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DYNAMIC COMPUTER SIMULATION OF THE FORT ST. VRAIN STEAM TURBINES*

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J. C. Conklin

Oak Ridge National Laboratory
Oak Ridge, Tennessee 37830

Abstract

A computer simulation is described for the dynamic response of the Fort St. Vrain nuclear reactor regenerative intermediate- and low-pressure steam turbines. The fundamental computer-modeling assumptions for the turbines and feedwater heaters are developed. A turbine heat balance specifying steam and feedwater conditions at a given generator load and the volumes of the feedwater heaters are all that are necessary as descriptive input parameters. Actual plant data for a generator load reduction from 100 to 50% power (which occurred as part of a plant transient on November 9, 1981) are compared with computer-generated predictions, with reasonably good agreement.

Introduction

The U.S. Nuclear Regulatory Commission has sponsored a program at the Oak Ridge National Laboratory to investigate the transient behavior of the Fort St. Vrain (FSV) High-Temperature Gas-Cooled Reactor, operated by the Public Service Company of Colorado (PSC). This nuclear reactor is capable of providing steam to the turbines at conditions comparable to those attainable at fossil fuel power stations. A computer simulation code ORTURB (Ref. 1) has been written to predict the FSV steam turbine transient response and is part of an overall FSV plant computer simulation.

The dynamic performance of the steam turbines and feedheaters can have significant influence on the remaining plant components. A flow diagram of the major plant components is presented in Fig. 1. ORTURB calculates the steam pressures, enthalpies, and flows within the turbine, the flow of extraction steam to the feedwater heaters ("feedheater"), the steam pressure in the shell of the feedheater, and ultimately the temperature of the feedwater leaving the feedheater. The temperature of the feedwater leaving the highest pressure feedheater is of interest to the study of plant dynamic response because this temperature is an inlet boundary condition for the steam generators. Additionally, the turbine inlet pressures and flows have an influence

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on the steam generator performance. A design characteristic unique to FSV that can have a significant effect on the plant dynamic response is that the exhaust steam from the high pressure turbine drives the helium circulators.

ORTURB is divided into two major subsystems: the high-pressure turbine (HPT) and the regenerative intermediate- and low-pressure turbine (ILPT). ORTURB can either calculate the generator output caused by given steam conditions at the turbine throttle valves or use the value of generator electrical output as a boundary condition to determine effects on the steam conditions at the turbine inlet.

On November 9, 1981, FSV was operating at 100% power [330 MW(e)] until 1 of 4 helium circulators tripped, causing 6 of 12 steam generators comprising 1 of 2 secondary coolant loops to be isolated with a corresponding generator load reduction to 50% power. The load was later reduced to 30% and then the reactor was taken out of service for scheduled maintenance. The plant data logger recorded certain operating conditions of FSV during this transient, particularly parameters of interest for evaluating turbine and feedheater dynamic computer simulation performance.

This paper presents the basic governing equations for the ILPT and feedheaters with a comparison of calculated results with actual plant data for the turbine load reduction from 100 to 50% power on November 9, 1981. Results were also obtained for the HPT, but the comparison between computed and measured values of first-stage shell pressure were not good. This anomaly requires investigation before a comparison is presented.

ILPT Modeling

The ILPT is divided into seven stage groups separated by points representing the turbine inlet, six steam extraction points, and the condenser as shown on Fig. 2.

A basic modeling assumption used for the steam turbine and crossover piping is that the time constants for the dynamic response of the steam conditions inside the turbine are much shorter than those occurring inside the feedheaters. This assumption is valid for the turbine at FSV because both the steam transit and thermal response times are much shorter than those of the feedheaters. Additionally, this assumption does not require design information of the turbine internals, which in any case is difficult to obtain from the manufacturer, and allows the governing equations for the steam inside the turbine to be algebraic, rather than differential equations. This decreases the total number of coupled differential equations needed to describe the turbine plant and allows the use of a nonstiff integration method. These characteristics are desirable for a computer code because they decrease computer execution time and costs.

This analysis also uses a component isolation assumption; that is, the external conditions experienced by the individual components do not change during a time step. Each of five feedwater heaters and the deaerator are considered separate components, as are the feedpump turbine and the ILPT. The feedheater modeling analysis is described in the next section.

For simplicity, the feedpump system for the steam side is modeled as one steam turbine stage. Feedwater flow through the pump is controlled by code input parameters. This simplification could be modified by substituting a feedwater pump computer simulation, which would include a feedwater feedpump steam turbine inlet flow control valve not presently modeled in ORTURB.

A turbine heat balance for the actual plant must be known, and steam conditions at each turbine extraction point and feedwater conditions at each feedheater must be specified to initialize certain constants used in the coding. Among these are a flow constant, a thermal efficiency constant for each turbine stage group, and constants representing heat transfer performance of the feedheaters.

The basic governing equation for pressure and flow through each of the modeled turbine stage groups of the ILPT was developed for ideal gas flowing through a nozzle under isentropic, adiabatic conditions:

$$W = A \left\{ \frac{k}{k-1} \frac{P_1}{\upsilon_1} \left[\left(\frac{P_2}{P_1} \right)^{\frac{2}{k}} - \left(\frac{P_2}{P_1} \right)^{\frac{k+1}{k}} \right] \right\}^{\frac{1}{2}} , \tag{1}$$

where

k = isentropic exponent,
P = pressure (Pa),
υ = specific volume (m^3/kg),
A = flow constant (m^2),
W = flow (kg/s).

The subscript 1 refers to an upstream value, and the subscript 2 refers to a downstream value.

This equation allows the effect of a downstream pressure variation to be reflected upstream when the pressure ratio (downstream to upstream pressure) is greater than critical. This is an important consideration in predicting the transient performance of the ILPT because changes in feedheater shell pressures, caused by flow perturbations on the tube side, will result in changes in turbine extraction flow and pressure.

For the ORTURB model, the pressure difference between an extraction point and the feedheater shell determines extraction flow to the shellside of a feedheater. Pressure loss ΔP in the extraction pipe is calculated as an assumed shape or form loss by

$$\Delta P = K \frac{\rho v^2}{2} , \tag{2}$$

where K is a loss coefficient, ρ is the density, and v is a characteristic velocity.

Using mass continuity, assuming that the loss coefficient is constant, the extraction flow W_{ex} is calculated by

$$W_{ex} = W_{ex,i} \left(\frac{\upsilon_i}{\upsilon} \right) \left(\frac{\Delta P}{\Delta P_i} \right) . \tag{3}$$

where the subscript i represents the initial turbine parameters.

Equation 1 can be reduced to Eq. (3) for small pressure drops.

The feedpump turbine has been modeled as one stage group; entrance and exit pressures are used as upstream and downstream pressures in the ideal gas flow equation. Inlet pressure is set equal to pressure at the second ILPT extraction point (point 3 of Fig. 2), and exit pressure is set equal to main condenser pressure.

Low-pressure turbine exhaust loss is calculated according to the procedure in Ref. 2. This loss is a unique function of steam velocity at the discharge of the last-stage buckets. Empirical data are used for this procedure and were developed from known dimensions (851-mm active length on the last-stage bucket) and published exhaust losses[3] at 100 and 25% power. Note that Ref. 2 is concerned with turbines operating at conditions typical of fossil plants. Different correlations would be necessary to model steam turbines for light-water reactors that operate with saturated steam.

Turbine flows resulting from the previous-time pressure distribution are all calculated initially for a time step. The turbine flow upstream from an extraction point is then compared with the sum of the turbine flow downstream and the extraction flow. If the flows do not balance, extraction pressure is modified accordingly, and the turbine group flow calculation is repeated until convergence for the entire turbine is obtained.

As the pressure-flow iteration advances through the turbine, required steam properties of temperature and specific volume are obtained from steam property subroutines originally written for the ORCENT code[4] rather than the American Society of Mechanical Engineers 1967 steam table equations.[5] The ORCENT subroutines have fewer iterative loops, thus consuming less computer time, and are of sufficient accuracy for transient analysis of steam turbines.

Feedwater Heater Simulation

There are five closed feedheaters in the simulated turbine plant (Figs. 1 and 2). Figure 3, taken from Delene,[6] is a diagram of such a closed feedheater. A turbine heat balance at 100% power, transmitted by PSC,[3] was used to specify feedheater inlet and outlet temperatures, pressures, and flows to initialize certain parameters such as heat transfer coefficients assumed to remain constant throughout the simulated transient. Feedheater volumes were taken from the FSV final safety analysis report.[7]

The physical process of heat transfer in the feedheater shell is assumed to occur as follows. Steam from the turbines first enters the shell of the feedheater. If this steam is superheated, the superheat is directly transferred to the feedwater leaving the feedheater. The assumption is that it will first lose this superheat to the feedwater by means of a simple heat balance. If the steam is wet, it is divided into a saturated steam part and a saturated liquid part. The liquid falls into a liquid stream on a tray or partition within the feedheater. Liquid from a previous higher pressure feedheater drain-cooler may also enter this stream. Because its temperature is usually hotter than the saturated vapor temperature, part of it flashes; this vapor goes into the vapor space. Steam in the vapor space condenses on the tubes containing the feedwater and falls into the liquid stream. This liquid eventually flows into the drain-cooler section of the feedheater and loses additional heat to the feedwater as it flows through the drain-cooler.

To complete the heat balance, feedwater in the tube side of the feedheater is assumed to exchange heat in the following manner. Feedwater enters the feedheater tube bundles and exchanges heat with the water in the drain-cooler section. After leaving the drain-cooler, the feedwater enters tube bundles in the vapor space where it gains additional heat as the steam condenses. If any superheat is in the extraction steam, the feedwater is assumed to absorb it just before exiting the feedheater.

Six time-dependent energy conservation equations are written: two for the liquid in the drain-cooler section, two for the feedwater in the drain cooler, and two for the feedwater in the vapor section. The heat transfer coefficient is assumed to remain at a constant value determined from steady state initialization values. A seventh differential equation is written for the saturation temperature of the vapor in the feedheater shell. This vapor temperature depends on the mass flow rate into and out of the shell. The mass flow into the shell consists of the vapor extraction flow and vapor flashed from a previous higher pressure drain-cooler. Condensed liquid leaves the evaporator section and enters the drain-cooler section. The vapor is compressible, and thermodynamic derivatives of temperature with respect to pressure and pressure with respect to density are evaluated along the saturation line to calculate the time rate of change in temperature from the time rate of change in mass of vapor in the shell. The ORTURB documentation elaborates on these relationships in equation form.

The set of seven coupled, first-order, ordinary differential equations is solved with LSODE (Ref. 8), a series of subroutines developed at Lawrence Livermore National Laboratory to solve the initial value problem for stiff or nonstiff systems of first-order ordinary differential equations. The system of equations for the feedheater is nonstiff for most postulated operating conditions of the turbines at FSV. Use of the nonstiff option has resulted in ORTURB executing significantly faster than the simulated time for certain transients. However, during low turbine flows, it is possible that the system of equations will become stiff. LSODE will indicate when such a situation is present. Additional coding to use the stiff option if warranted has been written for inclusion in ORTURB.

To complete the computer modeling of the feedheaters, the deaerator is modeled as a homogeneous mixing tank. The conservation equations of mass and energy are solved by a forward Euler method. The large mass inventory of the deaerator allows use of this simple integration method.

Comparison of Calculated and Measured Results

The plant data for hot reheat steam temperature and pressure, feedwater flow to the steam generator, condensate feedpump discharge temperature, and condenser pressure were used as boundary conditions for the ORTURB simulation of the FSV plant transient of November 9, 1981. Note that the ILPT inlet flow is determined by the hot reheat steam conditions and the pressure distribution inside to the turbine, as can be seen from Eq. (1).

The plant data logger also monitors the turbine extraction pressures and temperatures of the feedwater leaving each feedheater. Certain of these readings were obviously erroneous, such as a negative pressure for extraction points 6 and 7 of Fig. 2 or a constant pressure throughout the transient as recorded for all the extraction temperatures and feedwater temperature leaving feedheater 5.

Results were calculated for these parameters but are not presented.

Table 1 presents the ORTURB calculated pressures for the Fig. 2 extraction points 2-5 and the corresponding extraction pressures as recorded by the plant data logger. Table 2 presents the ORTURB results for the feedwater temperature leaving feedheaters 1, 2, 3, 4, and 6 and the temperatures as recorded by the plant data logger. Figures 4 and 5 present the measured and computed extraction pressures and feedwater temperatures for feedheaters 6 and 3, respectively. The differences between the reported values at time zero are caused by differences between the heat balance data used to initialize ORTURB and those of the data logger, both for 100% power.

The error limits and response characteristics of these plant transducers for pressure and temperature would probably not be comparable with those of laboratory instruments. With this in mind, the agreement is reasonably good (<10% difference for most values) over the first 460 s of the load reduction transient and particularly good (within 4%) for the extraction pressure of feedheater 6. Note, however, that the measured feedwater temperatures leaving feedheaters 1 to 3 and the measured pressure at extraction point 5 are significantly below those calculated by ORTURB for 90 to 390 s. This discrepancy is most likely cuased by the uncertainty of the condensate feedpump mass flow rate. This important plant operating parameter is controlled at FSV to attempt to maintain a constant liquid level in the deaerator. However, the recorded value from the data logger could not be used in the simulation because it was obviously erroneous. The calculated values presented on Tables 1 and 2 and plotted on Figs. 4 and 5 resulted from a simulation where the deaerator liquid level was held constant throughout the computation, which would represent perfect controller response. In another computation, the condensate feedwater flow rate was arbitrarily increased over that needed to deliver a constant deaerator level during the time period of interest, and results were more in agreement with those of the data logger.

An increase in deaerator liquid level was possible during this transient. The steam generator inlet feedwater flow rate was quickly reduced to 50% of that required for full power, reflecting the isolation of one-half of the steam generators, while the condensate feedpumps were possibly still at the full-power operating point or coasting down from it. The tabulated results for the constant deaerator level case are still in reasonably good agreement with those of the data logger.

Conclusions

The basic modeling used in the computer code ORTURB was developed which requires use of a minimum of turbine specific geometry. The only design information needed to initialize the flow and heat transfer constants used in ORTURB are a turbine heat balance at initial conditions and feedheater volumes. The calculated results for an actual plant transient at FSV agree reasonably well with those recorded by the plant data logger for the intermediate-and low-pressure turbines and feedheaters. Further information concerning the accuracy and response characteristics of the plant instrumentation transducers will be needed to justify the differences between calculated and measured values.

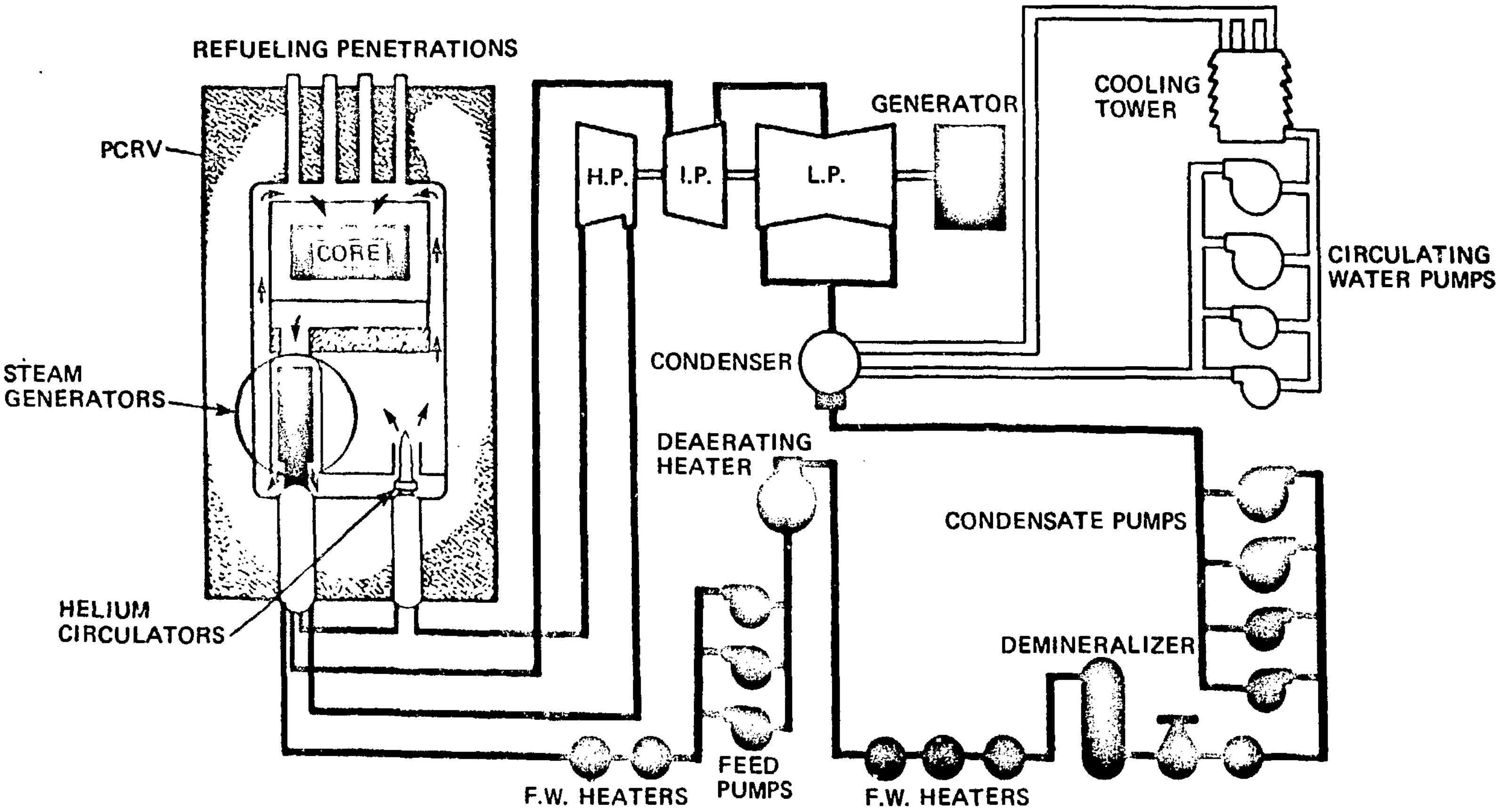

Fig. 1. Flow diagram of the FSV reactor

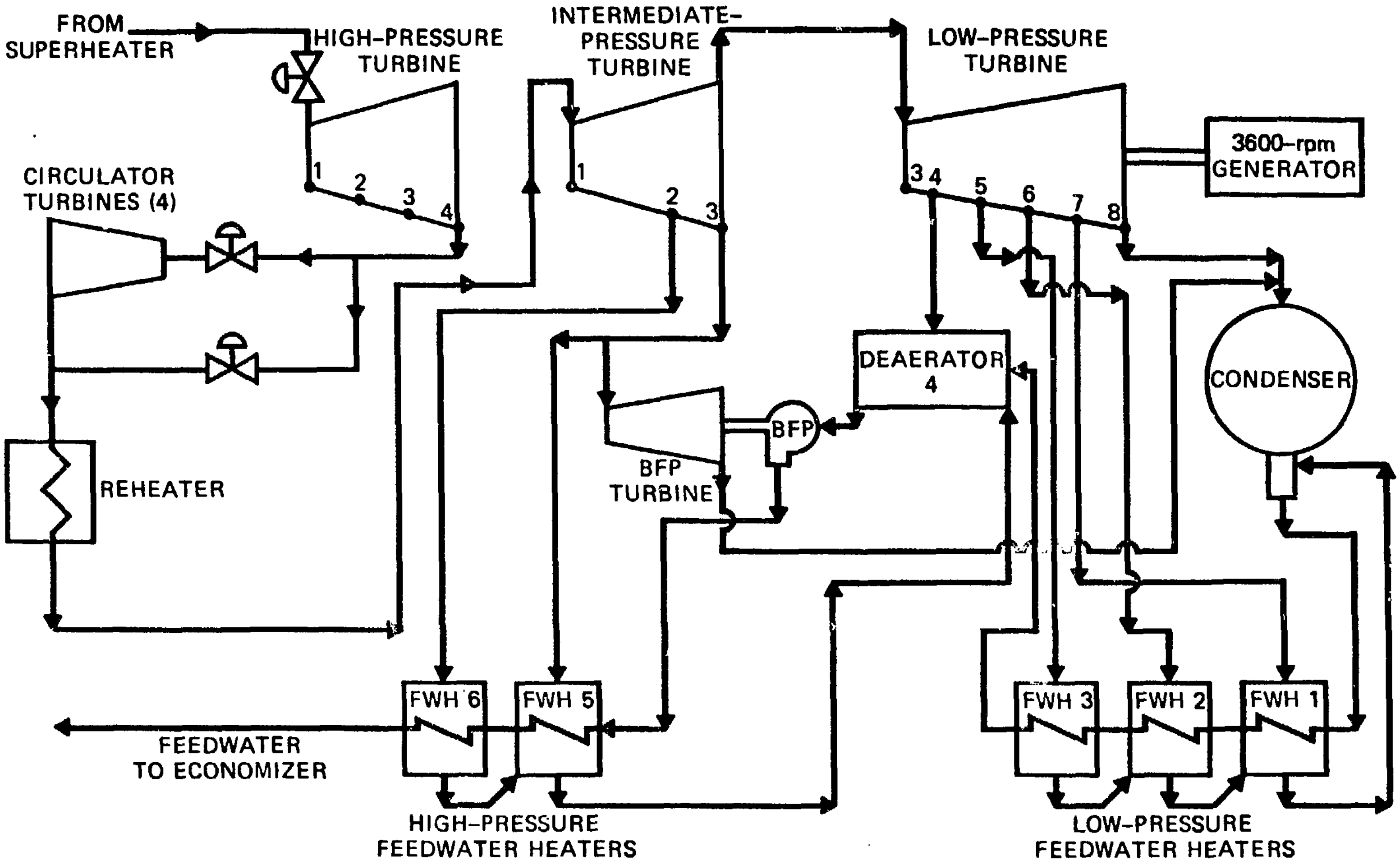

Fig. 2. FSV turbine generator plant diagram

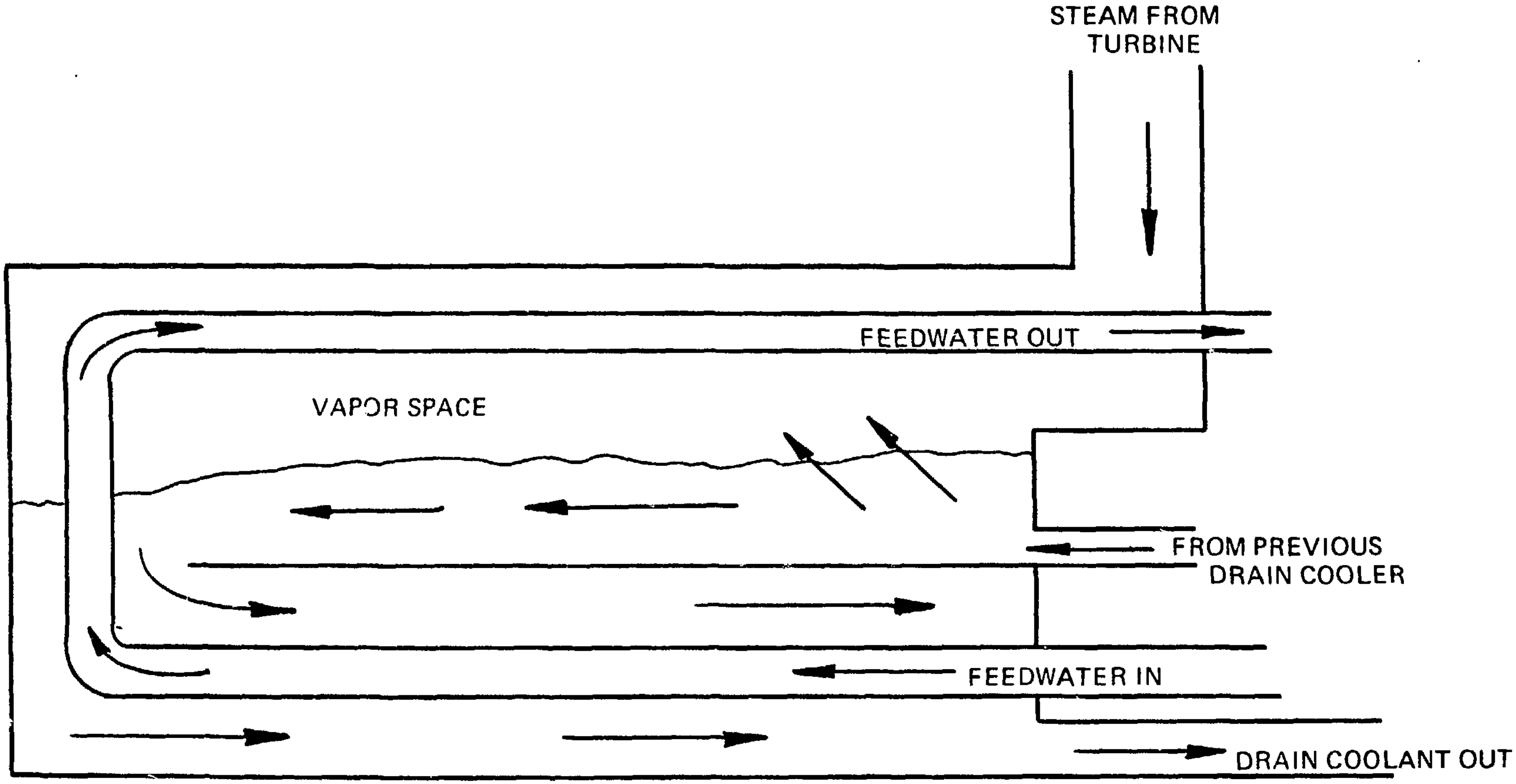

Fig. 3. Closed feedheater

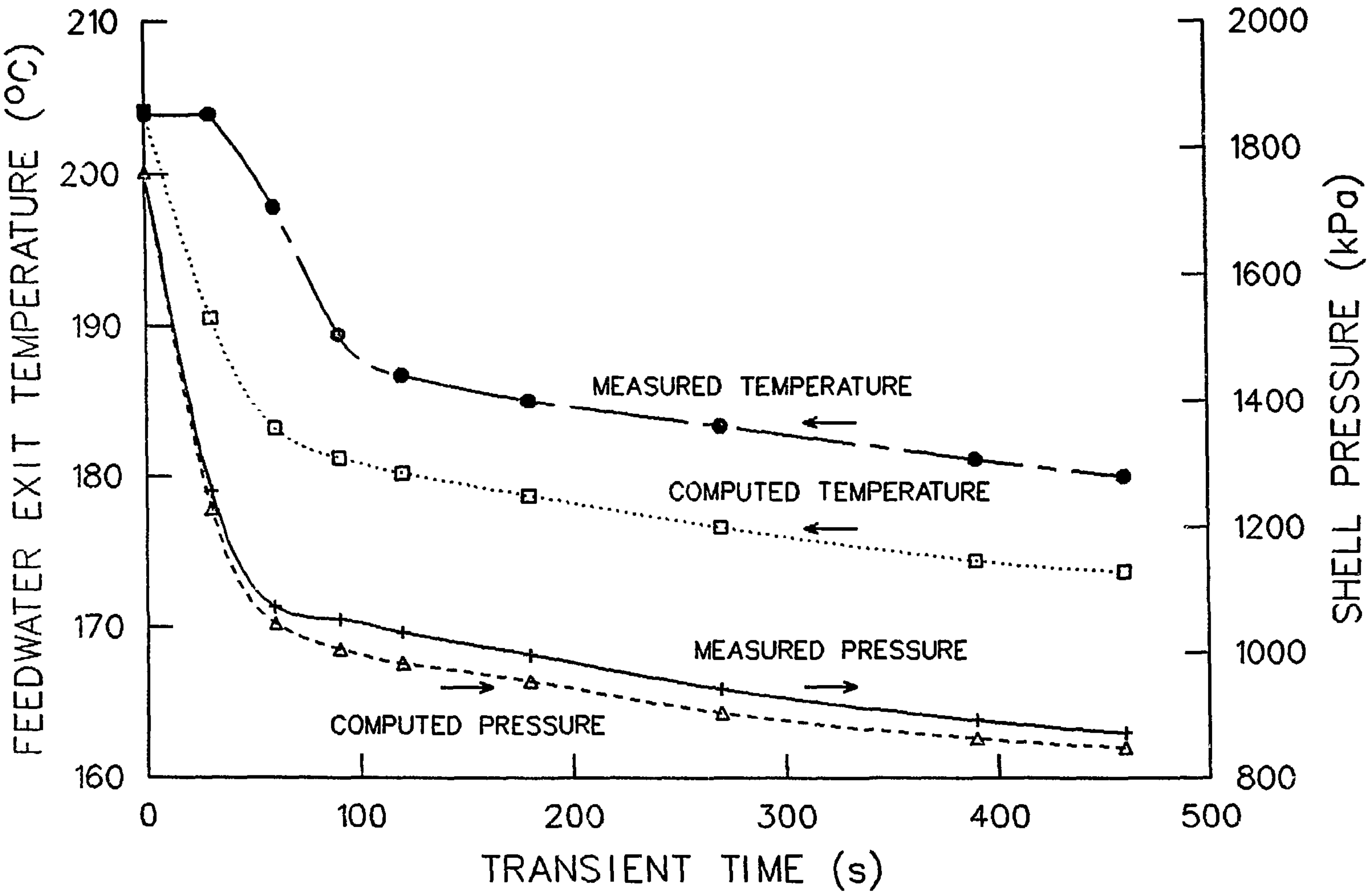

Fig. 4. Response of feedheater 6

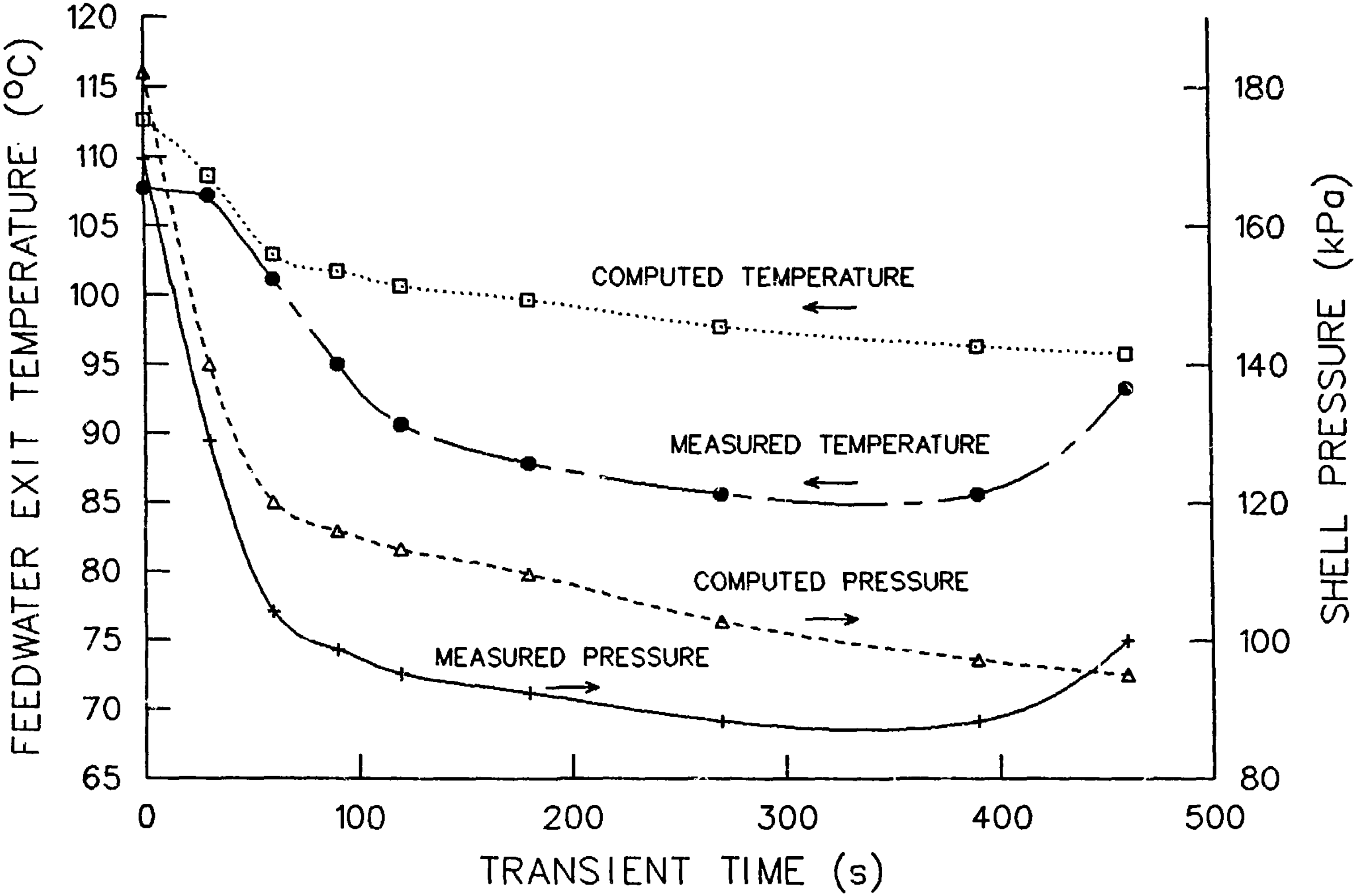

Fig. 5. Response of feedheater 3

Table 1. Pressures for FSV turbine transient of November 9, 1981

Transient time (s)	Extraction point 5 Feedheater 3		Extraction point 4 Feedheater 4		Extraction point 3 Feedheater 5		Extraction point 2 Feedheater 6	
	Computed	Measured	Computed	Measured	Computed	Measured	Computed	Measured
	[kPa (psia)]		[kPA (psia)]		[kPa (psia)]		[kPA (psia)]	
0	182.0 (26.4)	169.6 (24.6)	555.7 (80.6)	601.2 (87.2)	1039.7 (150.8)	1107.3 (160.6)	1762.3 (255.6)	1758.2 (255.0)
30	140.0 (20.3)	128.9 (18.7)	430.2 (62.4)	485.4 (70.4)	749.5 (108.7)	779.1 (113.0)	1228.0 (178.1)	1225.5 (182.1)
60	120.0 (17.4)	104.1 (15.1)	366.1 (53.1)	423.3 (61.4)	637.8 (92.5)	661.9 (96.0)	1045.1 (151.7)	1071.4 (155.9)
90	115.8 (16.8)	98.6 (14.3)	351.6 (51.0)	415.1 (60.2)	612.9 (88.9)	645.3 (93.6)	1004.6 (145.7)	1051.5 (152.5)
120	113.1 (16.4)	95.1 (13.8)	342.7 (49.7)	408.9 (59.3)	597.8 (86.7)	635.0 (92.1)	981.8 (142.4)	1030.8 (149.5)
180	109.6 (15.9)	92.4 (13.4)	333.0 (48.3)	399.9 (58.0)	578.5 (83.9)	619.8 (89.9)	935.5 (138.3)	995.6 (144.4)
270	102.7 (14.9)	88.3 (12.8)	311.6 (45.2)	388.2 (56.3)	541.9 (78.6)	598.5 (86.8)	903.2 (131.0)	941.1 (136.5)
390	97.2 (14.1)	88.3 (12.8)	297.2 (43.1)	373.0 (54.1)	521.2 (75.6)	572.3 (83.0)	862.5 (125.1)	891.5 (129.3)
460	95.1 (13.8)	100.0 (14.5)	289.6 (42.0)	369.6 (53.6)	508.1 (73.7)	560.5 (81.3)	848.1 (123.0)	871.5 (126.4)

Table 2. Feedheater exit temperatures for FSV turbine transient of November 9, 1981

Transient time (s)	Feedheater 1		Feedheater 2		Feedheater 3		Feedheater 4		Feedheater 6	
	Computed	Measured	Computed	Measured	Computed	Measured	Computed	Measured	Computed	Measured
	[°C (°F)]		[°C (°F)]		[°C (°F)]		[°C (°F)]		[°C (°F)]	
0	71.9 (161.4)	66.7 (152.0)	93.4 (200.1)	90.0 (194.0)	112.6 (234.7)	107.7 (226.)	153.3 (307.9)	153.9 (309.0)	204.1 (399.3)	203.9 (399.0)
30	69.6 (157.3)	67.8 (154.0)	91.5 (196.7)	88.9 (192.0)	108.6 (227.4)	107.2 (225.0)	152.1 (305.7)	153.9 (309.0)	190.5 (374.9)	203.9 (399.0)
60	65.4 (149.7)	63.3 (146.0)	86.0 (186.8)	83.9 (183.0)	102.9 (217.2)	101.1 (214.0)	150.7 (303.3)	152.8 (307.0)	183.2 (361.8)	197.8 (388.0)
90	64.0 (147.3)	57.8 (136.0)	83.8 (182.9)	77.8 (172.0)	101.7 (215.2)	95.0 (203.0)	149.2 (300.5)	148.3 (299.0	181.2 (358.2)	189.4 (373.0)
120	63.0 (145.5)	54.4 (130.0)	82.8 (181.0)	74.4 (166.0)	102.6 (213.2)	90.6 (195.0)	147.6 (297.7)	145.6 (294.0)	180.2 (356.3)	186.7 (368.0)
180	62.2 (143.9)	52.2 (126.0)	81.9 (179.5)	71.7 (161.0)	99.6 (211.4)	87.8 (190.0)	144.7 (292.4)	138.9 (282.0)	178.7 (353.7)	185.0 (365.0)
270	60.9 (141.6)	51.7 (125.0)	80.2 (176.3)	70.0 (158.0)	97.7 (208.0)	85.6 (186.0)	140.5 (284.9)	130.6 (267.0)	176.6 (349.8)	183.3 (362.0)
390	59.9 (139.8)	49.4 (121.0)	78.8 (173.9)	68.9 (156.0)	96.3 (205.4)	85.6 (186.0)	135.8 (276.5)	125.6 (258.0)	174.4 (345.9)	181.1 (358.0)
460	59.5 (139.1)	50.0 (122.0)	78.3 (173.0)	77.8 (172.0)	95.8 (204.4)	93.3 (200.0)	133.1 (271.6)	128.9 (264.0)	173.7 (344.7)	180.0 (356.0)

References

1. J. C. Conklin, *ORTURB: A Digital Computer Code to Determine the Dynamic Response of the Fort St. Vrain Reactor Steam Turbines*, ORNL/NUREG/TM-399 (March 1981).
2. R. C. Spencer, K. C. Cotton, and C. N. Cannon, *A Method for Predicting the Performance of Steam Generators ... 16,500 kW and Larger*, General Electric Company, GER-2007C (July 1974).
3. F. E. Swart, Public Service Company of Colorado, letter to J. C. Conklin, Oak Ridge National Laboratory, Feb. 8, 1977.
4. H. I. Bowers, *ORCENT: A Digital Computer Program for Saturated and Low Superheat Steam Turbine Cycle Analysis*, ORNL/TM-2395 (January 1969).
5. C. A. Meyer et al., *Thermodynamic and Transport Properties of Steam*, American Society of Mechanical Engineers, New York (1967).
6. J. G. Delene, *A Digital Computer Code for Simulating the Dynamics of Demonstration Size Dual-Purpose Desalting Plants Using a Pressurized Water Reactor as a Heat Source*, ORNL/TM-4104 (September 1973).
7. *Fort St. Vrain Nuclear Generating Station, Final Safety Analysis Report*, Part 10.2, Table 10.2-1, Public Service Company of Colorado.
8. A. C. Hindmarsh, "*LSODE and LSODI, Two Initial Value Ordinary Differential Equation Solvers,*" ACM Signum Newsletter (December 1980).