Health Physics Research Reactor Criticality Accident Alarm System Benchmark Overview

Mathieu N. Dupont

Oak Ridge National Laboratory, PO Box 2008, Oak Ridge, TN 37831-6170, dupontmn@ornl.gov

INTRODUCTION

From the countless critical experiments performed in the world during the past century, high-quality integral benchmarks experiments have been collected and gathered into the *International Handbook of Evaluated Criticality Safety Benchmark Experiments* (ICSBEP Handbook) [1], managed by the International Criticality Safety Benchmark Evaluation Project (ICSBEP) Working Group. This information preservation and dissemination effort is crucial for reactor licensing as well as criticality and radiation transport modeling validation.

This summary reports on the status of a tentative benchmark addition to the ICSBEP Handbook. The proposed benchmark arises from legacy operation data of the Oak Ridge National Laboratory (ORNL) Health Physics Research Reactor (HPRR). The HPRR was a small, unmoderated, unshielded fast burst reactor that was used for research in health physics and radiobiology as well as teaching and training. As part of a comprehensive investigation of the available HPRR operation data and characteristics, different possibilities for use of the valuable results were studied. A critical experiment benchmark evaluation was performed [2], analyzing data coming from sub-critical and critical operation of the HPRR during operator training, steady-state irradiation of samples and before critical bursts. The results of the evaluation do not satisfy for the ICSBEP standards as the benchmark relative standard uncertainty is of about 4% for k_{eff}, and the relative difference between sample calculations and expected k_{eff} results is of about 1.5%. Due to those unsatisfactory results, it was decided not to pursue critical experiments evaluation of the HPRR presently and to focus instead on shielding type data for the creation of a criticality accident alarm system (CAAS) and shielding category benchmark, which is currently very scarce in the ICSBEP handbook—especially concerning critical, pulsed assembly, or reactor operation data [3,4]. Several dosimetry and shielding experiments from HPRR burst operation were evaluated, with different benchmark metrics as sulfur fluence [5], Element 57 dose [6], or neutron fluence at different distances and under different shield materials conditions. An evaluation focusing on the Element 57 neutron dose as a benchmark metric was submitted to the ICSBEP Technical Review Group (TRG) meeting in October 2021, and the inclusion of the evaluation in the ICSBEP Handbook was deferred. The main change proposed by the international experiment evaluation experts is to use the neutron fluence measured by Bonner spheres as a benchmark metric. This represents a quantity closer to that actually measured by the experimentalists of the HPRR compared to the Element 57 dose, which adds another step of data transformation, thus potentially adding uncertainty to the benchmark. The evaluation has been updated and will be submitted to the 2022 ICSBEP TRG meeting for inclusion in the 2023 edition of the ICSBEP Handbook. The evaluation is performed using the KENO and MAVRIC [7] combination from the SCALE 6.2.4 [8] code suite which was previously used in similar CAAS benchmarks [9] to allow for the use of variance reduction techniques.

THE HEALTH PHYSICS RESEARCH REACTOR

The HPRR, also known as the Fast Burst Research Reactor, was designed and built at ORNL in 1961. It was part of the Dosimetry Application Research (DOSAR) facility where it was used for dosimetry, radiobiology studies with plants and animals, testing of radiation alarms, and teaching and training in radiation dosimetry and nuclear engineering. Between 1963 and 1987, the HPRR was operated for thousands of hours, achieving criticality close to 10,000 times [10]. The HPRR was decommissioned in 1987.

The HPRR core was a right circular annulus consisting of 11 nickel-coated highly enriched uranium (93.14% ^{235}U) and molybdenum alloy plates approximately 20 cm in diameter of various thicknesses, with a total height of approximately 23 cm. The plates were held by nine U-Mo hollow bolts, each filled with U-Mo or stainless-steel bolt inserts. A sample irradiation hole was drilled through the plates to allow for insertion of any testing apparatus. This hole could also be filled with a U-Mo plug. The remaining U-Mo elements of the core were moveable: three different control rods (the regulating rod, mass adjustment rod, and burst rod) and the safety block (placed in the center of the annulus, which could be scrammed to fall in a stainless-steel safety tube). All the U-Mo parts of the core contained 90 wt% uranium and 10 wt% molybdenum. Figure 1 shows the core and a portion of the auxiliary supporting structure.

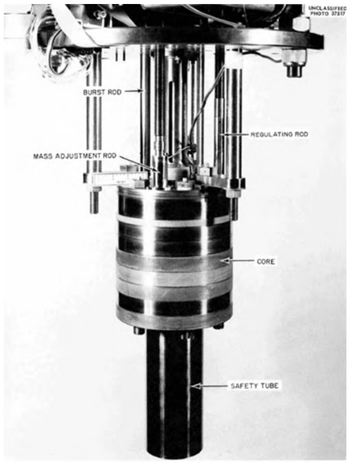

Fig. 1. HPRR core picture.

Considering all the components of the core, the total uranium is estimated to have been about 103.46 kg. The HPRR could be operated in pulse or steady-state mode. The average number of fissions per burst operation was 10^{17} for doses ranging from a few millirads to thousands of rads.

EVALUATION OF EXPERIMENTAL DATA

Because numerous reactor re-configurations over the years modified the reference dosimetry data—especially in 1985 with the positioning and storage system change—it was judged safer for the evaluation's quality to focus on the latest dosimetry report published before the reactor decommissioning in 1987 [11]. This report includes a large amount of radiation transport and dosimetry reference results for the HPRR's shielded and unshielded configurations after pulse operations. The most promising experiments for the evaluation are described in the following sub-sections.

Neutron source characterization

This section includes characterization of the neutron energy spectrum and fission yield from a burst. The yield was measured by sulfur pellet activation. It is a difficult task to accurately measure and model this part of the experiment, but it is also a necessary step for the CAAS benchmark, so it is detailed in the evaluation.

Threshold detector unit measurements

The threshold detector unit (TDU) measurements are performed from an HPRR burst at different distances from the HPRR centerline, shielded and unshielded. The exact TDU dimensions and composition could not be located, so a high uncertainty resides in these experiment series. Those experiments are not evaluated for now but are promising for a potential future update.

Sulfur pellet activation measurements

The HPRR was used in burst operation to irradiate sulfur pellets placed at different distances from the reactor centerline and shielded by different materials (steel, Lucite, concrete, and combinations thereof). Those experiments were previously evaluated [5] and the results were poor, with high expected and calculated discrepancies. The probable explanation for the discrepancies is a lack of understanding of the sulfur pellets counting process and sulfur fluence quantity definition. New documents were recently uncovered, increasing the trust in those measurements, and updated sulfur fluence results are included in the updated evaluation in an appendix.

Total neutron fluence measured by Bonner sphere spectrometry

A set of 12 Bonner spheres of different diameters was placed 3 m from the HPRR centerline during burst operation. The Bonner spheres consisted of central BF_3 neutron counters covered by different thicknesses of polyethylene. The polyethylene thickness is proportional to the moderation of the neutrons, and the BF_3 gas serves as an absorber. By using different Bonner spheres, different levels of neutron moderation appear, and different count rates are obtained, allowing for the unfolding of the HPRR spectrum. The issue with this experiment is that detailed information about the 12 Bonner spheres and associated count rates after burst could not be located. The only result available is the unfolded spectrum with a specific neutron energy group structure and a normalized number of incoming neutrons; thus, the modeling of the Bonner spheres, not standard, cannot be performed. Nevertheless, Bonner sphere spectrometry is a recognized and trusted method for neutron spectrum unfolding and neutron fluence measurement, as shown in an intercomparison exercise performed in 1997 [12]. A summary table from the intercomparison is shown in Figure 2. A mean neutron fluence was measured by different Bonner spheres, and a standard deviation of only 3.4% between 10 participants was observed. From this study, it was decided that the total neutron fluence is an adequate benchmark metric for the 2022 update of the evaluation, along with a comparison of measured and calculated neutron spectra.

Table 2. Results of full energy range spectrometry measurements, mainly Bonner spheres.

Energy range (eV)	Participating laboratory											Mean**	Stand. dev.** σ
	Calc. MCNP	IPSN Cad.	BsF	AECL	IRA	GSF	CMI*		PTB	NPL	IPSN FAR		
	Absolute fluence ($cm^{-2}.\alpha^{-1}$)												
<0.4	58.9	60.6	52.8	54.1	50.05	47.9	51.1	(62.9)	53.4	55.7	62.5	54.3	8.7%
0.4–10^4	28.0	26.4	36.2	33.7	26.8	32.9	24.2	(29.0)	36.1	35.3	30.0	31.3	12%
10^4–10^5	11.9	8.5	8.0	8.4	15.4	12.1	12.1	(15.1)	10.5	10.9	8.2	10.4	24%
10^5–10^6	11.4	11.3	8.3	14.4	12.1	11.8	16.8	(21.6)	12.2	10.0	10.3	11 9	21%
>10^6	1.5	1.5	2.0	1.7	0.4	0.6	0.60	(0.74)	1.4	1.7	1.2	1 25	47%
Total	111.6	108.3	107.3	112.3	105.0	105.4	104.9	(129.2)	113.7	113.7	112.1	109.2	3.4%

Fig. 2. Neutron fluence measured by Bonner spheres international intercomparison exercise.

Due to uncertainty in the dimensions and material compositions of the concrete and Lucite shields, the evaluation focuses on the bare and steel-shielded burst configurations. The HPRR was modeled with SCALE and the neutron fluence at 3 m from a burst operation of 10^{17} fissions was calculated through SCALE/MAVRIC and compared with the expected value from the ORNL-6240 measurements, shown in the third column of Figure 3. Additional responses and configurations, which were included in the evaluation mostly in appendices, are also computed, such as the neutron spectrum shape, Element 57 neutron dose, kerma in air, neutron per unit fluence, and attenuation due to shields of different materials.

Table 16. Reference neutron dosimetry for the HPRR: summary in terms of fissions[a]

Shield	Distance from HPRR, m	Total fluence for 10^{17} fissions, 10^{10}n/cm^2	Dose per unit fission, cGy/10^{17} fissions		Dose equivalent per unit fission, cSv/10^{17} fissions		
			Kerma	Element 57	Element 57	ICRP21	Effective
U	3	17.3	349.6	397.5	3951	4240	2792
L	3	4.09	56.9	65.6	637.8	690.7	462.9
S	3	9.50	152	163	1725	1871	1140

Fig. 3. Neutron fluence and different dose convention measurement results for 10^{17} fissions of the HPRR from ORNL-6240.

UNCERTAINTY STUDY

A CAAS shielding benchmark evaluation was created to be included in the ICSBEP Handbook, combining the ORNL-6240 measurements report results with data from reactor operation logbooks and other HPRR description documents (e.g., the operating manual, ORNL-9870 [13] for core dimensions and materials and NDA Spec. No. 12054 [14] for fuel specification). Much information about the reactor appears to be missing, and contradictory data were found between some documents concerning specific elements of the HPRR. For example, the thickness of the U-Mo plates' nickel coating and the impurities concentration of the U-Mo alloy are missing or uncertain. Also, there is a general lack of information concerning any element other than the core, such as the materials and dimensions of the support structure above the core and the reactor building walls. Parametric studies were performed to check the influence of those parameter uncertainties on the neutron fluence results. An overview of the preliminary uncertainty study is shown in Table I, focusing on the most significant estimated uncertainties factors for the steel-shielded configuration. The most significant uncertainty factors are the shield position and density. The benchmark HPRR SCALE model is shown in Figure 5. The model was highly simplified, and the geometry and neutron fluence results differences compared to a highly detailed model are described in the evaluation.

Table I. Preliminary Estimated Most Significant Experimental Uncertainties Factors for the Steel-Shielded Configuration

Element	**Standard Relative Uncertainty (%)**
Fission source	5
Concrete composition	4
Assumption of stainless steel 304	1
Presence of other components in the reactor room	5
Measurement uncertainty	10
Stainless steel 304 core elements density (g/cm^3)	4
Fuel alloy density (g/cm^3)	3
Hydraulic lift density (g/cm^3)	1
Shield Stainless steel density (g/cm^3)	21
Shield thickness (cm)	11
Shield position (cm)	21
Total Preliminary Estimated Standard Uncertainty	**34.6**

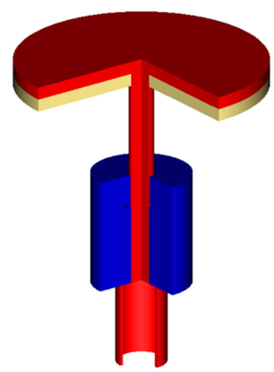

Fig. 5. Front-right 3D cut of a simplified SCALE model of the HPRR core, selected to be the benchmark model.

PRELIMINARY SAMPLE RESULTS

Preliminary sample results of the neutron fluence evaluation are shown in Table II. In both bare and steel-shielded configurations, the expected and calculated neutron fluence show good agreement, with calculated-to-expected (C/E) ratios of 1.39 for the bare and 1.24 for the steel-shielded neutron fluence. Additionally, the steel shield attenuation—defined as the steel shielded HPRR neutron fluence response at 3 m divided by the bare HPRR response at 3 m—is equal to 0.41 for expected results and 0.37 for SCALE/MAVRIC calculations, with a C/E ratio of 0.89. This result proves that the shielding effects of the steel shield are accurately modeled; however, a bias exists in the separate calculations, causing an overestimation of the neutron fluence by MAVRIC. By analyzing the measured and calculated neutron spectra, it can be noted that the most significant discrepancies appear for neutrons of thermal energy. By comparison, the rest of the spectrum is in relatively good agreement. The reported preliminary standard relative uncertainty values concern only a few perturbation factors and will probably be higher in the final version of the evaluation. The uncertainty values are high but are not surprising considering the general lack of information on the material and dimensions of the HPRR.

TABLE II. Results of preliminary sample calculations of the neutron fluence at 3 meters from a HPRR burst equivalent of 10^{17} fissions compared with experiment results from ORNL-6240

Case	Expected		Calculated		C/E
	Neutron Fluence (cm^{-2})	Relative Standard Uncertainty (%)	Neutron Fluence (cm^{-2})	Relative Standard Uncertainty (%)	
Bare	1.73E+11	13.6	2.41E+11	0.17	1.39
Steel Shield	9.50E+10	34.6	1.17E+11	0.20	1.24

CONCLUSIONS

HPRR reactor operation data were evaluated for the creation of an integral benchmark useful for the community. A valuable critical experiment benchmark seems to be compromised for now, and previously performed sulfur fluence and Element 57 evaluations present too much uncertainty to be accepted by the ICSBEP standards. An updated evaluation focusing on the neutron fluence results from HPRR burst operation seems to be the best option for the creation of a valuable CAAS benchmark. The benchmark relative uncertainty and C/E ratios are high but are judged acceptable for a shielding benchmark, especially considering the number of unknowns in the reactor. The evaluation will be presented to the ICSBEP TRG meeting in October 2022 for publication in the 2023 edition of the ICSBEP Handbook.

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