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DEVELOPMENT OF TRANSIENT ANALYSIS CODE FOR PRIMARY COOLING SYSTEM COUPLED WITH REACTOR AUXILIARY COOLING SYSTEMS

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ABSTRACT

A plant transient analysis code has been developed to analyze the thermal hydraulics in the primary cooling system, coupled with dynamic characteristics of the residual heat removal (RHR) system and the reactor core isolation cooling (RCIC) system . A new numerical scheme named "flow distribution function" has been developed to calculate long term transients quickly. Prediction accuracies of the code for each function of components, such as thermal transient of a heat exchanger, thermal transport in a pipe, and flow control characteristic of a control system were examined by the experimental data obtained from the tests using the full mock-ups of the advanced thermal reactor (ATR) and the prototype reactor "Fugen". Prediction accuracy for the whole plant behavior was verified by the test simulating the loss-of- power-transient with succeeding RCIC injection at the "Fugen". Main parameters of the plant are predicted within ±10% error. The CPU time needed for the calculation is about 1/30 - 1/300 of the physical time when a super computer VP-100 is used.

INTRODUCTION

A clean-up system, the RHR system, and the RCIC system of the ATR hold a part of their piping in common, as shown in Fig. 1. Heat exchangers, flow control valves, and pumpes are provided in the piping of the systems, and functions are changed by switching valves. Because the systems are linked to the primary cooling system under operations of transients and cool-down conditions, thermal hydraulic characteristics in the core should be calculated coupled with the characteristics of these systems. Moreover, thermal stresses at joints or nozzles of the heat exchangers affected by flow rate change should be estimated in the design to confirm the integrity of the components. Although the RELAP-4 code (1) is also available to analyze operational transients and cool-down processes in a day, it takes the long CPU time to get the result of the ATR configulation. Because, the ATR is a pressure tube type reactor of which core consists of hundreds piping.

The ATRECS (Analysis of Transient of REactor Cooling System) codehas been developed to analyze not only short term transient but also long term plant behavior. The targets of the ATRECS code development were
① the code can be applied to any piping network systems, including the core, heat exchangers, flow control valves, pumps, etc.,
② the code can calculate the thermal hydraulics of the systems for a day with a reasonable computing time,
③ the code can predict main thermal hydraulic parameters of the prototype reactor "Fugen" during transients within ±10% error.

To attain these purposes, a new numerical scheme has been introduced into the code. To verify the applicability of the new method, prediction accuracy was checked.

ANALYTICAL MODELS OF THE ATRECS CODE

The ATRECS code is composed of one dimensional network models, and can simulates the following components.

(1) pumps
(2) valves including check valves
(3) flow control systems
(4) heat exchangers (regenerative and non-regenerative)
(5) piping
(6) a core
(7) steam drums

In regard to boundary conditions, both pressure and flow rate can be considered at joints.

Hydraulic Models

Figure 2 shows an example of the calculation system. Piping is divided into several links by joints expressed as circles. The link is a piece of a pipe which contains inventory. The joint is a point where fluid is mixed or distributed, and it does not hold inventory except a joint which stands for a steam drum. Flow in the links is assumed as a one dimensional single-phase flow. Therefore, the continuity equation and the momentum equation are expressed as follows.

continuity: $$\sum_{i \in C_j} A_i W_i = 0 \tag{1}$$

momentum: $$\ell_i \frac{dW_i}{dt} = (P_{u,i} - P_{d,i}) - \lambda_i \frac{\ell_i}{D_i} \frac{|W_i| W_i}{2 \rho_i} - \rho_i g H_i + \rho_i g H_D \tag{2}$$

where subscript i is link number and C_j is a set of the links connected to the joint j. Temperatures in the links are calculated by the following one point mixing model considering heat transfer between the fluid and the pipe.

fluid: $$\rho C_p \frac{\partial T}{\partial t} + C_p W \frac{\partial T}{\partial z} = \frac{F_W}{A} K_W (T_W - T) \tag{3}$$

pipe: $$\rho_W C_W \frac{dT_W}{dt} = \frac{F_W}{A_W} K_W (T - T_W) \tag{4}$$

$$K_W = \frac{2 \pi K}{\dfrac{1}{r_I h} + \dfrac{1}{k_W} \ell n \dfrac{r_I + r_O}{2 r_I}} \tag{5}$$

where subscript i is eliminated.

On the other hand, a new numerical scheme named "flow distribution function" β, defined as a ratio of flow rate in the spatial point k and the flow rate at the inlet of the core W_i, is introduced to express the momentum equation in the core.

momentum:
$$L \frac{dW_{in}}{dt} = (P_u - P_d) - \phi^2 \zeta_k \frac{|\beta_k| \beta_{k+1}}{2 \rho_{l,k}} |W_{in}| W_{in} - \rho_k g H_k - A_k \left\{ \frac{\beta_{k+1}^2}{\rho_{k+1}} - \frac{\beta_k^2}{\rho_k} \right\} |W_{in}| W_{in} \tag{6}$$

where,

$$L = \sum_{k=in}^{out} Z_k \beta_k \tag{7}$$

$$\beta_k = \frac{W_k A_k}{W_{in} A_{in}} \tag{8}$$

Density ρ is defined as a function of void fraction α by the following expression.

$$\rho = \alpha \rho_g + (1-\alpha) \rho_l \tag{9}$$

The continuity equation and the energy equation in the core are expressed as follows.

continuity:
$$\frac{\partial \rho}{\partial t} + \frac{\partial W}{\partial z} = 0 \tag{10}$$

energy:
(axial direction)
$$\frac{\partial (\rho i)}{\partial t} + \frac{\partial (Wi)}{\partial z} = \frac{F_f}{A} q \tag{11}$$

In regard to radial direction, The following equations are used to solve the temperatures in a pellet, a cladding, and a pressure tube.

pellet:
$$\rho_P C_P \frac{dT_P}{dt} = \frac{F_P}{A_P} K_P (T_f - T_P) + \frac{q_P}{z} \tag{12}$$

cladding:
$$\rho_f C_f \frac{dT_f}{dt} = \frac{F_P}{A_f} K_P (T_P - T_f) + \frac{F_f}{A_f} K_f (T - T_f) \tag{13}$$

fluid:
$$\frac{\partial (\rho i)}{\partial t} + \frac{\partial (Wi)}{\partial z} = \frac{F_f}{A} K_f (T_f - T) + \frac{F_w}{A} K_w (T_w - T) \tag{14}$$

pressure tube: $$\rho_W C_W \frac{dT_W}{dt} = \frac{F_W}{A_W} K_W (T - T_W) + \frac{F_{W,0}}{A_W} K_{W,0}(T_0 - T_W) \qquad (15)$$

Because these equations are expanded to the finite-difference forms by the implicit method, a large time mesh is available in the calculation. In the present time step, the flow rate in the core entrance is obtained by solving a matrix. Since flow distribution in the core is calculated by the adoption of the flow distribution function in the past time step, only one integration takes over many integrations along the axis of the core. Therefore, calculational speed of the code is very high.

Pump Model

In regard to pumps, the following dynamic equation is used.

$$\frac{dN}{dt} = \frac{2}{\pi G_D{}^2} \left(T_m - \frac{\rho g H_D Q}{2\pi \eta N} - T_0 \right) \qquad (16)$$

Q - H curves are used to determine the relationship between volumetric flow rate and pump head.

Steam Drum Model

A steam drum is divided into a baffle region, a vapor region, a saturated water region, and a subcooled region under a feed water pipe as shown in Fig. 3. The following mass and energy balances for saturated region are considered.

$$\frac{dG_S}{dt} = n W_R A_R - G_{CD} - G_{MS} - G_{CU} \qquad (17)$$

$$\frac{dE}{dt} = n W_R A_R i_R - G_{CD} i_{CD} - G_{MS} i_{MS} - G_{CU} i_{CU} \qquad (18)$$

In regard to the subcooled region, mass balance of G_{CD}, G_{CU}, feed water flow rate and downcomer flow rate are considered. G_{CU} means flow rate of carryunder caused by the condensation at the feed water pipe level. This value was measured using a mock-up and the "Fugen", and correlated . Moreover, a safety relief valve can be considered by option. Discharge flow rate from the valve is calculated by the equation of critical flow based on a gas flow.

Volume Change Model

In the theory of a single phase flow, one dimensional piston flow is assumed, and density of the fluid is assumed constant in the interval of a time mesh. Therefore, volumetric change of the fluid due to temperature change should be considered. The flow rate due to shrink or expansion is calculated by the following equation.

$$G_C = \frac{\Sigma(\rho_i{}^n - \rho_i{}^{n-1}) V_i}{\Delta t} \qquad (19)$$

This flow rate must be added to the flow rate in the link i.

Heat Exchanger Model

A shell-and-tube exchanger is assumed in the model. Energy equations for fluid in the tube, fluid in the shell, tubes and a shell are expressed by the following equations.

$$\text{tube:}\quad \rho_1 Cp_1 \frac{\partial T_1}{\partial t} + W_1 Cp_1 \frac{\partial T_1}{\partial x} = \frac{F}{A_1} h_{1T}(T_T - T_1) \qquad (20)$$

$$\text{fluid in tube:}\quad \rho_2 Cp_2 \frac{\partial T_2}{\partial t} + W_2 Cp_2 \frac{\partial T_2}{\partial x} = \frac{F}{A_2} h_{2T}(T_T - T_2) + \frac{F}{A_2}(T_{SH} - T_2) \qquad (21)$$

$$\text{fluid in shell:}\quad \rho_T C_T \frac{\partial T_T}{\partial t} = \frac{F_{1T}}{A_T} h_{1T}(T_1 - T_T) + \frac{F_{2T}}{A_T}(T_2 - T_T) \qquad (22)$$

$$\text{shell:}\quad \rho_{SH} C_{SH} \frac{\partial T_{SH}}{\partial t} = \frac{F_{SH}}{A_{SH}} h_{SH2}(T_2 - T_{SH}) \qquad (23)$$

Control System Model

A proportional and integral (PI) control system is prepared to control flow rate by a valve. Models concerning PI, output limiter, dead band, dead time, Cv characteristic of a valve, and time lag of flow rate detection are considered in the system. This model is used to control flow rate to the set point.

Correlations

To solve the equations mentioned before, correlations about heat transfer coefficients, friction factors, two-phase multipliers, quality-void relationship, etc. are necessary.

The Dittus-Boelter (2) equation is used as the heat transfer correlation in single-phase. And the correlation of Jens-Lottes (3) is used to calculate the nucleate boiling heat transfer coefficient. The Donohue (4) correlation is used to evaluate the heat transfer in the shell of a shell-and-tube exchanger.

Friction factor is calculated by the approximate equation of the Moody's curves when Reynolds number is greater than 2300, and the correlation for laminar flow is used for Reynolds number less than 2300.

In regard to two-phase multipliers, several correlations are used. A typical correlation is one obtained assuming a homogeneous two-phase flow. And various correlations for a bundle, a bend, and a riser are incorporated into the codes based on the data obtained from characteristic tests using full mock-ups of the ATR.

In regard to quality-void relationship, the drift flux model proposed by Wallis (5), and other models like the Smith's (6) correlation are used.

VERIFICATION OF THE CODE AND DISCUSSION

The verification of the ATRECS code has been conducted from the stand point of grasping prediction accuracies in the calculations not only for each function but also for an integrated system. To check the functions of pump and heat exchanger models, data obtained from the 14 MW heat transfer loop shown in Fig. 4 was used. The loop is composed of pumps, 14 MW heaters, steam drums, heat exchangers. On the other hand, data of the prototype "Fugen" was used to check the controllability of the control valve and to check the plant behavior in the long term. A schematic diagram of one of two loops of the "Fugen" is shown in Fig. 5.

Pump Operation

Figure 6 shows the schematic diagram of joints and links used to calculate pump characteristics. A pump was provided at link 104, and pressure and flow rate were measured at the outlet of the pump. Rated conditions of the pump are listed in Table 1. The pump was operated at 6.4 MPa in the system pressure. Comparison of the outlet pressure and flow rate between measured and predicted results is shown in Fig. 7. The code can trace the experimental results concerened with flow rate and pressure with good precision.

Thermal Transient of A Heat Exchanger

Figure 8 shows the schematic diagram of the calculation system containing a shell-and-tube exchanger. In the test, the flow rate of the primary system was reduced from 75 t/h to 35 t/h and increased to the original flow rate. The system pressure of the primary system was 7 MPa, coolant temperature was 284℃. The flow rate of the secondary system was kept constant, and inlet temperature about 26 ℃. These temperatures were measured with resistant thermometer bulbs of 0.1℃ accuracy.

Figure 9 shows the comparison of the outlet temperatures of the primary and the secondary systems between experiment and prediction. Flow rates of both systems are given as boundary conditions. Temperature histories are precicted with good precision. Therefore, the ATRECS code can be used to evaluate the thermal stress occurring at nozzles due to rapid temperature change.

Flow Control

Figure 10 shows the schematic diagram for the analysis of the flow control test conducted at the "Fugen" using the RCIC system. The line is composed of a pump, a heat exchanger, a control valve and a steam drum. Flow rate of the RCIC system was controlled by the stepwise requirement signal. Figure 11 shows the comparison of flow rate between experiment and prediction. Both results coincide with each other. The flow control model incorporated into the ATRECS code has been proved to work well.

System Test

A simulating test of the loss of power accident (LOPA) and a RCIC water injection were conducted at the "Fugen" reactor site. Figure 12 shows the schematic diagram of the primary cooling system of the "Fugen" reactor for the evaluation of prediction accuracy. The plant had been operated at 55 % electric power. The plant was tripped at time zero. The RCIC system was operated after the plant became steady. Experimental and predicted results in regard to pressure, water level in the steam drum, temperature in the lower header, and revolutional speed of the recirculation pump are compared in Fig. 13.

When the plant was tripped, the pressure in the steam drum was increased due to closure of the main steam isolation valves. Voids in the core were colapsed and the amoumt of coolant in the core increased. Therefore, the water level in the steam drum decreased once. However, the system pressure decreased soon due to decreasing of void generation in the core. The plant parameters levelled off after 250 seconds. These behaviors are predicted well by the ATRECS code. The

RCIC system was initiated about 900 seconds after the LOPA. The system pressure was decreased and the water level was increased due to injection of subcooled water. The behaviors of water level recovery and pressure reducing are predicted with good precision by the ATRECS code. The CPU time needed for the calculation is about 1/300 of the real time in this case, when a super computer VP-100 is used.

The ATRECS code has an ability to analyze thermal hydraulics in the complex piping network shown in Fig. 1 thirty times as fast as the time of the real phenomena. Therefore, this code can be used for the design of the RHR and RCIC systems.

SUMMARY

The ATRECS code has been developed to analyze the thermal hydraulics in a complex piping network including heat exchangers, control valves, pumps, etc. A new numerical scheme was introduced to solve the momentum equation in the two-phase flow regime. As the result, the code can stably calculate complex piping network systems faster than the actual time. The prediction accuracy of the code has been checked by data of characteristic tests using full mock-ups of the ATR and system tests conducted using the prototype reactor "Fugen". Main parameters of the plant are predicted within ±10% error.

NOMENCLATURE

A : flow area or cross sectional area (m^2)
A_W : cross sectional area of pipe material (m^2)
C_j : a set of links connected to the junction j
C or C_p : specific heat (W/kg K)
D : hydraulic equivalent diameter (m)
E : energy (J)
F : heat transmission area per unit length (m^2/m)
g : grairtational acceleration (m/s^2)
$G_D{}^2$: Inertia of pump and motor ($kg \cdot m^2$)
H : height of a link (m)
H_D : pump head (m)
h : heat transfer coefficient (W/m^2K)
i : enthalpy (J/kg)
k : thermal concluctivity (W/m K)
K : over-all coefficient of heat transmission (W/m^2K)
ℓ : length of a link
n : number of channels
N : revolutional speed (1/s)
P : pressure (Pa)
q : heat flux (W/m^2)
Q : volumetric flow rate (m^3/s)
r : radius (m)
t : time (s)
T_m : torque of motor ($N \cdot m$)
T_o : torque of friction ($N \cdot m$)
V : volume of link (m^3)
W : mass velocity ($kg/m^2 \cdot s$)
z : axial mesh length (m)
α : void fraction (-)
β : flow distribution function (-)
ζ : loss coefficient (-)
ρ : density (kg/m^3)
ϕ^2 : two phase multiplier (-)

subscript

1 : in tube
2 : in shell
C : change
CD : saturated to subcooled region
CU : carryunder
d : downstream
f : cladding
g : vapor
i : link i
I : inner
j : junction j
k : axial point in core
ℓ : liquid
MS : main steam
O : outer
P : pellet
R : riser
S : saturated
SH : shell
T : tube
W : pipe

super script

n : calculation step

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(5) Wallis, G. B., "One-dimensional Two-phase Flow" , McGraw Hill Book Company.

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TABLE 1 PUMP CHARACTERISTICS

ITEM		RATED CONDITION
FLOW RATE	(m^3/h)	140
PUMP HEAD	(m)	150
REVOLUTION	(r. p. m.)	2960
POWER	(kW)	120
$\overline{GD^2}$	$(kg\ m^2)$	6.98

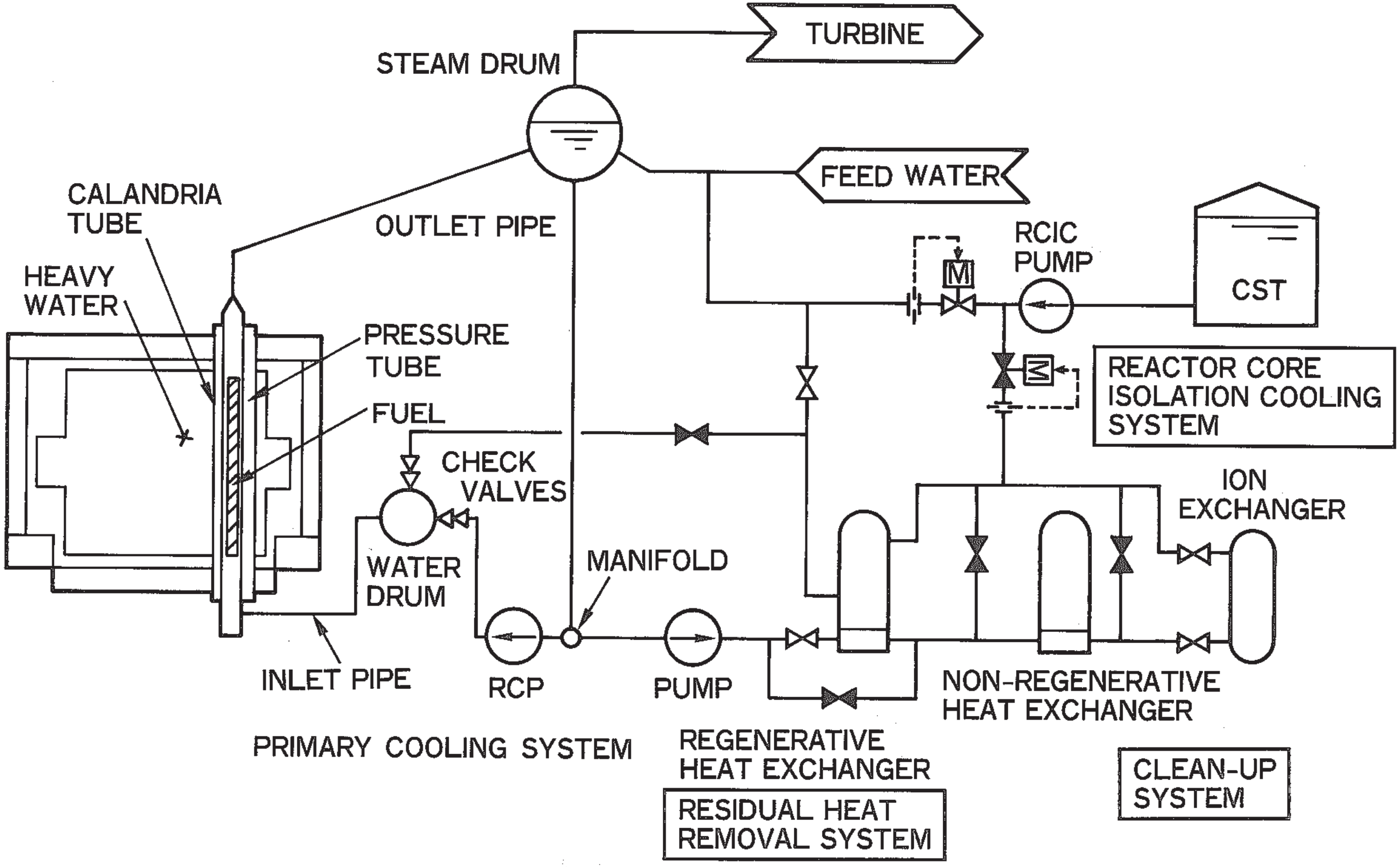


FIG. 1 SCHEMATIC DIAGRAM OF THE ATR AUXILIARY COOLING SYSTEM

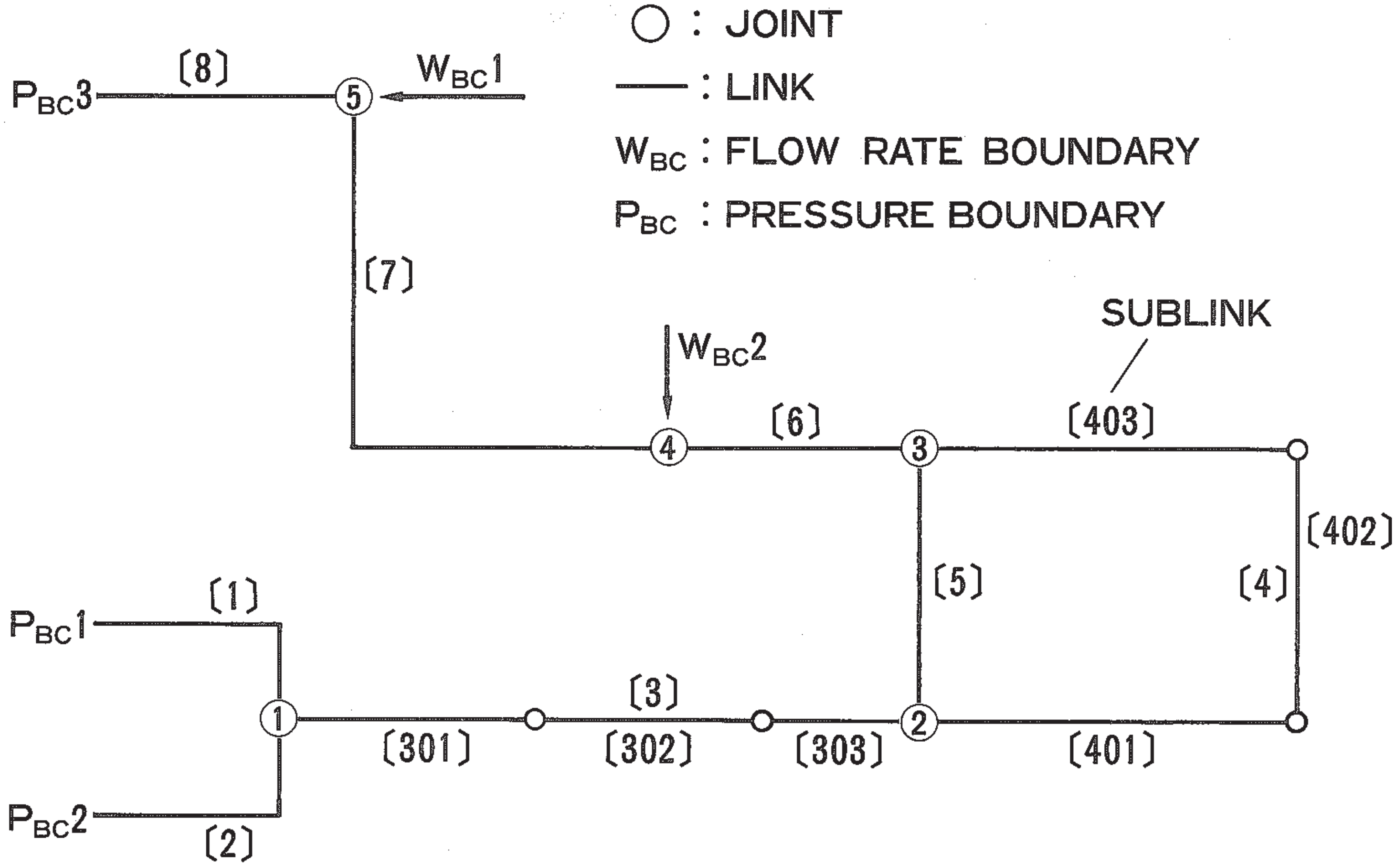


FIG. 2 AN EXAMPLE OF CALCULATION SYSTEM

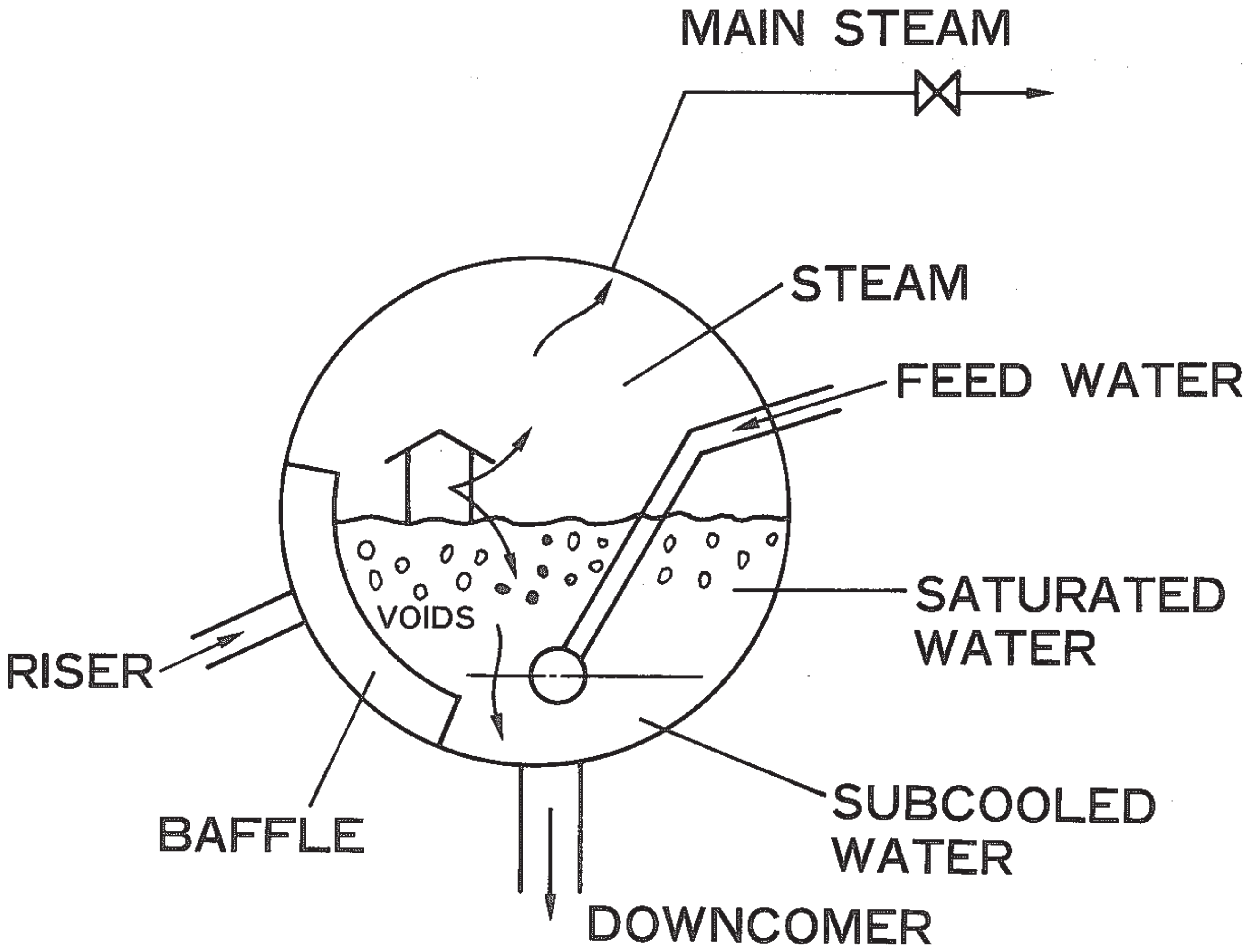


FIG. 3 STEAM DRUM MODEL

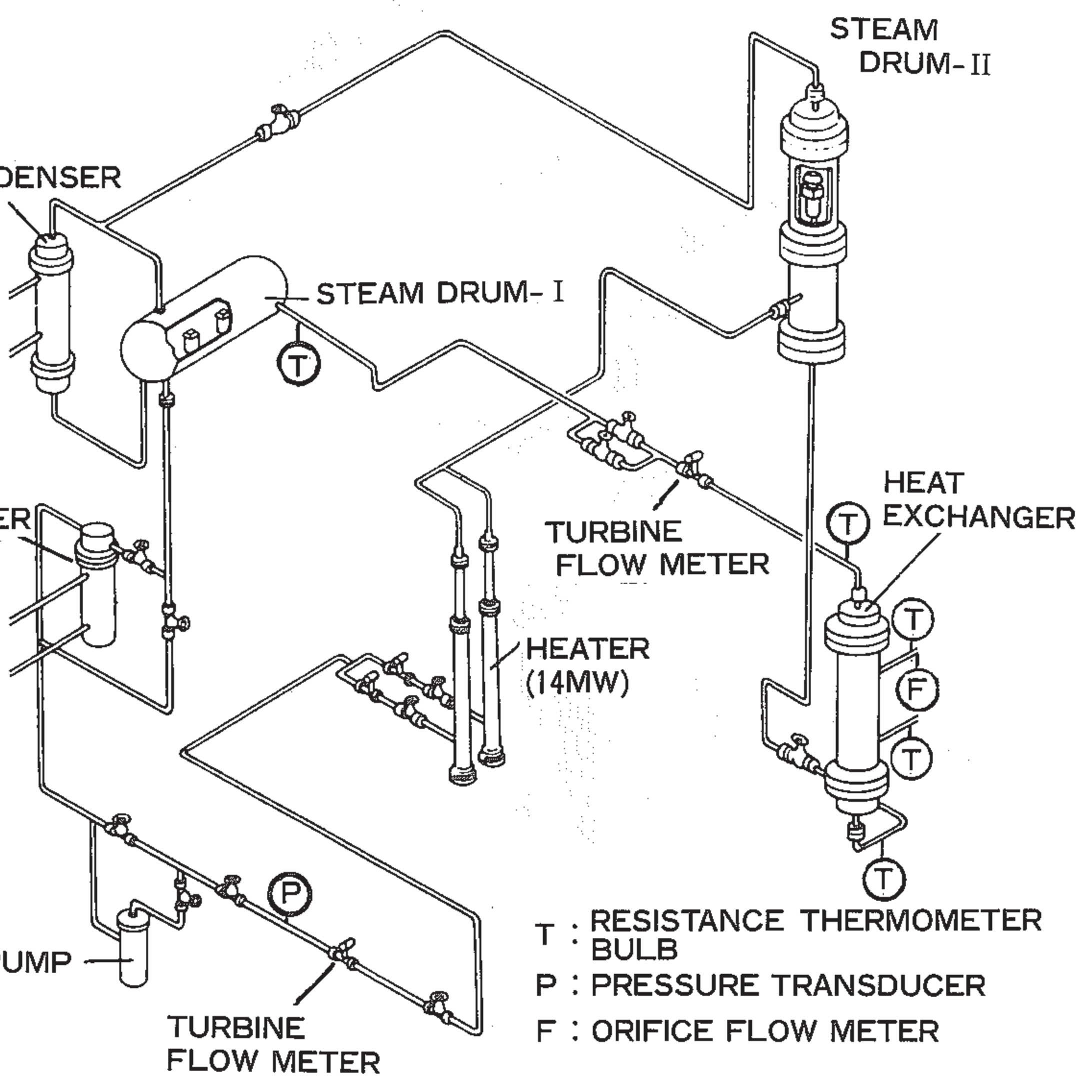


FIG. 4 THE 14MW HEAT TRANSFER LOOP

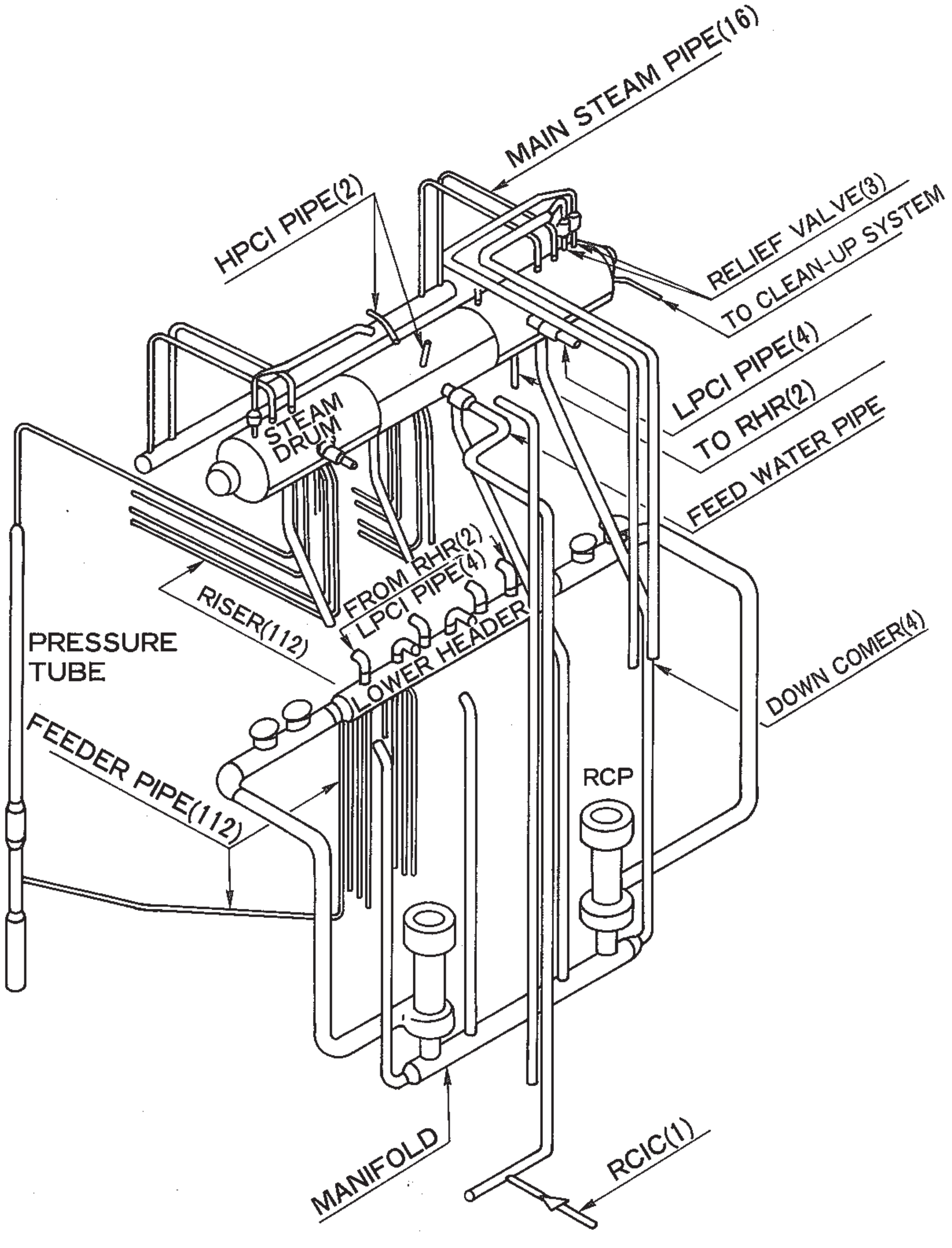


FIG. 5 SCHEMATIC DIAGRAM OF THE FUGEN PRIMARY COOLING SYSTEM

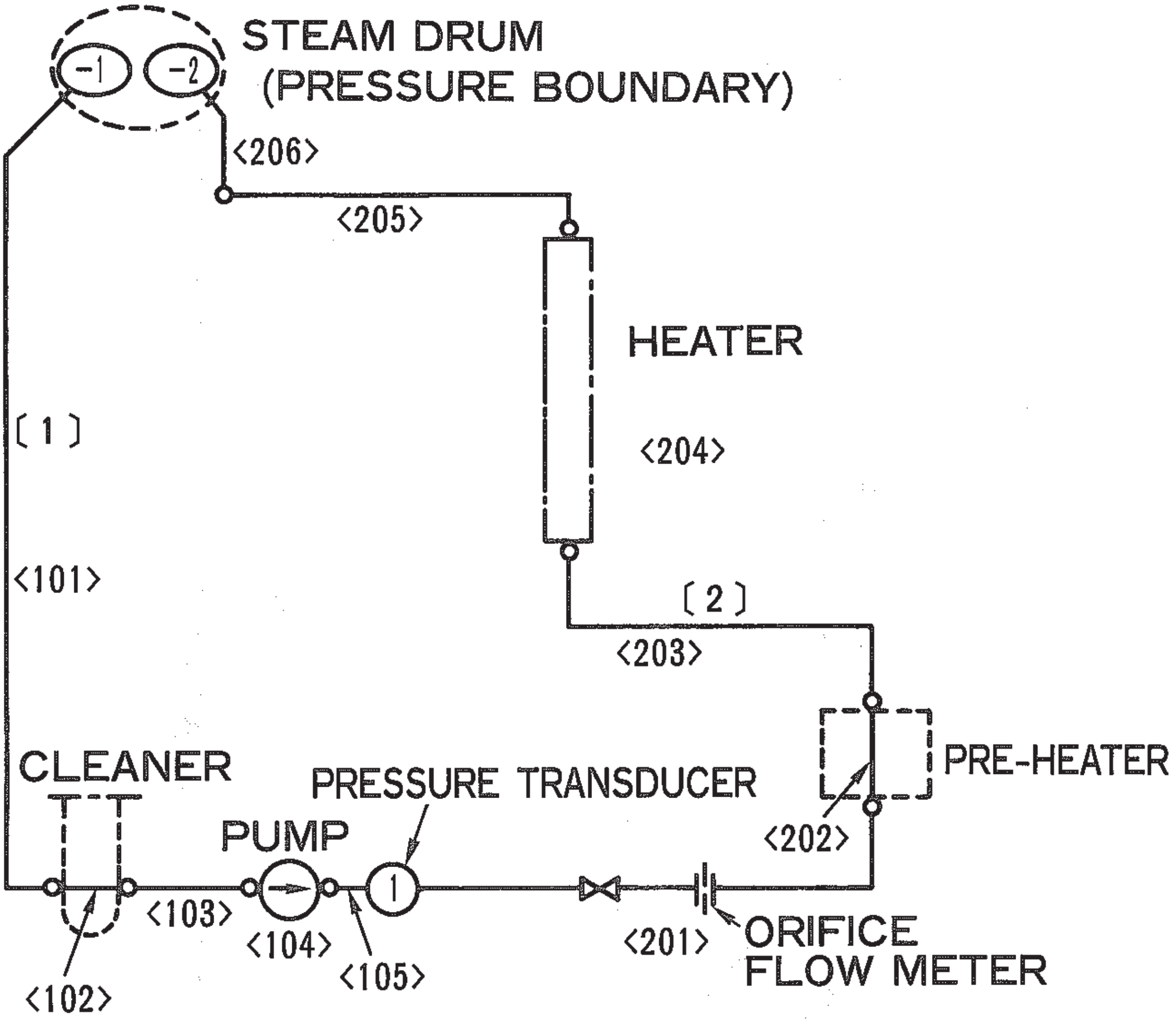


FIG. 6 SCHEMATIC OF PUMP CHARACTERISTIC TEST

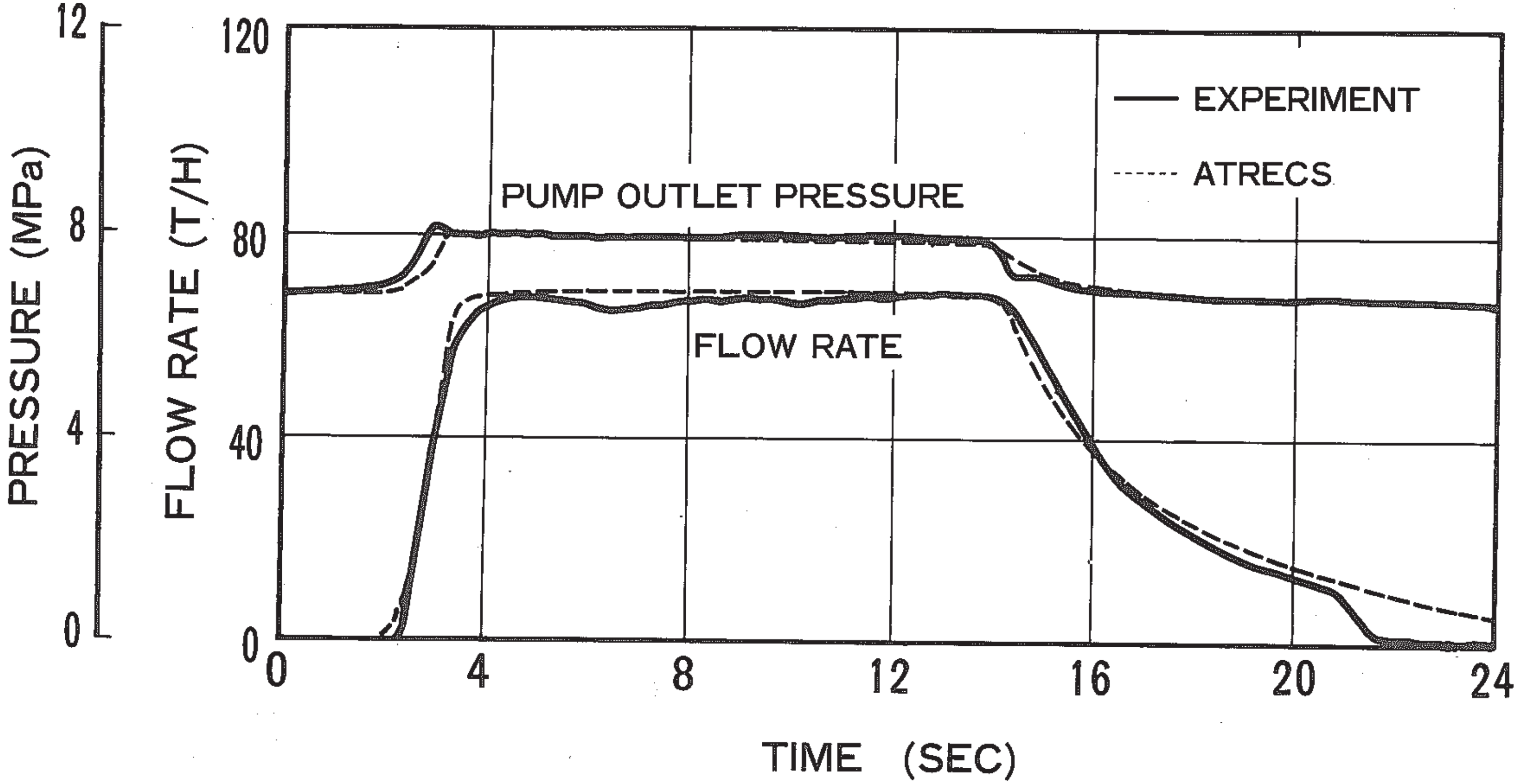


FIG. 7 PUMP CHARACTERISTIC TEST

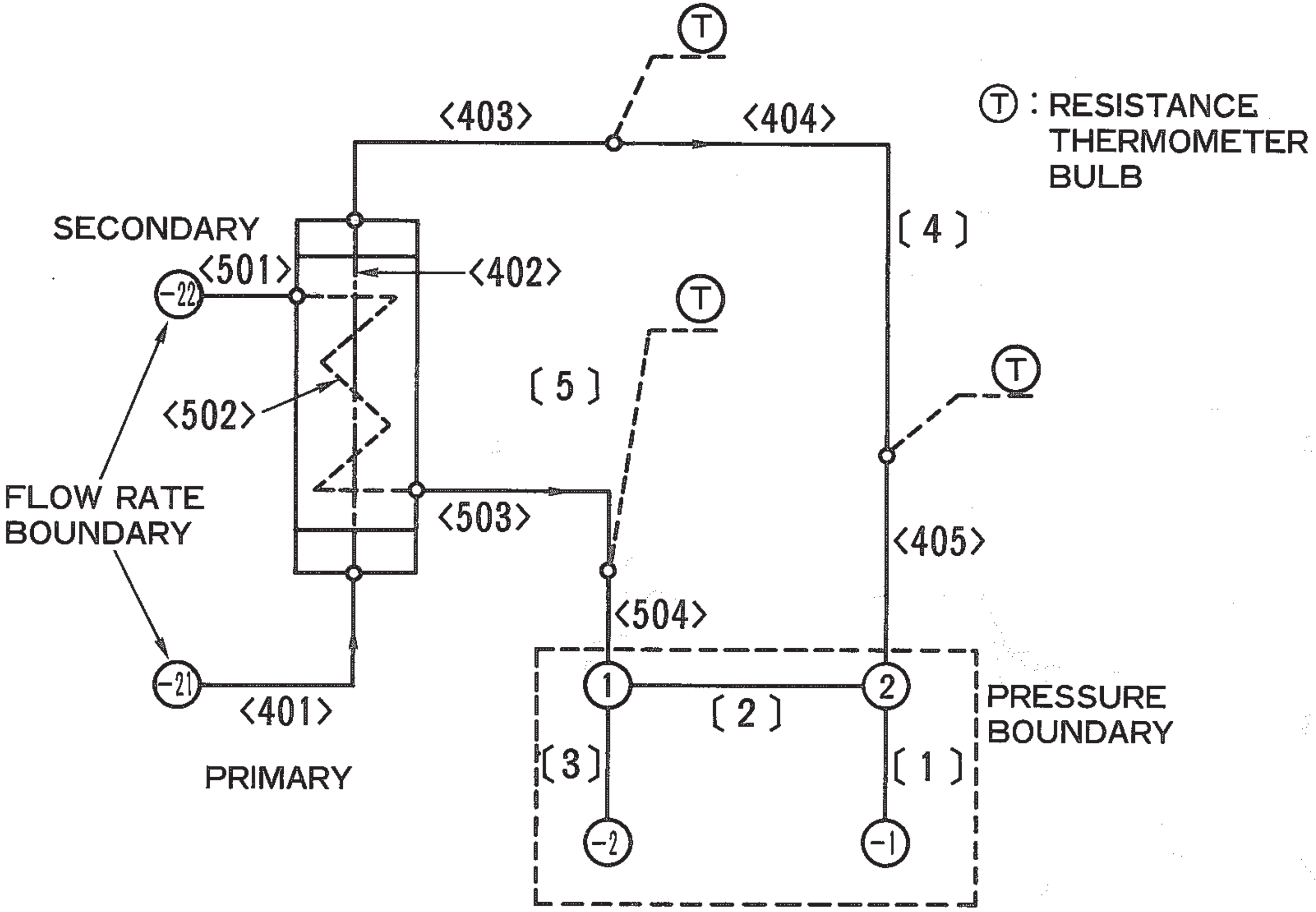


FIG. 8 SCHEMATIC OF HEAT EXCHANGER CHARACTERISTIC TEST

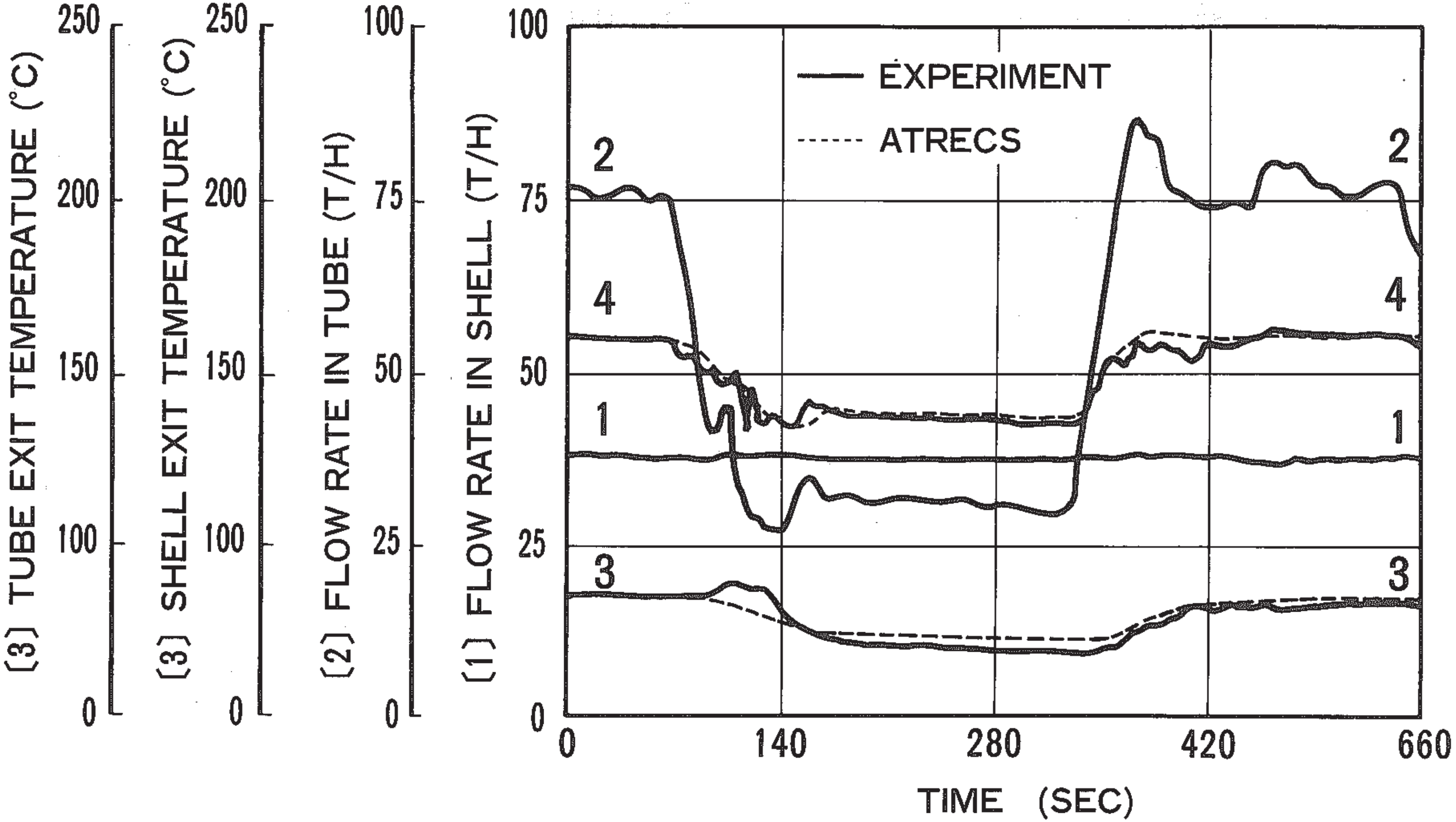


FIG. 9 HEAT EXCHANGER CHARACTERISTIC TEST

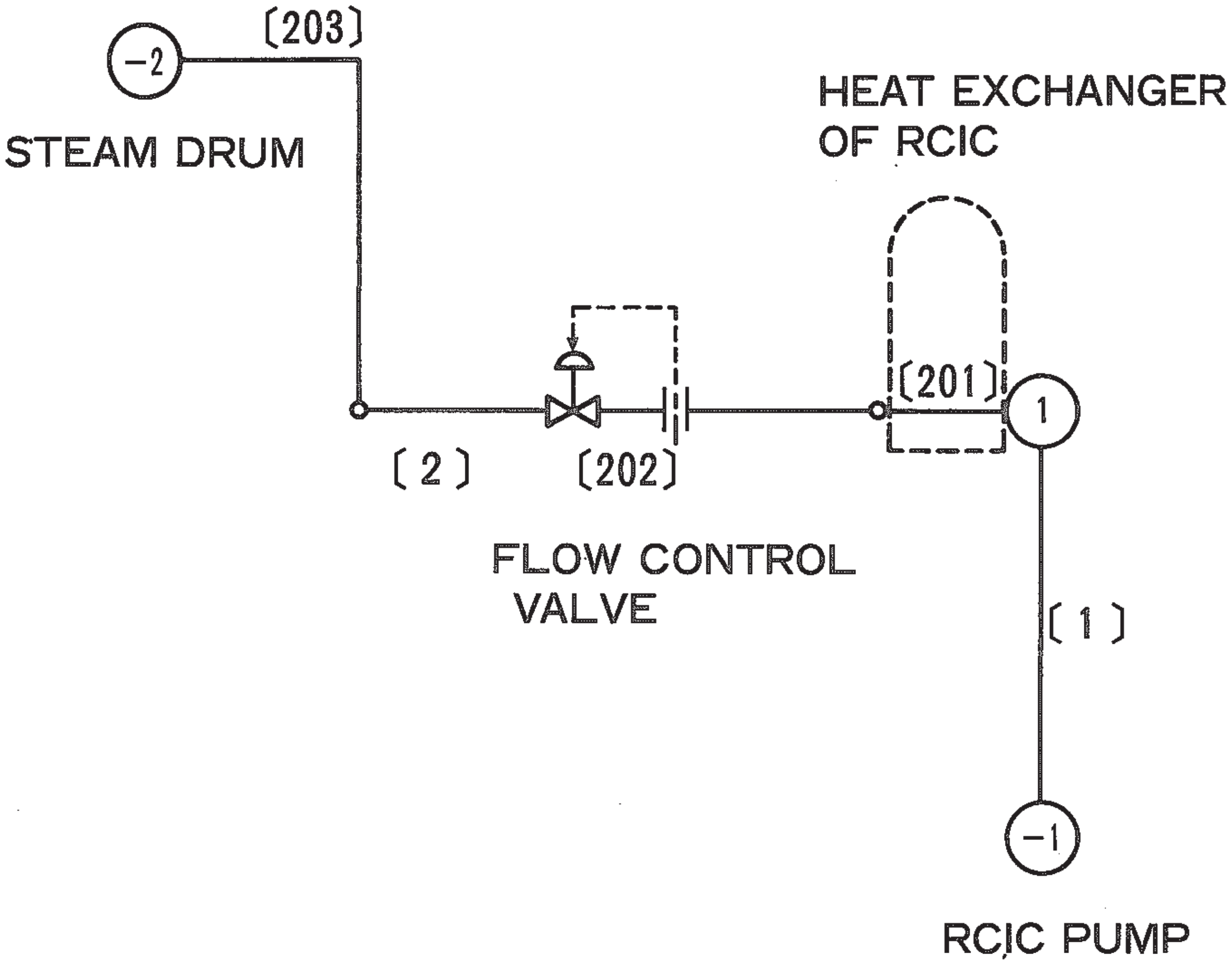
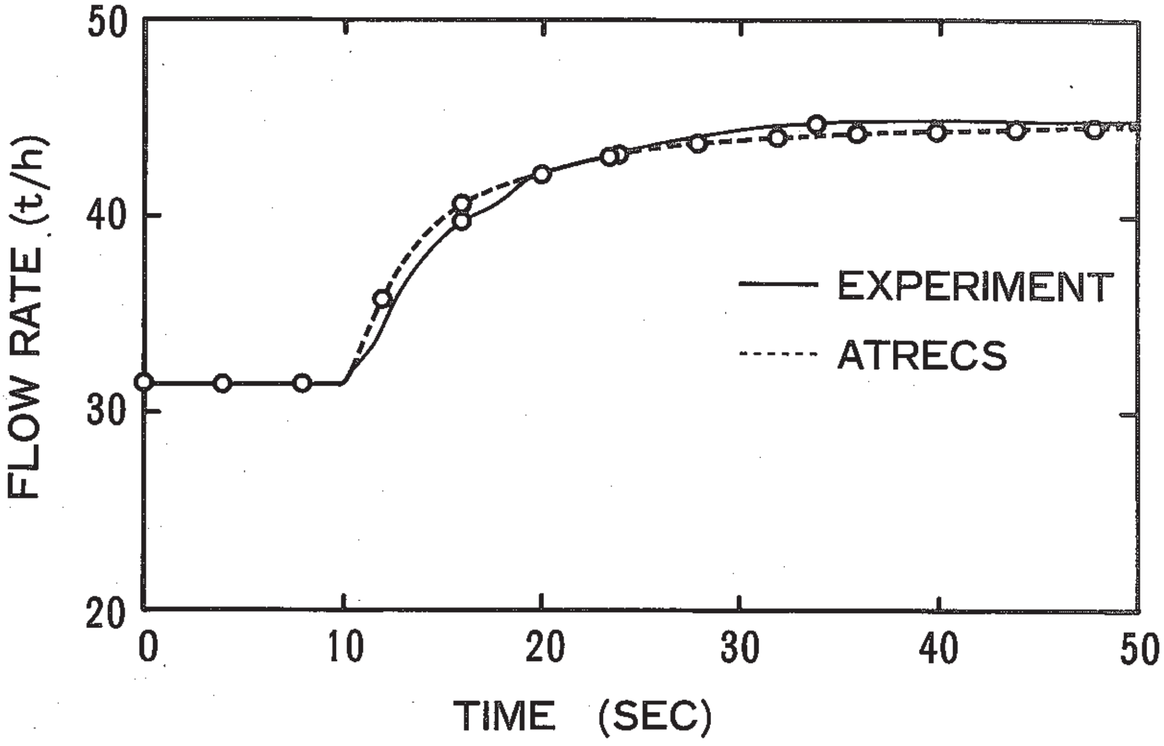


FIG. 10 SCHEMATIC OF FLOW CONTROL CHARACERISTIC TEST



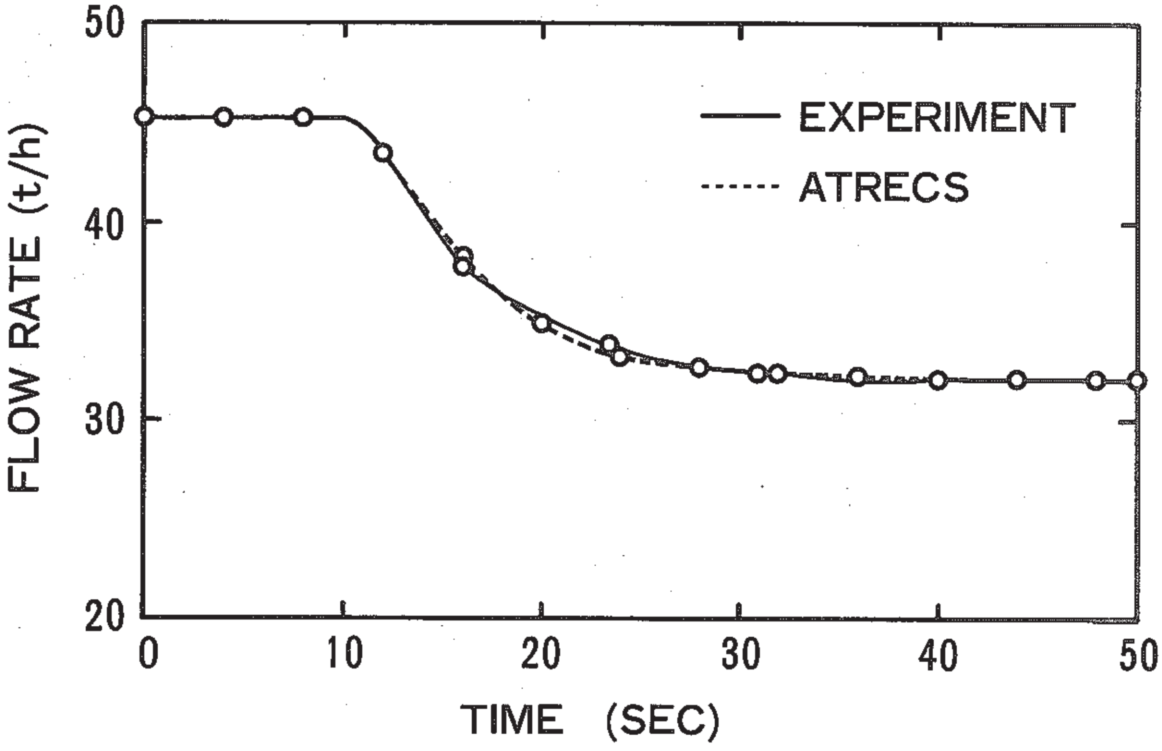


FIG. 11 FLOW CONTROL TEST

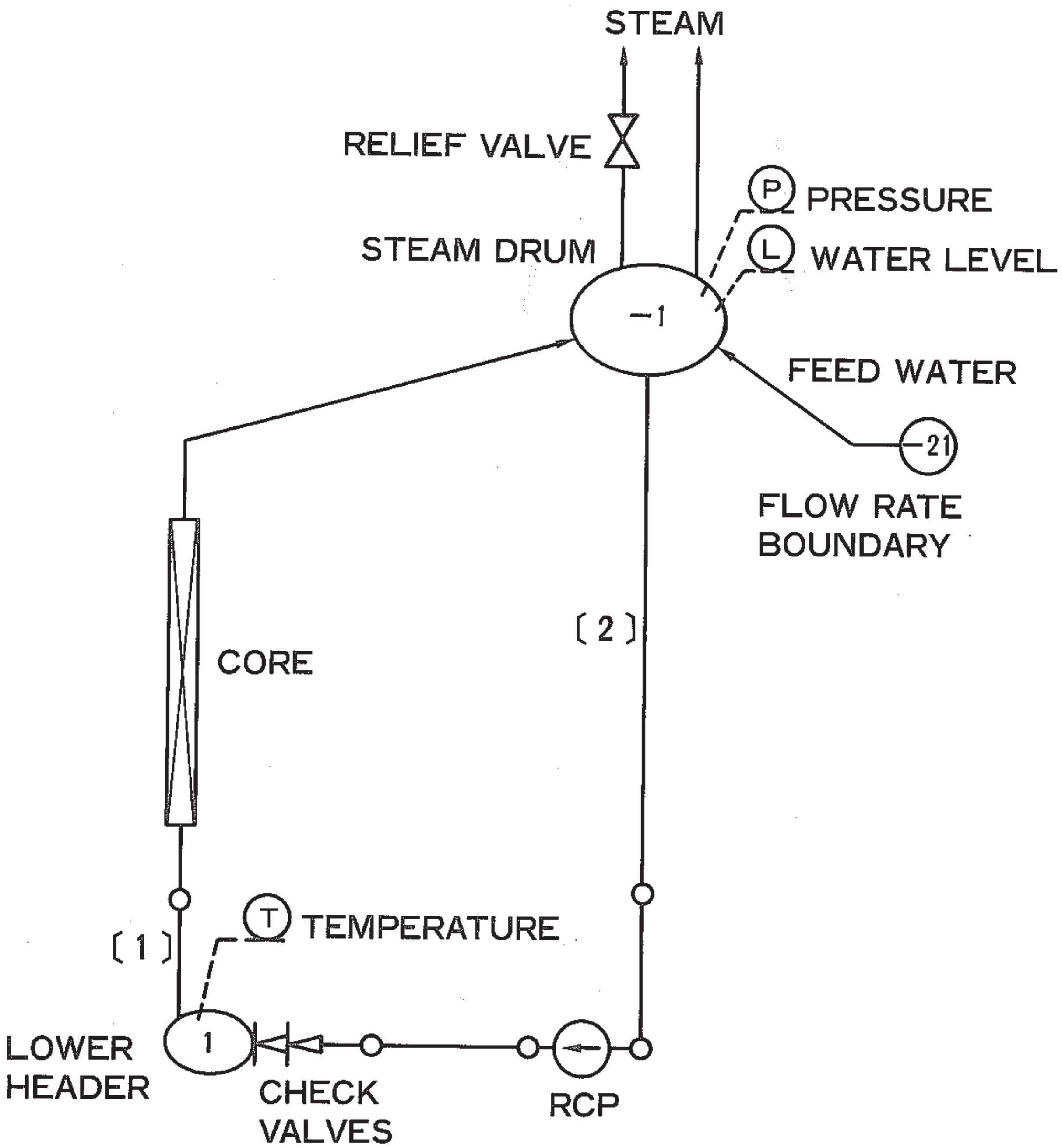


FIG. 12 SCHEMATIC OF SYSTEM TEST USING "FUGEN"

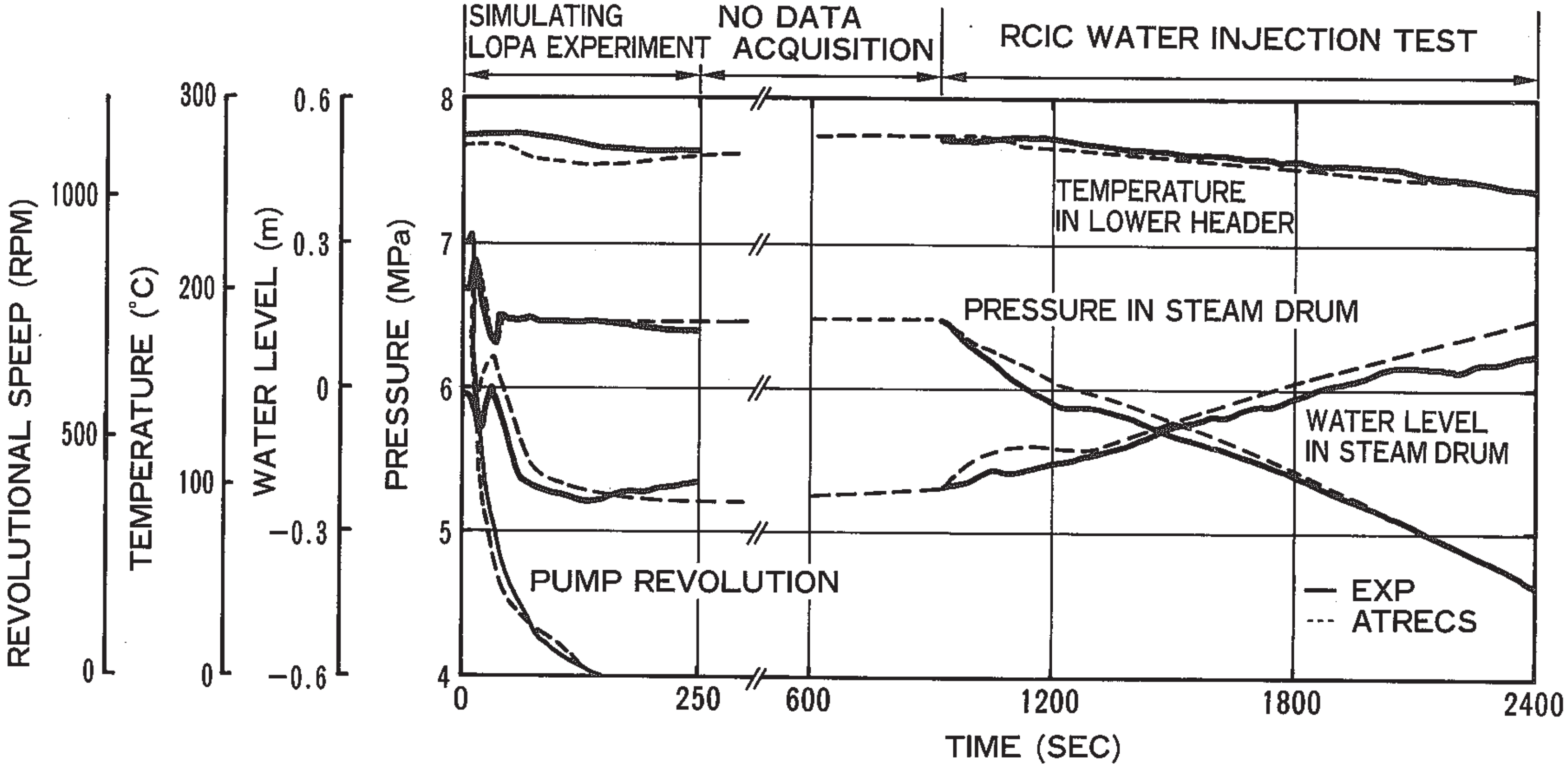


FIG. 13 LOPA AND RCIC OPERATION TEST