FREK Code Validation with the CEFR Control Rod Drop Experiments

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1. Introduction

FREK (Fast REactor Kinetics) is a multi-group neutron kinetics code capable of steady-state and transient-state analysis of hexagonal lattice reactor core in fast neutron environment developed by Seoul National University (SNU) and Korea Atomic Energy Research Institute (KAERI) around 2015 [1, 2].

The basis nodal diffusion solver incorporates the Triangle-based Polynomial Expansion Nodal (TPEN) method radially and the Nodal Expansion Method (NEM) axially. In order to simulate more accurately the massive neutron leakage transport effect in fast reactors, a Simplified P3 (SP3) method is combined with the TPEN/NEM [3]. The Coarse Mesh Finite Difference (CMFD) method is applied to the module to make the nodal diffusion solver accelerate. The FREK processes the ISOTXS formatted cross-section (XS) library and generates group constants with its own format. The transient analysis module employs the Backward Differentiation Formula (BDF) for time step control [4]. The FREK code has performed MARS/FREK coupled safety analyses [2] and has also performed neutron dynamic calculation for the Prototype Gen-IV Sodium-cooled Fast Reactor (PGSFR) core [1].

KAERI has been participating in the International Atomic Energy Agency (IAEA) Coordinated Research Projects (CRP): Neutronics Benchmark of China Experimental Fast Reactor (CEFR) Start-Up Tests [5], which started in 2018 and as it entered the extension phase in 2023, the China Institute of Atomic Energy (CIAE) has decided to provide more in-depth measurements, including burnup data and dynamic simulation data.

This paper presents the results of the dynamic simulation of CEFR rod drop experiments with the FREK code and validates its results with the obtained measured data through the CRP.

2. Methods and Results

This section introduces to the rod drop experiment and then presents the modelling and simulation results using FREK. The section 2.1, description of neutron dynamics experiment, is referred to [6, 7] mainly.

2.1 Method of Neutron Dynamics Experiment

The experiment was carried out at operation layout, which consists of 79 fuel subassemblies, shown in Fig. 1. The experiment was designed to be carried out at 250℃ of cold state, while the measured sodium temperature was about 245℃. The measured drop duration of each rod is provided in Table I. The safety rods (SA) drop is faster than the regulating rods (RE) and shim rods (SH) due to special structure design, so that they could better fulfil the task of emergent shutdown. [6, 7]

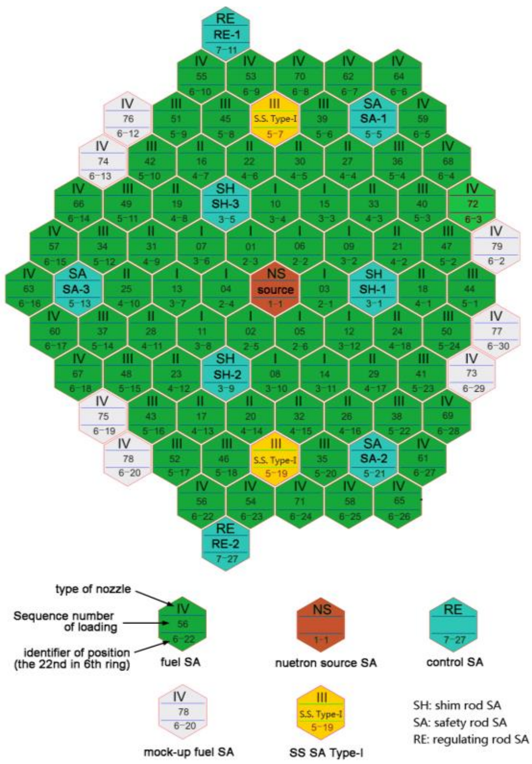

Fig. 1. Fuel loading pattern at operation layout. Mock-up fuel subassemblies are replaced by fuel subassemblies. [7]

Table I: Drop Duration of Each Rod at the Cold State [6]

Rod	RE1	RE2	SH1	SH2	SH3	SA1	SA2	SA3
Duration [sec]	2.15	2.2	2.3	2.3	2.4	0.48	0.54	0.54

The real measurement is by external source-range detector, which is about 5.7 m from the core centre radially. At the beginning of measurement, the rod to be measured was withdrawn to the out-of-core position; by moving other control rods, the core was kept at a certain positive reactivity, so that the neutron flux would increase; at the moment the count rate of detectors reached 30,000 counts/sec, the rod was dropped; the reactivity meter recorded the count rate and calculated the reactivity based on the inverse kinetics method by a time interval of 1.0 sec. One thing should be noted that the positions of the rod before and after the drop vary due to the uncertainty in the driving mechanism operation, the position detection system, and the compression of buffer spring. The exact positions in each rod drop experiment can be found in Table II and Table III. [7]

The focus is changed to the time-dependent behaviour of neutron population, which needs a neutron dynamics simulation through the duration of the rod drop and the following seconds [6].

Five cases are selected for comparison: RE1, SH1, SA1, 3*SA, and all 8 rods (All Rods). The main consideration in selecting these rod or rod groups is to cover a wide range of reactivity worths, from the smallest (RE1) to the largest (All Rods). For each rod or rod group, the transient simulation should start from the drop moment and lasts for at least 10 seconds, with an interval of 0.1 second for output and comparison [6].

Table II: Rod Positions Before/After Drop I: Cases for RE1, SH1 and SA1 [6].

Test Cases	RE1		SH1		SA1	
Rod/States	Before	After	Before	After	Before	After
RE1	501	-1	240	240	240	240
RE2	106	106	240	240	239	239
SH1	240	240	501	4	240	240
SH2	240	240	141	141	240	240
SH3	239	239	141	141	241	241
SA1	498	498	498	498	498	46
SA2	500	500	499	499	499	499
SA3	500	500	499	499	499	499

* Unit in mm, from the bottom of the fuel region

Table III: Rod Positions Before/After Drop II: Cases for 3*SA and All rods [6]

Test Cases	3*SA		All rods	
Rod/States	Before	After	Before	After
RE1	247	247	247	0
RE2	249	249	248	3
SH1	240	240	240	2
SH2	240	240	240	-2
SH3	240	240	240	0
SA1	498	46	499	45
SA2	500	56	500	56
SA3	499	40	500	40

* Unit in mm, from the bottom of the fuel region

2.2 Modelling with FREK

The core is modelled by referring to the cold state, thus its dimensions and number densities are the same as those of the core description in [7], which was modelled with MC2-3/DIF3D by KAERI.

The FREK uses its own format group constants file, which of name is XSEC, using data from the ISOTXS and DLAYXS libraries. ISOTXS and DLAYXS are generated by the MC2-3 [8]. The FREK uses macroscopic XS; thus, ISOTXS with macroscopic XS in ASCII file is generated by the MC2-3. The neutron velocity, υ, is also adopted from ISOTXS. DLAYXS provides delayed fission spectrum ($\chi_{delayed}$) in microscopic XS, therefore, user has to make material-wise delayed fission spectrum manually. ENDF/B-VII.0 nuclear data [9] is used in MC2-3. In the case of XS feedback considering control rod movement, a difference value between a XS of control rod region and that of un-rodded region should be added in the XSEC. While the measured effective delayed neutron fraction (β_{eff}) and neutron generation time (Λ) are present in the paper [10], the six-group of delayed neutron fraction (β_i) information is absent. Consequently, the point kinetics parameters refer to the calculated values generated by the Serpent in the paper [10].

Materials are homogenized in assembly-wise. If axial height of a component is smaller than few cm, then materials in thereof region are homogenized with axially adjacent components. Hexagonal lattice is divided in six triangles to solve with TPEN. Axial node size is divided in 4-5 cm.

Moving part of control rod subassembly consists of baffle, lower connector, neutron absorber, plenum, upper connector and shaft. XS feedback for all of these components is complicated but ineffective, accordingly, only the absorber part is considered during rod drop simulation, as depicted in Fig. 2.

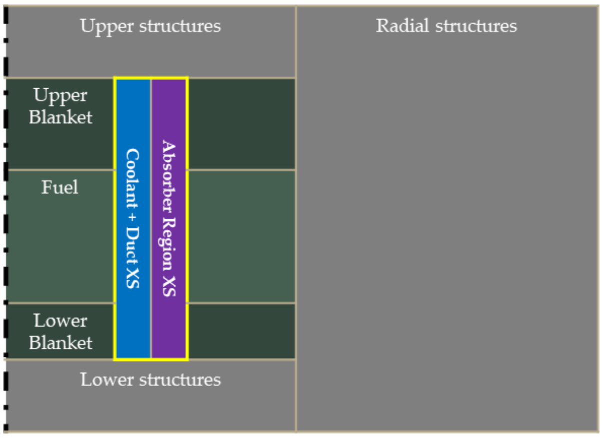

Fig. 2. Approximate core configuration in R-Z direction of FREK modelling.

2.3 Sensitivity Tests with Static Control Rod Worth

Before the rod drop simulation, sensitivity tests are conducted in FREK at the steady state in order to select appropriate calculation options. The static control rod worth is calculated using various options, such as the neutron diffusion solver and XS generation method for control rods. Thereafter, the calculated results are evaluated with measured data.

Isotropic scattering XS is generated and used in this CRP, and any other neutron transport correction for both total and scattering XS is not applied. Two different neutron diffusion solvers are applied, which are TPEN/NEM and TPEN SP3/NEM SP3. XS for control rods is generated in two different ways: 0-D model which considers only absorber material, 1-D slab model which models with its neighbour fuel material to consider the spatial self-shielding effect. The five different rod type cases are calculated with four different calculation options, and the results for TPEN/NEM and SP3 are listed in Table IV and Table V, respectively.

Table IV: Sensitivity Test of Rod Worth: TPEN/NEM

Rod type	Solver	TPEN/NEM			
	CR XS	0-D		1-D	
	Msrd.[pcm]	Δρ[pcm]	Err.[%]	Δρ[pcm]	Err.[%]
RE1	150	159	6.2	126	-16.0
SH1	2,019	2,274	12.7	2,094	3.7
SA1	945	1,091	15.5	952	0.7
3*SA	2,981	3,489	17.0	3,032	1.7
All rods	6,079	7,435	22.3	6,615	8.8

Table V: Sensitivity Test of Rod Worth: SP3

Rod type	Solver	TPEN SP3/NEM SP3			
	CR XS	0-D		1-D	
	Msrd.[pcm]	Δρ[pcm]	Err.[%]	Δρ[pcm]	Err.[%]
RE1	150	148	-1.1	117	-22.2
SH1	2,019	2,159	6.9	1,999	-1.0
SA1	945	1,020	8.0	897	-5.1
3*SA	2,981	3,274	9.8	2,865	-3.9
All rods	6,079	7,008	15.3	6,276	3.2

In conclusion, for the rod drop simulation calculation with the FREK, TPEN SP3/NEM SP3 and 1-D slab model are selected as options for the neutron diffusion solver and control rod XS generation, respectively. The RE1 worth is around 22% under-estimated with the selected calculation options. The RE banks are located at the periphery of the active core; in other words, they are surrounded by both fuel subassemblies and SS reflector subassemblies. However, 1-D slab model comprises only control rod region and fuel region, which is assumed to be the source of the discrepancy.

2.3 Rod Drop Simulation and Results Comparisons

The time interval is set to 0.01 sec from 0 to 10 sec for the transient scenario. In the case of “All rods”, RE and SH are inserted approximately halfway up the core height, therefore, each control rod insertion time is corrected according to their dropping speed. The starting points of the rod drop time in the measured data for comparison with the calculation results are selected by the authors, summarised in Table VI, and are the starting points for the detector count rates sharply decrease. The detector count rates are normalized to their values of five seconds prior to the time in Table VI. Once the normalized detector count rates are obtained, these are converted to the dynamic reactivity using the inverse point kinetics model, where the neutron population is assumed to be directly proportional to the detector count rate.

Table VI: Beginning Points of the Rod Drop Time in the Measured Data

Scenario type	Starting point [sec]
RE1	20.4
SH1	20.4
SA1	20.1
3*SA	30.3
All rods	30.1

The measured and calculated values are compared in Fig. 3 to Fig. 7, where the left-hand side figures show the normalized neutron population, and right-hand side figures show dynamic reactivity. The decrease slope of neutron population and stabilized time points of dynamic reactivity look good agreement with the measured data, except RE1 bank. The 21% discrepancy of RE1 may come from underestimation of FREK due to its methodologies and the location of RE1.

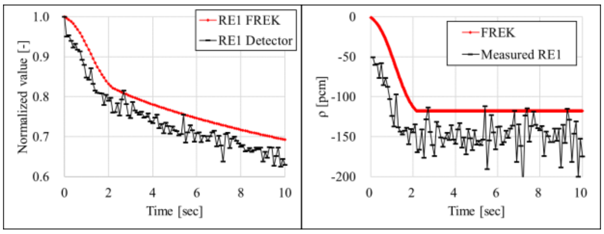

Fig. 3. Measured and calculated result comparison for RE1.

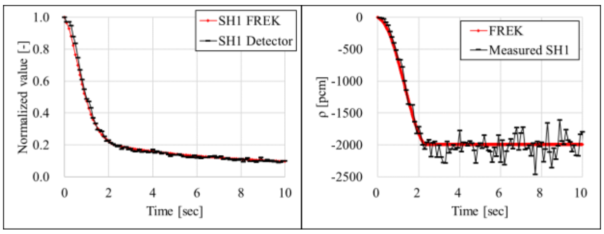

Fig. 4. Measured and calculated result comparison for SH1.

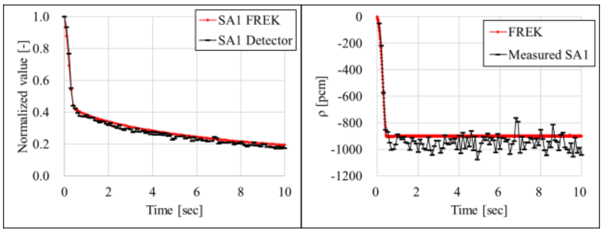

Fig. 5. Measured and calculated result comparison for SA1.

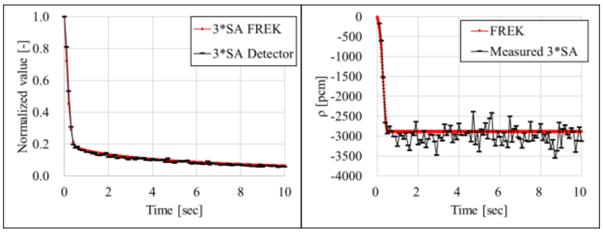

Fig. 6. Measured and calculated result comparison for 3*SA.

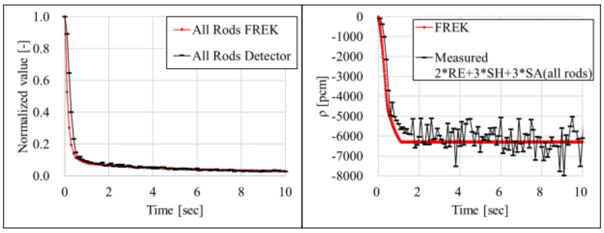

Fig. 7. Measured and calculated result comparison for All Rods.

The comparisons of dynamic rod worth between the measurements and calculations are shown in Table VII and Fig. 8. The measured static rod worths are referred to the measured data of the CRP Work Package 2, and the measured dynamic rod worths are obtained by averaging over ten seconds during which the reactivity measurements converge. There is discrepancy between two different measured values from the static rod worth and dynamic rod worth. In comparison of dynamic rod worth, the FREK results agrees within 5% with the measured worth.

Table VII: Comparisons of Rod Worth

Rod type	Dynamic Rod Worth		
	Msrd. [pcm]	FREK [pcm]	Err. [%]
RE1	150±22	118	-21.4
SH1	2,017±176	1,993	-1.2
SA1	947±63	900	-5.0
3*SA	2,998±243	2,883	-3.8
All Rods	6,265±646	6,299	0.5

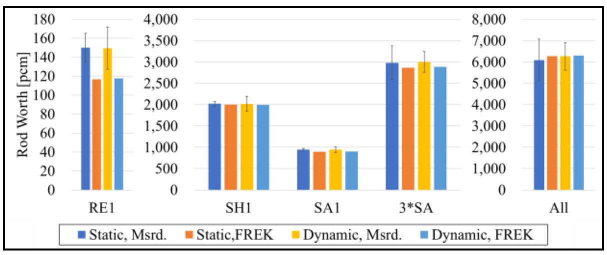

Fig. 8. Comparisons of the measured and calculated rod worth.

3. Conclusions

The FREK code has been validated with CEFR rod drop experiments. Sensitivity calculation is carried out before dynamic calculation through static rod worth calculations. The TPEN SP3/NEM SP3 is selected for the neutron diffusion solver, and control rod cross-section is generated with 1-D slab model. Both neutron population change and reactivity change shows good agreement with the measured data. The control rod worth results of FREK agrees within 5% with the measured worth, while the RE1 bank worth shows 21% discrepancy. Therefore, further investigation to reduce it will be performed including the cross-section generation sensitivity in future work.

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