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A Systems Engineering Approach to Multi-Physics Load Follow Simulation of the Korean APR1400 Nuclear Power Plant

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Abstract : Nuclear power plants in South Korea are operated to cover the baseload demand. Hence they are operated at 100% rated power and do not deploy power tracking control except for startup, shutdown, or during transients. However, as the contribution of renewable energy in the energy mix increases, load follow operation may be needed to cover the imbalance between consumption and production due to the intermittent nature of electricity produced from the conversion of wind or solar energy. Load follow operation may be quite challenging since the operators need to control the axial power distribution and core reactivity while simultaneously conducting the power maneuvering. In this paper, a systems engineering approach for multi−physics load follow simulation of APR1400 is performed. RELAP5/SCDAPSIM/MOD3.4/3DKIN multi−physics package is selected to simulate the Korean Advanced Power Reactor, APR1400, under load follow operation to reflect the impact of feedback signals on the system safety parameters. Furthermore, the systems engineering approach is adopted to identify the requirements, functions, and physical architecture to provide a set of verification and validation activities that guide this project development by linking each requirement to a validation or verification test with predefined success criteria.

Key Words : Systems Engineering, APR1400, Load Follow Operation, Multi−Physics, Modeling, and Simulation.

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1. Introduction

Nuclear power plants (NPPs) in South Korea are operated in a baseload mode, that is at 100% rated power, and do not deploy power tracking control except for startup, shutdown, and during transients.

The main reason for this is that operating a NPP at the rated power level is usually more efficient economically and simpler. This mode of operation is preferred when the share of nuclear energy in the national energy mix is relatively small, and the need to vary the rated power is limited to safety needs only.

However, the share of nuclear power in the national energy mix becomes so important that the Korean government decided to increase the contribution of nuclear energy in the power generation by up to 59% by 2030.[1] To accommodate the government plan in order to expand the deployment of large-scale renewable energy power plants which are intermittent in nature, existing or newly-built NPPs need to consider load follow operation to balance the variability in electricity generation.

1.1 Load Follow Operation

Load Follow operation (LFO) mode is defined as matching the electricity supply to daily or seasonal variations of the electrical demand. Furthermore, LFO can be used to cover the imbalance between power consumption and power production.[2]

LFO in NPPs is receiving more attention in Korea due to several reasons which can be summarized as follows:

- Utilities should overcome the expected fluctuations in the electrical grid due to the deployment of large scale power plants using renewable intermittent energy sources such as wind and solar
- Utilities need to implement or to improve the maneuverability and the availability capabilities of their NPPs.
- Utilities need to accommodate changes in the electricity market.

Unlike traditional thermal power plants, LFO may be quite challenging for NPPs. The difficulty arises from the fact that the reactor operators, need to simultaneously control the axial power distribution and core reactivity as they conduct the power maneuvering.[3]

There are many LFO modes developed by different utilities and research institutes around the world. In case of Korea, KAREI developed a LFO mode in 1990s and named it MODE-K.[4],[5]

MODE-K is an advanced reactor control logic algorithm. It uses boron (borating or dilution) with both regulating (R-Bank) and heavy-worth control (H-Bank) banks in controlling the reactor during load follow.

According to MODE-K, the reactor operators may manipulate the core reactivity during LFO using one of two methods. The first method is slow and uses the R-Bank and boron to control core reactivity (xenon, power defect following power changes, reactor average temperature). While the second method is fast and uses the H-bank to control the axial power distribution.

The analysis of the LFO is not straightforward due to the complex nature of the underlying physics and interrelated phenomena inside the reactor core which necessitates special modeling to properly reflect the feedback mechanisms on APR1400 system performance.

1.2 Multi-Physics Simulation

The accurate simulation of a nuclear power plant response relies on detailed physical models using sophisticated computer codes to reflect the complex physics and inherent feedback mechanisms.

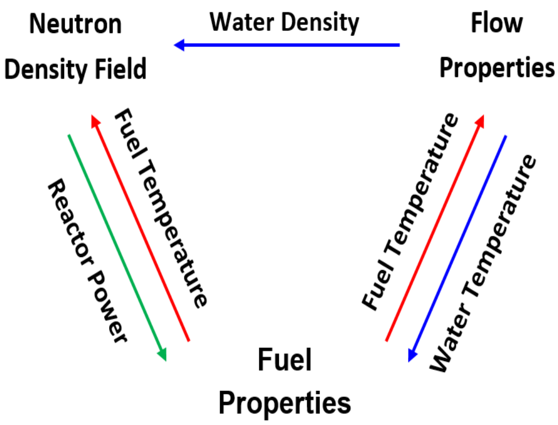
Reliable and accurate numerical simulation of the underlying complex physical phenomena often requires a computational multi-physics coupling approach.[6]

This involves the coupling of several different computer codes into an integrated multi-physics package.

To accurately estimate the reactor power several interrelated phenomena need to be considered: neutron transport, heat transfer, fluid dynamics, fuel performance…etc. as illustrated in Figure 1. Neutrons are thermalized by the moderator and hence induce a fission chain reaction in the nuclear fuel. The energy released by fission is transferred from the fuel, through the cladding, to the coolant via the various heat transfer mechanisms. Then the coolant flows to remove the heat from the core and dump it to the ultimate heat sink.

A number of research studies focused on LFO simulations have been published and can be summarized as follows [7],[8],[9]:

- Simulations using only neutronics codes without feedback mechanisms.
- Coupling the neutronics codes with simple lumped parameter models that describe both primary and secondary loops.



[Figure 1] Aspects of A Multi-Physics Simulation Inside The Nuclear Reactor Core

2. Work Objectives

The main objective of the current work is to analyze the Korean Advanced Power Reactor, APR1400, under load follow operation using a multi-physics simulation to predict the system response during load change.

The use of multi-physics simulation will help in understanding the underlying complex physical phenomena while taking into account the three-dimensionality of the system.

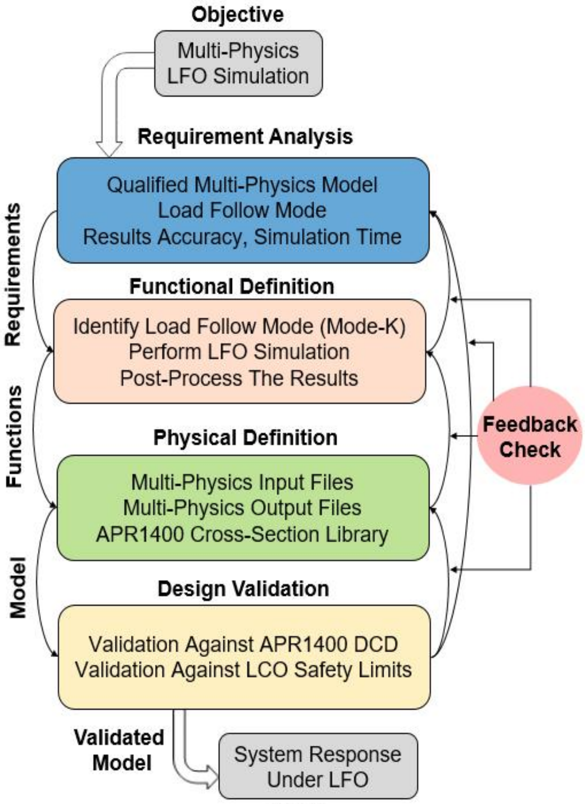
RELAP5/SCDAPSIM/MOD3.4/3DKIN package is selected to perform multi-physics load follow simulation in this work.

This package has the ability to model the three-dimensionality of the system, while simultaneously taking into account the effects of the feedback mechanisms. In this work, coupled Neutron-Kinetics (NK) / Thermal-Hydraulics (TH) will be conducted.

The Systems Engineering (SE) approach is adopted to guide the development of this work and break it down into various manageable tasks with corresponding checks and balances.

Mainly, the Kossiakoff SE method [10] is used in this work as illustrated in Figure 2. This method consists of four successive steps as follows:

1. Requirement Analysis (problem definition);
2. Functional Definition (functional analysis and allocation);
3. Physical Definition (synthesis, physical analysis, and allocation);
4. Design Validation (verification and evaluation)



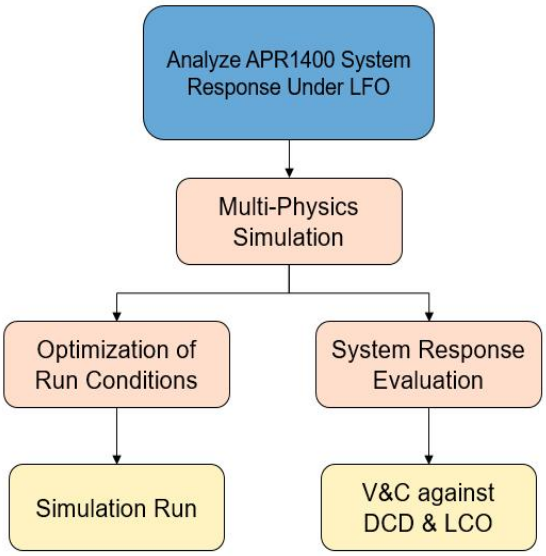
[Figure 2] Kossiekof Systems Engineering Method

The work breakdown structure is defined as follows:

1. Develop the multi-physics model for the Korean APR1400 plant based on the approved design control document (DCD).
2. Verify and validate the developed multi-physics model against the corresponding values from APR1400 DCD.
3. Perform LFO simulation using the Korean LFO mode (MODE-K).
4. Analyze the results and compare key parameters against the safety limits.

For this work, an objective hierarchy was developed, as shown in Figure 3, to identify the most important tasks to complete this work.

According to SE, planning and managing the project successfully begins by identifying the various stakeholders, their needs and requirements, followed by designing the system architecture and developing a set of verification and validation activities to ensure all requirements are met with predefined success criteria at every phase of development [10],[11] as shown in the V-Model of Figure 8.



[Figure 3] The Objective Hierarchy

2. Stakeholders Identification

The stakeholders for a nuclear power plant can be categorized into four groups according to the economic, social, environmental, and technical impacts on the plant project as shown in Table 1.

<Table 1> Stakeholders Categorization

Category	Stakeholders
Economic	• Utility Company • Government • Nuclear Industry
Social	• General Public • Media
Environmental	• Environmental Regulators • Neighboring Countries • Pressure Groups
Technical	• Regulators • Contractors • Researchers and scientists

3. Requirements Developments

The requirements addressed in this work can be divided into mission requirements, originating requirements, system requirements, and component requirements as summarized in Table 2.

<Table 2> Requirements for APR1400 Multi-Physics Load Follow Simulation

Requirements	Description
Mission Requirements	APR1400 system response shall meet all safety criteria under LFO utilizing MODE-K.
Originating Requirements	Multi-Physics simulation shall show APR1400 system response under LFO while satisfying (Axial offset, 3D pin peaking Factor, and Inlet Coolant Temperature).
System Requirements	1. APR1400 core should comply with a standard 100-50-100% load cycle. 2. The plant should withstand multiple load follow cycles. 3. The power ramp should be within ±5%/*min* in every load change. 4. The Axial offset should be within ±0.27 during power transient. 5. The peaking factor should be less than 2.43 for 100% power level and less than 4.86 for 50% power level.
Component Requirements	1. The coupled codes must have the capability of dealing with and analyzing any complex phenomena. 2. The coupled codes must be capable of modeling power distribution in individual fuel rods. 3. Accurate mapping of meshes or volumes between the codes is important to exchange information. 4. A convergence scheme is needed to be defined.

3.1 Mission Requirements

The mission requirements are derived from stakeholders' needs. They reflect the needs and goals of the stakeholders that are to evaluate the success of the new system design.

As mentioned earlier, the Korean government plans to increase the share of nuclear energy in the national energy mix. Therefore, the nuclear industry will get a push to invest more money in new designs and components that will serve the government's plan and revitalize the national economy.

Increasing the share of nuclear energy will decrease the electricity price which is in line with the public interest. On the other hand, anti-nuclear groups will question the feasibility of these new projects and the safety of the existing and new nuclear power plants as they adopt the new LFO concept utilizing MODE-K.

Furthermore, utilities have to spend more money to enhance the availability and reliability of power maneuvering capabilities of existing and new plants for LFO MODE-K inconsistency with the new requirements enforced by both nuclear and environmental regulators. The researchers and scientists are therefore compelled to create feasible solutions to enhance the nuclear power plants' safety under LFO mode.

3.2 Originating Requirements

The originating requirements are based on the stakeholders' inputs and mission requirements. For a given operational scenario, the objectives are identified and ordered according to their level of importance to formulate the objectives hierarchy.

For the current work, the objective hierarchy focuses on balancing the reactor power and turbine demand during load follow operation while simultaneously satisfying all safety limits.

During LFO power is changed to follow the load or to follow a scheduled order. The power increase or decrease should be within the safety limits to assure the safe operation of the plant according to the regulator's requirements.

Moreover, the power increase should not be done too fast in order to avoid hot spots inside the reactor core and maintain fuel integrity. Also, the power decrease should not be done too fast to avoid unplanned plant shutdown.

The originating requirements refer to the system capabilities which are derived from the mission requirements and based on the operational scenario and objective hierarchy.

3.3 System Requirements

The system requirements detail the LFO mode characteristics by adding safety constraints and performance requirements.

The system requirements impose a single daily standard MODE-K 100-50-100% load cycle curve. If the system parameters are within the limits and conditions of operation (LCO) during a single load cycle, it is recommended to perform multiple, schedule and unscheduled, load cycles and check if the plant withstands these loads while maintaining the system parameters within LCO.

Moreover, system requirements impose some limits during any power change for example, the power rate of change should be within $\pm 5\%/min$. Also, the axial offset (AO), which is a measure of the power difference between the top half and the bottom half of the reactor core, should be within ±0.27 during any power transient to avoid the violation of critical heat flux limits.

Another limit is the 3D pin peaking factor (Fq) with is a measure for hot spot locations inside the core. The limiting value of Fq depends on the reactor core power level. The Fq should be less than 2.43 at 100% power level while it should be less than 4.86 at 50% power level.

3.4 Multi−Physics Simulation Requirements

The Multi−Physics simulation or component requirements represent what is needed for developing or selecting a Multi−Physics package to simulate APR1400 under LFO mode.

The CRISSUE−S partners under the work−packages WP1, WP2, and WP3 published a list of requirements with regard to the coupling of thermal−hydraulics system codes and neutronics codes [12],[13],[14].

Coding and integration of nuclear codes is a very time−consuming process and can be overridden by selecting one of the available multi−physics packages. These packages are well verified and well−validated through extensive testing against experiments and benchmarking exercises.[14] This allows skipping the code development, implementation, and testing of the multi−physics package.

To select a multi−physics package, the individual codes must be verified and validated. Additionally, the codes must have the capability for modeling complex phenomena to analyze their effect on the system behavior.

Moreover, due to the strong density variation of water; the analysis of the power distribution in each fuel rod is indispensable. The coupled codes must be capable of modeling the power distribution in individual rods of the fuel assembly in order to study the effect of the local power distribution on the thermal−hydraulics property variation.

Furthermore, the main coupling design approach should be considered since it impacts the efficiency and accuracy of the simulation. Two options exist: either serial integration or parallel processing.

Additionally, the coupling may be conducted internally or externally and the coupling methodology may be implicit, semi−implicit, or explicit. Moreover, accurate mesh mapping is important to exchange information between the coupled codes. Exact, detailed mapping provides better spatial resolution in coupled calculations. However, this refinement requires significant computational resources even when taking advantage of recent progress in computer resources.[13]

Finally, a convergence scheme is needed to be defined for the coupled codes, which necessitates independent convergence in the individual codes.

Additional requirements exist for the neutronics and thermal−hydraulics physics models. These have been covered intensively by the code developers and are omitted for brevity.

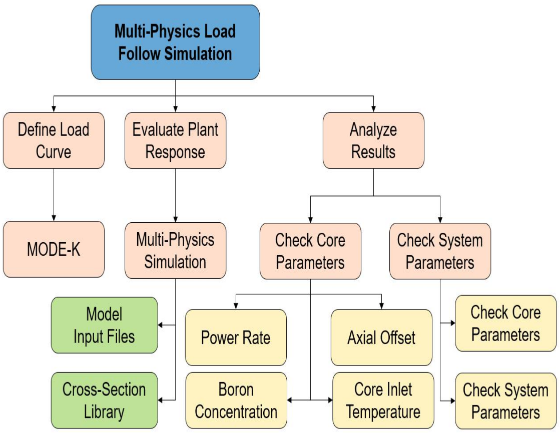
Based on the previously described requirements for selecting a multi−physics package, RELAP5/SCDAPSIM/MOD3.4/3DKIN is selected for this project

This package is developed by a US−based company, Innovative Systems Software (ISS). It consists of three independent codes. RELAP5 is a thermal−hydraulics system code developed by Idaho National Laboratory (INL). SCDAPSIM which is a severe accident code was also developed by INL. 3DKIN is a neuron kinetics code based on NESTLE code that is developed by North Carolina State University (NCSU). The three codes are implicitly coupled using an internal coupling type and serial integration approach.

4. System Architecture

4.1 Functional Architecture

This subsection shows the functional architecture of APR1400 under LFO as illustrated in Figure 4.



[Figure 4] Functional Architecture

The first level of functional architecture describes three main functions that are needed to evaluate the system response under LFO.

The first main function is to define the load curve which is the MODE-K 100-50-100% standard load curve as shown in Figure 5.

The second main function is to evaluate the APR1400 plant response by performing a multi-physics simulation. This function is accomplished by checking some system parameters such as the primary coolant temperature, secondary coolant temperature, mass flow rate, steam generator level, pressurizer level …etc.

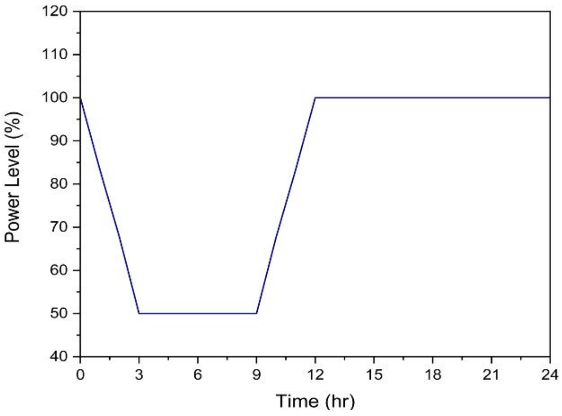
The third main function is to analyze the results. The first task is achieved by checking some reactor core parameters such as boron concentration, xenon oscillation, axial offset, power defect, axial power distribution, and axial temperature distribution.

4.2 Physical Architecture

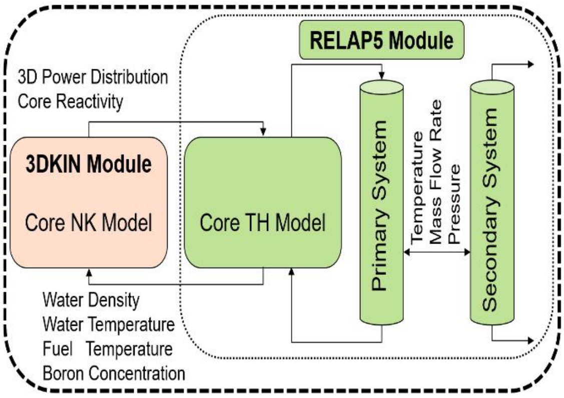
To perform the multi-physics simulation, the APR1400 system description needed to be modeled within the two modules.

The physical architecture, as shown in Figure 6, illustrates how the neutronics module 3DKIN and the thermal-hydraulics module RELAP5 within the multi-physics package interact with each other during LFO simulation.

The 3DKIN module transfers the 3D power distribution of the reactor core along with the



[Figure 5] The Daily Load Follow Scenario



[Figure 6] Data Exchange in Coupling Neutronics and Thermal-Hydraulics Modules feedbacks from the fuel, moderator, boron, and control rods reactivities.

On the other hand, RELAP5 transfers the spatial distributions of water temperature and fuel temperature along with boron concentration to update the cross-section library needed to start a new 3DKIN simulation.

While within RELAP5, the components of the primary and secondary systems exchange data for water temperature, water flow rate, and pressure via the u-tube structural element

The process of data exchange is conducted iteratively for every time step until the system results reach a pre-defined convergence criterion.

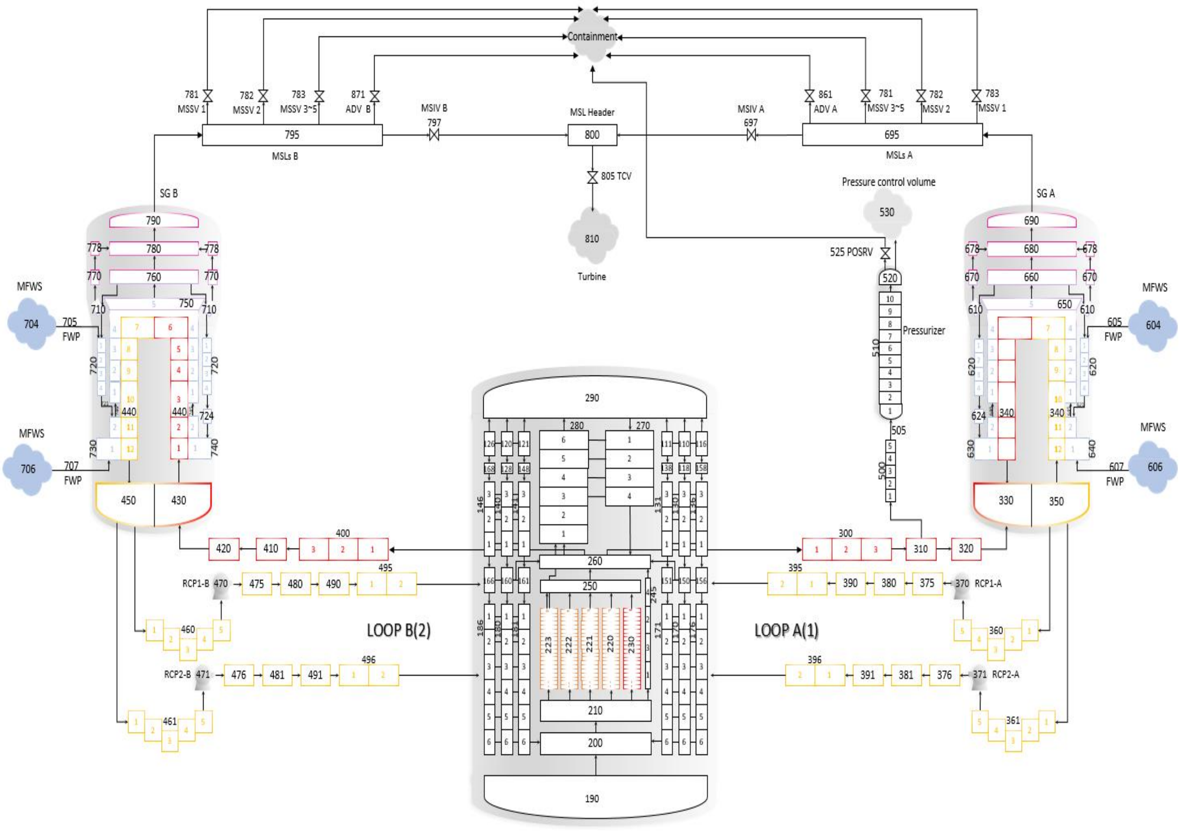
5. Multi-Physics Model Development

In the current work, the model development process consists of two main parallel steps. The first step is developing the APR1400 TH model while the second step is developing the NK model.

APR1400 is the Korean Advanced Power Reactor generating a nominal power of 1400 MWe. It is a two-loop pressurized water reactor.

A thermal-hydraulic model of APR1400 is developed using RELAP5 module to represent the key .systems and components using the nodalization shown in Figure 7.

The APR1400 nodalization includes the



[Figure 7] APR1400 System Nodalization

Reactor Coolant System (RCS) and two Steam Generators (SGs), one for every loop. The RCS consists of a Reactor Pressure Vessel, two hot Legs, four Cold Legs, and four Reactor Coolant Pumps. A Pressurizer is connected to one of the Hot Legs using a surge line. One Pilot Operated Safety Relief Valve is modeled to simulate the release of the RCS coolant in case of depressurization. The reactor core region is represented by five fuel channels along with one water reflector channel, each channel models a group of fuel assemblies (FAs).

The water level in the SGs is controlled automatically over the full operating range by the Main Feedwater System (MFWS). On the secondary side, the main steam system transfers the steam from the SGs to the turbine through two Main Steam Lines (MSLs).

Ten Main Steam Safety Valves (MSSVs), two Atmospheric Dump Valves (ADVs), two Main Steam Isolation Valves (MSIVs), and a Turbine Control Valve (TCV) are modeled on the MSL which is connected to the upper head of the SGs. The MSSVs prevent over−pressurization of the SGs, the TCV is used to isolate the Turbine and the ADVs are used by the operator to depressurize the SGs.

The turbine, the containment, and the MFWS are represented as boundary conditions by time−dependent volumes.

Subsequently, the neutronics model of APR1400 is modeled using 3DKIN module. The neutronics model uses an initial core loaded with 241 FAs with 800 ppm initial boron concentration. Only one control rod bank is used to control the core power.

6. Verification and Validation

This section refers to the verification and validation processes for using the multi−physics simulation tool in analyzing APR1400 under LFO to predict the system response during load changes.

As mentioned earlier, the Kossiekof SE method is used to develop the V−model to guide this project through each phase of development by linking each requirement to a validation or verification test to ensure that the predefined success criteria are met

The V−Model shown in Figure 8 consists of four essential steps for completing the multi−physics load follow simulation and the associated tests to verify the APR1400 safety under LFO in comparison with LCO.

6.1 Model Development & Verification Step

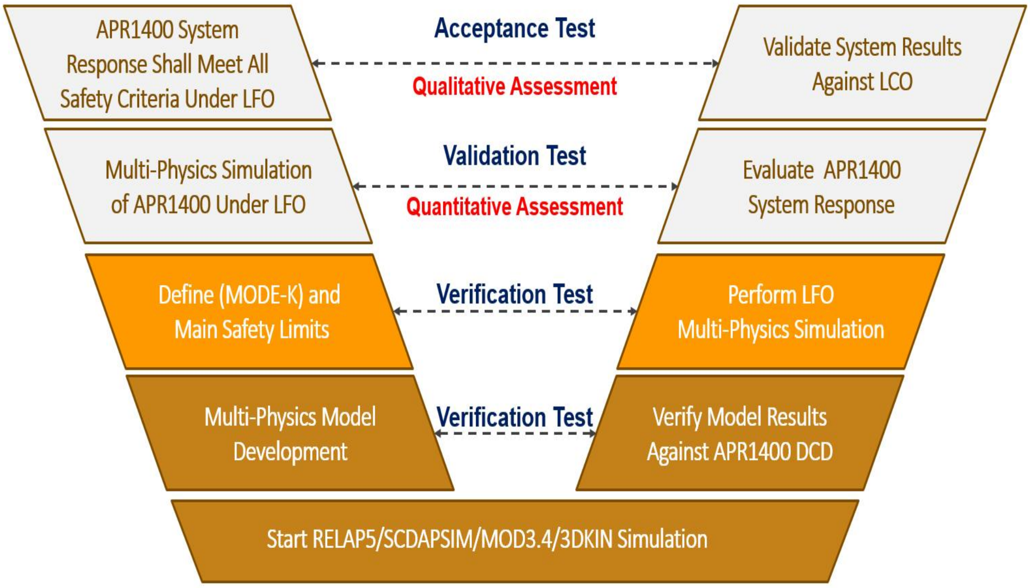
This step attempts to address the multi−physics component requirements. This test is at the code level and helps to eliminate issues at an early stage.

As discussed previously, the multi−physics package RELAP5/SCDAPSIM/MOD3.4/3DKIN is selected based on the stated multi−physics requirements.

This package is well−verified and well−validated through extensive testing against experiments and benchmarking.

So, using this package the multi−physics model was developed. The model includes input files for both NK and TH along with the cross−section library that describes the main characteristics of the APR1400 reactor core.

The objective of this step is to verify that the results of the multi−physics model match



[Figure 8] Systems Engineering V-Model For Simulating APR1400 Under LFO Using Multi-Physics Package

the corresponding values from the APR1400 DCD.

To demonstrate that multi-physics component requirements were met, several simulations at nominal power were performed and the results were compared with the corresponding DCD values. If the results were not matching the DCD, the model was modified to catch the APR1400 system performance during a normal operation before implementing the load follow operation.

6.2 LFO Verification Step

This verification step aims to ensure that the system requirements as defined by the Korean MODE-K, are properly reflected in the model input files.

Additionally, the main safety limits need to be monitored during performing the multi-physics simulation to demonstrate that the system requirements regarding power change rate, boron concentration, 3D pin peaking factor, and axial offset are met.

This test is also conducted at the code level to verify the successful simulation using the multi-physics package with MODE-K.

6.3 System Response Evaluation Step

In this step, a quantitative assessment process is performed to validate the system response with respect to the originating requirements. The main goal of the originating requirements is to simulate the APR1400 under LFO by implementing MODE-K using the multi-physics simulation tool. Subsequently, monitoring the safety limits while analyzing the system response during the load change over one daily cycle load.

6.4 LFO Acceptance Step

The acceptance step addresses the mission requirements. In this step, a qualitative assessment process is performed to check the system response, if it satisfies the stockholder's requirements, and shows if the LFO can be safely adopted in APR1400.

7. Implementation and Results

This section refers to the implementation of the previously discussed SE approach to design a simulation procedure for APR1400 under LFO using the commercial multi-physics package RELAP5/SCDAPSIM/MOD3.4/3DKIN to predict the system response during load change

7.1 APR1400 Model Verification

After developing the multi-physics model, a verification process was performed to verify that the results of the multi-physics simulation match the corresponding values from the APR1400 DCD as shown in Table 3.

<Table 3> Multi-Physics Model V&V

Parameter	DCD	Model
Total Core Heat Output (MWT)	3983	3983
Primary System Pressure (bar)	155	155
RPV Inlet Coolant Temperature (°C)	290.6	290.36
RPV Outlet Coolant Temperature (°C)	323.9	323.58
Total Coolant Flow (10^6 kg/h)	75.6	75.7
Pump Speed (rpm)	1190	1189.9
Steam Generators Pressure (bar)	68.94	67.20
Total Steam Flow (10^6 kg/h)	8.14	8.136

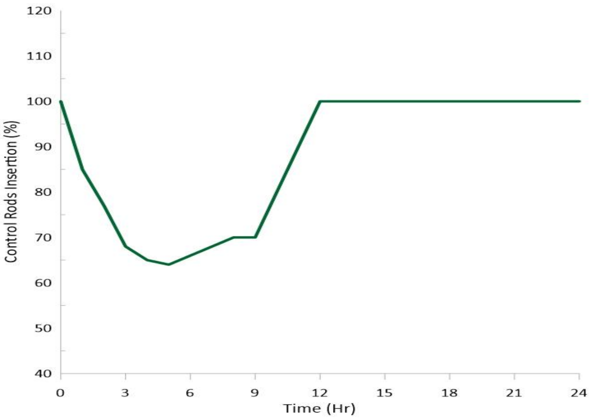
7.2 LFO Verification and Validation

A daily LFO simulation has been performed according to the power maneuvering scenario shown in Figure 5.

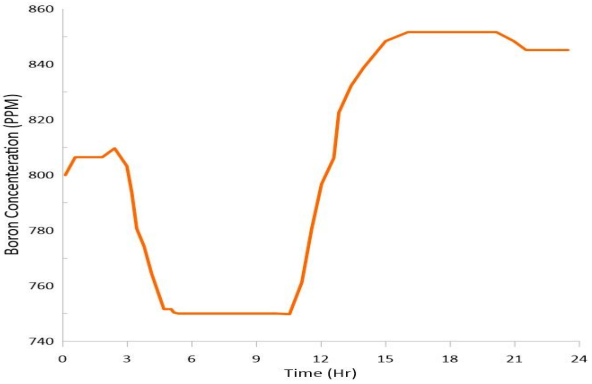
This daily load curve is achieved by manipulating the reactor power using regulating control rod bank, and soluble boron to maintain the critical state, while simultaneously monitoring the safety parameters such as core inlet temperature (Tin), 3D pin peaking factor (Fq), and axial offset (AO).

Then, these parameters are compared with the corresponding values in the APR1400 LCO to assure that the plant is safe and all safety limits are maintained.

To initiate the load operation, the control rod bank is inserted into the core aided with boration and dilution processes as shown in Figure. 9 and Figure. 10 respectively.



[Figure 9] Control Rod Bank Normalized Insertion Position



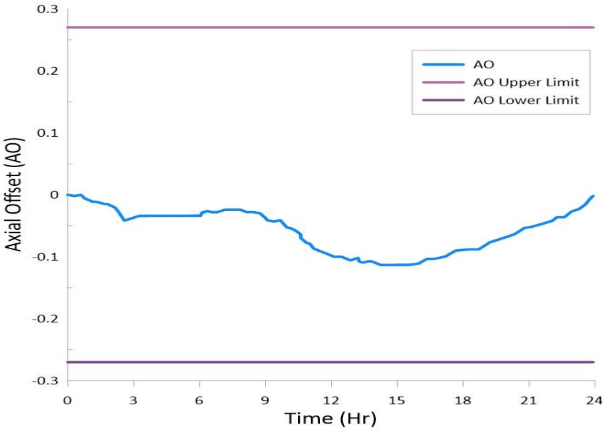
[Figure 10] Boron Concentration

The bank leads the power change from

100% to 50% within 3 hours by inserting them in the reactor core while the boron concertation is slightly increased to suppress core reactivity. After 3 hours the boron concentration is decreased allowing the core reactivity to reach a stable condition. After 9 hours the bank is withdrawn to increase the power while the boron concentration increases to suppress any excess positive reactivity until the core reaches its critical state.

The power change rate according is Figure 9 is − 0.278 %/min which is within the LCO limit of ±5%/min.

During LFO, the axial offset (AO) which is plotted as a function of time in Figure. 11, is always negative and the minimum value is −0.155 which is maintained within the limits of ±0.27 according to LCO.



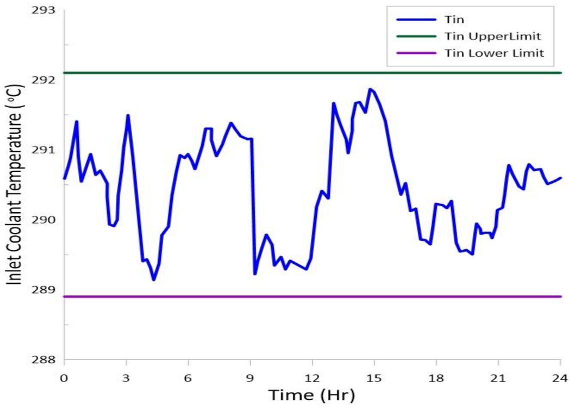
[Figure 11] Axial Offset

Another important parameter is the 3D peaking factor. It should be less than 2.43 for 100% power level and less than 4.86 for 50% power level. Table 4 shows the values of Fq against the corresponding values from LCO.

<Table 4> D Pin Peaking Values During LFO

3D Pin Peaking	LFO Results	LCO Limit
Fq at 100% Power	1.937	2.43
Fq at 50% Power	2.695	4.86

Figure. 12 shows the core inlet temperature (Tin) oscillations during load change However, these oscillations are maintained within the COLR limits of ±1.5 °C.



[Figure 12] Core Inlet Temperature Variations

Since the safety limits are maintained as illustrated in Figure 9 until Figure 11 along with Table 4, the results of the multi−physics simulation satisfy the stockholder's requirements and show that LFO can be safely adopted in APR1400.

8. Conclusion

Load follow operation is becoming of greater importance as the fraction of generation in energy mix using renewable energy resources increases. Accordingly, utilities work on improving the reliability of the power maneuverability of their NPPs.

The Systems Engineering approach based on V-model was demonstrated to be a useful tool to address the requirements and to show the relationships between each phase of the development and its phase of testing.

To accomplish the purpose of this work RELAP5/SCDAPSIM/MOD3.4/3DKIN is selected as a Multi-Physics simulation tool to perform a LFO simulation for APR1400. The chosen multi-physics package is an excellent tool to assess the plant's response by accurately providing the feedback mechanisms between the interrelated physical models in complex components like NPP. The results obtained, show that LFO can be conducted safely without breaching any of the safety limits.

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