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Providing Nuclear Criticality Safety Analysis Education Through Benchmark Experiment Evaluation

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INTRODUCTION

One of the challenges that today's new workforce of nuclear criticality safety engineers face is the opportunity to provide assessment of nuclear systems and establish safety guidelines without having received significant experience or hands-on training prior to graduation. Participation in the International Criticality Safety Benchmark Evaluation Project (ICSBEP) and/or the International Reactor Physics Experiment Evaluation Project (IRPhEP) provides students and young professionals the opportunity to gain experience and enhance critical engineering skills.

DESCRIPTION OF THE ACTUAL WORK

Both the ICSBEP and IRPhEP publish new editions of their respective benchmark handbooks each year that contain an ever-growing collection of collaborative international evaluations. The September 2009 edition of the ICSBEP Handbook[1] contains approximately 4,295 critical or subcritical benchmark configurations, twenty-four criticality-alarm/shielding benchmark configurations, and 200 fundamental physics benchmark quantities representing efforts from 20 contributing countries. The March 2009 edition of the IRPhEP Handbook[2] provides benchmarks from 36 experimental series from 21 reactor facilities representing efforts from 15 contributing countries.

Benchmark procedures require the student to investigate the background, methods, and results of the experiment being evaluated. Often experiments were performed with the intention to provide data for safety assessments and may have been subsequently utilized in the development of criticality safety standards. When possible, the original experimenters are contacted to clarify published documentation.

Additional research and often engineering judgment is required when an evaluator must assess incomplete or misleading experimental information throughout the course of the benchmark evaluation. Members of the ICSBEP and IRPhEP team, as well as other laboratory or institute personnel provide their expertise in developing an in-depth evaluation. The skills, tools, and network development established during this experience is of great benefit to students returning to their universities and young professional engineers entering the workforce.

The evaluator must also develop and analyze computational models of the experiment to assess uncertainty in the benchmark and provide benchmark specifications. Each evaluation report must undergo a thorough review by experienced staff with the evaluator's organization. The internal reviewer will often provide additional guidance prior to submission to an independent review from the international criticality safety, nuclear data, or reactor physics communities.

Once the independent review is completed and all concerns resolved, each evaluation report is submitted to the respective ICSBEP or IRPhEP Technical Review Group for review prior to the annual meeting. Each Technical Review Group is comprised of 30 to 40 experts from the international community. Evaluation reports that are proposed for publication in the ICSBEP or IRPhEP Handbooks are each discussed in detail at the Technical Review Meeting. Review group comments must be resolved prior to prior to publication in the respective Handbook. Evaluators are also encouraged to submit their activities for a presentation at professional conferences.

Student and young professional participation in the benchmark process is of benefit to the ICSBEP and IRPhEP, the various international user communities, the professional development of the individual, and ultimately, the company or laboratory at which the individual finds employment.

RESULTS

National laboratory, institute, university and industry participation in the ICSBEP and IRPhEP has provided benchmark research and evaluation experience to at least 30 students since 1995. Over that period students have authored or coauthored 51 ICSBEP or IRPhEP evaluations and several technical papers for various conferences and journals. A summary of student contributions to the ICSBEP and IRPhEP is given in Table 1.

ACKNOWLEDGMENTS

The ICSBEP and IRPhEP are collaborative efforts that involve numerous scientists, engineers, administrative support personnel, and program sponsors from 22 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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REFERENCES

1. *International Handbook of Evaluated Criticality Safety Benchmark Experiments*, NEA/NSC/DOC(95)03, OECD-NEA (2009).

2. *International Handbook of Evaluated Reactor Physics Benchmark Experiments*, NEA/NSC/DOC(2006)1, OECD-NEA, March (2009).

Table 1. Summary of Student Contributions[1] to the ICSBEP and IRPhEP

EVALUATION ID & TITLE (YEAR APPROVED)	AUTHOR[2] (University)	NATIONAL LABORATORY or COMPANY[3]
HEU-MET-FAST-007 – Uranium Metal Slabs Moderated with Polyethylene, Plexiglas, and Teflon (1995)	Catherine Crawford (North Western University)	INL
HEU-SOL-THERM-006 – Experiments with Boron-Poisoned Highly Enriched Uranyl Nitrate Solution (1997)	Catherine Crawford (North Western University)	INL
U233-SOL-THERM-012 – Water-Reflected Spherical Vessels Partially Filled or Filled with $^{233}UO_2(NO_3)_2$ Solution (2002)	Paul Foster (Brigham Young University)	INL
U233-SOL-THERM-013 – Unreflected Spherical Vessels Partially Filled or Filled with $^{233}UO_2(NO_3)_2$ Solution (2003)	Paul Foster (Brigham Young University)	INL
MIX-MISC-THERM-004 – Water-Reflected Triangular-Pitched Lattice of Mixed Oxide Fuel Rods Immersed in Plutonium / Uranyl Nitrate Solution Containing Gadolinium (2003)	Paul Foster (Brigham Young University)	INL
MIX-SOL-THERM-007 – Water-Reflected Plutonium-Uranyl Nitrate Solution Containing Gadolinium (2004)	Wade Butaud (Texas A&M University)	INL
HEU-SOL-THERM-050 – Unreflected Aluminum Cylinders Containing Uranyl Fluoride Solutions (2005)	Wade Butaud (Texas A&M University)	INL
HEU-MET-FAST-076 – Uranium (93.14 ^{235}U) Metal Annuli and Cylinders with Thick Polyethylene Reflectors and/or Internal Polyethylene Moderator (2006)	Tyler Sumner (Georgia Institute of Technology)	INL
HEU-MET-FAST-084 – HEU Metal Cylinders with Magnesium, Titanium, Aluminum, Graphite, Mild Steel, Nickel, Copper, Cobalt, Molybdenum, Natural Uranium, Tungsten, Beryllium, Aluminum Oxide, Molybdenum Carbide, and Polyethylene Reflectors (2007)	Bernard Jones (Georgia Institute of Technology)	INL
HEU-MET-FAST-085 – Highly Enriched Uranium Metal Spheres Surrounded by Copper, Cast Iron, Nickel, Nickel-Copper-Zinc Alloy, Thorium, Tungsten Alloy, or Zinc Reflectors (2007)	Jessica Feener (Georgia Institute of Technology)	INL
PU-MET-FAST-042 – Plutonium Hemispheres Reflected by Steel and Oil (2008)	John D. Bess (University of Utah)	INL
LEU-COMP-THERM-028 – Water-Moderated $U(4.31)O_2$ Fuel Rods In Triangular Lattices with Boron, Cadmium and Gadolinium as Soluble Poisons (2008)	Jose Ignacio Marquez Damian (Georgia Institute of Technology)	INL
LEU-MISC-THERM-004 – $U(4.31)O_2$ Fuel Rods In Uranyl Nitrate Solution Containing Gadolinium (2008)	Jose Ignacio Marquez Damian (Georgia Institute of Technology)	INL
IEU-COMP-THERM-012 – RA-0 Reactor: Graphite Reflected Arrangement of UO_2-Graphite Fuel Rods in Water (2008)	Jose Ignacio Marquez Damian (Instituto Balseiro - Universidad Nacional de Cuyo)	INL

[1] The author's intent is to include all student contributions and extend an apology to any who have inadvertently not been included.
[2] Only student authors are listed. Many evaluation reports include other authors the names of whom may be found in References 1 and 2.
[3] INL – Idaho National Laboratory, WSMS – Washington Safety Management Solutions under subcontract to the INL, ORNL – Oak Ridge National Laboratory, ANL – Argonne National Laboratory, LLNL – Lawrence Livermore National Laboratory, JSI – Jozef Stefan Institute IPPE – Institute of Physics and Power Engineering, NNL – National Nuclear Laboratory.

EVALUATION ID & TITLE (YEAR APPROVED)	AUTHOR[2] (University)	NATIONAL LABORATORY or COMPANY[3]
IEU-COMP-THERM-009 – Power Burst Facility: U(18)O_2-CaO-ZrO_2 Fuel Rods in Water (2009)	Jose Ignacio Marquez Damian Alexis Weir (Instituto Balseiro - Universidad Nacional de Cuyo)	INL
HEU-SOL-THERM-026 – Highly Enriched Uranyl Nitrate in Annular Tanks with Concrete Reflection: 1 × 3 Line Array of Nested Pairs of Tanks (2009)	James Cleaver (Idaho State University)	INL
FFTF-LMFR-RESR-001 – Evaluation of the Initial Isothermal Physics Measurements on the Fast Flux Test Facility, A Prototypic Liquid Metal Fast Breeder Reactor (TBD)	John D. Bess (University of Utah)	INL
HEU-SOL-THERM-034 – Water-Moderated and -Reflected Slabs of Uranium Oxyfluoride (TBD)	Margaret A. Marshall (University of Utah)	INL
HEU-MET-FAST-054 – Concrete Reflected Arrays of Highly Enriched Uranium Cylinders (TBD)	Mackenzie L. Gorham (Idaho State University)	INL
HEU-SOL-THERM-009 – Water-Reflected 6.4-Liter Spheres of Enriched Uranium Oxyfluoride Solutions (1996)	Michelle Pitts (Georgia Institute of Technology)	WSMS
HEU-SOL-THERM-010 – Water-Reflected 9.7 Liter Spheres of Enriched Uranium Oxyfluoride Solutions (1996)	Michelle Pitts (Georgia Institute of Technology)	WSMS
HEU-SOL-THERM-011 – Water-Reflected 17 Liter Spheres of Enriched Uranium Oxyfluoride Solutions (1996)	Michelle Pitts (Georgia Institute of Technology)	WSMS
HEU-SOL-THERM-012 – Water-Reflected 91-Liter Sphere Of Enriched Uranium Oxyfluoride Solution (1996)	Michelle Pitts (Georgia Institute of Technology)	WSMS
HEU-SOL-THERM-013 – Unreflected 174-Liter Spheres Of Enriched Uranium Nitrate Solutions (1996)	Michelle Pitts (Georgia Institute of Technology)	WSMS
LEU-SOL-THERM-002 – 174 Liter Spheres Of Low Enriched (4.9%) Uranium Oxyfluoride Solutions (1997)	Michelle Pitts (Georgia Institute of Technology)	WSMS
PU-MET-FAST-016 – Flooded 3x3x3 Arrays of 3-Kg Plutonium Metal Cylinders - Phase 1 (1997)	Michelle Pitts (Georgia Institute of Technology)	WSMS
PU-MET-FAST-037 – Flooded 2x2xN Arrays of 3-Kg Plutonium Metal Cylinders - Phase 2 (1998)	Michelle Pitts (Georgia Institute of Technology)	WSMS
MIX-COMP-THERM-005 – Water-Moderated Mixed Plutonium-Uranium Oxide Pins, 4.0 Wt.% PuO_2, 18% ^{240}Pu, Natural Uranium (1999)	Darby S. Kimball (University of Virginia)	WSMS
MIX-COMP-THERM-006 – Water-Moderated Mixed Oxide Hexagonal Lattices - 2.0 Wt.% PuO_2, 8% ^{240}Pu, Natural Uranium (2000)	Jim W. Campbell (Georgia Institute of Technology)	WSMS
HEU-MET-FAST-078 – HEU Metal Cylinders, Partially Reflected by Water, Polyethylene, Lucite, and Paraffin (2006)	Nick Schira (University of Cincinnati)	WSMS
PU-SOL-THERM-018 – Water-Reflected 24-Inch Diameter Cylinder of Plutonium (42.9% ^{240}Pu) Nitrate Solution (2006)	Doug Warner (University of Cincinnati)	WSMS
PU-SOL-THERM-034 – Plutonium (8.3 Wt.% ^{240}Pu) Nitrate Solution With Gadolinium In Water-Reflected 24-Inch Diameter Cylinder (2007)	Nick Schira Kyle Knecht (University of Cincinnati)	WSMS
HEU-MET-FAST-051 – Uranium (93.2) Metal Cylinders (7-Inch, 9-Inch, 11-Inch, 13-Inch, and 15-Inch Diameter) and Two 11-Inch-Diameter Interacting Uranium (93.2) Metal Cylinders (2002)	Robert H. Elwood, Jr. (University of Tennessee - Knoxville)	ORNL
U233-SOL-THERM-016 – Unreflected Solutions of $^{233}UO_2(NO_3)_2$ in Cylinders (2005)	Shane E. Parkey (University of Tennessee - Knoxville)	ORNL
U233-SOL-THERM-017 – Water-Reflected Solutions of $^{233}UO_2(NO_3)_2$ in Cylinders (2005)	Shane E. Parkey (University of Tennessee - Knoxville)	ORNL
LEU-MET-THERM-007 – Water-Moderated and Water-Reflected 0.300 Inch Diameter U(4.95) Metal Rods in 1.3, 1.53, 1.8, 2.05, 2.453 and 2.9 Cm Square-Pitched Arrays (TBD)	Carlos H. Juarez-Gosselin (University of Tennessee - Knoxville)	ORNL

EVALUATION ID & TITLE (YEAR APPROVED)	AUTHOR[2] (University)	NATIONAL LABORATORY or COMPANY[3]
MIX-COMP-FAST-001 – ZPR-6 Assembly 7: A Cylindrical Assembly with Mixed (Pu,U)-Oxide Fuel and Sodium with a Thick Depleted-Uranium Reflector (2003)	Pedro Moneo, Paul A. Van den Hende (Institut National des Sciences et Techniques Nucléaires)	ANL
HEU-MET-FAST-057 – Highly Enriched Uranium Metal Spheres and Cylinders Reflected by Lead (2004)	Mark Lee (University of California – Berkeley)	LLNL
MIX-MISC-THERM-005 – Water-Reflected Triangular-Pitched Lattice of Mixed Oxide Fuel Rods Immersed in Plutonium-Uranyl Nitrate Solution Containing Boron and Gadolinium (2005)	Milan Tomazin University of Ljubljana	JSI
MIX-SOL-THERM-010 – Water-Reflected Plutonium-Uranyl Nitrate Solution Containing Boron and Gadolinium (2006)	Milan Tomazin Luka Snoj University of Ljubljana	JSI
LEU-COMP-THERM-081 – PWR Type UO_2 Fuel Rods with Enrichments of 3.5 and 6.6 Wt.% with Burnable Absorber ("Otto Hahn" Nuclear Ship Program, Second Core) (2007)	Petra Rogan Luka Snoj University of Ljubljana	JSI
KRITZ-LWR-RESR-001 – KRITZ-2:19 Experiment on Regular H2O/Fuel Pin Lattices with Mixed Oxide Fuel at Temperatures 21.1 and 235.9 °C (2009)	Luka Snoj University of Ljubljana	JSI
KRITZ-LWR-RESR-002 – KRITZ-2:1 Experiment on Regular H2O/Fuel Pin Lattices with Low Enriched Uranium Fuel at Temperatures 19.7 °C and 248.5 °C (2009)	Luka Snoj University of Ljubljana	JSI
KRITZ-LWR-RESR-003 – KRITZ-2:13 Experiment on Regular H2O/Fuel Pin Lattices with Low Enriched Uranium Fuel at Temperatures 22.1 °C and 243 °C (2009)	Luka Snoj University of Ljubljana	JSI
HEU-MET-THERM-032 – 1x1 HEU/Polyethylene Reflected and Moderated by Polyethylene (TBD)	Luka Snoj Gasper Zerovnik University of Ljubljana	JSI
BFS1-FUND-EXP-001 – BFS-97, -99, -101 Assemblies: Experimental Program on Critical Assemblies with Heterogeneous Compositions of Plutonium, Depleted-Uranium Dioxide, and Polyethylene (2007)	Olga Pavlova (Institute of Atomic Power Engineering)	IPPE
BFS1-FUND-EXP-002 – Experimental Program Performed at the BFS-42 Assembly – K-Infinity Experiments for ^{238}U in Fast Neutron Spectra: Measurements with Plutonium Mixed with Depleted Uranium Dioxide and Polyethylene (2007)	Olga Pavlova (Institute of Atomic Power Engineering)	IPPE
BFS2-FUND-EXP-001 – Experimental Program Performed at the BFS-31 Assemblies – K-Infinity Experiments for ^{238}U in Fast Neutron Spectra: Measurements with Plutonium Mixed with Depleted Uranium Dioxide (20	Olga Pavlova (Institute of Atomic Power Engineering)	IPPE
BFS1-FUND-EXP-003 – BFS-57 And BFS-59 Assemblies: Experimental Program on Critical Assemblies with Heterogeneous Compositions of Enriched-Uranium Dioxide or Plutonium, Depleted-Uranium Dioxide, and Polyethylene (2008)	Olga Pavlova (Institute of Atomic Power Engineering)	IPPE
FUND-JINR-1/E-MULT-TRANS-001 – Neutron Transmission Through Samples of Depleted Uranium, Highly – Enriched Uranium, and Plutoniu for Determination of Resonance Self-Shielding of Total Cross Section and Fission Cross Section of ^{238}U, ^{235}U, and ^{239}Pu (2008)	Olga Pavlova (Institute of Atomic Power Engineering)	IPPE
VENUS-PWR-EXP-005 – Experimental Study of the VENUS-PRP Configurations No. 9 and 9/1 (TBD)	Christopher Grove (Birmingham University-UK)	NNL