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A BWR POWER PLANT SIMULATOR FOR BARSEBÄCK

P. la Cour Christensen and A.M. Hvidtfeldt Larsen

Abstract. A computer simulator of a Barsebäck power plant unit has been developed in cooperation between Sydkraft AB, Lund Institute of Technology, and Risø National Laboratory. The simulator is of the kind often referred to as a compact simulator, because it involves only a computer with display screens and other input/output devices plus the software needed for calculation and presentation of the plant state as a function of time, and no sort of model of the control room as in large reactor simulators for operator training. The purpose of training courses with the compact simulator is to give students a better understanding of the behaviour of the power plant under transient conditions by displaying variables, e.g. pressures, temperatures, reactivity, nuclear power, as functions of time, thereby showing the interactions between different parts of the plant during the transient and the influence of a number of possible operator actions.

(Continued on next page)

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The present paper describes the Barsebäck compact simulator with the emphasis on the software developed at Risø National Laboratory. The Risø work comprises the programming of the dynamic plant model, in the form of a number of Fortran subroutines containing the physical description of the power plant.

INIS-descriptors: BWR TYPE REACTORS; COMPUTERIZED SIMULATION; TRANSIENTS.

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CONTENTS

Page

1. INTRODUCTION

A simulator for a Barsebäck power plant unit has been developed in a cooperation between the Power Company Sydkraft AB, the Department of Automatic Control at Lund Institute of Technology, and the Department of Energy Technology at Risø National Laboratory. The first phase of the work was completed and the simulator taken into use late in 1984.

The simulator has a structure quite different from the well-known large simulators including a control room model with instrumentation and control desk which are used for the education of reactor operators. The Barsebäck simulator is a so-called compact simulator implemented on a general purpose computer equipped with four multicolour display terminals. It is used to calculate specific transients and store the results on disk files. Later on selected variables can be shown and studied on the display screens. The calculations cannot normally be performed in real time as the processor is too slow for the simulator system size.

The simulator is used for training of operators and engineers at Barsebäck with the emphasis on providing a better understanding of the dynamics of the physical processes in the whole plant as well as in separate units.

2. SIMULATOR STRUCTURE

2.1. Hardware

The simulator is implemented on a VAX 750 computer with a floating point processor, 2 Mbytes of core memory and a hard disk with 200 Mbytes of storage. A magnetic tape station is used for loading of programs and a lineprinter is available for printed output. These units are placed in the computer room which is situated between the control rooms of the two Barsebäck units. Four multicolour display terminals and an operators console are placed in the adjoining room used for education courses. In here is also a plotter that may be used to make hard copies of the graphs being studied at the screens.

2.2. Software

The entire simulation and display process is based upon the SIMNON system (Ref. 1) from Lund Institute of Technology. SIMNON utilizes the general interactive language for VAX computers, called INTRAC, which makes it possible to store sequences of instructions in so-called MACROs. Thus it is possible to set up model parameters and SIMNON commands for specific transients in a MACRO which can be activated by a single command.

SIMNON takes care of all administration of the simulation process: System definition with separation in modules, input/output connections for the modules, definition of variables, integration of differential equations, storage of variables for display and allocation of variables for diagrams to be shown at selected screens.

SIMNON has its own simple programming language, but provision is also made for inclusion of Fortran subroutines. This facility is used for the Barsebäck simulator, because SIMNON's own language is insufficient for systems of such complexity as a whole nuclear power plant.

SIMNON has for this particular application been extended with routines for administration of a number of parallel display screens each showing several variables simultaneously in different colours. From the terminal consoles the operator can ask for any diagram of a preprogrammed set belonging to the transient being investigated.

3. MODEL STRUCTURE

The model structure is basically given by the SIMNON language, which is designed to operate with a system divided into independent modules. Each module of the model corresponds to a physical unit. A compromise must be made in connection with the model layout regarding the number and the size of modules.

Small modules are easy to program and test, on the other hand coupling together a large number of modules can become a complicated task. Here only seven modules are used, but with the experience gained during the work a larger number of smaller modules would have been preferred today. The modules are:

* The reactor with recirculation pumps.
* The steam line.
* The turbine with feedwater preheaters.
* The control system for station power.
* - - - - steam line pressure.
* - - - - feedwater supply.
* A limit control routine.

All modules are made as Fortran subroutines communicating with SIMNON via a COMMON field and a coupling routine, one for each module, also written in Fortran. By this procedure it has been possible to use the same subroutines for both SIMNON and for the Risø simulation system DYSIM (Ref. 2); only the coupling routines are written specifically for SIMNON. For use with DYSIM the coupling between modules and the connection to DYSIM are programmed in one single subroutine. Each COMMON field in the subroutines is divided into areas with different types of variables which are:

- State variables
- Derivatives; one for each state variable.
- Input variables.
- Parameters (i.e. input constants).
- Algebraic variables containing two types of SIMNON variables: Output and auxiliary variables.

The coupling routines are written according to conventions given by SIMNON; the main part is specifications for the variables mentioned above: Type, local address and a symbolic name.

SIMNON needs information about the connection of input variables in the form of an extra module called the CONNECTING SYSTEM and written in the SIMNON language. Here every input variable must be linked to either a state or an output variable, or it can be given as a function of time and other variables and parameters. For instance an input can be programmed as a ramp function using the time and two parameters: ramp time and ramp size.

Calculations of transients require two sorts of specifications:

1. The initial conditions for the state variables, normally steady-state values, and corresponding parameters.

2. A system perturbation causing the transient specified by one or more parameters going direct to the modules or used in the connecting system. Note that parameters are constant during a calculation while input variables can be changed.

4. SIMULATOR MODULES

4.1. The reactor with recirculation pumps

The reactor model is programmed in one module which describes the contents of the pressure vessel plus the recirculation loop. For the modelling the reactor has been divided into sections as indicated in Fig. 1. By far the most complicated of these sections is the reactor core which is given a one-dimensional coupled neutron kinetics and thermal-hydraulics description using 12 nodes for the neutron kinetics and 10 for the thermal-hydraulics. In addition to the core the model comprises 10 hydraulic volumes, i.e. two bypass volumes, riser, steam separator, steam dome, top volume around the separator, feedwater mixing volume, downcomer and two lower plenum volumes. The downcomer is connected to lower plenum 1 by four parallel recirculation lines each containing a recirculation pump and represented as a time delay.

Feedwater, both normal and auxiliary, enters the reactor in the mixing volume called feedwater chamber in Fig. 1, between the top annulus and the downcomer. Steam leaves the reactor from the steam dome at the top, normally through the steam line, but in case of blowdown also through the blowdown valves which are assumed to be connected directly to the reactor vessel. If steam line isolation occurs the steam line volume between the steam dome and the isolation valves is included in the steam dome as if the valves were situated between the vessel and the beginning of the steam line, but with a somewhat larger steam dome volume. This is done in order to avoid steam line oscillations requiring extremely small integration steps.

The neutron kinetics is described by the one-dimensional diffusion equation with the prompt-jump approximation. The delayed neutrons are simulated by one single group in order to save computing time.

Variation of Xenon concentration during transients is neglected because of the small change during short term transients (60 - 1000 s); but the equilibrium steady-state distribution for the initial state is calculated along with the other initial values and kept constant for the transients.

The diffusion equation requires three macroscopic neutron physical parameters; the diffusion coefficient D, the absorption cross section Σ_a and the production cross section $\nu\Sigma_f$. These parameters are determined from polynomials in the coolant density, the fuel temperature and the control rod density based upon two-group cross sections calculated by the Risø program system for neutron cross section generation. Iteration for steady state at 100% power with predetermined control rod positions is done by adjustment of a radial buckling term giving a correction factor for $\nu\Sigma_f$.

The neutron flux is converted to power and divided into two parts, a larger one which is released promptly and a smaller one released as a sum of three exponential decay functions giving the power after reactor scram.

The total power is further divided into three parts, a larger one giving the power released inside the fuel pins and two smaller parts released directly in the coolant inside the fuel box and in the bypass water between the boxes.

For the fuel rod radial heat transfer a single node is used in the fuel pellet with a temperature dependent heat transfer coefficient from fuel to cladding. The coefficient is calculated by a steady-state 10-node model in the temperature range 300 - 1200 ^{o}C.

The water and steam flows through the fuel elements are described by the mass and energy balance equations giving the coolant temperature and void fraction as state variables. The slip factor is calculated by the Bryce correlation (Ref. 3), and the water-steam mixture is described in a non-equilibrium state with subcooled water at the bottom and a slightly superheated mixture in the top. The boiling-condensation model as proposed by Malnes (Ref. 4) is used in a modified form with a surface boiling and a bulk boiling term, the last one positive when the temperature is higher than saturation and negative when the temperature is lower than saturation.

The heat transfer is calculated as the sum of two terms: one given by the Dittus-Boelter correlation and the other by the Thom correlation. The first term is used to heat the coolant and the last one to evaporate water by surface boiling. This procedure is similar to the Chen correlation, but much simpler to calculate, and it has the advantage of giving the heat flow in two terms as needed for the boiling model.

Local pressure variation through the core is not taken into account; the pressure derivative needed for the flow, void and temperature equations is taken as the pressure derivative in the riser, thus neglecting transient pressure effects in the core.

The riser is described as a core section without heat supply, but with a cold water inlet flow from the core bypass. The steam separators are assumed to give an ideal separation of steam and water, with a pressure drop giving rise to steam flashing. Here it is further assumed that the water leaves the separators with the saturation temperature giving an energy exchange between steam and water to account for the riser temperature deviation from the saturation point.

All the other water volumes in the circulation loop are described by the energy balance equation giving the water temperature. The thermal expansion of water gives an integral volume expansion calculated from the individual temperature derivatives. The mass balance equation for the steam dome gives the steam pressure, and an integral volume balance equation for the pressure vessel gives the water level.

The recirculation is described with four individual loops containing recirculation pumps which can be operated independently. The flow in each loop is calculated by the momentum equation from pressure vessel outlet to inlet. The vessel inlet-outlet pressure is calculated by friction correlations for the individual flow volumes corrected by a term for the dynamic pressure drop due to flow variations.

4.2. The steam line

The steam line with a total length of 120 m is divided into six sections described by mass and momentum balance equations giving the flow and pressure as state variables. Six sections were found to be sufficient to reproduce the main characteristics of steam line behaviour. The outlet enthalpy is assumed to be equal to the inlet enthalpy as the pressure dependence is small. Isolation valves are placed between sections 2 and 3.

Closure of up to three of the four steam valves is described by reducing the steam line flow area correspondingly. In case of total steam line isolation the steam line calculation is omitted and the steam dome volume increased to include the first part of the steam line for numerical reasons, as mentioned earlier.

4.3. The turbine with feedwater preheaters

A flow diagram of the complete system is shown in Fig. 2. It consists of two main parts: The turbine and the feedwater preheaters.

4.3.1. The turbine with condenser

The turbine system has two different units, a high pressure (HP) section and a low pressure (LP) section, with a moisture separator and reheater in between. Control valves and fast acting stop valves are placed in front of the HP- and LP-sections and in the high pressure line to the reheater. A bypass line with a control valve can be used to pass the steam directly to the condenser. All steam valves are under control of the steam pressure controller.

The steam pressure is calculated at five points with concentrated volumes: at the HP- and LP-turbine inlets, in the reheater, in the bypass line after the control valve, and on the high pressure side of the reheater tubes.

The Mollier diagram in functional form is used to calculate the enthalpy drop in the turbine sections, assuming known thermal efficiencies, giving the turbine power. In the moisture separator a perfect separation is assumed followed by reheating with steam condensation on the hot side of the tubes. The dynamics is described in the same way as for the steam coolers mentioned below. Steam flows through valves and turbine sections are calculated according to the usual equations giving either critical or subcritical flow depending on the pressure ratio across the unit.

The condenser receives steam from the LP-turbine and sometimes from the bypass line. Drainage from the preheaters and the reheater will for special conditions also go to the condenser. An energy balance equation is used to calculate the tube surface temperature which is assumed to be equal to the steam temperature giving the steam pressure as the saturation pressure. The cooling conditions are given by the coolant flow and inlet temperature; the coolant outlet temperature is calculated by an energy balance equation.

4.3.2. The feedwater preheaters

The preheater system actually has two parallel trains, but only one is simulated in order to save computing time. Five heater stages are used: FV1-FV3 between condensate pumps and feedwater pumps, and FV4-FV5 after the feedwater pumps. Stages FV2-FV5 consist each of a steam cooler, a drainage collecting tank and a drain cooler; stage FV1 has no drain cooler. The preheaters are connected in cascade as shown in Fig. 2 with the drainage flowing from FV5 to FV1, where it is pumped into the feedwater line between FV1 and FV2. The moisture separator and the reheater can be regarded as extra stages as far as drainage is concerned.

The preheaters are divided into three groups: FV1, FV2-FV3 and FV4-FV5. Simulation of full and half bypass of each group is possible; half bypass is an approximate simulation of a double train system with bypass in one train only. With full bypass the preheater modules are used to simulate the cooldown of the preheaters. With half bypass the same modules are used to simulate the active train, while the units in the train with bypass are omitted from the simulation and the steam and drain flows here are assumed to drop to zero instantaneously.

Part of the drainage from a feedwater group is transferred to the condenser when the receiving group is in a bypass condition; the fraction depends of the detailed bypass situation for both the group in question and the receiving group. The actual situation with two trains is simulated as closely as possible with a one-train model.

The dynamics of both steam coolers and drain coolers is simulated by point models with concentrated heat capacities for the tube walls and the water volumes. The heat flow from the hot side to the tubes and further to the cold side is calculated by mean temperatures for the water flows. The weighting factor is determined by steady-state integration of the space dependent differential equations for an idealized configuration. The weighting factor appears to be dependent of the ratio between the heat transfer capacity of the tube wall and the heat transport capacity of the water flow (or flows for the drain cooler).

The tubes connecting the preheaters are simulated as pure time delay functions as far as propagation of temperature variations is concerned. The tube wall heat capacity is neglected. The time delay calculation assumes constant water velocity across the flow area. This approximation with pure time delays between preheaters and complete mixing inside them (a consequence of point models) is supposed to give a reasonable model of the real system with the smallest number of state variables.

The water levels in the drain tanks are controlled by PI-controllers with control valves. The real configuration with two valves, one working as the normal control valve and another one working as an emergency valve that opens for high controller outputs is not simulated; only one control valve is used, followed by a pair of valves working in opposite phases and controlled by the bypass logics as explained above.

4.4. The control system for station power

The reactor recirculation pumps are used to control the station power by variation of the RC-pump speed and thereby the coolant flow and void volume in the reactor core. The control system with a PI-controller, signal limitation and pump rundown control is implemented in one small module.

The pump speed can be controlled by either the power controller or a speed setpoint signal. For turbine trip, reactor scram or pump rundown the pump speed is reduced to 20% by a step followed by a ramp function.

The output signal from the control system is used as setpoint for the pump speed servo, here simulated as a second order system.

4.5. The control system for steam line pressure

The main pressure control system consists of three parts: An electronic controller, a hydraulic system with limitation and signal distribution functions, and the steam valve servo drives. The electronic controller has three independent channels, a coarse, a fine and a spare controller similar in design, but with some differences in the pressure transducer, the setpoint, the gain and the signal limitation. Each controller has a PI-unit followed by a dynamic correction circuit of second order. Switching circuit for the selection of the appropriate controller is included.

The hydraulic system has a channel that controls the turbine speed in case of loss of load. In case of turbine trip the same channel is used to shift the steam flow from the turbine to the dump line.

Four steam valves are controlled by the pressure controller: The HP-turbine valve being the main valve, the LP-turbine valve and the reheater high pressure steam valve both fully open at normal power operation, and finally the dump valve which is normally closed.

The module also includes simulation of the blowdown system with four sets of valves. The system is activated by an input signal. Three of the valve groups are switched on at three different power levels and off again individually when the steam pressure decreases below their three respective setpoints. The fourth valve group is controlled by a simple pressure PI-controller.

4.6. The control system for the feedwater supply

The feedwater module contains three control systems: The main flow controller, the auxiliary flow controller, and the main feedwater pump pressure controller. Also feedwater flows, pressure setup in pumps and pressure drops in valves and preheaters are calculated here.

The main feedwater flow path from the condenser through the preheaters can be followed in Fig. 2. The main flow controller creates a pump speed setpoint as a sum of three signals: A water level deviation signal going through a PI-controller, a static signal from the steam pressure and a dynamic signal from the difference between steam and feedwater flow. The setpoint passes a limiter with variable upper limit before it goes to the pump speed servo simulated as a second order system.

The main flow calculation involves calculation of six pressure drops in valves and preheaters, pressure setup in three pumps, determination of flow distribution between the condensate pumps (CP in Fig. 2) and the drain pumps (DP in Fig. 2), and finally setting up the momentum balance equation for the feedwater line from the condenser to the reactor. Pump pressure setup is calculated by second order polynomials in flow and pump speed.

The outlet pressure from the feedwater pumps is regulated at low flow rates by a P-controller and a control valve in the feedwater line in order to keep the pump speed within the permissible range. A bypass valve will be closed when the flow decreases below a certain value in order to put the pressure control valve into operation.

The feedwater flow can be blocked by a pair of isolation valves which are normally open, but can be closed individually by an input variable for the module.

The auxiliary feedwater system has a single line from the condenser to the reactor through two pairs of pumps, two valves in parallel, one control valve and one bypass valve, and finally through one isolation valve.

The auxiliary feedwater controller has only one channel with the water level as input. The signal passes a dynamic correction circuit before it is compared with the level setpoint. The error signal goes through a PI-controller, the output of which is used as setpoint for a control loop with the flow as the controlled variable and the control valve as the controlling device. The bypass valve is opened to permit the maximum water supply at very low water levels. The system is in operation all the time, but the isolation valve is normally closed until an input variable starts the valve opening. At that time the bypass valve will normally be closed and the control valve open, dependent of the water level history.

4.7. Limit control routine

This module is quite different from the other six, as it has no state variables. It is used for checking a number of key variables such as reactor power, coolant flow, water level and steam pressure against limits and initiation of automatic actions such as reactor scram, turbine trip and RC-pump rundown. Also manual activation of these actions is possible through input variables, and it is possible to prevent the actions by parameters.

4.8. Other modules

After the installation of the simulator at Barsebäck, Sydkraft staff have modified some of the routines and added some extra ones. The main modifications are:

- Introduction of modules for the generator and the voltage control system, giving the load for the turbine.
- Introduction of a small module with filters for the nuclear power and the reactor coolant flow as used for limit control.
- A relatively large extension of the limit control routine with the use of some extra outputs.
- Storage of axial distributions of variables in the reactor core at time zero and at the end of the transient.
- A routine used for displaying axial values as profiles before and after the transient.
- A similar routine used to display transients in a power-flow diagram for the reactor.
- Introduction of several extra input and auxiliary variables and renaming of SIMNON-variables to obtain a better correspondence with the names used by the operating personnel.

5. CALCULATION EXAMPLE, LOSS OF LOAD TRANSIENT

In Figs. 3-12 the results of a transient calculation with the Barsebäck model and the Risø integration system DYSIM are shown. The transient which is simulated is loss of offsite electric load at time zero. The variation of some selected variables during the first 60 s. is shown.

The Risø model has no calculation for the generator. Instead the turbine speed of rotation is calculated by the torque balance equation assuming an internal load of 5% of normal power. The speed is shown in Fig. 3. It increases at first by 9%, then stabilizes at the value 6.7% above normal. The variation of the turbine power is shown in Fig. 4. The power drops rapidly down to zero, and is then increased to the 30 MW needed for the on-site consumption.

One of the four main recirculation pumps is stopped at once when loss of load occurs. The remaining three pumps are run down to minimum speed. The resulting reduction of the reactor recirculation flow is shown in Fig. 5. The immediate result hereof is a void increase in the core as demonstrated in Fig. 6 with a corresponding drop of the nuclear power because of the negative reactivity feedback from the void. Fig. 7 shows the variation of the water level in the pressure vessel with the upsurge caused by the core void formation.

The reactivity variation during the transient is shown in Fig. 8. After the initial oscillations the reactivity stabilizes just below zero. The thermal power of the reactor also oscillates at the beginning and then shows a steady decrease as can be seen from Fig. 9.

In Fig. 10 the pressure in the reactor vessel is shown. At first a pressure increase is seen to about 72.5 bar. As a result hereof part of the core void is collapsed and this again results in a reactivity insertion (Fig. 8) with a corresponding increase in the power (Fig. 9). After some time the pressure goes back to normal, 70 bar. Finally Figs. 11 and 12 show the steam flows to the high-pressure turbine and to the condenser via the bypass line. It is seen that the HP-turbine valve is closed at first and opened later on to allow steam flow to the turbine for the lower in-house power. The rest of the steam production is dumped to the condenser.

6. CONCLUSION

A BWR compact simulator has been developed, primarily for the training of control room staff at Barsebäck. The contribution from Risø is the dynamic plant model described in this paper. The simulator in its present form is able to analyse a range of transients starting from full or nearly full power. A planned extension is a model for low power conditions to handle for instance transients occuring during the startup phase of the reactor.

The reactor model was programmed and tested at Risø with the DYSIM integration system. The transfer of the model to the SIMNON system on the Barsebäck VAX computer has been successfully accomplished with only trivial problems. Also, it has been possible for Barsebäck staff after the model was transferred to make modifications and additions with the aid of the documentation from Risø.

In the present paper the results are shown of a transient calculation performed with DYSIM at Risø. The results are shown as diagrams each containing a single variable. In the completed simulator at Barsebäck with the SIMNON system results can be displayed simultaneously on four colour screens, and with several variables of different colours per diagram. This greatly improves the possibilities for comparing the variables and at the same time gives the system a very attractive appearance.

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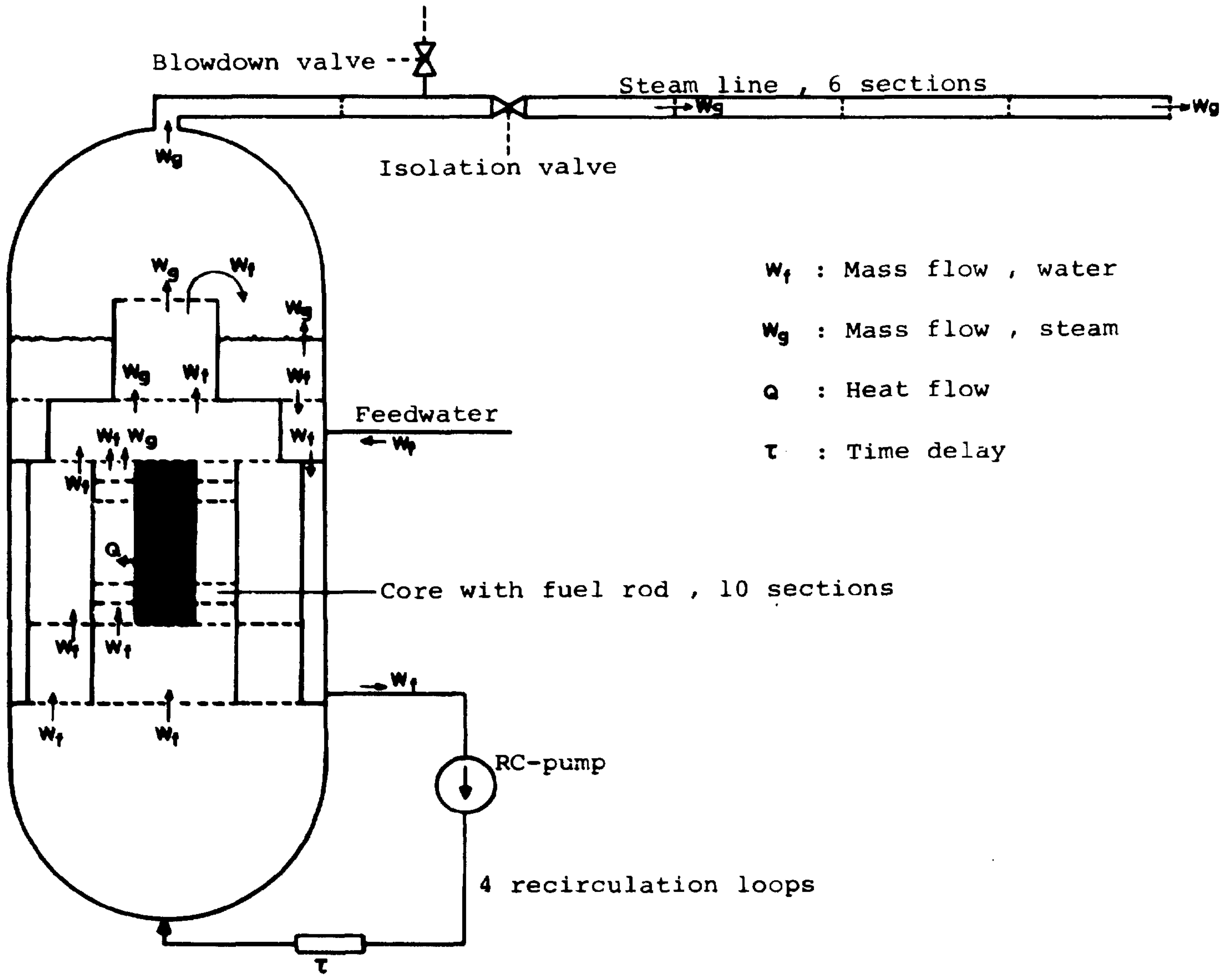

Fig. 1. Reactor and steam line.

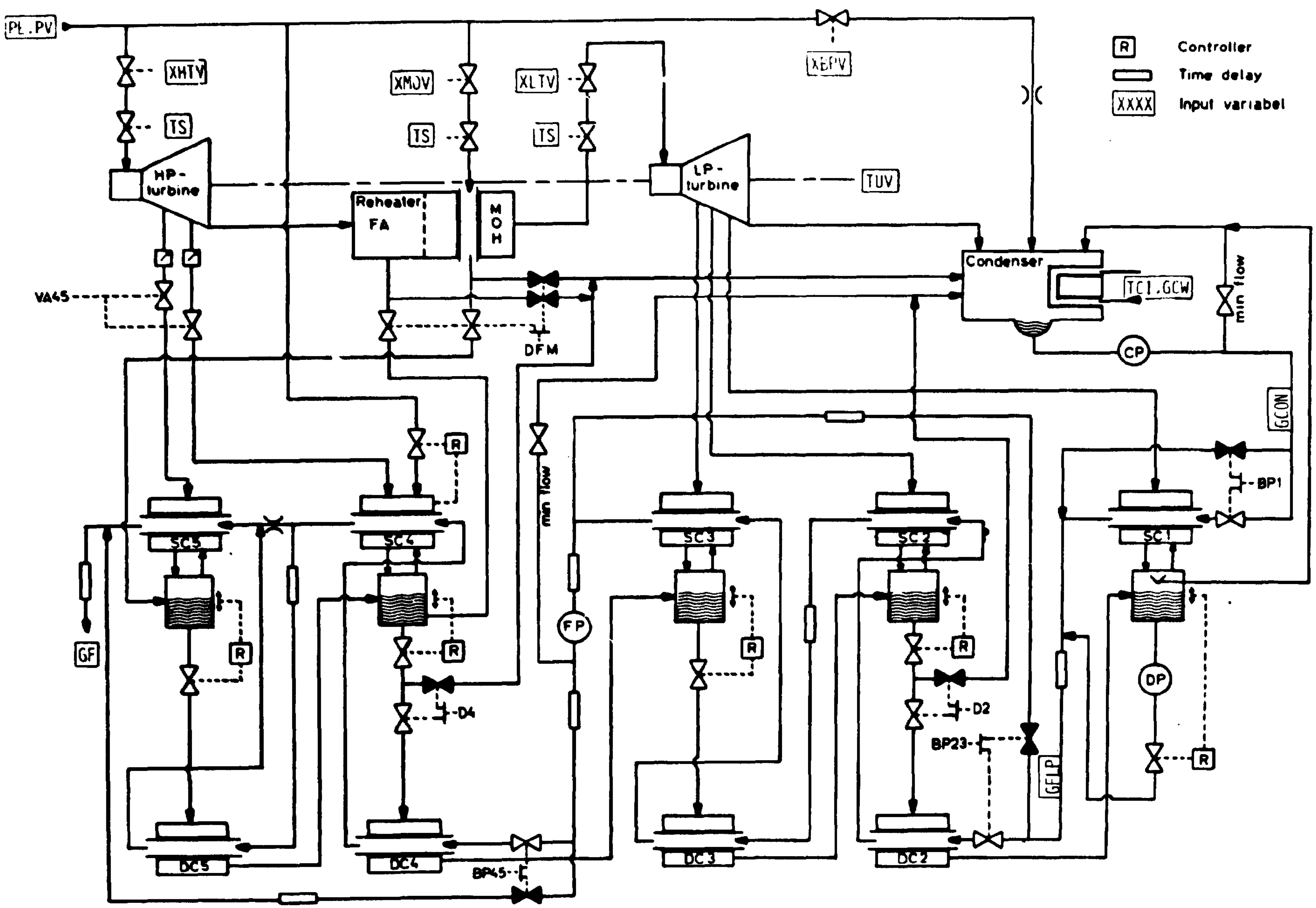

Fig. 2. Flow diagram for the turbine and feedwater heaters.

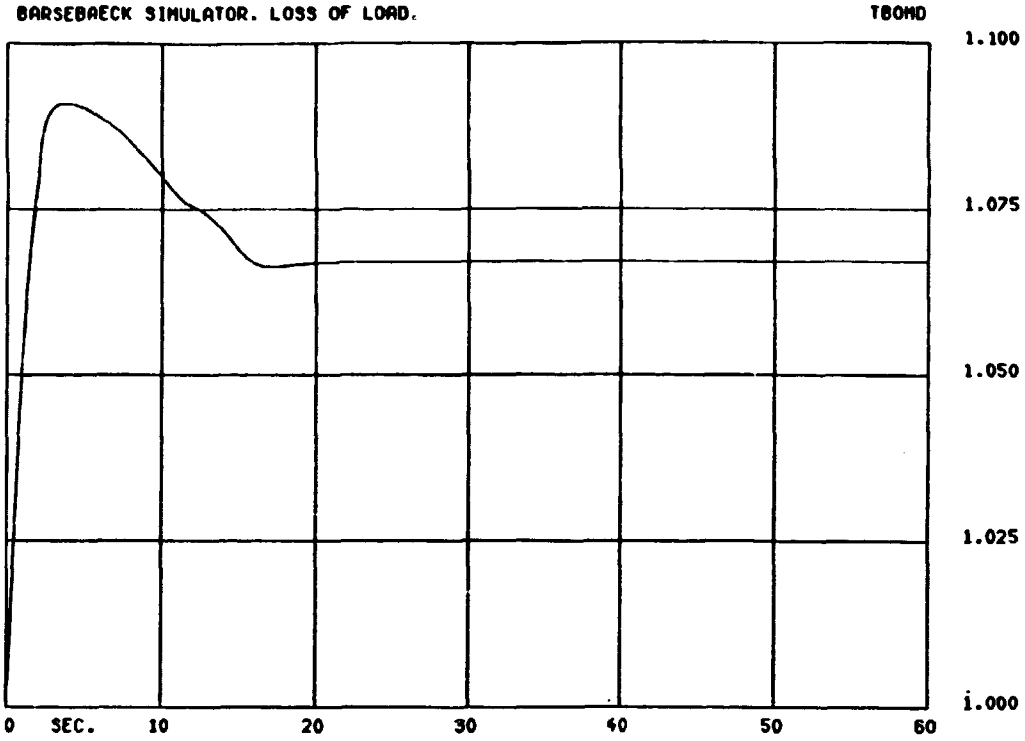

Fig. 3. Turbine relative number of revolutions.

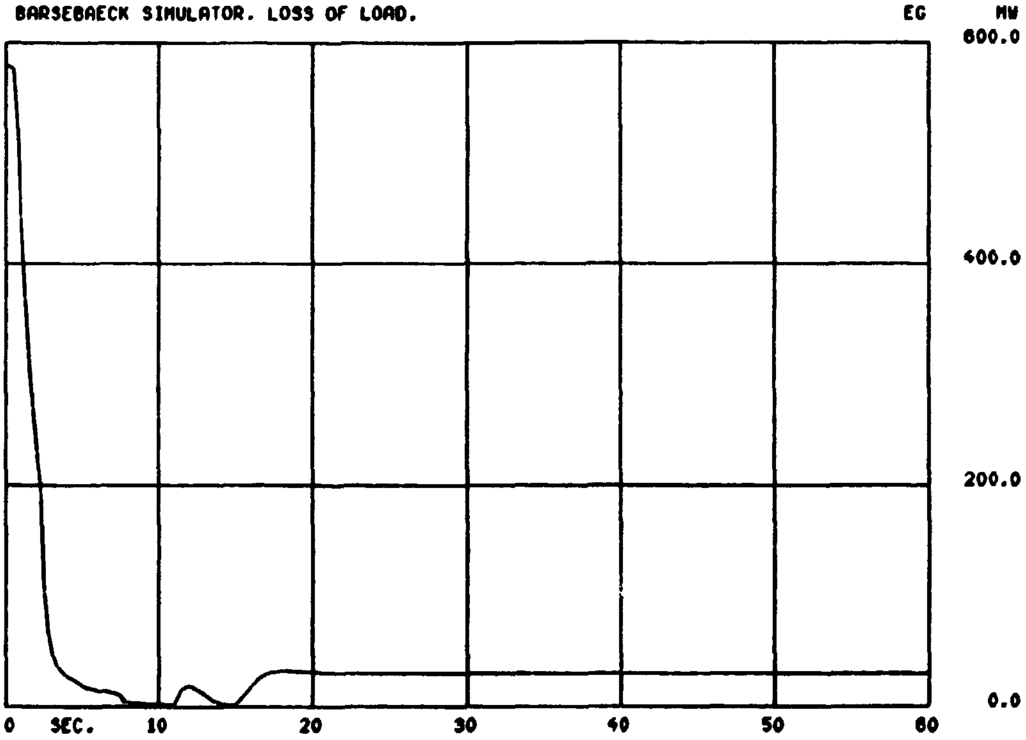

Fig. 4. Turbine power.

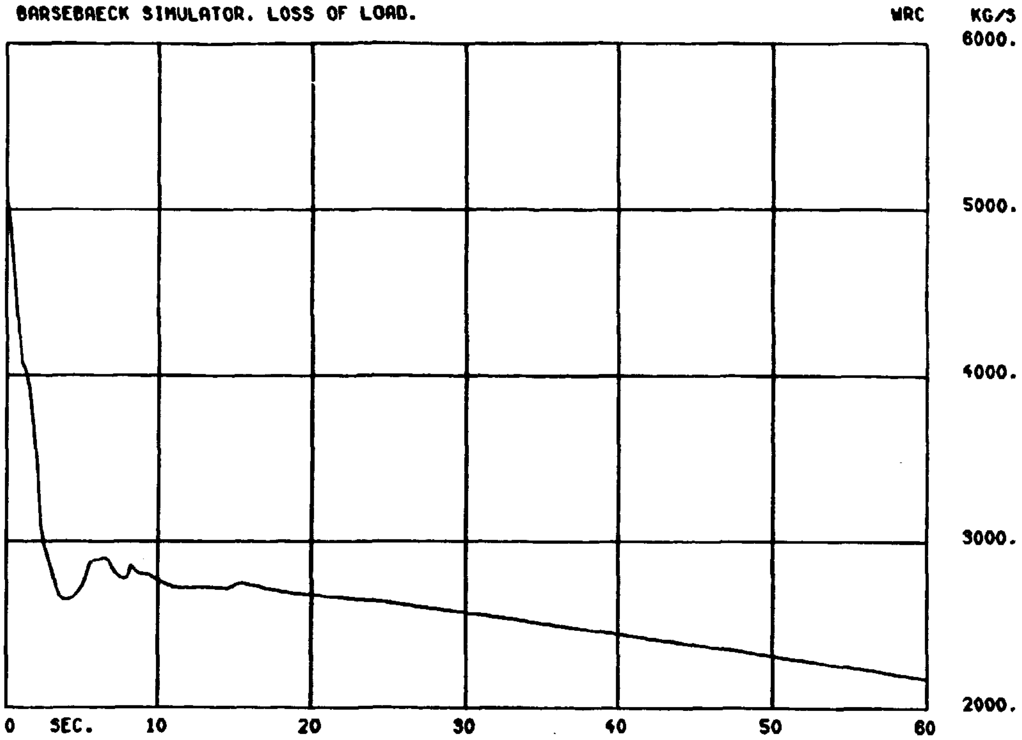

Fig. 5. Reactor recirculation flow.

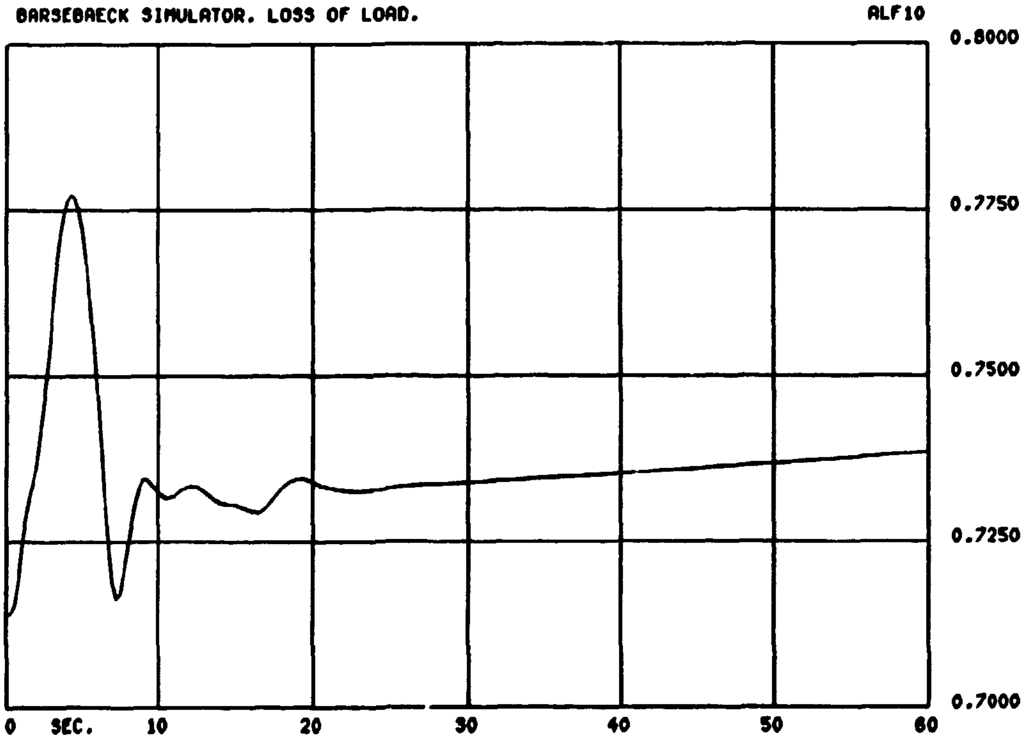

Fig. 6. Coolant void fraction at core exit.

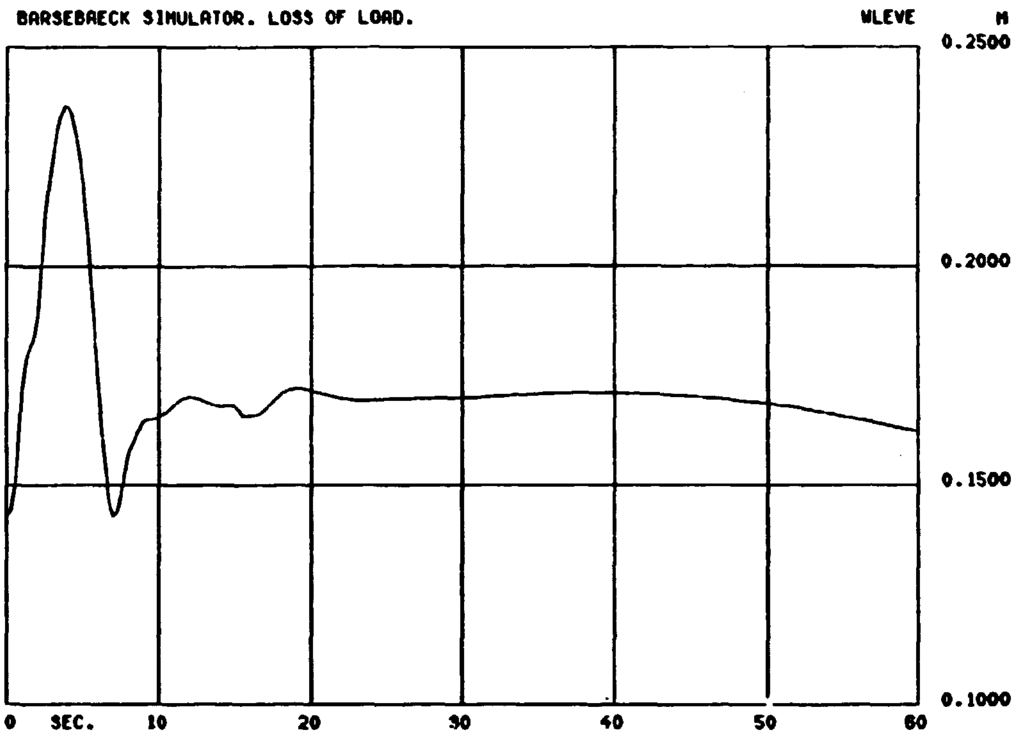

Fig. 7. Water level in the pressure vessel, measured from 4 m above the top of the core.

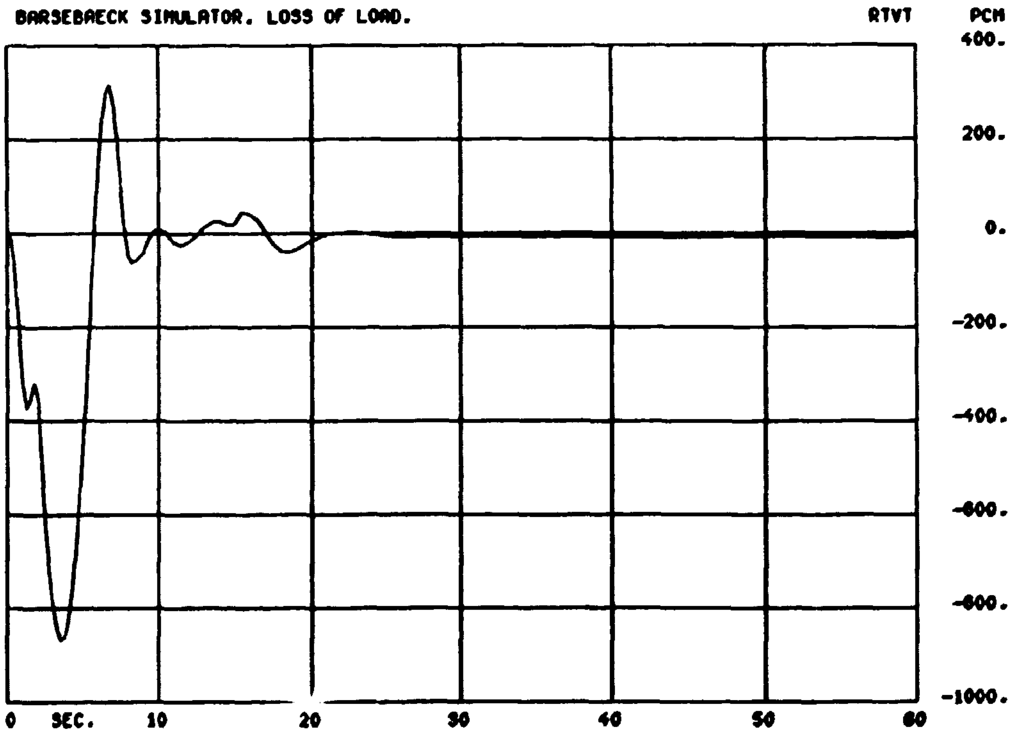

Fig. 8. Reactivity.

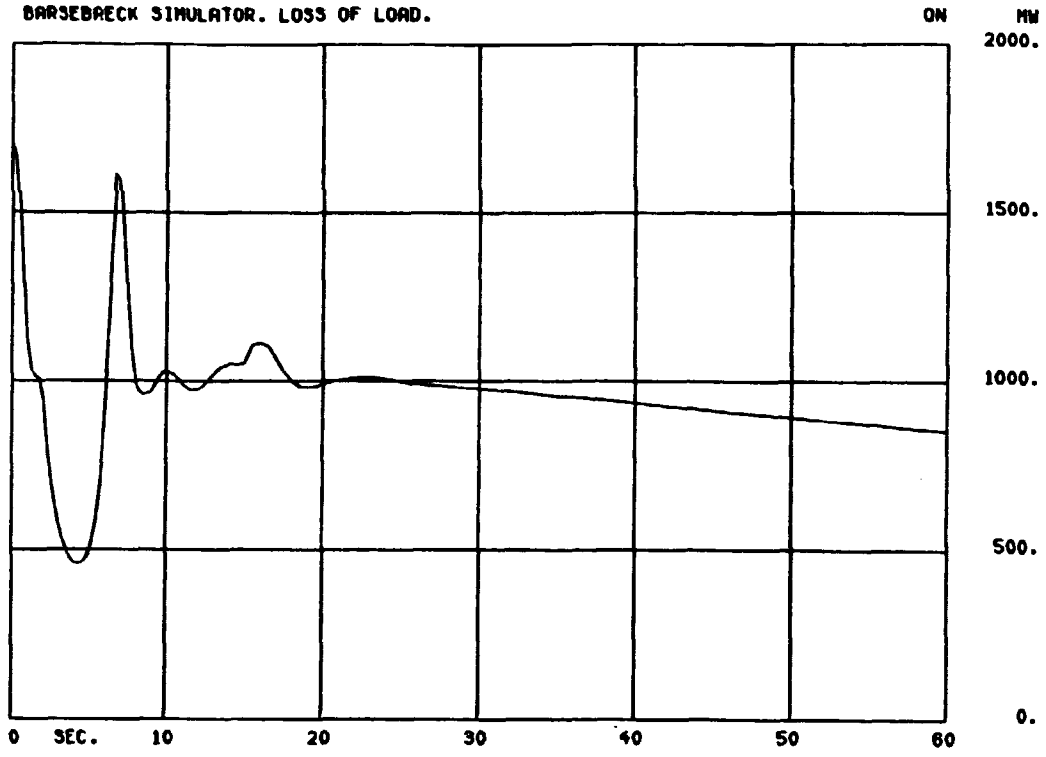

Fig. 9. Reactor thermal power.

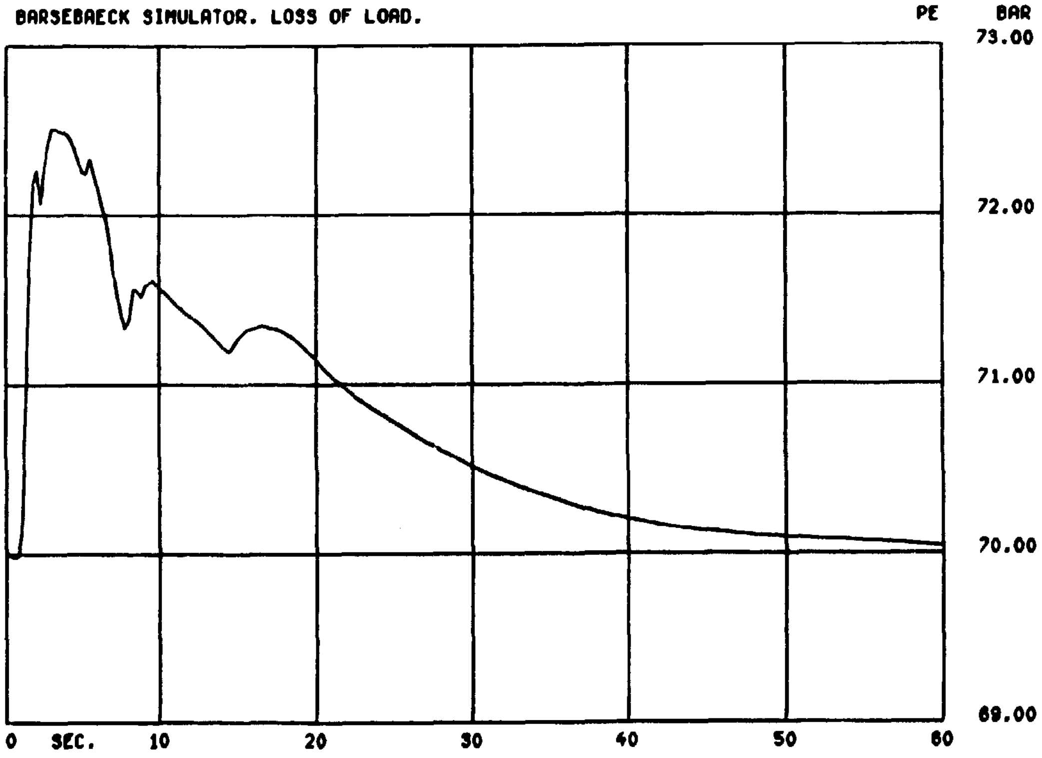

Fig. 10. System pressure.

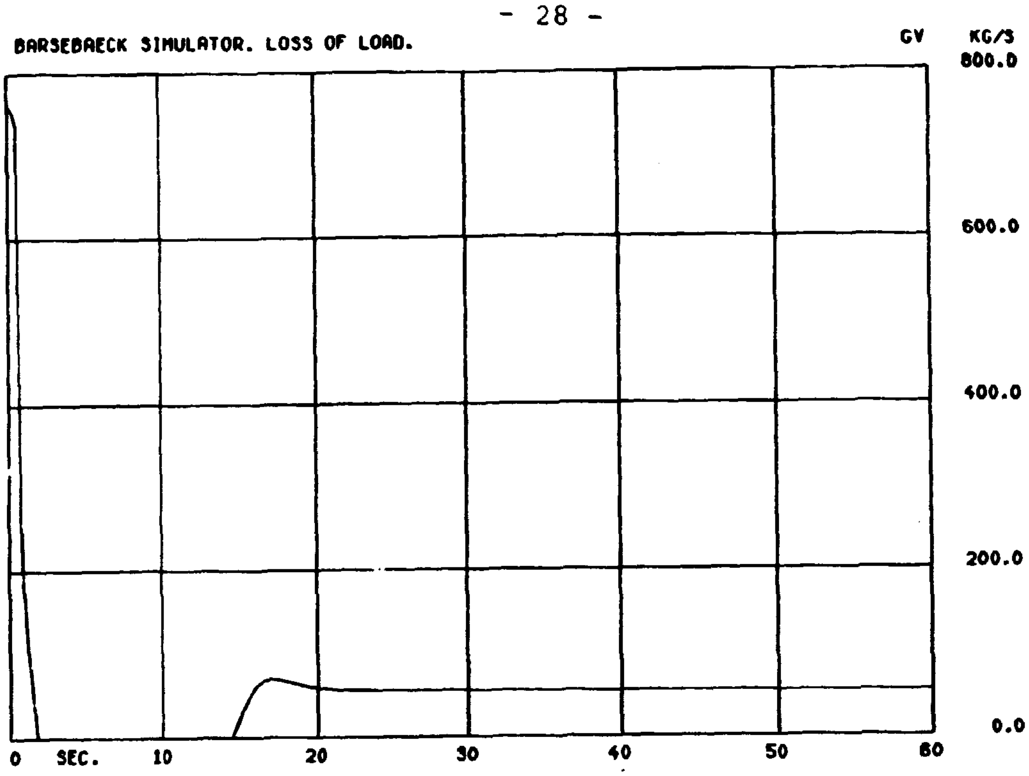

Fig. 11. Steam flow to the high-pressure turbine.

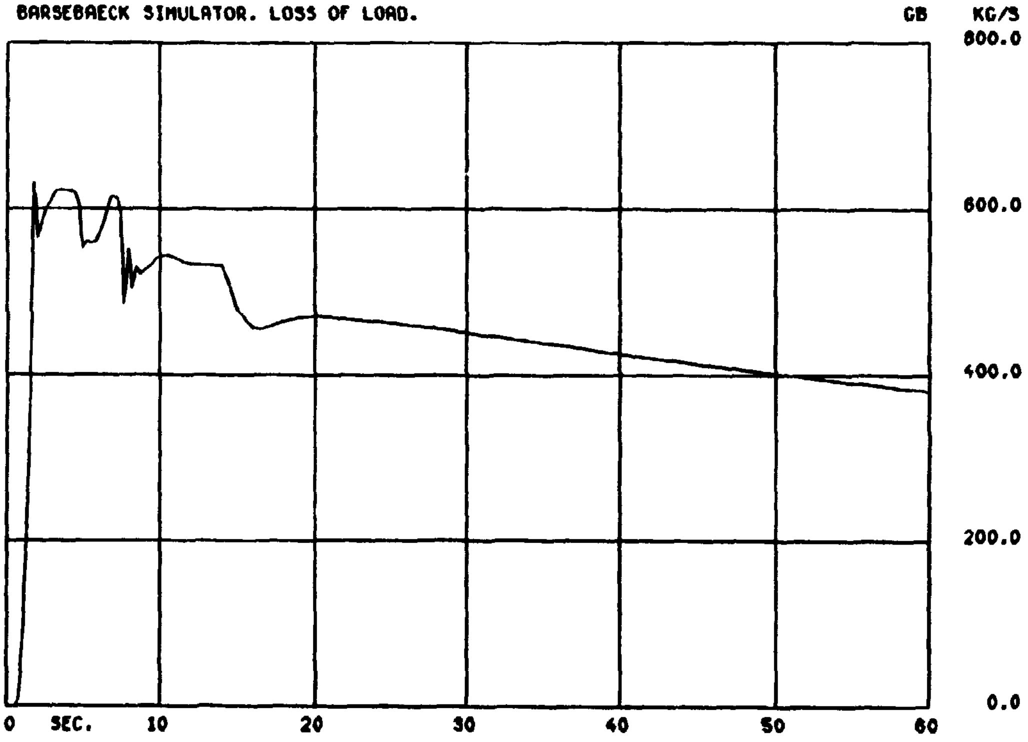

Fig. 12. Bypass flow.

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Abstract

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Abstract. A computer simulator of a Barsebäck power plant unit has been developed in cooperation between Sydkraft AB, Lund Institute of Technology, and Risø National Laboratory. The simulator is of the kind often referred to as a compact simulator, because it involves only a computer with display screens and other input/output devices plus the software needed for calculation and presentation of the plant state as a function of time, and no sort of model of the control room as in large reactor simulators for operator training. The purpose of training courses with the compact simulator is to give students a better understanding of the behaviour of the power plant under transient conditions by displaying variables, e.g. pressures, temperatures, reactivity, nuclear power, as functions of time, thereby showing the interactions between different parts of the plant during the transient and the influence of a number of possible operator actions.

The present paper describes the Barsebäck compact simulator with the emphasis on the software developed at Risø National Laboratory. The Risø work comprises the programming of the dynamic plant model, in the form of a number of Fortran subroutines containing the physical description of the power plant.

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