Evaluation of Oak Ridge National Laboratory Health Physics Research Reactor Operation Data for Critical Benchmark Creation

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ABSTRACT

The Oak Ridge National Laboratory (ORNL) Health Physics Research Reactor (HPRR) was a research reactor designed and built at ORNL in 1961. The critical assembly used a highly enriched uranium and molybdenum alloy as the fuel, and could be operated in steady-state or burst modes. The HPRR has recently been the object of an investigation to create a criticality benchmark. Such benchmarks are very important, as they are used primarily to show the accuracy of newly developed modeling codes and to help experimental validation and reactor licensing. The evaluated experiments considered in this paper were carried out between 1974 and 1986 from various HPRR activities such as steady-state subcritical, steady-state critical, and burst prompt super-critical operations of the reactor for dosimetry, irradiation, or training purposes. By using the HPRR experimental logbook information and the as-built drawings of the critical assembly, a highly detailed model of the HPRR was created with SCALE 6.2.4/KENO-VI, and a first version of a critical benchmark of the HPRR was developed following the International Criticality Safety Benchmark Evaluation Project (ICSBEP) guidelines for thorough description and uncertainty/sensitivity quantification. Unfortunately, in most of the evaluated experiments, the obtained difference between calculated and experimental k_{eff} is around 1,000 pcm, corresponding to a relative error of approximately 1%, beyond the quality standards of the ICSBEP recommending a relative error below 0.1%. Moreover, the derived experimental uncertainty is high, around 4% relative, mainly due to the U-Mo fuel density uncertainty, but also from numerous other factors. For these reasons, the creation of a valuable critical benchmark from HPRR operation data is thus far compromised. In this paper, the different steps of the experiments' evaluation are summarized, and the reasons for the experimental/calculation discrepancies and potential ways to solve them are explored. This paper also aims to remind us always to exercise considerable care when performing experimental work, and to record all the data possible for potential future uses.

Key Words: HPRR, critical benchmark, ICSBEP, U-Mo, fast neutron

1 INTRODUCTION

For safe and reliable use of any modeling computer codes by the scientific community, the accuracy of the code must be clearly evaluated. To do so, the best method is to use data from existing experiments and compare the experimental result to the result given by the computer code, also known as *benchmarking*. In the nuclear reactor engineering and licensing field, a particular need exists to develop reliable and accurate tools for radiation shielding and criticality safety modeling. The main reliable source of benchmarks for criticality analysis is the *International Handbook of Evaluated Criticality Safety Benchmark Experiments* (ICSBEP Handbook) [1]. Over the past few decades, the International Criticality Safety Benchmark Evaluation Project (ICSBEP) Working Group has been focusing on gathering critical and subcritical benchmark experiment data from different facilities around the world for inclusion in the ICSBEP Handbook. As of 2022, thousands of different critical benchmarks configurations are available in the handbook, and the database is constantly being updated with new benchmarks [2] created either from newly designed experiments [3] or from legacy experiments [4]. The newly added benchmarks broaden the range of validation possibilities, and new additions are always welcome to help criticality safety and radiation shielding analysts.

In 2019, the evaluation of previously performed experiments at the ORNL Health Physics Research Reactor (HPRR) was started under The Nuclear Criticality Safety Program (NCSP), funded and managed by the National Nuclear Security Administration (NNSA) for the U.S. Department of Energy (U.S. DOE). If enough information about the HPRR legacy experiment's dimensions, material composition, operating conditions and uncertainty can be recovered, HPRR benchmarks could be created and included in the ICSBEP database. The HPRR was a small unmoderated and unshielded fast burst reactor used for research in health physics, radiobiology, and for teaching and training. A lot of valuable data and publications originated from HPRR operation [5–6]; however, it was decommissioned in 1987 and no modern benchmark has been created since then. All available documentation and information were thoroughly inspected to judge the quality of potential criticality and/or radiation shielding benchmarks. An HPRR radiation shielding benchmark was created and is currently being reviewed by the ICSBEP Technical Review Group for a potential inclusion in the 2023 version of the handbook [7–8].

As the HPRR was used for irradiation and dosimetry purposes, no proper criticality report was created. Nevertheless, subcritical, critical and prompt-critical configurations of the HPRR could be located from experimental logbooks and training operations. In those references, the position of the different control rods and other core elements were recorded, as well as the measured reactor criticality. From the experimental logbooks, as-built drawings, and other sources of information, a benchmark was created and sample calculations were performed with the SCALE code system [9] version 6.2.4 and KENO-VI, previously validated for criticality calculations [10]. Following the ICSBEP guidelines for publication [11] and uncertainty quantification [12], 11 experiments in total were evaluated and are described in this paper; moreover, assessment of the similarities between calculation and experiments is given herein.

The main challenge encountered during this evaluation was the lack of information concerning numerous components of the experiments, including dimensions, material composition and other discrepancies. For example, it is known that the reactor configuration was changed in 1985 and new dosimetry experiments were performed, but no information about the exact changes could be located—meaning we do not know if there was any impact on the critical configuration of the reactor. The impact of uncertainties is also evaluated in this paper. The inclusion of the proposed HPRR critical evaluation in the ICSBEP handbook would bring new validation possibilities to the community because it combines the highly detailed and strict process associated with the creation of an ICSBEP benchmark and the rare/unique reactor and shielding characteristics of the HPRR, such as the use of highly enriched U-Mo fuel and the unmoderated fast reactor configuration.

This paper aims to describe the different steps of the HPRR data evaluation and criticality benchmark creation process. A quick overview of the HPRR historical data and characteristics is given in section 2. The experiments of interest are described in section 3 and the evaluation of the experiments, benchmark model description and sample calculation results with comparison to the experiment results are introduced in section 4.

2 THE HEALTH PHYSICS RESEARCH REACTOR

The HPRR was designed and built at ORNL in 1961. The reactor was initially sent to the Nevada Test Site in 1962 for operation BREN [13], where it was used to study the radiation effects of dose rate similar to the Hiroshima and Nagasaki bombings during World War II. The reactor was then sent back to ORNL to be part of the Dosimetry Application Research (DOSAR) facility a few years later and was operated there until its decommissioning in 1987. The DOSAR facility included a reactor building and a control/laboratory separated by approximately 300 meters. For more than two decades, the HPRR critical assembly profited many fields of work, including: industry with detector calibration, characterization and intercomparison of different detectors capacities, radiobiology with irradiation of plants and animals, teaching and training of reactor operators on nuclear criticality and radiation safety principles. Many of those studies were published and are still available today. Between 1963 and 1987, the HPRR went critical approximately 10,000 times and was very reliable, with an exemplary short yearly downtime.

The HPRR core was similar to the Los Alamos National Laboratory Godiva II critical assembly [14] and the White Sands Missile Range Fast Burst Reactor (FBR) [15]. It was designed to allow very efficient and safe operation, learning from the few criticality incidents that occurred in the similar burst assemblies at the time [16]. The HPRR main fuel components are 11 right cylindrical annuli made of nickel-coated highly enriched uranium (93.14 wt% ^{235}U) and molybdenum alloy. The annuli are approximately 20 cm in diameter and of various thicknesses, with a total height of 23 cm. The plates were held together by nine U-Mo hollow bolts, each filled with U-Mo or stainless steel bolt inserts. A sample irradiation hole with a diameter of ~0.67 cm was drilled through the plates to allow for insertion of another U-Mo plug or any testing apparatus. The other U-Mo elements of the core are three control rods (the regulating rod, mass adjustment rod, and burst rod) and the safety block (placed in the center of the annuli, used to stop the burst by falling out of the assembly in a stainless steel safety tube). All the U-Mo parts of the core contained 90 wt % uranium and 10 wt % Mo. The total uranium in the core 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. Figure 1 shows a drawing and a photograph of the critical assembly without the aluminum safety cage [17]. As of 2022, the reactor building, and the control room buildings are still intact at ORNL: however, the HPRR critical assembly and most of the control instruments have been removed.

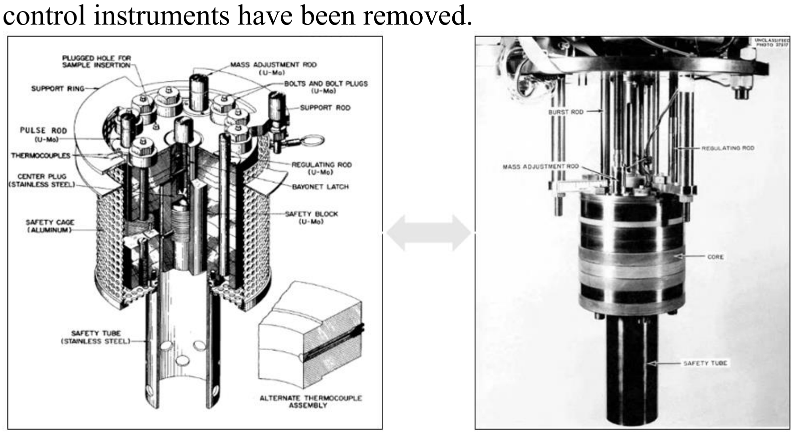

Figure 1: Drawing of the HPRR critical assembly (left), Photography of the HPRR critical assembly without the aluminum safety cage (right).

3 EXPERIMENTS OF INTEREST

3.1 Description of experiments candidates

The HPRR could be operated in various configurations, with numerous elements being flexible. Several U-Mo core elements could be removed from the core or replaced by aluminum or other material elements of equivalent or different dimensions. For a given core configuration, the position of four U-Mo elements has a direct influence on the core reactivity and must be known: the mass adjustment rod (MAR), the regulating rod (RR), the burst rod (BR), and the safety block (SB). Moreover, the axial position of the assembly could be changed, with a nominal height of about 1.4 m from the concrete floor of the building. To obtain the best evaluation results possible, a thorough description of the core elements, their position, and the corresponding criticality must be known. The HPRR was used for irradiation and dosimetry purposes, mainly in burst mode, meaning essentially no proper criticality report was created in the past. The most valuable information about the reactor criticality was found in the report on one of the first HPRR preliminary calibration experiments written by John T. Mihalczo in 1968 [5]. At this time, the core did not have an Al safety cage around the U-Mo fuel elements, and other potential unknown core differences could exist, so the configurations described in that article were not evaluated in this work. Additional core information was located in the most recent HPRR Operating Manual, written in 1985 [17], including control rods and safety block worth, but no explicit critical configuration was described. Nevertheless, subcritical, critical, and prompt-critical configurations of the HPRR could be located from experimental logbooks and training operations. In those references, the position of the different control rods and other core elements were recorded, as well as the measured reactor criticality. No information about the exact process to determine a critical core could be found, other than when a “stable power” of the reactor is achieved. In the evaluated subcritical experiments, the experimentalists manually measured the negative stable period of the reactor by finding out the duration it takes for the reactor power to be divided by two. Then, they used a specific derivation of the Inhour equation found in an unpublished University of Tennessee Nuclear Engineering class document entitled “Approach to Criticality and Control Rod Calibration at The HPRR” to obtain a subcritical reactivity in units of cents, as shown in Eq.(1), in which T is the reactor period:

$$\rho_{cents} = \frac{1}{0.64}\left(\frac{168.84}{T+80.4} + \frac{459.2}{T+32.8} + \frac{112.25}{T+8.98} + \frac{84}{T+3.52} + \frac{6.51}{T+0.88} + \frac{0.89}{T+0.33}\right). \qquad (1)$$

The HPRR was operated at steady-state critical for at least hundreds of times, as recorded in experimental logbooks. The goal of those experiments was to irradiate samples for a longer period of time and at a lower intensity than that during burst operation. The core configuration for steady-state operation was recorded on specific steady-state log sheets. These experimental results are considered the most thrustworthy as they were performed a few months before the reactor decommissioning. The HPRR was also used for Senior Reactor Operator and students training. During those operations, a steady-state log sheet was filled, as it was also in steady-state operation. The goal of those experiments was to show the trainees the influence of the position of the control rods on the reactor reactivity. Different reactor configurations were tested, and the reactor was alternated between critical and subcritical states. Those experiments results are valuable because they explicitly describe critical and subcritical configurations of the HPRR; however, the accuracy of the data can be questioned as it comes from trainees and was performed in 1974, with a potentially different core than in the 80s. The main operation of the HPRR was in burst mode, to reproduce very high dose similar to criticality accidents or to study the effects of high-intensity irradiation on materials. Before each burst, the reactor was in a slightly subcritical state with the BR fully out. As the burst started, the BR would be fully inserted within a few milliseconds, and the reactor would become prompt-critical before the SB was expulsed at the bottom of the core due to the nearly instantaneous temperature increase of a few hundred degrees. In the HPRR Burst Log Sheets, the configuration of the core in the subcritical state before a burst was recorded. Those experiments’ results are valuable because they indicate two different measurements of the subcritical reactivity, and they are from a different configuration compared to that of the steady-state experiments (BR is fully out). The prompt critical configurations of the burst experiments are not studied in this paper.

3.2 Evaluated Experiments Description

A few of each of the three experiment types described in Section 3.1 were selected for evaluation. The evaluated critical experiments are shown in Table I. A discrepancy between configurations number 3 and 4 should be noted. Both experiments are supposed to be critical, but the MAR position is slightly different in the training sheet (5.821 in.) and in the logbook sheet (6 in.). These differences will be investigated in the uncertainty study and sample calculations. The evaluated subcritical experiments are shown in Table II. Note that the experiments from training sheets have only a single reactivity measurement and RR position.

Table I. Evaluated Critical Experiments

Configuration Number	1	2	3	4	5	6	7
Origin	Training sheet			Logbook			
Operation Number	1469	1469	1469	1469	2881	2883	2946
Date	4/9/1974	4/9/1974	4/9/1974	4/9/1974	1/3/1986	1/7/1986	5/29/1986
Height above floor (m)	1	1	1	1	1.43	1.4	1.4
Safety Block (in)	−0.135	−0.135	−0.135	−0.135	−0.113	−0.116	−0.13
Regulating Rod (in)	0	2.5	8.24	8.24	7	7	7
Mass Adjustment Rod (in)	6.515	6.31	5.821	6	6.487	6.734	6.227
Burst rod (in)	IN	IN	IN	IN	IN	IN	IN

Table II. Evaluated Sub-Critical Experiments

Configuration Number	1	2	3	4
Origin	Training sheet		Logbook	
Operation Number	1469	1469	B1014	B1016
Date	4/9/1974	4/9/1974	10/29/1985	12/11/1985
Height above floor (m)	1	1	1.44	1.4
Safety Block (in)	-0.135	-0.135	-0.112	-0.115
Regulating Rod (in)	2.5	4.5	0	0
New Regulating Rod (in)	-	-	1.4	1.1
Mass Adjustment Rod (in)	6.515	6.31	3.38	3.84
Burst rod (in)	IN	IN	OUT	OUT
Reactivty 1 (cents)	−4.9	−5.3	−2.8	−2.23
Reactivity 2 (cents)	-	-	−2.75	−2.23

4 EVALUATION OF EXPERIMENTS

4.1 Missing and Contradictory Data

Outside of contradictory information described previously, other issues appeared during the evaluation of the experiments. The experiments were performed between 1974 and 1986, and at that time, fewer methods of dimensions/materials characterization were available, and less care was given to uncertainty analysis. In 1987, the HPRR was decommissioned, and most of the reactor building elements were removed, limiting the ability to perform dimension/material measurements and analysis today. For these reasons, no uncertainty values are available for any dimension or material composition. All the dimensions inferred during this work are from mechanical drawings, documents, or logical assumptions. The accuracy of the drawings and writings is unknown. Moreover, the HPRR was reconfigured multiple times over the years, so care was given to use data from the latest reconfiguration, but sometimes the data were not available. Similarly, all the material composition information found is from documents: no isotopic composition analysis was performed at the time and cannot be performed today. In some cases, contradictory information was found between drawings and technical reports, and in other cases, no dimensions or material data were available, so total assumptions were necessary. A hierarchy of data confidence was established, privileging mechanical drawings first, followed by the most recent writings, and then the inferred dimensions from drawings to scale, with logical assumptions being the last resort if no information could be located.

Besides basic dimensions and material composition uncertainties, some uncertainty remains on the core configuration during the evaluated experiments. For example, the exact position of the safety block when fully inserted is not clear, as the writings found indicate 0.135 in. and 0 in. for a fully inserted position. The same applies for the control rods exact position and the stainless steel tubes where they are contained. Another very important piece of contradictory information is about the RR. In ORNL-TM-9870 [17], two different RRs are introduced, one being fully U-Mo and the other one partially Al and U-Mo. It is suggested that the U-Mo RR is used only during reactor calibration, but no further mention of this could be found in all the other references studied. No details about the partially aluminum and U-Mo RR could be located, and no information about which RR was used during the evaluated experiments was found. A similar uncertainty resides in the sample irradiation hole plug, defined as being either 4.53 in., 8.25 in. or 9.04 in., and no information about which plug was inserted in the core during the evaluated experiments could be located. Another uncertainty about the HPRR critical assembly dimensions and material is regarding the coating. Different layers of coatings were applied around some U-Mo parts of the core, and the thicknesses are not known. To evaluate this uncertainty, two versions of the core were created, with and without any coating. Those uncertainties were all evaluated and taken into account for a potential critical benchmark creation of the HPRR.

4.2 Benchmark Values

In the evaluated critical configurations, the measured k_{eff} is considered to be 1 as the reactor is exactly critical, and it can be directly compared to the calculated k_{eff} with KENO-VI. In the evaluated subcritical experiments, the experimentalists manually measured the negative stable period of the reactor and used a specific derivation of the Inhour equation shown in Eq. (1) to obtain a subcritical reactivity in units of cents. To be able to compare experimental and calculation results, the subcritical reactivity values in cents were converted to a k_{eff} value by using Eqs. (2) and (3). The delayed neutron fraction β_{eff} was obtained with KENO-VI by activating and deactivating the production of delayed neutrons as shown in Eq. (4), with $k_{p,eff}$ the k_{eff} value obtained by turning off the delayed neutrons in KENO-VI (`pnu=yes` turns off the delayed neutron). The calculation of β_{eff} with KENO was validated for a few known benchmarks [18].

$$\rho_{cents} = \frac{\rho}{\beta_{eff}}, \tag{2}$$

$$\rho = \frac{k_{eff} - 1}{k_{eff}}, \tag{3}$$

$$\beta_{eff} = 1 - \frac{k_{p,eff}}{k_{eff}}. \tag{4}$$

4.3 Uncertainty Study

An uncertainty study was performed to determine the influence of dimensions and material composition uncertainty on the core criticality. The uncertainty study was performed with KENO-VI calculations of a single created model corresponding to configuration number 6 described in Table I. The obtained uncertainty will be used in all the evaluated experiments in this work. Additionally, the complete addition and subtraction of some elements were analyzed when a simple perturbation was not possible. The results of the uncertainty study are shown in Table III. As expected, the estimated experimental uncertainty is very high, approximtaley 3,803 pcm, corresponding to about 3.8% relative uncertainty. The main contributor with approximately 3,700 pcm is the uncertainty on the U-Mo fuel density that could not be recovered and was determined according to the ICSBEP guide to express uncertaintities guidelines [12]. Other significant contributors are the safety block position uncertainty, the stainless steel 304 core elements density, and the fuel coating uncertainty. The low influence of the BR and RR positions on k_{eff} is explained by the fact that the rods are respectively fully out and almost fully out of the core in the particular configuration studied (Configuration 6 in Table I).

Table III. Estimated Experimental Uncertainties

Element	**Uncertainty**
BR position	−0.00004
MAR position	−0.00100
RR position	−0.00040
Safety Block position	0.00749
Fuel U content	−0.00142
Fuel Mo content	negligible
Fuel alloy density (g/cm^3)	0.03668
Fuel ^{235}U content	−0.00139
Core elements SS304 Cr content	negligible
Core elements SS304 Ni content	negligible
Core elements SS304 density (g/cm3)	0.00538
Thermocouple presence	negligible
Coating presence	0.00300
RR is aluminum rod	negligible
Reactor height position	negligible
Aluminum safety cage presence	0.00113
Sample irradiation plug height	0.00061
Sum in quadrature	**0.03803**

4.4 Benchmark Model

A highly detailed model of the HPRR and the reactor building was created, respecting the as-built drawings and other written information to the extent possible. An overview of the SCALE 6.2.4 model is shown in Figure 2 for the entire building and in Figure 3 for a front right quarter view zoomed on the HPRR. All the elements of the core are modeled and the control rods and other various flexible elements of the core can be easily modified to accommodate to the desired reactor configuration.

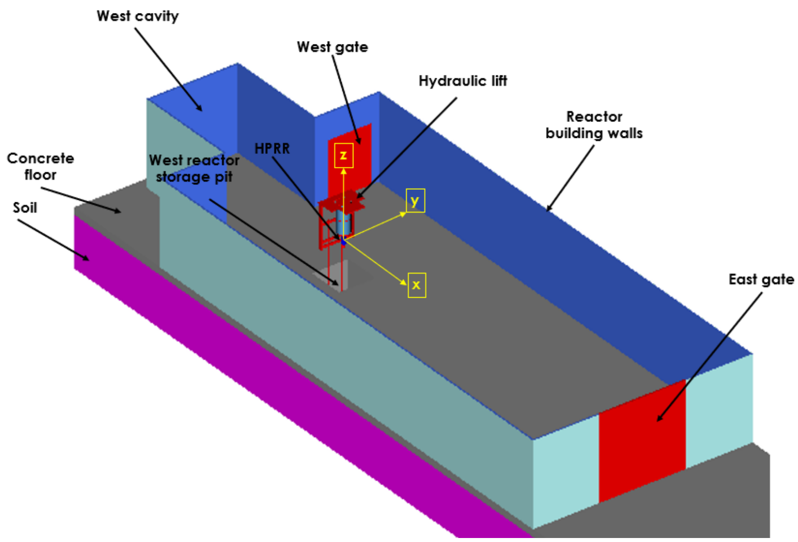

Figure 2: Overview of the HPRR reactor building and core model.

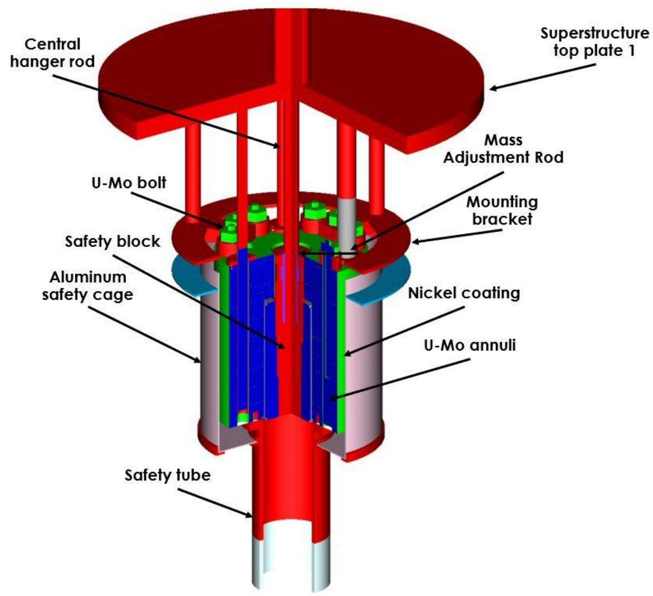

Figure 3: Overview HPRR critical assembly model.

4.5 Sample Calculation Results

The results of the evaluation of the 11 core configurations previously introduced is shown in Table IV. Without considering the estimated uncertainty, there is between 1,000 and 1,200 pcm difference between expected and calculated values, corresponding to a relative difference of about 1%. This kind of bias is considered a large difference in criticality safety validation. It is worth noting that the bias seems to be close to constant, meaning that whatever unknown errors made in the model have an equal effect in each of the evaluated experiments. Taking into account the estimated uncertainty, the conclusions about the potential benchmark are even worse, as the uncertainty is far too high to consider going further and creating a useful and valuable benchmark.

Table IV. Sample Calculation Results and Comparison to Expected Values

Reactor State	Configuration Number	k_{eff}				
		Expected	Uncertainty	Calculated	Uncertainty	Relative difference (%)
Critical	1	1.00000	0.03798	1.01385	0.00010	1.4%
	2	1.00000	0.03798	1.01331	0.00010	1.3%
	3	1.00000	0.03798	1.01029	0.00018	1.0%
	4	1.00000	0.03798	1.00958	0.00017	0.9%
	5	1.00000	0.03798	1.00951	0.00021	0.9%
	6	1.00000	0.03798	1.00948	0.00018	0.9%
	7	1.00000	0.03798	1.00988	0.00021	1.0%
Sub-Critical	1	0.99966	0.03797	1.01288	0.00010	1.3%
	2	0.99964	0.03797	1.01150	0.00010	1.2%
	3	0.99981	0.03797	1.01229	0.00016	1.2%
	4	0.99985	0.03797	1.01166	0.00019	1.2%

5 CONCLUSIONS

To help broaden the range of available valuable critical benchmarks to the community, an evaluation of legacy data from HPRR operation was performed to create a critical benchmark to be included in the ICSBEP Handbook. The HPRR, because of its unique characteristics and extensive operation history, is a good candidate for such a benchmark creation. Critical and subcritical experiments were selected and evaluated, and the analysis of numerous as-built drawings and written sources allowed for the creation of a benchmark model and an uncertainty study. Unsurprisingly, both the estimated experimental uncertainty and the expected to calculated difference results obtained are poor when compared to the usual ICSBEP critical benchmark standards, due to a great deal of unknown, contradictory information and other kinds of uncertainties. The estimated uncertainty is approximately 3,800 pcm, compared to typically acceptable uncertainties of a few hundred pcm in the critical benchmarks in the ICSBEP handbook. The relative difference between the expected and calculated k_{eff} values is about 1%, compared to usual difference below 0.1% in the ICSBEP Handbook. Because of these results, it is concluded that the creation of a valuable HPRR critical benchmark is not possible. This work also serves as a reminder to all of us in the future always to record all the information related to experimental work, and always to try to precisely document any dimension and material composition information that could be useful in the future. HPRR legacy data are also currently being considered for the creation of a shielding benchmark, and an updated evaluation will be submitted to the ICSBEP for a publication in the 2023 version of the handbook.

6 ACKNOWLEDGMENTS

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