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Yoshihiro KIKUCHI and Kazuo HAGA

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ABSTRACT

Experimental studies were carried out on transient sodium boiling in an electrically heated 19-pin bundle under loss-of-flow conditions.

In the first series of experiments temperature distributions in the bundle were measured under initial steady state non-boiling conditions. The measured temperature distributions agreed fairly well with the calculation by the computer code NORMAL.

In the second series of experiments transient boiling phenomena were investigated under loss-of-flow conditions. No high superheat was observed for boiling initiation. The observed coolant voiding was initially limited to the center subchannel because of steep temperature gradient in the bundle and then spread slowly.

INTRODUCTION

In the earlier forced convection boiling experiments(1)(2) the observed two-phase flow pattern was in the sequence of bubbly flow, slug flow and annular (mist) flow in sodium as in the case of water. In the transient boiling experiments under loss-of-flow conditions,(3)(4)(5) however, it was revealed that the voiding pattern observed in the single-pin geometry agreed fairly well with the calculation by the NAIS-P2 code (single-bubble slug expulsion model), whereas in the seven-pin geometry two-dimensional voiding patterns were dominant.

The present experiments have been conducted to investigate transient sodium boiling in a 19-pin bundle under loss-of-flow conditions. In addition, the experimental results of temperature distributions in the bundle under initial steady state non-boiling conditions will be compared with the calculation by a computer code NORMAL.

EXPERIMENTAL EQUIPMENT AND OPERATING PROCEDURES

Loop

A series of experiments were carried out in the Sodium Boiling and Fuel Failure Propagation Test Loops, SIENA at PNC's O-arai Engineering Center. The details of the SIENA loops are described in reference 3. Only a brief recapitulation will be given here.

The SIENA loops have three test sections : T-1, for single-pin experiments; T-2, for 7-pin experiments; and T-3, for 19-pin and 37-pin experiments. The main circulation pump can provide sodium flow up to $5 \times 10^{-3} m^3/s$. The maximum power of 650 KW can be supplied to the electrically heated pins.

Test Section

Figure 1 shows a sketch of the 19-pin bundle test section. In order to simulate an LMFBR fuel subassembly, an electrically heated 19-pin bundle was centered in a hexagonal tube, 36.7mm flat-to-flat distance inside. The heater pins, which were specially made for the present study by Sukegawa Electric Co., Ltd., were 6.5mm in diameter and approximately half as long as the fuel pins of the Japanese prototype LMFBR, MONJU. The heater pins had an effective heating length of 465mm and could be operated at the maximum heat flux of 300 W/cm^2 in the flowing sodium of 900°C. Each pin was wrapped with a 1.3mm diameter wire clockwise in the flow direction at a 264.8mm pitch and assembled together into a tight bundle. The distance between pin centers (i.e. pin pitch) was 7.9mm and the pitch-to-diameter ratio (P/D) was 1.22.

A compensating heater and a thermal insulator were equipped on the outer wall of the hexagonal tube to keep the outer wall in an adiabatic condition. The by-passes of the test section simulated other subassembly channels adjacent to the boiling subassembly.

The pin surface temperatures (T-1011, through T-3124) were measured by many chromel-alumel thermocouples of 0.3mm in diameter, which were embedded in the outer surface of each pin. The local coolant temperatures (T-101, through T-306) were measured by 1.3mm diameter themocouples, the leads of which formed the spacer wires. Thermocouples T-102-1, through T-102-4 were welded on the outside surface of the hexagonal tube to measure the local tube temperatures. The inlet and outlet temperatures were measured by the thermocouples T-113 and T-114, respectively. Thermocouples T-4 and T-10 were provided at the outlet to measure the local coolant temperatures.

Potential-tap type void meters (VoT-1, through VoT-14) were used for detecting the formation of vapor bubbles at boiling inception and their subsequent behavior.

The sodium velocities at the inlet and outlet were measured by the electromagnetic flowmeters F-106 and F-107, respectively. A compact eddy-current type flowmeter FEC-1 also was used for measuring the outlet flow velocity.

Strain-gauge type pressure transudcers P_N-106 and P_N-107 were provided at the inlet and outlet, respectively, to measure the pressure changes in boiling sodium.

Three types of acoustic transducers were used in order to measure the boiling acoustic noises. The first were quartz accelerometers AC-101 and AC-102. Secondly lead zirconate-titanate microphones M-103 and M-104 were mounted onto waveguides placed to the expansion tank and the inlet of the test section, respectively. The third were high-temperature lithium niobate microphones BD-101, BD-102 and BD-103.

All the signals from these instruments were recorded by analog data recorders as well as by a digital data acquisition system.

Operating Procedure

The experiments were performed in the following manner. The oxygen concentration in sodium was controlled down to 10 ppm with a purification system. All the instruments were calibrated before the experiments and checked periodically during experiments.

In the first series of experiments, where temperature distributions were measured in the bundle under steady state non-boiling conditions, the flow rate was set and the heater pins were adjusted to a fixed power level. Sufficient time was allowed for the test section to reach steady-state conditions prior to experiments. To verify the consistency of the data, several runs were repeated.

The non-boiling experiments were conducted under the following conditions:

Flow velocity	0.45 ∿ 5.16 m/s
Inlet temperature	245.4 ∿ 297.8 °C
Heat flux	2.8 ∿ 55.3 W/cm^2

In the second series of experiments, however, where transient boiling phenomena were investigated under loss-of-flow conditions, the sodium flow rates of the test section and the by-passes were controlled by adjusting the pump power and throttling valve opening. The inlet temperature and the cover gas pressure were regulated. The heat flux was held at a fixed value by adjusting the input power supplied to the heater pins. Thereafter, the flow was reduced or stopped according to the following methods.

Pump coastdown method   This method was employed to simulate a pump coastdown accident. The flow rate was reduced by decreasing gradually the pump power. The forced convection flow existed during the transients.

Sudden pump stop method   This method simulated the flow coastdown caused by a pipe rupture accident. The flow rate was reduced rapidly by switching off the pump power. The sodium flow was maintained by the natural circulation after the pump stop.

Valve closure method   An inlet channel flow blockage accident was simulated by closing the entrance valve. The sodium flow into the test section was stopped completely.

The inception of boiling was anticipated from the hottest temperature and actual onset of boiling was detected by the output signals from the acoustic transducers, pressure transducers, flowmeters and void meters.

The boiling experiments were conducted under the following conditions:

Flow velocity at boiling inception	0 ∿ 0.99 m/s
Inlet temperature	354 ∿ 397 °C
Heat flux	58 ∿ 186 W/cm^2
Cover gas pressure	1.04 ∿ 1.06 bar.

RESULTS AND DISCUSSIONS

Temperature Distributions under Non-Boiling Conditions

Figure 2 shows a typical measured pin surface temperature distribution in the 19-pin bundle at the distance of 440 mm downstream from the start of the heated section under a steady state non-boiling condition. The experimental results were compared with the analytical results calculated by the NORMAL code, which could treat the effect of mixing due to spacer wires. The thermocouple arrangement to measure the temperatures of each pin surface is shown in Fig. 2. The vertical axis $T_w - T_{in}$ is the temperature difference between the pin surface temperature and the inlet coolant temperature. It can be seen from the figure that the center pin surface temperature is higher than the outer pin surface temperatures.

Calculations by the NORMAL code were performed for the same conditions: flow velocity in the bundle, 0.95 m/s ; heat flux, 11.2 W/cm^2 ; and inlet temperature, 286.1 °C. The parameters C_T, C_D and C_S are the dimensionless turbulent, pressure-diversion and sweeping cross-flow coefficients respectively. The calculation for C_S=1.0 agreed fairly well with the measured temperature distribution. The weaker effects of C_T and C_D were confirmed by other calculations.

Figure 3 shows the measured pin surface temperature distribution in the higher flow velocity 4.66 m/s. The experimental results were again compared with the NORMAL code calculation. The calculation was performed for C_T=0.005, C_D=0.001 and C_S=1.0, and agreed fairly well with the measured temperature distribution.

Records during Boiling Transients

Figure 4 shows typical signals from thermocouples and flowmeters during a pump coastdown experiment (run No. 19FC-111). The experimental conditions were the heat flux of 150.0 W/cm^2, the initial steady-state flow velocity of 2.44 m/s, the inlet temperature of 366 °C and the cover gas pressure of 1.04 bar. The flow velocity decreased gradually after the pump power started to be reduced at 0 s. Throughout the time interval from 0 to 15.4 s, the coolant was single-phase liquid. All temperatures except the inlet temperature T-113 rose with the elapse of time.

As can been seen in the figure, the outlet flowmeter F-107 registered an abrupt change at the boiling inception. No high superheat was observed for boiling initiation. Because of the large radial temperature gradient between the center subchannel (T-101) and the outer subchannels (T-202 and T-303) the coolant voiding was initially limited to the center in the bundle. While the vapor bubbles repeated their formation and collapse, the outer subchannel temperature (T-202) increased and the boiling region then spread to the outer subchannels. The heater power was switched off at 17.2 s and sodium temperatures (T-101, T-202 and T-303) then fell gradually.

Figure 5 shows typical signals from void meters, flowmeters and pressure transducers during the same transient boiling run 19FC-111. The flowmeters and pressure transducers registered abrupt changes upon boiling inception followed by oscillations. The initial bubble growth was markedly retarded and condensed immediately since the liquid around the bubble was highly subcooled. Thus, the void meters could not detect the boiling inception since they sent no output signals before a considerable amount of bubbles had accumulated.

The boiling region then spread slowly. Even though the heater power was switched off at 1.8 s, the boiling continued for a while. When the fairly large bubble collapsed at 1.95 s, the upper liquid column collided with the lower column and the pressure pulse was associated with this sodium hammer phenomenon. The pressure transducers P_N-106 and P_N-107 sent their larger output signals at the vapor collapse than at its formation.

The observed negative void fractions were attributed to the decrease of electrical resistance due to the temperature fall.

A similar effect of steep temperature gradient on transient boiling phenomena was observed in the other experiments, which were conducted by the sudden pump stop and valve closure methods.

CONCLUSIONS

Experimental studies were carried out on transient sodium boiling in a 19-pin electrically heated LMFBR fuel subassembly mockup under loss-of-flow conditions. In the first series of experiments temperature distributions in the bundle were measured under initial steady state non-boiling conditions. In the second series of experiments transient boiling phenomena were investigated under loss-of-flow conditions.

Analyses of the results obtained permit the following conclusions to be drawn:

(1) In the non-boiling experiments the center pin surface temperature was higher than the outer pin surface temperatures. The measured temperature distribution was in fairly good agreement with the calculation by the NORMAL code.

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Larger-scaled experiments in a 37-pin bundle are scheduled for next year.

ACKNOWLEDGMENTS

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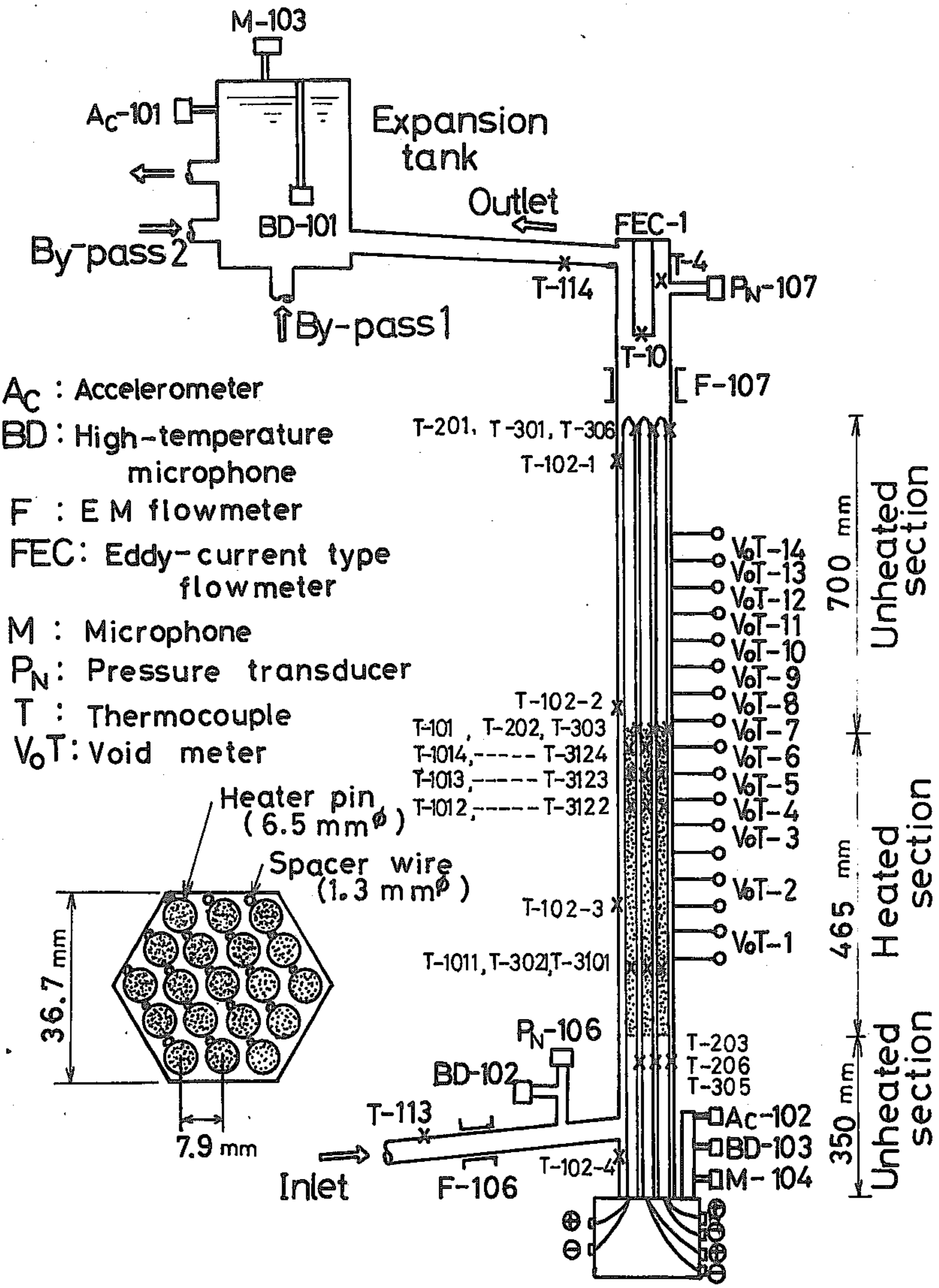


Fig. 1 19-pin bundle test section

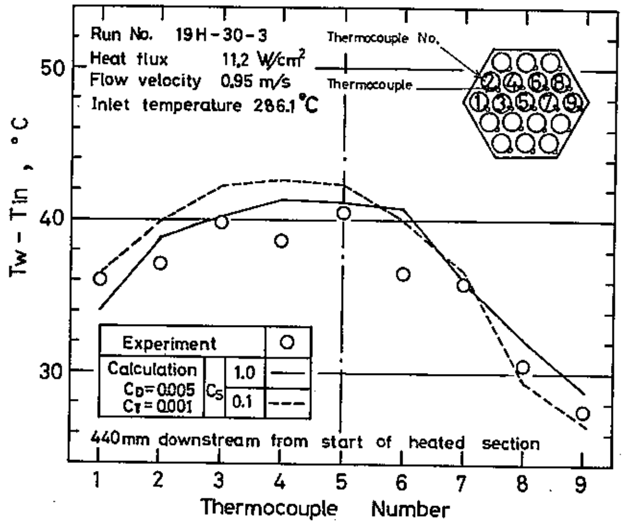
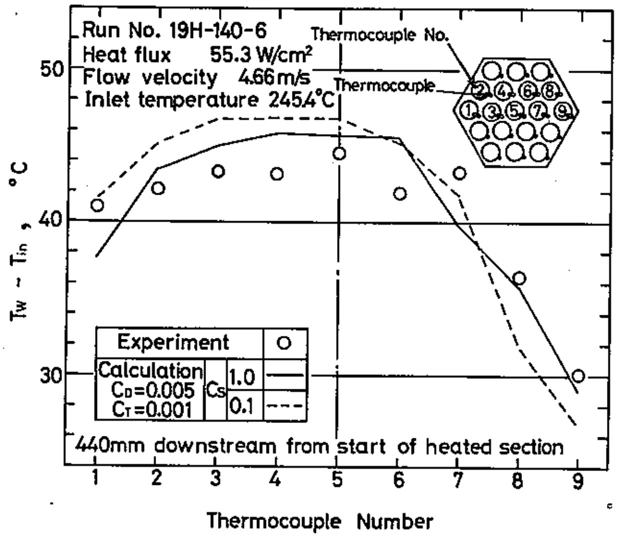


Fig. 2 Comparison of measured pin surface temperature distribution with NORMAL code calculation; case of low velocity



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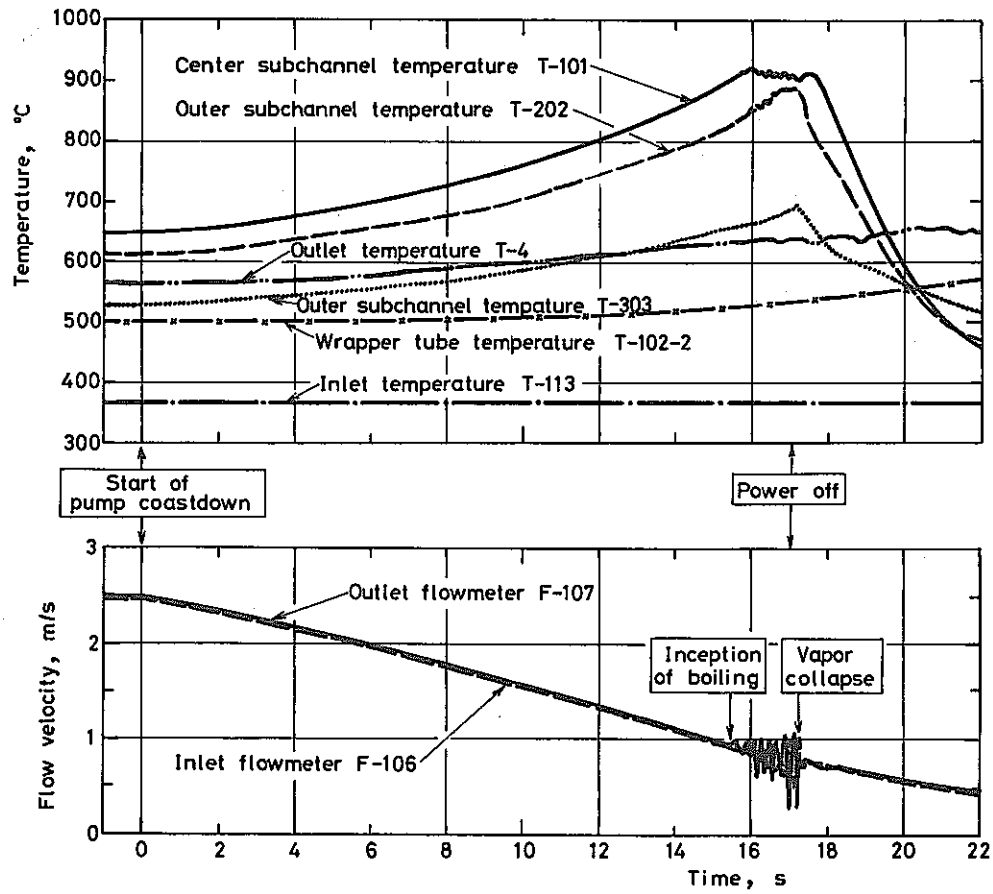

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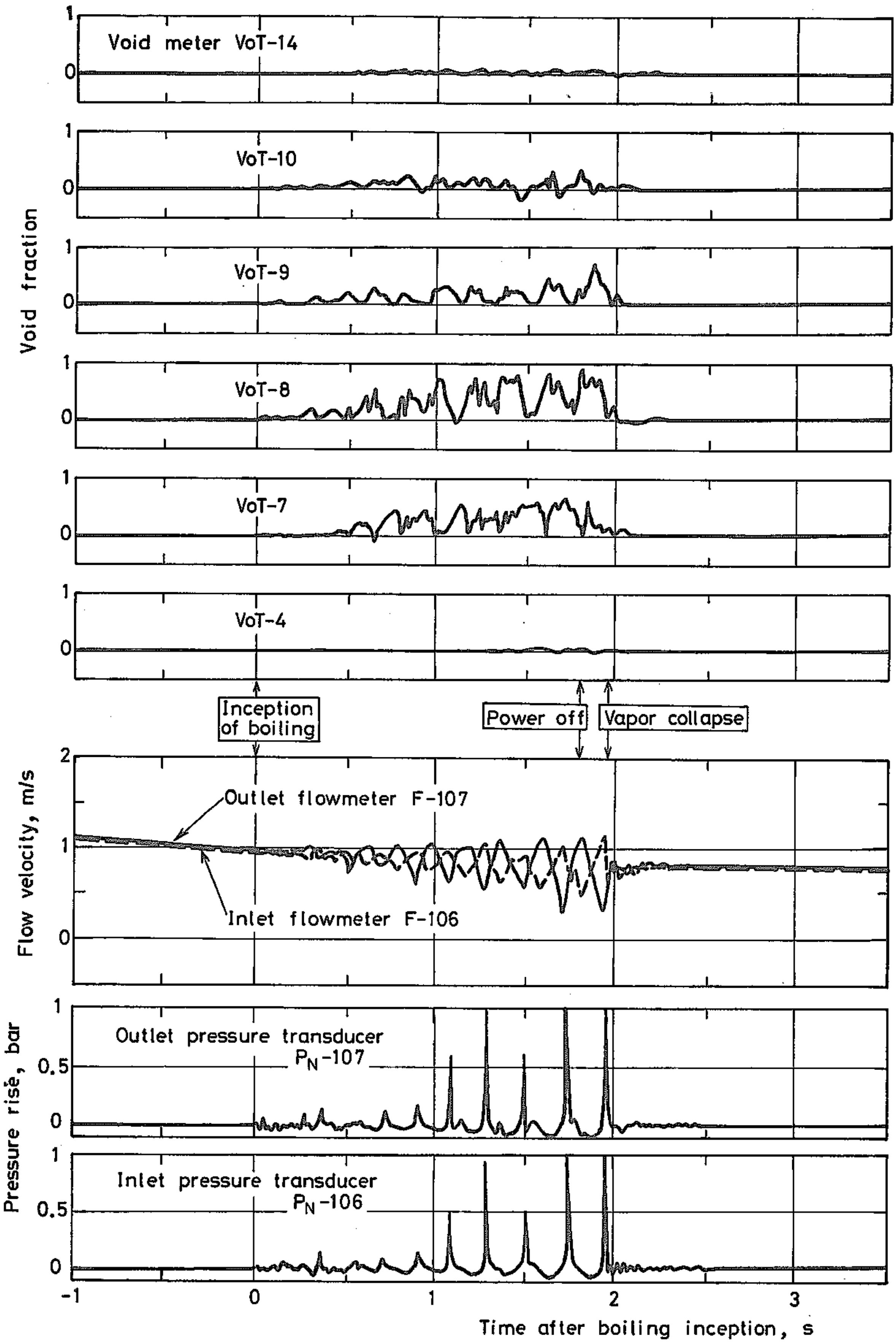

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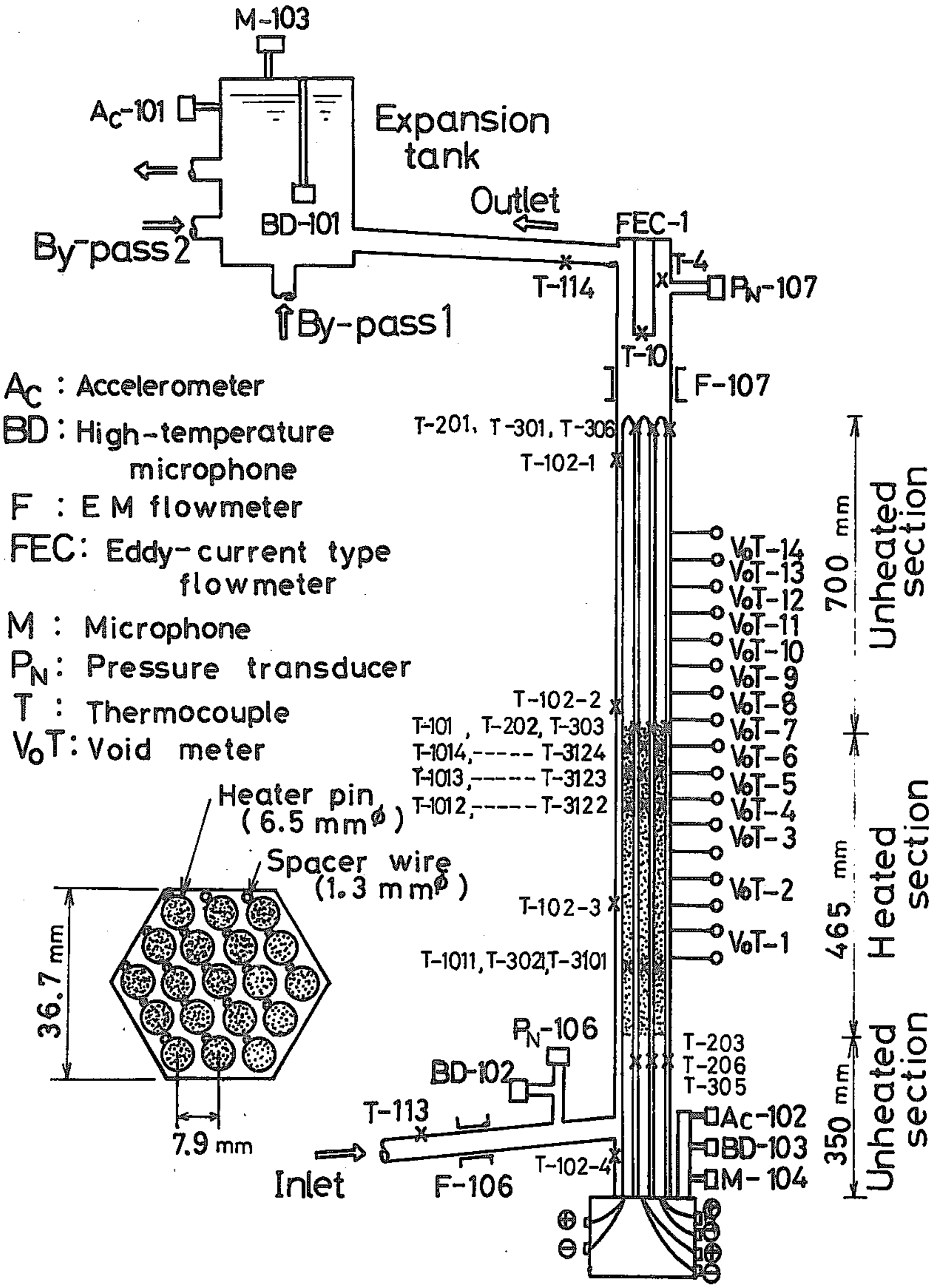

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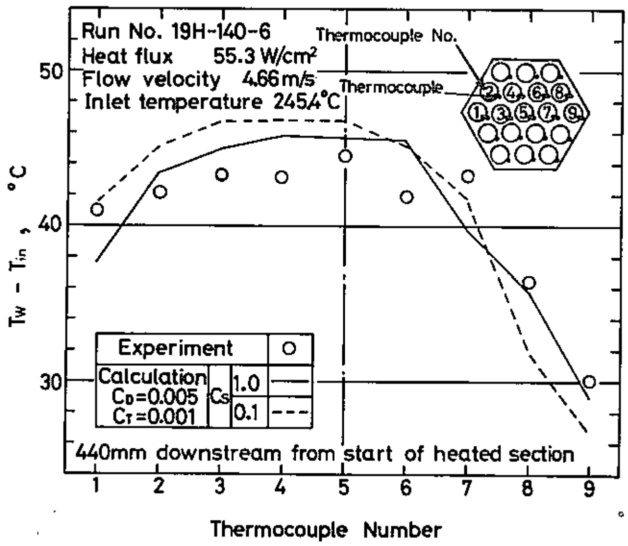

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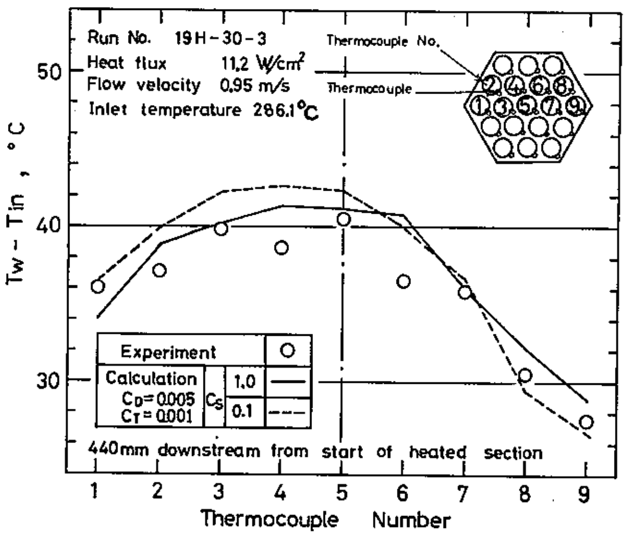

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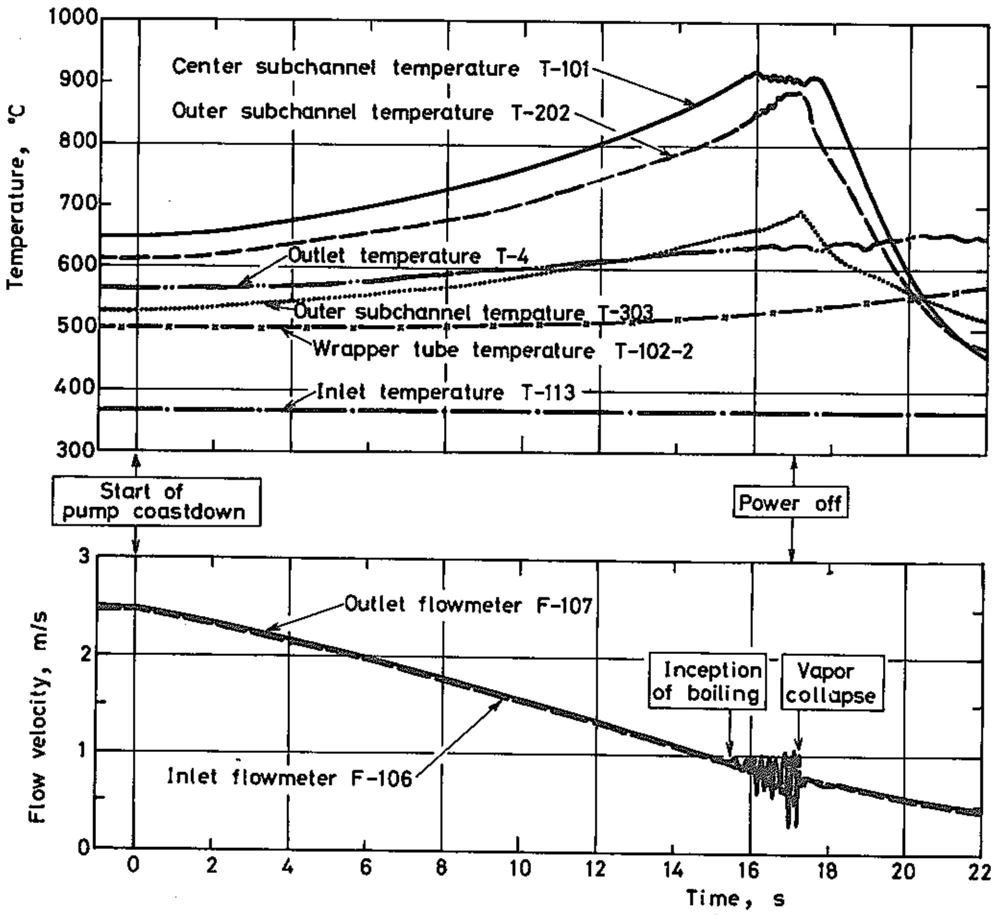

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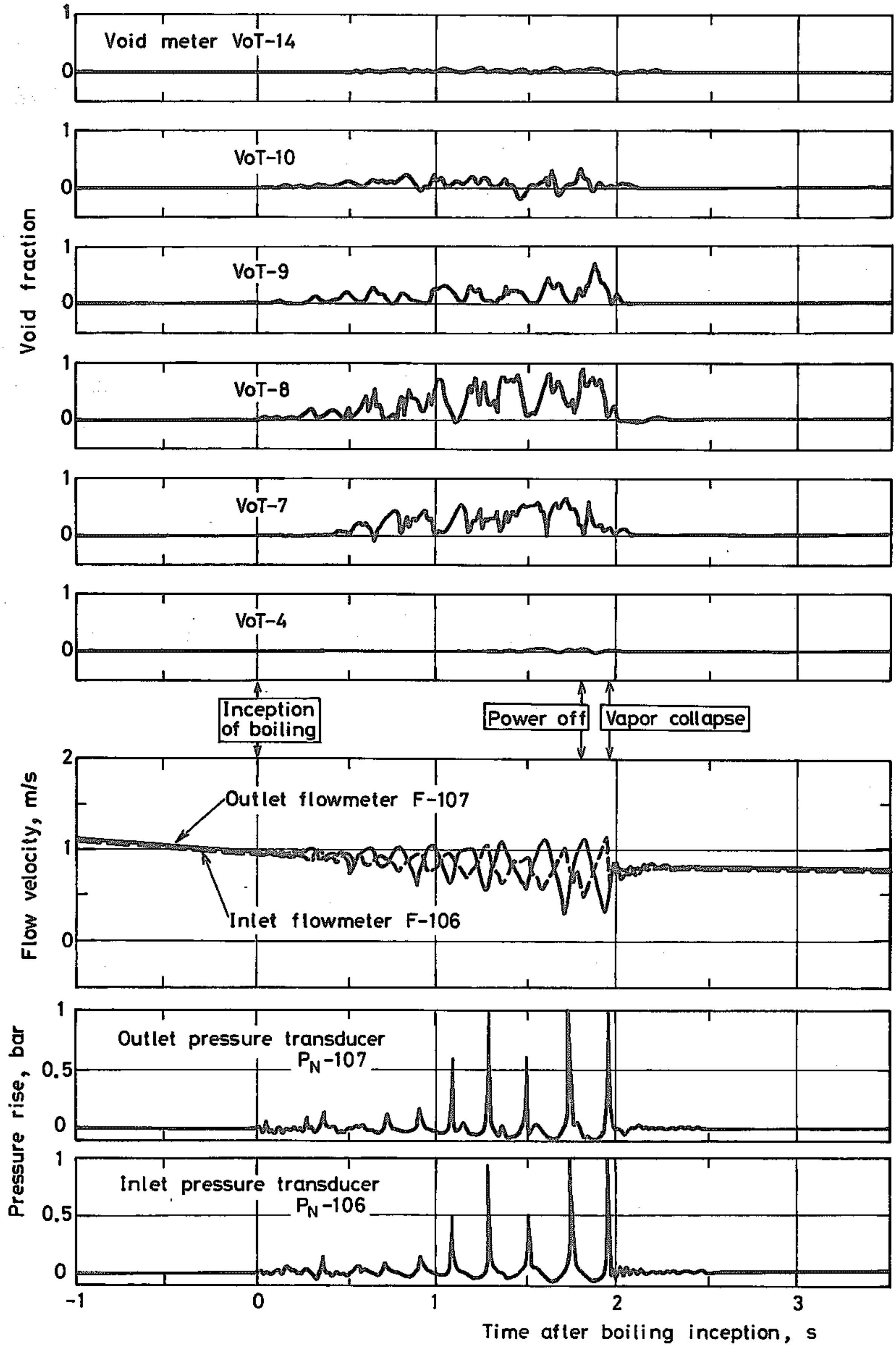

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