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International Agreement Report

Assessment of the TRACE Code Using Transient Data from Maanshan PWR Nuclear Power Plant

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ABSTRACT

This study consists of two steps. The first step is the establishment of TRACE (TRAC/RELAP Advanced Computational Engine) models for important components, such as pressurizers, steam generators, the feedwater control system, the steam dump control system, and so on, in Maanshan Nuclear Power Plant (NPP) using SNAP (Symbolic Nuclear Analysis Program) /TRACE. These component models were tested and compared with Maanshan startup test data to verify their accuracy. Key parameters were identified to refine the models further. The next step is the incorporation of the above component models into the Maanshan NPP TRACE model. TRACE transient analyses of scenarios such as load reduction and turbine trip were performed and their results were compared with the corresponding plant data from Maanshan startup tests. The TRACE model of Maanshan NPP is also used to analyze Loss of Flow transient as defined in FSAR Chapter 15 which includes Partial Loss of Flow (PLOF), Complete Loss of Flow-Under Voltage (CLOF-UV), and Complete Loss of Flow-Under Frequency (CLOF-UF). Analysis results indicate that the Maanshan NPP TRACE model predicts not only the behaviors of important plant parameters consistent with the plant data, but also their associated numerical values with respectable accuracy.

FOREWORD

The USNRC is developing an advanced thermal hydraulic code named TRACE for nuclear power plant safety analysis. The development of TRACE is based on TRAC, integrating RELAP5 and other programs. NRC has determined that in the future, TRACE will be the main code used in thermal hydraulic safety analysis, and no further development of other thermal hydraulic codes such as RELAP5 and TRAC will be continued. A graphic user interface program, SNAP, which processes inputs and outputs for TRACE is also under development. One of the features of TRACE is its capacity to model the reactor vessel with 3-D geometry. It can support a more accurate and detailed safety analysis of nuclear power plants. TRACE has a greater simulation capability than the other old codes, especially for events like LOCA.

Taiwan and the United States have signed an agreement on CAMP (Code Applications and Maintenance Program) which includes the development and maintenance of TRACE. INER (Institute of Nuclear Energy Research, Atomic Energy Council, R.O.C.) is the organization in Taiwan responsible for the application of TRACE in thermal hydraulic safety analysis, for recording users' experiences of it, and providing suggestions for its development. To meet this responsibility, we built a TRACE model of TPC (Taiwan Power Company) Maanshan PWR NPP. In this report, TRACE models of components or control systems such as pressurizers, steam generators, the feedwater control system, and the steam dump control system in the Maanshan NPP were developed first. Startup tests of Maanshan NPP were utilized and conducted to confirm the accuracy of these TRACE component models. Then, the models were integrated into a whole-plant TRACE model. Finally, the accuracy of the whole-plant TRACE model was evaluated using Maanshan NPP startup tests and FSAR data.

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EXECUTIVE SUMMARY

An agreement which includes the development and maintenance of TRACE has been signed between Taiwan and USA on CAMP. INER (Institute of Nuclear Energy Research Atomic Energy Council, R.O.C.) is the organization in Taiwan responsible for applying TRACE to thermal hydraulic safety analysis in order to provide users' experiences and development suggestions. To fulfill this responsibility, we will establish a TRACE model of TPC (Taiwan Power Company) Maanshan PWR nuclear power plant (NPP).
Maanshan NPP is the first PWR in Taiwan. Its reactor is made by Westinghouse Company and has the rated power of 2775 MWt. The reactor coolant system has three loops and each loop has a reactor coolant motor and a steam generator. Besides, the pressurizer is connected with the hot-leg piping in loop 2.
The codes used in this research are SNAP v 1.1.8 and TRACE v 5.0p1. The methodology of Maanshan NPP TRACE model is described as follows: First, collecting the power startup tests and FSAR data [7]-[12] from Maanshan NPP. Second, establishing the Maanshan TRACE models of several important components such as pressurizer, steam generators, the feedwater control system, the steam dump control system, etc. by SNAP/TRACE. Then, the startup tests of Maanshan NPP will be used to verify the accuracy of the TRACE models. Third, adding other necessary components (e.g., the vessel and the main steam piping) into the TRACE model mentioned above to construct the Maanshan NPP TRACE model. Finally, testing the convergence of steady state of the Maanshan NPP TRACE model, comparing the TRACE data in a steady state, analyzing the transients, and comparing the TRACE data of the transients with the startup tests and FSAR data of Maahshan NPP. The TRACE model of Maanshan NPP is shown in Fig. 1.

Analysis results indicate that the Maanshan NPP TRACE model predicts not only the behaviors of important plant parameters consistent with the startup tests and FSAR data, but also their associated numerical values with respectable accuracy.

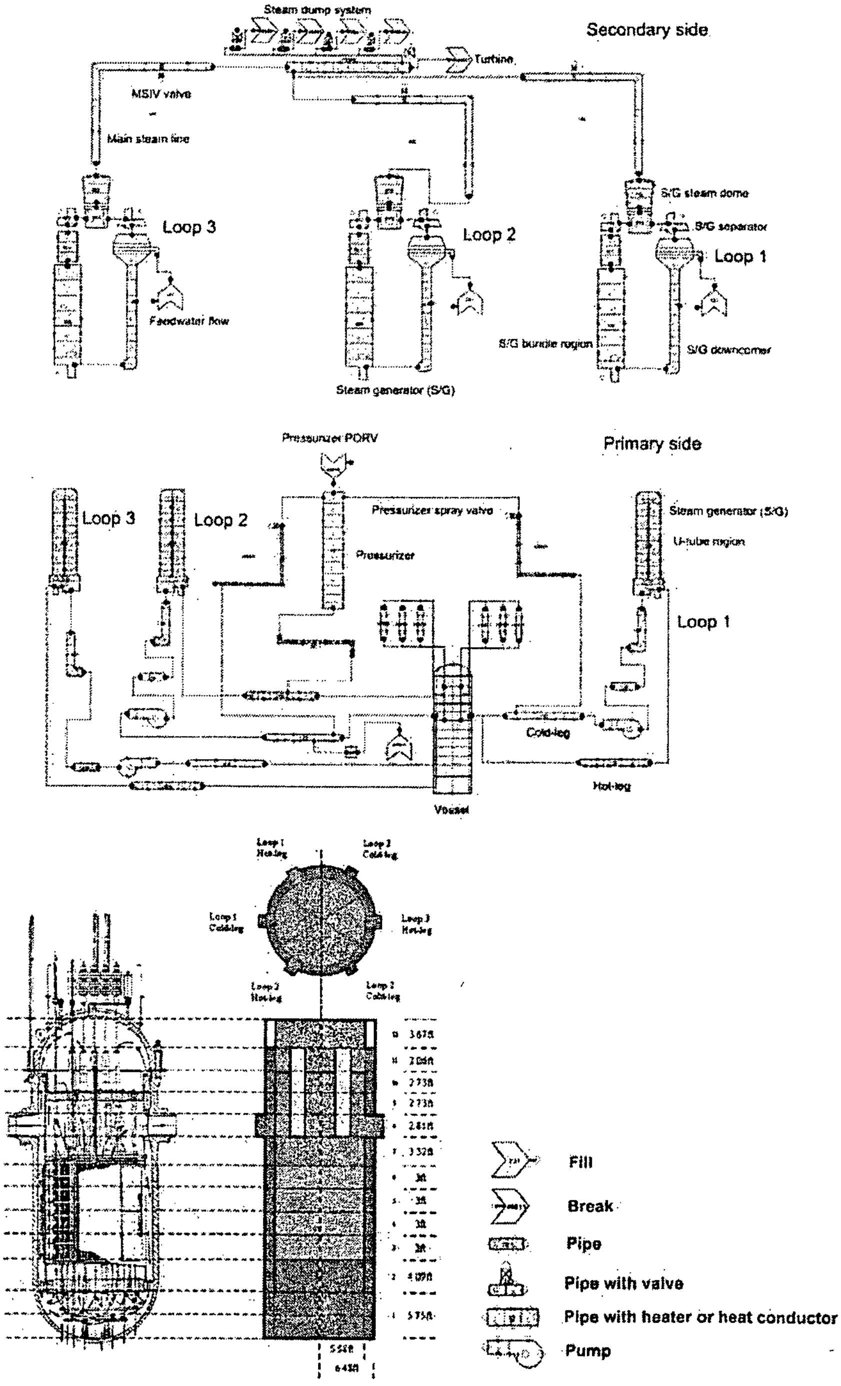


Fig. 1 The TRACE model of Maanshan NPP

ABBREVIATIONS

CAMP	Code Applications and Maintenance Program
CLOF-UF	Complete Loss of Flow-Under Frequency
CLOF-UV	Complete Loss of Flow-Under Voltage
FSAR	Final Safety Analysis Report
INER	Institute of Nuclear Energy Research Atomic Energy Council, R.O.C.
LOCA	Loss Of Coolant Accidents
NPP	Nuclear Power Plant
NRC	Nuclear Regulatory Commission
PLOF	Partial Loss of Flow
PORVs	Power-Operated Relief Valves
S/G	Steam Generator
SNAP	Symbolic Nuclear Analysis Program
SVs	Safety Valves
TPC	Taiwan Power Company
TRACE	TRAC/RELAP Advanced Computational Engine
US	United States

1. INTRODUCTION

The US NRC (United States Nuclear Regulatory Commission) is developing an advanced thermal hydraulic code named TRACE for nuclear power plant safety analysis. The development of TRACE is based on TRAC, integrating RELAP5 and other programs. NRC has determined that in the future, TRACE will be the main code used in thermal hydraulic safety analysis, and no further development of other thermal hydraulic codes such as RELAP5 and TRAC will be continued. A graphic user interface program, SNAP, which processes inputs and outputs for TRACE is also under development. One of the features of TRACE is its capacity to model the reactor vessel with 3-D geometry. It can support a more accurate and detailed safety analysis of nuclear power plants. TRACE has a greater simulation capability than the other old codes, especially for events like LOCA. Accordingly, an increasing number of researchers is using TRACE code to analyze test facilities and nuclear power plants. Gonza' lez *et al.* [1]-[2] established a TRACE model for Almaraz NPP and analyzed the Loss of Residual Heat Removal System (RHRS) event under midloop operating conditions. Their results revealed that the TRACE model can simulate the event accurately. Jasiulevicius *et al.* [3] also constructed a TRACE model of a Large-Scale Test Facility (LSTF), and confirmed its accuracy against data on the small-break loss of coolant accidents (SB-LOCA). Jaeger *et al.* [4] adopted a TRACE and PARCS model of Bulgarian nuclear power plant Kozloduy unit 6, and verified its accuracy using data from OECD/NEA VVER-1000 Coolant Transient Benchmark Phase 2. Barten et al. [5] established the TRACE model of UMSICHT water hammer experiments and the analysis results showed good agreement with the experiments data. Xu et al. [6] used TRACE/PARCS to do the validation of the stability analysis of Ringhals. Their results showed good agreement with the plant data. These investigations demonstrate that the TRACE code predicts results that agree reasonably with plant data.

Taiwan and the US have signed an agreement on CAMP which includes the development and maintenance of TRACE. INER is the organization in Taiwan that is responsible for the application of TRACE in thermal hydraulic safety analysis, for recording users' experiences of it, and providing suggestions for its development. To meet this responsibility, we built a TRACE model of TPC Maanshan PWR NPP. In this report, TRACE models of components or control systems such as pressurizers, steam generators, the feedwater control system and the steam dump control system in the Maanshan NPP were developed first. Startup tests data [7]-[11] of Maanshan NPP were utilized and conducted to confirm the accuracy of these TRACE component models. Then, the models were integrated into a Maanshan NPP TRACE model. Finally, the accuracy of the Maanshan NPP TRACE model was evaluated using Maanshan NPP Startup tests and FSAR data [7]-[12].

2. Methodology

The code versions used in this research are SNAP v 1.1.8 and TRACE v 5.0p1. The methodology of Maanshan NPP TRACE model as follows: First, collecting the power startup tests and FSAR data [7]-[12] from Maanshan NPP. Second, the Maanshan TRACE models for several important components such as pressurizer, steam generators, feedwater control system and steam dump control system etc. are established by SNAP/TRACE. Then the startup tests of Maanshan NPP will be used to verify the accuracy of the TRACE models. Third, the other necessary components (e.g. vessel and main steam piping) were added into the TRACE model mentioned above to construct the Maanshan NPP TRACE model. Finally, testing the convergence of steady state, comparing the TRACE data at steady state, analyzing the transients, and comparing the TRACE data at transients with the startup tests and FSAR data for Maahshan NPP TRACE model are performed. The complete process is presented in Fig. 2.1.

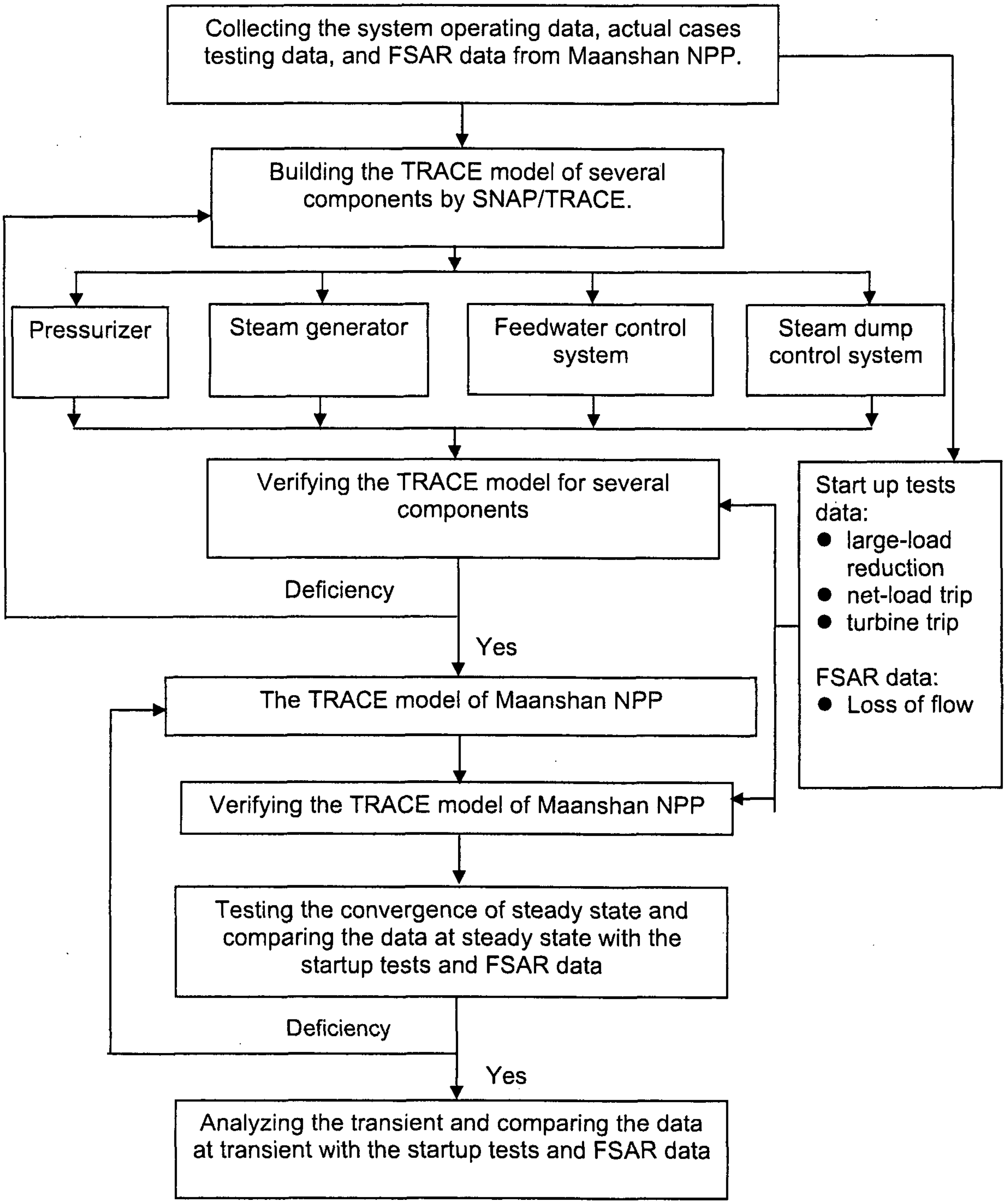


Fig. 2.1 The flow chart of establishing and verifying the TRACE model of Maanshan NPP

3. Establishment and verification of TRACE model for important components of Maanshan NPP

Maanshan NPP is the only Westinghouse-PWR in Taiwan. The rated core thermal power is 2775 MW. The reactor coolant system has three loops, each of which includes a reactor coolant pump and a steam generator. The pressurizer is connected to the hot-leg piping in loop 2. Because of the complexity of the equipment and systems at the Maanshan NPP, establishing component models first, for integration into a whole plant model, is the most effective approach. With reference to the TRACE user manual [13], and related information [7]-[12], component models of the pressurizer, steam generator, control system and steam dump control system were established.

3.1 Pressurizer and its control systems [14]

The pressurizer is made up of steel tank which contains saturated water in the lower section and saturated steam in the upper section in normal operation. It is connected to the hot leg of loop 2 through a surge line. The important components of the pressurizer include a sprayer, electric heaters, power-operated relief valves (PORVs), safety valves (SVs), a surge line, and a relief tank. The sprayer, the PORVs and the SVs are equipped at the top of the tank, while electric heaters are immersed in the water. The sprayer and the electric heaters are used to control the system pressure while load transients. While the reactor power increases, the coolant volume increases correspondingly such that the coolant surges into the pressurizer. In such a case, the sprayer is activated to spray water from the top of the tank to limit the pressure by condensing the steam. While the reactor power decreases, the coolant volume decreases and the coolant surges out the pressurizer. At this time, some of the water flashes to steam due to pressure drop. The electric heaters are activated to heat up the water in the tank to maintain the desired operating pressure.

The sprayer is activated by the pressure-difference setpoint. In normal operating condition, a low fluid flow rate of 2 gpm is sprayed into the pressurizer. When the pressure difference exceeds 25 psi, the flow rate starts to increase. The flow rate increases linearly from 2 gpm (1.00E3 lbm/hr) to 700 gpm (3.49E5 lbm/hr) as the pressure difference increases from 25 psi to 75 psi. The electric heaters can be classified into a proportional heater and a backup heater. The control of the proportional heater and backup heater is based on the pressure-difference setpoints and water-level setpoints. The proportional heater adds half of the rated heat to the liquid in normal operation, generates heat of 376 KW at a full rate as the pressure error signal is less than -15 psi, and is turned off completely as the pressure error signal is greater than +15 psi. The backup heater can only be fully turned on or off, and is controlled by the pressure error signal together with the level error signal. The backup heater is turned on completely only when the level error signal exceeds the setpoint by +5 % and the pressure error signal is less than the setpoint of -25 psi. On the other hand, the backup heater may be turned off completely if the pressure error signal is greater than -17 psi. The proportional heater and backup heater are totally turned off as the water level is lower than 14 %, no matter the pressure is high or low. Therefore, the water level for heater cutoff is 5.095 ft.

The PORVs are open when the pressure-difference setpoint 100 psi is reached, and the PORVs are closed when the pressure difference drops down to 80 psi. The release capability for each of the three PORVs is 210,000 lb/hr. The SVs are open when the pressure-difference setpoint

235 psi is reached, and the SVs are closed as the pressure difference is lower than 235 psi. The release capability for each of the three SVs is 380,000 lb/hr. Table 3.1 presents its important design parameters.

The pressurizer model was built by SNAP/TRACE. TRACE includes several hydraulic components such as PIPEs, PLENUMs, PRIZERs (pressurizers), CHANs (BWR fuel channels), PUMPs, JETPs (jet pumps), SEPDs (separators), TEEs, TURBs (turbines), HEATRs (feedwater heaters), CONTANs (containment), VALVEs, and VESSELs. Powered and heated components are denoted by POWER, FLPOWER (fluid power), and HTSTR (heat structure) in TRACE. FILL and BREAK components supply the coolant-flow and pressure boundary conditions. Therefore, the PIPE component is used to model the feature of the pressurizer. The FILL component models the phenomena of insurge and outsurge at the surge nozzle, the spray mechanism through the spray nozzle, and the pressure relief by letting steam exit through the power-operated relief valves (PORVs) and safety valves (SVs). The HTSTR component is added at the bottom of the pressurizer to model the heaters. To fulfill the control procedures of the open position of the spray valve, the opening and closing of PORVs and SVs, the proportional heater and backup heater, the control systems (trips, signal variables, control blocks, and component action tables) are properly combined for TRACE to follow. The fill table of the FILL component is edited to simulate the flow insurge and outsurge as the boundary condition of the pressurizer model. Therefore, the mass flow rates relative to time must be initially given. However, flow meters were not installed along the surge line to measure the flow rates during the tests conducted in 1985. We managed to adjust the mass flow rates at the surge nozzle by matching the calculated water level inside the pressurizer with those from the test data. Thus, trial and error is applied to search out the proper inputs of the mass flow rates. All of the plant tests collected in this study have the records of the variations in water level. Consequently, the time-varying mass flow rates input to the fill table for each test are successfully obtained. After the pressurizer model is constructed and the boundary conditions are given, each test retrieves its fluid initial conditions using the steady-state calculation function in TRACE.

The TRACE model of the pressurizer is shown in Fig. 3.1. Besides, the turbine trip test at 100% power (PAT50), the large-load reduction at 100% power (PAT49), and the net-load trip at 100% power(PAT51) transients [7]-[11] were used to verify the TRACE model of the pressurizer.

The turbine trip test was initiated by manually tripping the turbine while the plant was operating at full power. As a result, the reactor was directly tripped with control rods in full-in position. The decrease in the reactor coolant temperature led a large flow outsurge of the pressurizer. To simulate this transient, the mass flow rates relative to time are given in the fill table of FILL component as the boundary conditions. It is adjusted so that the calculated water levels match those in the plant test data. The solid line in Fig. 3.2 shows the water levels during the 100% turbine trip test. The circles in Fig. 3.2 represent the resultant water level after the mass flow rates of the FILL component are well adjusted. Fig. 3.3 plots the calculated pressurizer pressure histories together with the measured pressure histories. This figure reveals that the pressure histories in the pressurizer predicted by TRACE are in agreement with the plant test data.

The large-load reduction test was initiated by reducing the steam flow passing through the turbine from 100 to 50% of the rated capacity. This test is used to verify that the rod control system and the steam dump system can be automatically initialized, and the reactor power can be reduced from 100 to 50% corresponding to the reduction in steam flow. To simulate this transient, the mass flow rates related to time at the surge nozzle are also properly given. The given inputs result in that the calculated water levels meet the measured water levels, as shown in Fig. 3.4. Comparison between the measured and calculated pressurizer pressure during the transient is shown in Fig. 3.5. It can be seen that the calculated pressure histories follow the plant test data, caused by a combination of insurge, outsurge, spray actuation, and electric heater action. However, a discrepancy between the calculated and the measured pressure histories is observed. In this simulation, the pressure response seems over-reactive when the pressure is increasing.

The 100 % net-load trip test was initiated by manually rejecting load while the plant was operating at full power. All the control systems were in auto mode. Fig. 3.6 shows that the calculated water levels meet the measured water levels. The calculated and the measured pressurizer pressures during the transient are plotted in Fig. 3.7. As revealed from this figure, the calculated pressure histories follow the trend of the plant test data. The calculated pressure in this net-load trip test reaches the sprayer setpoint plus 25 psi at time 175 sec. Therefore, the sprayer starts to spray cool liquid into the pressurizer to suppress the pressure.

The 50 % net-load trip test was initiated by manually rejecting load while the plant was operating at 50 % power. All the control systems were in auto mode. Fig. 3.8 shows that the calculated water levels meet the measured water levels. The calculated and the measured pressurizer pressures during the transient are plotted in Fig. 3.9. The calculated pressure histories follow the plant test data, caused by a combination of insurge, outsurge, spray actuation, opening of PORVs and electric heater action. However, a discrepancy between the calculated and the measured pressure histories is also observed.

This study develops a pressurizer model for the Maanshan NPP, and the predicted results of TRACE are compared with the startup tests data. The results show that the comparisons are in reasonable agreement.

Table 3.1 The parameters of the pressurizer for Maanshan NPP

Parameter	
Pressurizer volume	39.64 m^3
Full power water level	56.5 %
Pressurizer flow length	11.74 m
Sprayer valve max. flow rate (total 2 valves)	44 L/sec
Heater (proportional heater and backup heater)	1400 W
Safety valve setpoint	1.7236×10^7Pa
Power-operated relief valve setpoint	1.6202×10^7Pa

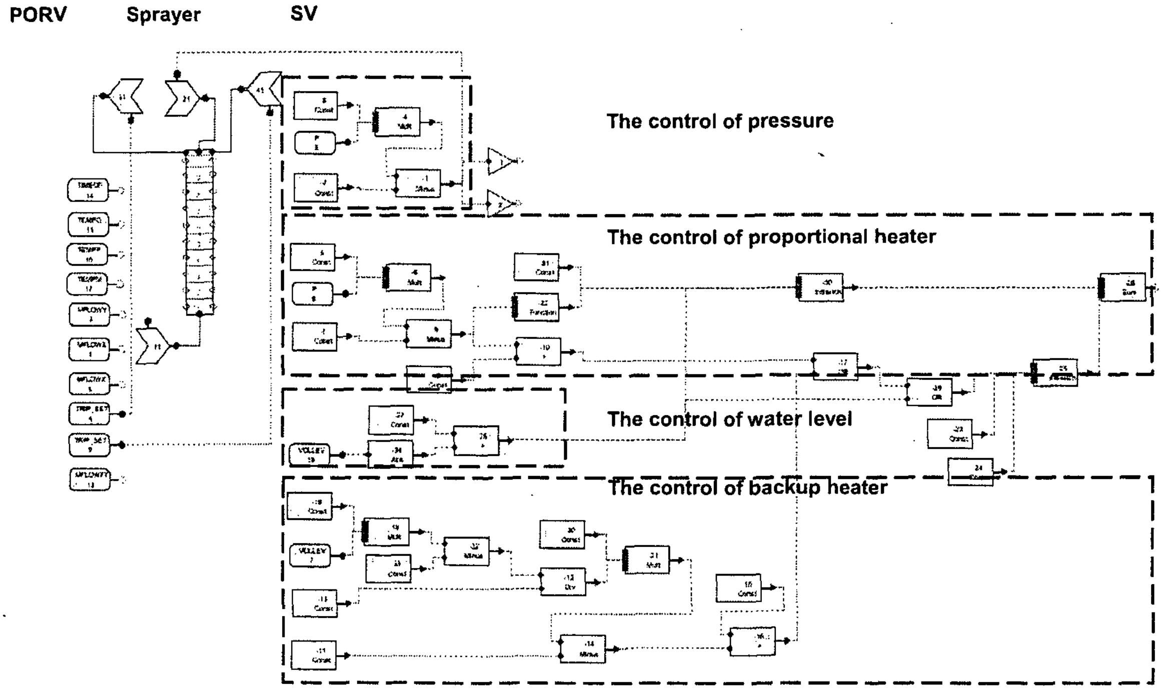


Fig.3.1 The TRACE model of the pressurizer for Maanshan NPP

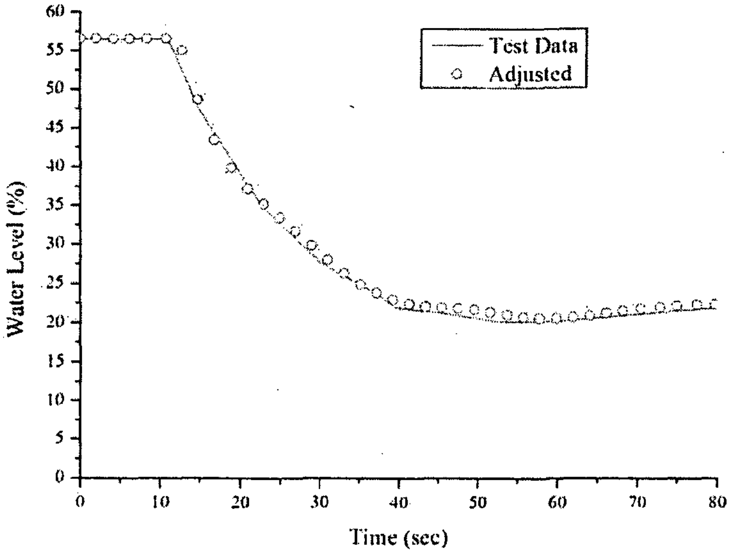


Fig. 3.2 Water level during the 100 % turbine trip test

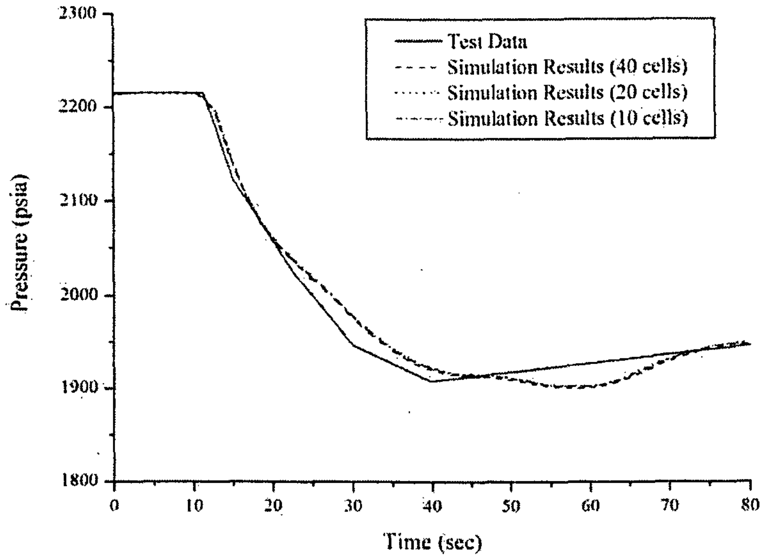


Fig. 3.3 Comparison of the measured and calculated pressurizer pressure histories during the 100 % turbine trip test

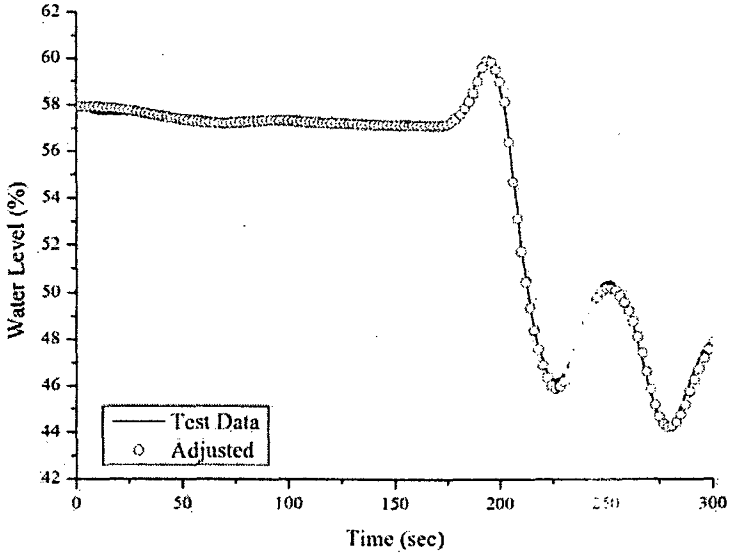


Fig. 3.4 Water level during the 100 % large-load reduction test

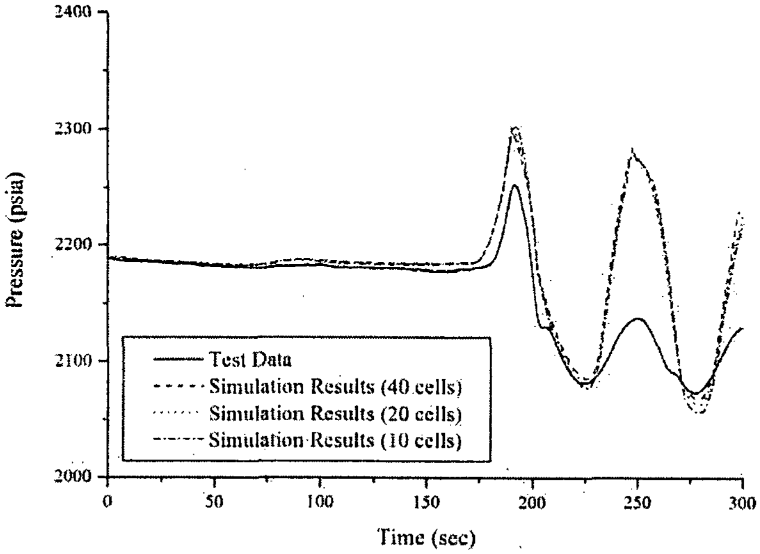


Fig. 3.5 Comparison of the measured and calculated pressurizer pressure histories during the 100 % large-load reduction test

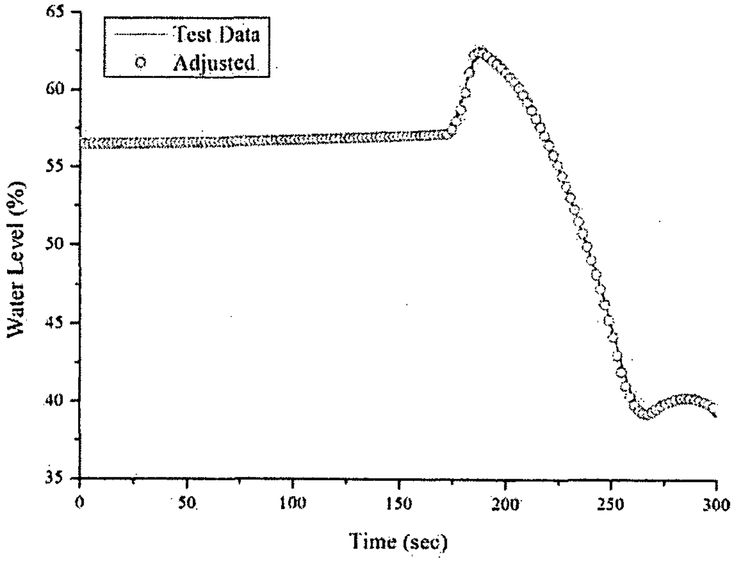


Fig. 3.6 Water level during the 100 % net-load trip test

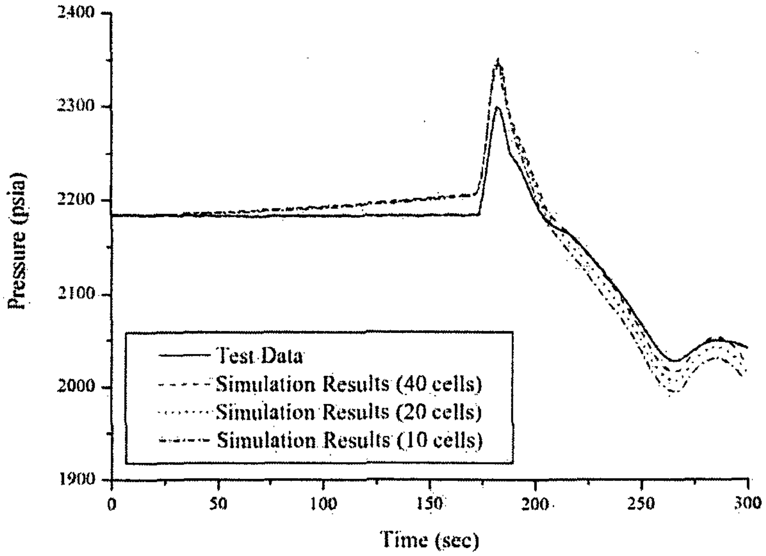


Fig. 3.7 Comparison of the measured and calculated pressurizer pressure histories during the 100 % net-load trip test

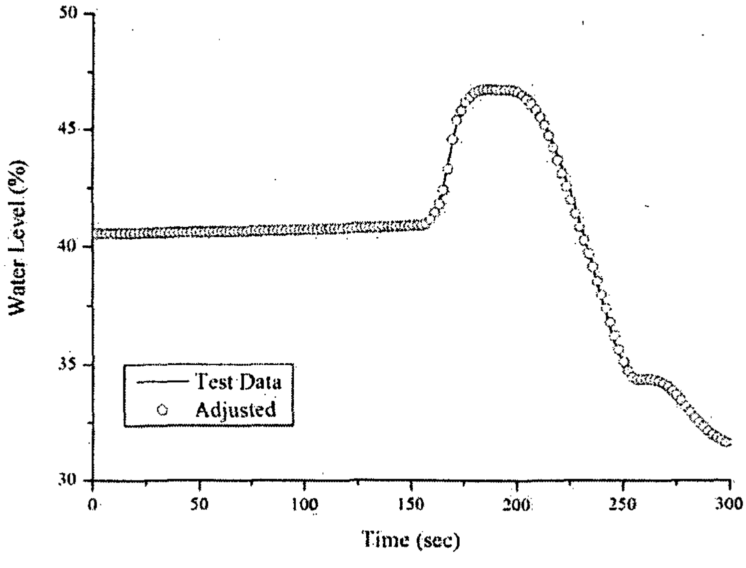


Fig. 3.8 Water level during the 50 % net-load trip test

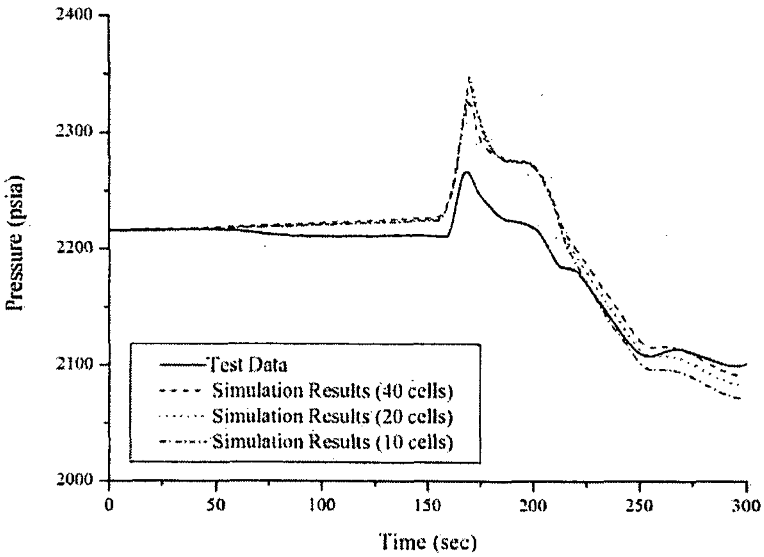


Fig. 3.9 Comparison of the measured and calculated pressurizer pressure histories during the 50 % net-load trip test

3.2 Steam generator with feedwater control system [15]

The steam generator of the Maanshan power plant is a Model F, vertical U-tube heat exchanger, with a total of 5,624 U-tubes. The establishment of the TRACE model of the steam generator was based on the TRACE V5.0 user manual [13], and the INER report [10]. Wang and Wang [10] employed RETRAN to carry out the simulation and analysis of the steam generator, and compared the feedwater flow thus obtained with the plant test data. No significant difference between the results obtained using RETRAN and the plant data was found.

Fig. 3.10 displays the TRACE model of the steam generator in Maanshan. According to Fig. 3.10, the U-Tube at the primary side is separated into 18 volumes. A FILL component represents "HOT-LEG fluid inflow", and a BREAK component is used to represent "COLD-LEG fluid outflow". Their inputs were derived from the real plant temperature and pressure time histories [7]-[11]. Then, at the secondary side, the region of the boiler is separated into seven volumes; the region of the downcomer is separated into 13 volumes, and the region of the steam dome and the separator is separated into 13 volumes. Next, a FILL component is added to represent "feedwater inletflow", and a BREAK component is added to represent "steam outflow". The plant data for feedwater flow and other input parameters derived from velocity, temperature and pressure were used to set the initial conditions. The feedwater flow was then controlled by a three-element feedwater control system after the transient began. In Fig. 3.10, components in red represent in which heat conductions or heat exchanges exist. The most important heat exchanges in the steam generator take place between the primary side and the secondary side.

Fig. 3.10 depicts the TRACE component model of the feedwater control system in the Maanshan NPP. The model was established according to the INER report [7]. The main function of the feedwater control system is to maintain a fixed water level of the steam generator at the secondary side when it is operating normally. The feedwater control system controls the main feedwater control valve using three signals including the water level error signal, the steam flow signal, and the feedwater flow signal. The water level error signal is calculated as the difference between the actual water level and the preset water level (typically 50%). Another value is calculated as the difference between the steam flow and the feedwater flow. These two differences are taken as the control signals of feedwater valve.

The TRACE model of the steam generator and feedwater control system was verified with a large-load reduction at 100% power test at Maanshan NPP (PAT49). Fig. 3.11 shows the comparison between the results for feedwater flow from the TRACE model and from the plant data. Fig. 3.12 and Fig. 3.13 compare steam flows and water levels in the steam generator. The results of TRACE are almost the same as the measured values from power plant, except when larger fluctuations occur.

In brief, the results of the steam generator and feedwater control system in the TRACE component model agree closely with the plant data and exhibit respectable accuracy.

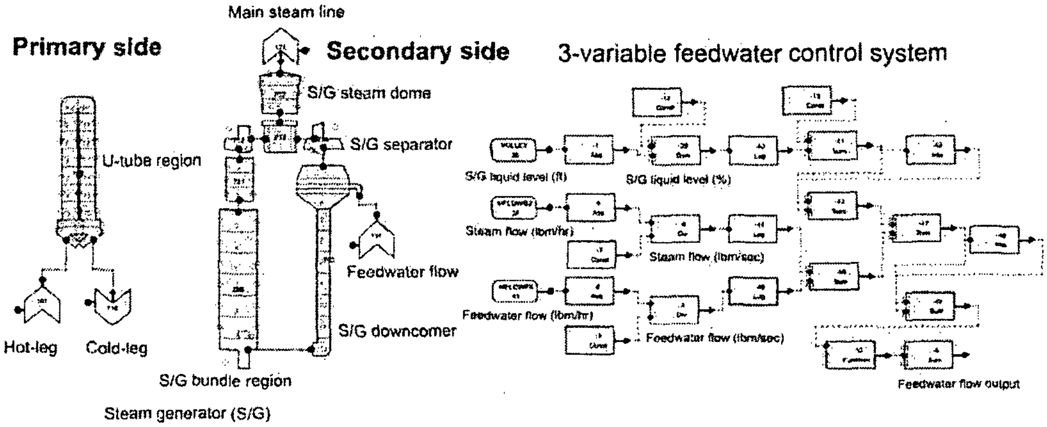


Fig. 3.10 The TRACE model of the steam generator and feedwater control system in Maanshan NPP

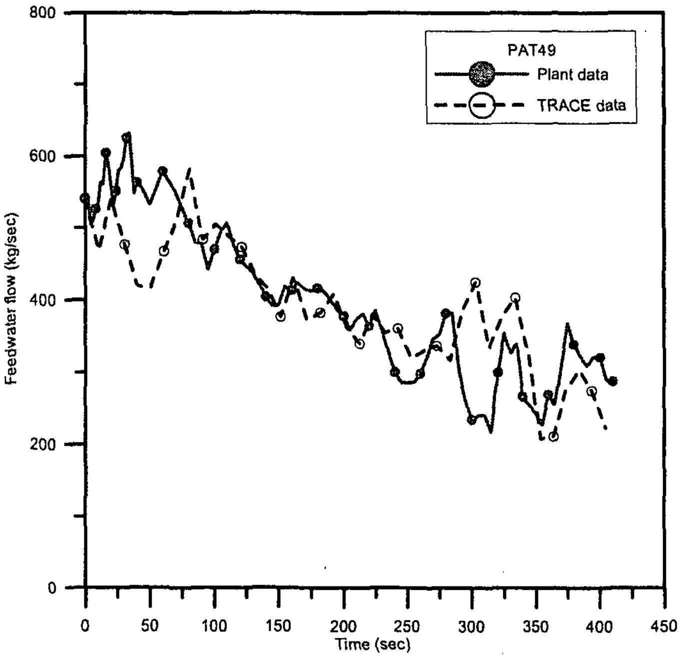


Fig. 3.11 The feedwater flow comparison between TRACE and the measured value of Maanshan NPP

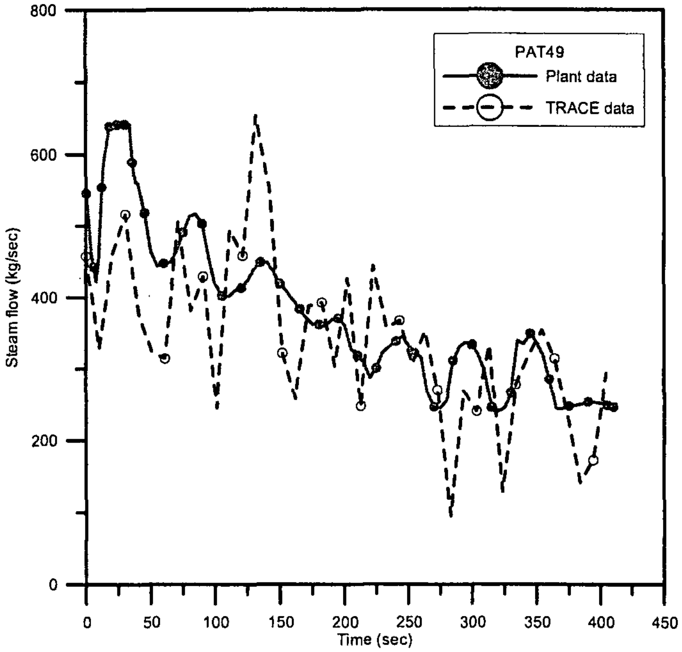


Fig. 3.12 The steam flow comparison between TRACE and the measured value of Maanshan NPP

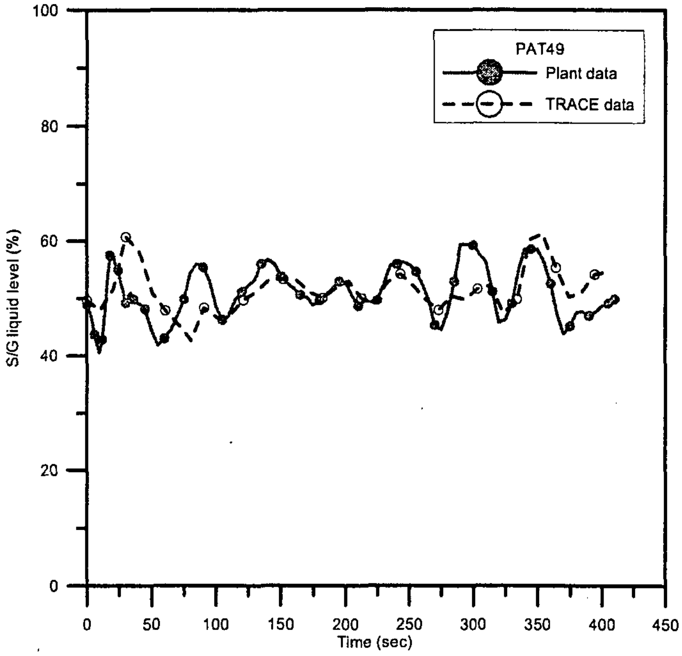


Fig. 3.13 The S/G water level comparison between TRACE and the measured value of Maanshan NPP

3.3 Steam dump control system [15]

The steam dump control system is composed of ten atmospheric venting valves, six turbine bypass valves and the associated piping control apparatus. Fig. 3.14 shows the TRACE model of the steam dump control system. This model was established and described in the INER [7]. The ten atmospheric venting valves and six turbine by-pass valves are grouped into four sets in this model. Three turbine bypass valves comprise the first set and the other three as the second set. Five atmospheric venting valves are considered as the third set and the rest as the fourth set.

When the turbine trip occurs, an electrical signal converted from the error signal between the highest Tavg and Tnoload is sent to the turbine trip controller. Through the P/I controller, air that flows from the air supply piping is directed to the first and second sets of turbine bypass valves to control the degree of valve openings.

For the load rejection of load reduction, an electrical signal converted from the error signal between the highest Tavg (maximum) and Tref (converted from first-stage steam pressure) is sent to the load rejection controller. Through the P/I controller, air that flows from the air supply piping is directed to the turbine bypass valves and atmospheric venting valves (the first through fourth sets of valves) to control the degree of valve openings.

The TRACE model for the steam dump control system was confirmed using the large-load reduction at 100% power test (PAT49) in Maanshan. Figs. 3.15-3.18 compares the results of the openings between the TRACE model and the plant data; they generally agree closely. Notably, in Fig. 3.15 and 3.16, the first and second sets of valves were closed at 375s and remained closed afterwards. However, the simulated results of TRACE indicate that the first and second sets of valves open again. The temperature difference from the plant testing records reveals that the first and second sets of valves should have opened again. Hence they are suspected to have been manually closed during the test. Fig. 3.16 demonstrates that the valve opening in TRACE reduces to 0% (200s to 400s), but was in fact about 4.5% in the plant data. In the steam dump control system, Tavg signal activates the valves. All of the second set of valves should close, according to the Tavg difference records, but in fact, they close only to around 4.5%. Therefore, the second set of valves could not be fully closed or were poorly calibrated in the testing process. The results for the steam dump control system obtained using the TRACE model are thus concluded to agree closely with the plant data.

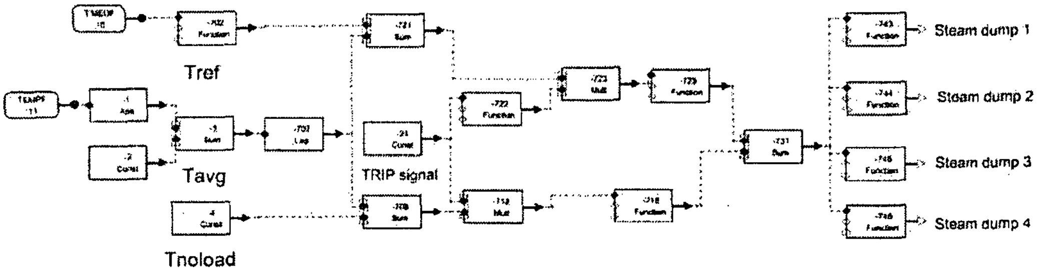


Fig. 3.14 The TRACE model of the steam dump control system for Maanshan NPP

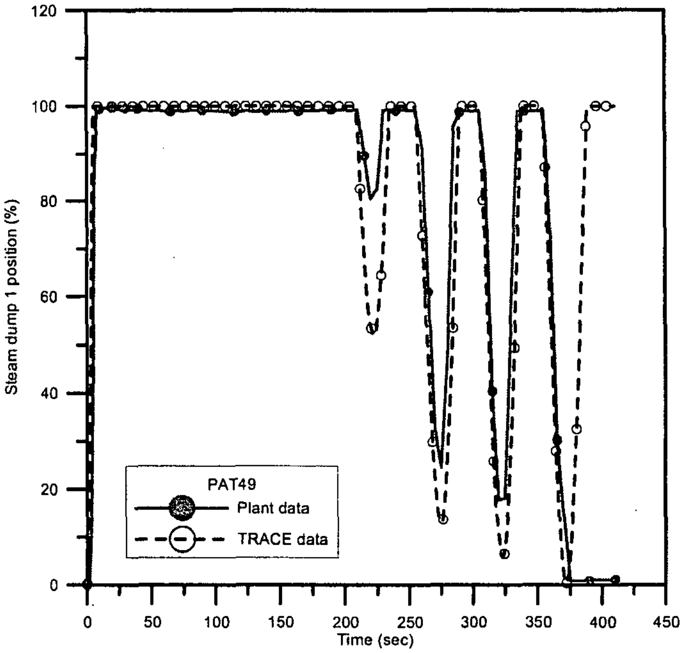


Fig. 3.15 The first set comparison between the steam dump analysis results of TRACE model and the measured values by Maanshan NPP for steam dump control system

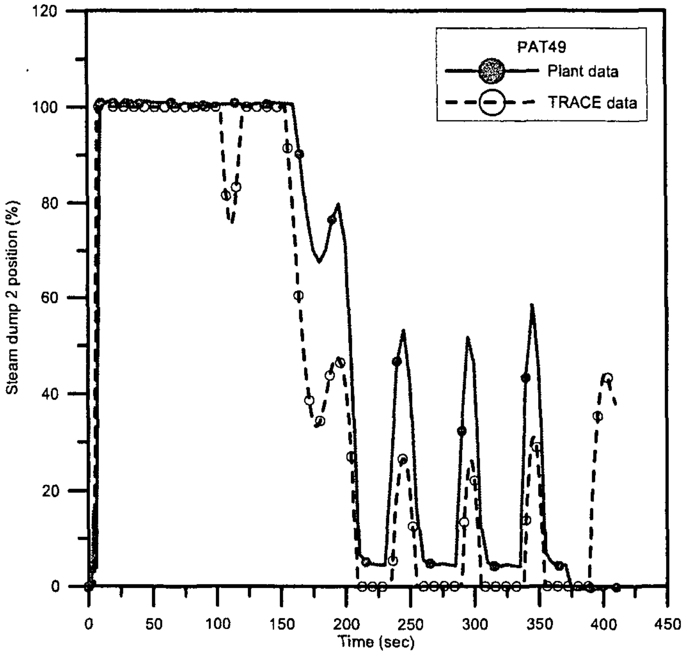


Fig. 3.16 The second set comparison between the steam dump analysis results of TRACE model and the measured values by Maanshan NPP for steam dump control system

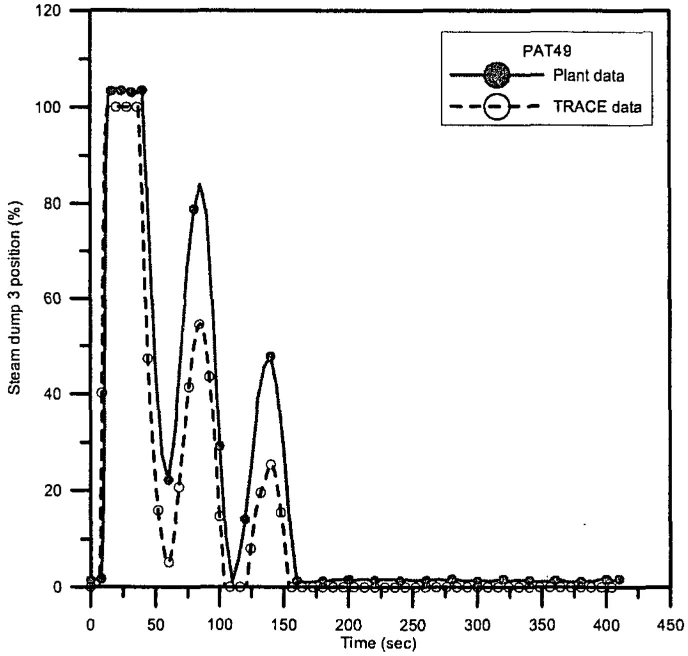


Fig. 3.17 The third set comparison between the steam dump analysis results of TRACE model and the measured values by Maanshan NPP for steam dump control system

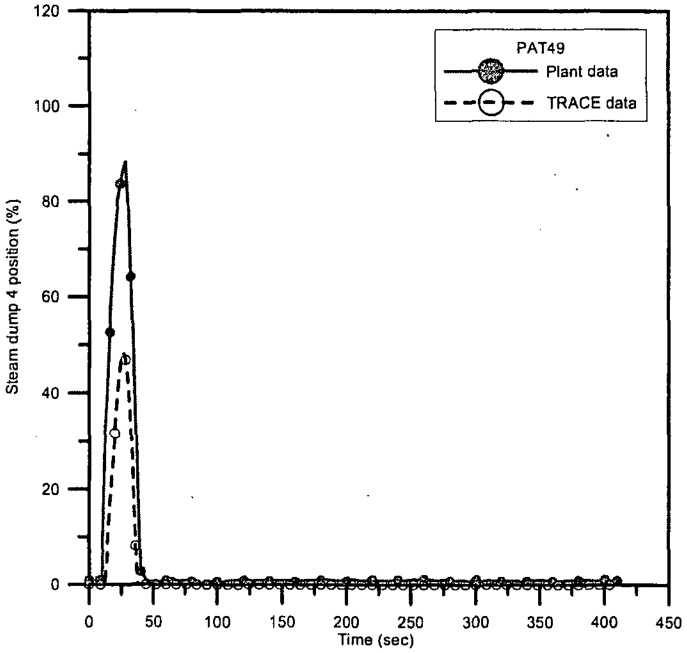


Fig. 3.18 The fourth set comparison between the steam dump analysis results of TRACE model and the measured values by Maanshan NPP for steam dump control system

4. TRACE Modeling of Maanshan NPP

4.1 Model description

The TRACE component models of the pressurizer, steam generator, feedwater control system, and steam dump system were illustrated and verified against the turbine trip, net-load trip, and load reduction startup test data. These models were then integrated into a TRACE model of Maanshan NPP, as presented in Fig. 4.1. It is a three-loop model, and each loop has a feedwater control system. The main structure of this model includes the pressure vessel, pressurizers, steam generators, steam piping at the secondary side (including four sets of steam dump and vent valves) and the steam dump system. The pressure vessels are cylindrical, and its divisions are as shown in Fig. 4.1. It is divided into 12 levels in the axial direction, two rings in the radial direction (internal and external rings) and six equal azimuthal sectors in the "θ" direction. The control rod conduit connects the 12th and 7th layers of the vessel from end to end. The fuel region is between the third and sixth layers, and heat conductors were added onto these structures to simulate the reactor core.

Before any transient analysis can begin in the TRACE model of Maanshan NPP, a consistent set of parameters used in TRACE must be obtained in the process of steady-state initialization. In TRACE, steady-state initialization was performed with real plant power input [7]-[11]. The resulting calculated parameters such as the feedwater and steam flows of the steam generators, the water levels in the steam generators and the pressurizer, the pressure of the pressurizer, and the hot-leg temperatures were then compared with data from the startup tests [7]-[11]test data. Table 4.1 shows the comparison between the steady-state results of the TRACE model and the measured values in Maanshan. The results are clearly mutually quite consistent, except in the case of the steam generator feedwater flow, which exhibits about 6.67% differences. We suspect that this deviation is probably caused by the larger measurement errors in the startup tests.

Table 4.1 The comparison between the steady state data of TRACE and the measured values from the power plant

Parameter (PAT49)	Plant data	TRACE data	Error (%)
Power (W)	2.8026×10^9	2.8026×10^9	0.00
Tavg (K)*	582.90	582.63	0.05
Pressurizer liquid level (%)	57.04	56.59	0.79
Pressurizer pressure (Pa)	1.5334×10^7	1.4972×10^7	2.36
Steam generator liquid level (%)	48.94	50.10	2.37
Steam generator feedwater flow (kg/sec)	541.50	505.37	6.67
Steam generator outlet steam pressure (Pa)	6.8465×10^6	6.9327×10^6	1.24

*Tavg = (Hot-leg temperature +Cold-leg temperature)/2

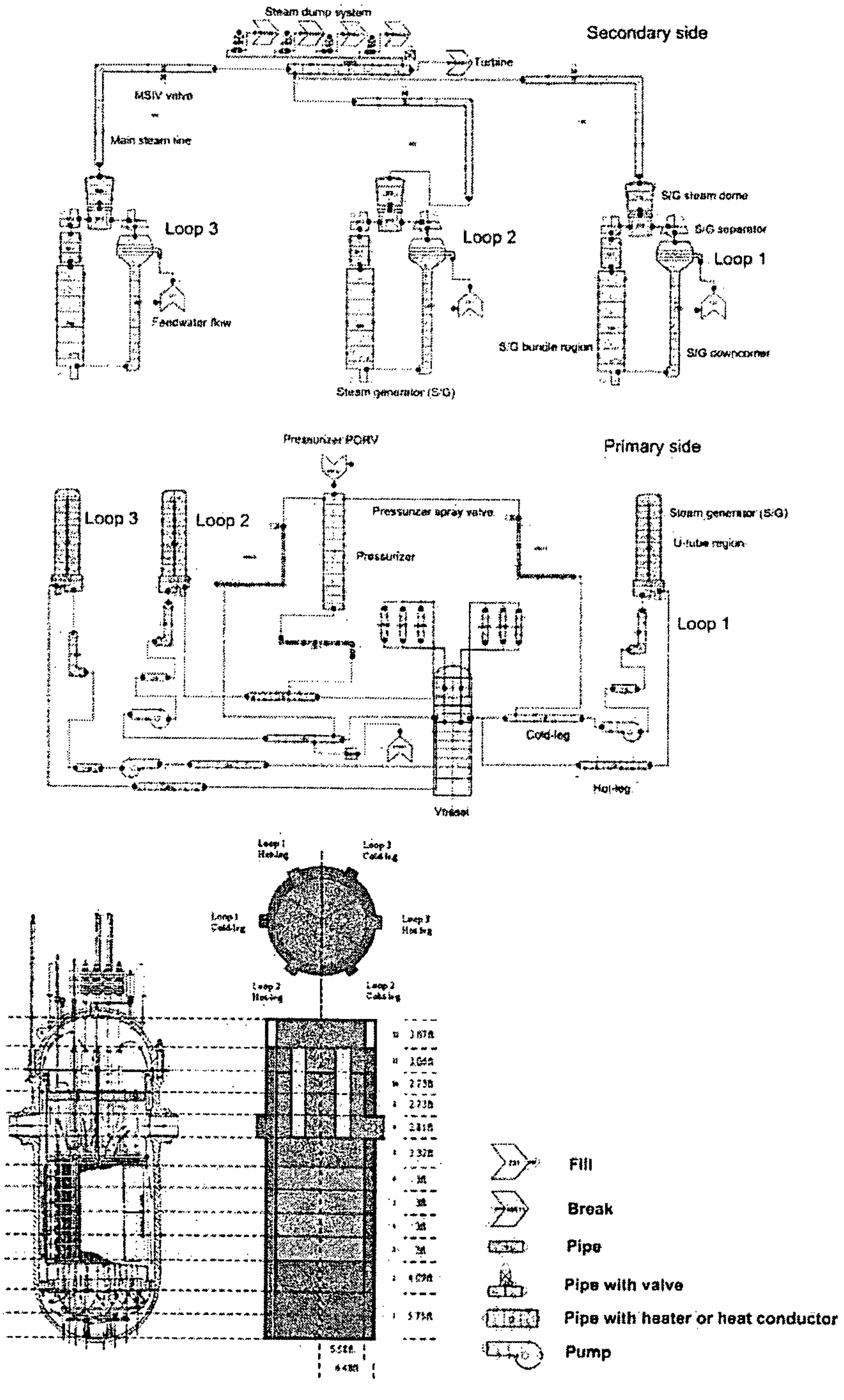


Fig. 4.1 The TRACE model of Maanshan NPP

4.2 Results and discussions [15]-[17]

Following the steady state initialization, the TRACE model of Maanshan NPP was verified using three startup test transients [7]-[11] including the large-load reduction at 100% power (PAT49), the net-load trip at 100% power (PAT51) and the turbine trip test at 100% power (PAT50), and three FSAR transients [12] including Partial Loss of Flow (PLOF), Complete Loss of Flow-Under Voltage (CLOF-UV) and Complete Loss of Flow-Under Frequency (CLOF-UF).

Besides, in transient analysis, there are two methods to simulate or calculate power in Maanshan NPP TRACE model. One is to input the power curve by "power table" into the TRACE model of Maanshan NPP which is the same as the startup tests data to simulate the power for the transient analysis. Another is to use "point kinetic" data (e.g., the delay neutron fraction, Doppler reactivity coefficient, and Void reactivity coefficient) in the Maanshan NPP TRACE model and let TRACE to calculate the power for the transient analysis. The first method is used in the PAT49 and PAT51 transients and the second method in the PAT50, PLOF, CLOF-UV, and CLOF-UF transients.

Tables 4.2-4.7 present the sequence of each transient and the timings of events predicted by TRACE. The transient sequences of TRACE arose from the actuation of the related control system, which in turn had to be actuated by physical parameter signals. If the parameters predicted by TRACE differ from the plant data, then the event sequences will also differ. Such deviations can be observed in the comparisons of transient event analyses. For example, the variation of Tavg affects the opening times of the turbine bypass valves and atmospheric valves.

4.2.1 Large-load reduction at 100% power (PAT49)

Table 4.2 shows the Large-load reduction sequences of Maanshan NPP startup test data and TRACE. It can be observed that these sequences of the plant data and TRACE are roughly the same. Fig. 4.2 plots the core power curves of the Maanshan NPP and TRACE in the case of PAT49. In TRACE, the core power can be specified by a power table, and is essentially the same as that given by the plant data. Fig. 4.2 compares Tavg from the plant data with that from TRACE predictions. The temperatures calculated by TRACE almost equal the measured values in Maanshan NPP. Fig. 4.3 compares the water levels and pressures in pressurizer, revealing that the water level calculated by TRACE is slightly lower but follows the trend of the plant data. The pressure calculated using TRACE also follows the trend of the plant data, with larger fluctuations. Fig. 4.4 plots the results for steam generator feedwater flow and water level. The feedwater flow is in good agreement with the plant data except for the period between 50 sec. and 150 sec. The water level calculated by TRACE is close to the measured values of the plant, but with smaller fluctuations.

4.2.2 Net-load trip at 100% power (PAT51)

Table 4.3 shows the Net-load trip sequences of Maanshan NPP startup tests data and TRACE model. It can be seen that these two sequences are approximately the same. Figs. 4.5-4.7 present the verified results for case PAT51. The predicted Tavg are approximately the same as those from the plant data, except in the period between 320 sec. and 400 sec. Fig. 4.6 compares the water levels and pressures in the pressurizer indicating that the water level calculated by TRACE is slightly lower than that in the startup tests data. The pressure of TRACE is also lower at most of the time, but with larger fluctuations. The trends of pressurizer water level and pressure are quite similar between predictions and startup tests data. Fig. 4.7 compares steam generator feedwater flows and water levels. The feedwater flow of TRACE is close to the measured value in the tests, except between 60 and 120s. The water level calculated by TRACE is close to that given by the plant data, but with smaller fluctuations.

4.2.3 Turbine trip test from 100% power (PAT50)

Table 4.4 shows the Turbine trip test sequences of Maanshan NPP startup tests data and TRACE. It indicates that these two sequences are approximately the same. Fig. 4.8 plots the power curve of the Maanshan NPP and that calculated from TRACE in the case of PAT50. In TRACE, the core power can be specified by a power table, which is essentially the same as that given by the plant data, or by calculation using the built-in point kinetics model. As a result, the power calculated from TRACE includes decay heat, and stays at a level higher than the neutron flux-determined power from plant after 10 sec. The comparison of Tavg is also shown in Fig. 4.8. The temperature calculated by TRACE approximately follows the trend of the test data, but at a slower pace. Fig. 4.9 compares the pressures and water levels of the pressurizer and suggests that the water level calculated by TRACE approximately follows the trend of the plant data but decreases slower. Fig. 4.10 compares the steam generator feedwater flows and water levels. It reveals that the feedwater flow predicted by TRACE agrees closely with the results of the tests, except between 10 sec. and 30 sec. However, the water level calculated by TRACE falls gradually and then down to 0 at about 70 sec., while the level in the test declines rapidly after 10 sec. and then down to 0 at about 35 sec. Therefore, a large difference exists between the predicted and actual steam generator water levels.

4.2.4 Partial Loss of Flow (PLOF)

Table 4.5 shows the PLOF sequences of FSAR, RETRAN and TRACE. It can be observed that these three sequences are approximately in good agreement. Besides, it displays the slower time response in TRACE. As for the verification of PLOF cases, Fig. 4.11 compares the power and core flow of FSAR, RETRAN and TRACE. It displays that the power curve of TRACE is almost the same as those of FSAR and RETRAN. It also shows that the core flow curve of TRACE approximately follows the trends of FSAR's and RETRAN's. Fig. 4.12 compares the pressurizer pressure and Tavg among FSAR, RETRAN and TRACE. The pressure curve of TRACE generally follows the trends of FSAR's and RETRAN's. It also can be found that the Tavg of TRACE and RETRAN are almost the same.

4.2.5 Complete Loss of Flow-Under Voltage (CLOF-UV)

Table 4.6 shows the CLOF-UV sequences of FSAR, RETRAN and TRACE. It can be seen that these three sequences are roughly the same. In the verification of CLOF-UV cases, Fig. 4.13 shows the powers and core flows of FSAR, RETRAN and TRACE. In this figure, the TRACE curve is nearly similar to FSAR's and RETRAN's. It also reveals that the core flow curve of TRACE approximately follows the trends of FSAR's and RETRAN's. Fig. 4.14 shows the pressurizer pressures and Tavg of FSAR, RETRAN and TRACE. The pressure curve of TRACE generally follows the trends of FSAR's and RETRAN's but shows a difference from RETRAN's curve after 5 sec. It also displays that the Tavg of TRACE and RETRAN are almost the same.

4.2.6 Complete Loss of Flow-Under Frequency (CLOF-UF)

Table 4.7 shows the CLOF-UF sequences of FSAR, RETRAN and TRACE. It can be shown that these three sequences are approximately the same. In the verification of CLOF-UF cases, Fig. 4.15 plots the power curves of FSAR, RETRAN02 and TRACE, and the TRACE curve is nearly similar to FSAR's and RETRAN's. Fig. 4.15 also shows the core flows of FSAR, RETRAN and TRACE. It can be observed that the core flow curve of TRACE approximately follows the trends of FSAR's and RETRAN's. Fig. 4.16 plots the pressurizer pressures of FSAR, RETRAN and

TRACE. The pressure curve of TRACE generally follows the trends to FSAR's and RETRAN's but shows bigger differences from FSAR's and RETRAN's after 5 sec. It also reveals the Tavg of TRACE and RETRAN. It can be found that the temperatures of TRACE are almost the same a RETRAN's.

In summary, after the comparisons of all the LOF events shown in above figures including all cases of PLOF, CLOF-UV and CLOF-UF, the variation trend of each important thermal parameter calculated by the TRACE model of Maanshan NPP could conform to the results of FSAR and RETRAN. However, it shows that there is a larger difference in the pressurize pressure. We suspect that the differences of the results among FSAR, RETRAN and TRACE are caused by the difference of the calculation procedure or modeling of FSAR, RETRAN and TRACE. Furthermore, the animation of this model is presented using the animation function of SNAP/TRACE interface with above models and analysis results. The animation model of Maanshan NPP is shown in Fig. 4.17.

Table 4.2 The large load reduction sequences in TRACE model and Maanshan NPP

Large load reduction (PAT49)*	Plant data Time(sec)	TRACE Time(sec)
Initial load reduction to 50%	10.0	10.0
T/B bypass valves fully open	20.0	19.2
T/B atmospheric valves fully open	38.0	28.9

***On steady status at first 10sec**

Table 4.3 The net load trip sequences in TRACE model and Maanshan NPP

Net load trip (PAT51)*	Plant data Time(sec)	TRACE Time(sec)
Initial load rejection	10.0	10.0
T/B bypass valves fully open	14.0	11.8
PZR spray valves fully open	17.8	16.1
T/B atmospheric valves fully open	18.0	18.2

***On steady status at first 10sec**

Table 4.4 The turbine trip sequences of TRACE model and Maanshan NPP

Turbine trip (PAT50)*	Plant data Time(sec)	TRACE Time(sec)
Manual T/B trip	10.0	10.0
T/B stop valve full closure	10.1	10.1
Reactor trip	10.1	10.1
T/B bypass valves fully open	12.0	10.7
Feedwater pump trip	28.5	29.0

***On steady status at first 10sec**

Table 4.5 The sequences of PLOF in FSAR, RETRAN and TRACE

	FSAR time (sec)	RETRAN time (sec)	TRACE time (sec)
One RCPs coastdown begins	0	0	0
Low flow scram setpoint reached	1.4	1.47	1.68
Rods begin to drop (scram)	2.4	2.47	2.68

Table 4.6 The sequences of CLOF-UV in FSAR, RETRAN and TRACE

	FSAR time (sec)	RETRAN time (sec)	TRACE time (sec)
All RCPs coastdown begins	0	0	0
Undervoltage scram signal	0	0	0.13
Rods begin to drop(scram)	1.5	1.5	1.63

Table 4.7 The sequences of CLOF-UF in FSAR, RETRAN and TRACE

	FSAR time (sec)	RETRAN time (sec)	TRACE time (sec)
All RCPs coastdown begins	0	0	0
Undervoltage scram signal	0.6	0.6	0.65
Rods begin to drop (scram)	1.2	1.2	1.25

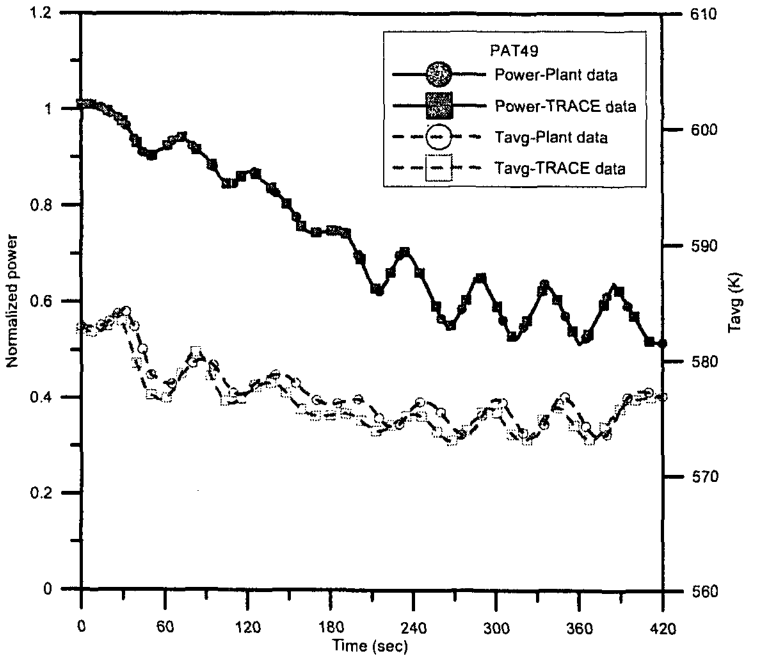


Fig. 4.2 The comparisons of power and Tavg between TRACE model and Maanshan NPP (PAT49)

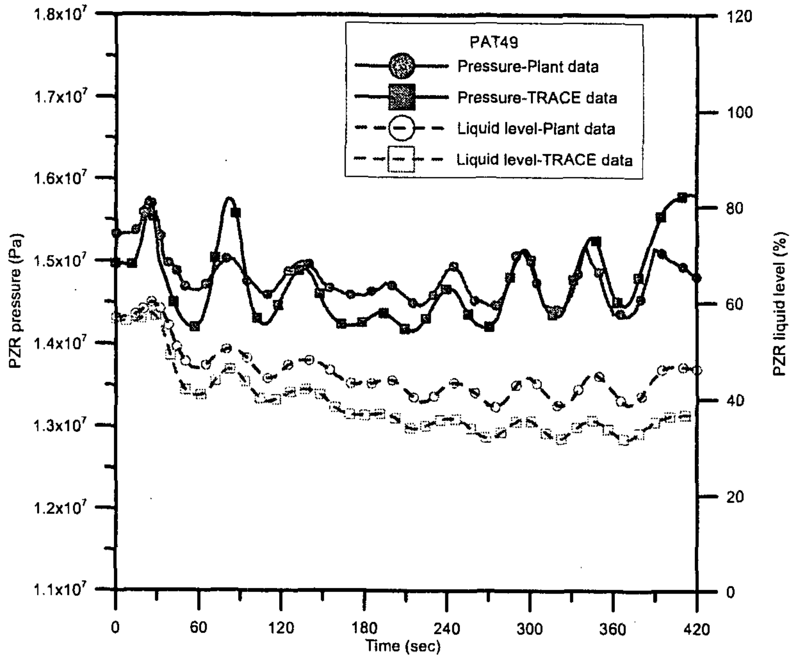


Fig. 4.3 The comparisons of the PZR's water level and pressure between TRACE model and Maanshan NPP (PAT49)

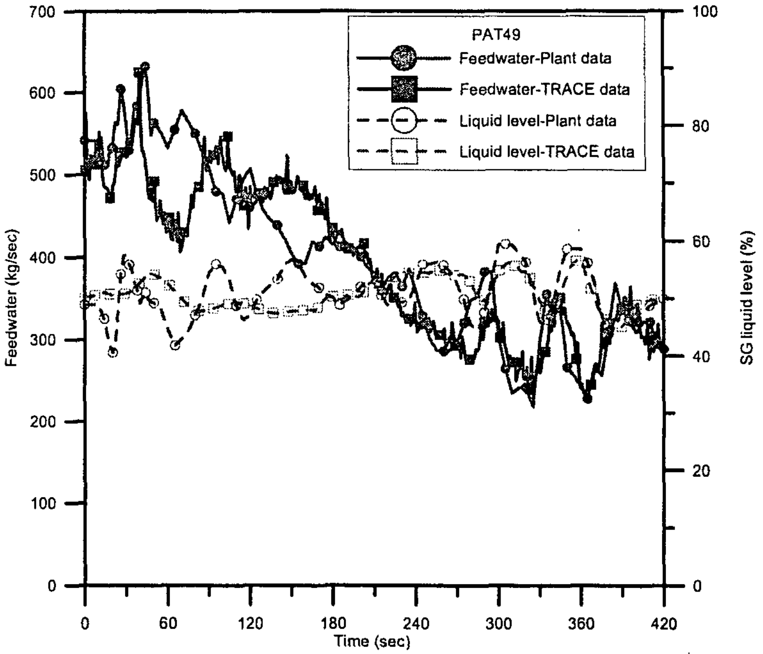


Fig. 4.4 The comparisons of the SG's feedwater flow and water level between TRACE model and Maanshan NPP (PAT49)

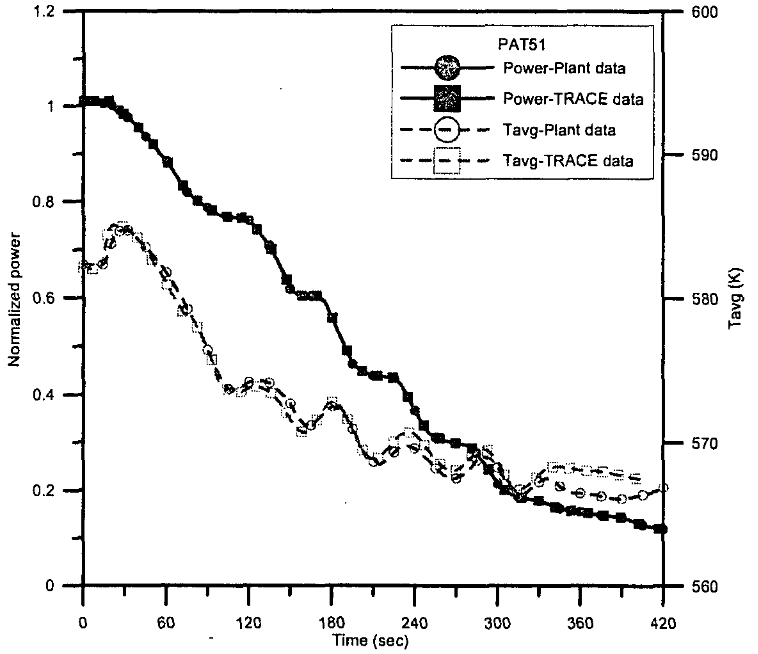


Fig. 4.5 The comparisons of power and Tavg between TRACE model and Maanshan NPP (PAT51)

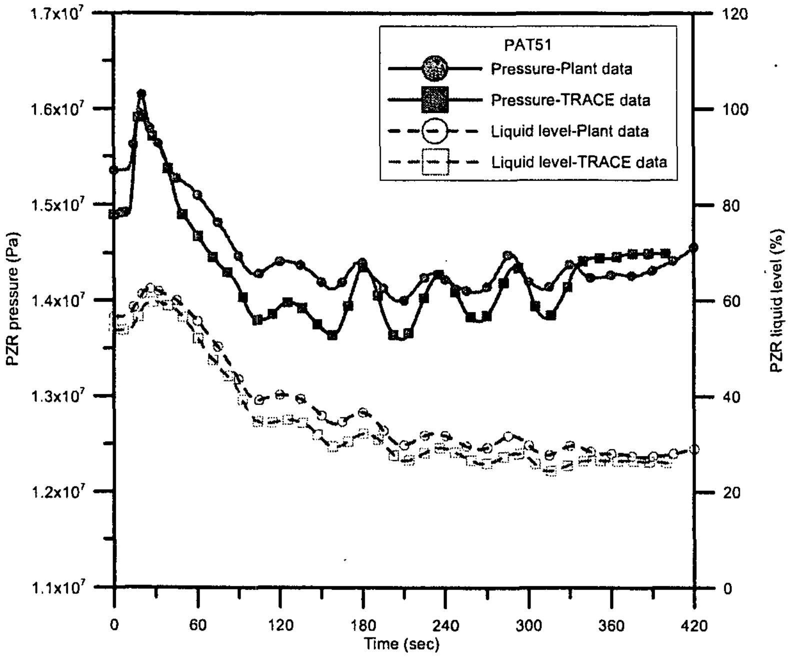


Fig. 4.6 The comparisons of the PZR's water level and pressure between TRACE model and Maanshan NPP (PAT51)

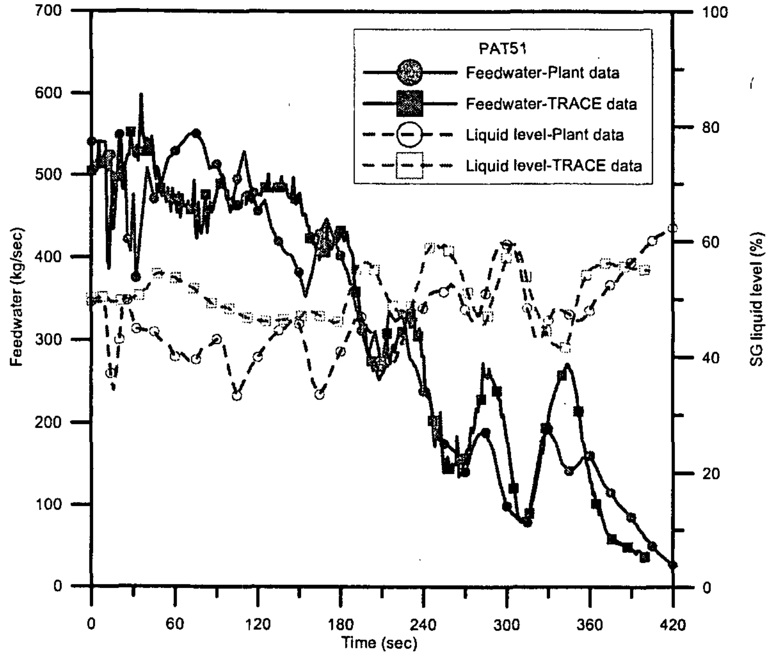


Fig. 4.7 The comparisons of the SG's feedwater flow and water level between TRACE model and Maanshan NPP (PAT51)

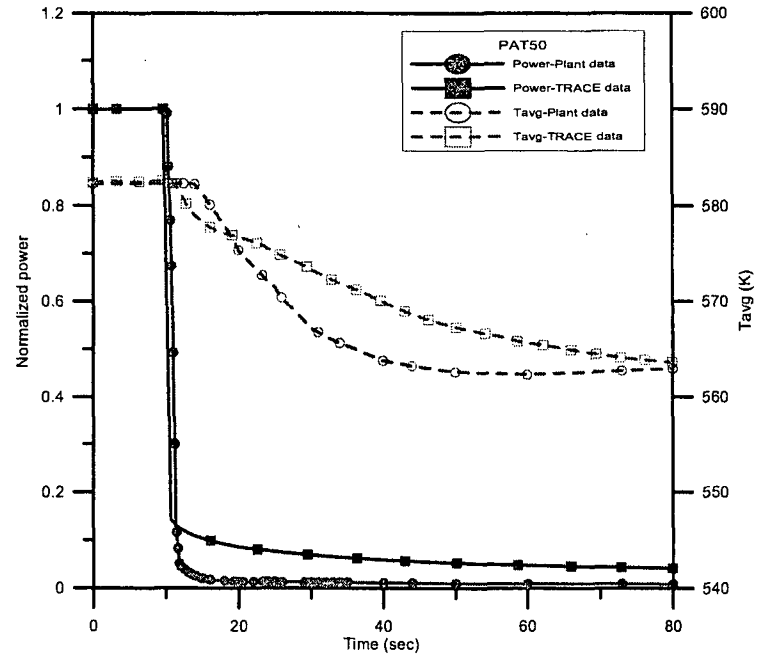


Fig. 4.8 The comparisons of power and Tavg between TRACE model and Maanshan NPP (PAT50)

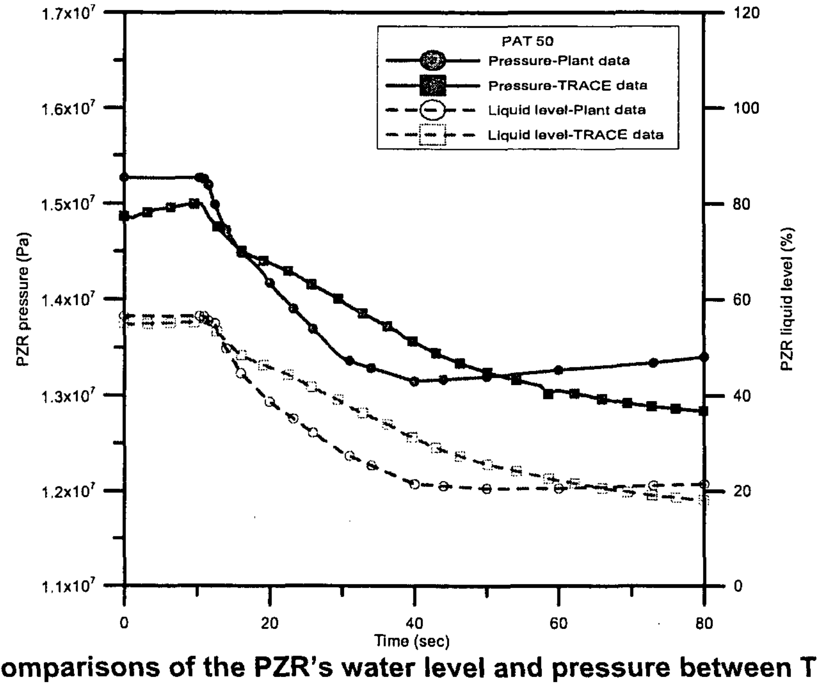


Fig. 4.9 The comparisons of the PZR's water level and pressure between TRACE model and Maanshan NPP (PAT50)

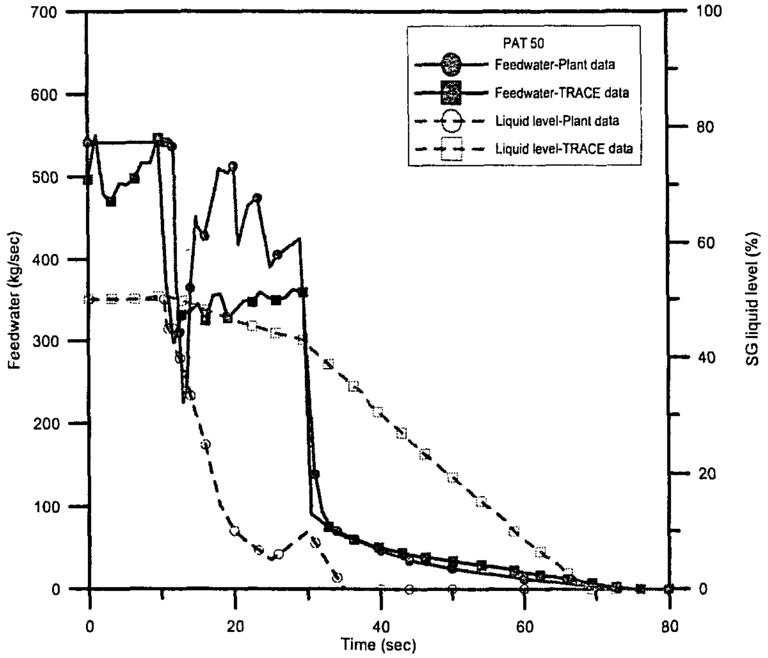


Fig. 4.10 The comparisons of the SG's feedwater flow and water level between TRACE model and Maanshan NPP (PAT50)

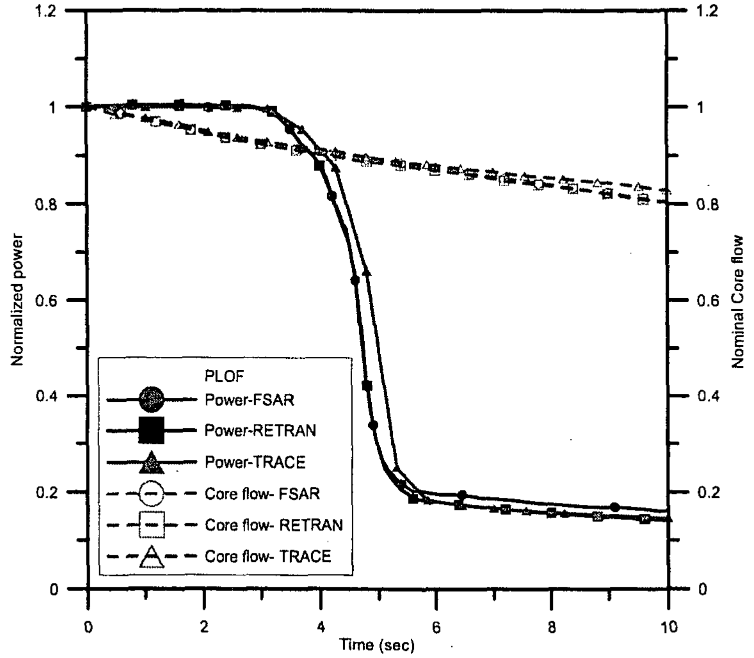


Fig. 4.11 Comparisons of the power and core flow of PLOF among FSAR, RETRAN and TRACE

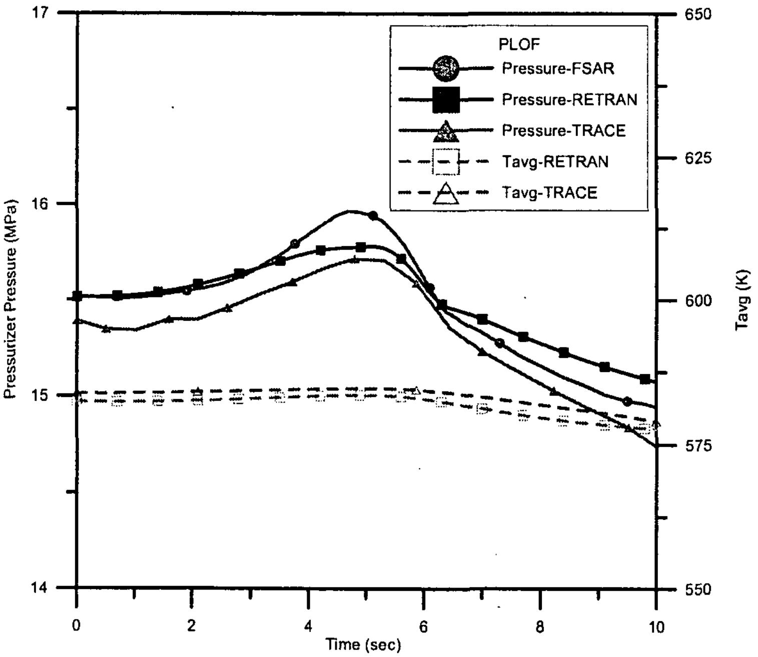


Fig. 4.12 Comparisons of the pressurizer pressure and Tavg of PLOF among FSAR, RETRAN and TRACE

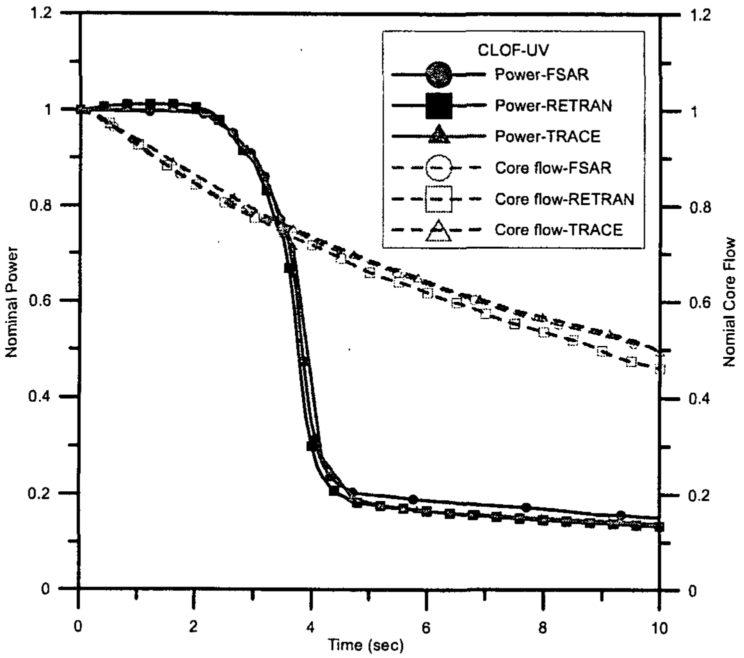


Fig. 4.13 Comparisons of the power and core flow of CLOF-UV among FSAR, RETRAN and TRACE

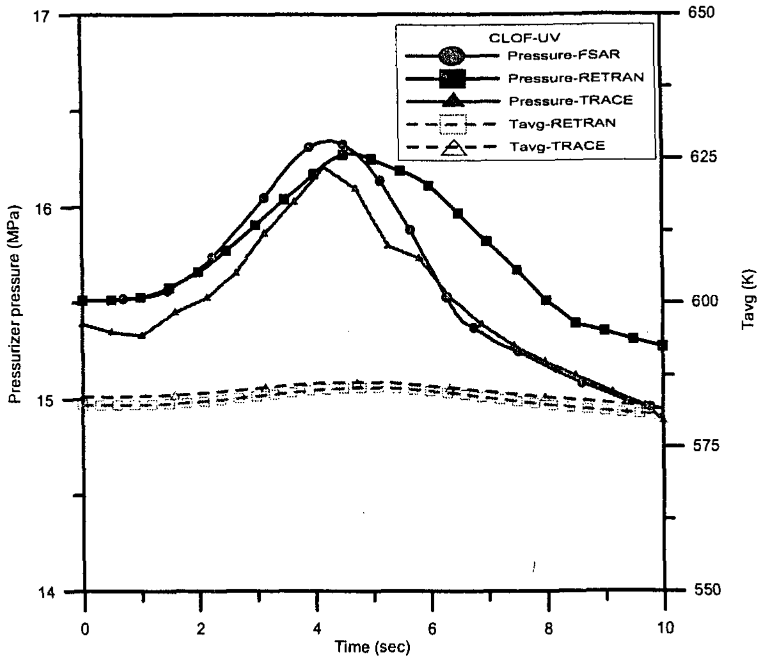


Fig. 4.14 Comparisons of the pressurizer pressure and Tavg of CLOF-UV among FSAR, RETRAN and TRACE

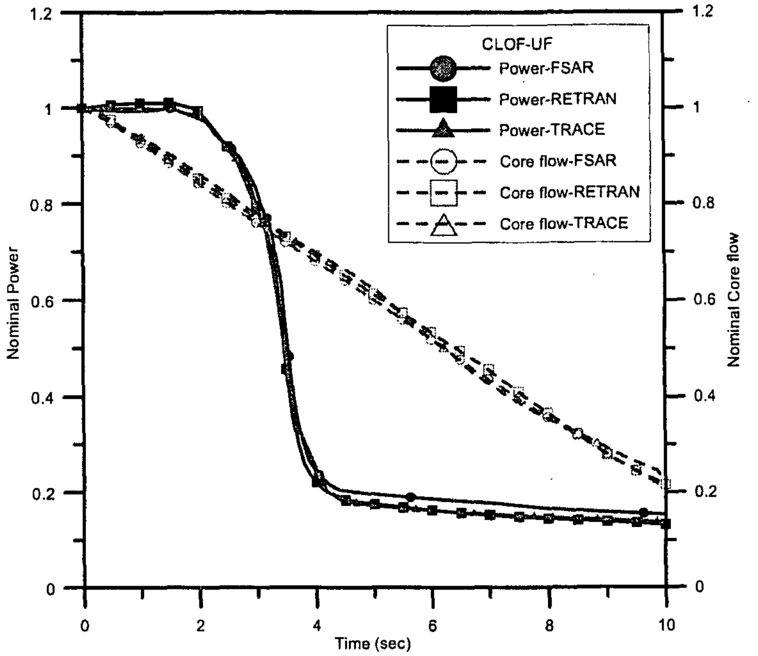


Fig. 4.15 Comparisons of the power and core flow of CLOF-UF among FSAR, RETRAN and TRACE

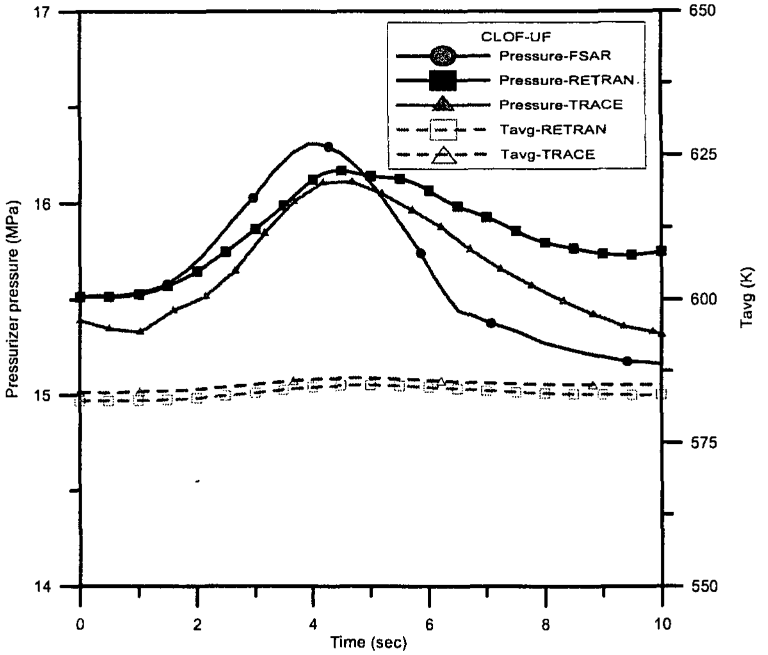
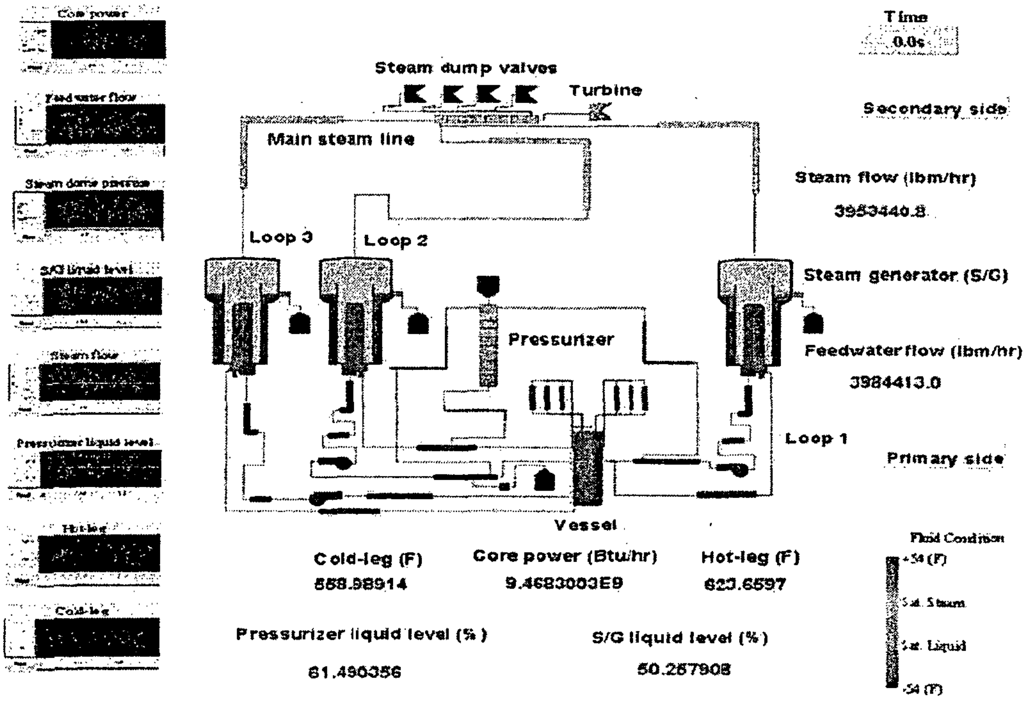


Fig. 4.16 Comparisons of the pressurizer pressure and Tavg of CLOF-UF among FSAR, RETRAN and TRACE



Time
0.0s

Steam flow (lbm/hr)
3953440.8

Feedwater flow (lbm/hr)
3984413.0

Cold-leg (F)
558.98914

Core power (Btu/hr)
9.4683003E9

Hot-leg (F)
623.6597

Pressurizer liquid level (%)
61.490356

S/G liquid level (%)
50.267908

Fig. 4.17 Animation of Maanshan NPP model

5. CONCLUSIONS

By using SNAP/TRACE, this study developed a TRACE model of the Maanshan NPP. Effectiveness of the proposed model was verified with the large-load reduction at 100% power (PAT49), the net-load trip at 100% power (PAT51), the turbine trip test at 100% power (PAT50), Partial Loss of Flow (PLOF), Complete Loss of Flow-Under Voltage (CLOF-UV), and Complete Loss of Flow-Under Frequency (CLOF-UF) in Maanshan startup tests and FSAR data. Analytical results indicate that the Maanshan NPP TRACE model predicts not only the behaviors of important plant parameters in consistent trends with the startup tests and FSAR data, but also their numerical values with respectable accuracy. The TRACE model of Maanshan NPP can be used in future safety analysis with confidence, such as the applications for power uprating, life extensions, and design modifications.

6. REFERENCES

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11. ABSTRACT *(200 words or less)*

This study consists of two steps. The first step is the establishment of TRACE (TRAC/RELAP Advanced Computational Engine) models for important components, such as pressurizers, steam generators, the feedwater control system, the steam dump control system, and so on, in Maanshan Nuclear Power Plant (NPP) using SNAP（Symbolic Nuclear Analysis Program)/TRACE. These component models were tested and compared with Maanshan startup test data to verify their accuracy. Key parameters were identified to refine the models further. The next step is the incorporation of the above component models into the Maanshan NPP TRACE model. TRACE transient analyses of scenarios such as load reduction and turbine trip were performed and their results were compared with the corresponding plant data from Maanshan startup tests. The TRACE model of Maanshan NPP is also used to analyze Loss of Flow transient as defined in FSAR Chapter 15 which includes Partial Loss of Flow (PLOF), Complete Loss of Flow-Under Voltage (CLOF-UV), and Complete Loss of Flow-Under Frequency (CLOF-UF). Analysis results indicate that the Maanshan NPP TRACE model predicts not only the behaviors of important plant parameters consistent with the plant data, but also their associated numerical values with respectable accuracy.

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