VERIFICATION OF THE COUPLED CODE RELAP5-QUABOX/CUBBOX BY LARGE LOAD REJECTION ANALYSIS FOR NPP KRŠKO

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ABSTRACT -Results of two large load rejection cases: 100-15 % and 100-50 % for point kinetics (RELAP5 standalone code) and 3D coupled code RELAP5-QUABOX/CUBBOX are analyzed. A coupled code comprises the multidimensional neutron kinetics code model of QUABOX/CUBBOX and thermal hydraulic system code RELAP5. This coupled code version enables best-estimate analyses of dynamic behavior of nuclear power plant (NPP) due to two facts. First, a realistic simulation of the reactor core in three dimensions (3D) is performed. Secondly, a sophisticated thermal hydraulic code RELAP5 provides a respective thermal hydraulic analysis for all components in the plant on one side and on the other side its control variables and trips enable the realistic description of plant protection and control systems. A RELAP5/mod3 input data set for NPP Krško at uprated conditions (1.06 P_N) after steam generator (SG) replacement was extended with realistic feedwater system and all major control systems.

1. Introduction

Realistic simulation of NPP behavior is important for a variety of applications (e.g., licensing, probabilistic risk assessment, operational practice, operator training). It helps to estimate and eventually decrease the range of conservative margins that are used in NPP design and operation. In order to perform best-estimate calculations, application of sophisticated thermal hydraulic system code together with multidimensional neutron kinetics model is necessary. This enables realistic simulation of interactions between reactor core behavior and plant dynamics. At Faculty of Electrical Engineering and Computing (FER) Zagreb a coupling between thermal hydraulic system code RELAP5 and 3D neutronics code QUABOX/CUBBOX was performed. The 3D neutronics model of QUABOX/CUBBOX has been developed at Gesellschaft für Anlagen- und Reaktorsicherheit (GRS), Garching, Germany. It solves two energy group diffusion equations for steady state and time dependent problems in three dimensions using a coarse mesh method based on polynomial approximation of spatial neutron flux distributions and taking into account up to six groups of delayed neutrons. The coupling approach has following characteristics: 1) Thermal hydraulics and heat conduction as well as average core channel thermal hydraulics and heat conduction calculation are performed by RELAP5. 2) QUABOX/CUBBOX calculates 3D neutron kinetics in the core. 3) Plant protection and control systems actuation as well as control rod movement according to specific rod movement program (e.g. stuck rod, rod ejection) or rod control program are modeled by RELAP5 control variables and trips. 4) Time stepping and organization of calculation is performed by RELAP5. Comparison of the results of the coupled code with point kinetics calculation is an important step in the better understanding and interpretation of results. It provides the validation of the coupled code versus well-known point kinetics method. On the other side the results obtained with coupled code representing more realistic simulation of NPP behavior can help in determination of lumped parameters, which relate to the point kinetics method.

A comprehensive RELAP5/mod3 input data set for NPP Krško at uprated conditions (reactor power 1994 MW) with plant protection and control systems has been created. In the paper the results of the analysis of two large load rejection cases are discussed. The large load rejection case is important for proper performance of steam dump system, which ensures adequate heat removal from primary side without SG safety valves opening, and without reactor trip, while the rod control system brings the reactor to no-load conditions.

The simulation has been performed using RELAP5-QUABOX/CUBBOX code with one and four coolant channels and RELAP5 as stand alone code. 3D model of Rod Control System in RELAP5-QUABOX/CUBBOX is based on 3D control rod banks explicitly modeled in QUABOX which are connected through special interface with RELAP5 control variables that provide the current position of the control rod bank. In the RELAP5 stand alone code, the integral rod worth curve taking into account all control rod banks versus steps withdrawn provides the lumped reactivity for the point kinetics analysis.

2. Calculational model for NPP Krško

The model of the plant nodalization used both in point kinetics and coupled code is based on standard NEK RELAP5/mod2 nodalization [5]. The nodalization has been adapted for NEK power uprate (nuclear power 1994 MW) and adjusted to RELAP5/mod3.2.2 gamma usage [4]. The scheme of the NEK nodalization is presented in Figure 1. In Figure 2 the nodalization scheme for main feedwater system (from feedwater pumps delivery point to SG entrance) is presented. The total number of volumes and junctions in the presented nodalization is 512 and 547, respectively. The core is subdivided into 24 equidistant volumes. Number of heat structures is 407, and total number of mesh points is 2346. Feedwater heating is modeled by power-dependent heat source in the heat structures 645 and 655 (Figure 2) in such a way that realistic feedwater temperature is attained (ranging from 373 K for 0 % power to 492.55 K for 100 % power).

The nuclear data of the core, based on NPP Krško cycle 14 BOL (Beginning Of Life) and HFP (Hot Full Power) conditions (150 MWD/MTU), are normalized to uprated nominal thermal power of 1994 MW. Delayed neutron data and prompt neutron lifetime are taken from core design report for cycle 14 [6]. Boron concentration for both point kinetics and 3D coupled code was 1315 ppm at BOL, HFP, ARO (All Rods Out), EQXE (EQuilibrium XEnon). Integral control rod worth curve for point kinetics is taken from [6]. Thermal hydraulic feedback in point kinetics is modeled using SEPARABL option [4]. Thermal hydraulic feedback reactivity tables as required in RELAP5 input have been calculated by LEOPARD computer code from FUMACS package [7]. Thermal hydraulic feedback in 3D coupled code is modeled using thermal-hydraulic dependence of cross sections. Homogenized cross sections for each fuel element for cycle 14 BOL, HFP are calculated using CORD-2 package [8]. The influence of control rods in 3D case is taken into account by rodded cross sections. There are 373 unrodded and 110 rodded compositions in the core. The procedure for calculation of reactivity coefficients for both point kinetics and 3D calculation has been described in [1]. Coupled code calculations were performed with one and four thermal hydraulic channels in the core, Figure 3.

In order to accurately simulate dynamic plant behavior during operational power changes, use of realistic control systems is necessary. Following control systems for NPP Krško are modeled in the RELAP5/mod3 input data set: 1) Rod control system, 2) Pressurizer pressure control, 3) Pressurizer level control, 4) Steam dump control system and 5) Steam generator level control. The automatic rod control system is designed to control the reactor in the power range: 15 – 100 % of the rated power for the following transients: ± 10 % step load change, 5 % per minute ramp load change and full load rejection (with steam dump system). The rod control system consists of two error channels: 1) Power mismatch channel (turbine – reactor power) difference which is led to power impulse unit and which provides fast response of control rods upon turbine power perturbation and 2) Average temperature channel that brings the average temperature to a programmed value which is a function of turbine power level. In the 3D neutronics model (QUABOX/CUBBOX), control rod positions are explicitly defined in radial and axial direction. In the RELAP5/mod3 input data set, position of regulating rod banks (A, B, C and D) and shutdown rods (SA and SB) are defined. In order to connect RELAP5 control variables describing particular control rod positions with 3D QUABOX/CUBBOX, an additional interface channel was added to the already existing interfaces between these two codes (core average thermal-hydraulics sent from RELAP5 to QUABOX/CUBBOX and integrated 3D neutronics power sent from QUABOX/CUBBOX to RELAP5). Regulating rods move with overlap (103 steps) during power operational change. A realistic RELAP5 model of the rod control system by means of RELAP5 trips and control variables was created. Model enables the simulation of different modes of operation: normal T_{avg} mode (with rod overlap) – load follow from the turbine, rod withdrawal stop – turbine runback program, as well as control rod transients (e.g. rod ejection, rod stuck). In the point kinetics model only reactivity vs. time can be defined. In the case of integral rod worth curve which describes the reactivity versus rod position (for particular rod distribution and control rod position) for each time step, control rod position according to rod control program and related reactivity is calculated, while in the case of scram the scram reactivity (reactivity vs. time) is used. Verification of the model of the rod control system for RELAP5 standalone code and 3D coupled code was performed by calculating of reactor trip from full power for NPP Krško [1].

3. Transient results and discussion

The comparison between point kinetics (RELAP5 standalone code) and 3D model (coupled code RELAP5-QUABOX/CUBBOX) with one and four hydraulic channels in the core was performed by analyzing two transient cases: 1) Large load rejection case from full power (100-15 %) in 1 second and 2) Load rejection: 100-50 % in 15 seconds. Transients were initiated after 200 seconds steady state calculation. Load rejection represents large turbine flow decrease proportional to load change. Plant load rejection control is designed to bring the plant to a new steady state after large load rejection without reactor trip and without opening of pressurizer relief valves as well as SG relief valves. Load rejection controller in the steam dump system provides fast energy removal from the secondary side after turbine valve closure and prevents the SG relief and safety valves opening. This is performed by impulse unit $\tau_{11}s/(1+\tau_{11}s)$ whose output is used for steam dump valves actuation (when greater than 10% a half of steam dump valves are enabled and when greater than 50% all steam dump valves are enabled). On the other side, power mismatch channel in the rod control system provides fast response upon power difference between reactor and turbine. Main feedwater control (actuating the main feedwater control valves 471 and 571 in Figure 2) is in operation in the power range: 15-100 % and below 15 % feedwater bypass control (actuating the feedwater bypass control valves 472 and 572 in Figure 2) system controls the SG level. In the analysis it was assumed that an eventual switch to feedwater bypass control (for power less or equal 15 %) does not take place during the first four minutes of the transient. Maximum feedwater bypass valve opening was limited to 70 % and the maximum valve position change was 5 % of full valve opening per second. Results of the calculation are presented in Figure 4 through 8. Results for 3D coupled code are marked with 1CH for one thermal hydraulic channel in the core and 4CH for four channels, respectively, while point kinetics results are designated with POINT. Results for both analyzed cases (100 – 15 %) and (100 – 50 %) are shown on one plot for comparison. Only transient results (200 – 1000 seconds) are presented. Large load rejection transient is initiated by turbine control valve closure. Turbine mass flow is reduced in one second from value at full power to 15 % in the case 100 – 15 % and to 50 % in 15 seconds for the case 100 – 50 %, respectively (Figure 4). Turbine mass flow decrease causes pressure rise as well as temperature rise on the secondary side. As a consequence of pressure and temperature rise on the secondary side the transferred heat from the primary to secondary side (SG power in Figure 5) decreased. Load rejection controller in the steam dump system enabled the opening of the all steam dump valves in the case 100 – 15 % and 50 % of steam dump valves in the case 100 – 50 % (Figure 4) thus preventing the SG relief valves opening. Almost immediately after turbine power decrease the power mismatch channel (turbine – nuclear power) in the rod control system generated the signal to insert the control rods (control rod bank insertion sequence: D, C, B, A) at maximum speed in order to decrease the nuclear power (Figure 6). In the point kinetics case the position of particular rod bank was derived from integral rod worth curve for plot purposes. Nuclear power decrease and steam bypass flow to the condenser have prevented the pressurizer as well as SG relief valves opening. Following the steam flow decrease, feedwater valve opening was reduced (Figure 7). In the large load rejection case: 100 – 15 %, SG level (Figure 8) fell to 47 % and oscillated around 51 % while main feedwater system was active (till 240 s after transient begin). After turning off the main feedwater and the feedwater bypass valves still not opened (Figure 7), SG level fell to 41 % for the case: 100 – 15 % for 3D calculation. SG level recovered after feedwater bypass had opened and approached its setpoint value (69.35 %) at the end of simulation. For point kinetics calculation feedwater bypass valve started to close at the very end of simulation. For the case 100 – 50 % main feedwater control was active during the whole transient. About 400 seconds after transient begin nuclear as well as SG power stabilized at theirs new steady state value (approximately 5 % above final turbine power) for both analyzed transient cases (Figure 5). Power mismatch channel output in the rod control system died out after initial large power difference between reactor and turbine was imposed. After maximum rod insertion velocity (Figure 6) in the first phase (200-400 s), a minimum control rod insertion velocity (average temperature channel output) resulted in order to bring the average temperature to a new setpoint value which corresponds to a new turbine power.

4. Conclusion

In the paper the results of two large load rejection cases for NPP Krško are presented. The calculations were performed using RELAP5 standalone (point kinetics) and coupled code (RELAP5-QUABOX/CUBBOX) using one and four thermal hydraulic channels in the core. Calculation times for 800 s simulation on Pentium II 350 MHz PC were 1.2 hours CPU time for point kinetics, and 10.15 hours for 3D calculation. Analyzed transients made demands on proper modeling of all control systems in the plant. It was demonstrated that developed nodalization with models of plant control systems has enabled realistic transient simulation. Comparison of the results for both methods (RELAP5 standalone, coupled code with one and four thermal hydraulic channels in the core) has shown similar results for global thermal hydraulic parameters. The results for control rod insertion depth are different for point kinetics and 3D method. In the first analyzed case (100-15%), the insertion depth for C rods was for 3D calculation 50 cm greater than for point kinetics (in the case 100-50% the difference for C rods was about 23 cm). This can be explained by different way of calculation of influence of control rods in the core for both methods. In the 3D calculation control rod insertion is taken into account by change of cross sections, while in the point kinetics case, the control rod reactivity (for given steps of control rods inserted into the core) does not consider the actual spatial distribution of inserted reactivity resulting thus in "more efficient" control rods.

5. References

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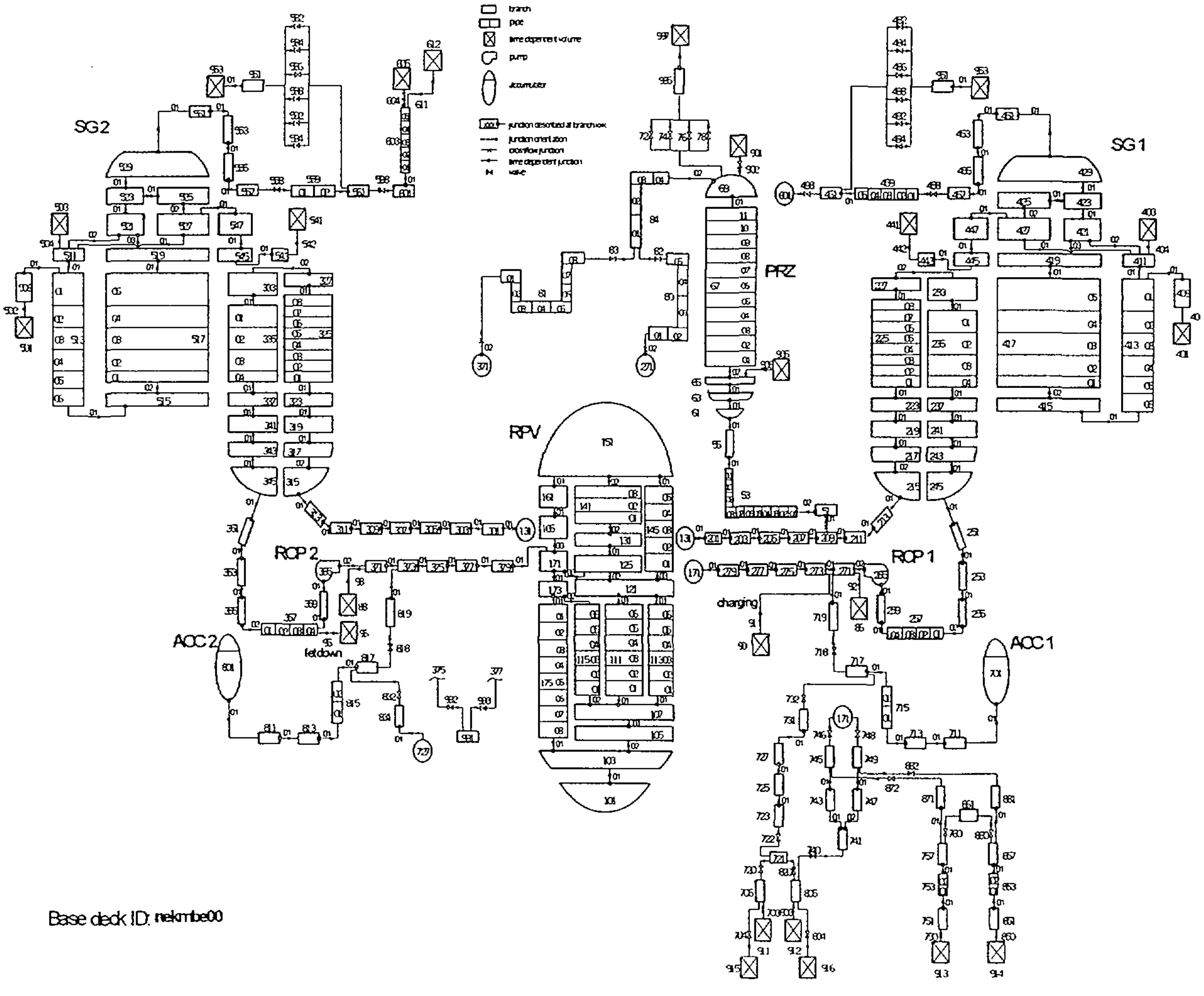

Figure 1. NEK nodalization for RELAP5/mod3 code calculation

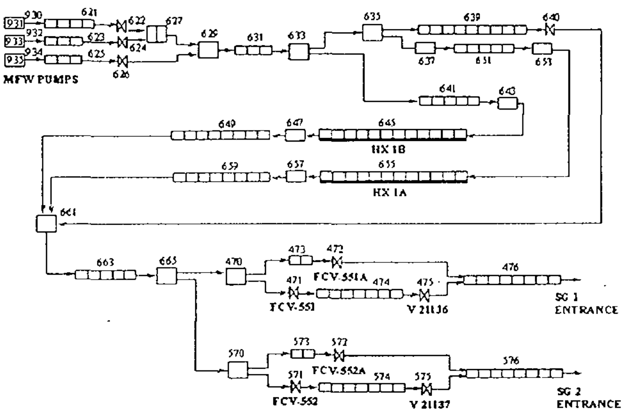

Figure 2. NEK nodalization of the main feedwater system for RELAP5/mod3 code calculation.

					R	R	R	R	R					
			R	R	R	4	4	4	R	R	R			
		R	R	4	4	4	4	4	4	4	R	R		
	R	R	4	3	3	3	3	3	3	3	4	R	R	
	R	4	3	3	2	2	2	2	2	3	3	4	R	
R	R	4	3	2	2	1	1	1	2	2	3	4	R	R
R	4	4	3	1	1	1	1	1	1	1	3	4	4	R
R	4	4	3	1	1	1	1	1	1	1	3	4	4	R
R	4	4	3	1	1	1	1	1	1	1	3	4	4	R
R	R	4	3	2	2	1	1	1	2	2	3	4	R	R
	R	4	3	3	2	2	2	2	2	3	3	4	R	
	R	R	4	3	3	3	3	3	3	3	4	R	R	
		R	R	4	4	4	4	4	4	4	R	R		
			R	R	R	4	4	4	R	R	R			
					R	R	R	R	R					

Figure 3. Arrangement of four TH channels in the core (Distribution- 1: 21/121, 2: 24/121, 3: 32/121, 4: 44/121, R: reflector).

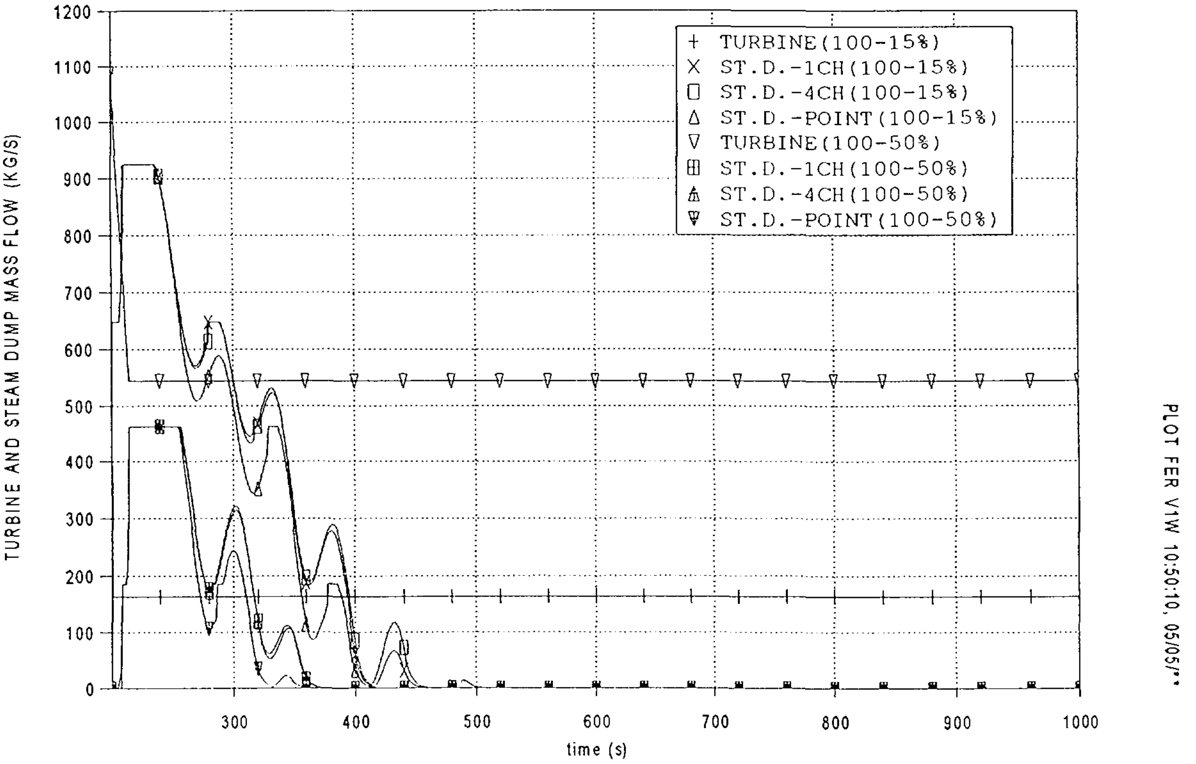

Figure 4. Turbine and steam dump mass flow for large load rejection: 100-15% and 100-50%.

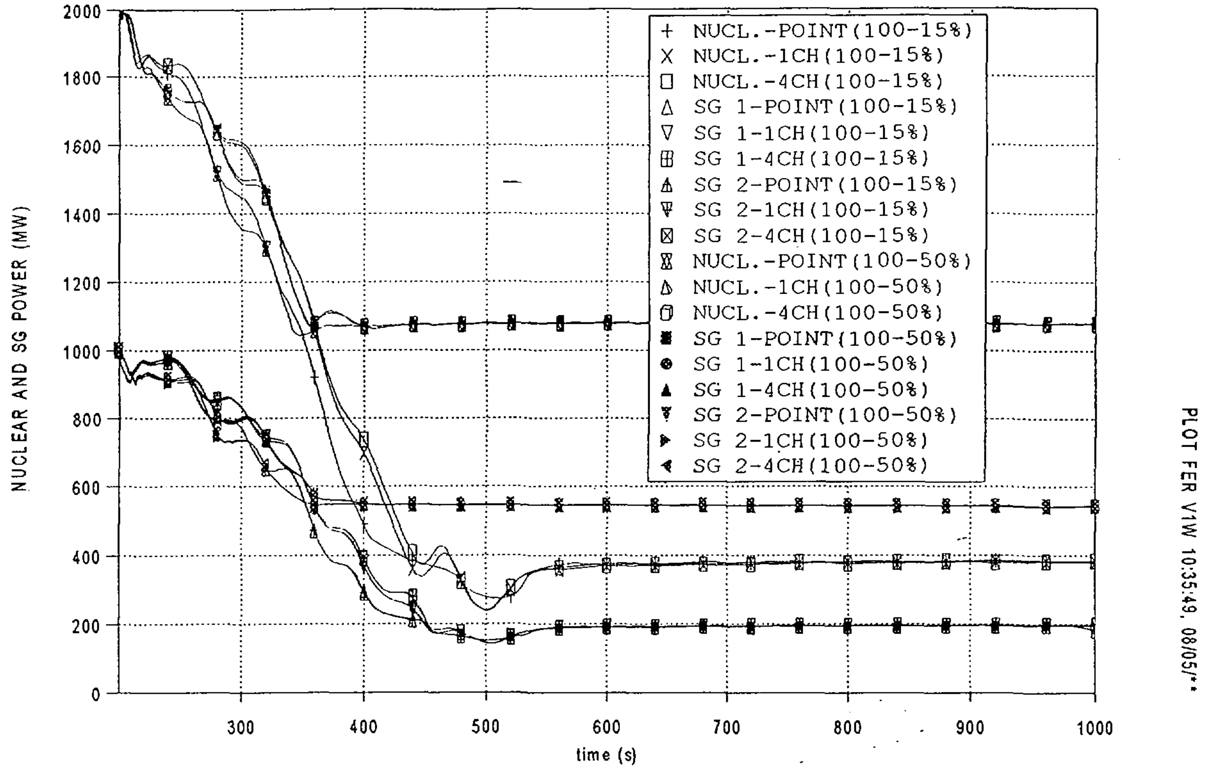

Figure 5. Nuclear and SG power for large load rejection: 100-15% and 100-50%.

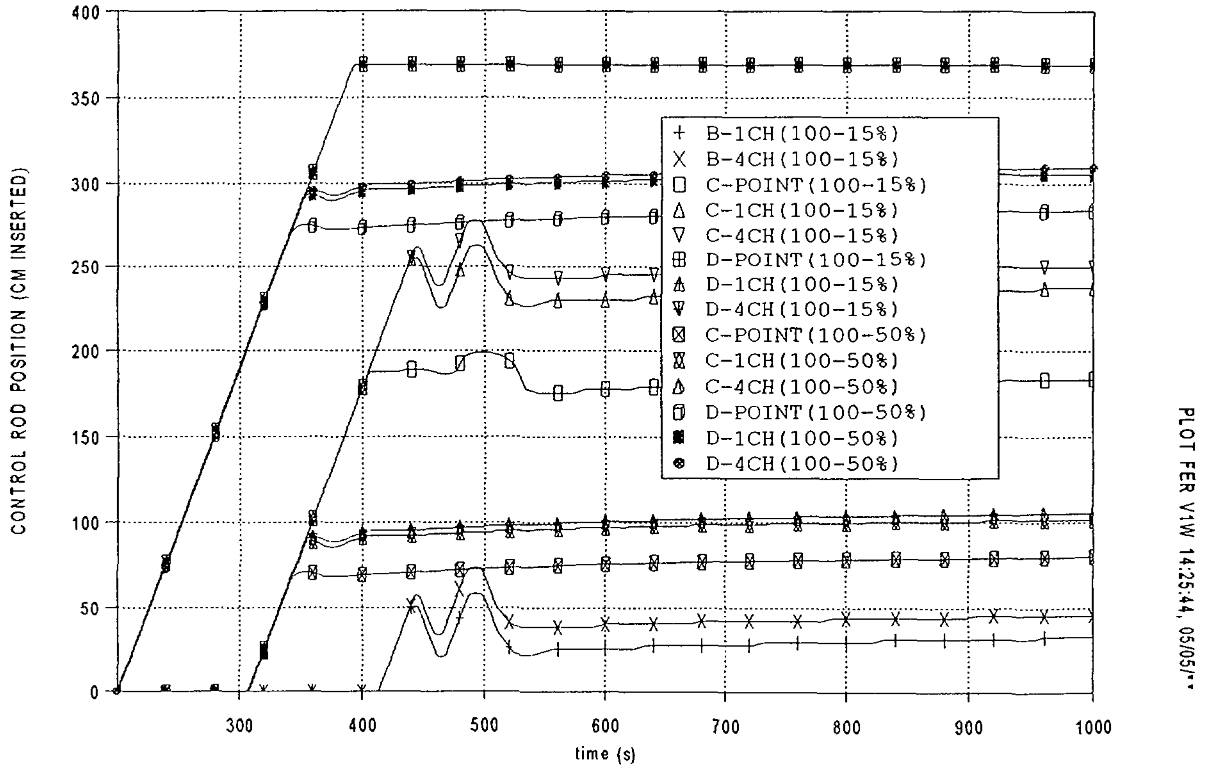

Figure 6. Control rods position for large load rejection: 100-15 % and 100-50 %.

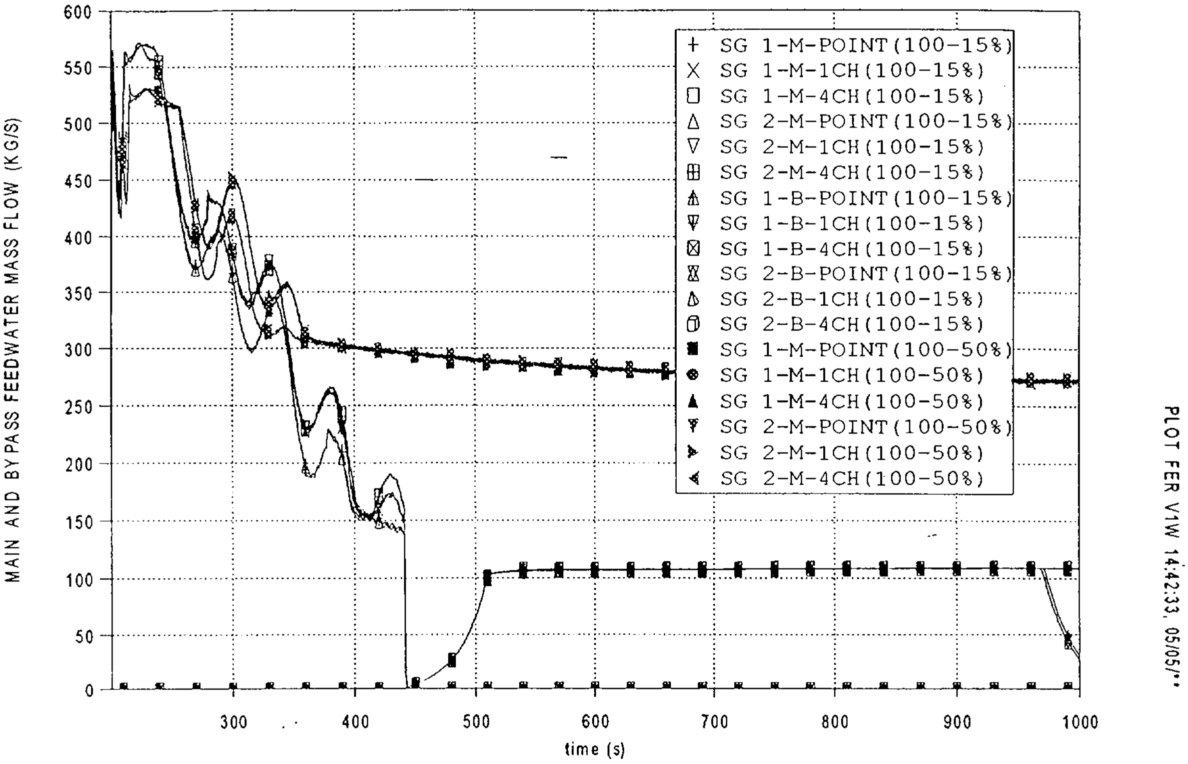

Figure 7. Main (M) and bypass (B) feedwater flow for large load rejection: 100-15 % and 100-50%.

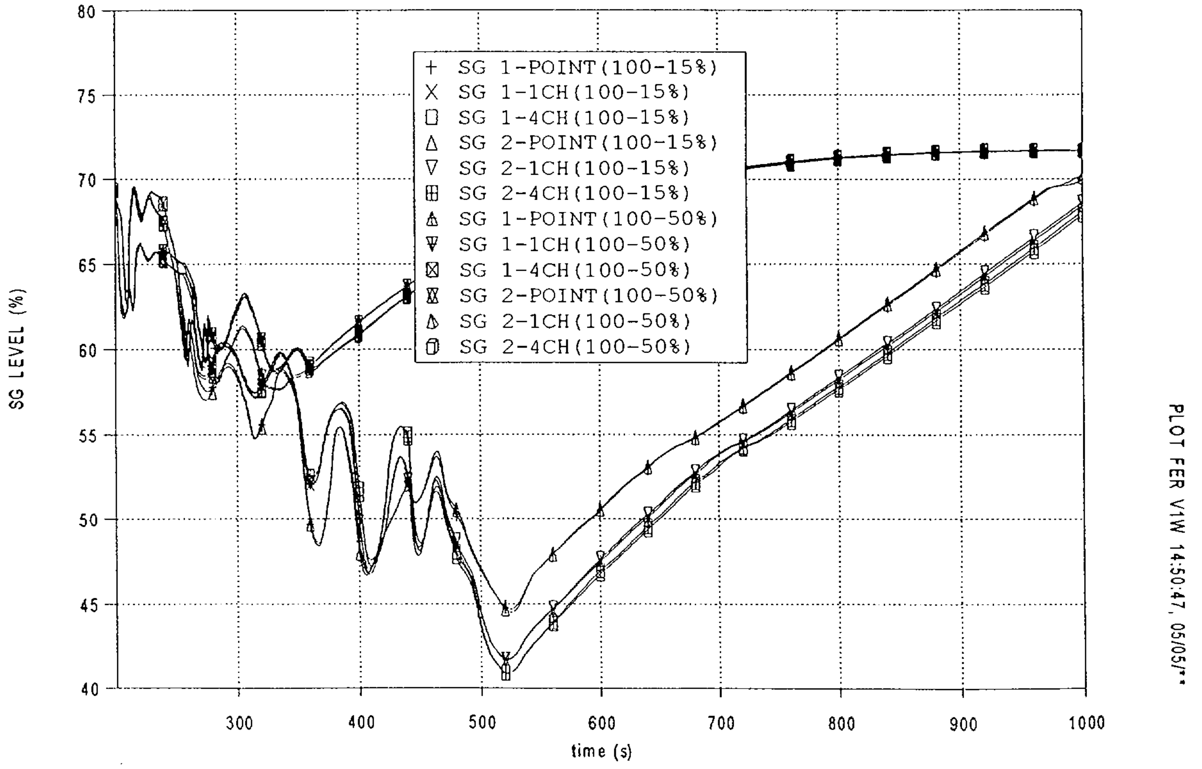

Figure 8. SG level for large load rejection: 100-15 % and 100-50 %.