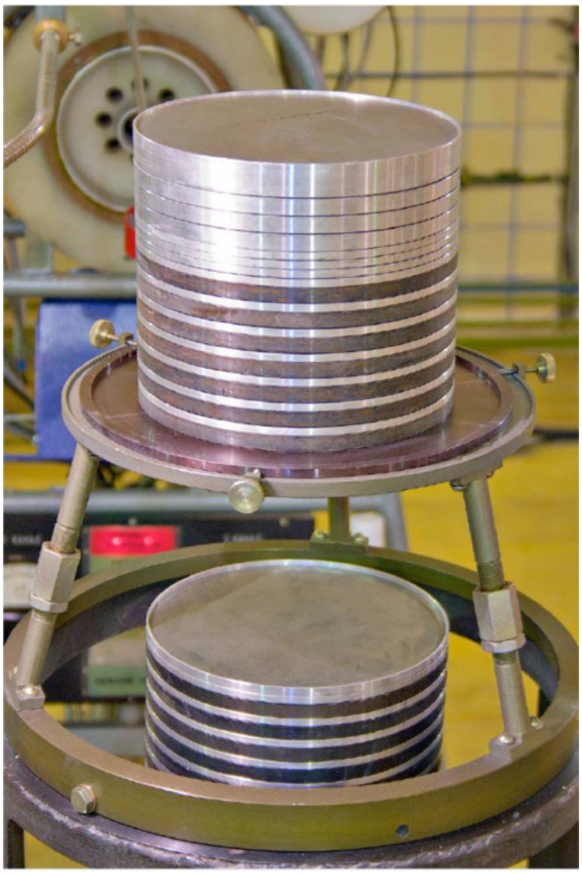

Figure 4. Molybdenum-diluted HEU cylinder approach to critical.

3.7. Graphite data

Of the numerous graphite- and polyethylene-reflected HEU metal experiments reported for the Oak Ridge Critical Experiments Facility (ORCEF), three configurations for bare annuli with internal graphite cores were evaluated [HEU-MET-FAST-077] following prior evaluation of HEU annuli and cylinders reflected by thin graphite reflectors [HEU-MET-FAST-071] from the same experimental series. These experiments are reported with high accuracy and precision for dimensions and mass of the assembly components, resulting in a 1σ uncertainty in k_{eff} of ±0.0006 Δk.

An evaluation of the Japan Atomic Energy Agency (JAEA) Very High Temperature Reactor Critical Assembly (VHTRC) [VHTRC-GCR-EXP-001] was prepared for inclusion in the IRPhEP Handbook. The VHTRC was constructed to verify the calculation accuracy related to the neutronic design of the High Temperature Engineering Test Reactor (HTTR). The core of the VHTRC consists of pin-in-block type fuel using carbon-coated particles of $LEUO_2$ (2 and 4 wt.% enriched) moderated and reflected by significant quantities of graphite. The temperature effect on reactivity in the VHTRC core is the main focus of this evaluation. Benchmark specifications for seven critical configurations at isothermal temperatures between 8 °C to 200.3 °C and temperature reactivity coefficient measurements are currently available.

The Paul Scherrer Institute (PSI) HTR-PROTEUS experimental program was conducted to provide benchmark data for assessing reactor physics computer codes for high temperature reactors. Moderator and fuel pebbles (containing 16.7 wt.% ^{235}U in TRISO particles) were packed with varying arrangements within the core cavity in various moderator-to-fuel ratios. A comprehensive amount of data was measured during the course of the four-year program. The remaining seven critical configurations (Cores 4, 5 through 8, and 9 & 10) were evaluated in three additional benchmark reports [PROTEUS-GCR-EXP-002, −003, and −004], complementing previous benchmark evaluation work on Cores 1 through 3 [PROTEUS-GCR-EXP-001]. PROTEUS is a zero-power research reactor based on a cylindrical graphite annulus with a central cylindrical cavity. Cores 1, 1A, 2, and 3 have hexagonal close packing with a 1:2 moderator-to-fuel pebble ratio; Core 4 has random packing with a 1:1 moderator-to-fuel pebble ratio; Cores 5, 6, 7, and 8 have columnar hexagonal point-on point packing with a 1:2 moderator-to-fuel pebble ratio; and Cores 9 and 10 also have columnar hexagonal point-on point packing with a 1:1 moderator-to-fuel pebble ratio. All core configurations, except Core 4, were hand-stacked such that exact placement of the each pebble type was known. Benchmark specifications are available for all critical configurations, but currently, only reactivity effects measurements are available for Cores 4 through 10.

3.8. Heavy metal reflectors data

The IPEN/MB-01 reactor was also utilized to perform thirty-five critical experiments with the west face of the reactor covered by a set of either carbon steel or nickel laminates to simulate a heavy reflector [LEU-COMP-THERM-088, IPEN(MB01)-LWR-RESR-015]. Each laminate was approximately 3 mm thick and large enough to completely cover the active core region of the reactor. The configurations include a reference case with no laminate reflectors and seventeen configurations for each reflector type, using up to 32 laminate plates in the thickest configuration for each metal reflector (see Fig. 5). These experimental data are useful to validate calculations comparing water moderation versus iron/nickel reflection, with the most notable discrepancy in calculations identified at the point where the further addition of metal laminates increases core reactivity through neutron backscatter instead of reducing it due to reduction in core moderation.

3.9. Heavy water data

The RB (Reactor B) reactor (critical facility) at the Vinča Institute of Nuclear Sciences in Belgrade, Serbia, operates using natural or LEU metal fuel in a heavy water tank. Three critical configuration were evaluated for testing neutron accident dosimeters for the IAEA (International Atom Energy Agency) in 1973, for testing an External Neutron Converter (ENC) in 1978, and for investigation of an Experimental Fuel Channel (EFC) in 1982 for creation of an epithermal and fast neutron spectrum in the center of the core [RB-FUND-EXP-001, −002, and −007, respectively]. The 1σ benchmark uncertainty is $\pm$0.0010 Δk, $\pm$0.0015 Δk, and $\pm$0.0018 Δk, respectively, for the three configurations. Neutron spectral and spatial distributions, as well as gamma ray dose rate benchmark measurements are provided for the ENC configuration.

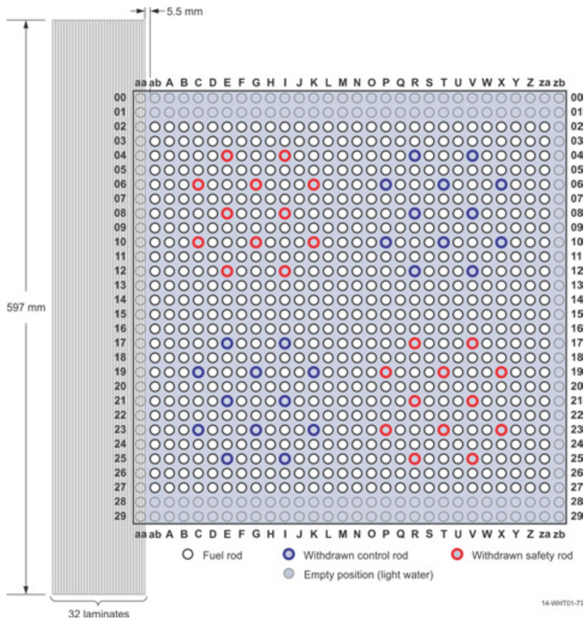

Figure 5. IPEN/MB-01 reactor with 32 nickel plates.

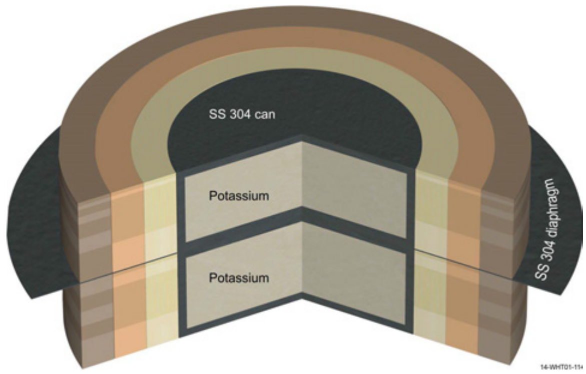

Figure 6. Oralloy metal annuli with potassium-filled steel cans.

3.10. Potassium data

A pair of critical configurations were evaluated from ORCEF that were performed to test the fast neutron cross sections of potassium [HEU-MET-FAST-099, ORCEF-SPACE-EXP-001] as it was a candidate for coolant in some early space power reactor designs, such as the MPRE program. Oralloy annuli were stacked around two empty stainless steel cans for the first configuration. The second configuration (as shown in Fig. 6) used an identical loading except that the stainless steel cans were filled with approximately 2.4 kg of potassium. The benchmark worth of the potassium is 11.4 $\pm$ 1.2 ¢ (4.8 $\pm$ 0.5 ¢/kg); however Monte Carlo calculations of the addition of potassium are approximately 70% to 80% lower than the benchmark value. Currently this evaluation represents the only benchmark available for integral testing of potassium cross section data until the aforementioned SCCA potassium measurement is completed. The identification and evaluation of additional potassium-sensitive integral benchmark data would be welcome additions to the ICSBEP and IRPhEP Handbooks.

3.11. Neutron streaming through sodium data

The ANL ZPPR-12 assembly represented a clean, cylindrical, single-zone core mock-up used to study fuel properties of the Clinch River Breeder Reactor (CRBR) [ZPPR-LMFR-EXP-010]. Measurements included sodium void worth, cell heterogeneity, neutron streaming, and a discrepancy between calculated and measured control rod worths. A critical configuration and the sodium void worth measurements, including neutron streaming, are currently evaluated. One purpose of the ZPPR-12 was to compare sodium void worth measurements in a plate-loaded core versus a pin-loaded core. Sufficient information was unavailable to evaluate the pin-loaded core as a benchmark. Part of the plate-loaded core analysis included rearrangement of the plates to maximize and reduce neutron streaming through the sodium region of the core. The uncertainty in the evaluated measurements is rather large for a benchmark evaluation supporting integral neutron data validation of sodium, the information is useful when considering applications where the simulation of neutron streaming might be of interest.

4. Conclusions

The ICSBEP and IRPhEP continue to provide high-quality integral benchmark data from around the world that are of great value for nuclear data testing, uncertainty reduction, criticality safety, reactor physics, and advanced modelling and simulation. Data contributed from 25 countries to these projects will be of value for future decades, enabling current and future activities as long as experimental validation remains relevant.

The ICSBEP and IRPhEP are collaborative efforts that involve numerous scientists, engineers, administrative support personnel, and program sponsors from 25 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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