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The Paucity Problem: Where Have All the Space Reactor Experiments Gone?

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Abstract. The Handbooks of the International Criticality Safety Benchmark Evaluation Project (ICSBEP) and the International Reactor Physics Experiment Evaluation Project (IRPhEP) together contain a plethora of documented and evaluated experiments essential in the validation of nuclear data, neutronics codes, and modeling of various nuclear systems. Unfortunately, only a minute selection of handbook data (twelve evaluations) are of actual experimental facilities and mockups designed specifically for space nuclear research. There is a paucity problem, such that the multitude of space nuclear experimental activities performed in the past several decades have yet to be recovered and made available in such detail that the international community could benefit from these valuable historical research efforts. Those experiments represent extensive investments in infrastructure, expertise, and cost, as well as constitute significantly valuable resources of data supporting past, present, and future research activities. The ICSBEP and IRPhEP were established to identify and verify comprehensive sets of benchmark data; evaluate the data, including quantification of biases and uncertainties; compile the data and calculations in a standardized format; and formally document the effort into a single source of verified benchmark data.

The recovery of space nuclear experiments before they become permanently lost plays a synergistic role with current-day needs and could be of great service to unknown future efforts. Numerous experiments were performed investigating the capability to construct and operate autonomous compact nuclear reactors in harsh, remote locations. Such capabilities are of interest supporting development of small modular reactors for terrestrial applications. Unique materials such as tungsten, tantalum, lithium, and potassium, to name a few, were investigated in some of the space programs. Some of these experiments may represent our best, if not only, experiments available for refinement and integral validation of some nuclear data libraries. Interest in advanced modeling and simulation of multi-physics experiments can benefit from modern space nuclear experimentation, which includes the measurement of thermal, hydraulics, or material effects coupled with the neutronic conditions. Fission product buildup, minor actinide cross sections and decay properties, and radiation shielding aspects for building advanced fast reactors have needs that must be addressed to support both terrestrial and space nuclear applications.

So where have all the space reactor experiments gone? More importantly, what must be done to preserve these components of our nuclear heritage before the usefulness of what remains to be recovered becomes insignificant? Recorded knowledge beyond summary reports and journal articles such as logbooks, memos, and drawings need located and digitized. While the time and cost necessary to completely evaluate all space nuclear experiments is limited, the first key step is to recover and preserve what can be found, making that information publicly available such that we enable our next generation of nuclear scientists and engineers to someday evaluate and apply the information before designing and implementing next generation test facilities and reactors. Otherwise, if we continue to ignore, and effectively support, this paucity problem, our next generation may well take its first steps reinventing heritage space nuclear research.

Keywords: Benchmarks, Data, Experiments, Preservation, Validation.

INTRODUCTION

Numerous benchmark experiments have been evaluated and documented for use in the validation of nuclear data, neutronics codes, and models of various nuclear systems. These approved benchmarks are available internationally through the Organisation for Co-operation and Development (OECD) Nuclear Energy Agency (NEA) in the *International Handbook of Evaluated Criticality Safety Benchmark Experiments* (ICSBEP Handbook) [1] and the *International Handbook of Evaluated Reactor Physics Benchmark Experiments* (IRPhEP Handbook) [2]. Unfortunately, to date only a minute selection of data within these handbooks pertains directly to actual experimental facilities and mockups designed specifically for space nuclear research. A summary of these twelve evaluations, available in entirety within the IRPhEP Handbook, or provided in Table 1. Both the International Criticality Safety Benchmark Evaluation Project (ICSBEP) and the International Reactor Physics Experiment Evaluation Project (IRPhEP) were established to identify and verify comprehensive sets of benchmark experiment data; evaluate the data, including quantification of biases and uncertainties; compile the data and calculations into a standardized format; and formally document the effort within a single source of verified benchmark data. A summary of the benchmark evaluation process is provided in Figure 1.

TABLE 1. Available Neutronics Benchmark Data for Space Nuclear Systems in the IRPhEP Handbook [2].

Reactor/Facility	**IRPhEP Identifier**	**Evaluation Title**
Oak Ridge Critical Experiment Facility (ORCEF)	ORCEF-SPACE-EXP-001	Fast Neutron Spectrum Potassium Worth for Space Power Reactor Design Validation
Small Compact Critical Assembly (Performed at ORCEF)	SCCA-SPACE-EXP-001	Critical Configuration and Physics Measurements for Assemblies of U(93.15)O_2 Fuel Rods
	SCCA-SPACE-EXP-002	Critical Configuration and Physics Measurements for Assemblies of U(93.15)O_2 Fuel Rods (1.506-cm Pitch)
	SCCA-SPACE-EXP-003	Critical Configuration and Physics Measurements for Beryllium Reflected Assemblies of U(93.15)O_2 Fuel Rods (1.506-cm Pitch and 7-Tube Clusters)
TOPAZ Critical Assemblies at the Narciss-M Facility	TOPAZ-SPACE-RESR-001	Intermediate Heterogeneous Assembly with Highly Enriched Uranium Dioxide (96% ^{235}U) and Zirconium Hydride Moderator
	TOPAZ-SPACE-RESR-002	Intermediate Heterogeneous Assembly with Highly Enriched Uranium Dioxide and Sand/Water Radial Reflector
UKS-1M Critical Facility	UKS1M-SPACE-EXP-001	Beryllium- and Molybdenum-Reflected Cylinders of Highly Enriched Uranium
Zero Power Physics Reactor (ZPPR)	ZPPR-SPACE-EXP-001	ZPPR-20 Phase C: A Cylindrical Assembly of U Metal Reflected by Beryllium Oxide
	ZPPR-SPACE-EXP-002	ZPPR-20 Phase D: A Cylindrical Assembly of Polyethylene-Moderated U Metal Reflected by Beryllium Oxide and Polyethylene
	ZPPR-SPACE-EXP-003	ZPPR-20 Phase E: A Cylindrical Assembly of U Metal Reflected by Beryllium Oxide and Sand
	ZPPR-SPACE-EXP-004	ZPPR-20 Phase D: A Cylindrical Assembly of Polyethylene-Moderated U Metal Reflected by Beryllium Oxide and Polyethylene
Zero Power Reactor (ZPR)	ZPR-SPACE-EXP-001	ZPR-9 Assemblies 7, 8 and 9: Cylindrical Cores with HEU (93% ^{235}U), Tungsten, and Aluminum or Aluminum Oxide with a Dense Aluminum, Aluminum Oxide, or Beryllium Oxide Reflector

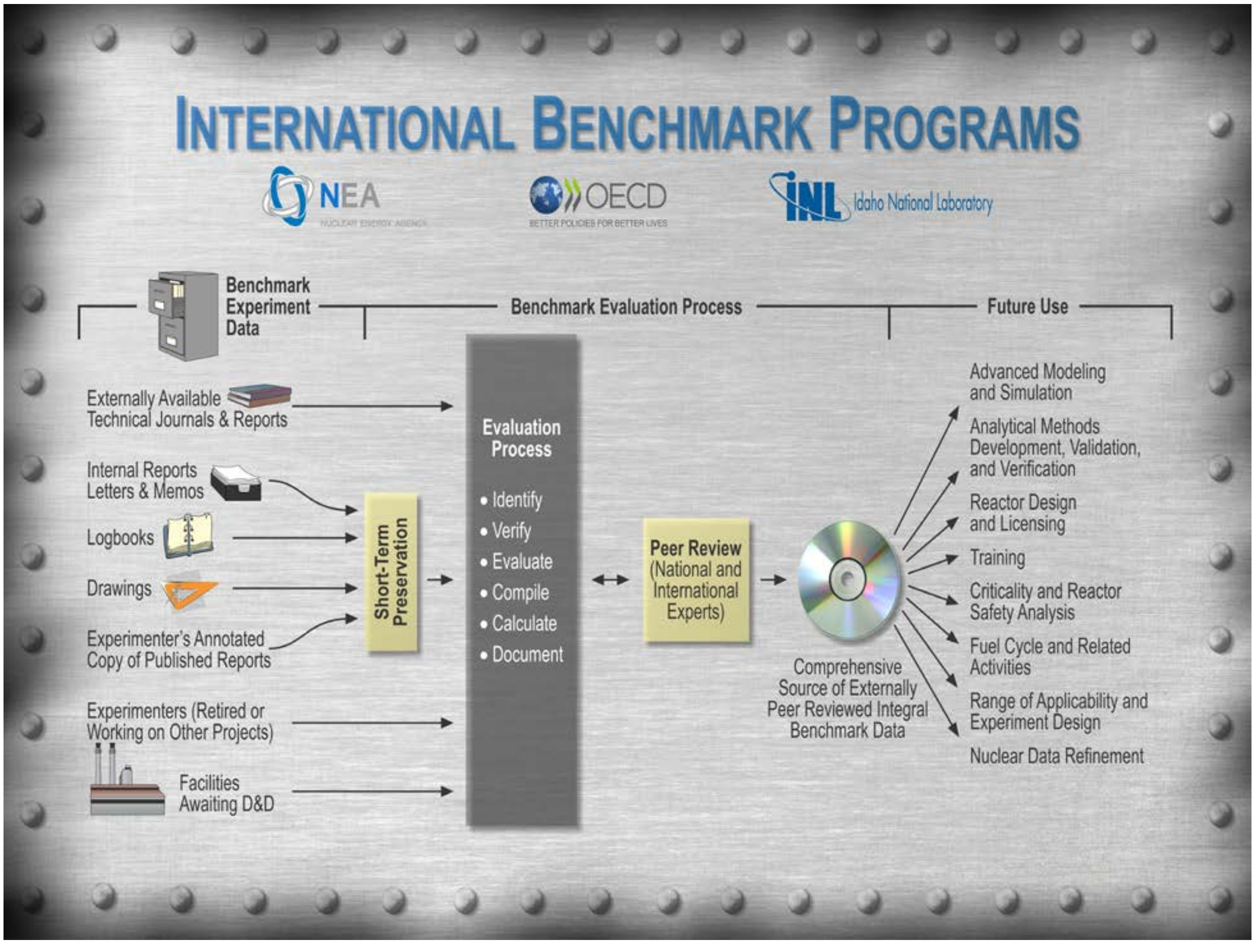

FIGURE 1. Benchmark Evaluation Process for the ICSBEP and IRPhEP.

There is paucity problem, such that of the multitude of space nuclear experimental activities performed over the past several decades, not just in the United States but also internationally, have yet to be recovered, evaluated, and made available in such detail that the international community could benefit from these valuable historical research efforts. Those experiments represent extensive investments in infrastructure, expertise, and cost. The comprehensive recovery and subsequent evaluation of those significantly valuable data serve as resources supporting past, present, and future research activities for both terrestrial and space reactor applications.

EXISTING BENCHMARKS AND POTENTIAL FOR MORE

Existing Neutronic Benchmark Data

Of the twelve benchmark evaluations listed in Table 1, most only represent the critical, or subcritical, configurations, (i.e. a single snapshot) of the experiment relative to the various supporting reactor physics measurements performed on a given assembly or at a given facility, within a given campaign. The Oak Ridge Critical Experiment Facility (ORCEF) experiment provides a simple geometry for the testing of potassium coolant worth (see Figure 2) [3]. A similar potassium worth measurement (see Figure 3) was performed for the mockup configuration of the Small Compact Critical Assembly (SCCA) [4]. Unfortunately, modern calculations with contemporary nuclear simulation codes and nuclear data libraries cannot reproduce the benchmark experiment values, indicating either a flaw in the experimental measurements, errors in potassium cross section data, or both. Potassium coolant has been a recurring option for use in space nuclear reactor design and proper simulation of its worth in reactor design is important not just for operational considerations but simulated accident and criticality safety conditions. The evaluation of additional experimental data for systems with potassium would be of benefit in resolving this issue.

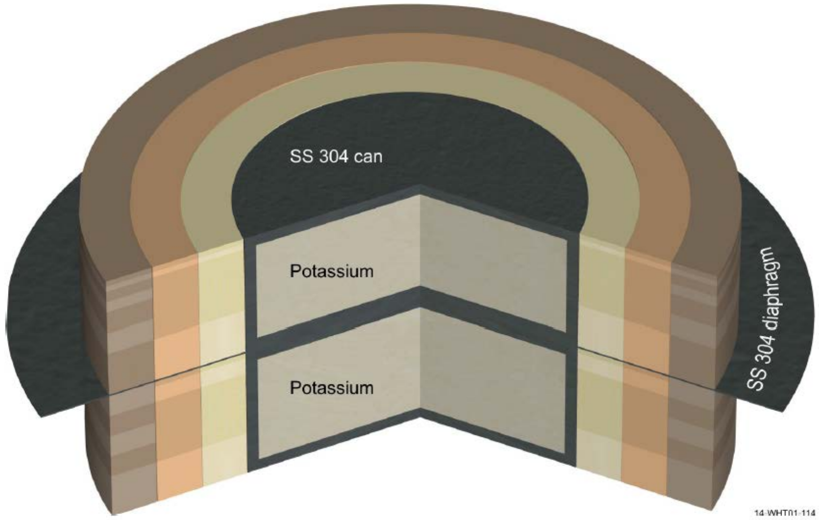

FIGURE 2. ORCEF Experiment for Measurement of Fast Neutron Spectra Potassium Worth.

The first two SCCA evaluations provide different configurations of graphite-reflected mockup cores and the third evaluation provides mockup configurations with beryllium reflectors. In addition to criticality, benchmark measurements and specifications for the graphite-reflected configuration are provided that include cadmium ratio radial distributions, simple fuel and graphite worth measurements, axial fission-rate distributions, and radial fission-rate distributions. The beryllium-reflected evaluation of SCCA includes cadmium ratio distributions, various fuel and material reactivity worth measurements, axial and radial fission-rate distributions, as well as the potassium worth measurement. This series of experiments were performed to support study of power plants for electrical power production in space vehicles.

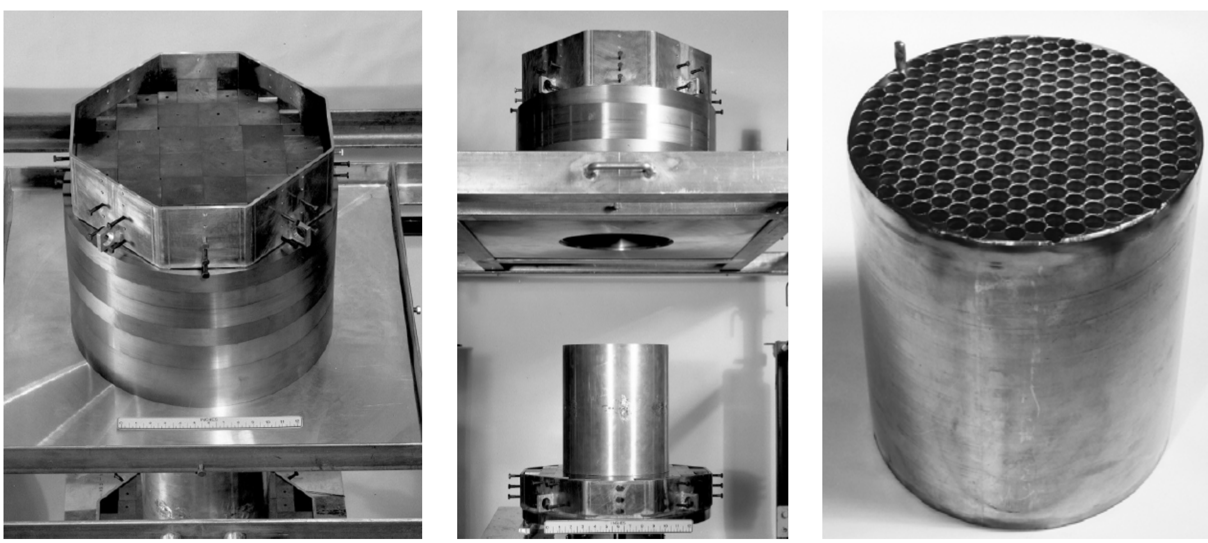

FIGURE 3. Photos of the SCCA Mockup for Potassium Worth Measurements.

The TOPAZ critical experiments (see Figure 4) were performed to investigate the accidental water immersion of a thermionic intermediate reactor-converter with highly-enriched fuel. The first evaluation includes six configurations representing water ingress into various reactor cavities and complete water immersion. The second evaluation includes five configurations representing water ingress into various reactor cavities and immersion in sand and water. While a large number of additional reactivity-worth and neutron activation cross section were performed on these configurations, currently none have been evaluated as additional benchmark data. A subcritical configuration with dry sand reflection was not evaluated as a benchmark, but details and sample calculations are provided in an appendix of the second TOPAZ evaluation.

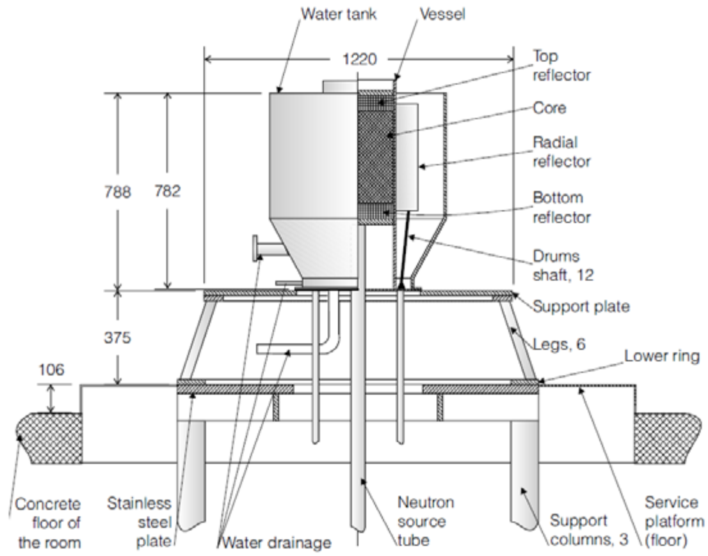

FIGURE 4. Schematic of TOPAZ Critical Assembly.

The UKS-1M experiment evaluation contains benchmark specifications for six critical assemblies of highly-enriched U-3.32Mo fuel surrounded by varying arrangements of beryllium and/or molybdenum reflectors (see Figure 5). The purpose of these loadings was to support reactor design of a power supply for outer-space apparatus with a reactor operating with a fast-neutron core moderated by varying reflector materials. Asymptotic neutron-flux decay constants were measured for each configuration but not evaluated as benchmark data.

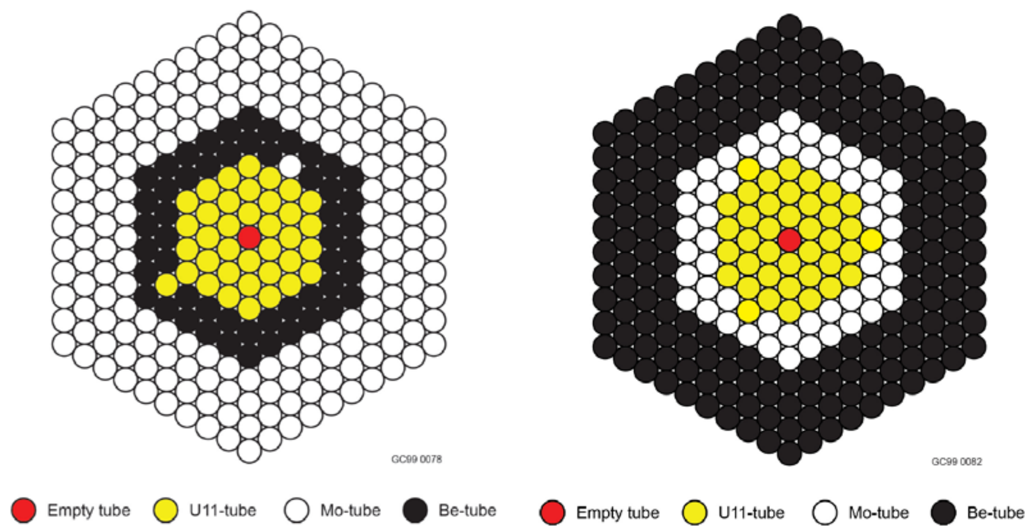

FIGURE 5. Example Core Loadings for UKS-1M Critical Assembly.

The four Zero Power Physics Reactor (ZPPR) benchmark evaluations correspond to various loadings of ZPPR-20 that were constructed to support design of the SP-100 core with some material substitutions due to availability of materials at the time. ZPPR-20C (see Figure 6) serves as the reference flight configuration for the reactor design. Phases D and E simulated accident scenarios: water immersion scenario during a launch accident, and earth burial scenario during a launch accident, respectively. The first two ZPPR-20 evaluations are critical loadings while the second two are subcritical. Numerous additional measurements were performed during the ZPPR-20 experiments, the bulk of which pertained to Phase B; measurements were performed for all configurations from Phases A through G. Only the reference critical and subcritical loadings of these four evaluations have been evaluated currently as benchmark experiments.

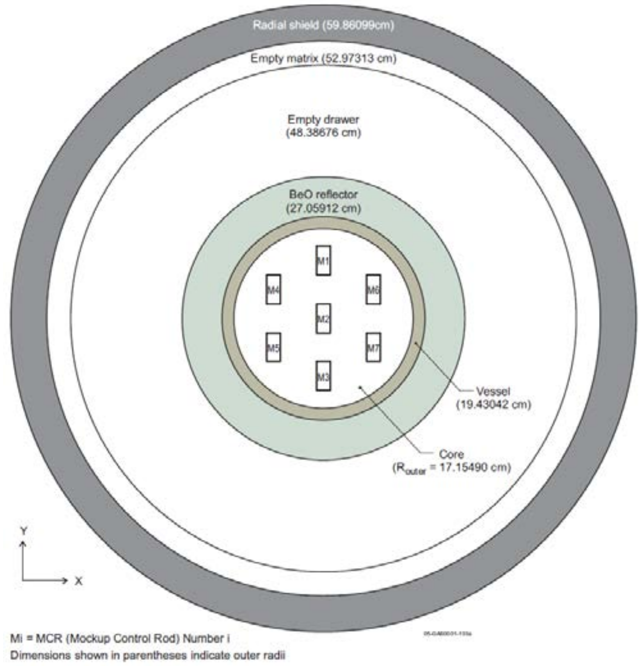

FIGURE 6. Benchmark Model Midplane Geometry for ZPPR-20C.

The Zero Power Reactor (ZPR) evaluation of ZPR-9 (see Figure 7) Assemblies 7, 8 and 9 represent three members of a series of cores built to study the neutronics of high temperature fast reactors proposed for the nuclear rocket program. The reactor contains tungsten refractory metal with varying lightweight reflector materials. Development of the final core design is documented as benchmark configurations of Assemblies 1 through 6 and are available on the ICSBEP Handbook [1] in IEU-MET-FAST-013, IEU-MET-FAST-01, HEU-MET-FAST-060, and HEU-MET-FAST-067. Currently only the three critical configurations are evaluated as benchmark experiment data. Additional measurements performed for these loadings, but not currently evaluated, include kinetics parameters, control rod calibrations, reaction-rate distributions, and reactivity worths for various materials, poisons, reflectors, fuel, and gaps.

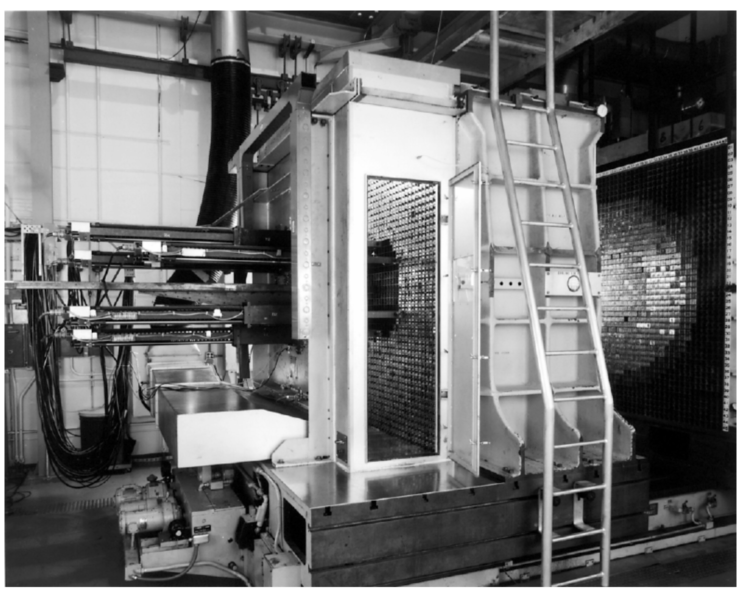

FIGURE 7. ZPR-9 Critical Facility.

Potential Benchmark Progression

There were, and still are, numerous experiments performed worldwide that appear throughout the annals of literature as potential candidates for benchmark evaluation. Unfortunately time, funding, and effort are now necessary to potentially recover sufficient data for modern benchmark evaluation assessment. The recovery of space nuclear experiments before they become permanently lost plays a synergistic role with current-day needs and could be of great service to unknown future efforts. Experiments were performed to test and investigate the capability to construct and autonomously operate robust, compact nuclear reactors in harsh, remote locations. Such capabilities are of interest when supporting development of small modular reactors for terrestrial applications as well. Unique materials such as tungsten, tantalum, lithium, and potassium, to name but a few, once investigated as part of space programs also represent some of our best, if not only, experiments available for refinement and integral validation of nuclear data libraries needed to evaluate future reactor designs.

Synergy exists with nuclear criticality safety programs throughout the world. Benchmark validation data for fluorine and chlorine does not exist currently in the ICSBEP Handbook. Fluorine is of interest regarding the safe storage of uranium hexafluoride. The series of experiments culminating in the spherical gas core critical experiment [5] provides excellent benchmark data to support gas core reactor design but also supports fluorine cross section validation (see Figure 8). Spent nuclear fuel management in geological repositories requires investigation into the neutron absorption in water from impurities such as chlorine [6]. Improvement of cross section data for chlorine would support more realistic analysis of seawater immersion studies for space reactor accident considerations.

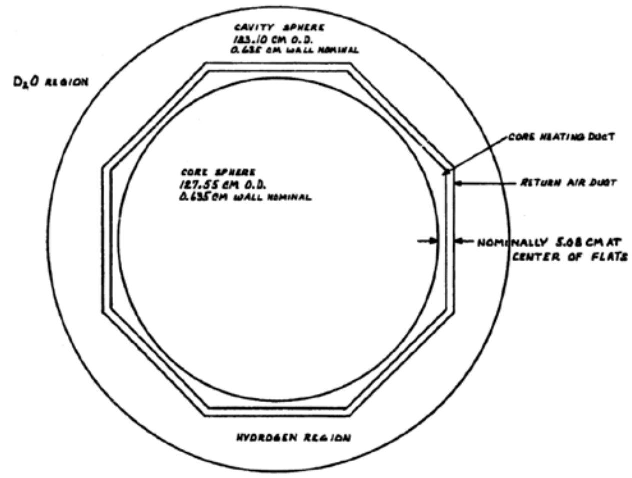

FIGURE 8. UF_6 Transportation Cylinder (Left) and Spherical Gas Core Reactor Schematic (Right).

There is an ever growing interest in the advanced modeling and simulation of multi-physics experiments that can benefit from historic and modern space nuclear experimentation, including measurement of thermal, hydraulics, and/or material effects coupled amongst themselves or also with neutronics conditions. Significant effort went into the development of Systems for Nuclear Auxiliary Power (SNAP) reactors [7] culminating in the launch of a SNAP-10 reactor into space. Various tests relevant to space nuclear reactor design historically still apply today and the ability to satisfactorily simulate extreme reactor accident conditions, such as the SNAPTRAP destructive tests [8], using modern capabilities are vital in overcoming prohibitive experimental costs. A simpler modern example of a coupled multi-physics experiment capable of serving as a benchmark is the Demonstration Using Flattop Fission (DUFF) test that coupled the Flattop critical assembly to a heat-pipe-powered Stirling converter [9]. The OECD NEA has established an Expert Group on Multi-physics Experimental Data, Benchmarks and Validation (EGMPEBV) to address the many activities associated with certification of experimental data and benchmark models, along with establishing the processes and procedures for using them for validation of modelling and simulation tools and data. The efforts to develop a handbook for multi-physics benchmark data follows along the heritage of the ICSBEP and IRPhEP Handbooks.

Fission product buildup, minor actinide cross sections and decay properties, and radiation shielding aspects for advanced fast reactors have needs that must be addressed to support both terrestrial and space nuclear applications. Benchmark evaluation of space reactor tests and experiments provide insight into the development and testing of ground reactors. Similarly, evaluation of terrestrial fast reactor irradiation experiments can serve to improve the nuclear data available for modeling and simulation of space reactor concepts. For example, various high-purity actinide samples were irradiated in the Dounreay Prototype Fast Reactor to support evaluation of neutron cross-section data and burnup calculations [10].

ADDRESSING THE PAUCITY PROBLEM

So where have all the space reactor experiments gone? More importantly, what must be done to preserve these components of our nuclear heritage before the usefulness of what information remains recoverable becomes insignificant? Recorded knowledge beyond summary reports and journal articles such as logbooks, memos, and drawings need located and digitized. Often the typical end-point for an extensive experimental series culminates with publication of final reports dutifully summarizing what was actually performed without providing the information necessary to simulate the experiments in detail. Benchmark specifications require known geometries, material properties, quantities, environmental conditions, and measured parameters for quality development and implementation. Uncertainties in the reported parameters, and known biases, while not typically reported for experimental conditions are equally important and often developed during the benchmark evaluation process to ascertain the quality of the derived benchmark specifications.

While the time and cost necessary to completely evaluate all space nuclear experiments is limited, the first key step is to recover and preserve what can be located, making that information publicly available such that we enable our next generation of nuclear scientists and engineers to someday evaluate and apply the information prior to designing and implementing next generation test facilities and reactors. Otherwise, if we continue to ignore, and effectively support, this paucity problem, our next generation may well take its first steps reinventing heritage space nuclear research.

The first step requires donning your Fedora hat, coiling your bullwhip, and holstering your pistol, with the intention to get down and dirty with your nuclear archaeology. It isn’t enough to rely solely upon the conventional institutional data preservation techniques of digitizing remaining interim and final reports. Heritage data needs identified and preserved beyond these basic summaries. Where the proverbial “tribal knowledge” yet remains, that information needs transcribed and retained for future use. The IRPhEP Handbook allows for the contribution of experimental data prepared into the proper format for handbook data preservation. While such means allows for the preservation of a comprehensive set of space nuclear reactor data, it will be marked as a Draft evaluation and not considered a formally evaluated benchmark. However, sufficient information might be retained that should time, funding, and interest prevail, future engineers could complete the benchmark evaluation(s) to support their future intended use. The challenge is set before us to actively engage ourselves in the preservation of historic and contemporary space nuclear experimental data.

CONCLUSION

There is currently a very limited data set of benchmark data to support validation of nuclear data, neutronics codes, and modeling of space nuclear reactor systems. Those neutronics benchmarks currently available are found in the ICSBEP and IRPhEP Handbooks available through the OECD NEA. There is a paucity problem, such that the multitude of space nuclear experimental activities performed over the past several decades have yet to be recovered in sufficient detail to provide comprehensive data to support development of high-quality benchmark specifications in support of current and future research activities. Data recovery becomes paramount as access to historic drawings, logbooks, personnel, and facilities becomes more difficult. Synergy exists between space nuclear and terrestrial activities such as criticality safety, cross section data validation, and small modular reactor design, not just for neutronics but complete multi-physics studies using modern simulation tools. Efforts should be undertaken to collect and make available existing space nuclear data not just as an act of preservation, but a preliminary step in sifting through remaining information to optimize future benchmark evaluation work. An existing available option includes submission of space nuclear reactor experimental data to the IRPhEP Handbook.

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