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VVER-1000 benchmark criticality analysis using SCALE code

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1. Introduction

The OECD/NEA benchmark NEA/NSC/DOC(2006)1 (LR(0)-VVER-RESR-002) for Criticality measurements of VVER-1000 mock up using the reactor LR-0, which is an experimental light-water-moderated zero-power reactor, originally designed for the research of the VVER-1000 and VVER-440 type reactor cores, spent-fuel storage lattices and benchmark experiments, consisting of hexagonal lattices of low enriched UO_2 fuel assembly in light water with H_3BO_3 [1]. In this paper, this benchmark results have been analyzed using SCALE 6.2.3 code, which is a widely used modeling and simulation suite for nuclear safety analysis and design that is developed, maintained, tested, and managed by the Reactor and Nuclear Systems Division (RNSD) of Oak Ridge National Laboratory (ORNL) [2]. This paper interprets the criticality analysis of benchmark VVER-1000 mock up core with 32 fuel assemblies for six different critical configuration using SCALE code. Such criticality analysis validation will increase confidence on VVER design given that Bangladesh is constructing a nuclear power plant with two VVER-1200 reactor unit and the reactors are anticipated to be operational by 2025.

2. Experimental configuration and Benchmark Modeling

2.1 Reactor Geometry and Configuration

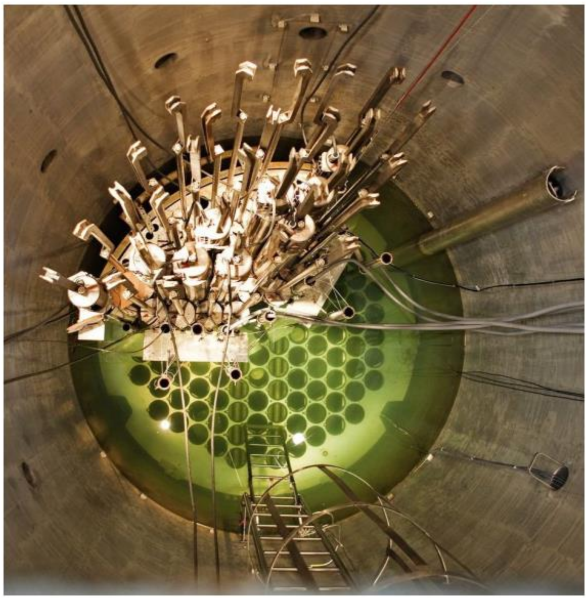
The criticality measurement of VVER-1000 type core loading has been performed on the reactor LR-0, which is located in the Czech Republic, under the common project between Nuclear Research Institute Řež (NRI) and National Research Centre Kurchatov Institute (NRC KI). The LR-0 fuel elements are shortened to about one-third the lengths of the elements in VVER nuclear power plants. The enrichment used in the fuel elements are 2 wt.%, 3wt.%, and 3.3wt.%. The experiment performs at atmospheric pressure and room temperature. Power control is carried out by changing moderator level or in fully flooded scenario, 2 control cluster using 3 control rods [1].

In this experiment, the core assembled with 32 fuel assemblies, whereas 20 fuel assemblies are 2.01 wt.%, 3 assemblies 2.02 wt.%, 1 assembly 2.0 wt.%, 6 assemblies 3.01 wt.%, 1 assembly 3.29 wt.%, and 1 assembly 3.30 wt.%, ^{235}U enrichment. The benchmark support plate, which is also positioned above the standard support plate, is used to hold all of the fuel assemblies. Each fuel assembly (FA) contains total 312 fuel elements in a triangular lattice with pitch 12.75 mm, 18 stainless steel guide tubes for control cluster, a central zirconium-alloy instrumentation tube and 5 spacing grids to hold control cluster and assembly element together. The fuel element consists of a UO_2 pellet with zirconium alloy cladding. The active length of the UO_2 fuel column is 1250 mm. The control cluster tube is 1444 mm in length with 12.6 mm outer diameter. The emergency control clusters is placed in the six different fuel assembly positions and the control clusters positioned in the two fuel assembly using three control tubes are partially inserted to 60.4 cm. Five axially distributed honeycomb stainless steel spacing grids are used for fixing the fuel elements' pitch. Criticality is achieved by changing the moderator level, which is the mixture of demineralized water with different concentration of boric acid, and by 2 control clusters with reduced reactivity worth (3 control rod per cluster only) in the case of the fully flooded by moderator with high boric acid concentration. The experimentally determined critical moderator level and boric acid concentration are presented in Table: 1 [3].

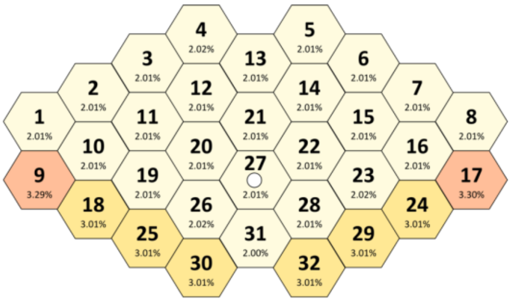
Table 1: Critical moderator level

Case	Hcr		C(H_3BO_3)	
	[cm]	unc.	[g/kg]	unc.
1	51.34	0.05	2.85	0.06
2	65.91	0.05	3.63	0.05
3	79.11	0.05	4.06	0.05
4	96.71	0.05	4.44	0.05
5	103.37	0.05	4.53	0.05
6	150		4.68	0.08

The LR-0 reactor with VVER-1000 mock up experimental arrangement is shown in Figure 1(a) and fuel assembly arrangement pattern with enrichment information is shown in Figure 1(b). Fuel assembly pin numbering with control rod tube and central instrumentation tube position are presented in figure 1(c) [1].



(a)



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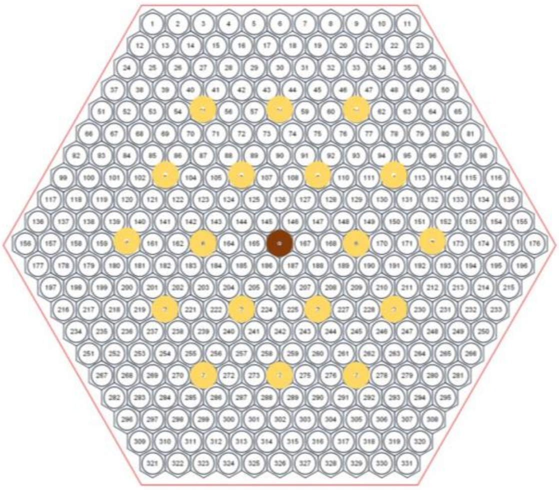


(c)

Figure 1: a) LR-0 Reactor with 1000 Mock up, b) Fuel assembly pattern and their enrichment c) Fuel assembly with pin numbering and arrangement of control cluster and central instrumentation channel.

2.2 Benchmark Modeling:

The benchmark experiment has been modeled using KENO-VI code package of the SCALE 6.2.3 code system, which is a three-dimensional (3D) Monte Carlo criticality transport program. The KENO-VI modeling used the exact geometry dimensions (fuel pin, fuel assembly, cluster rod, barrel, baffle, supporting structure etc.), material composition (moderator and boric acid density, fuel atomic density, cladding composition etc.), and operating condition (temperature) specified in the benchmark documentation. Some assumptions have been made during the modeling of benchmark such as: 1) spacing grid material below the critical water height is modeled as a homogeneous water and steel mixture, 2) ^{234}U and ^{236}U content in fuel is omitted, 3) the reactor tank is not included in the model for criticality calculation, 4) the model ends with barrel outer surface. The simulations are conducted using 10,000 neutron histories per cycle, 50 inactive cycle and 250 active cycle. The convergence of the fission source distribution is checked by means of Shannon entropy during the inactive cycle. Continuous energy ENDF/B-VII.1 nuclear data library is used for all six cases of criticality calculation. The modeling of the VVER-1000 mock up using SCALE code is presented in the figure 2 and 3.

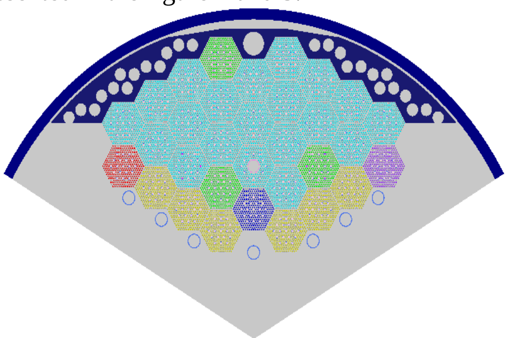
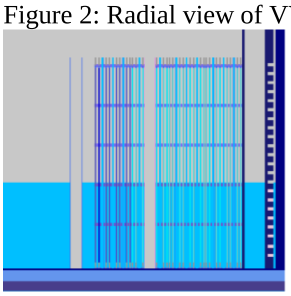
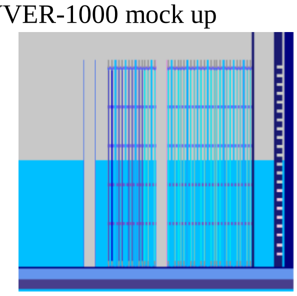


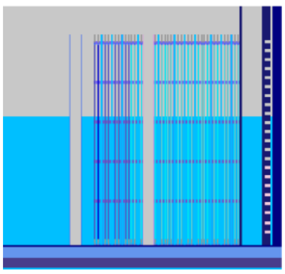
Figure 2: Radial view of VVER-1000 mock up



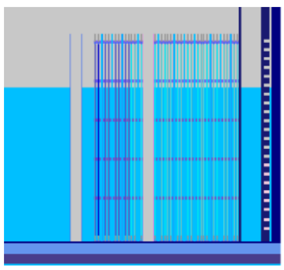
(case 1)



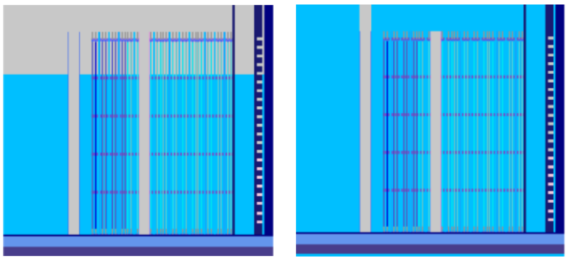
(case 2)



(case 3)



(case 4)



(case 5) (case 6)

Figure 3: Axial view (Y-Z plane) of six critical Configuration of VVER-1000 mock up

3 Numerical Results:

The effective neutron multiplication factor (K_{eff}) is calculated with the SCALE code using ENDF/B-VII nuclear data library for the six critical configurations of the reactor by varying moderator level. A comparative study of K_{eff} among SCALE, Benchmark result which is obtained by MCNP5 and experimental result is presented in the Tables 2 and 3. A good agreement of K_{eff} is observed between the benchmark result and SCALE output with Monte Carlo standard deviation less than 45 pcm.

Table 2: K_{eff} and difference between Scale and Benchmark

	SCALE	**Benchmark**	**Diff (SCALE-Benchmark) ±σ [pcm]**
Case 1	1.00245	1.00217	28±41
Case 2	1.00375	1.00355	20±41
Case 3	1.00425	1.00457	-32±45
Case 4	1.00480	1.00501	-21±42
Case 5	1.00560	1.00510	50±35
Case 6	1.00470	1.00446	24±32

Table 3: K_{eff} value and difference between Scale and Experiment

	SCALE	**Experiment**	**Diff (SCALE-exp.)[pcm]**	**Bias Corr.(a)**
Case 1	1.00245	1.00000	245	-0.00156
Case 2	1.00375	1.00000	375	-0.00194
Case 3	1.00425	1.00000	425	-0.00137
Case 4	1.00480	1.00000	480	-0.00155
Case 5	1.00560	1.00000	560	-0.00156
Case 6	1.00470	1.00000	470	-0.00134

(a) The effect of omitting ^{234}U content added as bias correction.

4. Conclusions

The benchmark outcome of the VVER-1000 mock up LR-0 reactor experiment using hexagonal lattices of low enriched UO_2 fuel assemblies in light water with boric acid concentration is interpreted in this paper. KENO-VI code of SCALE code is used in this verification to mimic the VVER-1000 mock up benchmark specification in detail. The six critical configurations of moderator level and boric acid concentration were analyzed by the modelling, and the results showed good agreement between SCLAE and the benchmark criticality. This benchmark criticality analysis result is a first step towards the full interpretation of the OECD/NEA benchmark, which comprises the neutron spectrum in the core central dry channel and reactor pressure vessel, the radial and axial power distribution. The modelling of the geometry and material composition uncertainties are also included in the future scope of full-scale interpretation.

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