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# TRANSIENT ANALYSIS OF BLOWDOWN THRUST FORCE UNDER PWR LOCA

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Toshikazu YANO, Noriyuki MIYAZAKI and
Toshikuni ISOZAKI

日 本 原 子 力 研 究 所
Japan Atomic Energy Research Institute

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# Transient Analysis of Blowdown Thrust Force under PWR LOCA

Toshikazu YANO, Noriyuki MIYAZAKI and Toshikuni ISOZAKI
Division of Nuclear Safety Research,
Tokai Research Establishment, JAERI

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The analytical results of blowdown characteristics and thrust forces were compared with the experiments, which were performed as pipe whip and jet discharge tests under the PWR LOCA conditions. The blowdown thrust forces obtained by Navier-Stokes momentum equation about a single-phase, homogeneous and separated two-phase flow, assuming critical pressure at the exit if a critical flow condition was satisfied. The following results are obtained. (1) The node-junction method is useful for both the analyses of the blowdown thrust force and of the water hammer phenomena. (2) The Henry-Fauske model for subcooled critical flow is effective for the analysis of the maximum thrust force under the PWR LOCA conditions. The jet thrust parameter of the analysis and experiment is equal to 1.08. (3) The thrust parameter of saturated blowdown has the same one with the value under pressurized condition when the stagnant pressure is chosen as the saturated one. (4) The dominant terms of the blowdown thrust force in the momentum equation are the pressure and momentum terms except that the acceleration term has large contribution only just after the break. (5) The blowdown thrust force in the analysis greatly depends on the selection of the exit pressure.

Keywords: Blowdown Thrust Force, LOCA, PWR, Pipe Whip, Jet Discharge, Thrust Force Parameter, RELAP4, DEPCO-MULTI, Blowdown

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This work was performed under contract between the Science and Technology Agency of Japan and JAERI to demonstrate the safety for pipe rupture of the primary coolant circuits in nuclear power plants.

# PWR・LOCA条件下でのブローダウン反力の過渡状態解析

日本原子力研究所東海研究所安全工学部
矢野　歳和・宮崎　則幸・磯崎　敏邦

（1982年9月13日受理）

本報はPWR・LOCA条件下のパイプホイップ試験およびジェット放出試験に関してブローダウン特性とその反力について解析を行い，実験結果と比較したものである。ブローダウン反力はナビア・ストークスの運動量式を変形し，出口が臨界流のとき臨界圧力を出口圧力として単相流，均質および分離二相流について求めた。以上から次の結果を得た。(1)ノード・ジャンクション法はブローダウン反力と水撃現象の両方の解析に役立つ。(2)Henry－Fauskeのサブクール臨界流モデルによりPWR・LOCA条件の最大反力を求めると実験値とよく一致する。最大反力時のジェット反力係数は1.08が得られた。(3)飽和ブローダウン時のジェット反力係数はよどみ点圧力を飽和圧力とするとサブクール状態での反力係数と一致する。(4)反力の各成分のうち破断直後は加速度項が，それ以降は圧力項と運動量項が支配的である。(5)解析におけるブローダウン反力は出口圧力の選択に大きく依存する。

本報告書は，電源開発促進対策特別施行令に基づき，科学技術庁から日本原子力研究所への委託研究，昭和54年度および昭和55年度配管信頼性実証試験のうち，PWR・LOCA条件下の4インチ口径管によるパイプホイップ試験およびジェット放出試験に関しブローダウン特性とその反力についての解析結果をまとめたものである。

CONTENTS

# 目　　次

## 1. INTRODUCTION

When the instanteneous pipe rupture, which is one of the hypothetical accidents, occurs in a primary coolant circuit of the light water reactor (LWR), the piping network will start moving caused by the blowdown thrust force. This phenomenon is called as "pipe whip". The nuclear power plants have the restraints to stop the dynamic movement of pipes in the loss of coolant accident (LOCA). To analyze such an interaction of the pipes and restraints, the reaction force must be made clear both in the experiment and the analysis. Okazaki, et al.[1] investigated the pressure response by giving oscillation to the pipe exit with both the node-junction method and the method of characteristics, on the blowdown initiation. They showed the applicability of these methods to the simple pipe. Moody[2][3] obtained the blowdown thrust force by the method of characteristics, and Strong and Baschiere[4] calculated the thrsut force by use of the computer program, RELAP4[5]. The PRTHRUST[6] and PRTHRUST-J1[7] codes are based on the RELAP3 code[8], in which node-injection method is used. Recently, Hsu, et al.[9] have developed the REPIPE as a post processor of the RELAP4 code. Among these studies, it is not clarified whether or not the critical pressure or the average pressure of the volume is used for the exit pressure in the computer programs and the momentum term of the blowdown thrust force is considered for the separated two-phase flow.

In this paper, the following characteristics exist; (1) The calculating method of the blowdown thrust force is introduced in a single-phase, homogeneous and separated tow-phase flow by Navier-Stokes momentum equation. (2) The critical pressure is assumed for the exit pressure of the test pipe if the critical flow condition is satisfied. (3) The blowdown thrust forces are compared with the analytical results

by the node-junction method using the critical flow models of Henry-Fauske[10], Moody[11] and the homogeneous equilibrium model (HEM)[5].
(4) The thrust force can be obtained by the hydraulic properties by the method of characteristics.

In this paper, the thermalhydraulic analysis is carried out on the test results of the pipe whip, which were performed at the Japan Atomic Energy Research Institute (JAERI) with a 4 inch pipe under the PWR LOCA conditions. Furthermore, the analytical results of the blowdown thrust force are compared with the measured experimental values which were obtained from the jet discharged test with a 4 inch pipe under the same conditions and shapes as the pipe whip tests.

# 2. ANALYTICAL METHOD

## 2.1 Blowdown Thrust Force by the Node-Junction Method

### (1) Fundamental Equation

The balance of mass, momentum and energy must be satisfied among the nodes and junctions. Equation (1) shows the Navier-Stokes momentum equation in the integral form.

$$\frac{\partial}{\partial t}\int_V \rho\vec{u}dV + \int_S \rho\vec{u}(\vec{u}\cdot\vec{n})dS = -\int_S P\vec{n}dS - \int_S \vec{\tau}dS - \int_V \rho\vec{g}dV \qquad (1)$$

The following equation can be obtained by applying equation (1) to the control volume shown in Fig. 1.[4]

$$\frac{\partial}{\partial t}\int_V \rho\vec{u}dV + \int_{S_1} \rho_1\vec{u}_1(\vec{u}_1\cdot\vec{n}_1)dS_1 + \int_{S_2} \rho_2\vec{u}_2(\vec{u}_2\cdot\vec{n}_2)dS_2$$

$$= -\{\int_{S_1} P_1\vec{n}_1dS_1 + \int_{S_2} P_2\vec{n}_2dS_2 + \int_{S_3} P_3\vec{n}_3dS_3 - \int_{S_3} \vec{\tau}dS_3 - \int_V \rho\vec{g}dV \qquad (2)$$

The force acting on the pipe comprises body forces and surface forces. The thrust force $\vec{F}$ is shown in equation (3).

$$\vec{F} = \int_{S_3} P_3\vec{n}_3dS_3 + \int_{S_3} \vec{\tau}dS_3 \qquad (3)$$

Equation (2) and (3) lead to the thrust force.

$$-\vec{F} = \frac{\partial}{\partial t}\int_V \rho\vec{u}dV + \int_{S_1} \rho_1\vec{u}_1(\vec{u}_1\cdot\vec{n}_1)dS_1 + \int_{S_2} \rho_2\vec{u}_2(\vec{u}_2\cdot\vec{n}_2)dS_2$$

$$+\int_{S_1} P_1\vec{n}_1dS_1 + \int_{S_2} P_2\vec{n}_2dS_2 + \vec{g}\int_V \rho dV \qquad (4)$$

Next, equation (4) is applied to the constant area pipe shown in Fig. 2. The gravitational term of equation (4) can be neglected because of its smallness. The density $\rho_i$ and velocity $u_i$ for the i-th node can be linearlized by introducing the arithmetic avarage value in the volume.

Thus, equation (4) can lead to the following expression for the blowdown thrust force of the i-th node.

$$-F_i = A_i \ell_i \left(u_i \frac{\partial \rho_i}{\partial t} + \rho_i \frac{\partial u_i}{\partial t}\right) + A_i(\rho_{2i} u_{2i}^2 - \rho_{1i} u_{1i}^2) + A_i(P_{2i} - P_{1i}) \tag{5}$$

Assemblage of equation (5) for all the nodes contained in a bounded pipe leads to the blowdown thrust force in a single-phase flow and homogeneous two phase flow as follows:

$$F = \Sigma F_i = FA + FM + FP \tag{6}$$

where

$$\text{Acceleration Force} : \quad -FA = \Sigma \frac{\ell_i}{g} \frac{\partial W_i}{\partial t} \tag{7}$$

$$\text{Momentum Force} : \quad -FM = \Sigma \frac{A_i}{g} (\gamma_{2i} u_{2i}^2 - \gamma_{1i} u_{1i}^2) \tag{8}$$

$$\text{Pressure Force} : \quad -FP = \Sigma A_i (P_{2i} - P_{1i}) \tag{9}$$

and $\Sigma$ is the summation in the bounded pipe.

The thrust force can be also obtained from equation (4) for the separated two-phase flow which has the velocity difference between the vapor and liquid.

$$\begin{aligned} -F_i = {} & \ell_i \left\{ A_{gi} u_{gi} \frac{\partial \rho_{gi}}{\partial t} + A_{\ell i} u_{\ell i} \frac{\partial \rho_{\ell i}}{\partial t} \right) + \left( A_{gi} \rho_{gi} \frac{\partial u_{gi}}{\partial t} + A_{\ell i} \rho_{\ell i} \frac{\partial u_{\ell i}}{\partial t} \right\} \\ & + (A_{g2i} \rho_{g2i} u_{g2i}^2 + A_{\ell 2i} \rho_{\ell 2i} u_{\ell 2i}^2 - A_{g1i} \rho_{g1i} u_{g1i}^2 - A_{\ell 1i} \rho_{\ell 1i} u_{\ell 1i}^2) \\ & + A_i (P_{2i} - P_{1i}) \end{aligned} \tag{10}$$

The mass flow rate is defined by

$$W = W_g + W_\ell \tag{11}$$

$$W_g = A_g \gamma_g u_g = xW \tag{12}$$

$$W_\ell = A_\ell \gamma_\ell u_\ell = (1 - x) W \tag{13}$$

The acceleration force FA and momentum force FM are given as follows:

$$-FA = \Sigma \frac{\ell_i}{g} \left(\frac{\partial W_{gi}}{\partial t} + \frac{\partial W_{\ell i}}{\partial t}\right) = \Sigma \frac{\ell_i}{g} \frac{\partial W_i}{\partial t} \tag{14}$$

$$-FM = \Sigma\{\frac{W_2}{g} [x_2 u_{g_2} + (1 - x_2) u_{\ell_2}] - \frac{W_1}{g} [x_1 u_{g_1} + (1 - x_1) u_{\ell_1}]\}_i \tag{15}$$

Here, the pressure force FP for the separated two-phase flow is shown by the same equation as that of the single-phase flow, expressed in equation (9).

Finally, the blowdown thrust force of the opened pipe can be given in equation (16) through (19) as follows:

(A) Acceleration Force : $-FA = \Sigma \frac{\ell_i}{g} \frac{\partial W_i}{\partial t}$ (16)

(B) Momentum Force :

[a] Single-Phase Flow and Homogeneous Two-Phase Flow

$$-FM = [\frac{A}{g} \gamma u^2]_e = [\frac{W^2}{g\gamma A}]_e \tag{17}$$

[b] Separated Two-Phase Flow

$$-FM = \{\frac{W}{g} [x u_g + (1 - x) u_\ell]\}_e \tag{18}$$

(C) Pressure Force : $-FP = A_e(P_e - P_\infty)$ (19)

(2) Calculation Method

The blowdown thrust force is calculated according to equation (6) as follows.

(A) Acceleration Force : FA

The acceleration force can be given by the differential of mass flow rate between each segment as shown in equation (16). If the RELAP4 code is used for the thermalhydraulic analysis of the LOCA, the acceleration force can be calculated by the output parameter, "DELA" term[5], which is shown as "junction acceleration pressure differential". It is indicated by Strong and Baschiere[4] as equation (20).

$$(DELA)_i = \frac{\ell_i}{g} \frac{\partial G_i}{\partial t} \tag{20}$$

With the equation (16), the acceleration force is obtained as

$$-FA = \Sigma \frac{\ell_i}{g} \frac{\partial W_i}{\partial t} = \Sigma (A \cdot DELA)_i \tag{21}$$

(B) Momentum Force : FM

In the single-phase or homogeneous two-phase flow, the momentum force can be obtained by equation (17) with the thermalhydraulic properties which are given by the analysis of the RELAP4. The momentum force of the separated two-phase flow is calculated as follows. The velocities of vapor and liquid phases are defined as equation (22) and (23).

$$u_g = \frac{xW}{\alpha \gamma_g A} \tag{22}$$

$$u_\ell = \frac{(1 - x)W}{(1 - \alpha)\gamma_\ell A} \tag{23}$$

The relationship between the slip ratio K and void fraction $\alpha$ is given as follows:

$$K = \left( \frac{x}{1 - x} \right) \left( \frac{1 - \alpha}{\alpha} \right) \frac{\gamma_\ell}{\gamma_g} \tag{24}$$

or

$$\alpha = 1/\{1 + \left( \frac{1 - x}{x} \right) \frac{\gamma_g}{\gamma_\ell} \cdot K\} \tag{25}$$

In this paper, Moody's model[11] of the separated two-phase flow is exclusively used for calculation of the blowdown thrust force. According to Moody's model, the slip ratio of the critical two-phase flow is defined by equation (26).

$$K = (\gamma_\ell/\gamma_g)^{1/3} \tag{26}$$

Then, the momentum force can be calculated from equation (18) when the thermalhydraulic properties, W, x, and P are obtained from such an analytical program of the LOCA as RELAP4.

(C) Pressure Force : FP

When the flow is satisfying the critical flow condition, the exit pressure $P_e$ is assumed to be critical pressure $P_c$. The pressure force FP can be expressed in equation (27) for each flow pattern.

$$- FP = A_e(P_c - P_\infty) \tag{27}$$

In this critical pressure calculation, Henry-Fauske model[10] is applied to the non-equilibrium state for the PWR LOCA initiations although it is derived for the small ratio of the L/D. According to Henry-Fauske model, the critical pressure ratio in the subcooled region is expressed as equation (28).

$$\eta = \frac{P_c}{P_o} = 1 - \frac{G_c^2}{2g\gamma_{\ell o}P_o} \tag{28}$$

Then, the pressure force FP can be obtained from equation (28) with the properties, $P_o$, $\gamma_{\ell o}$ and $G_c$.

Similarly, when the flow reaches the saturated critical flow, $P_c$ can be calculated from the thermalhydraulic properties by the analysis with each model of Moody, Henry-Fauske or HEM.

## 2.2 Calculation of Blowdown Thrust Force by the Method of Characteristics

The blowdown thrust force by the method of characteristics can be obtained by the same way as the node-junction method during subcooled decompression as equation (29).

$$F = FA + FM + FP \tag{29}$$

where

$$-FA = \Sigma \frac{A_i \ell_i}{g} \left( \frac{\Delta \gamma_i}{\Delta t} \cdot u_i + \gamma_i \frac{\Delta u_i}{\Delta t} \right) \tag{30}$$

$$-FM = \left[ \frac{A \gamma u^2}{g} \right]_e = \left[ \frac{W^2}{g \gamma A} \right]_e \tag{31}$$

$$-FP = A_e (P_e - P_\infty) \tag{32}$$

The Mass flow rate W and pressure difference $\Delta P$ caused by water hammer phenomena can be given by equation (33) and (34).

$$u = \frac{\Delta P \cdot g}{\gamma c} \tag{33}$$

$$W = \gamma u A = \frac{\Delta P \cdot g A}{c} \tag{34}$$

# 3. RESULTS AND DISCUSSION

## 3.1 Analytical Conditions

Figure 3 shows the schematic of the pipe whip tests[12] with a 4 inch pipe under the PWR LOCA conditions. The initial conditions before the break were 15.6 MPa and 345°C in the pressurizer, and 15.6 MPa and 320°C in the pressure vessel, test pipe and other components. The instanteneous guillotine break was simulated by break of a rupture disk. In Fig. 4 are shown the load cell to measure the blowdown thrust force and the setting procedure. The weight of 130 kg was used to make the test pipe contact with the load cell.

The thermalhydraulic properties were obtained by either the RELAP4/MOD5 or DEPCO-MULTI code. The former employs the node-junction method for the transient analysis and the latter were developed by Namatame and Kobayashi[13], in which the method of characteristics was applied.

The broken area of rupture disk was taken up as the exit flow area, which showed the minimum area in vertical projection as shown in Fig. 6. Table 1 shows the broken flow area and its ratio obtained by the experiments. The broken area was about 80 per cent of the nominal flow area except for RUN 5508.

## 3.2 Results by the Node-Junction Method

### (1) Decompression Process

Figure 7 shows the decompression histories obtained by the RELAP4. Henry-Fauske model (HF) was used in a subcooled critical flow, and Moody (M) or HEM model was used in a saturated critical flow, respectively. The analytical results by HF-M model agree quite well with the experimental results when the discharge coefficient $C_D$ is selected as 0.63. This value agrees with that of the previous work[14].

The analytical value of $C_D$ has, however, only the meaning of time average because it depends on quality[14]. Then, on the assumption that $C_D$ is equal to 1.0, the blowdown thrust force was compared among the critical flow models of Henry-Fauske, Moody and HEM, respectively.

(2) Relaxation Process of the Subcooling

Figure 9 (a) and (b) show the decompression histories in the test pipe both at the broken exit and near the pressure vessel. The relaxation process of subcooling and the saturated blowdown are observed in Fig. 9(a). The analytical pressure is in good agreement with the experimental one during subcooled decompression process, in which the pressure decreases rapidly under the saturation pressure and then recovers gradually. Afterward, the pressure decreases with the temperature under the saturated conditions. Figure 9(b) shows a water hammer with pressure oscillation in the test pipe near the pressure vessel. The amplitude of oscillation obtained by the analysis is smaller and the absolute pressure is larger than the experimental value, but the period of oscillation obtained by the analysis is equal to about 30 msec, which is in good agreement with the experimental value. Figure 10 shows the analytical history of quality at the exit. In this figure, the first maximum quality is observed only near the exit just after the initiation of the pipe break. Then, the quality decreases and equals almost zero during the pressure recovery from about 0.1 sec to 0.3 sec. In succession, the quality increases with the propagation of flashing vaporization from the broken end to the inner pipe. The increase of quality begins at the time of about 0.3 sec, which corresponds to the termination of water hammer.

(3) Blowdown Thrust Force

From Fig. 10 to Fig. 15 are shown the thermal-hydraulic properties, x, G, $\gamma$ and $P_e$. Fig. 11 shows that there is the maximum flow rate at 0.1 sec after the break and the specific weight has the largest value as shown in Fig. 12. Figures 13, 14 and 15 indicate the pressure histories obtained by each critical flow model. $P_a$ shows the volume average pressure of the last pipe volume, No. 13, and $P_c$ expresses the critical pressure calculated by the stagnant conditions, respectively. The experimental pressure, PU110, is the output of the pressure transducer at 90 mm from the exit. It is clarified from these results that the pressure by Henry-Fauske model shows a good agreement with the experimental one in the subcooled region.

The blowdown thrust force can be obtained from the quantities given above. The blowdown thrust forces in Fig. 16, 17 and 18 indicate that the acceleration force FA contributes little to the overall thrust force except for the initial value of the blowdown, and the pressure force FP and the moemntum force FM are dominant for a long time. It becomes clear that the maximum force appears at about 0.1 sec after break, when the values of G, $\gamma$ and $P_e$ show the maximum and x reahces the minimum.

Figure 19 and 20 shows the analytical blowdown thrust forces, which are compared with the experimental ones. In the analysis, it was selected a volume average pressure, $P_a$, at the exit node, or a critical pressure, $P_c$, which was calcualted by each critical model from the stagnation conditions in the last exit node. $P_a$ is always higher than $P_c$. Then the blowdown thrust force obtained by use of the $P_a$ shows a larger value than that of $P_c$. It must be noticed what is selected for the exit pressure at the broken end. In this paper, the analysis of blowdown thrust force were performed on the assumption that the exit pressure is equal to the critical one.

Table 2 shows the analytical and experimental blowdown thrust forces. In the analysis, the critical pressure $P_c$ was used. Here, $F_{NE}$ is the force of non-equilibrium state in the subcooled relaxiation process and $F_{EQ}$ is that of equilibrium state in the saturated blowdown. The analytical value of $F_{NE}$ shows good agreement with the experimental force, but the analytical value of $F_{EQ}$ is lower than the experimental value.

Table 3 shows the jet thrust parameter of the subcooled maximum force at 0.1 sec, and the saturated maximum force at 0.5 sec. The jet thrust parameter $J_t$ is defined by equation (35).[3][15]

$$J_t = \frac{F}{A_e(P_o - P_\infty)} \qquad (35)$$

In the subcooled non-equilibrium sate, the value of $J_{t,NE,max}$ is equal to 1.08 both in the analysis and the experiment when the initial pressure, $P_{o,in}$, is 15.6 MPa and the initial temperature is 320°C. In addition, the maximum thrust parameter, $J_{t,EQ,max}$, of saturated equilibrium state is equal to 1.08 in the experiment if $P_{o,sat}$ is 11.3 MPa corresponding to the saturaton pressure of 320°C. The analytical results are lower in the saturated blowdown as shown in Table 3. The difference between the analytical and experimental value of the jet thrust parameter is caused in the determination of exit pressure and discharge coefficient on each critical flow model.

In this work, fL/D is used to be nearly equal to 1.0 by assuming the friction factor, f = 0.01. According to the results obtained by Jains and Hestings[15], and Moody[3], $J_t$ should be equal to about 1.0, when fL/D is equal to 1.0. In this paper, $J_{t,NE,max}$ is slightly larger than Jains and Hastings' value, and $J_{t,EQ,max}$ is equal to or smaller than Moody's value. Therefore, it can be concluded that the method presented in this paper has the applicability for the analysis of the blowdown thrust force, and that the best fitting can be obtained by changing a discharge coefficient or using the best critical flow model.

### 3.3 Results by the Method of Characteristics

Figure 21 shows the analytical results of the water hammer phenomena during the non-equilibrium state after the instanteneous pipe break, in which the computer program the DEPCO-MULTI code was used.[13] This figure shows that the analytical value of the pressure amplitude, the period and the termination of oscillation agree well with the experimental values. However, the analytical results obtained by the DEPCO-MULTI code are a little different from the experimental results in the flashing region of the test pipe from the exit to about 2 m inside.

Figure 22 shows the analytical thrust force obtained by the results of DEPCO-MULTI code. It is shown that the maximum thrust force occurs at about 0.1 sec after the break as obtained in the node-junction method, and that the total value F of the blowdown thrust force in the maximum, 68 kN, is devided into two portions of each component as follows: FP= 7/10 and FM=3/10. The maximum thrust force is smaller than the values in the experiment and by the node-junction method. The reason is that the FM term at the peak force is smaller than the value acquired by the node-junction method.

## 4. CONCLUSIONS

The following conculsions are obained from the results of the blowdown characteristics and thrust forces analyzed by some computer programs on the pipe whip and jet discharge tests using 4 inch pipe under the PWR LOCA conditions.

(1) The node-junction method by the RELAP4/MOD5 code is useful for the analysis both in the non-equilibrium state of the water hammer and in the saturated blowdown of equilibrium quasi-steady state.

(2) The blowdown thrust force of a single-pahse, homogeneous and separated two-phase flow can be obtained from Navier-Stokes momentum equation. The dominant terms of the blowdown thrust force are the pressure and momentum terms, except that the acceleration force contributes largely to the total force only just after the break.

(3) The first maximum of quality occurs only near the broken exit, and the flashing vaporization propagates from the exit into the pipe. The thrust force reaches the maximum at 0.1 sec when the quality has the minimum value.

(4) The Henry-Fauske model for the subcooled critical flow is effective for the analysis of the maximum thrust force under the PWR LOCA conditions. The jet thrust parameter obtained by the analysis and experiment is equal to 1.08 for the maximum thrust force.

(5) The blowdown thrust force in the analysis greatly depends on the selection of the exit pressure.

(6) The thrust parameter of the saturated blowdown has the same one with the value under the pressureized condition when the stagnant pressure is chosen as the saturated one.

(7) The method of characteristics by the DEPCO-MULTI code indicated the good agreement with the water hammer phenomena in the test pipe except for the flashing exit. The analytical thrust force by this method is lower than the value by the node-junction method.

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NOMENCLATURE

$A$ = cross sectional flow area

$C_D$ = discharge coefficient

$c$ = sonic velocity

$F$ = blowdown thrust force

FA = acceleration force

FM = momentum force

FP = pressure force

$f$ = Darcy's friction factor

$G$ = mass flow rate per unit area

$g$ = gravitational constant

$J_t$ = jet thrust parameter

$K$ = slip ratio, $u_g/u_\ell$

$L$ = pipe length

$\ell$ = node length

$P$ = pressure

$S$ = area

$t$ = time

$u$ = velocity

$V$ = volume

$W$ = mass flow rate

$x$ = quality

$\alpha$ = void fraction

$\varepsilon_b$ = ratio of opening area

$\eta$ = critical pressure ratio, $P_c/P_o$

$\rho$ = density

$\gamma$ = specific weight

$\tau$ = shear stress

$\Sigma$ = summation

SUBSCRIPTS

| | | | |
|---|---|---|---|
| 0 | = stagnation | EQ | = equilibrium state |
| 1 | = inlet | g | = vapor phase |
| 2 | = outlet | i | = node number |
| 3 | = wall | in | = initial state |
| a | = average value of node | $\ell$ | = liquid phase |
| c | = critical flow condition | m | = mixture |
| e | = exit | max | = maximum value |
| exp | = experimental value | NE | = non-equilibrium state |
| | | $\infty$ | = ambient |

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Table 1 Experimental break area and its ratio of the pipe, 4in × sch 160, 87.3 mm I.D.

| RUN No. | Break Area Ratio $\varepsilon_b$ | Break Area $A_e$ | Test Condition |
|---|---|---|---|
| 5506 | 79.4 % | 47.5 $cm^2$ | Whip |
| 5507 | 78.1 % | 46.7 $cm^2$ | 〃 |
| 5508 | 38.9 % | 23.3 $cm^2$ | 〃 |
| 5509 | 79.1 % | 47.3 $cm^2$ | Jet |
| 5604 | 77.5 % | 46.4 $cm^2$ | Whip |
| (ideal) | 100 % | 59.86 $cm^2$ | —— |

Table 2 Comparison between the experimental and analytical thrust forces

| Peak Thrust Force | $F_{NE.max}$ | $F_{EQ.max}$ |
|---|---|---|
| Condition | Non-Equilibrium | Equilibrium |
| Time After Break | 0.1 sec | 0.5 sec |
| Experimontal Thrust Force 5509 | 80 kN | 57 kN |
| Analytical Thrust Force Method of Node-Junction (RELAP4/MOD5) | HF 80 kN | HF 54 kN<br>HF-HEM 48 kN<br>HF-M 45 kN |
| Analytical Thrust Force Method of Characteristics (DEPCO-MULTI) | 67 kN | |

Table 3 The results of experimental and analytical jet thrust parameters

| Condition | Non - Equilibrium 0.1 sec after break | Equilibrium 0.5 sec after break |
|---|---|---|
| $\varepsilon_b$ \ $J_t$ | $\frac{F_{NE,\,max}}{A_e\,(P_{o,in} - P_\infty)}$ | $\frac{F_{EQ,\,max}}{A_e\,(P_{o,in,sat} - P_\infty)}$ |
| 79 % Experimental | 1.08 | 1.08 |
| (85 %) | 1.01 | 1.01 |
| 79 % Analytical RELAP4/MOD5 | HF 1.08 | HF 1.01<br>HF-HEM 0.90<br>HF-M 0.84 |

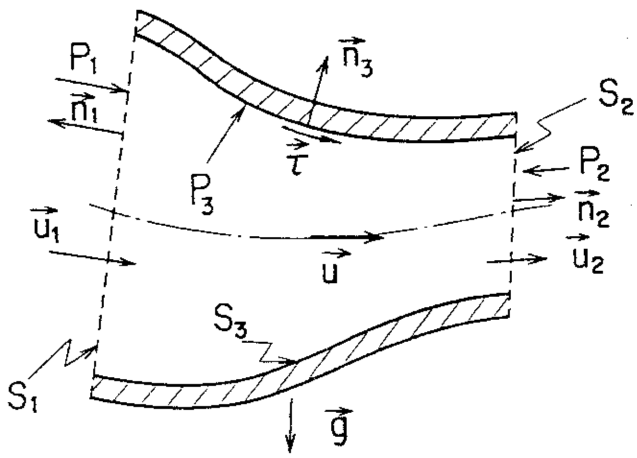


Fig. 1 Control volume for thrust force calculation[4]

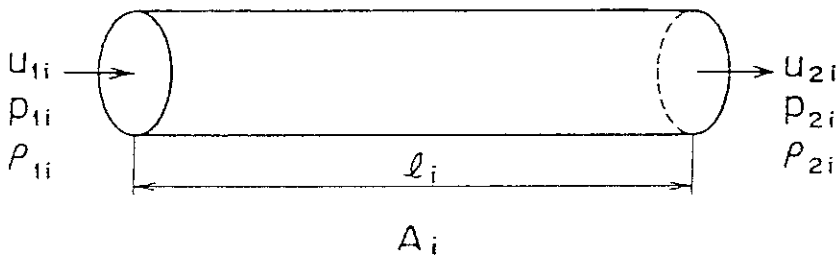


Fig. 2 Control volume of constant area

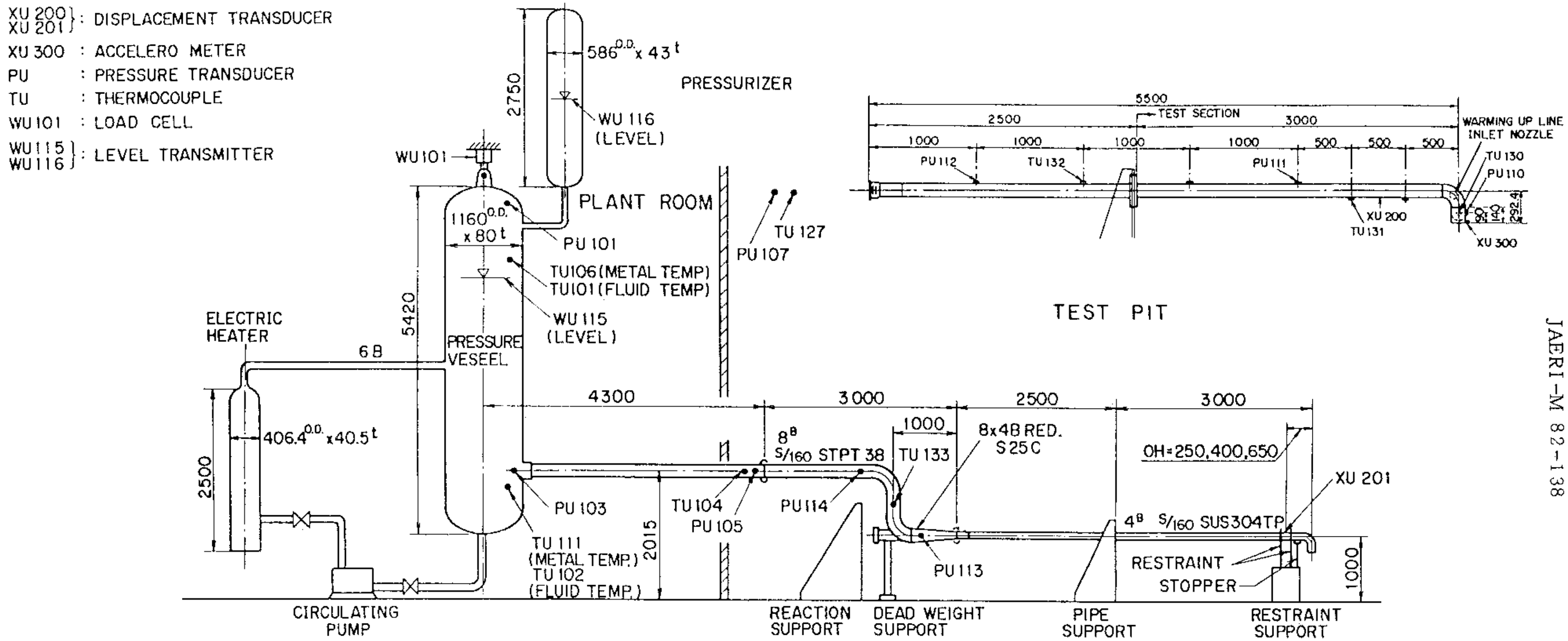


Fig. 3 Dimensions of the test equipment and locations of instrumentation

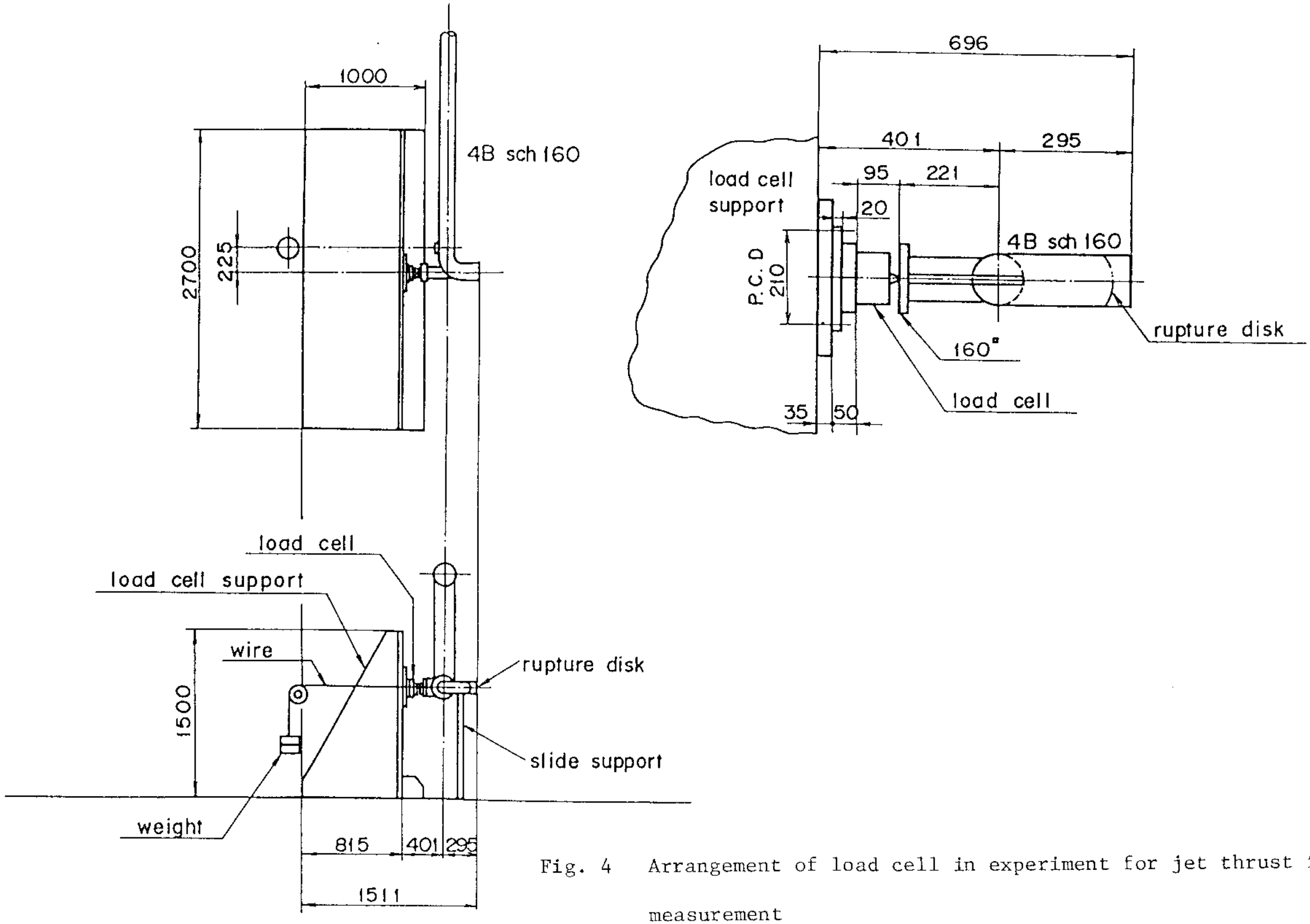


Fig. 4 Arrangement of load cell in experiment for jet thrust force measurement

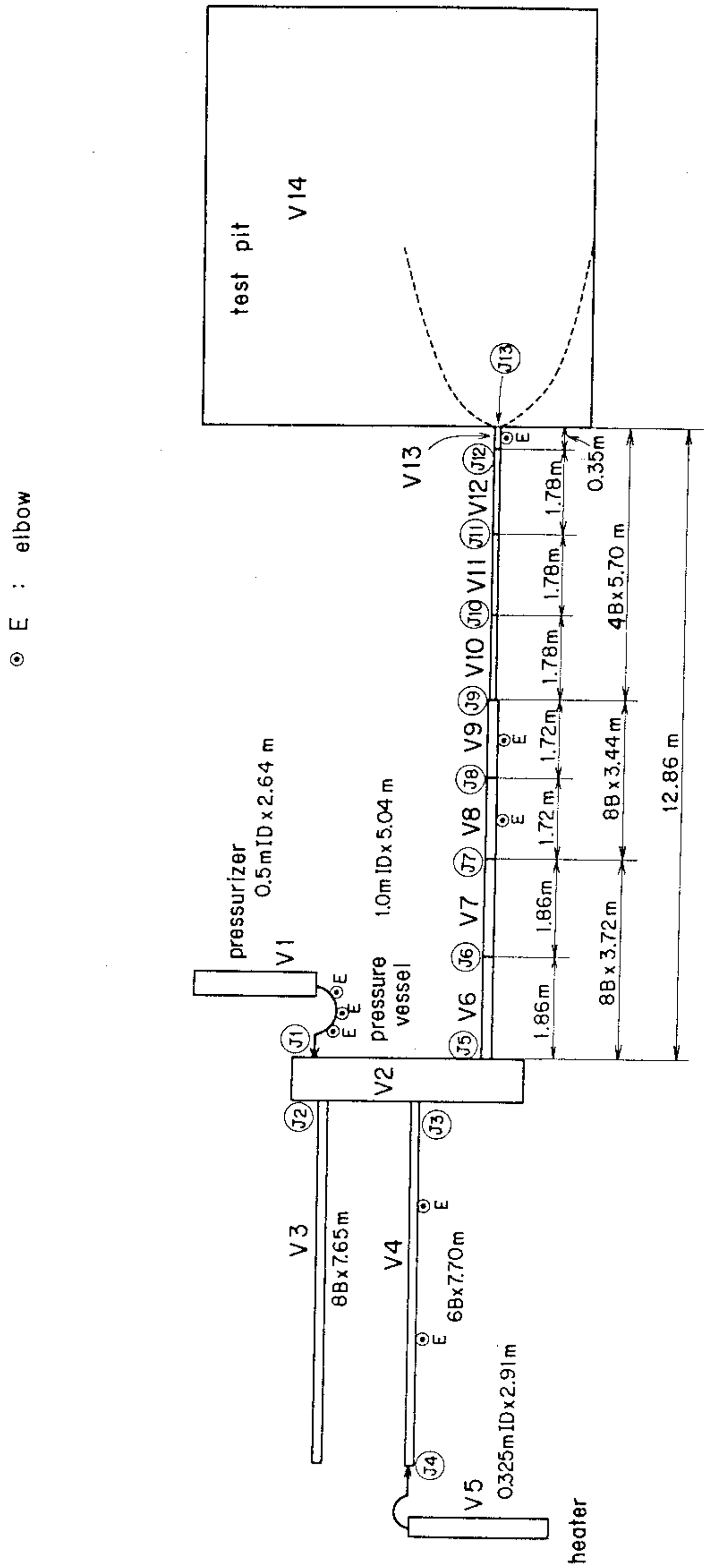


Fig. 5 Analytical model of test equipment

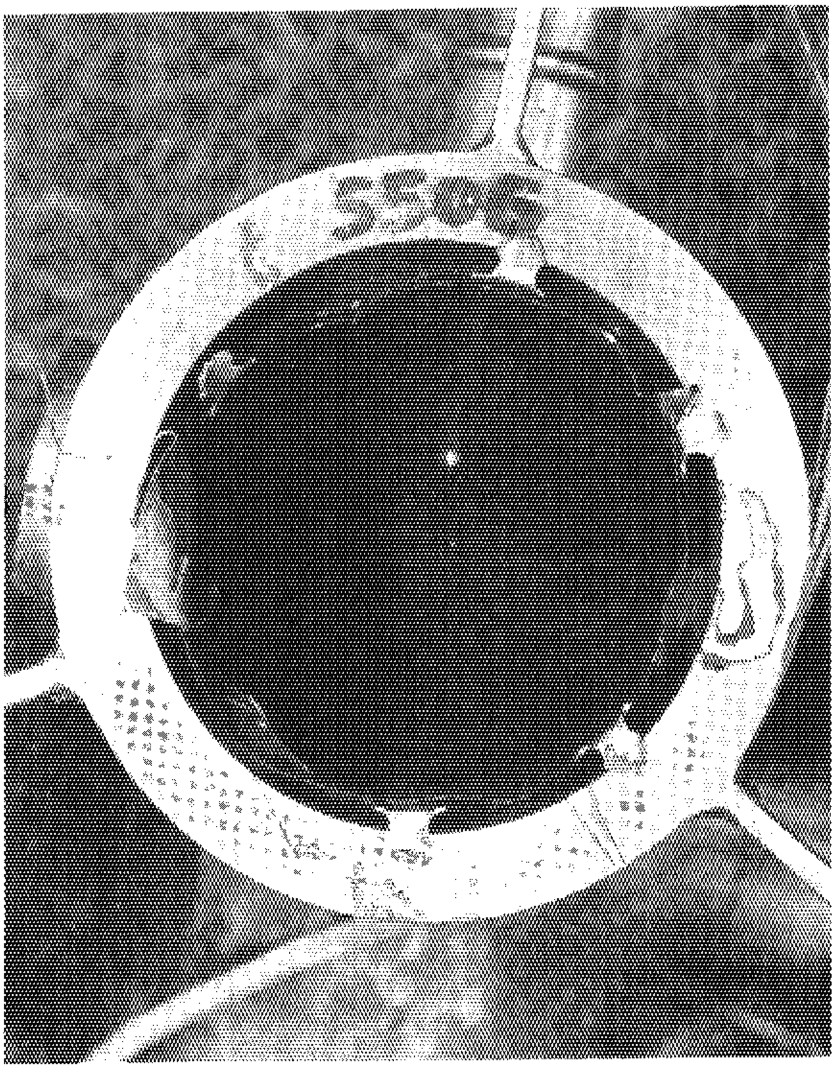


Fig. 6  Typical photograph of vertical cross-section of welded rupture disk after break

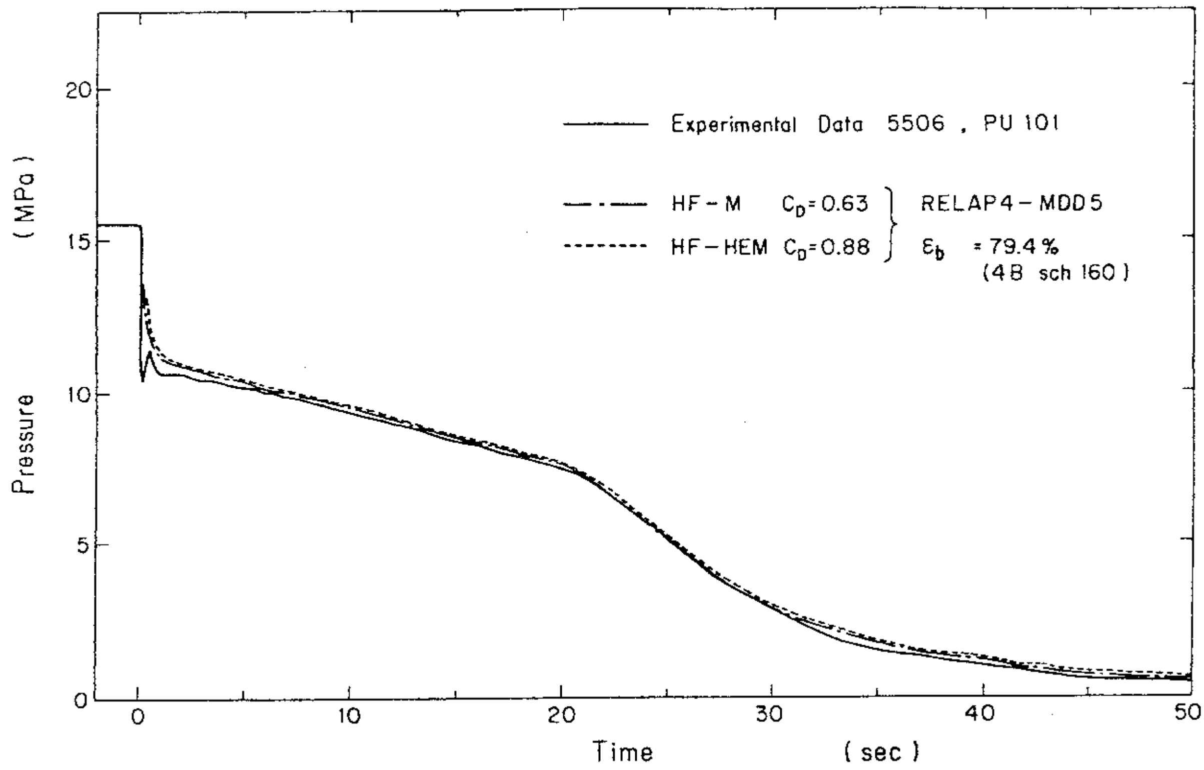


Fig. 7 Pressure history of blowdown in pressure vessel

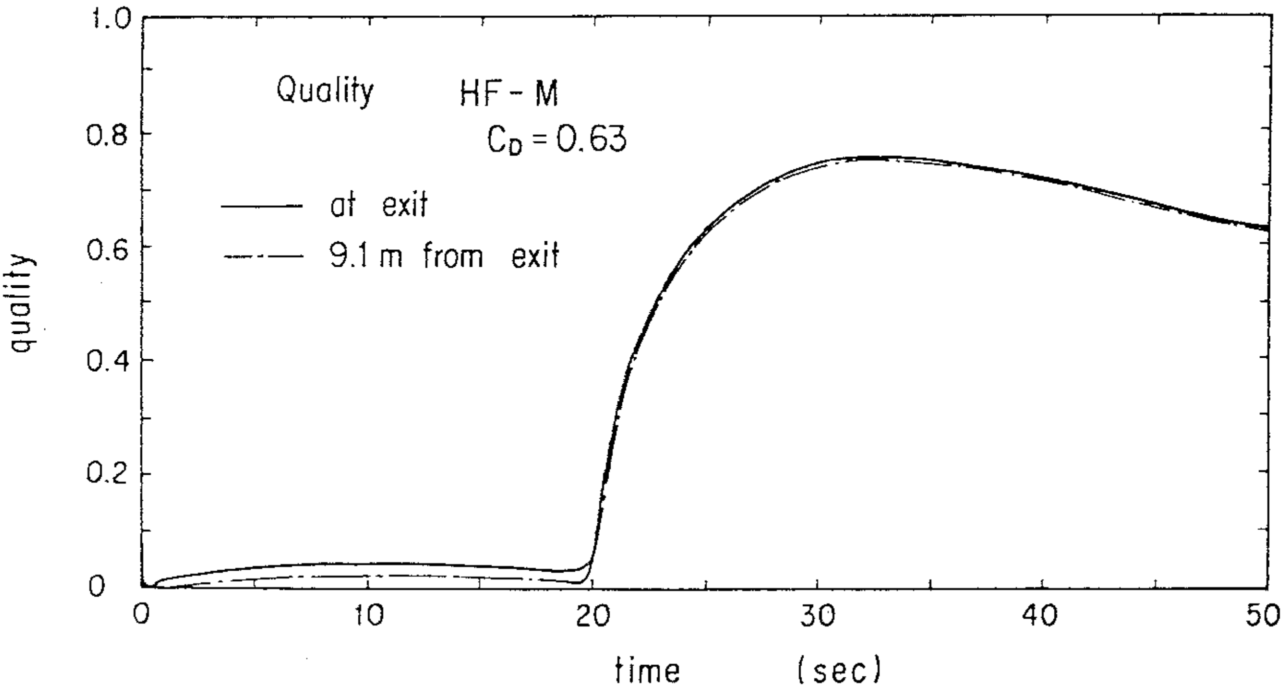


Fig. 8 Quality in the test pipe

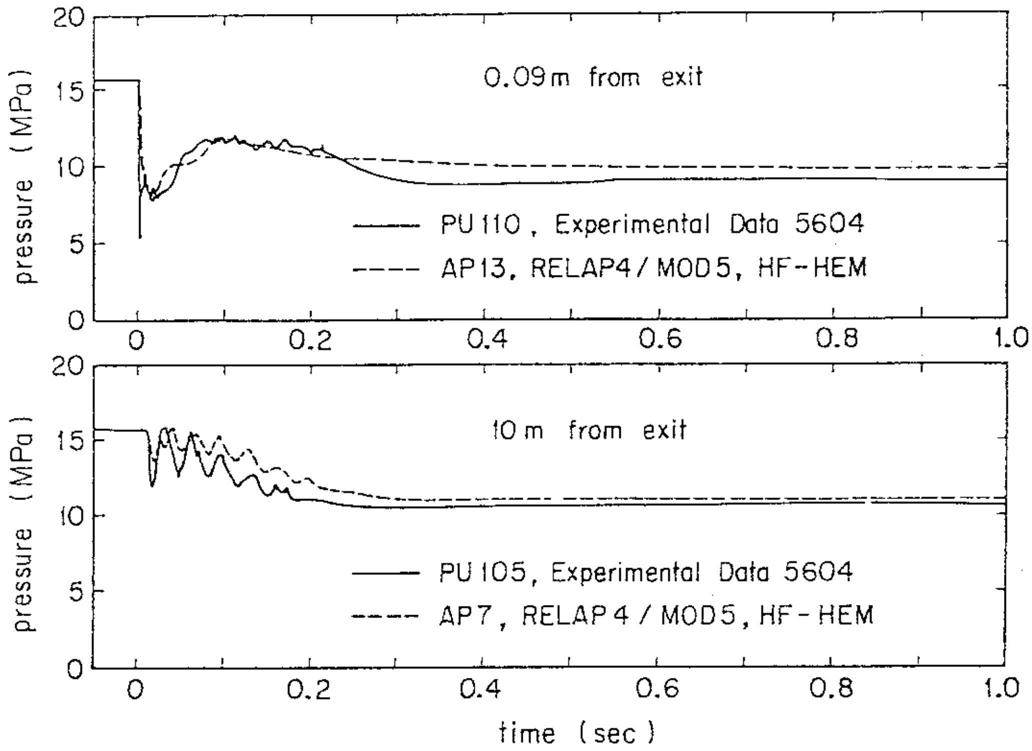


Fig. 9 Decompression process and water hammer phenomena just after break

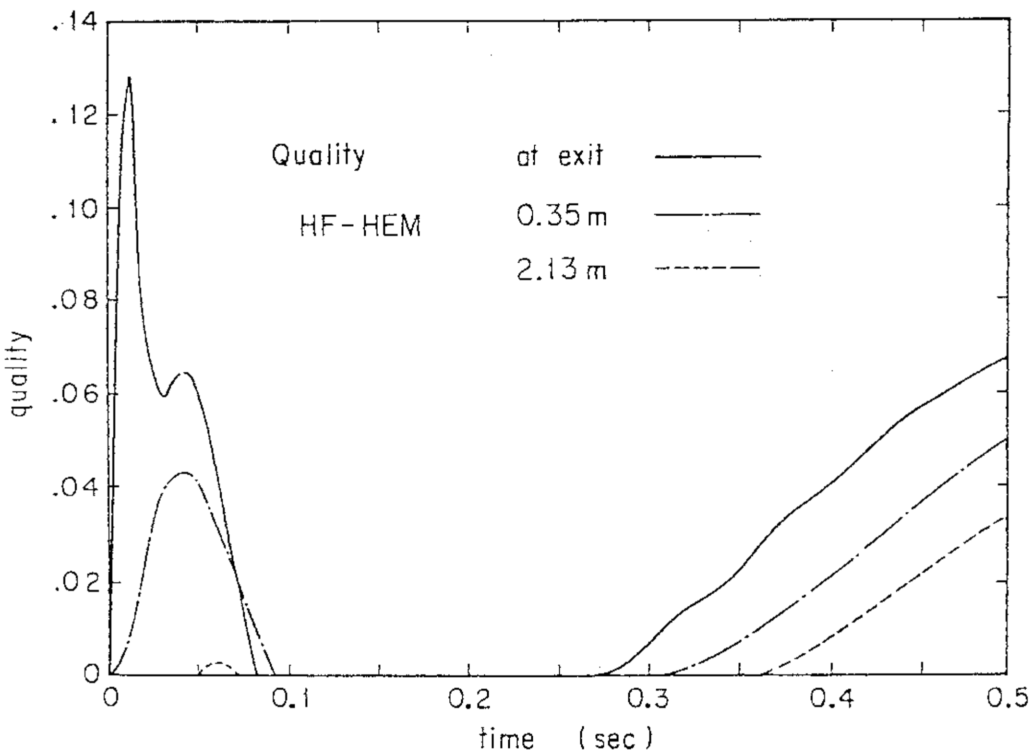


Fig. 10 Propagation of flasing vaporization from the exit

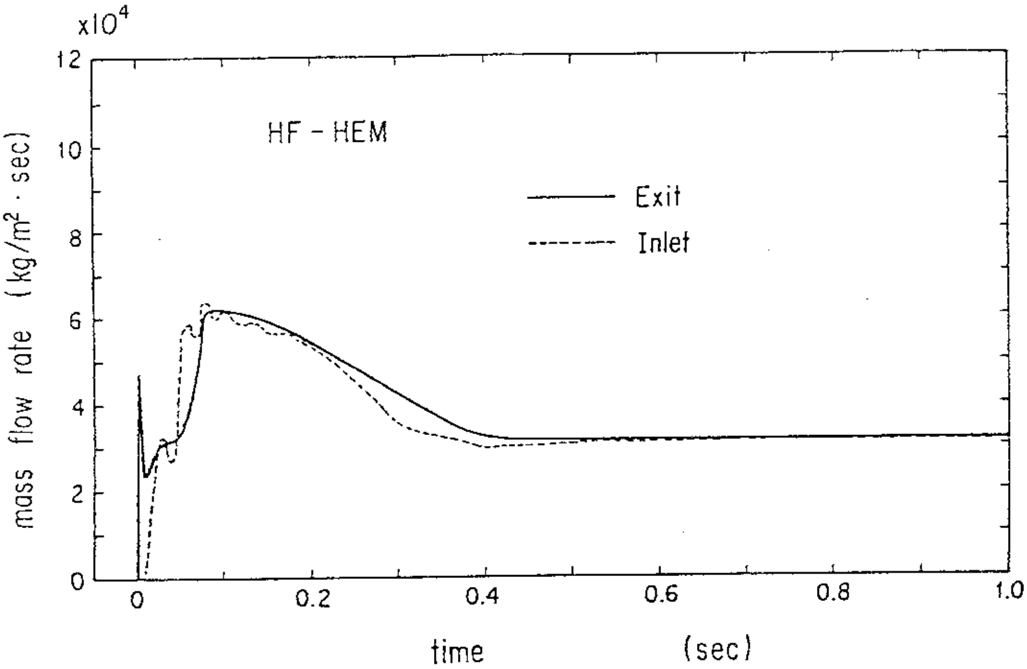


Fig. 11 Mass flow rate in the test pipe by HF-HEM

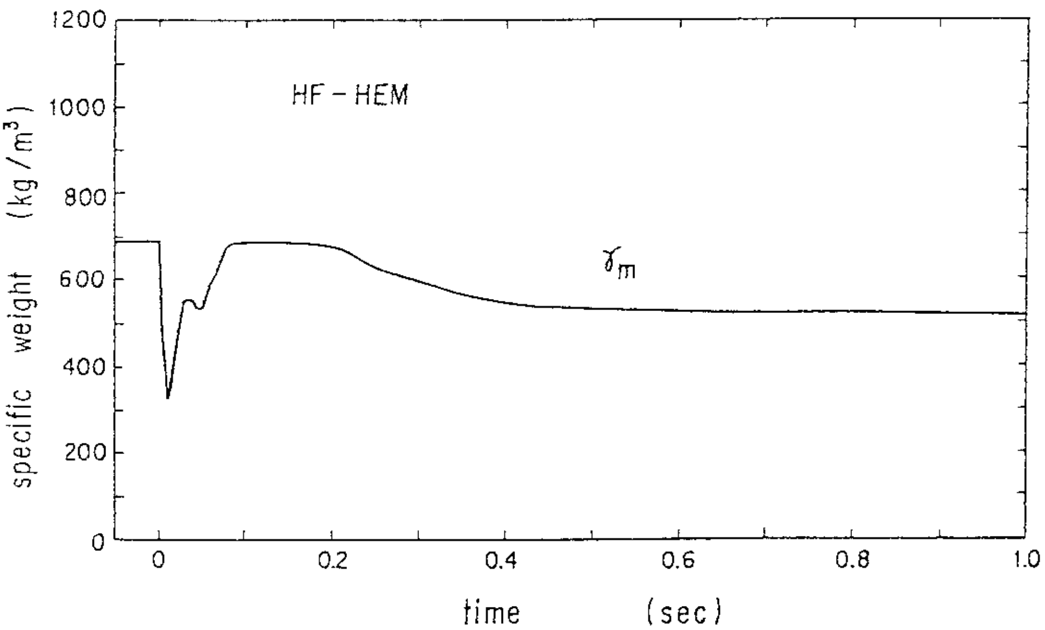


Fig. 12 Specific weight of the exit by HF-HEM

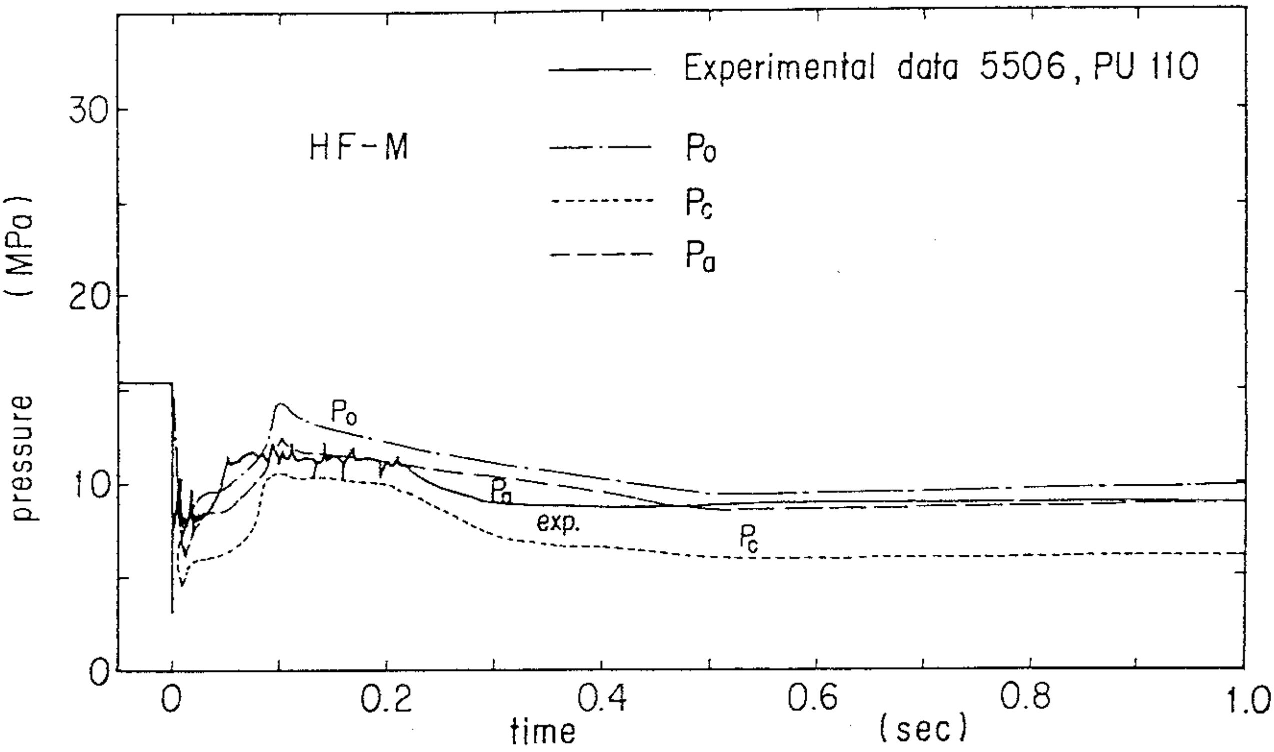


Fig. 13 Exit pressure by HF-M

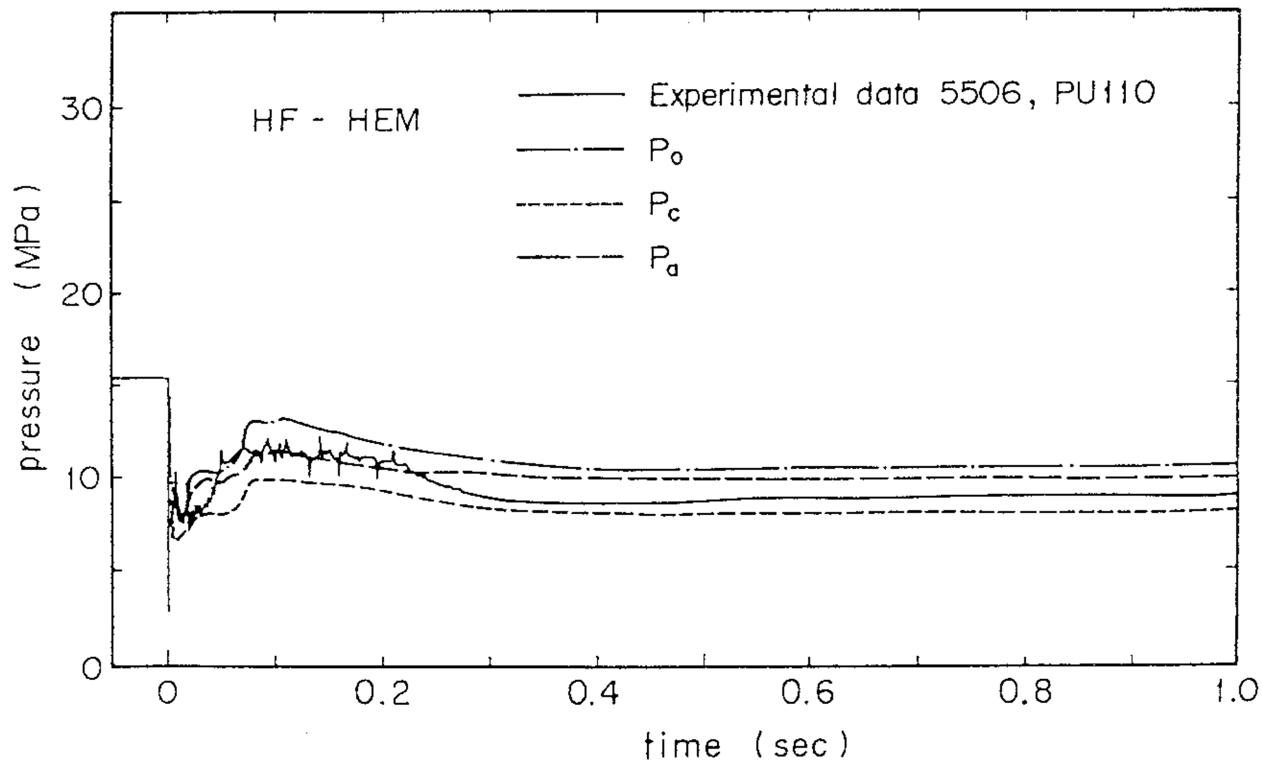


Fig. 14 Exit pressure by HF-HEM

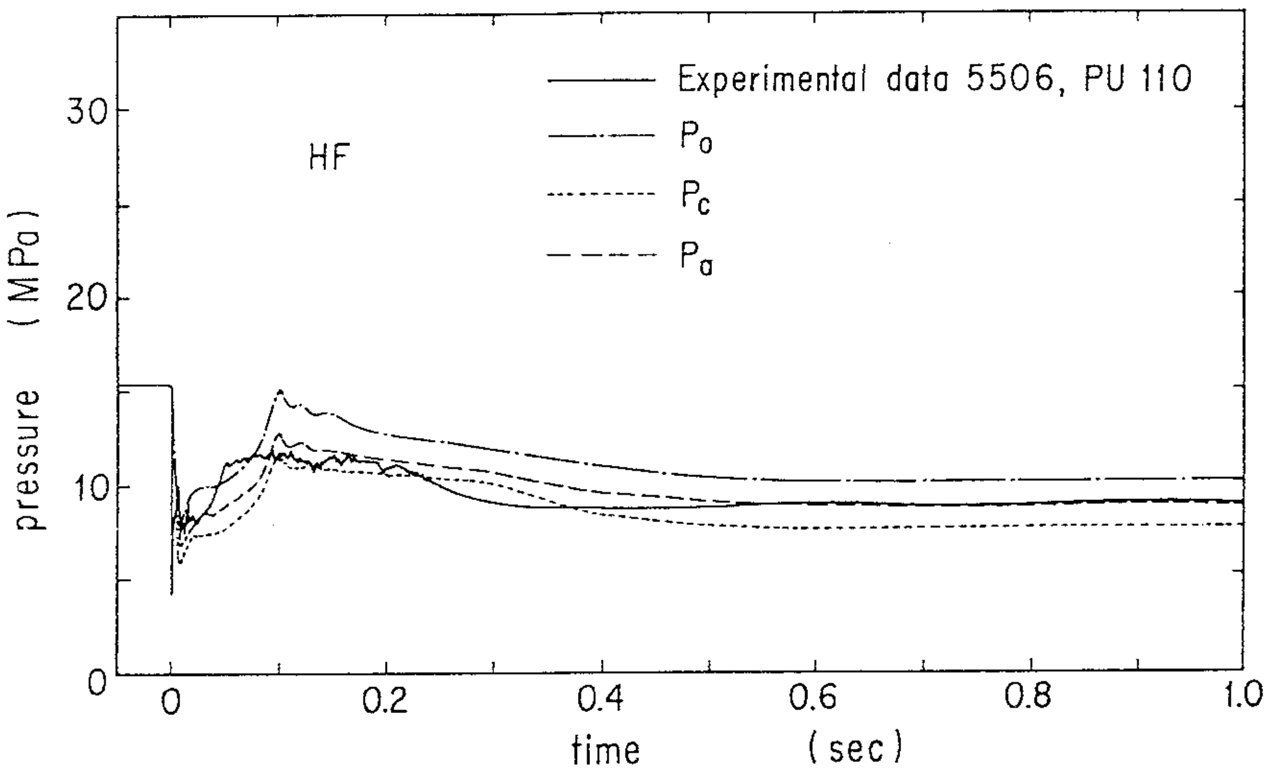


Fig. 15 Exit pressure by HF

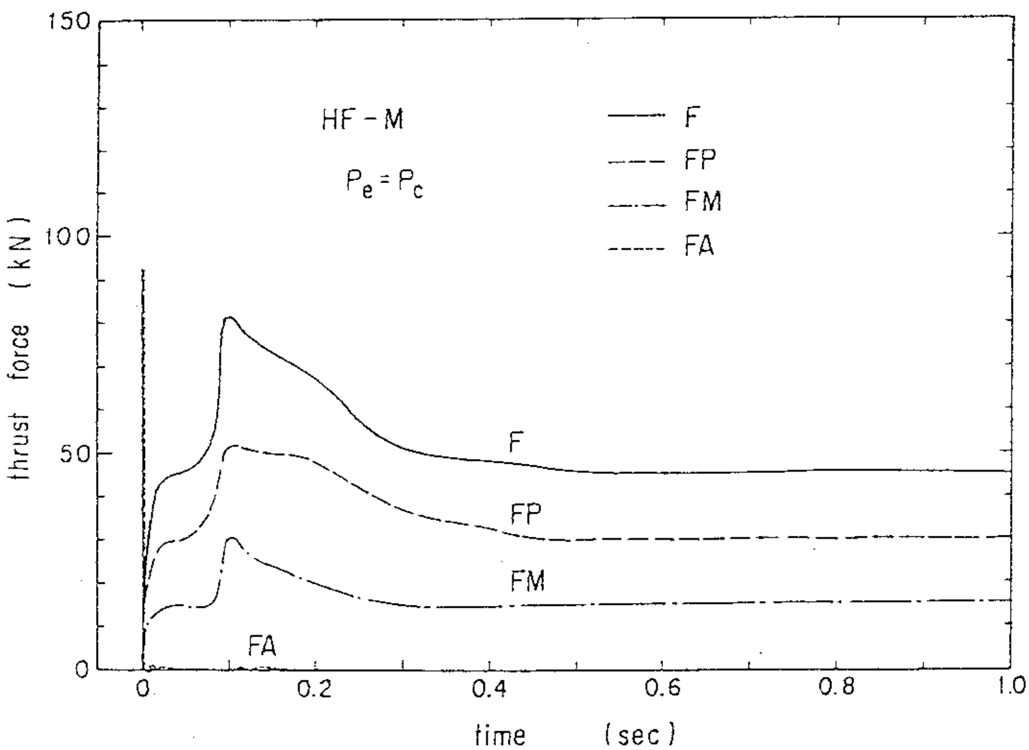


Fig. 16 Blowdown thrust force by HF-M

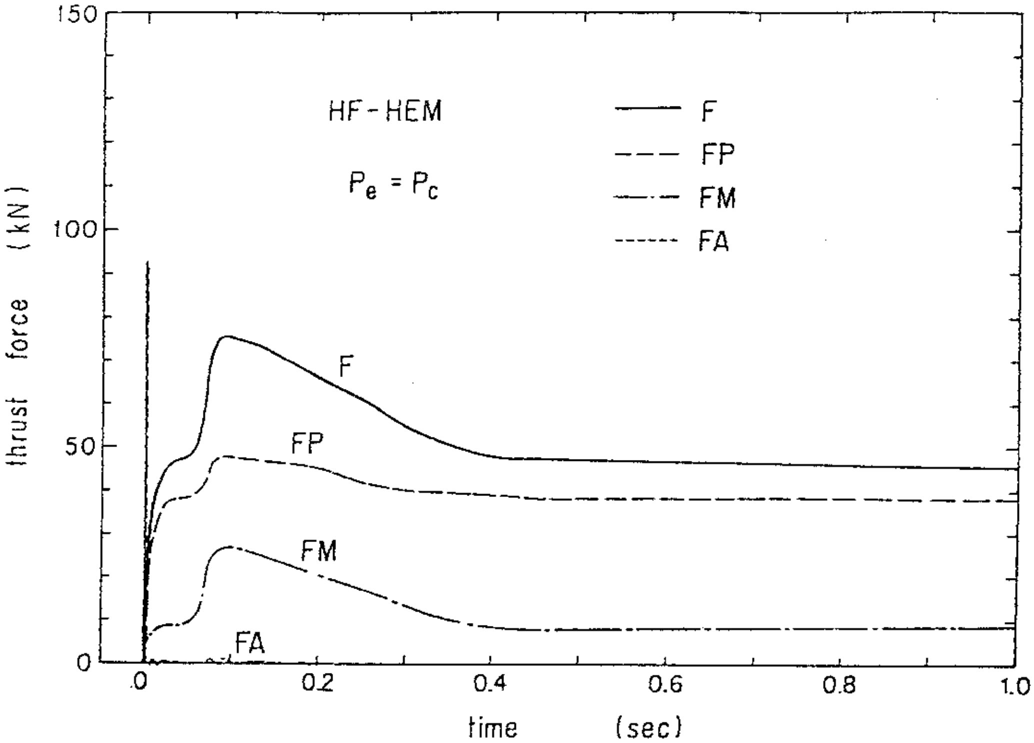


Fig. 17 Blowdown thrust force by HF-HEM

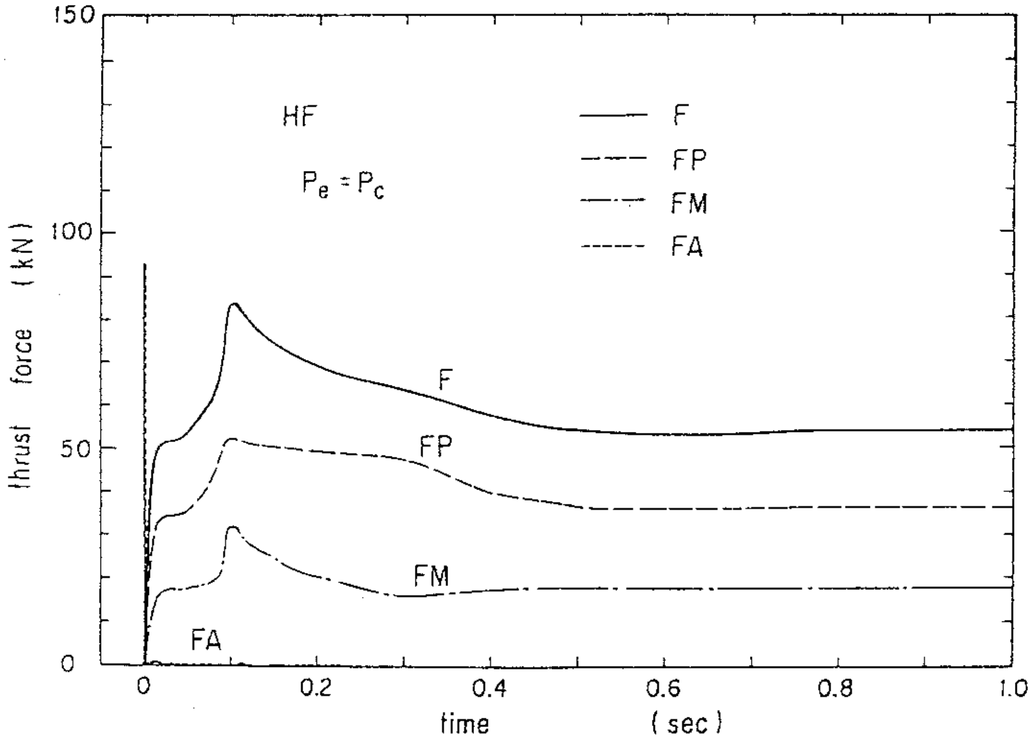


Fig. 18 Blowdown thrust force by HF

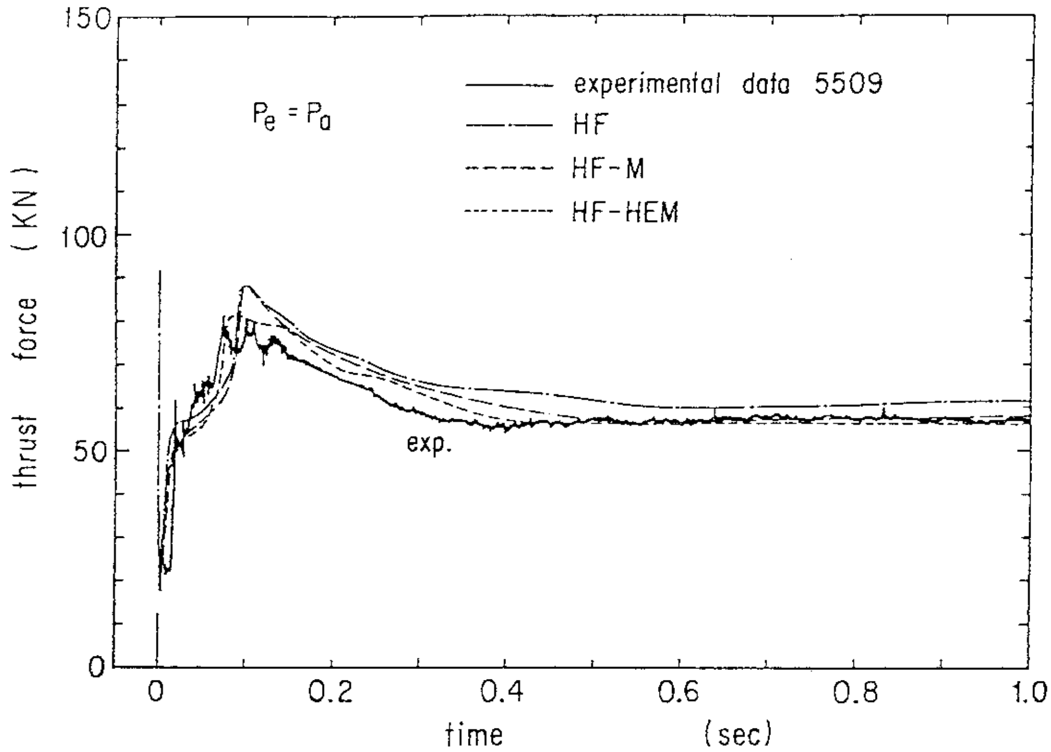


Fig. 19 Comparison of the blowdown thrust forces between the experiment and the analysis by each model, $P_e = P_a$

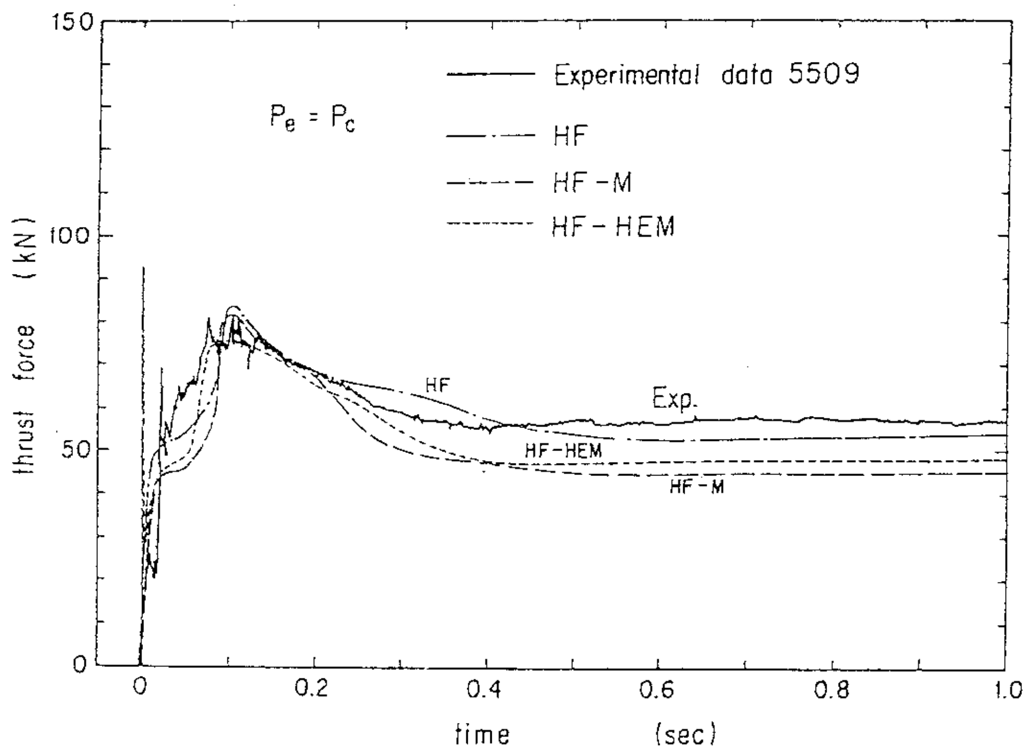


Fig. 20 Comparison of the blowdown thrust forces between the experiment and the analysis by each model, $P_e = P_c$

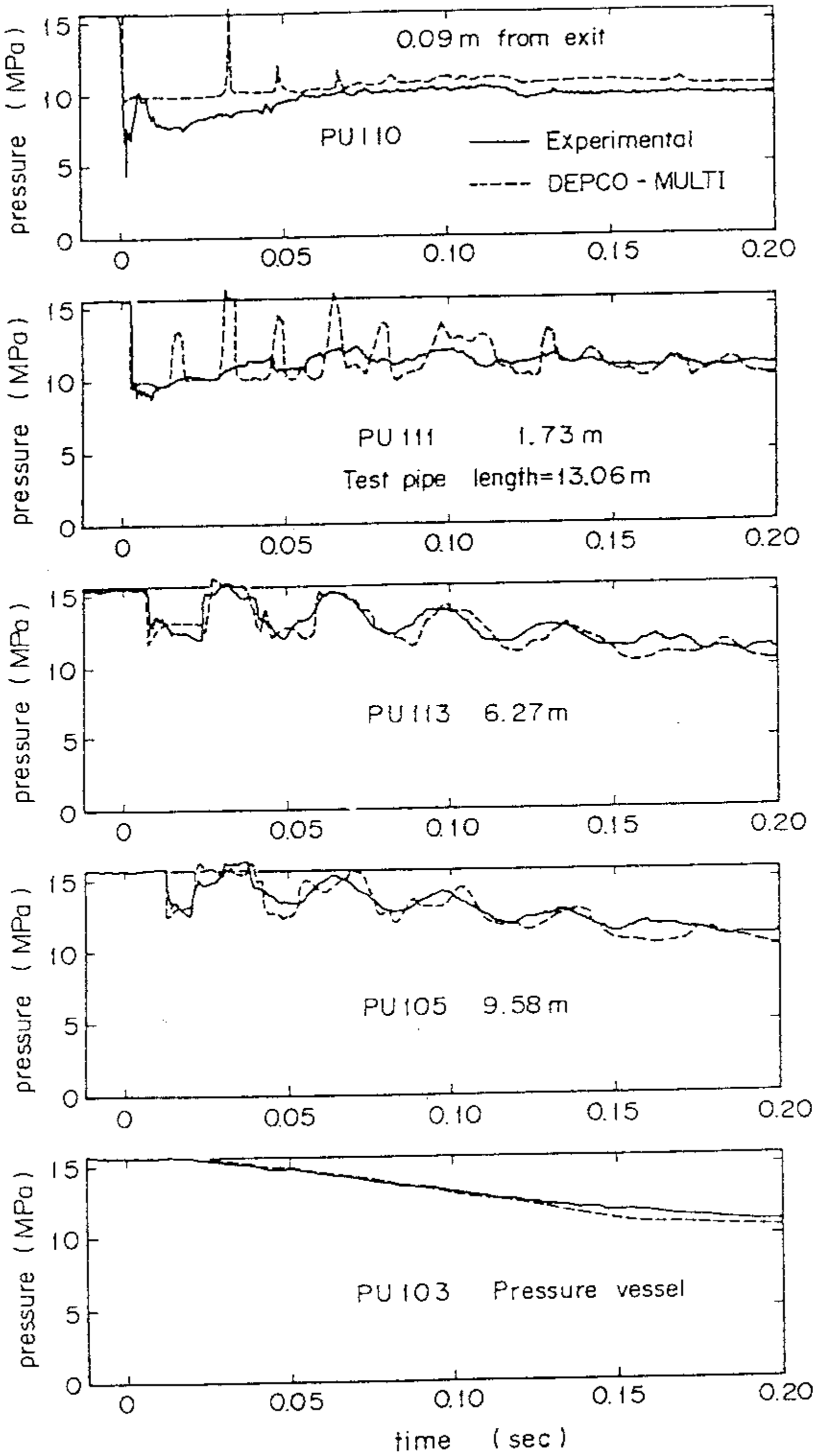


Fig. 21 Comparison of the water hammer between the experiment and the analysis by DEPCO-MULTI[13]

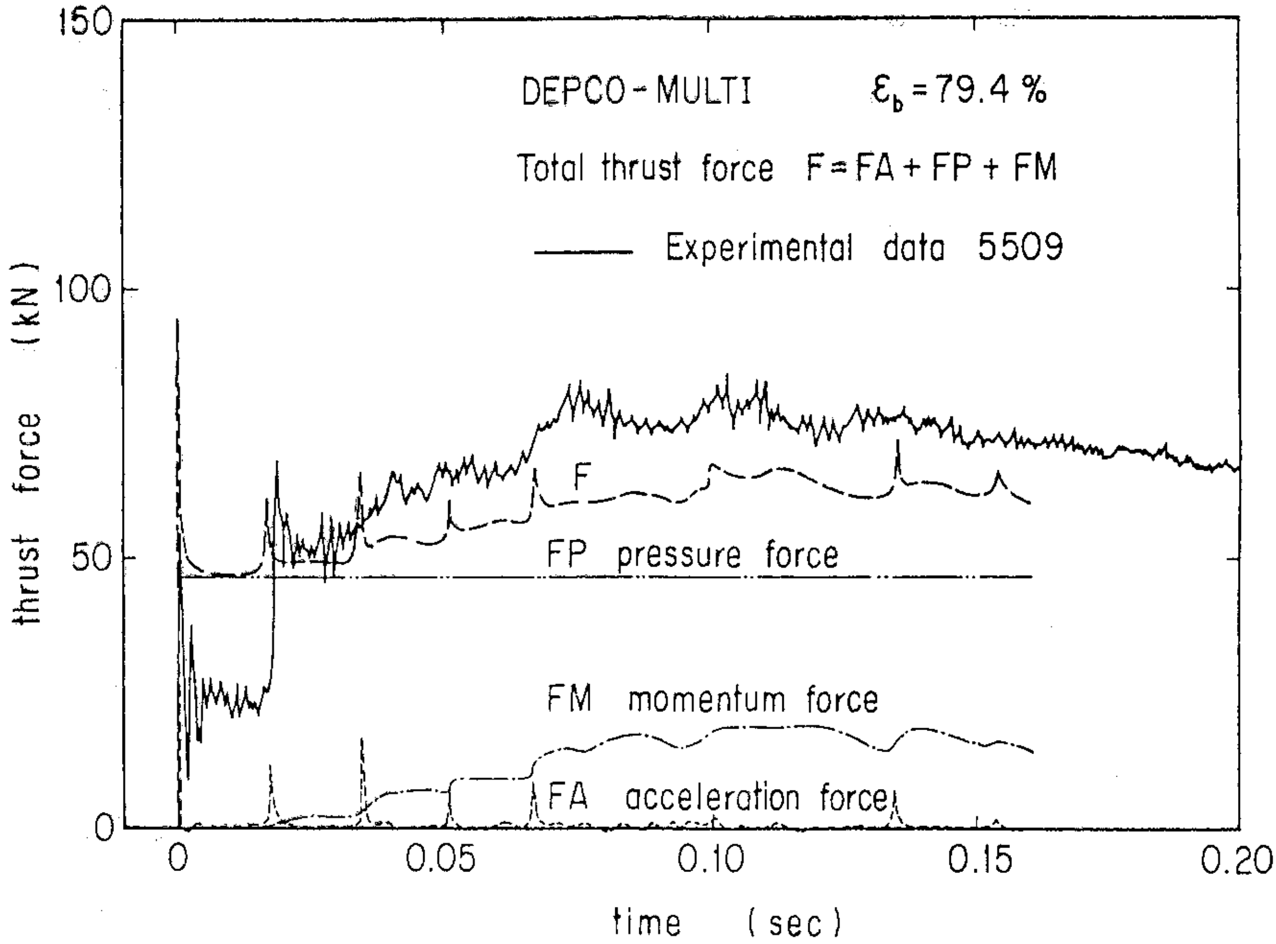


Fig. 22 Thrust force and its component forces by the method of characteristics