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Evaluating the fulfilment of control rod related nuclear design bases for an SMR core using the Kraken computational framework

Unna Lauranto, Ville Valtavirta, Antti Rintala, Jaakko Leppänen
VTT Technical Research Centre of Finland Ltd,
P.O. Box 1000, FI-02044 VTT, FINLAND
Unna.Lauranto@vtt.fi, Ville.Valtavirta@vtt.fi, Antti.Rintala@vtt.fi, Jaakko.Leppanen@vtt.fi

ABSTRACT

The development of a new computational framework called Kraken has recently begun at VTT Technical Research Centre of Finland Ltd. The main goal of the development process is to combine the new generation of Finnish reactor analysis codes such as the Serpent Monte Carlo code, Ants nodal neutronics code and FINIX fuel behaviour module into a reactor analysis tool that can be utilized in licensing relevant analyses. Here, the Kraken framework will be used to evaluate the fulfilment of control rod related nuclear design bases for a small modular reactor (SMR) core based on a combination of data from the NuScale licensing documents and the BEAVRS benchmark. Shutdown margins as well as control rod bank integral worths will be evaluated for HZP and HPF conditions at the beginning of the first cycle using the reduced-order (nodal diffusion) neutronics solver of the Kraken framework coupled to the thermal hydraulic and fuel behaviour solvers of the framework.

1 INTRODUCTION

Kraken is a computational framework for nuclear analysis developed at VTT technical Research Centre of Finland Ltd. Kraken combines several codes, including neutronics solvers, a thermal hydraulics code, and a fuel behaviour module, to form a complete reactor analysis tool. Kraken is still under development, although some of the codes, such as Serpent, a high-fidelity Monte Carlo neutronics solver, are already well established in the research community. In addition to Serpent, Kraken contains Ants, a reduced-order nodal neutronics solver, SuperFINIX, a core level fuel behaviour module, and Kharon, a thermal hydraulics code. This work includes Ants simulations coupled with Kharon, FINIX and SuperFINIX using Cerberus as an interface between the codes.

Kraken is developed for analysis for nuclear licensing, which includes safety analysis containing validation of the reactivity control systems. Evaluation of control rod worths and shutdown margin (SDM) is relevant in safety analyses for determining capabilities for the reactivity control systems to execute and maintain shutdown in the case of nuclear transient or postulated accident conditions, and to return the reactor to cold conditions. The aim of this work is to determine control rod worths and evaluate the shutdown margin for an SMR core model using Kraken. Total available control rod worth as well as individual control rod group worths are evaluated in hot-full-power (HFP), hot-zero-power (HZP) and cold-zero power (CZP) conditions.

2 REACTOR CORE MODEL

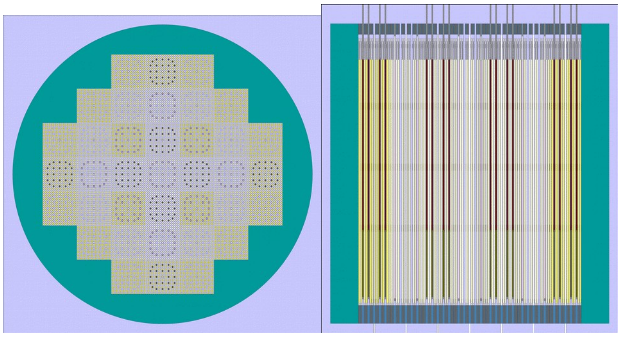

Figure 1: Horizontal and vertical plots of the modelled core geometry Serpent model. The plots show the regulating bank inserted into the core and the shutdown bank extracted.

The reactor is a PWR-type light water reactor with the size of the core reduced to the SMR-scale. The reactor core geometry is based on a combination of data from BEAVRS[1], a full-core PWR benchmark for nuclear analysis, and the NuScale licensing documents[2], containing general information of an SMR design by NuScale Power.

The radial size of the core and active fuel length were designed according to the NuScale reactor. Additionally, the radial reflector surrounding the core was based on the NuScale specifications. Material compositions of the reactor core as well as detailed geometry of the fuel assemblies were based on the BEAVRS benchmark reactor core. The arrangement of the fuel assemblies by fuel enrichment was designed to produce as uniform radial power distribution as possible. Borosilicate glass burnable absorbers were placed in several assemblies to minimize assembly power peaking. The geometry of the control rods was designed according to the BEAVRS benchmark with the rod length decreased to match the NuScale core height. Control rod group positions were based on the NuScale specifications.

The number of grid spacers from BEAVRS was reduced to account for the scaled down length of the core. The grid spacer axial positions were recalculated by scaling intermediate distances of the grid spacers relative to the core height.

Horizontal and vertical geometries of the core are shown in figure 1. A more detailed description of the reactor core geometry and materials are available in the Serpent-wiki.

3 RELEVANT REGULATIONS

Regulations and requirements for nuclear power plants are listed by the U.S. Nuclear Regulatory Commission in the Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants[3] (NUREG-0800). The regulations include reactivity control requirements and control rod reactivity worth provisions. These regulations aim at ensuring sufficient shutdown capability and compensation of long-term reactivity changes.

It is required that two individual Reactivity Control Systems (RCSs) with different operating principles are provided, which in PWRs are control rods and soluble boron. Of these two, one is required to have capability to individually control normal reactivity changes. Furthermore, one RCS should be capable of returning the reactor to cold conditions and to hold the reactor subcritical under cold conditions. This includes compensating for power defect, moderator cooling and xenon decay. The requirements also include that, by insertion of control rods, the reactor can be returned to HZP conditions from any power level. Reactivity changes due to transitions from cold shutdown conditions to HFP conditions and vice versa, assuming reactor poison addition, should be accounted for.

There must be a sufficient amount of negative reactivity available for a reactor shutdown in all conditions to assure that fuel design limits are not exceeded. The shutdown margin is defined as the amount of reactivity by which the reactor would be subcritical from the current condition, assuming that the highest worth control rod assembly (CRA) is stuck out and all other CRAs fully inserted. The RCSs combined must be able to provide a sufficient amount of negative reactivity to exceed the limit of the shutdown margin. Therefore, the control rods have Power Dependent Insertion Limits (PDILs) beyond which they are not inserted during normal operation. It is required in the Finnish Regulatory Guides on nuclear safety and security[4] (YVL) that no malfunction of an individual component, e.g., a reactivity control system, should result in a shutdown margin less than 1%.

4 MODELLING APPROACH

The core geometry is built using the geometry routine of the Serpent code. The geometry routine follows the three-dimensional constructive solid geometry technique that utilizes elementary surfaces to form complex material cells. Serpent is also used to perform spatial homogenization for the reduced-order neutronics solver. The spatial homogenization is executed by dividing the core into node types and, for each node type, evaluating group constants that contain relevant information about the neutronics of the system. The group constants include macroscopic reaction cross sections and diffusion parameters. For each assembly, the group constants are evaluated in different axial setups present in the core. These setups include presence of control rods and grid spacers. Additionally, group constants are generated separately in different operating conditions (HFP/HZP and CZP). The neutron energies are condensed into the two-group energy structure, i.e., a thermal group and a fast group.

The group constants are obtained by running the Serpent nuclide composition calculation for each node type in different momentary condition variations, including fuel temperature, moderator temperature and boron concentration variations. Group constants for the radial and axial reflector are generated separately. The group constants generated with Serpent are parametrized with the SXSFit-tool to a format compatible with Ants. SXSFit finds the fitting coefficients for the group constants and converts the data into an appropriate format that can be applied to Ants as input.

The geometry of the full-core Ants model consists of the homogeneous calculation nodes. The Ants full-core calculations are run via Cerberus that allows running successive Ants simulations automatically in different setups, including control rod positionings. In HFP calculations, Cerberus is used for data transfer between Ants, Kharon and SuperFINIX. Kharon calculates the thermal hydraulics properties of the system, and SuperFINIX is used for evaluating fuel behaviour.

The capability of the control rods to maintain cold conditions is determined by calculating total available CRA worth as well as the shutdown margin in the CZP condition with zero boron concentration. The hot-shutdown capability of the control rods is evaluated by calculating total CRA worth in HFP. Reactivity changes due to moderator and fuel temperature variations between zero and full power are determined by calculating the difference in the core reactivity between HFP and HZP conditions. Reactor poison is accounted for by evaluating the equilibrium xenon concentration for HFP and calculating the reactivity difference in HZP between the zero xenon condition and the HFP equilibrium xenon condition. In this model, the power dependent insertion limits are based on the limits in NuScale, although specific limits for the model could be calculated separately.

5 RESULTS

Integral control rod worth for Regulating Bank 1 (RB1) in HZP conditions is shown in figure 2. Capability for executing shutdown and maintaining shutdown conditions are characterized in table 1. The values in table 1 are evaluated with the HFP critical boron concentration (931 ppm). The total available CRA worth in HZP and CZP are calculated with zero xenon concentration, whereas equilibrium xenon concentration is used for the CRA worths in HFP. The net margin for hot shutdown describes the negative reactivity available, assuming that the highest worth CRA is stuck out and the regulating bank is at the power dependent insertion limits (PDILs), while accounting for power defect. For long-term shutdown capability, the positive reactivity resulting from moderator cooling to cold conditions and xenon decay are accounted for. The value of moderator cooling is determined by evaluating the change in reactivity between hot and cold conditions with zero xenon concentration. The value for xenon worth is calculated as the difference in reactivity in HZP between zero xenon concentration and the equilibrium concentration of HFP conditions. The power defect is obtained from the reactivity difference between HFP and HZP due to reactivity feedbacks.

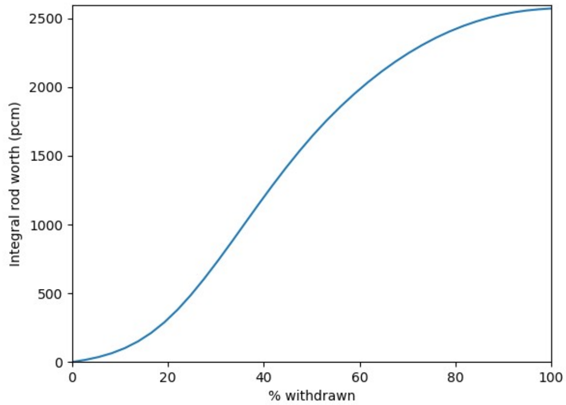

Figure 2: Integral control rod worth as a function of regulating bank 1 height in HZP.

Table 1: Capability for long-term shutdown.

Parameter	Reactivity (pcm)
1. Total Available CRA Worth:	
a. HFP Value b. HZP Value c. CZP Value	18187 18064 12453
2. PDILs:	
a. HFP Value b. HZP Value	332 929
3. Highest worth CRA stuck out	5317
4. Power Defect	662
5. Moderator Cooling	924
6. Xenon Worth	2353
7. Net margin for hot shutdown (1.a. - 2.a. - 3. - 4.)	11876
8. Net margin for long-term shutdown (7. - 5. - 6.)	8599

The values of individual control rod group worths are presented in tables 2 and 3 for both HFP and HZP conditions. Table 2 shows individual group worths with other CRA groups withdrawn. In table 3, the group worths are evaluated with respect to the power dependent insertion limits using the critical boron concentration calculated in HFP with the regulating bank at PDILs (893 ppm).

Table 2: Individual CRA group worths with 931 ppm boron concentration.

Group	HFP (pcm)	HZP (pcm)
Regulating Bank 1	2687	2572
Regulating Bank 2	1877	1808
Shutdown Bank 3	3732	3654
Shutdown Bank 4	3732	3654

Table 3: Individual group worths with the regulating bank in PDILs with 893 ppm boron concentration.

Group	HFP (pcm)	HZP (pcm)
Regulating Bank 1	2561	2150
Regulating Bank 2	1798	1708
Shutdown Bank 3	3744	3674
Shutdown Bank 4	3744	3674

The shutdown margin is determined in each condition (HFP, HZP and CZP) by calculating the reactivity by which the reactor is subcritical after insertion of all control rods, except for the highest worth CRA. The results are shown in table 4. In general, the design limit for the shutdown margin is determined by safety analysis for a specific reactor unit. In PWRs, the limit for the shutdown margin is generally 1-5%[5]. With the critical boron concentration of the HFP conditions (931 ppm), the shutdown margin exceeds the requirement of a 1% (1000 pcm) minimum shutdown margin set in the Finnish Regulatory Guides on nuclear safety and security.

With zero boron concentration in zero power conditions, the reactor is supercritical with the control rods inserted, which appears in table 4 as a negative shutdown margin. Clearly, the 1%-limit is not exceeded with zero boron concentration in zero power conditions. On the other hand, it is stated in the Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants (NUREG-0800) that the RCSs should have the combined capability to provide a sufficient shutdown margin, which in cold conditions is fulfilled with the critical boron concentration. To reach criticality in zero-power conditions, the boron concentration should be set to 119 ppm in HZP conditions and 656 ppm in CZP conditions. To further fulfil the required 1%-limit for the shutdown margin, the boron concentration would have to exceed 205 ppm in HZP conditions and 723 ppm in CZP conditions. Additional Kraken calculations could be executed to achieve the required limits for the shutdown margin in zero-power conditions by optimizing the core loading pattern.

Table 4: Shutdown margin (SDM).

State	SDM (pcm)
HFP with critical boron	12871
HFP with zero boron	2185
HZP with critical boron	9470
HZP with zero boron	-1421
CZP with critical boron	4190
CZP with zero boron	-10068

ACKNOWLEDGEMENTS

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