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SIMULATION AND ANALYSIS OF A MAIN STEAM LINE TRANSIENT WITH ISOLATION VALVES CLOSURE AND SUBSEQUENT PIPE BREAK

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ABSTRACT

Simulation and analysis of a real main steam line break transient at the Thermal Power Plant Drmno are presented. The main events of the transient were the closure of isolation valves in front of a high pressure turbine, an opening of a by-pass line, and subsequent pipe break in front of isolation valves. Intensive pressure waves were generated and they propagated through the pipe network of the steam line, causing high fluid dynamic forces on the structure. The transient has been simulated by the computer code TEA-01, based on the Method Of Characteristics with three characteristic directions.

Several main steam line boundary conditions have been modelled and verified. Numerical results are compared with plant data logger records. Simulation has been performed for various scenarios in order to investigate the plant behaviour sensitivity on the boundary conditions. The phenomenology of the pressure waves propagation and the influence of the boundary conditions on these processes are described in detail, as well as fluid dynamic forces during the closure of isolation valves and subsequent pipe break in a section of the steam line in the vicinity of the pipe break.

KEY WORDS Steam line Valve closure Pipe break

NOMENCLATURE

A	pipe cross-sectional area, m^2	p	pressure, Pa
c	sonic velocity, m/s	q	volume heat flux, W/m^3
D_H	hydraulic diameter, m	t	time, s
F	fluid dynamic force, N	u	fluid velocity, m/s
f	friction coefficient	V	volume, m^3
h	specific enthalpy, kJ/kg	x	spatial coordinate, m
L	pipe length, m	ρ	density, kg/m^3
m	mass flow, kg/s		

INTRODUCTION

The main steam lines at a conventional thermal power plant conduct superheated steam at a high temperature and pressure (up to 540°C and 190 bar) from a superheater of a steam boiler to a high pressure turbine. At the turbine, parallel main steam lines terminate in a common header which feeds the four admission leads to the turbine, see *Figure 4*. Each steam turbine

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lead has an automatic turbine isolation valve, which is being closed at the turbine trip. Also, by-pass lines are connected with the main steam lines, which pass steam to the turbine condenser in the case of a turbine trip. Closure of isolation valves and opening of by-pass lines cause intensive pressure wave propagation, non-linear pressure wave superposition at steam lines junctions, and a fluid transient which exerts high fluid dynamic forces on the pipes and pipelines supports. A phenomenological understanding of the steam flow and pressure wave propagation during this transient, and the proper prediction of the fluid dynamic forces, are necessary for the design of the pipeline and protection systems. This type of transient has been analysed within the scope of the nuclear power plant safety[1]. Suitable modelling approaches and computer code simulation have been verified by the Method Of Characteristics[2,3], because this method gives, potentially, the most accurate solutions[4], especially for one-phase, compressible fluid flows, and it enables proper modelling of boundary conditions[5].

In this paper, the numerical simulations and analysis of a real main steam lines transient at the coal fired, 300 MW, Thermal Power Plant Drmno are presented. The main events of the transient were the closure of isolation valves in front of the high pressure turbine, the opening of by-pass lines and subsequent pipe break in front of one isolation valve[6].

The transient has been simulated by the computer code TEA-01, based on the Method of Characteristics and verified for fast thermal-hydraulic transients[7,8]. Simulations and analysis had specific tasks: to estimate the pressure pulse load caused by temporal action of the turbine isolation valves and the by-pass system, and to predict the intensity of the blowdown force in the broken steam line. Several main steam line boundary conditions have been modelled and verified. Numerical results are compared with plant data logger records. Simulations have been performed for various scenarios in order to investigate the plant behavioural sensitivity relating to the boundary conditions. The phenomenology of the pressure wave propagation and the influence of the boundary conditions on these processes are described in detail, as well as fluid dynamic forces in the portion of the steam line in the vicinity of the pipe break.

COMPUTER CODE TEA-01

The code TEA-01 has been developed for the simulation and analyses of fast thermal-hydraulic transients in Thermal Power Systems (components of Thermal and Nuclear Power Plants, Steam Boilers, District Heating Piping Networks, etc.) during various disturbances and operational conditions. The characteristics of thermal-hydraulic processes and systems‘ flow networks have determined the following features of the TEA-01 code:

- The model is based on one-dimensional, unsteady mass, momentum and energy balance equations, which are solved numerically using the Method of Characteristics.
- One and two-phase flows of water and steam are modelled, where the two-phase flow is described by a homogeneous model (appropriate for bubble or a dispersed droplets flow pattern, low/high voids and high pressures).
- Evaporation/condensation and propagation of phase change fronts are included using an equilibrium model. (The extension towards nonequilibrium phase change is possible.)
- Hydraulic forces by which fluid acts on a pipe are modelled.
- Model built-in discontinuities in geometry of the flow network enable the modelling of various plant systems.
- A system's network can be easily defined by simple input parameters.

These features make the TEA-01 code especially suitable for the calculation of pressure waves, enthalpy and phase change front propagations, and the hydraulic forces during system decompression (for instance pipe break, water hammer phenomena, pump trips, valve operations, etc.).

One-dimensional transient flow of a homogeneous fluid, in a flow channel of constant area is described by using mass, momentum and energy balance equations:

$$\frac{D\rho}{Dt} + \rho\frac{\partial u}{\partial x} = 0 \tag{1}$$

$$\frac{Du}{Dt} + \frac{1}{\rho}\frac{\partial p}{\partial x} + \frac{fu|u|}{2D_H} + g\sin\theta = 0 \tag{2}$$

$$\frac{Dh}{Dt} - \frac{1}{\rho}\frac{Dp}{Dt} - \frac{fu|u|^2}{2D_H} - \frac{\dot{q}}{\rho} = 0 \tag{3}$$

and by the equation of state: $\rho = \rho(p, h)$.

This system of equations is solved for the appropriate initial and boundary conditions by the Method of Characteristics.

Three characteristic directions are used, where two correspond to the pressure wave propagation and the third to fluid particle flow (enthalpy front propagation), *Figure 1*.

The time step of integration is determined according to the Courant criterion:

$$\Delta t \leqslant \min\left(\frac{\Delta x}{c_j + |u_j|}\right), \quad j = 1, 2, \ldots, n \tag{4}$$

where n is a maximum number of nodes.

The steam boiler is represented with a point model, which comprises equilibrium two-phase mixture, heat source, feedwater inflow and steam outflow. The model is based on the mass and energy balance equations:

$$\frac{\mathrm{d}M}{\mathrm{d}t} = \sum \dot{m}_{\mathrm{in}} - \sum \dot{m}_{\mathrm{out}} \tag{5}$$

$$\frac{\mathrm{d}M}{\mathrm{d}t} = \dot{Q} + \sum \dot{m}_{\mathrm{in}} h_{\mathrm{in}} - \sum \dot{m}_{\mathrm{out}} h_{\mathrm{out}} + V\frac{\mathrm{d}p}{\mathrm{d}t} \tag{6}$$

and equations of state and functional characteristics of the system (feedwater inflow and steam boiler heat power).

The TEA-01 code has been validated on the various physical tests data which are available in the literature[7,8]: blowdown of one-phase (water and steam) or two-phase systems, pressure wave propagation in one or two phase systems, pressure wave propagation in a complex pipeline network (T-junctions, the junction of two or more pipes), transients in district heating systems, transient steam flow with accumulation within the pipeline, and determination of hydraulic forces. The module for the steam boiler simulation has been validated against the transient pressurizer operation, with electrical heaters as the module heat source[9].

BOUNDARY CONDITIONS

In order to simulate the complex pipe networks and various transient scenarios, code TEA-01 comprises several models of boundary conditions (i.e. the flow channel discontinuities) which can be linked with the code in a modular way. The calculation of the flow parameters at the ends of a pipe must be done using additional hydraulic models. These additional equations describe the mass, momentum or energy balance at a point of discontinuity, and they replace the equations of the characteristics which do not belong to the physical domain of a pipe. The general form of these equations is:

- balance of mass: $\Delta(\rho u A) = 0$, (7)

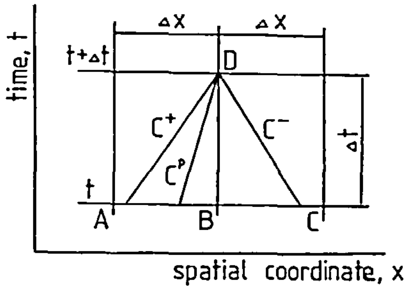


Figure 1 x–t plane and characteristic directions

- balance of momentum: $\Delta\left(\frac{\rho u^2}{2}\right) + \Delta p = \Delta \mathrm{M}(t)$, (8)
- balance of energy: $\Delta(h + \frac{1}{2}u^2) = 0$, (9)

where $\Delta \mathrm{M}$ is the momentum change due to the local friction loss. It can be time dependent (for instance in the case of valve closure). The following boundary conditions are included in the code: a subcritical or critical leakage from a pipe, a closed end of a pipe, a pipe joining a tank, a junction of two or more pipes, with or without pumps or heat exchangers, a valve in a pipe and flow parameters determined as functions of time.

FLUID DYNAMIC FORCES

The transient fluid dynamic force in a pipe which is bounded by other flow components, such as elbows or orifices, is caused by the propagation pressure waves. This transient wave force is exerted on the pipe in the direction of the pipe axis. It is calculated by the expression[10]:

$$F = \int_L \frac{\mathrm{d}\dot{m}}{\mathrm{d}t}\,\mathrm{d}x \tag{10}$$

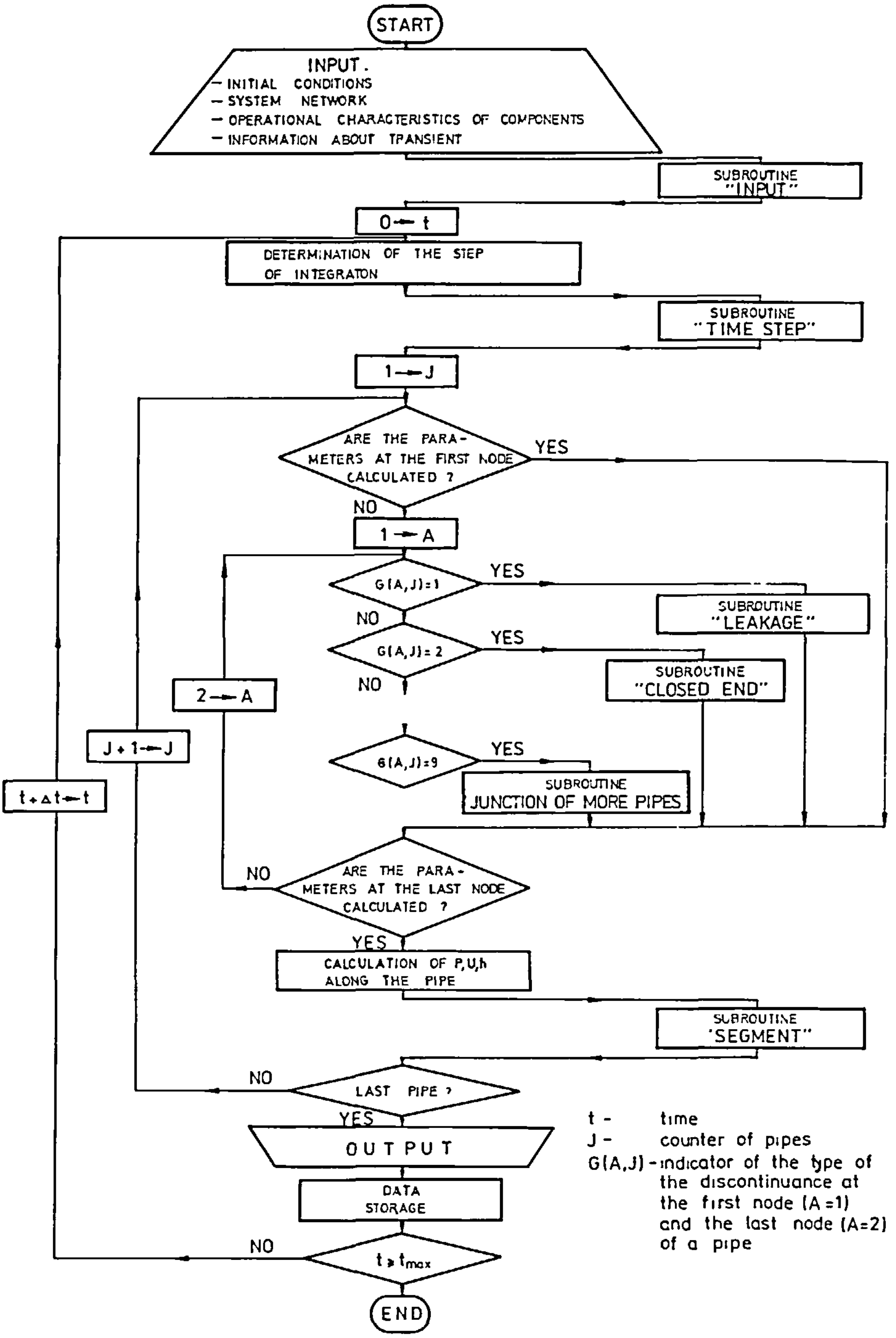
The fluid force exerted on a pipe with an open end (expulsion from a pipe) includes both a wave force and a blowdown component associated with momentum expulsion and the difference between discharge and ambient pressure. It acts along the pipe axis and the force intensity is:

$$F = \int \frac{\mathrm{d}\dot{m}}{\mathrm{d}t}\,\mathrm{d}x + [(p_{\mathrm{out}} - p_{\infty}) + \rho_{\mathrm{out}} u_{\mathrm{out}}^2]A \tag{11}$$

The pipe wall is assumed to be rigid.

Flowchart of the TEA-01 code

In order to enable the applicability of the code to the wide variety of the Thermal Power Systems' networks, the flowchart of the TEA-01 code is designed in a way that the system network can be defined by the input parameters. The flowchart of the TEA-01 code is given in *Figure 2*.



t - time
J - counter of pipes
G(A,J) - indicator of the type of the discontinuance at the first node (A=1) and the last node (A=2) of a pipe

Figure 2 Algorithm of the TEA-01 code

NUMERICAL SIMULATION OF THE MAIN STEAM LINE TRANSIENT

The main steam line break transient occurred at the coal fired, 300 MW Thermal Power Plant Drmno-Yugoslavia, in April 1991. The accident resulted in the rupture of the main steam line at the junction with the high pressure turbine isolation valve (double-ended guillotine), and subsequent blowdown of the steam boiler. The main events of the transient were consequently:

- the plant was on constant power
- the high pressure turbine isolation valves were closed by the operators because of the small leakage on the main steam line, which was observed as a sound effect
- after 20 s from the turbine isolation valve closure the great rupture of the steam line occurred in front of the isolation valve
- the steam leakage proceeded from the boiler through the break on the main stream line to the turbine building.

In order to derive the sensitivity of the systems behaviour to the instant of the isolation valve action, the time duration of the valve closure, and the by-pass system's action, as well as to obtain the most conservative case of the possible system parameters change during transients, various modelling scenarios were prepared, for the following time intervals[6]:

- less than one second in order to simulate the pressure wave propagation and transient fluid dynamic forces during and after the isolation valve closure;
- a few seconds in order to predict the global pressure in the steam lines and steam boiler after the isolation valves closure, and
- a few minutes in order to simulate the system's blowdown after the pipe break.

The main goal was to determine maximum pressures and fluid dynamic forces acting on to the main steam pipeline in the vicinity of the break, and to evaluate whether these loads had been able to cause the break.

Pressure wave propagation and fluid dynamic forces during isolation valve closure – time interval less than one second

The main steam pipeline was modelled in detail with 16 pipes including various *Y* and *T* junctions, isolation valves, outflow through the by-pass line, and a junction with the steam boiler. The system nodalization is shown in *Figure 3*. Once-through steam boiler is represented by its water side as a volume filled with two-phase steam and water mixture under equilibrium conditions, determined by the global pressure (which correspond to the pressure at the exit from the evaporating section – the separator).

Four scenarios have been prepared, *Table 1*.

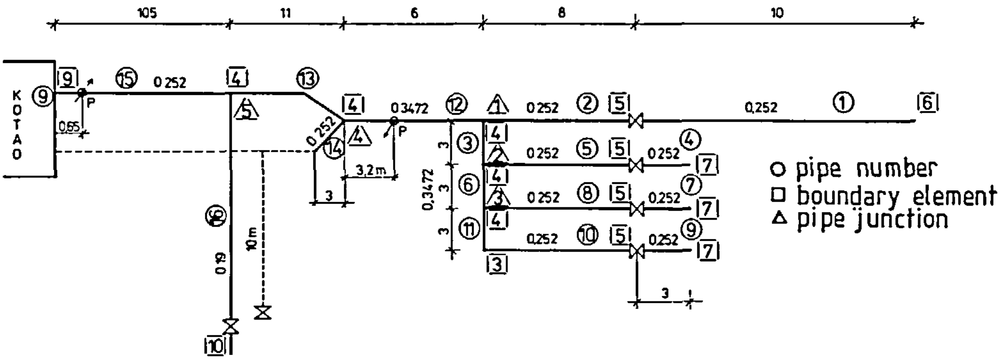


Figure 3 Nodalization of the main steam line

Table 1 Scenarios for isolation valves closures

Scenario	1	2	3	4
Time period of valve closure	30 ms	0.2 s	0.2 s	0.2 s
Time instant of by-pass opening	0.1 s	0.2 s	1.0 s	0.1 s

Stationary initial conditions (steam: $\dot{m}$ = 260 kg/s, T = 540°C); isolation valves start closing at 0 2.

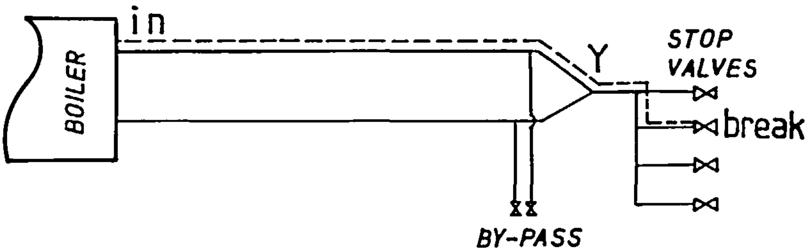


Figure 4 Observed path

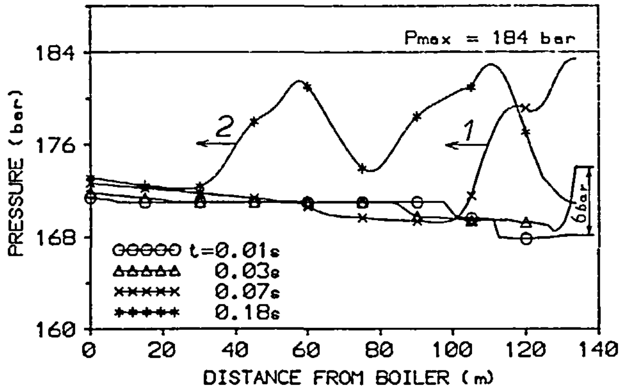


Figure 5 Pressure distribution in the main steam line – scenario 1 (isolation valve closure for 0.03 s, by-pass activated at 0.1 s)

Simulated pressure distributions are shown for the path marked with the dotted line in *Figure 4*. Pressure distributions for the first scenario are given in *Figure 5*, for the second scenario in *Figure 6*, for the third in *Figure 7* and for the fourth in *Figure 8*.

The following conclusions can be derived:

- maximum pressure increase in front of the isolation valves, at the end of valve closing, is approximately 6 bars; that is less than maximum possible pressure increase (9 bar) caused by the sudden stop of steam flow, given by the equation:

$$\Delta p = \rho c \Delta u \tag{12}$$

- maximum pressures in front of the isolation valves, at the instant of complete valve closing, are similar in the case of 30 ms speed of valve closing and 0.2 s speed of closing;
- maximum pressure increase is a result of nonlinear superposition of four compression waves, which propagate from the isolation valves, through the pipeline, to the boiler
- maximum pressure increase in the main steam line, after the closure of the isolation valves in front of the high pressure turbine, is determined by the efficiency of the by-pass action

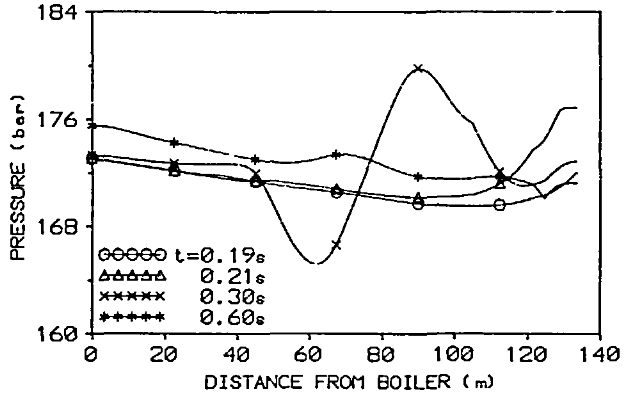


Figure 6 Pressure distribution in the main steam line – scenario 2 (isolation valve closure for 0.2 s, by-pass activated at 0.2 s)

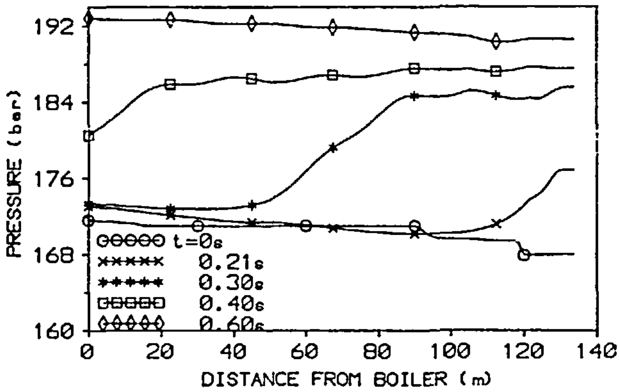


Figure 7 Pressure distribution in the main steam line – scenario 3 (isolation valve closure for 0.2 s, by-pass is closed)

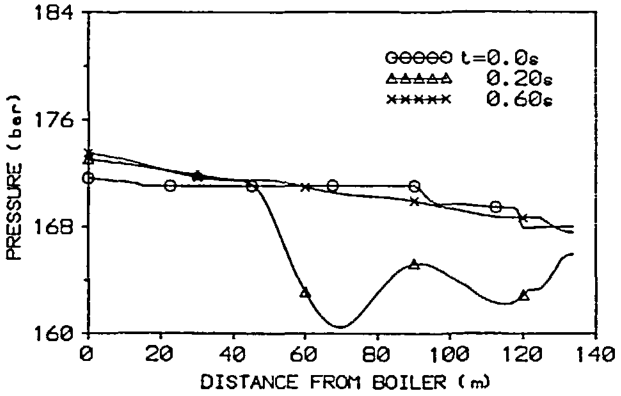


Figure 8 Pressure distribution in the main steam line – scenario 4 (isolation valve closure for 0.2 s, by-pass activated at 0.1 s)

- analyses show that the maximum pressure increase, after the isolation valve closure, is approximately 16 bars, in the case of proper by-pass action
- a delay of by-pass action causes much higher pressure increase.

The transient fluid dynamic forces are calculated for the parts of the pipeline where the rupture took place (pipes 1, 2 and 3 in *Figure 9*), during the main isolation valves closure, *Figure 10*. The results show that:

- during the valve closure the pulse of dynamic force propagates from the isolation valve through the steam pipeline; the force is generated by the propagation of intensive compression wave;
- the maximum force is generated immediately after the valve closure, while the subsequent impulses are smaller and attenuated;
- the impulse of transient fluid dynamic force is shifted in time from one pipe to another, according to the time required by the compression wave to propagate from pipe to pipe.

Global pressure change in the main steam line after the isolation valve closure – a time period of a few seconds

In order to predict the maximum global pressure in the period after the isolation valve closure and up to the pipe break, thermal-hydraulic processes are modelled in the main steam line and

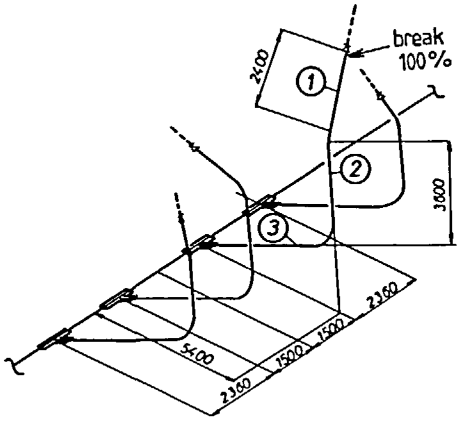


Figure 9 Spatial configuration of the pipe where the break took place

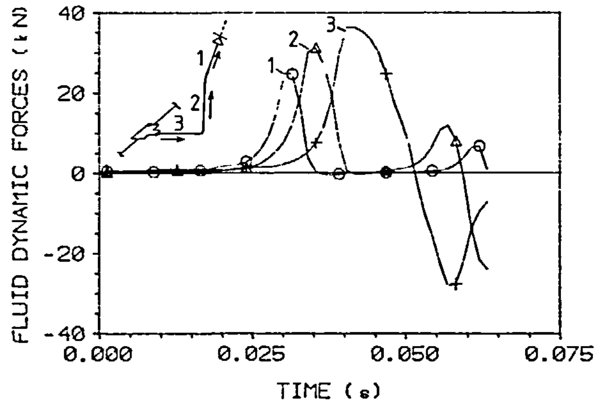


Figure 10 Transient fluid force – isolation valve closure for 0.03 s

Table 2 Scenarios for by-pass action

Scenario	1	2
Time period of valve closure	0.2 s	0.2 s
Time instant of by-pass opening	0.2 s	closed
Time of pipe break	20 s	20 s

Isolation valves start closing at 0 s.

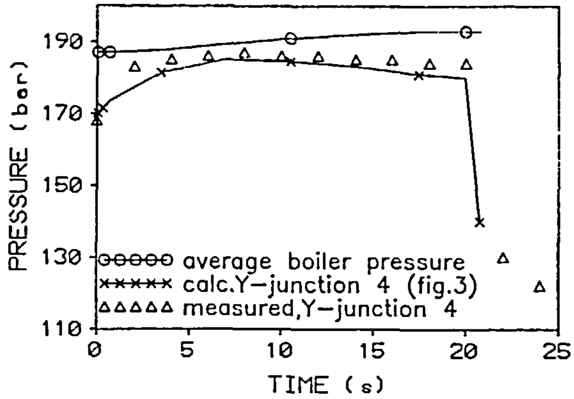


Figure 11 Global pressure in the main steam line – by-pass is activated

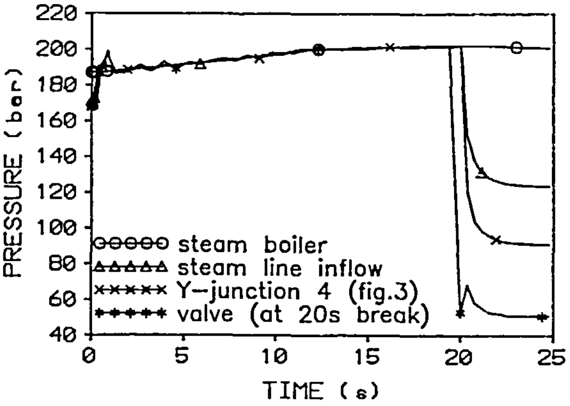


Figure 12 Global pressure in the main steam line – by-pass is closed

in the steam boiler during the period of 20 s. The system is divided into nodes, as is shown in *Figure 3*, and two scenarios have been performed, *Table 2*.

Figure 11 shows the simulated and measured pressure at various points within the system for the first scenario. Pressure reaches the global value – 185 bar in the system as a whole. There are no pressure wave propagations. The calculated results are in agreement with the measured values (recorded by the process computer). The intensive pressure decrease occurs at 20 s because of the pipe rupture.

Figure 12 shows simulated results for the second scenario. Steam boiler heat power and feedwater inflow are the same as for the first scenario, but the by-pass line is not opened. That

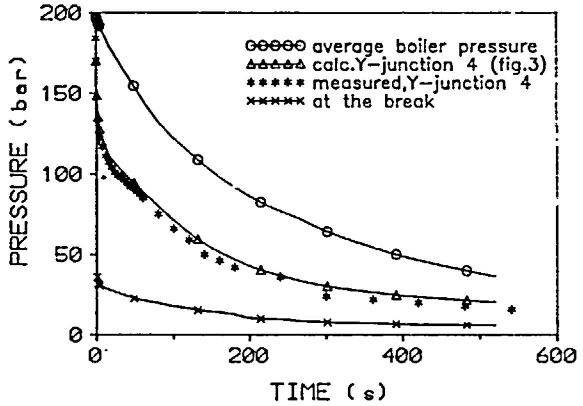


Figure 13 Pressure change during blowdown (100% break)

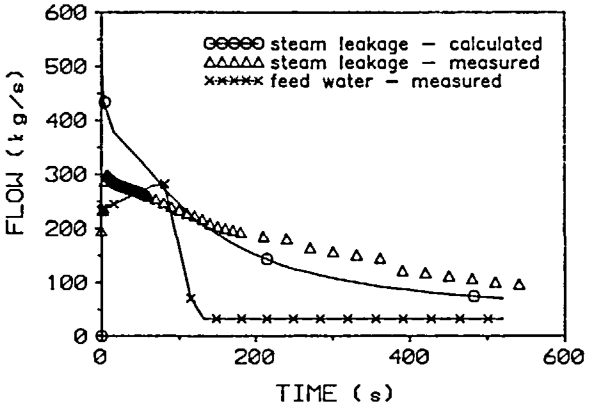


Figure 14 Steam flow during blowdown (100% break)

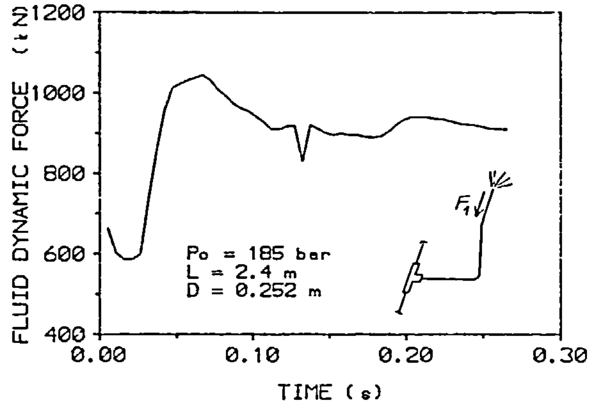


Figure 15 Reactive fluid force at the ruptured pipe

is the reason that the pressure increases from 168 bar to 203 bar for 20 s. The pressure in the steam line is approximately the same as in the steam boiler.

The results of simulations show that the main steam line pressure is within allowed margins if the by-pass system acts properly, as happened in this transient.

Decompression after the pipe rupture – time period of a few minutes

An instantaneous 100% pipe rupture in front of the isolation valve is assumed at 0 s. The critical outflow of steam is reached at the pipe break.

Figure 13 shows the computed and measured pressures during the blowdown at the various points of the system. The pressure reaches 40 bars at the break immediately, and this pressure is 10 bar after 200 s. During the first 500 s the steam is mainly generated because of the adiabatic evaporation in the steam boiler, and 80% of the initial water and steam mass in the boiler is discharged into the turbine hall.

Measured and simulated steam blowdown flows are shown in *Figure 14*. The overall agreement between measured and calculated values is fair. Some discrepancy at the beginning of blowdown exists because the maximum measuring range of the instrument at the plant was overcome.

Figure 15 shows the fluid force in pipe 1, *Figure 9*, after the pipe rupture in front of the isolation valve. The force is calculated by (11), where the reactive component is dominant (expression in the parentheses on the r.h.s.). This high value of the reactive force led to 1 m pipe movement in the direction of the force at the Plant Drmno.

CONCLUSION

Simulation and analysis of the main steam line transient with the isolation valves closure and subsequent pipe break has been undertaken. The accident took place at the coal fired Thermal Power Plant Drmno. The procedure is based on the engineers' knowledge and experience, and the transients' simulations with the computer code. The methodology is shown for the evaluation and analysis of pressure wave propagations, fluid dynamic forces generation during isolation valve closure and pipe rupture, and intensive Plant blowdown. These results could be used, with care, as the input data for the stress analysis of the main steam pipeline. Also, measured and calculated data of steam leakage were used as input data for a determination of temperature and pressure history in the turbine hall during blowdown[6].

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