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Benchmark Evaluation of Reduced Enrichment Experiments to Expand Available International Handbook Validation Data

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ABSTRACT

The International Criticality Safety Benchmark Evaluation Project (ICSBEP) and International Reactor Physics Experiment Evaluation Project (IRPhEP) provide well-respected handbooks containing extensively peer-reviewed validation benchmarks in support of nuclear data and software. These projects have enabled efforts in nuclear safety, waste storage, transportation, reactor design, training, etc., culminating in over 5000 benchmark configurations representing various types of fuels, materials, and geometries implemented in the nuclear fuel cycle. Experiments performed to support reactor conversion can further expand existing international benchmark databases. The converted reactor cores provide experimental data beyond criticality with fresh fuel and upgraded facilities. Comparison of HEU vs LEU reactor loadings enable further interrogation into the capabilities and limitations of modern nuclear codes and data. Irradiation experiments performed to evaluate and test new fuel types and designs further provide a level of experimental detail and quality not typically available to support modern validation efforts.

1 Introduction

The International Criticality Safety Benchmark Evaluation Project (ICSBEP) was established to identify a comprehensive data set of verified criticality benchmark data, evaluate the data and quantify overall uncertainties, compile the data into a standardized format, perform calculations of each experiment with standard criticality safety codes, and formally document the work in to a single source of verified benchmark data. [1] Over two decades of international collaboration under the auspices of the OECD NEA have led to the development and continued contribution to the well-established international benchmark standards contained within the International Handbook of Evaluated Criticality Safety Benchmark Experiments (ICSBEP Handbook). [2] The contents of the ICSBEP Handbook include benchmark specifications that have been derived from experiments performed at various nuclear facilities worldwide. These benchmark specifications are intended for use by criticality safety engineers to validate their calculation techniques and establish margins for safe use of fissile material, including the determination of requirements and placement of criticality alarms. Many of these benchmark specifications have also been found useful for the testing of nuclear data.

The International Reactor Physics Experiment Evaluation Project (IRPhEP) [3] was established to preserve and evaluate integral reactor physics experiment data, including separate or special effects measurements for nuclear energy and technology applications. Numerous international experiments have been performed over the past several decades to support reactor operations, safety, measurements, and design. Those experiments represent a significant investment of infrastructure, cost, and expertise that, in many instances, cannot be as easily reproduced. They represent valuable resources of data for present and future research, and provide the basis for recording, development, and validation of methods [4]. The IRPhEP was closely patterned after the ICSBEP and has been coordinated closely with the ICSBEP so as to avoid duplication of efforts and publication of conflicting information. Some benchmarks are applicable to both the nuclear criticality safety and reactor physics technology communities, and as such, are published in both the ICSBEP Handbook and the International Handbook of Evaluated Reactor Physics Benchmark Experiments (IRPhEP Handbook). [5] The IRPhEP Handbook provides benchmark specifications intended for use by reactor designers, safety analysts, and nuclear data evaluators to validate computational techniques and data.

Both of these handbooks undergo extensive peer review more rigorous than most publications and are available freely to member countries of the OECD NEA and countries actively participating in the respective international benchmark projects. The ICSBEP Handbook includes data from 574 evaluations containing benchmark specifications for 4,916 critical, subcritical, or near-critical configurations representing contributions from over 20 countries. There is a total of seven criticality-alarm-placement/shielding evaluations containing a total of 45 benchmark configurations, and eight fundamental physics evaluations containing a total of 215 measurements relevant to criticality safety applications. The IRPhEP Handbook currently contains a total of 159 experimental measurement series from 54 unique reactor facilities from 20 different countries. Further information regarding ongoing activities of these projects and to request a free copy of the handbooks, use the following webpage links:
ICSBEP: https://www.oecd-nea.org/science/wpncs/icsbep/
IRPhEP: https://www.oecd-nea.org/science/wprs/irphe/

These efforts consolidate and preserve an international nuclear information base; retrieve lost data; identify areas where additional data are necessary; incorporate resource from the international community to fill identified data gaps; identify discrepancies between calculations and experiments resulting from deficiencies in reported experimental data, cross section data, cross section processing codes and neutronics codes; eliminate large quantities of redundant research and processing of existing data; and improve future experiment planning, execution, and reporting.

The expertise, practices, methodologies, and application to support and sustain integral benchmark data initially developed through the ICSBEP can be applied towards expanded success in evaluation and utilization in various other areas for modernized computational validation. An overview of the rigorous process from experimental data, through the benchmark evaluation, to the end user, is shown in Figure 1.

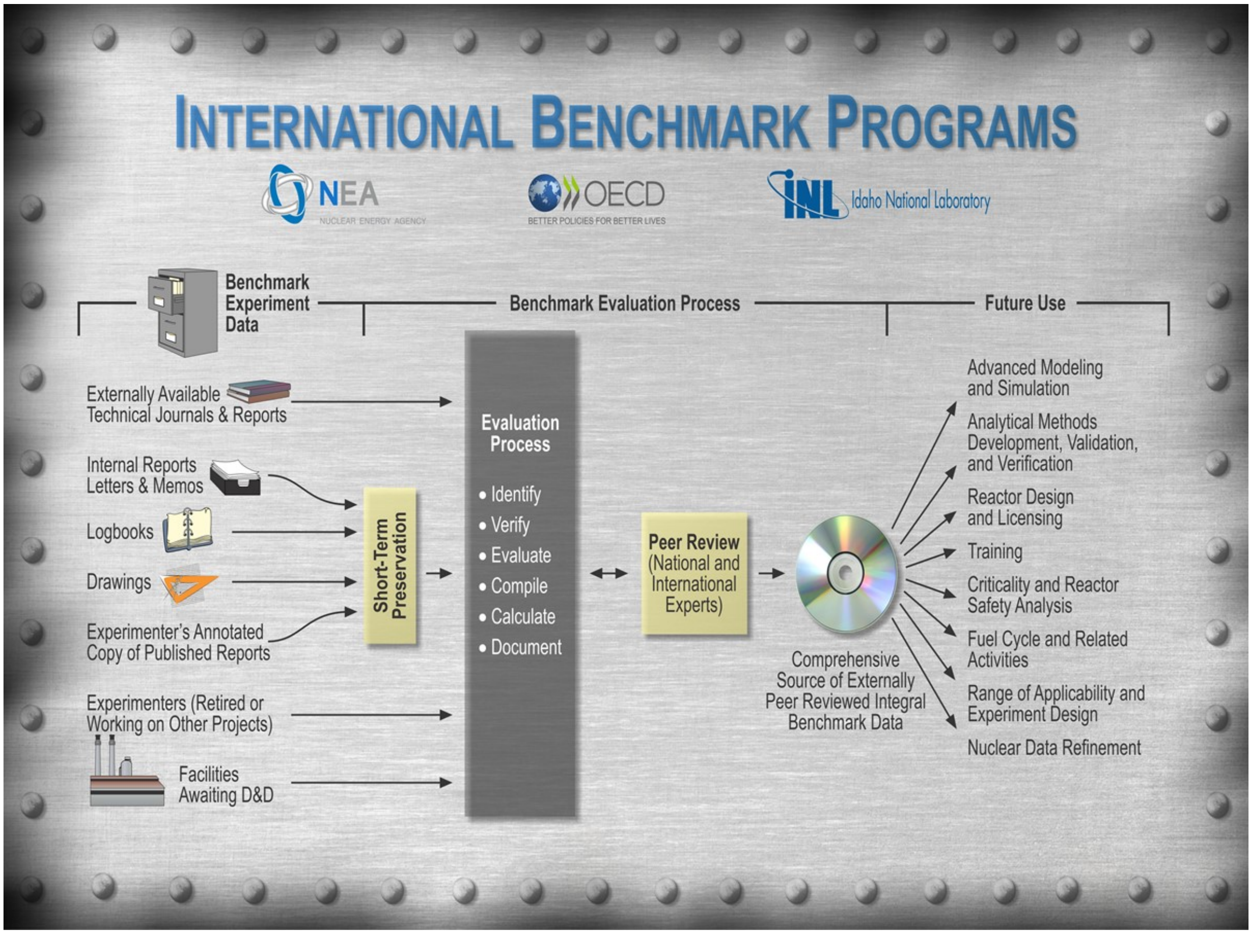

Figure 1. Overview of the Benchmark Evaluation Process.

One of the most significant challenges in benchmark evaluation remains the availability of experimental data from which high-quality benchmarks can be prepared. Detailed characterization of facility specifications, measurement practices, fuel and material properties, detection capabilities and limitations, known biases and uncertainties, etc., represent just some of the data lost through time pertaining to legacy nuclear reactors and their associated experimental measurements and tests. Preservation of these measurements, in conjunction with a thorough benchmark analysis, can provide international benchmark data to the existing ICSBEP and IRPhEP Handbooks. The quality design and modeling necessary for provisioning conventional research reactors with reduced enriched fuel entails comprehensive characterization that can be implemented as part of the benchmark evaluation process. These opportunities enable validation of modern codes and nuclear data; design and development support of new reactor types using low enriched uranium (LEU) fuel; criticality safety analysis for the transportation, storage, reprocessing, and ultimate disposal of 20 wt.% enriched LEU fuel types; and well-characterized experiment results supporting High Power Research Reactor (HPRR) conversion, including the validation of new fuel types.

2 Example Benchmark Evaluations

Current 20 wt.% Enriched Benchmark Evaluation on the ICSBEP Handbook

There is currently a very limited number of benchmark evaluations on the ICSBEP Handbook with uranium fuel enriched to approximately 20 wt.% ^{235}U. Of the nearly 5000 cases, only 32 criticality cases have fuel enrichments within ±1 wt/%, and 50 within ±5 wt.%. Most of the fuel forms utilized in these benchmark experiments were in uranium metal or oxide form. There is very little data for other fuel types, and none for LEU UMo fuel, which is being tested for use in HPRRs. A summary of the current available benchmarks supporting 20 wt.% enriched uranium fuel is provided in Table 1.

Neutron Radiography (NRAD) Reactor

The neutron radiography (NRAD) reactor is a 250 kW TRIGA® (Training, Research, Isotopes, General Atomics) Mark II tank-type research reactor at the Idaho National Laboratory (INL). It is primarily utilized for indirect neutron radiography analysis of both irradiated and unirradiated fuels and materials. The NRAD reactor core was completely defueled and refueling with LEU begining in September 2009; start-up testing after the HEU-to-LEU fuel conversion of the NRAD TRIGA reactor was performed between March and June 2010, with a core loading of 60 fuel elements. Because the core excess reactivity was lower than originally predicted and would not allow for extended operations, the NRAD reactor core was later upgraded via the addition of four fuel elements and four graphite elements. Start-up measurements for the upgraded NRAD core were performed in April 2013. [6] Complete benchmark evaluation reports for the initial start-up measurements [7] and the final upgraded core [8] are available in the IRPhEP Handbook.

The benchmark evaluation of the NRAD reactor has been beneficial in characterizing the uncertainties in k_{eff}, rod worth measurements, and graphite reflector block worth measurements. Biases between high-fidelity computational models and experimental measurements in k_{eff} have been attributed to uncertainties and errors in nuclear data that can be resolved through further benchmark evaluation of UErZrH and UZrH fueled reactors followed by further nuclear data adjustment. The development of a benchmark model, shown in Figure 2, has also been of benefit to the user facility to support analyses for experiment design and core loading management. Potential facility users also have the ability to utilize the verified and validated models to support the design of their proposed experiments.

Table 1. Currently Available ~20 wt.% ^{235}U Benchmarks on ICSBEP Handbook.

Evaluation ID	Evaluation Title	# Cases	wt.% ^{235}U	Fuel Form
IEU-MET-FAST-002	Natural Uranium Reflected Assembly of Enriched and Natural Uranium Plates	1	16.19	Uranium Metal
IEU-MET-FAST-012	ZPR-3 Assembly 41: A Cylindrical Assembly of U Metal (16% ^{235}U), Aluminum, and Steel, Reflected by Depleted-Uranium	1	16.79	Uranium Metal
IEU-MET-FAST-014	ZPR-9 Assemblies 2 and 3: Cylindrical Assemblies of U Metal and Tungsten with Aluminum Reflectors	2	15.5 & 20.54	Uranium Metal
IEU-MET-FAST-020	The FR0 Series 1: Copper-Reflected "Cylindrical" Uranium (20 % ^{235}U) Metal	9	20.05	Uranium Metal
IEU-MET-FAST-021	The FR0 Series 4: 20%-Enriched "Cylindrical" Uranium Metal Reflected by Natural Uranium	1	20.05	Uranium Metal
IEU-MET-FAST-022	The FR0 Experiments with Diluted 20%-Enriched "Cylindrical" Uranium Metal Reflected by Copper	7	20.05	Uranium Metal
IEU-SOL-THERM-001	Graphite-Reflected Uranyl Sulphate (20.9% ^{235}U) Solutions	4	20.71	Uranyl Sulfate
IEU-COMP-FAST-004	ZPR-3 Assembly 12: A Cylindrical Assembly of Highly Enriched Uranium, Depleted Uranium and Graphite with an Average ^{235}U Enrichment of 21 Atom %	1	20.98	Uranium Metal
IEU-COMP-INTER-005	ZPR-6 Assembly 6A: A Cylindrical Assembly with Uranium Oxide Fuel and Sodium with a Thick Depleted-Uranium Blanket	1	16.35	Uranium Metal & Uranium Oxide
IEU-COMP-INTER-006	Single Cores of 30.14% ^{235}U Enriched UO_2 / Wax Mixtures – Bare and with Single Reflector Materials	1	23.67	Uranium Oxide
IEU-COMP-THERM-002	Water-Moderated $U(17)O_2$ Annular Fuel Rods without Absorber and with Gadolinium or Cadmium Absorbers in 6.8-Cm-Pitch Hexagonal Lattices at Different Temperatures	6	17	Uranium Oxide
IEU-COMP-THERM-003	TRIGA Mark II Reactor: U(20) – Zirconium Hydride Fuel Rods in Water with Graphite Reflector	2	19.9	Uranium Hydride
IEU-COMP-THERM-008	Graphite Annular Core Assemblies with Spherical Fuel Elements Containing Coated UO_2 Fuel Particles	5	20.91	Uranium Oxide
IEU-COMP-THERM-009	Power Burst Facility: $U(18)O_2$-CaO-ZrO_2 Fuel Rods in Water	2	18.31	Uranium Oxide
IEU-COMP-THERM-010	Evaluation of the Initial Critical Configuration of the HTR-10 Pebble-Bed Reactor	1	17	Uranium Oxide
IEU-COMP-THERM-013	Fresh-Core Reload of the Neutron Radiography (NRAD) Reactor With Uranium(20)-Erbium-Zirconium-Hydride Fuel	1	19.74	Uranium Hydride
IEU-COMP-THERM-014	RA-6 Reactor: Water Reflected, Water Moderated $U(19.77)_3Si_2$-Al Fuel Plates	1	19.77	Uranium Silicide
IEU-COMP-MIXED-002	Unreflected UF_4-CF_2 Blocks with Uranium of 30, 25, 18.8, and 12.5% ^{235}U	4	18.93 & 21.16	Uranium Tetrafluoride
	Total	**50**		

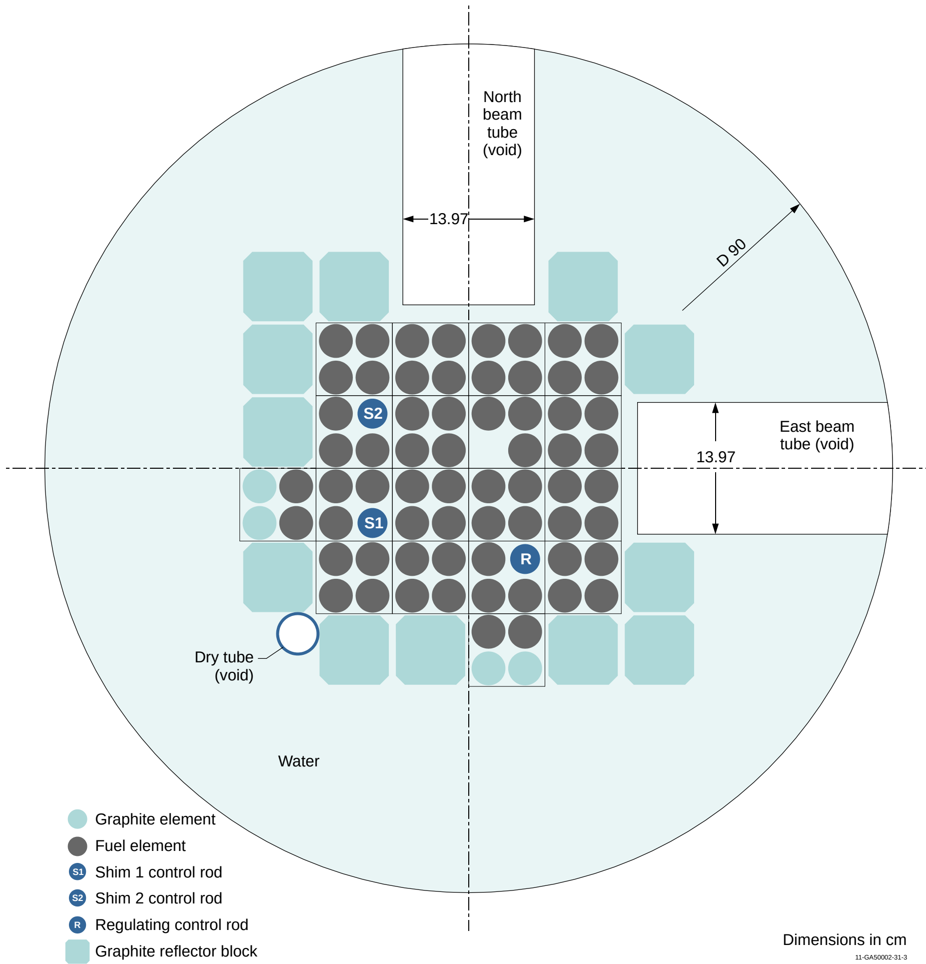

Figure 2. NRAD Benchmark Model Mid-Plane Cross Section (64 Fuel Element Loading) [8].

Molybdenum Rod Measurements in IPEN Reactor

A series of critical experiments with water-moderated square-pitched lattices with $LEUO_2$ fuel (4.346 wt.% ^{235}U) and molybdenum metal rods was conducted at the IPEN/MB-01 research reactor facility, located in the city of São Paulo, Brazil, in 2014 [9]. The IPEN/MB-01 reactor has been utilized for basic reactor-physics research and as an instructional laboratory system. The core of the reactor was configured with fuel and molybdenum rods to test the nuclear data for molybdenum under light water reactor conditions at room temperature. A variable number of fuel and molybdenum rods were used for each case in the experiments. Case 1, with 30 molybdenum rods, is shown in Figure 3. Comparison of computational results with the benchmark eigenvalues demonstrated agreement within the 1σ uncertainty of ± 50 pcm.

A more recent set of experiments from the IPEN facility includes critical experiments performed with an array of U7Mo plate fuel enriched to 19.80 % located in the center of the IPEN/MB-01 core. These experiments were performed in 2016 and are currently under review for inclusion in the 2019 edition of the ICSBEP Handbook. Preliminary results demonstrate excellent agreement between modern Monte Carlo calculation measurements and the benchmark eigenvalues.

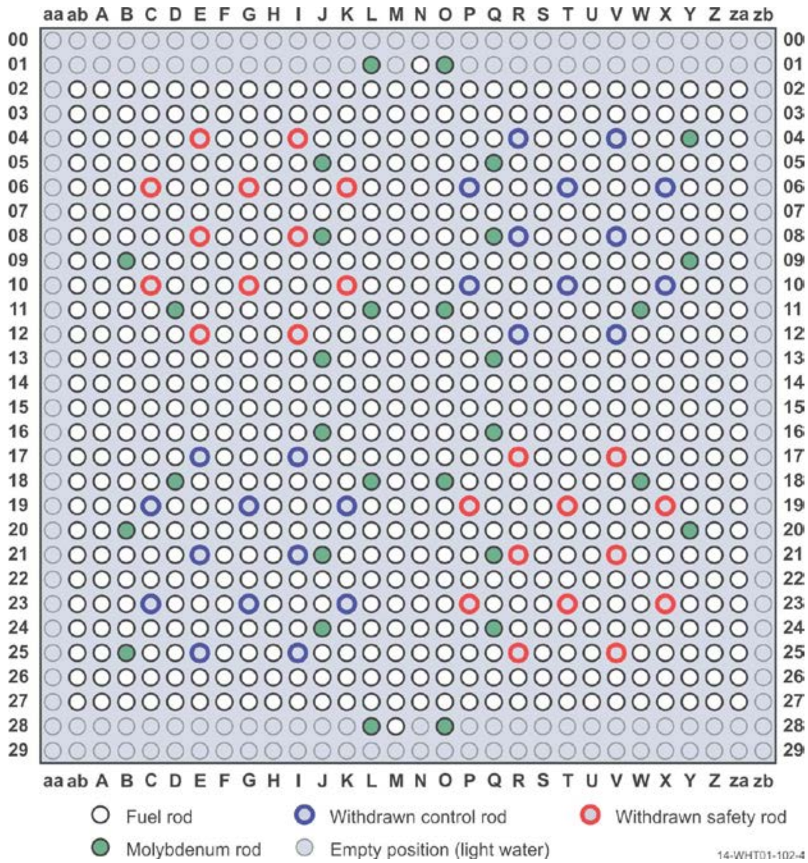

Figure 3. Core Configuration for the IPEN/MB-01 Reactor with 30 Molybdenum Rods [9].

3 Opportunities for Benchmark Evaluation

With the conversion of many research reactors to LEU fuel types, there are various opportunities to prepare benchmark evaluations from the start-up characterization tests and subsequent measurements and tests performed since (see Table 2). The wide gambit of different reactor types with varying fuels and components can provide significant value to the current validation databases to support modeling and simulation activities and promote nuclear data evaluation improvement. Experiments performed as part of fuel development could also provide unique and valuable validation databases. Two, of numerous international examples, irradiation experiments are briefly summarized below.

Advanced Test Reactor Critical (ATRC) Facility Experiments

Experiments performed in the Advanced Test Reactor (ATRC) Facility represent high-quality and well-characterized experiments in a low-power highly enriched uranium (HEU) reactor environment simulating that of the ATR HPRR. High-fidelity experiments performed within an HEU core and then later within the same LEU core facilitate detailed comparison between fuel types within the same reactor environment. Similarly, demonstrated measurement and calculation changes in the ATRC can be applied to the ATR to further understand new LEU plate fuel performance and expectations for implementation in other HPRRs. Recommended experiments from the ATRC for comprehensive benchmark evaluation and submission to the IRPhEP includes detailed neutron spectra measurements in key irradiation positions [10], fuel element-to-element power distributions with intra-element fission distributions [11], and a series of measurements performed with the KiJang Research Reactor (KJRR) LEU-Mo fuel assembly in an experiment test position [12].

Table 2. Research Reactor Converted to LEU (* denotes benchmarks(s) available).

Country	Facility	Country	Facility
Argentina	RA-3	Netherlands	HFR
Argentina	*RA-6	Pakistan	PARR-1
Australia	HIFAR	Philippines	PRR-1
Austria	TRIGA II	Poland	Maria Research Reactor
Austria	ASTRA	Portugal	RPI
Brazil	IEA-R1	Romania	SSR Pitesti
Canada	NRU - National Research Universal Reactor	Russia	ARGUS
Canada	Slowpoke - 2 Montreal	Slovenia	*TRIGA-MARK II
Canada	MNR McMaster	South Africa	SAFARI-1 - Building 1800
Chile	RECH-1	Sweden	R2
China	HFETR	Sweden	R2-0
China	HFETR CA	Switzerland	*Paul Scherrer Institute (PSI)
China	MJTR	Taiwan	THOR
China	CIAE Beijing MNSR-IAE	Turkey	TR-2
Colombia	IAN-R1	Ukraine	WWR-M
Czech Republic	VR-1 Vrabec (Sparrow)	USA	Michigan, Ford
Czech Republic	REZ 10 MW Research Reactor	USA	RTR - Critical Assembly, RPI
Denmark	DR-3	USA	RTR - GE, Worcester Poly Research Reactor
France	Osiris	USA	RTR - Research Reactor
Germany	FRG-1	USA	RTR - UTR-10
Germany	BER-II	USA	Manhattan College Zero Power Reactor
Ghana	GHARR-1 MNSR	USA	MSTR Building
Greece	GRR-1	USA	Rhode Island Nuclear Science Center
Hungary	BRR	USA	Georgia Institute of Technology Research Reactor
Iran	TRR (NRCRR)	USA	University of Virginia Reactor
Jamaica	Slowpoke UWI CNS	USA	RTR - University Of Massachusetts Lowell RTR
Japan	JMTR	USA	RTR - Texas A&M Nuclear Science Center Reactor
Japan	JRR-4	USA	RTR - University of Florida Training Reactor
Japan	KUR	USA	RTR - Electrical Engineering Building
Kazakhstan	VVR-K CA	USA	RTR - Nuclear Radiation Center
Kazakhstan	VVR-K	USA	RTR - OSU
Libya	Critical Facility	USA	RTR - University of Wisconsin - Research Reactor
Libya	IRT-1	USA	*NRAD - Neutron Radiography Reactor
Mexico	TRIGA Mark III	Uzbekistan	VVR-SM
Netherlands	HOR	Vietnam	Dalat Research Reactor

UMo Fuel Plate Tests

Irradiation test have been and will be performed in the Advance Test Reactor and the BR2 Reactor to support the fuel development and qualification effort for high-density UMo fuels (Figure 4). [13] Detailed design planning, characterization, computational assessment, and measurements are involved with each of the many irradiation tests performed. Benchmark evaluation of these experiments provides these experiment measurements with additional international peer review while providing the international community with high-quality, well-characterized, benchmarks to support validation of methods, computational models, and nuclear data. Furthermore, the additional post irradiation experiments (PIE) and burnup data inherent with these types of measurements can provide a level of experiment data above and beyond what is currently available for typical validation efforts.

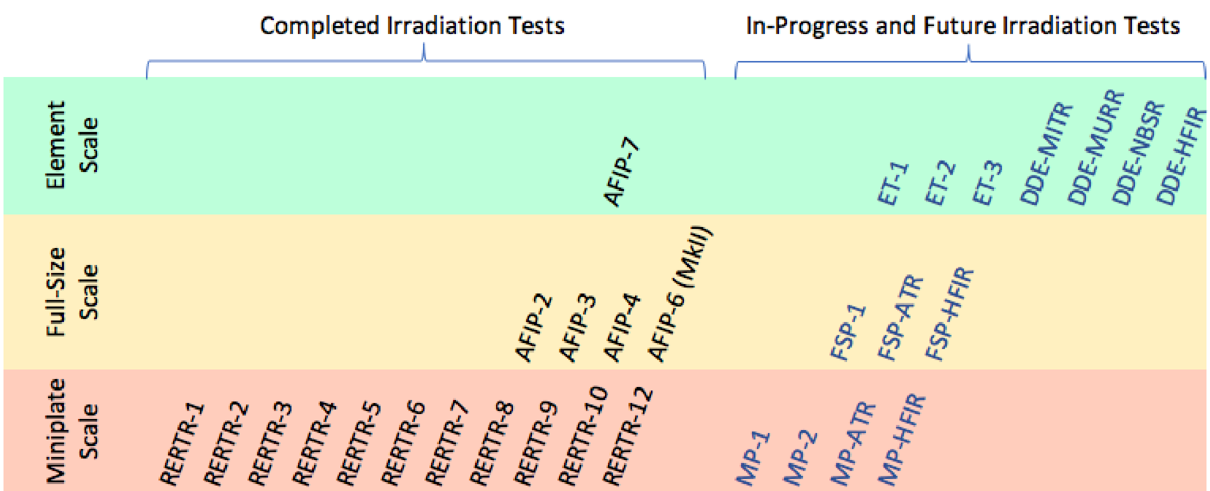

Figure 4. Irradiation Testing to Support Conversion of U.S. High Performance Research Reactors.

4 Conclusions

The extensive validation database currently found in the ICSBEP and IRPhEP Handbooks can be significantly augmented with benchmark experiment data obtained from reactors converted from HEU to LEU and the series of ongoing experiments performed to support the conversion of plate fuel research reactors. A limited quantity of benchmarks currently exists for systems containing 20 % enriched uranium fuel. Benchmark evaluations for the NRAD reactor and IPEN/MB-01 are current examples of what can be evaluated. Experiments performed in the ATR, and similar facilities, would provide high-quality data unique to supporting PIE and burnup validation.

5 Acknowledgments

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6 References

[1] J. B. Briggs, L. Scott, A. Nouri, "The International Criticality Safety Benchmark Evaluation Project," *Nucl. Sci. Eng.*, **145**, 1-10 (2003).

[2] *International Handbook of Evaluated Criticality Safety Benchmark Experiments*, NEA/NSC/DOC(95)/03, OECD-NEA, Paris, France (2018).

[3] J. B. Briggs, J. Gulliford, "An Overview of the International Reactor Physics Experiment Evaluation Project," *Nucl. Sci. Eng.*, **178**, 269-279 (2014).

[4] G. Palmiotti, J. B. Briggs, T. Kugo, E. Trumble, A. C. Kahler, D. Lancaster, "Applications of Integral Benchmark Data," *Nucl. Sci. Eng.*, **178**, 295-310 (2014).

[5] *International Handbook of Evaluated Reactor Physics Benchmark Experiments*, NEA/NSC/DOC(2006)1, OECD-NEA, Paris, France (2018).

[6] J. D. Bess, T. L. Maddock, A. T. Smolinski, M. A. Marshall, "Evaluation of Neutron Radiography Reactor LEU-Core Start-Up Measurements," *Nucl. Sci. Eng.*, **178**, 1-12 (2014).

[7] J. D. Bess, T. L. Maddock, M. A. Marshall, "Fresh-Core Reload of the Neutron Radiography (NRAD) Reactor with Uranium(20)-Erbium-Zirconium-Hydride Fuel," NRAD-FUND-RESR-001, *International Handbook of Evaluated Reactor Physics Benchmark Experiments*, NEA/NSC/DOC(2006)1, OECD-NEA, Paris, France (2018).

[8] J. D. Bess, "Neutron Radiography (NRAD) Reactor 64-Element Core Upgrade," NRAD-FUND-RESR-002, *International Handbook of Evaluated Reactor Physics Benchmark Experiments*, NEA/NSC/DOC(2006)1, OECD-NEA, Paris, France (2018).

[9] A. dos Santos, et al., "Critical Loading Configurations of the IPEN/MB-01 Reactor Composed of Fuel and Molybdenum Rods," LEU-COMP-THERM-067, *International Handbook of Evaluated Criticality Safety Benchmark Experiments*, NEA/NSC/DOC(95)/03, OECD-NEA, Paris, France (2018).

[10] J. W. Nielsen, D. W. Nigg, D. R. Norman, "Extension of the Advanced Test Reactor Operating Envelope via Enhanced Reactor Physics Validation Techniques," *Nucl. Tech.*, **201**, 228-246 (2018).

[11] J. W. Nielsen, D. W. Nigg, A. W. LaPorta, "A Fission Matrix Based Validation Protocol for Computed Power Distributions in the Advanced Test Reactor," *Nucl. Eng.*, **295**, 615-624 (2015).

[12] J. W. Nielsen, D. W. Nigg, "Physics Validation Measurements for the KJRR Experiment in the ATRC," ECAR-2996, Idaho National Laboratory (2015).

[13] N. E. Woolstenhulme, J. I. Cole, I. Glagolenko, K. K. Holdaway, G. K. Housley, B. H. Rabin, "Irradiation Tests Supporting LEU Conversion of Very High Power Research Reactor in the US," *37th International Meeting on Reduced Enrichment for Research and Test Reactors (RERTR 2016)*, Antwerp, Belgium, October 23-27 (2016).