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PRTHRUST AND PRTHRUST-JI--COMPUTER
CODES FOR CALCULATING BLOWDOWN
THRUST FORCE

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PRTHRUST and PRTHRUST-J1 --- Computer Codes
for Calculating Blowdown Thrust Force *)

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This paper describes the outlines of PRTHRUST code and PRTHRUST-J1 code which is a modification of the former one. This paper also presents some numerical examples in order to show the effectiveness of PRTHRUST-J1 code.

PRTHRUST code can calculate transient blowdown thrust force and jet impingement force resulting from a postulated pipe rupture. This code, however, has the following limitations; (1) The region from break point to first elbow must be modeled by one control volume. (2) Only the blowdown thrust force at the first elbow can be obtained. Then, PRTHRUST code was so modified as to model the system more precisely and analyze the pipe rupture test performed in JAERI. This modified code is named PRTHRUST-J1.

The two problems of the saturated steam blowdown and the jet test performed in JAERI were solved by PRTHRUST-J1 code. The results of the former analysis were compared with those of the simplified method by Moody. In the latter analysis, it was examined how the difference of modeling the system influenced on the results.

Keywords : PRTHRUST Code, PRTHRUST-J1 Code, Blowdown Thrust Force,
Jet Impingement Force, Pipe Rupture Test

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ブローダウンスラスト力解析コード PRTHRUST および
PRTHRUST-J 1 コードについて ※)

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本報では PRTHRUST コードおよびこれに新しい機能を追加した PRTHRUST-J 1 コードについて概説するとともに PRTHRUST-J 1 コードの有効性を示すために、いくつかの解析例を示した。

PRTHRUST コードは配管破断により生じるスラスト力およびジェット衝撃力を計算するコードである。しかしこのコードでは破断口から第 1 エルボまでを 1 ボリュームでモデル化しなければならないこと、および第 1 エルボにおけるブローダウンスラスト力しか求められないという制約がある。そこで、PRTHRUST コードをベースとしてより精密なモデル化ができ、日本原子力研究所で実施される配管破断試験の解析が可能となるように PRTHRUST-J 1 コードを作成した。

PRTHRUST-J 1 コードの有効性を示すために、飽和蒸気のブローダウンおよび配管破断予備試験で行われたジェット試験の解析を行った。前者の問題については PRTHRUST-J 1 コードによる結果を Moody による簡易計算の結果と比較してその有効性を示した。一方、後者の解析では種々のモデルを用いて解析を行い、モデル化の違いが結果にどのような影響を与えるかを検討した。

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目 次

1. 緒 言	1
2. PRTHRUST コードについて	3
3. PRTHRUST-J 1 コードについて	8
4. 数値解析例	15
5. 結 言	20
謝 辞	20
参照文献	21
付録 PRTHRUST-J 1 入力データ	22

CONTENTS

1. Introduction	1
2. Outline of PRTHRUST Code	3
3. Outline of PRTHRUST-J1 Code	8
4. Numerical Examples	15
5. Concluding Remarks	20
ACKNOWLEDGEMENT	20
REFERENCES	21
APPENDIX PRTHRUST-J1 INPUT DATA	22

1. Introduction

Both jet tests and pipe whip tests are performed with the facilities for the pipe rupture test⁽¹⁾ in JAERI. In the jet tests, the guillotine break of a pipe is caused by breaking rupture disk attached to the end of the pipe. The main measurement items of the jet tests are blowdown thrust force and jet impingement force. The former is measured by the load cell attached to the elbow of the pipe. The latter is measured by the target installed in front of the discharging end of the pipe. PRTHRUST code⁽²⁾, which was developed by Nuclear Service Corporation, was introduced in JAERI to evaluate the blowdown thrust force and jet impingement force obtained from the jet tests, and the driving force of the pipe whipping. This code, however, has the following limitations;

- (1) The region from break point to first elbow must be modeled by one control volume.
- (2) Only the blowdown thrust force at the first elbow can be obtained. Then, the thrust force caused by propagation of pressure wave cannot be calculated.

In the preliminary test performed in October through November, 1978, the jet tests were implemented with a pneumatic stop valve as shown in Fig.1. Discharging jet was controlled by the valve to which the discharging nozzle was connected. The blowdown thrust force was measured by the load cell WU111. In calculating the blowdown thrust force of this system, the stop valve and reducers which exist between the break point and first elbow should be modeled. It is, however, difficult to do so in the analysis with PRTHRUST code, because the region from the break point to the first elbow must be modeled by one control volume.

PRTHRUST code was so modified as to analyze the jet tests including the preliminary test. This modified code is named PRTHRUST-J1 code. In PRTHRUST-J1 code, the region from the break point to the first elbow can be divided into the plural numbers of control volume. Therefore, PRTHRUST-J1 code may deal with the complicated system including valves and reducers in the region from the break point to the first elbow. PRTHRUST-J1 code may also calculate the blowdown thrust forces not only at the first elbow but also at the other ones. Moreover, the ramp characteristics of valve operation are newly included in this code. The acceleration term of blowdown thrust force and the discharging coefficient were also made change in PRTHRUST-J1 code.

In this report, Section 2 describes the outline of PRTHRUST code. In Section 3, the outline of PRTHRUST-J1 code is presented in relation to the modification of PRTHRUST code. The calculational examples of the saturated steam blowdown and the jet test performed in JAERI are included in Section 4 in order to show the effectiveness of PRTHRUST-J1 code. The concluding remarks are described in Section 5, together with some future problems. Moreover, the input format of PRTHRUST-J1 code are given in APPENDIX.

2. Outline of PRTHRUST Code

PRTHRUST code is a modification of RELAP-3 code⁽³⁾, a loss of coolant accident code. The modification consists of incorporating the blowdown thrust force and jet impingement force equations into RELAP-3 code and eliminating the thermal effect parts of reactor core and heat exchangers from this code. These eliminated parts are thought to have little effect on the blowdown thrust force and jet impingement force, because these forces are important during a few seconds after a pipe breaks.

2.1 Modelling of PRTHRUST code

The modelling of PRTHRUST code is the same as RELAP-3 code, since PRTHRUST code is based on RELAP-3 code.

In PRTHRUST code, the fluid system is modeled as an assemblage of control volumes interconnected by flow paths called junctions. Control volumes are used to model such components as pressure vessels, steam generators, heat exchangers and piping volumes. On the other hand, junctions are used to interconnect control volumes and may include control valves, check valves, fills, pumps and leaks. 200 control volumes and 250 junctions may be used to model the fluid system in PRTHRUST code. The control volume including leak junction is called break volume. The break volume geometry gives directly effects on the calculated results of blowdown thrust force. Therefore, PRTHRUST code recommends the following guideline in selecting break volume according to the break type.

(a) Circumferential Break

For the circumferential (guillotine) breaks, break volume should extend from the break junction to the first elbow, as shown in Fig.2-1. Fifty percent (50 %) of the break volume inertia (L/A) and zero percent (0 %) of the frictional loss term ($KJUN$) should be applied to the break junction. $KJUN$ of the break junction is calculated in the program from the orifice equation.

(b) Longitudinal and Crack Break

For the longitudinal and crack breaks, the break volume should extend two pipe diameters in each direction from the center of the break, as shown in Fig.2-2. One hundred percent (100 %) of the break volume inertia (L/A) and zero percent (0 %) of the friction loss term ($KJUN$) should be

applied to the break junction. KJUN of the break junction is internally generated in the program. For the small longitudinal or crack breaks with break area less than 25 % of the pipe area, the following break volume inertia should be used

$$\frac{L}{A} = \frac{D_P}{A_B} \quad (1)$$

where D_P = pipe diameter
 A_B = break area

2.2 Basic Equations

The basic equations are the equations of mass, energy and momentum balance, and equation of blowdown thrust force.

Mass and energy balance in each control volume are given as follows:

- Mass balance

$$\frac{dM_i}{dt} = \sum_{j=1}^N W_{ij} \quad (2)$$

- Energy balance

$$\frac{dU_i}{dt} = \sum_{j=1}^N W_{ij} h_{ij} \quad (3)$$

in which

- M_i = total mass in volume i
- W_{ij} = mass flow rate into volume i through junction j
- U_i = energy in volume i
- h_{ij} = enthalpy of flowing fluid into volume i through junction j
- N = number of junctions in volume i

Heat input into volume i is neglected in eq.(3) because of short term analysis.

Junction flows are calculated from one-dimensional momentum equation:

$$\frac{1}{g_c} \left(\frac{L}{A} \right) \left(\frac{dW_j}{dt} \right) = (P_i - P_{i+1}) + \Delta P_p + \iiint_{V_j} \rho dz - \frac{K_j W_j |W_j|}{\rho_j} \quad (4)$$

where

- g_c = gravitational conversion constant
 $\frac{l}{A}$ = junction inertia
 W_j = average flow rate from volume i to volume i+1 through junction j
 $(P_i - P_{i+1})$ = thermodynamic pressure differential across the fluid contained in the flow volume
 ΔP_p = pump head
 $\iiint_{V_j} \rho dz$ = gravitational head across fluid column
 K_j = net friction coefficient including normal friction losses
 ρ_j = fluid density at junction

The following Moody's two-phase choked flow model⁽⁴⁾ is used to calculate a limiting (choked) mass flow:

$$W_{choke} = A_{choke} f_n(P_o, h_o) \quad (5)$$

in which

- W_{choke} = maximum junction flow rate
 A_{choke} = minimum area in junction
 f_n = mass flux as a function of stagnation pressure P_o and enthalpy h_o

The flow through the junction is chosen as the smaller of the inertial flow calculated from eq.(4) and the choked flow given by eq.(5). Moody's model also defines the static pressure existing at throat.

The blowdown thrust force caused by discharging fluid is calculated based on the momentum equation applied to the break junction of the break control volume. From Reference (4), p.18,

$$\Sigma F = F - F_p = \frac{d}{dt} \iiint_{c.v.} \frac{\rho v dV}{g_c} + \iint_{c.s.} \frac{\rho(v \cdot dA)v}{g_c} \quad (6)$$

where

- ΣF = sum of external forces acting on fluid control volume
 F = blowdown thrust force
 F_p = pressure force
 t = time

ρ = density
 v = velocity
 c.v. = fluid control volume
 V = volume
 A = area
 g_c = gravitational constant
 c.s. = fluid control surface

Transposing terms in eq.(6) results in the simplified equation,

$$F = F_a + F_m + F_p \quad (7)$$

in which,

F_a = acceleration force (wave thrust)

$$= \frac{d}{dt} \iiint_{c.v.} \frac{\rho v dV}{g_c} \quad (8)$$

$$F_m = \text{momentum force} = \iint_{c.s.} \frac{\rho(v \cdot dA)v}{g_c} \quad (9)$$

$$F_p = \text{pressure force} = A(P_e - P_a) \quad (10)$$

P_e = static exit (throat) pressure

P_a = ambient pressure

Blowdown thrust force can be obtained by applying eq.(7) to the break volume.

The wave thrust, F_a , is caused by the change in momentum with time within the break volume and can be approximated by:

$$F_a = \frac{\Delta(Mv)}{\Delta t(g_c)} \quad (11)$$

where

Δt = time increment

M = mass

The momentum force, F_m , represents momentum flow from the break volume and can be approximated by

$$F_m = \frac{\rho A v^2}{g_c} \quad (12)$$

where v is the exit velocity from the leak junction determined from Moody's

model or the momentum equation given in eq.(4).

The pressure force, F_p , given by the eq.(10) has a positive value, when flow is choked at the leak junction. Otherwise, the pressure force term is equal to zero because of the equality of P_e and P_a .

The jet impingement force, J_F , is given as follows:

$$J_F = F_m + F_p \quad (13)$$

The pressure in the control volume, P_i , is determined from the following equation through an iterative process.

$$h_i = \frac{U_i}{M_i} + P_i \left(\frac{V_i}{M_i} \right) \quad (14)$$

in which

h_i = enthalpy

(V_i/M_i) = specific volume

3. Outline of PRTHRUST-J1 code

PRTHRUST code was so changed as to analyze the pipe rupture test performed in JAERI. In the modified code, PRTHRUST-J1,

- (1) the blowdown thrust force at the arbitrary elbow in the pipe line can be calculated and obtained in the form of plotter output,
- (2) the blowdown thrust force at the first elbow can be obtained in the three separate terms of acceleration force (wave thrust), momentum force and pressure force, and each term can be obtained in the form of plotter output,
- (3) the ramp characteristics of valve operation are so included to the control valve (trip type: $\pm 6 \sim \pm 10$)^(*) to analyze the preliminary jet test using stop valve, and
- (4) new options are added to the discharging coefficient and the procedure for calculating wave thrust.

The detailed description of modification from PRTHRUST code to PRTHRUST-J1 code are given in this section.

3.1 Procedure for Calculating Blowdown Thrust Force

The procedure for calculating blowdown thrust force discussed in Ref.(6) is presented here.

Now, considering a segment of contained fluid as shown in Fig.3, the fluid forces which may act upon the container enclosing a fluid are the local pressures and shear forces as

$$\bar{F} = \iint_{S_W} p \bar{n} dS_W + \iint_{S_W} \bar{\tau} dS_W \quad (15)$$

where

- \bar{F} = total unbalanced force acting on the pipe
- S_W = wetted surface of container
- $\bar{\tau}$ = local shear force
- p = local static pressure
- \bar{n} = local surface normal unit vector

The momentum equation for the control volume shown in Fig.3 is given as follows,

(*) Referred to APPENDIX

$$\begin{aligned}
 & \frac{\partial}{\partial t} \iiint_V \frac{\bar{u}\bar{\rho}}{g_c} dV + \iint_{S_1} \frac{\bar{u}_1}{g_c} (\bar{\rho}\bar{u}\cdot\bar{n})_1 dS_1 + \iint_{S_2} \frac{\bar{u}_2}{g_c} (\bar{\rho}\bar{u}\cdot\bar{n})_2 dS_2 \\
 = & - \iint_{S_W} \bar{p}\bar{n}dS_W - \iint_{S_W} \bar{\tau} dS_W - \iint_{S_1} p_1 \bar{n}_1 dS_1 - \iint_{S_2} p_2 \bar{n}_2 dS_2 \\
 & - \iiint_V \frac{\rho g_a \bar{k}}{g_c} dV
 \end{aligned} \tag{16}$$

in which

- g_a = gravitational acceleration
- g_c = gravitational constant
- V = control volume
- t = time
- ρ = fluid density
- S = control surface
- \bar{u} = local velocity
- \bar{n} = local surface normal unit vector
- \bar{k} = unit vector orientation for gravitation

and subscripts 1 and 2 represent the values on the control surfaces S_1 and S_2 shown in Fig.3. The left hand side of eq.(16) gives the momentum change rate. On the other hand, each term in the right hand side of eq.(16) represents the pressure applied by wetted walls, shear force supplied by surface friction, pressure applied by adjoining fluid, and gravity as the only body force, respectively. Using eq.(16) in eq.(15), the force acting on the container due to fluid is given as follows.

$$\begin{aligned}
 F &= \iint_{S_W} p \bar{n} dS_W + \iint_{S_W} \bar{\tau} dS_W \\
 &= - \left\{ \frac{\partial}{\partial t} \iiint_V \rho \frac{\bar{u}}{g_c} dV + \iint_{S_1} \left[p_1 \bar{n}_1 + \frac{\bar{u}_1}{g_c} (\bar{\rho}\bar{u}\cdot\bar{n})_1 \right] dS_1 \right. \\
 &\quad \left. + \iint_{S_2} \left[p_2 \bar{n}_2 + \frac{\bar{u}_2}{g_c} (\bar{\rho}\bar{u}\cdot\bar{n})_2 \right] dS_2 + \iiint_V \frac{\rho g_a}{g_c} \bar{k} dV \right\}
 \end{aligned} \tag{17}$$

Next, by assuming that u and ρ are uniform with radius at any time and axial position, a mass flow rate which is dependent only upon length

ℓ and time t , is defined as

$$q(t, \ell) \bar{m} = \bar{q}(t, \ell) = \rho(t, \ell) \bar{u}(t, \ell) A(\ell) \quad (18)$$

where \bar{m} is the unit vector along pipe axis and directs towards positive flow. Then, $\bar{m} \cdot \bar{n}$ is equal to ± 1 on the control surfaces S_1 and S_2 . Substituting eq.(18) into eq.(17) and neglecting the gravity term in eq.(17), the following equation is obtained.

$$\begin{aligned} -F = & \frac{\partial}{\partial t} \iiint_V \frac{\bar{q}}{A g_c} dV + [p \bar{n} + \frac{\bar{q}(\bar{q} \cdot \bar{n})}{\rho A^2 g_c}]_1 \iint_{S_1} dS_1 \\ & + [p \bar{n} + \frac{\bar{q}(\bar{q} \cdot \bar{n})}{\rho A^2 g_c}]_2 \iint_{S_2} dS_2 \end{aligned} \quad (19)$$

Using the relation $\bar{m}(\bar{m} \cdot \bar{n}) = \bar{n}$ on the control surfaces S_1 and S_2 , eq.(19) becomes

$$\begin{aligned} -\bar{F} = & \frac{\partial}{\partial t} \iiint_V \frac{q}{A g_c} \bar{m} dV + [p + \frac{q}{\rho A^2 g_c}]_1 A_1 \bar{n}_1 \\ & + [p + \frac{q^2}{\rho A^2 g_c}]_2 A_2 \bar{n}_2 \end{aligned} \quad (20)$$

in which A denotes pipe area. For simplicity, we define an area weighted average mass flow rate as

$$G = \int_{\ell} (q/A) d\ell / \int_{\ell} (1/A) d\ell \quad (21)$$

Then, the acceleration term in eq.(20) is transformed as

$$\frac{\partial}{\partial t} \iiint_V \left(\frac{q}{A}\right) dV = \frac{\partial}{\partial t} \iint_A [G \int_{\ell} \frac{d\ell}{A}] dA = [\iiint_V \frac{1}{A} dV] \frac{\partial G}{\partial t} \quad (22)$$

For convenience, a force equivalent area, FEA, is defined for the pipe within V as

$$FEA = \iiint_V \frac{1}{A} dV / \int_{\ell} \frac{1}{A} d\ell \quad (23)$$

Considering that $\int \frac{1}{A} d\ell$ is equal to I (inertia), eq.(20) becomes as follows.

$$\begin{aligned}
 -F = \frac{1}{g_c} \cdot FEA \cdot I \cdot \frac{\partial G}{\partial t} \bar{m} + [p + \frac{q^2}{\rho A^2 g_c}]_1 A_1 \bar{n}_1 \\
 + [p + \frac{q^2}{\rho A^2 g_c}]_2 A_2 \bar{n}_2
 \end{aligned}
 \tag{24}$$

The FEA defined by eq.(23) is easily simplified for the following cases.

- (i) When there is no area change in the region along ℓ , the expressions for FEA and I are simplified to:

$$FEA = \iiint_V \frac{dV}{\int_{\ell} d\ell} = \frac{V}{\ell} = A \text{ (constant area)}
 \tag{25}$$

$$I = \int_{\ell} \frac{1}{A} d\ell = \frac{\ell}{A}
 \tag{26}$$

- (ii) Where A may be assumed constant over each of K subdivision of ℓ , the expression reduces to simply

$$\begin{aligned}
 FEA = \iiint_V \frac{dV}{A} / \int_{\ell} \frac{d\ell}{A} = \iiint_V \left(\frac{dV_1}{A_1} + \frac{dV_2}{A_2} + \dots + \frac{dV_K}{A_K} \right) / I \\
 = (\ell_1 + \ell_2 + \dots + \ell_K) / I
 \end{aligned}
 \tag{27}$$

- (iii) In general, with A known as a specific function $f(\ell)$, such as at a reducer or venturi,

$$FEA = \iiint_V \frac{dV}{A} / \int_{\ell} \frac{d\ell}{A} = \ell / \int_{\ell} f(\ell)^{-1} d\ell
 \tag{28}$$

Applying eq.(24) to the system model of Fig.4 yields

$$\begin{aligned}
 -F_i = FEA_i I_i \frac{1}{g_c} \frac{\partial G_i}{\partial t} \bar{m}_i + [p + \frac{q^2}{\rho A^2 g_c}]_{i-\frac{1}{2}} (A \bar{n})_{i-\frac{1}{2}} \\
 + [p + \frac{q^2}{\rho A^2 g_c}]_{i+\frac{1}{2}} (A \bar{n})_{i+\frac{1}{2}}
 \end{aligned}
 \tag{29}$$

in which i designates such a junction that $i \pm \frac{1}{2}$ are the volume centers. The pressure and momentum terms will cancel at the internal junctions by incrementing i in the above equation. Therefore, the blowdown thrust force at the first elbow is given by

$$RT = - \sum_i F_i = \sum_i FEA_i I_i \frac{1}{g_c} \frac{\partial G_i}{\partial t} \bar{m}_i + [p + \frac{q^2}{\rho A^2 g_c}]_{\text{exit}} (A \bar{n})_{\text{exit}} \quad (30)$$

where \sum_i means the summation from break junction to first elbow and $()_{\text{exit}}$ denotes the value at the break junction. The above equation is written in the following form by using Junction Acceleration Pressure Difference, $DELA_i$,

$$RT = \sum_i FEA_i DELA_i \bar{m}_i + (AP + \frac{q^2}{\rho A g_c})_{\text{exit}} \bar{n}_{\text{exit}} \quad (31)$$

in which $DELA_i$ is calculated in PRTHRUST code and given by

$$DELA_i = \frac{1}{g_c} I_i \frac{\partial G_i}{\partial t} \quad (32)$$

Therefore, the acceleration term FA, the momentum term FM and the pressure term FP are respectively given by

$$RT = FA + FM + FP \quad (33)$$

$$\begin{aligned} FA &= \sum_i FEA_i I_i \frac{1}{g_c} \frac{\partial G_i}{\partial t} \bar{m}_i \\ &= \sum_i FEA_i DELA_i \bar{m}_i \end{aligned} \quad (34)$$

$$FM = (\frac{q^2}{\rho A g_c} \bar{n})_{\text{exit}} \quad (35)$$

$$FP = (Ap \bar{n})_{\text{exit}} \quad (36)$$

when flow is choked at the break junction, FP becomes

$$FP = A_{\text{exit}} (p_e - p_a) \quad (37)$$

because the local static exit pressure p_e is greater than the ambient pressure p_a . Except at the first elbow, the blowdown thrust force is equal to the wave thrust FA as follows

$$\begin{aligned} RT = FA &= \sum_i FEA_i I_i \frac{\partial G_i}{\partial t} \bar{m}_i \\ &= \sum_i FEA_i DELA_i \bar{m}_i \end{aligned} \quad (39)$$

in which \sum_i means the summation for the junctions in the straight pipe section.

In PRTHRUST-J1 code, eqs.(33) through (36) are used for calculating blowdown thrust force at the first elbow, while eq.(39) is used for other elbows. Therefore, the following Minor Edit Variables are added in PRTHRUST-J1 code.

- (i) FA : Acceleration term of thrust force (wave thrust)
- (ii) FM : Momentum term of thrust force
- (iii) FP : Pressure term of thrust force
- (iv) RT : Thrust force = FA + FM + FP
- (v) SE : Specific volume at the throat
- (vi) PR : Pressure at the throat

Up to 36 variables abovementioned may be defined in PRTHRUST-J1 code.

The input format is given in APPENDIX. The variables FM, FP and RT are defined only for the leak junction. The results of FA, FM, FP and RT can be obtained in the form of plotter output. For some problems, unreasonable oscillation appears in RT and FA. The Hanning's window method is used in PRTHRUST-J1 to smooth the plotter output.

3.2 Introduction of Ramp Characteristics to Control Valves

The step-function type operation is assumed for the control valve (trip type : $\pm 6 \sim \pm 10$) in PRTHRUST code. It is impossible to analyze the preliminary jet test with stop valve because this valve opens approximately linearly with time. Therefore, the ramp characteristics of valve operation shown in Figs.5-1 and 5-2 were introduced in PRTHRUST-J1 code. The following input data are required in order to introduce the ramp characteristics to the control valve.

- (i) K_f : Friction coefficient when a valve is fully open
- (ii) T_r : Operation time of valve
- (iii) A_r : Area of flow path when a valve is fully open

By using the above values, the friction coefficient K during valve operation is given by

$$(i) \text{ Opening operation : } K = K_f \left(\frac{A_f}{A}\right)^2 \quad (40)$$

$$(ii) \text{ Closing operation : } K = K_f \left\{1 - \left(\frac{A_f}{A}\right)^2\right\} \quad (41)$$

In eqs.(40) and (41), A denotes the area of flow path during valve operation.

3.3 New Option for Calculating Wave Thrust

In PRTHRUST code, wave thrust FA is taken equal to zero when flow is choked. However, this is thought to be unreasonable, because in the choked flow a mass flow is not always constant with time and FA may have some value other than zero. Therefore, the new option is added to PRTHRUST-J1 code in order to calculate FA according to eq.(34) for the choked flow.

3.4 Introduction of Discharging Coefficient for Each Junction

In PRTHRUST code, the mass flow discharged from the leak junction is adjusted by multiplying the discharging coefficient (or contraction coefficient), CNCO, into the cross-sectional area at the leak junction. The physical meaning of this coefficient is that the flow area is less than the cross-sectional area of piping at the break point. In spite of this physical meaning, the discharging coefficient is so selected as to agree with experimental data⁽⁷⁾. Eqs.(34) through (36) also show that the acceleration, momentum and pressure terms of blowdown thrust force are directly affected by reducing the cross-sectional area at the break point. Therefore, the new discharging coefficient, DISCO, was introduced in PRTHRUST-J1 in order to reduce the critical mass flow rate obtained from Moody's model instead of reducing the cross-sectional area of the leak junction. DISCO can be defined not only at the leak junction but also at the other ones so as to analyze the preliminary jet tests where choking will occur at the other location than the leak junction.

4. Numerical Examples

Two numerical examples analyzed by PRTHRUST-J1 code are shown in this section.

4.1 Analysis of Saturated Steam Blowdown

The first numerical example is the problem of saturated steam blowdown from the piping system shown in Fig.6, the results of which are given by Moody⁽⁸⁾. The area and total length of piping are assumed to be 100 in² and 160 ft. long, respectively. The piping is composed of the three segments of straight piping, the lengths of which are 64 ft., 32 ft. and 64 ft. long, respectively. The volume of pressure vessel is assumed to be larger enough than that of piping. Initially, saturated steam of 1000 psia is contained in this system. The area of break point increases with time and fully opens after the time of 0.02 sec. This problem was analyzed by both PRTHRUST code and PRTHRUST-J1 code and the results were compared with each other. Fig.7 shows the volume divisions of sample problem. In the volume division for PRTHRUST code, the region from the break point to the first elbow was modeled by one volume and four volumes were taken to divide the total system. In case of the analysis by PRTHRUST-J1 code, the total system was approximated by 26 control volumes.

Figs.8-1 and 8-2 show the blowdown thrust force and jet impingement force obtained by PRTHRUST code. The same results obtained by PRTHRUST-J1 code are given in Figs.9-1 and 9-2. Fig.9-3 through Fig.9-5 show the wave thrust, momentum force and pressure force of F_1 , respectively. Furthermore, Figs.9-6 and 9-7 show the wave thrusts of F_2 and F_3 , respectively. In case of the analysis by PRTHRUST-J1, FA is not taken equal to zero for the choked junction and the option of smoothing the output of plotter is also used. Fairly large difference can be found between the results by PRTHRUST code (Figs.8-1 and 8-2) and those by PRTHRUST-J1 code (Figs.9-1 and 9-2).

Next, the results by PRTHRUST-J1 code are compared with those of the simplified method by Moody. The simplified method gives the summation of initial momentum force and pressure force, $F_{B,initial}$ ($= F_{M,initial} + F_{P,initial}$), initial acceleration force, $F_{A,initial}$, and initial thrust force, $R_{T,initial}$, as follows.

$$F_{B,initial} = 0.68 P_o A = 68000 \text{ lb}_f$$

$$FA_{\text{initial}} = 0.32 P_0 A = 32000 \text{ lb}_f$$

$$RT_{\text{initial}} = F_{B,\text{initial}} + FA_{\text{initial}} = 100000 \text{ lb}_f$$

in which P_0 and A denote initial pressure and break area, respectively. This method also gives the time of emergence of wave thrust as follows, assuming that the sonic velocity C_0 is 1600 fps in the saturated steam.

(1) Propagation toward Pressure Vessel Segment No. Containing Wave

$$0 < t < \frac{L_1}{C_0} = \frac{64}{1600} = 0.04 \text{ sec} \quad 1$$

$$0.04 < t < \frac{L_1+L_2}{C_0} = \frac{96}{1600} = 0.06 \text{ sec} \quad 2$$

$$0.06 < t < \frac{L_1+L_2+L_3}{C_0} = \frac{160}{1600} = 0.10 \text{ sec} \quad 3$$

(2) Propagation toward Break Point Segment No. Containing Wave

$$0.10 < t < \frac{L_1+L_2+2L_3}{C_0} = \frac{224}{1600} = 0.14 \text{ sec} \quad 3$$

$$0.14 < t < \frac{L_1+2(L_2+L_3)}{C_0} = \frac{256}{1600} = 0.16 \text{ sec} \quad 2$$

$$0.16 < t < \frac{2(L_1+L_2+L_3)}{C_0} = \frac{320}{1600} = 0.20 \text{ sec} \quad 1$$

It takes about 0.29 sec to reach steady state by the Moody's estimation. The thrust force at the steady state, RT_{steady} , is also given as follows.

$$RT_{\text{steady}} = 1.22 P_0 A = 122000 \text{ lb}_f$$

From Figs.9-3, 9-6 and 9-7, PRTHRUST-J1 code provides good agreement with the simplified method by Moody in the time of emergence of wave thrust. Fairly good agreement is also found in the initial thrust force and wave force between these two calculations. It can be seen from Figs.9-3 and 9-6 that the second peak of wave thrust is smaller than the first one. The reason is that wave damps when it enters pressure vessel through piping.

The results without using the option of smoothing the output of plotter are presented in Fig.10-1 through Fig.10-7 for the same problem as shown in Fig.9-1 through Fig.9-7. Some oscillations are found in the wave thrust after the time of 0.16 sec, as shown in Figs.10-1, 10-3, 10-6 and 10-7. These oscillation are thought to be not the physical phenomenon

but the numerical one, because these were moderated when the smaller time increments were used for calculation. Comparing Fig.10-1 through Fig.10-7 with Fig.9-1 through Fig.9-7, the oscillations found in wave thrust are eliminated and the effect of reflective wave propagating from pressure vessel to break point is, therefore, clarified.

The results of the sample problem are shown in Fig.11-1 through Fig.11-7 for the case of which acceleration terms are taken equal to zero for the choked junctions. In these figures, the plotter outputs are smoothed by Hanning's windowing method. In this sample problem, flow is choked at the junctions far from the leak junction. Therefore, the second peaks of wave thrusts F_1 and F_2 are smaller than those of Figs.9-3 and 9-6 in which the acceleration terms are not taken equal to zero for the choked junctions.

4.2 Analysis of Preliminary Jet Tests

In this section, the analytical results obtained by PRTHRUST-J1 are shown for one of the preliminary jet tests, RUN NO.5314⁽⁹⁾. These tests were performed by using the test facilities shown in Fig.1. The main test parameters for RUN NO.5314 are given in Table 1. In the preliminary jet tests, discharging jet was controlled by the stop valve. Fig.12 shows the variation of pressure measured by the pressure transducer attached to the discharging nozzle PU112. From the sudden increase of pressure from the time of 0.45 sec to 0.57 sec shown in Fig.12, it is assumed for the analysis by PRTHRUST-J1 that the stop valve starts to open at the time of 0.45 sec and opens fully at the time of 0.57 sec. Fig.13 shows the pipe line layout. This pipe line is divided into 16 volumes as shown in Fig.14. The stop valve is located at the junction of 13.

The analyses were implemented for the following models.

- (1) Model 1 : The leak junction was assumed to open linearly with time and was fully open at the time of 0.12 sec (= 0.57 sec - 0.45 sec). It was also assumed that, at the junction of 13 where the stop valve was located, friction loss factor was given in order to consider the pressure drop due to this valve. The stop valve used in the preliminary tests was Y-pattern globe valve whose stem had inclination of 50 degrees from flow path. The equivalent friction coefficient for this type of valve was decided from Crane's Handbook⁽¹⁰⁾.

(2) Model 2 : The ramp characteristics of the valve described in the section 3.2 were used for the stop valve and the leak junction was assumed to open instantaneously at the time of 0 sec. Although Model 2 is more real than Model 1, it remains uncertainty for Model 2 how to assume the initial condition for the volumes between the leak junction and the junction containing the stop valve. Then, the following two model were considered.

- (i) Model 2-1 : In these volumes, water of 20 °C was assumed to be filled on the level of 5 mm, above which the air of 1.03 kg/cm²a was assumed to be contained.
- (ii) Model 2-2 : Saturated steam of 100 °C was assumed to be contained in these volumes.

It is reasonable to assume the two-phase state with certain quality as a initial state of these volumes, because the stop valve was partially open before the time of 0.45 sec, as shown in Fig.12. However, it is impossible to know this two phase state, precisely. The analytical results presented in this section were obtained by using the option of calculating acceleration terms for the choked junctions.

Fig.15-1 through Fig.15-7 show the results for Model 1. The wave thrust (Fig.15-4) and pressure force (Fig.15-5) are found to increase linearly with time as the stop valve becomes open and to reach constant when this valve is fully open. The wave thrusts at the first and second elbows (Figs.15-3 and 15-6), and pressure vessel (Fig.15-7) show more complicated behaviors than the momentum and pressure forces. It can be seen from these figures that the wave thrust appears at the time of 0 sec for the first elbow, 0.08 sec for the second elbow and 0.1 sec for the pressure vessel, respectively. The reason for time delay described above is that the wave thrust is caused by the propagation of pressure wave.

The results for Model 2-1 and Model 2-2 are shown in Fig.16-1 through Fig.16-7 and Fig.17-1 through Fig.17-7, respectively. Compared with the results for Model 1, the following differences are found.

- (i) The jet impingement force (Fig.15-2) and the pressure and momentum terms of thrust force at the first elbow start to increase at the time of 0 sec for Model 1, while time delay is found for Model 2. These start to increase at the time of 0.03 sec for Model 2-1 (Figs.16-2, 16-4 and 16-5) and 0.01 sec for Model 2-2 (Figs.17-2, 17-4 and 17-5), respectively.

- (ii) The wave thrusts at the second elbow and pressure vessel begin to appear earlier for Model 2 (Figs.16-6, 16-7, 17-6 and 17-7) than for Model 1 (Figs.15-6 and 15-7).

The reasons for item (i) are as follows. For Model 2, in the earlier stage of discharge, extremely small flow is caused, because low pressure such as $1.03 \text{ kg/cm}^2\text{a}$ is assumed for the volumes between the stop valve and break point, and flow is choked at the inner junctions due to the flow restriction by the stop valve. Therefore, in the earlier stage of discharge, momentum force and pressure force have, respectively, very small and zero values for Model 2. For Model 2, the choked junctions move from the junction of 13 to leak junction with time. The time of 0.03 sec for Model 2-1 and 0.01 sec for Model 2-2 means the time when a flow is choked at the leak junction.

On the other hand, the reason for item (ii) is as follows. For Model 1, decompression wave is generated at the breaking point, while at the location of the stop valve for Model 2. Then, the pipe length effective in wave propagation is shorter for Model 2 than for Model 1.

Next, Model 2-1 is compared with Model 2-2. There is found to be large difference in the wave thrust at the first elbow (Figs.16-3 and 17-3) between these two model, which affects the thrust force at the same elbow (Figs.16-1 and 17-1). However, the difference becomes small after the time of 0.075 sec. This is because all fluid initially contained between the stop valve and break point are discharged during this time and, afterwards, the wave thrust is not affected by the difference of the initial condition. It is also found that there are no differences in the wave thrusts at the second elbow and pressure vessel.

Fig.18 shows the thrust force measured by the load cell WU111 for RUN NO.5314. It can be seen from this figure that the thrust force has maximum value of 2.2 ton and average value of 1.8 ton. The results by PRTHRUST-J1 code provide larger value for any model than the experimental one. Modification of critical mass flow by discharging coefficient would be required in order that analytical results may agree well with experimental ones. This type of modification was used for the blowdown analyses by RELAP-3 code⁽⁷⁾. The results are given for Model 1 and Model 2-2 with the discharging coefficient DISCO described in the section 3.4. Fig.19-1 through Fig.19-7 and Fig.20-1 through Fig.20-7 show the results for Model 1 with DISCO of 0.8 and 0.6, respectively. The momentum terms of thrust

force F_1 for these cases are smaller, compared with Fig.15-1 through Fig.15-7 which are the results for DISCO = 1.0. This is because discharging rate of momentum is smaller due to multiplying critical mass flow rate by DISCO. Fig.21-1 through Fig.21-7 and Fig.22-1 through Fig.22-7 show the results for Model 2 with DISCO of 0.8 and 0.6, respectively. The same tendencies as model 1 can be seen for Model 2.

5. Concluding Remarks

The outlines of PRTHRUST code and PRTHRUST-J1 code are described in this paper. Two numerical examples are presented in order to show the effectiveness of PRTHRUST-J1 code.

The numerical evaluation of blowdown thrust force obtained from experiment can be performed by using PRTHRUST-J1 code. The driving force of pipe whipping can be also calculated by this code.

PRTHRUST-J1 code or PRTHRUST code is based on RELAP-3 code, so that momentum flux term is omitted in momentum equation. This term has an effect on the blowdown behavior, when the flow area changes abruptly at such locations as reducers and junction of pressure vessel and piping⁽¹¹⁾. Therefore, momentum flux term should be introduced in PRTHRUST-J1 code.

The calculation scheme of blowdown thrust force described in the section 3.1 can be easily introduced in the code for calculating subcooled decompression analysis in PWR LOCA such as DEPCO-MULTI⁽¹²⁾. The code for calculating blowdown thrust force in subcooled water blowdown will be required, since this type of experiment will be also performed in the pipe rupture tests in JAERI.

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APPENDIX PRTHRUST-J1 INPUT DATA

PRTHRUST-J1 input data are given in this appendix. Units for input quantities are shown in parentheses () for the English System and in [] for the Metric System.

Card Set (1) Title Card (one card)

FORMAT : 18A4, 2A4

At least one nonblank character must appear somewhere in columns 1-72. This title is also used as the force plot title.

Card Set (2) Problem Dimension Card (one card)

This card set establishes program control for reading data input.

FORMAT : 12I3, 9X, I3, 9X, I2, I1, I2, 2I4, 2I1

N1 = 0

N2 = NEDI = Number of minor edit variables desired. See Card Set (3-1). ($1 \leq NEDI \leq 9$)

N3 = NTC = Number of time step cards. See Card Set (4). ($1 \leq NTC \leq 20$)

N4 = NTR = Number of trip control cards. See Card Set (5). ($1 \leq NTR \leq 20$)

N5 = NVOL = Number of control volume cards. See Card Set (6). ($1 \leq NVOL \leq 200$)

N6 = NBUB = Number of bubble parameter set cards. A set may be used in several volumes. See Card Set (7). ($0 \leq NBUB \leq 5$)

N7 = NJUN = Number of junction or flow path cards.

N8 = NPMPC = Number of pump curves. A curve may be used for more than one junction. See Card Sets (9) and (10). ($0 \leq NPMPC \leq 5$)

N9 = NCKV = Number of check valve type cards. A parameter set may be used for more than one junction. See Card Set (11). ($0 \leq NCKV \leq 5$)

N10 = NLK = Number of normalized leak area vs. time curves. May be used many times. See Card Set (12). ($0 \leq NLK \leq 5$)

- N11 = NFLL = Number of fill system curves. May be used many times.
See Card Set (13). ($0 \leq \text{NFLL} \leq 5$)
- N12 = NRFE = Number of additional minor edit variables desired.
See card Set (3-2). ($0 \leq \text{NRFE} \leq 36$)
- N13 = UNITS = 0 or blank, English Units will be used for input and output.
= 1, Metric Units will be used for input and output.
- N14 = IPLSM = Number of applications of smoothing plotter output.
($0 \leq \text{IPLSM} \leq 99$)
- N15 = IPLF = 0 or blank, plotter output will be obtained.
= 1, Plotter output will not be obtained.
- N16 = IDBG = Debugging print will be obtained, when IDBG is set equal to 99.
- N17 = NSTP1 = Number of time step at which debugging print starts.
- N18 = NSTP2 = Number of time step at which debugging print stops.
- N19 = ISWCA = 0
- N20 = SWFLOW = 0 or blank, Acceleration term of thrust force is taken equal to 0 for choked junctions.
= 1, Acceleration term of thrust force is calculated from Eq.(34) for choked junctions.

Card Set (3-1) Minor Edit Variable Cards (one card)

This card set established variables to be printed.

FORMAT : 9(1X, A2, I3)

1 - 3	4 - 6	7 - 9	10 - 12	13 - 15	16 - 18	
X1	N1	X2	N2	X3	N3	-----

X1, X2, X3, etc = Minor edit variable symbol.

N1, N2, N3, etc = Number of volume or junction for which data is to be printed.

Note : The leak force (LF) to be calculated and plotted must be listed first. Maximum number of minor edits is nine and parameters which can be selected from the list of variables are as follows.

Symbol of available minor edit variables

<u>Symbol</u>	<u>Variable</u> (with reference to a specific control volume number $1 \leq N1 \leq NVOL$)
AP	Average pressure
TM	Total mass
TE	Total energy
AT	Average temperature
AR	Average density
AH	Average enthalpy
AX	Average quality
BM	Bubble mass
ML	Mixture level
VF	Specific volume of fluid
VG	Specific volume of gas
HF	Specific enthalpy of fluid
HG	Specific enthalpy of gas
TS	Saturation temperature
PS	Saturation pressure
WM	Liquid mass

<u>Symbol</u>	<u>Variable</u> (with reference to a specific junction number $1 \leq N1 \leq NJUN$)
---------------	---------------------------------------------------------------------------------------

LF	Blowdown thrust force at the first elbow
JW	Junction flow
JH	Jet impingement force
JX	Junction quality
TD	Total pressure differential
FD	Pressure differential due to friction
ED	Pressure differential due to elevation
PD	Pressure differential due to pump
AD	Pressure differential due to acceleration

Card Set (3-2) Additional Minor Edit Variable Cards

FORMAT:

First card 9(1X, A2, I3)

1 - 3	4 - 6	7 - 9	10 - 12	13 - 15	16 - 18	
X1	N1	X2	N2	X3	N3	-----

Second card 9(I3, I3)

| JS1 | JE1 | JS2 | JE2 | JS3 | JE3 |-----

In the first card,

X1, X2, X3, etc. = Additional minor edit variable symbol.

N1, N2, N3, etc. = Number of junction which data is to be
printed.

The following minor edit variables are added to PRTHRUST-J1 code.

<u>Symbol</u>	<u>Variable</u>
FA	Acceleration term of blowdown thrust force
FM	Momentum term of blowdown thrust force
FP	Pressure term of blowdown thrust force
RT	FA + FM + FP
SE	Specific volume at throat junction
PR	Pressure at throat junction

On the other hand, the second card defines the start and end junctions of the pipe segments where blowdown thrust force generate.

JS1, JS2, JS3, etc. = Number of start junction of pipe segment.

JE1, JE2, JE3, etc. = Number of end junction of pipe segment.

A pair of the first and second cards may define up to 9 additional minor edit variables and up to 4 pairs may be set. If NRFE is equal to zero on Card Set (2) of Problem Dimension Card, skip this card set.

- Note :
1. The junction number, Ni, defined in the first card must be contained in the junction numbers, JSi and JEi, defined in the second card.
 2. The minor edit variable LF which is originally contained in PRTHRUST code is effective to calculate and plot the blowdown thrust force for only one leak junction. If there are plural leak junctions, the additional minor edit variables must be defined on this card set to calculate and plot the blowdown thrust forces for these junctions.
 3. If RT is calculated and plotted, LF must be given on the Card Set (3-1).
 4. Sample input data are given as follows for the model shown in Fig.A-1.

F ₁		F ₆		F ₂		F ₃		F ₄		F ₅		F ₇	
RT	5	RT	29	FA	8	FA	14	FA	17	FA	23	FA	24
1	5	29	34	6	8	9	14	15	17	18	23	28	24

All remaining card set except for Card Set (5) use the following
 FORMAT : 4I3, 6E10.6, 2A4

```

1 - 3  4 - 6  7 - 9  10 - 12  13 - 22  23          62 63 - 72 73
| N1  |  N2  |  N3  |  N4  |  X1  | ----- |  X6  |  ID  |
    
```

If fewer than four integers are required, the remaining integer fields are left blank. If more card are required to fill the tables, a similar format is used:

```

1 - 3  4 - 6  7 - 9  10 - 12  13 - 22  23          62 63 - 72 73
|      |      |      |      |  X7  | ----- |  X12 |  ID  |
    
```

Card Set (4) Time Step Cards (NTC cards)

This card set establishes the time steps used in the computation and printing frequency.

- N1 Number of time steps per minor edit.
(0 is interpreted as 1) Normally 0.
- N2 Number of minor edits per major edit.
(0 is interpreted as 50) Normally 0.
- X1 DELTM = Time step size (seconds). (0 < DELTM)
- X2 TLAST = End of current time step data (seconds).
(TLAST_{i-1} < TLAST_i)

Card Set (5) Trip Control Cards (NTR cards)

This card set is used to set up actions based on specific parameter values.

FORMAT : 4I3, 2E10.6, 6X, A4, 3E10.6

- N1 IDTRP = Action to be taken (1 ≤ IDTRP ≤ 10)
 - 1 = End of problem
 - 2 = Open leaks
 - 4 = Trip pumps
 - 5 = Start fills

6 - 10 = Open (or close) valves, up to 5 valves may be defined

and tripped by different trip controls.

- N2 IDSIG = Signal being compared. ($1 \leq |IDSIG| \leq 9$)
 1 = Elapsed time + = HIGH, - = LOW
 4 = Pressure (Vol.N3) + = HIGH, - = LOW
 5 = Mixture Level (Vol.N3) + = HIGH, - = LOW
 6 = Liquid Level (Vol.N3) + = HIGH, - = LOW
 7 = Water Temperature (Vol.N3) + = HIGH, - = LOW
 9 = Flow Rate (JUNC.N3) + = HIGH, - = LOW
- N3 IX1 = Volume index number where trip pressure, mixture level,
 liquid level, or water temperature is measured.
 Or:
 Junction index number where trip flow is measured.
- N4 IX2 = If pressure or temperature differentials are used for
 trip control (IDSIG = 4, -4, 7, or -7), this is the
 number of the second volume, i.e., $\Delta P = P_{(IX1)} - P_{(IX2)}$.
- X1 SETPT = The setpoint value of the variable at which the trip
 occurs. SETPT Units are as follows:

<u>IDSIG VALUE</u>	<u>SETPT UNITS</u>
1 Elapsed Time	seconds
4 Pressure	(psia) [kg/cm ²]
5 Mixture Level	(feet) [m]
6 Liquid Level	(feet) [m]
7 Water Temperature	(°F) [°C]
9 Flow Rate	(lb/sec.) [kg/sec.]

- X2 DELAY = The delay time for initiating the action after reaching
 the setpoint value.

The following data are added to the above ones, when the valve defined
 by N1 has ramp characteristics of operation.

- 39 col. - 42 col. The four characters, RAMP, are written.
 43 col. - 52 col. Time of ramp operation. (sec.)
 53 col. - 62 col. Flow area when valve is fully open. (ft²) [m²]
 63 col. - 72 col. Friction coefficient when valve is fully open.
 (lb_f-sec²/lb_m-ft³-in²) [$\frac{\text{sec}^2}{\text{cm}^2\text{m}^3}$]

Card Set (6) Control Volume Data Cards (NVOL cards)

This card set defines volume geometry and initial conditions.

- N1 IBUB = Bubble data index. If IBUB = 0, a homogeneous mixture is assumed. If IBUB > 0, phase separation is calculated based on bubble data input in card set (7).
($0 \leq \text{IBUB} \leq \text{NBUB}$)
- X1 P = Pressure. ($0.1 \leq P \leq 3206.2$ psi)
[$0.007031 \leq P \leq 225.4$ kg/cm²]
- X2 TEMP = Temperature or quality of mixture. Quality must be input as a negative number, such that $0. \leq |\text{QUAL}| \leq 1.0$
($32 \leq ^\circ\text{F} \leq 5600$) [$0. < ^\circ\text{C} \leq 3093.3$]
(Quality : dimensionless).
- X3 V = Volume (ft³)[m³]. ($0. < V$)
- X4 ZVOL = Volume height from bottom to top.
- X5 ZM = Mixture level from bottom of volume. (ft)[m].
($0. \leq \text{ZM} \leq \text{ZVOL}$)
Liquid phase : ZM = 0. is interpreted as ZM = ZVOL.
Liquid phase : $0. < \text{ZM} < \text{ZVOL}$ implies an air head over the liquid.
- X6 ELEV = Elevation at bottom of the volume. (ft)[m].

Card Set (7) Bubble Data Cards (NBUB cards)

This card set is used to define the 2 phase separation model.

- X1 ALPH = Bubble gradient parameter (dimensionless). ($0. \leq \text{ALPH}$)
- X2 VBUB = Bubble velocity (ft/sec.)[m/sec.]. ($0 \leq \text{VBUB}$)

Bubble data set number 0 is built into the program. This data set defines ALPH = 0.0 and VBUB = 0.0. It is recommended that bubble data set number 0 be used for piping while a bubble data set with ALPH = 0.8 and VBUB = (3 ft/sec.)[0.914 m/sec.] be used for plenums and tanks.

Card Set (8) Junction Data Cards (NJUN cards)

This card set defines flow network, location of pumps, valves, fills, leaks and restrictions, pressure losses, fluid inertia, and initial conditions.

- N1 IW1 = Volume index at junction inlet. ($0 \leq \text{IW1} \leq \text{NVOL}$)
- N2 IW2 = Volume index at junction exit. ($0 \leq \text{IW2} \leq \text{NVOL}$)
- N3 IPUMP = (a) For IW1 > 0 and IW2 > 0 : Pump index where
 $0 \leq \text{IPUMP} \leq \text{NPMPC}$.

For IPUMP = 0 the junction is a normal junction.

(b) For $IW1 > 0$ and $IW2 \leq 0$: Leak index where $1 \leq IPUMP \leq NLK$.

(c) For $IW1 > 0$ and $IW2 > 0$: Fill index where $1 \leq IPUMP \leq NFLL$.

(d) $IW1 \leq 0$ and $IW2 \leq 0$ defines a null junction and is not normally used.

N4 IVALVE = Valve index where $0 \leq |IVALVE| \leq NCKV$ or $6 \leq |IVALVE| \leq 10$

(a) IVALVE = 0 for no valve.

(b) $1 \leq IVALVE \leq NCKV$ defines a type 1 check valve with the characteristics defined by IVALVE data.

(c) $NCKV \leq IVALVE \leq -1$ defines a type 2 check valve with the characteristics defined by IVALVE data.

(d) $6 \leq IVALVE \leq 10$ defines an initially open valve which closes under trip control.

(e) $-10 \leq IVALVE \leq -6$ same as (d) above except valve is initially closed and opens under trip control.

X1 WP = Initial flow (lb/sec.)/[kg/sec.]. Positive flow is defined as flow going from Volume IW1 to Volume IW2.

X2 AJUN = Minimum flow area (ft²)/[m²]. Minimum flow area is used for the choked flow calculation.

(a) For $IW1 > 0$ and $IW2 > 0$, AJUN = 0.0 implies no restriction.

(b) For $IW1 > 0$ and $IW2 \leq 0$, AJUN = 0.0 is interpreted as 1 for leakage.

(c) For $IW1 \leq 0$ and $IW2 > 0$, AJUN = 0.0 is interpreted as 1 for filling.

(d) For $IW1 \leq 0$ and $IW2 < 0$, AJUN is ignored.

X3 ZJUN = Junction elevation (ft)/[m].

(a) For $IW1 > 0$ and $IW2 > 0$, ZJUN must lie between bottom and top of both inlet and exit volumes.

(b) For $IW1 > 0$ and $IW2 \leq 0$, ZJUN must be between bottom and top of inlet volume.

(c) For $IW1 \leq 0$ and $IW2 > 0$, ZJUN must be between bottom and top of exit volume.

(d) For $IW1 \leq 0$ and $IW2 \leq 0$, ZJUN is ignored.

X4 INERTA = Junction effective L/A (ft⁻¹)[m⁻¹]. (INERTA ≥ 0.0)
 X5 KJUN = Friction coefficient (lb_f-sec²/lb_m-ft³-in.²) [$\frac{\text{sec}^2}{\text{cm}^2\text{m}^3}$].

(0. ≤ KJUN)

(a) IW1 > 0 and IW2 > 0

KJUN = 0, defines option where value will be computed by the program from the pressure drop data. Must give positive answer, otherwise job will be terminated. It is recommended that KJUN be input from hand calculation.

(b) IW1 ≤ 0

KJUN is ignored.

(c) IW2 ≤ 0

If KJUN ≤ 0, then KJUN is calculated internally from the orifice equation,

$$\begin{aligned} \text{KJUN} &= \frac{1}{144 g_c 2(\text{AJUN})^2} \quad (\text{English}) \\ &= \frac{1}{10000 g_c 2(\text{AJUN})^2} \quad [\text{Metric}] \end{aligned}$$

X6 DISCO = Contraction coefficient defined at each junction (dimensionless). (0. ≤ DISCO). DISCO = 0 is interpreted as DISCO = 1.0.

Card Set (9) Pump Coastdown Cards (one curve if NPMPC > 0)

This card set defines the pump coastdown characteristics and is a must if card set (10) is included in the input deck.

N1 NPUCD = Number of data points. If NPUCD > 0, interpolation only will be performed. If NPUCD < 0, extrapolation as well as interpolation will be performed.

(2 ≤ |NPUCD| ≤ 20)

X1 CAVCON = Cavitation constant (dimensionless)

X3 TIME1 = (sec)

X4 MULTIPLIER1 (dimensionless)

X5 TIME2

X6 MULTIPLIER2

X7 TIME3

X8 MULTIPLIER3

where TIME1 < TIME2 < TIME3 < -----

Card Set (10) Pump Head Cards (NPMPC curves)

This card set defines the pump operating characteristics and is required if card set (9) is included.

- N1 NPUMP = Number of data points. If NPUMP positive, interpolation only will be performed. If negative, extrapolation will also be done. ($2 \leq |NPUMP| \leq 20$)
- N2 IX = Flow variable type.
 $IX \leq 0$, (lb/sec.)(kg/sec.)
 $IX > 0$, (gal/min)(liters/min)
- N3 IY = Head variable type.
 $IY \leq 0$, (lb/in²)(kg/cm²)
 $IY > 0$, (ft)(m)
- X1 SPUMP = Net positive suction head (ft)(m).
- X2 FPUMP = Shutdown friction coefficient (lb_f-sec²/lb_m-ft³-in²)(sec²/cm²m³).
- X3 FLOW1 = (lb/sec or gal/min)(kg/sec or liters/min).
- X4 HEAD1 = (lb/in² or ft)(kg/cm² or m)
- X5 FLOW2
- X6 HEAD2
- etc.

where FLOW1 < FLOW2 < -----

Card Set (11) Check Valve Cards (NCKV cards)

This card set defines check valve operating characteristics.

- X1 PCV = Back pressure for closure (lb/in²)(kg/cm²).
- X2 CV1 = Forward flow friction coefficient (lb_f-sec²/lb_m-ft³-in²)(sec²/cm²m³).
- X3 CV2 = Reverse flow friction coefficient, valve open
 (lb_f-sec²/lb_m-ft³-in²)(sec²/cm²m³).
- X4 CV3 = Reverse flow friction coefficient, valve closed
 (lb_f-sec²/lb_m-ft³-in²)(sec²/cm²m³).

Card Set (12) Leak Set Cards (NLK curves)

This card defines the break junction characteristics.

- N1 NAREA = Number of data point. ($2 \leq NAREA \leq 20$)
- N2 ICHOKE = Leak type.
 $ICHOKE \leq 0$, no liquid phase choking.

ICHOKE > 0, liquid phase choking allowed.

- X1 SINK = Sink pressure (lb/in^2)[kg/cm^2].
- X2 CONCO = 1.0
- X3 TIME1 = (sec)
- X4 AREA1 = (ft^2 , normalized and dimensionless if AJUN > 0)
[m^2 , normalized and dimensionless if AJUN > 0].
- X5 TIME2
- X6 AREA2
- etc.

where TIME1 < TIME2 < -----

Card Set (13) Fill Set Cards (NFLL curves)

This card defines the fill junction characteristics.

- N1 NFILL = Number of data points. If NFILL positive, only interpolation will be performed. If negative, extrapolation will also be done. ($2 \leq \text{NFILL} \leq 20$)
- N2 IX = Independent variable.
IX = 0, time.
IX > 0, pressure ($P_{\text{vol}} + P_{\text{grav}}$).
IX < 0, differential pressure ($P_{\text{vol}} + P_{\text{grav}} - P_{\text{fill}}$).
- N3 IY = Flow type.
IY \leq 0, (lb/sec/in^2)[kg/sec/m^2].
IY > 0, (gal/min/ft^2)[liters/min/m^2].
- X1 FILPRS = Pressure in fill reservoir, (psia)[kg/cm^2].
- X2 FILTEM = Temperature ($^{\circ}\text{F} \geq 32$)[$^{\circ}\text{C} \geq 0$] or quality in fill reservoir. Quality must be input as a negative number such that $0. \leq |\text{Qual}| \leq 1$.
- X3 TIME1 or PRESSURE1 = (sec or lb/in^2)[sec or kg/cm^2].
- X4 FLOW1 = (lb/sec/ft^2 or gal/min/ft^2)[kg/sec/m^2 or liters/min/m^2].
- X5 FLOW2
- etc.

where TIME1 < TIME2 < -----

or PRESSURE < PRESSURE2 < -----

Card Set (14) End Card (1 card, optional)

Column 1 through 72 blank. Omit this card if another problem follows.

Table 1 Test Conditions for RUN No. 5314 of
Preliminary Jet Test

TEST MODE	BWR
BREAK LOCATION	Lower Nozzle
BREAK DIAMETER	66.9mm (3B, sch160)
PRESSURE IN PRESSURE VESSEL	65Kg/cm ² a
TEMPERATURE IN PRESSURE VESSEL	280°C
WATER LEVEL BEFORE DISCHARGE	4.8m
WATER LEVEL AFTER DISCHARGE	2.93m
DURATION OF DISCHARGE	16sec

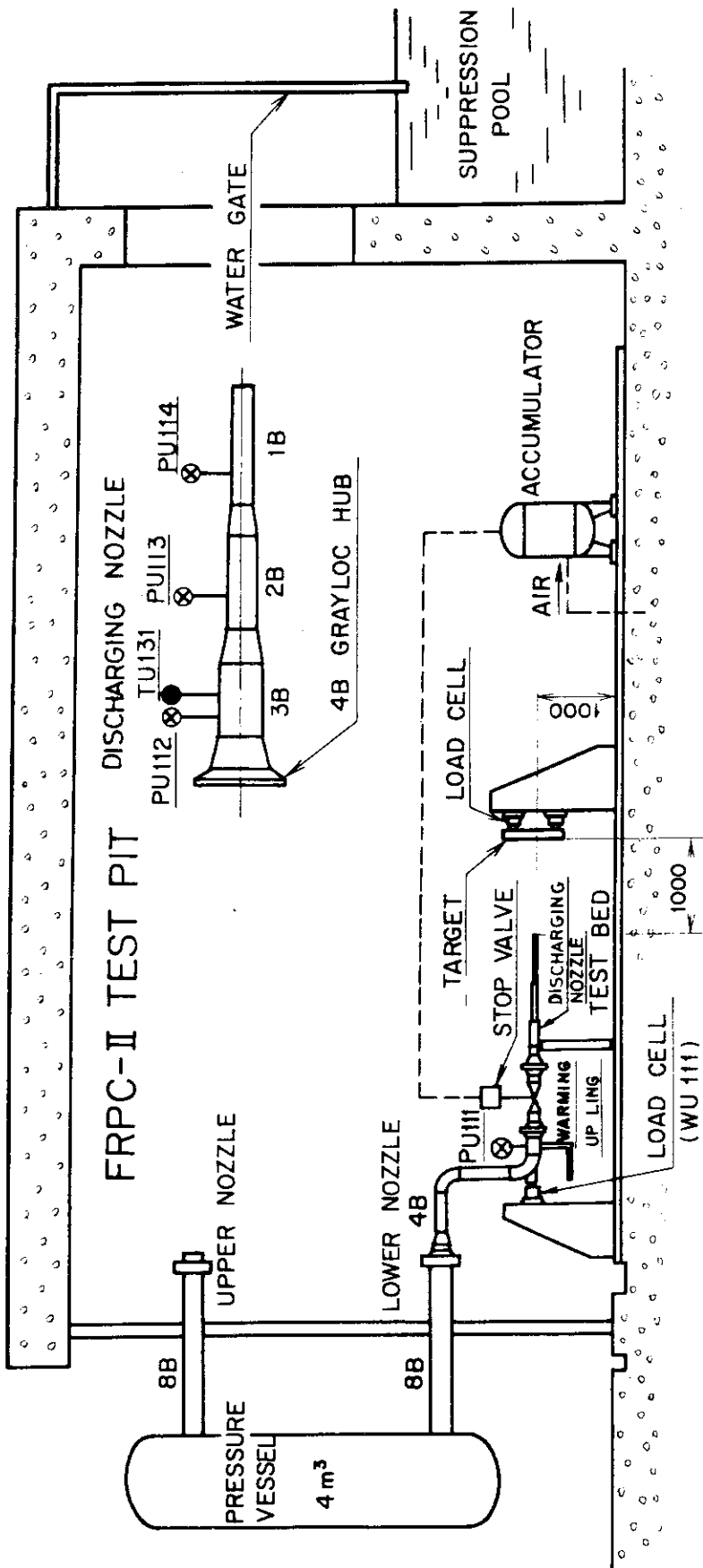


Fig. 1 Schematic Diagram of Preliminary Jet Test.

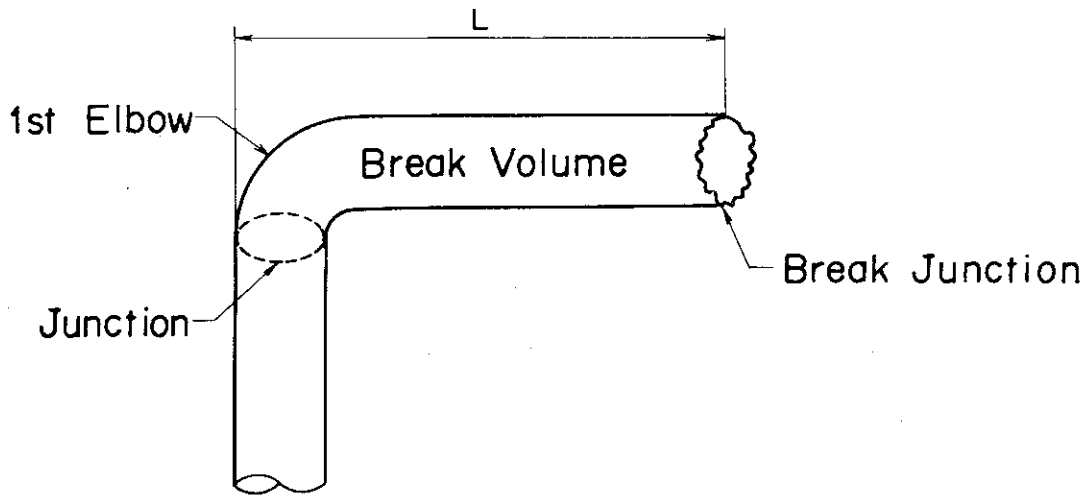


Fig. 2-1 PRTHRUST Break Volume for Circumferential Breaks.

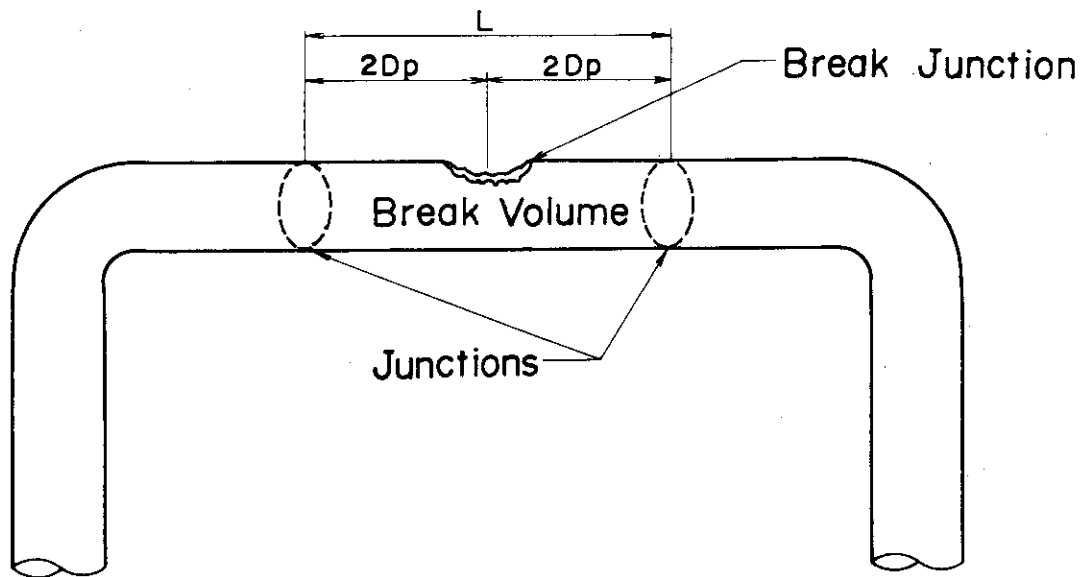


Fig. 2-2 PRTHRUST Break Volume for Longitudinal and Crack Breaks.

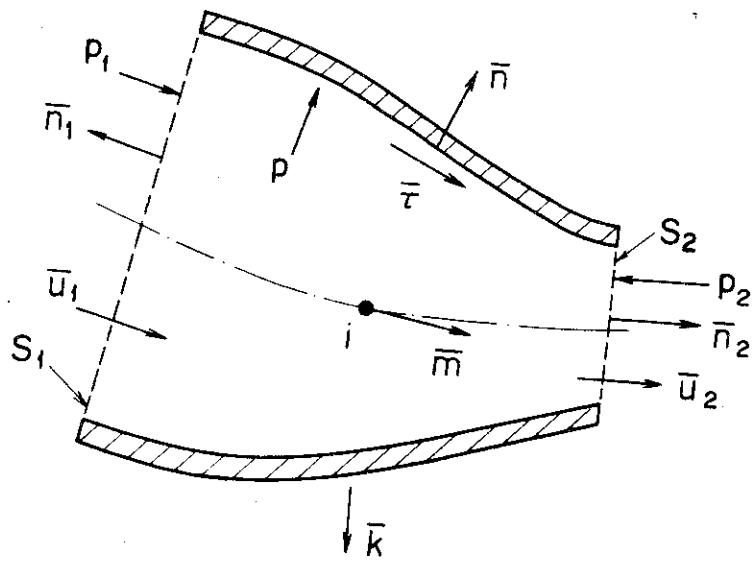


Fig. 3 Flow and Force Elements for a Segment of Contained Fluid.

$i - 1, i, i + 1, i + 2$ ----- : Junction

$i - 1/2, i + 1/2$ ----- : Volume Center

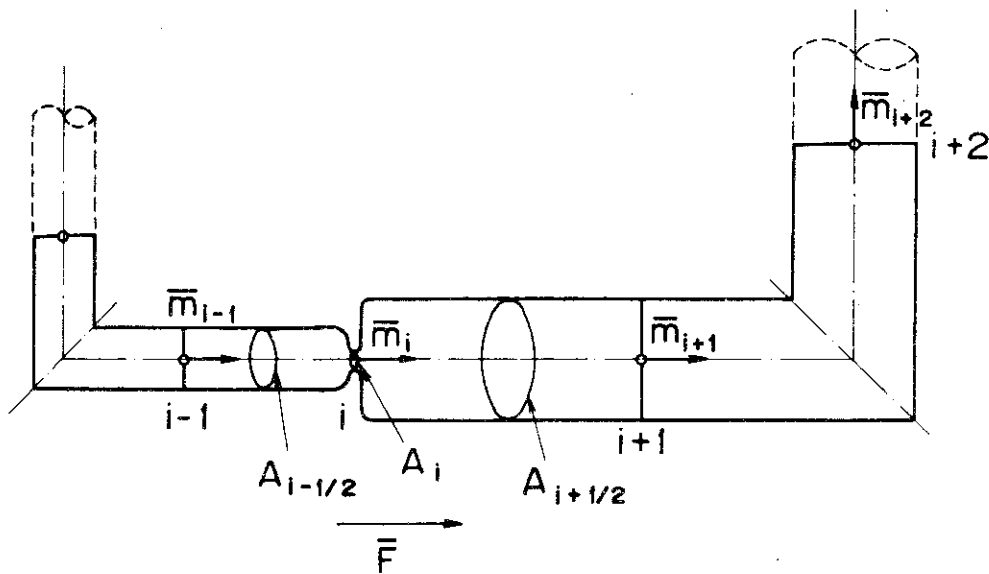


Fig. 4 PRTHRUST-J1 Flow Path and State Control Volumes.

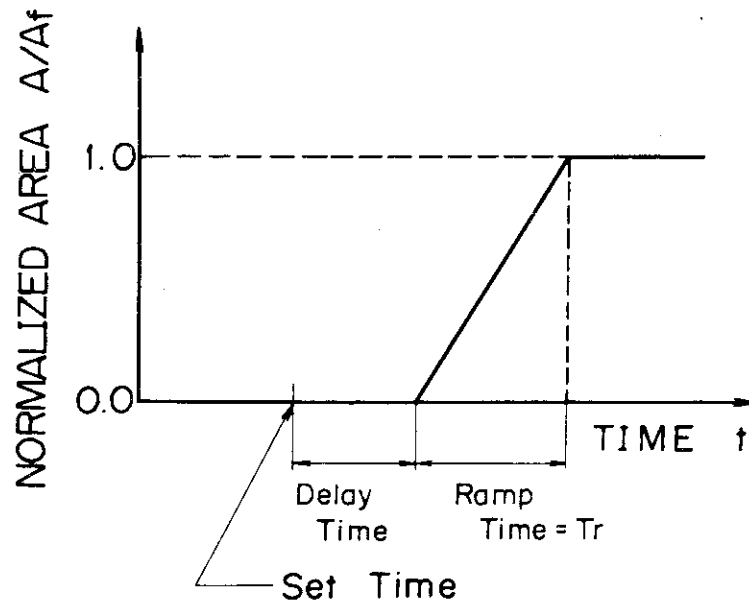


Fig. 5-1 Ramp Characteristic When Valve Opens.

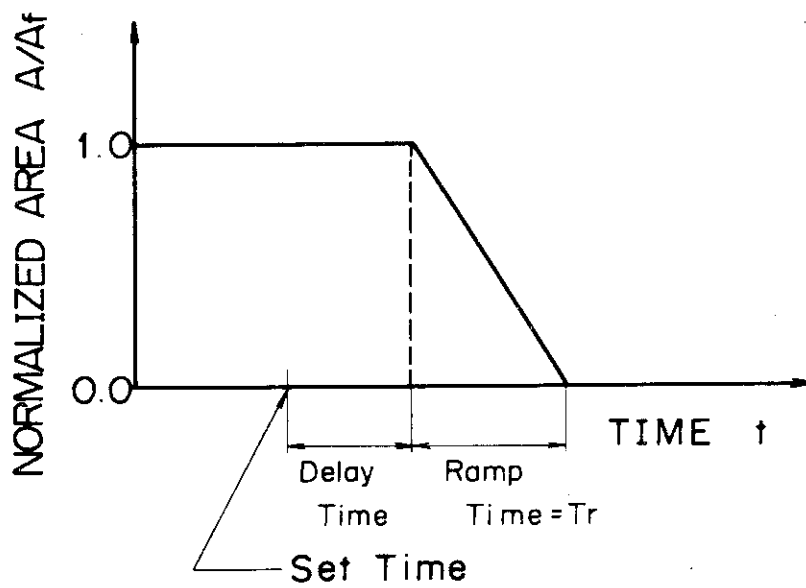


Fig. 5-2 Ramp Characteristic When Valve Closes.

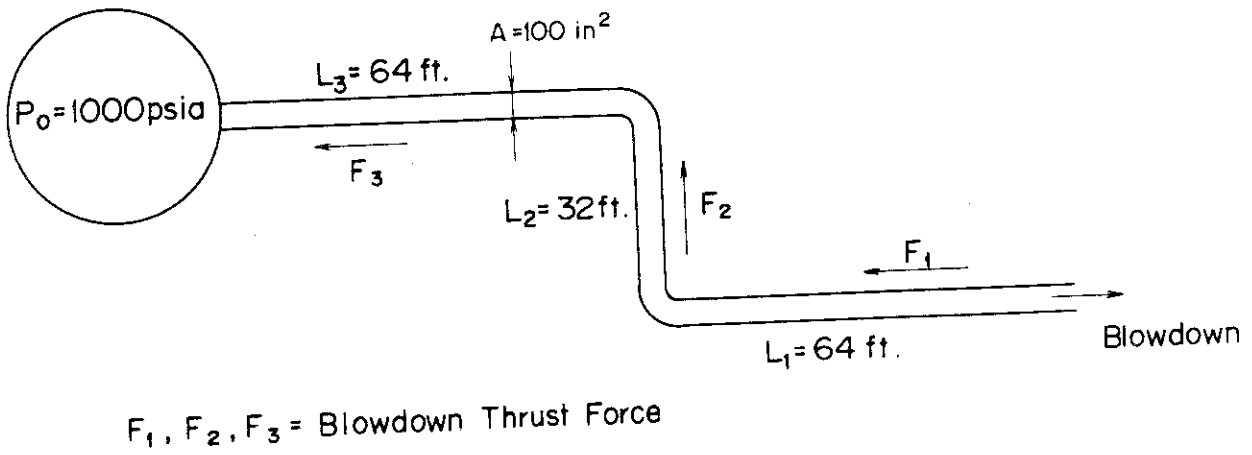


Fig. 6 Sample Problem of Steam Blowdown.

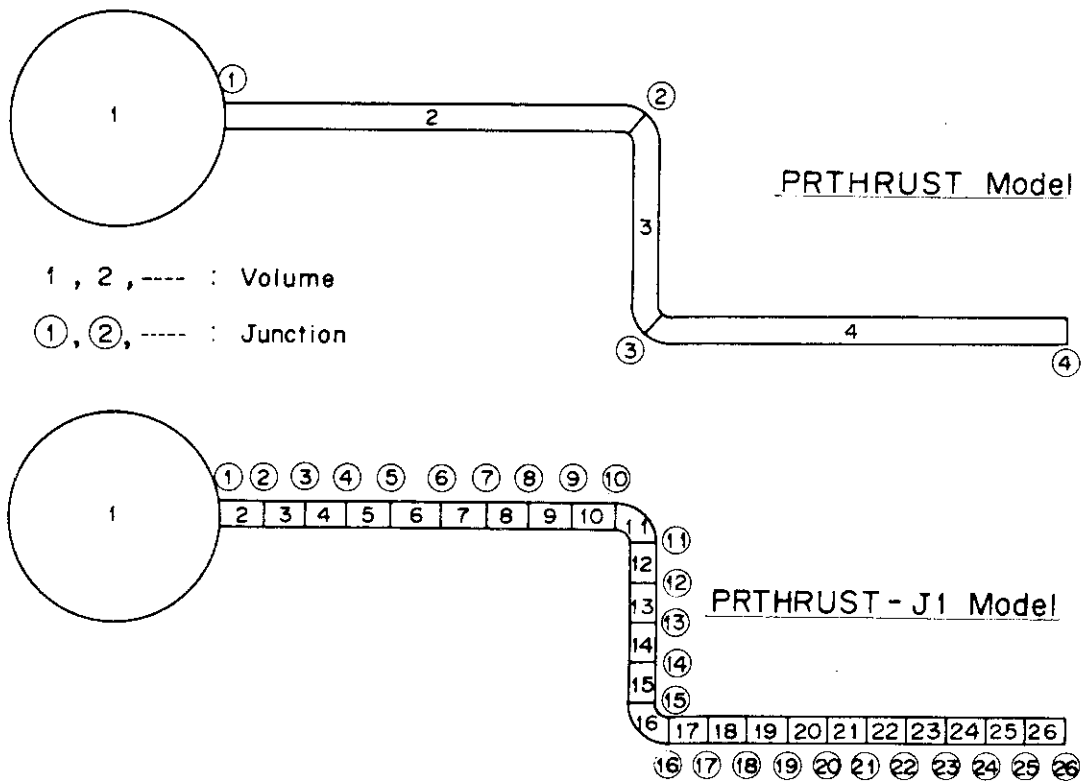


Fig. 7 Volume Divisions of Sample Problem.

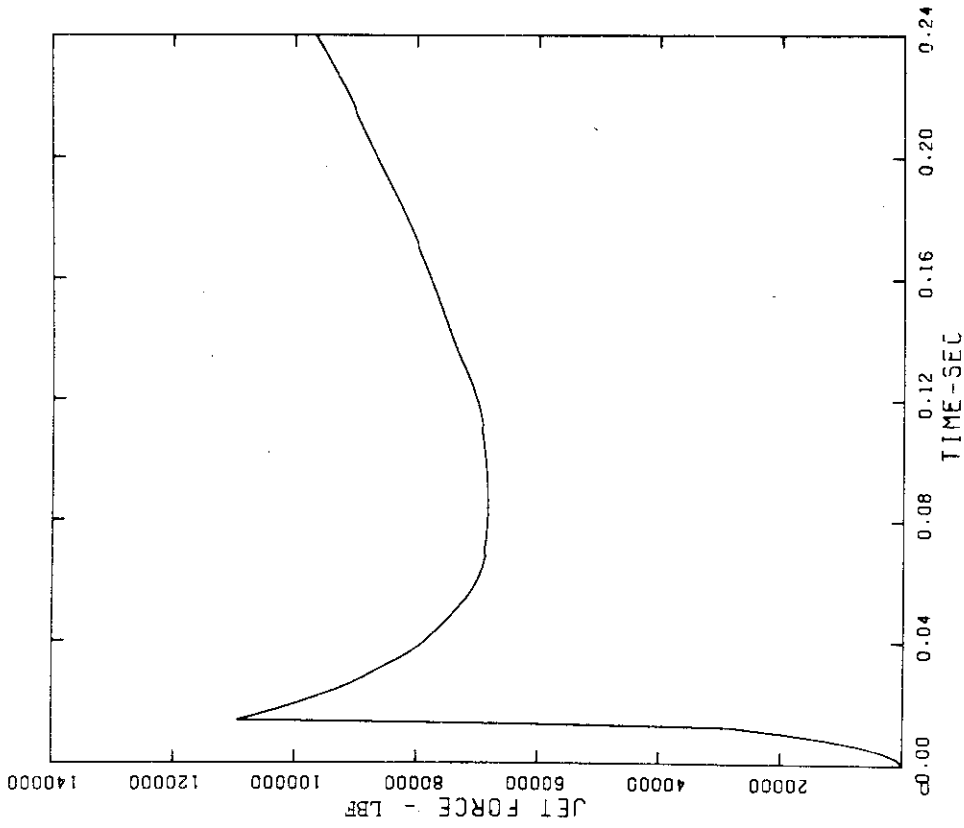


Fig. 8-2 Time History of Jet Impingement Force for Sample Problem of Steam Blowdown Analyzed by PRTHRUST.

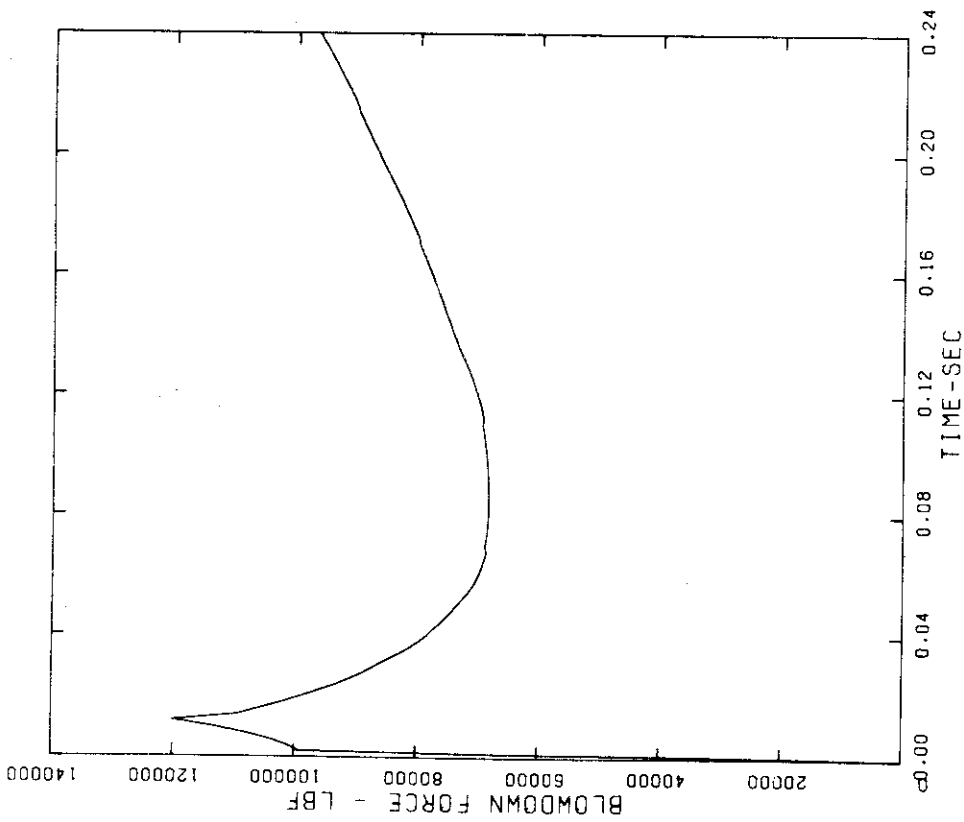


Fig. 8-1 Time History of Thrust Force, F_1 , for Sample Problem of Steam Blowdown Analyzed by PRTHRUST.

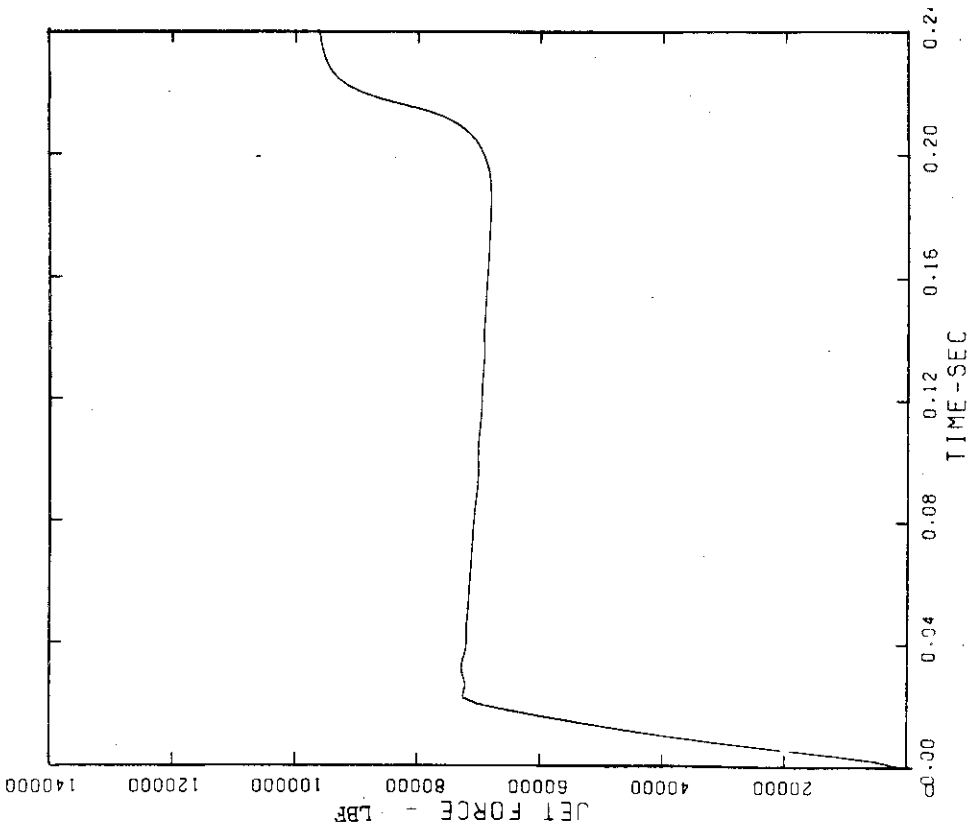


Fig. 9-2 Time History of Jet Impingement Force for Sample Problem of Steam Blowdown Analyzed by PRTHRUST-J1 ----- FA is not taken equal to zero for the choked junction and the option of smoothing the output of plotter is used.

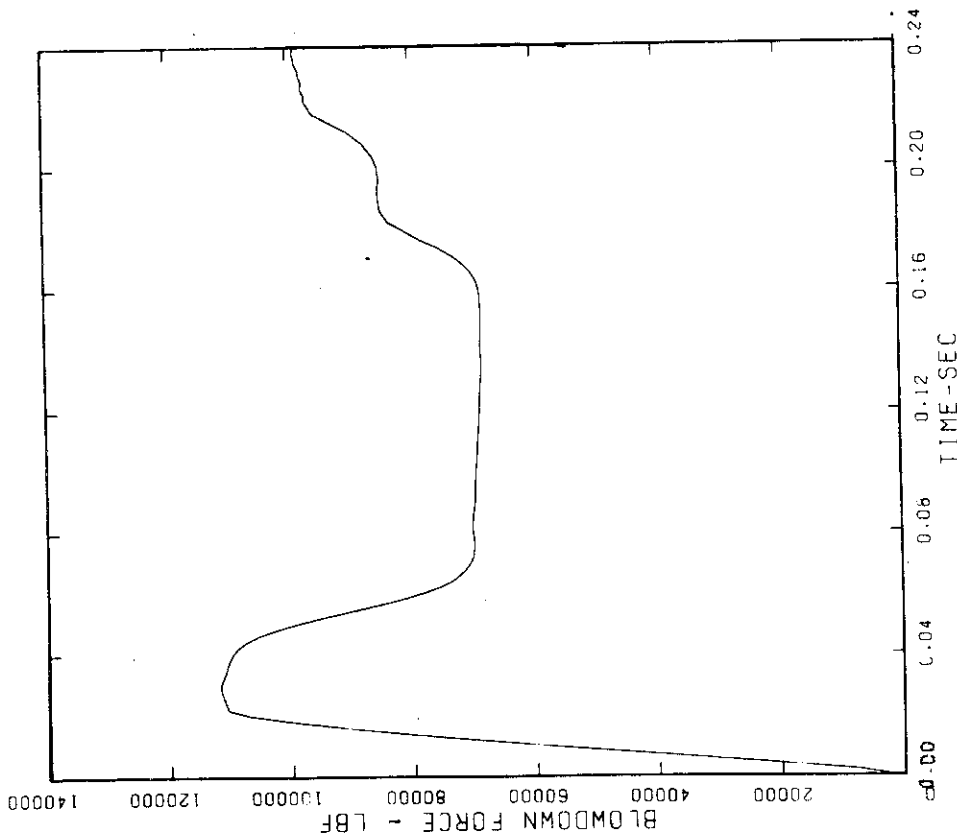


Fig. 9-1 Time History of Thrust Force, F₁, for Sample Problem of Steam Blowdown Analyzed by PRTHRUST-J1 ----- FA is not taken equal to zero for the choked junction and the option of smoothing the output of plotter is used.

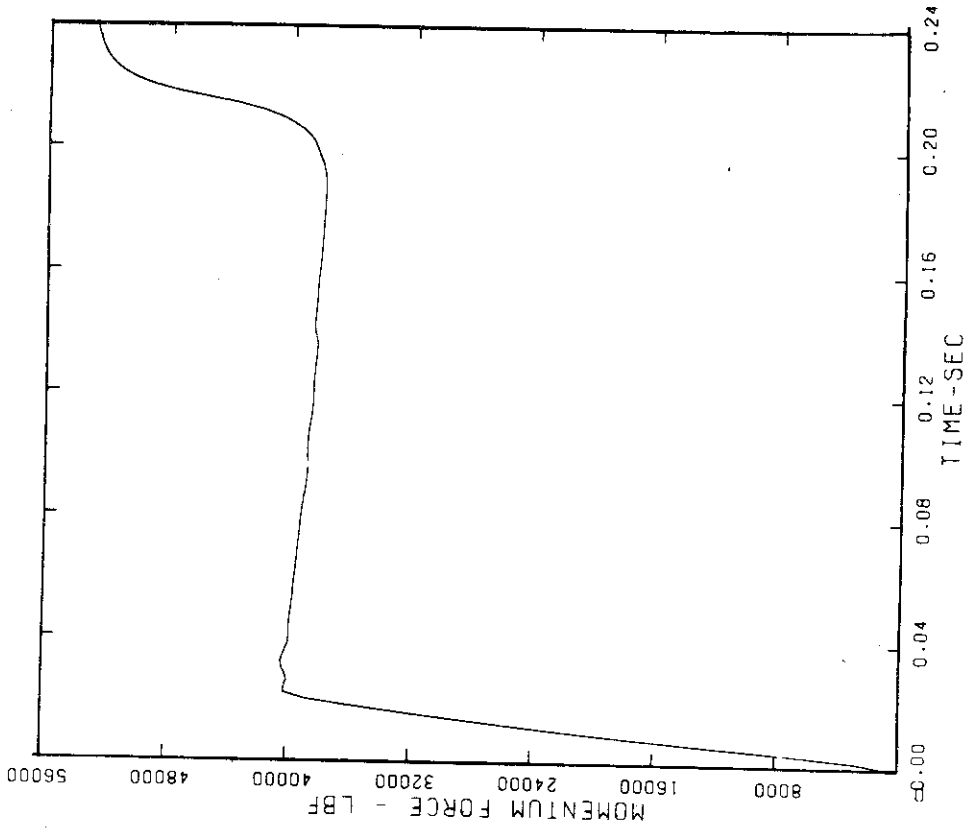


Fig. 9-4 Time History of Momentum Force of F_1 for Sample Problem of Steam Blowdown Analyzed by PRTHRUST-J1 ----- FA is not taken equal to zero for the choked junction and the option of smoothing the output of plotter is used.

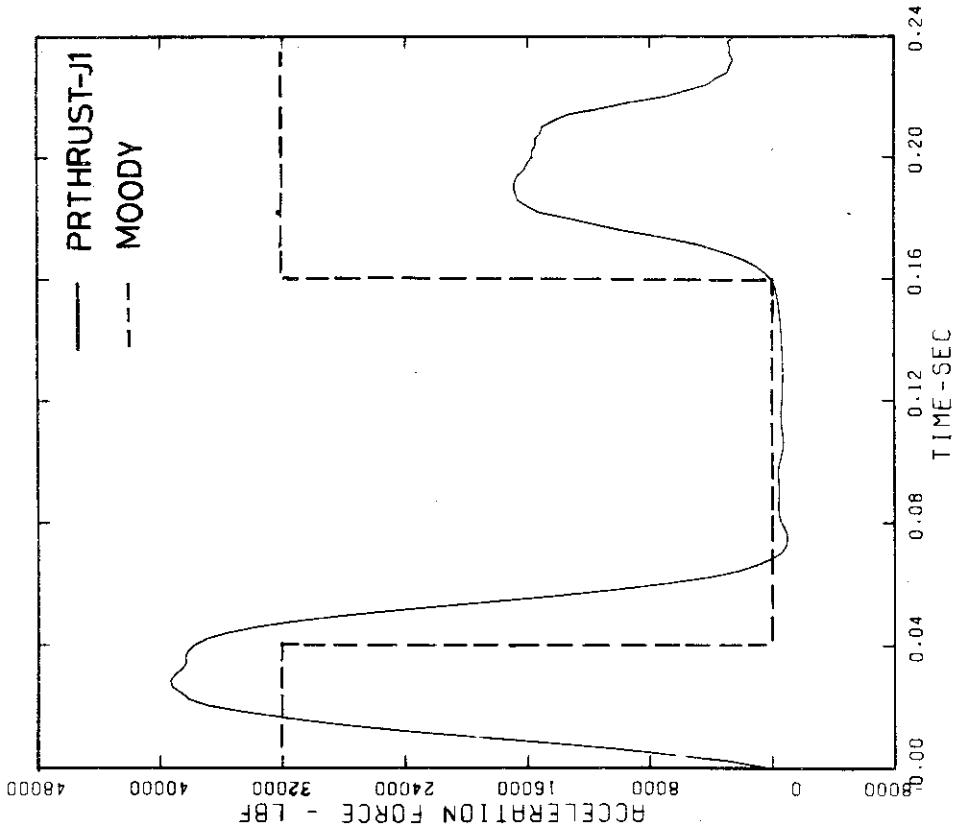


Fig. 9-3 Time History of Wave Thrust of F_1 for Sample Problem of Steam Blowdown Analyzed by PRTHRUST-J1 ----- FA is not taken equal to zero for the choked junction and the option of smoothing the output of plotter is used.

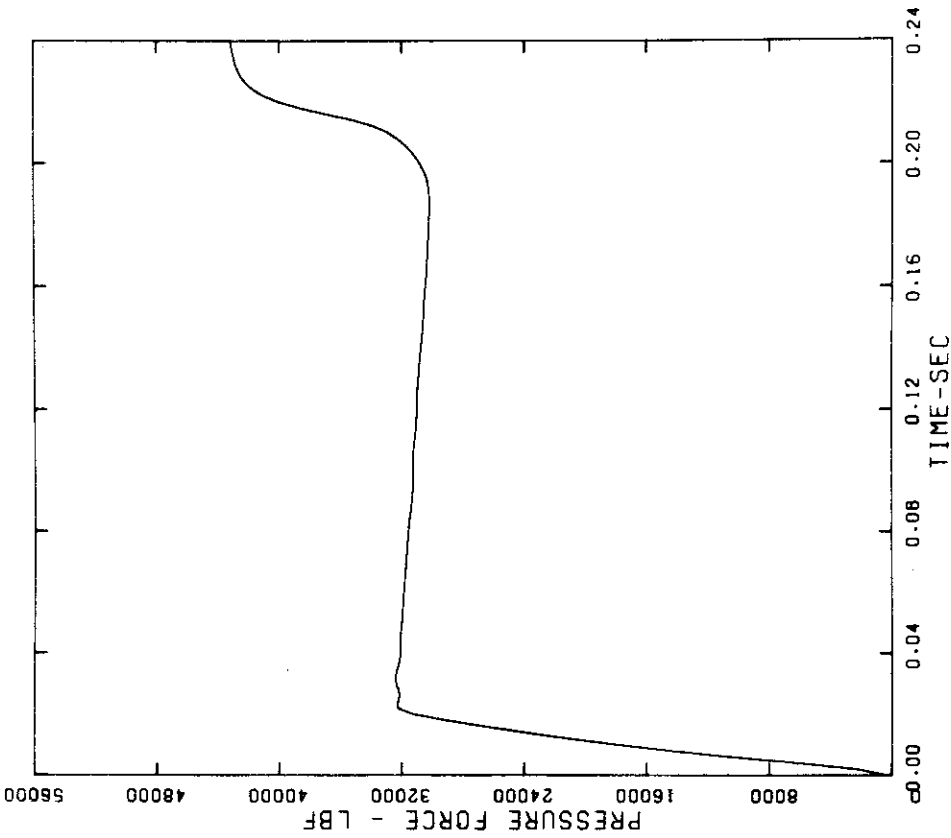


Fig. 9-5 Time History of Pressure Force of F₁ for Sample Problem of Steam Blowdown Analyzed by PRTHRUST-J1 ----- FA is not taken equal to zero for the choked junction and the option of smoothing the output of plotter is used.

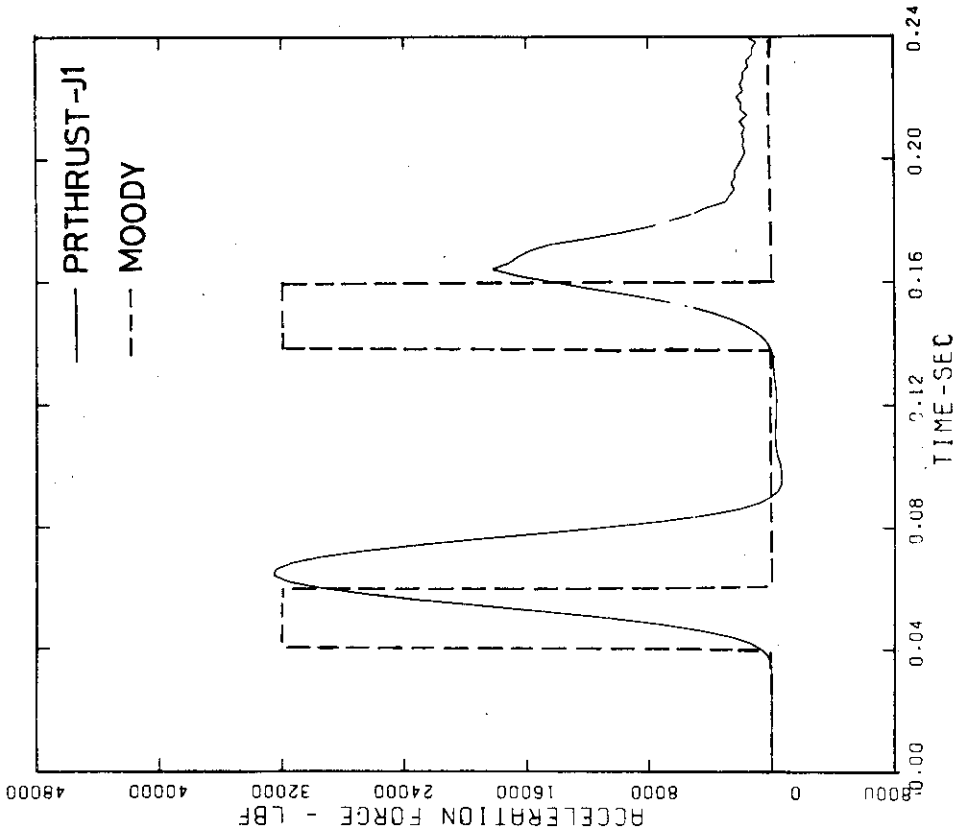


Fig. 9-6 Time History of Wave Thrust, F₂, for Sample Problem of Steam Blowdown Analyzed by PRTHRUST-J1 ----- FA is not taken equal to zero for the choked junction and the option of smoothing the output of plotter is used.

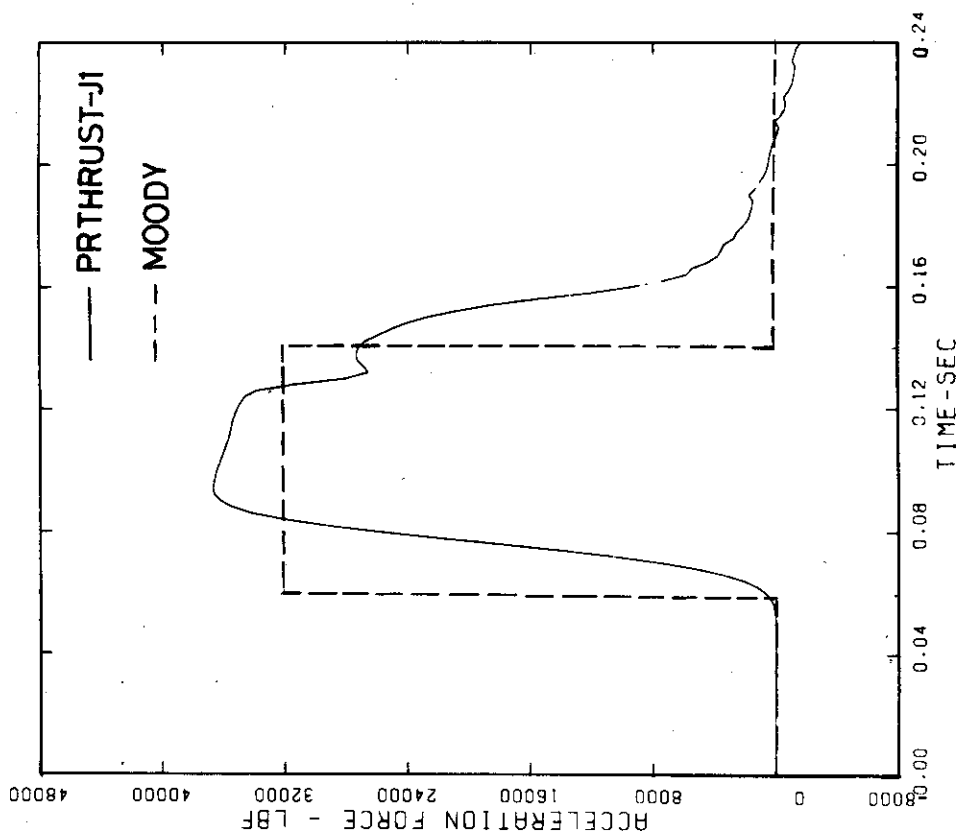


Fig. 9-7 Time History of Wave Thrust, F₃, for Sample Problem of Steam Blowdown Analyzed by PRTHRUST-J1 ----- FA is not taken equal to zero for the choked junction and the option of smoothing the output of plotter is used.

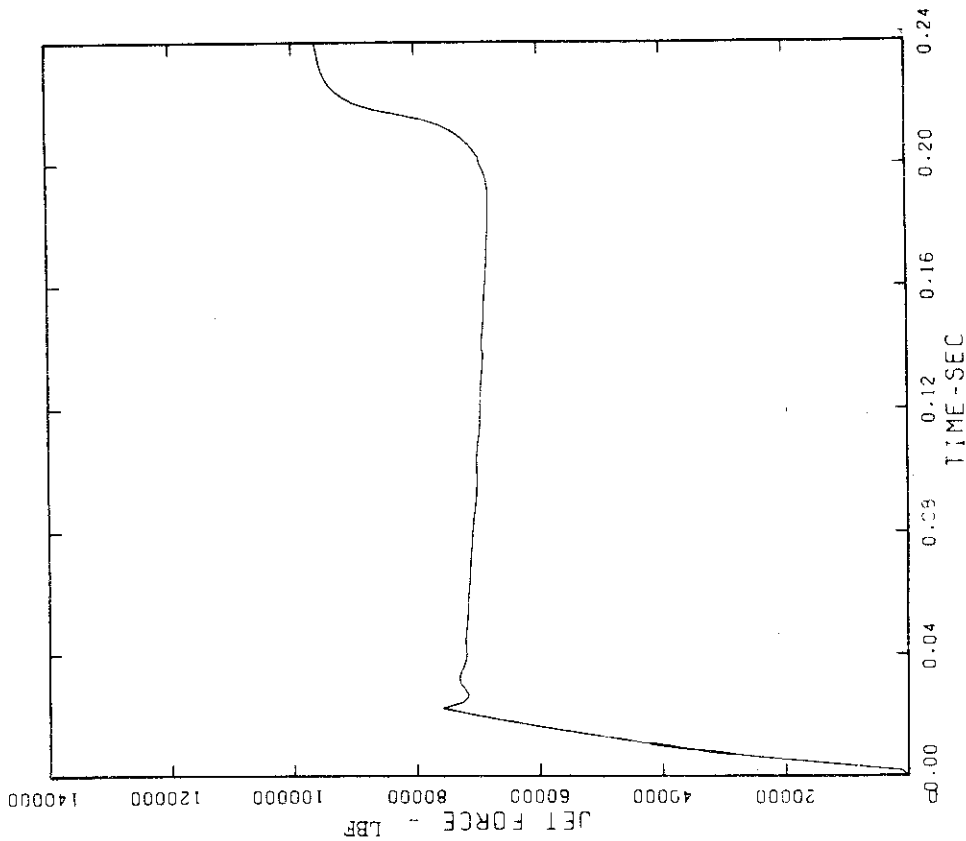


Fig.10-2 Time History of Jet Impingement Force for Sample Problem of Steam Blowdown Analyzed by PRTHRUST-J1 ----- FA is not taken equal to zero for the choked junction and the option of smoothing the output of plotter is not used.

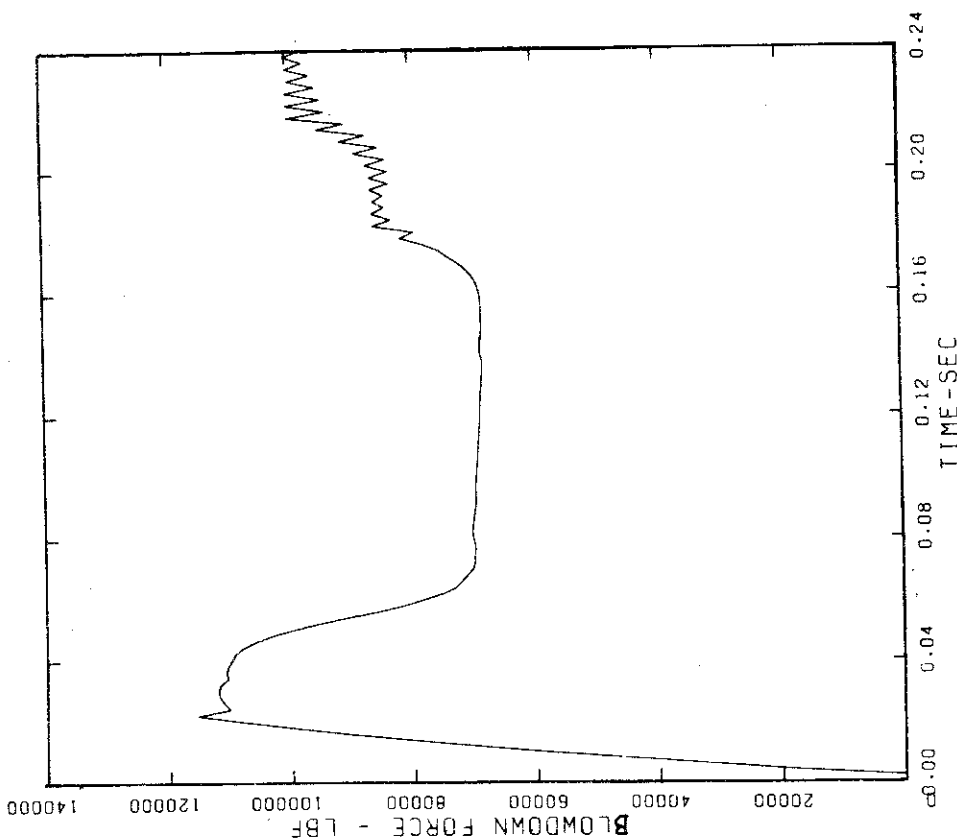


Fig.10-1 Time History of Wave Thrust, F_1 , for Sample Problem of Steam Blowdown Analyzed by PRTHRUST-J1 ----- FA is not taken equal to zero for the choked junction and the option of smoothing the output of plotter is not used.

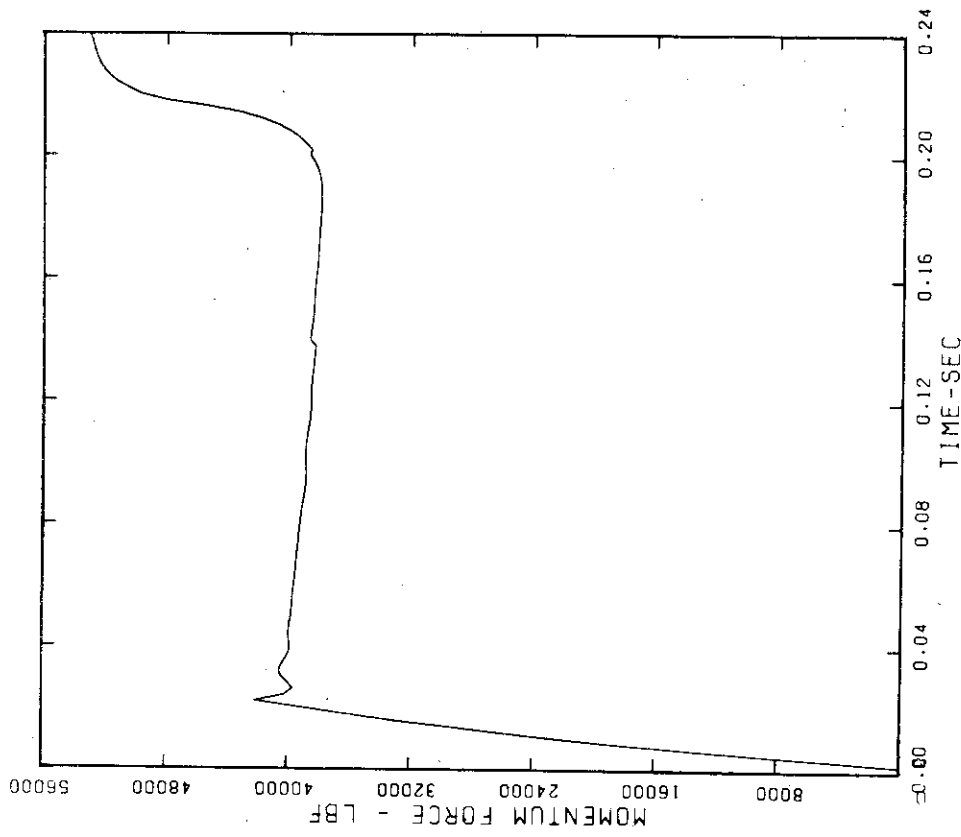


Fig.10-4 Time History of Momentum Force of F_1 for Sample Problem of Steam Blowdown Analyzed by PRTHRUST-J1 ----- FA is not taken equal to zero for the choked junction and the option of smoothing the output of plotter is not used.

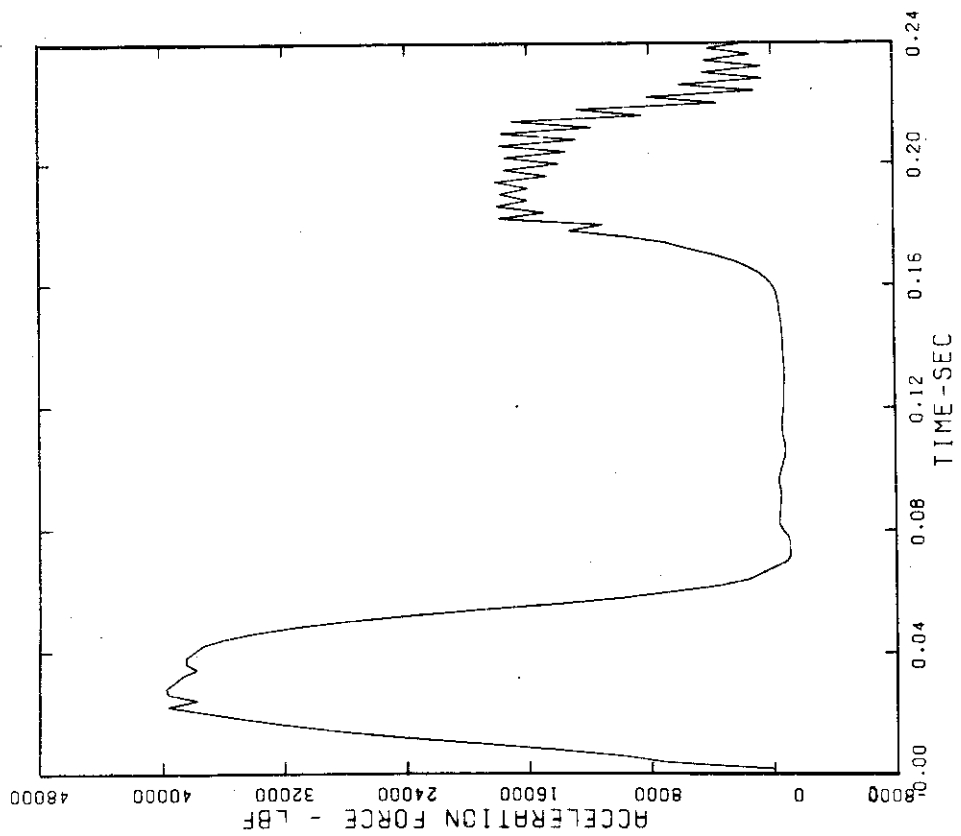


Fig.10-3 Time History of Wave Thrust of F_1 for Sample Problem of Steam Blowdown Analyzed by PRTHRUST-J1 ----- FA is not taken equal to zero for the choked junction and the option of smoothing the output of plotter is not used.

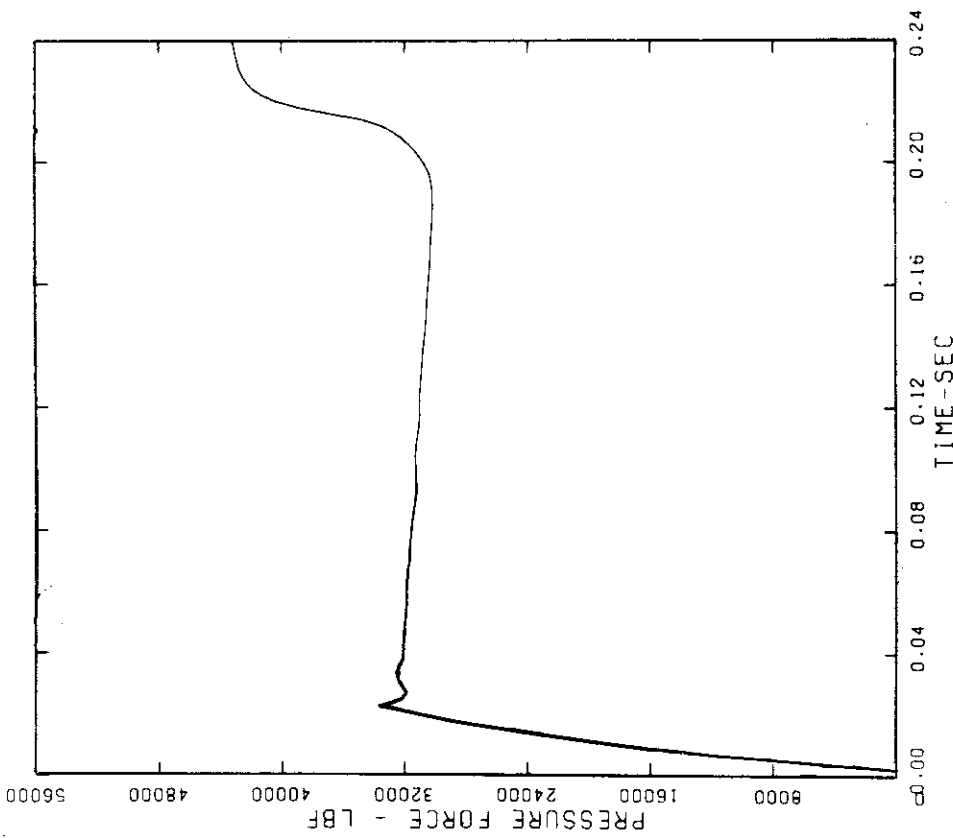


Fig.10-5 Time History of Pressure Force of F1 for Sample Problem of Steam Blowdown Analyzed by PRTHRUST-J1 ----- FA is not taken equal to zero for the choked junction and the option of smoothing the output of plotter is not used.

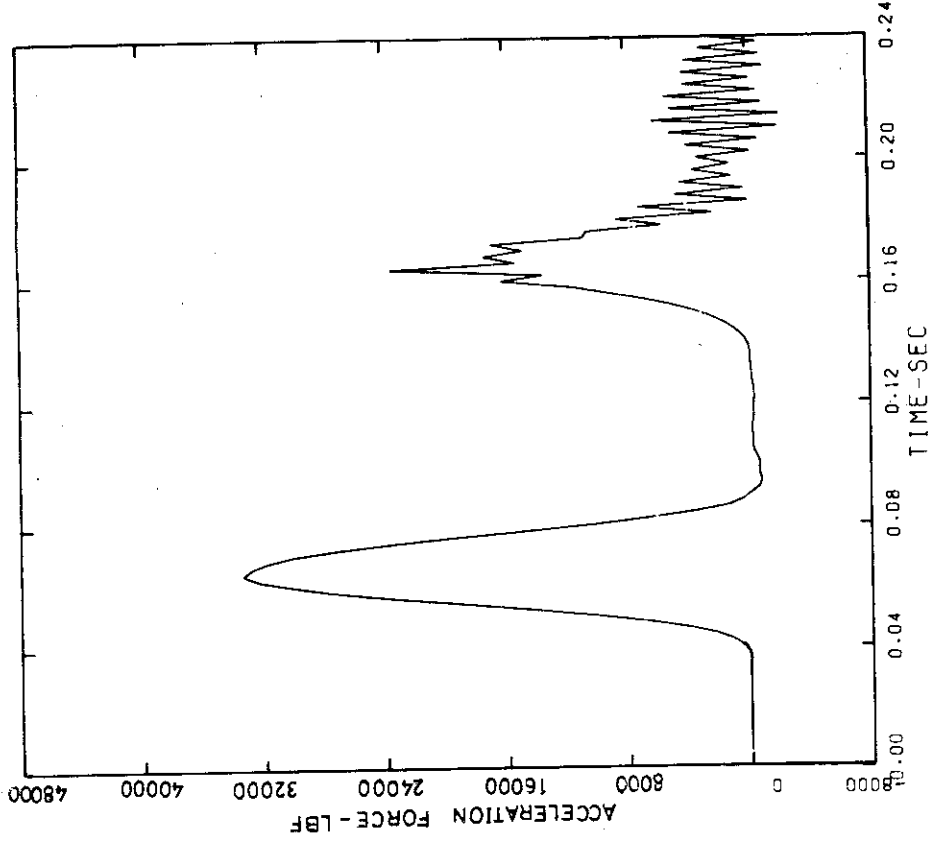


Fig.10-6 Time History of Wave Thrust, F2, for Sample Problem of Steam Blowdown Analyzed by PRTHRUST-J1 ----- FA is not taken equal to zero for the choked junction and the option of smoothing the output of plotter is not used.

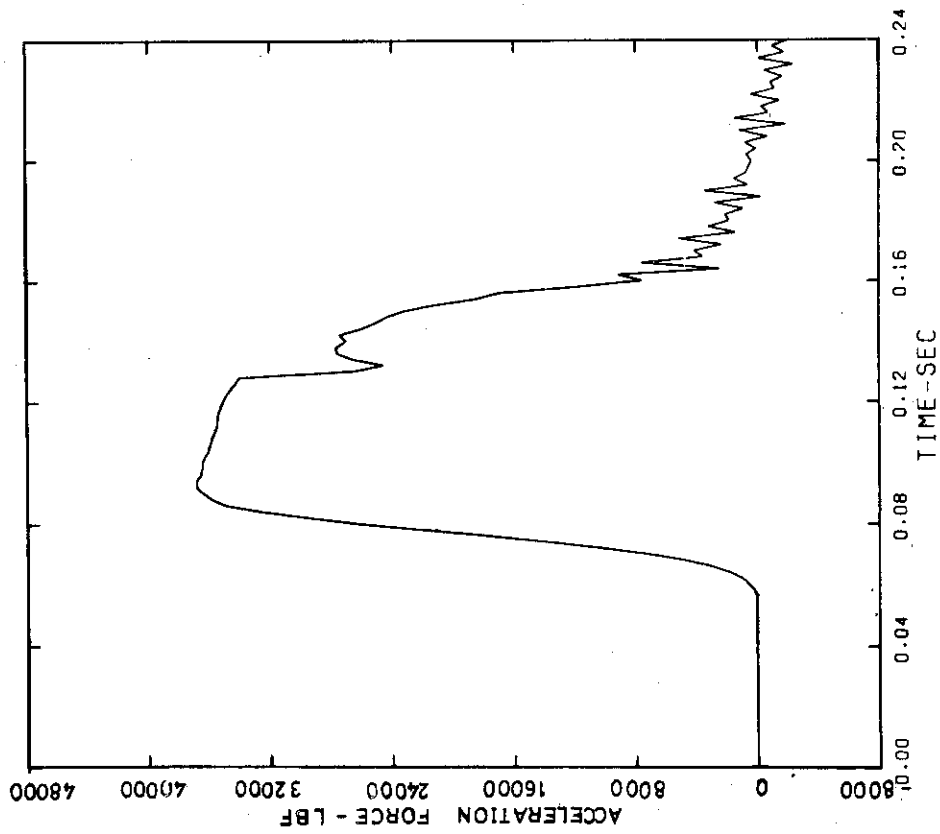


Fig.10-7 Time History of Wave Thrust, F_3 , for Sample Problem of Steam Blowdown Analyzed by PRTHRUST-J1 ----- FA is not taken equal to zero for the choked junction and the option of smoothing the output of plotter is not used.

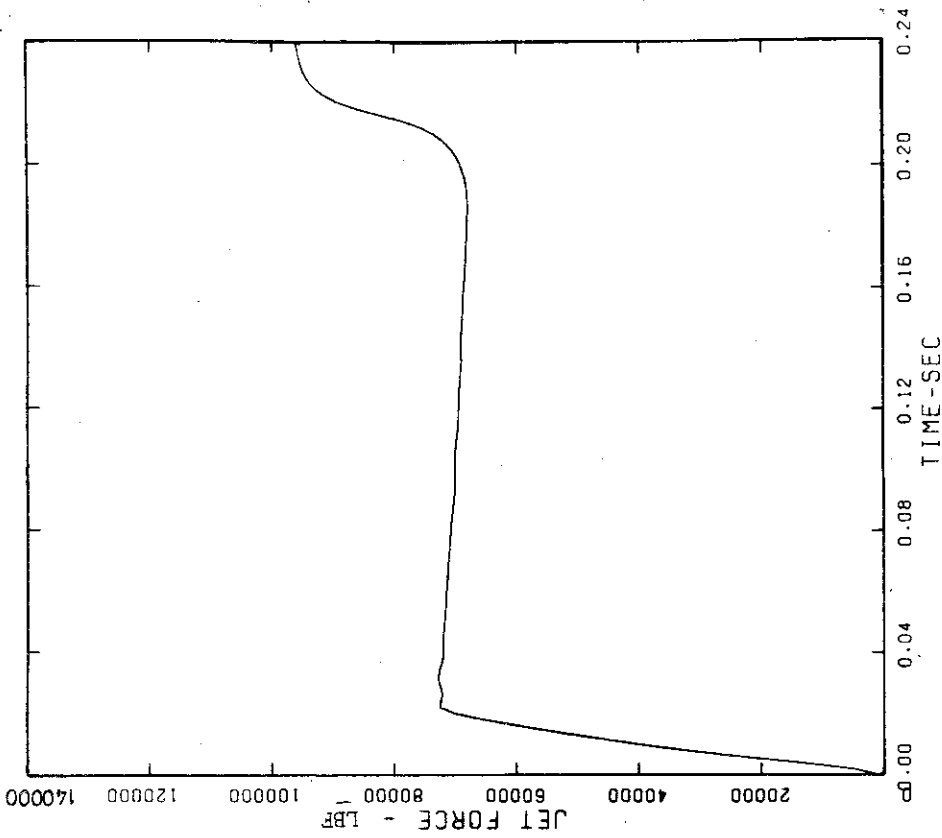


Fig.11-2 Time History of Jet Impingement Force for Sample Problem of Steam Blowdown Analyzed by PRTHRUST-J1 ----- FA is taken equal to zero for the choked junction and the option of smoothing the output of plotter is used.

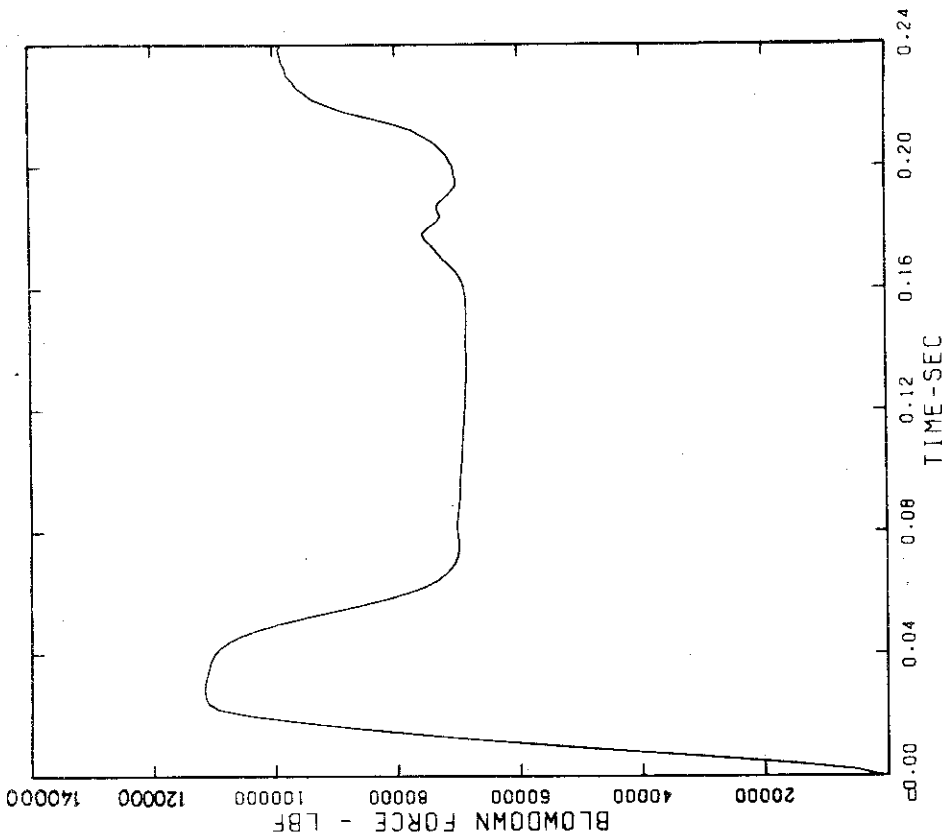


Fig.11-1 Time History of Thrust Force, F_1 , for Sample Problem of Steam Blowdown Analyzed by PRTHRUST-J1 ----- FA is taken equal to zero for the choked junction and the option of smoothing the output of plotter is used.

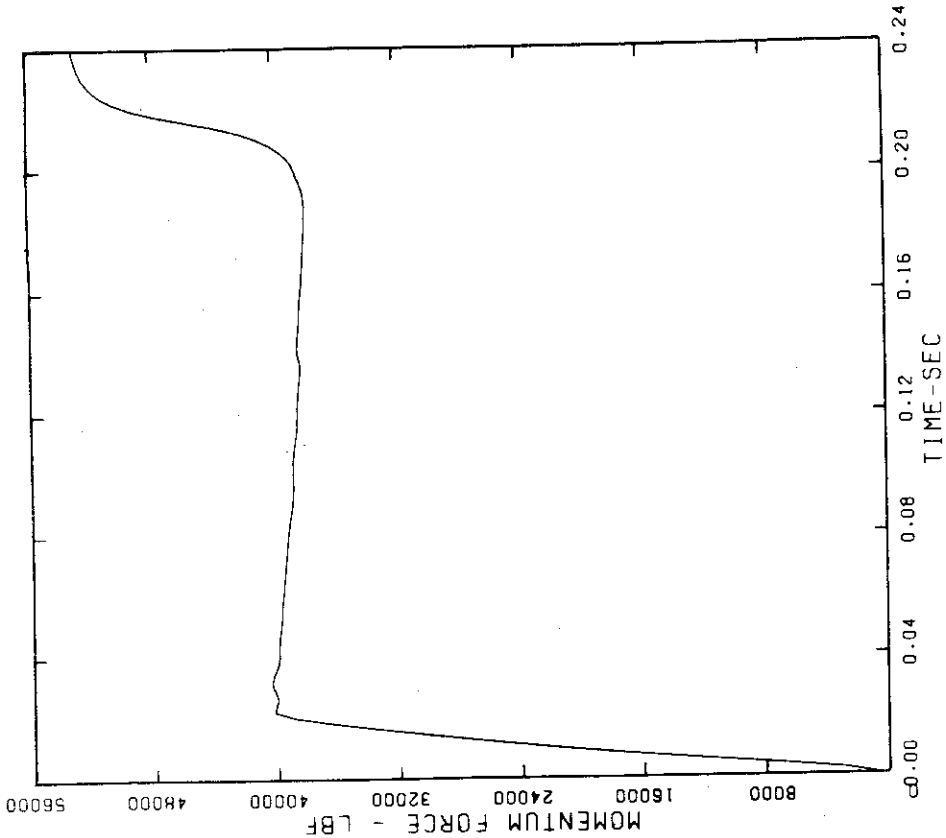


Fig.11-4 Time History of Momentum Force of F₁ for Sample Problem of Steam Blowdown Analyzed by PRTHRUST-J1 ----- FA is taken equal to zero and the option of smoothing the output of plotter is used.

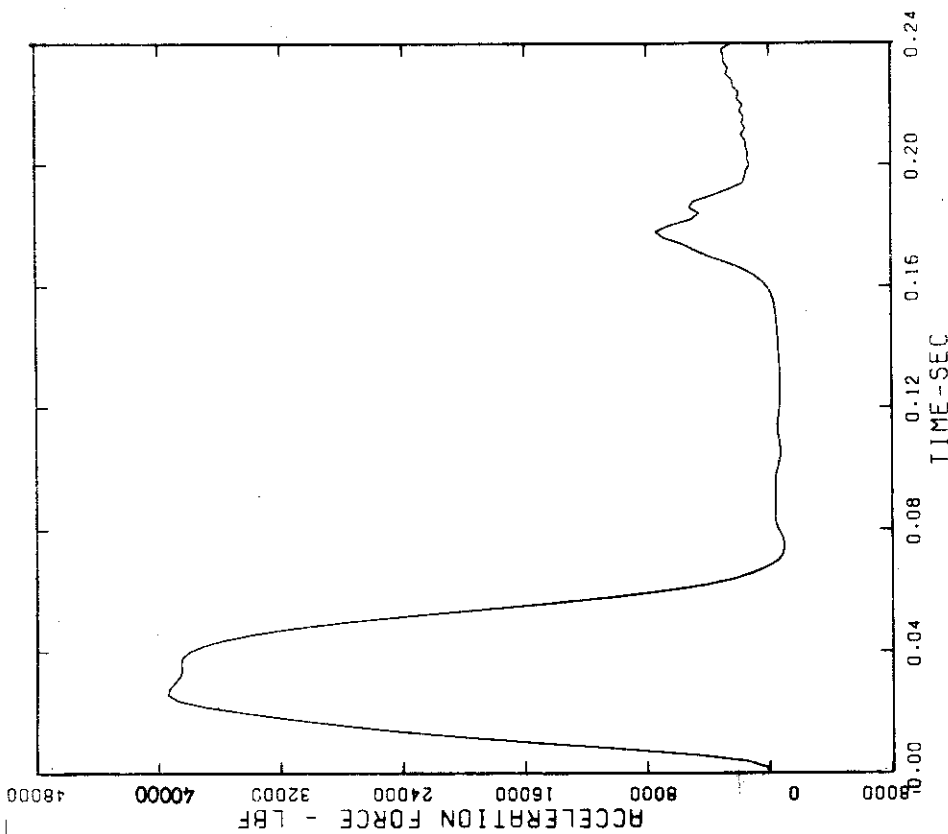


Fig.11-3 Time History of Wave Thrust of F₁ for Sample Problem of Steam Blowdown Analyzed by PRTHRUST-J1 ----- FA is taken equal to zero for the choked junction and the option of smoothing the output of plotter is used.

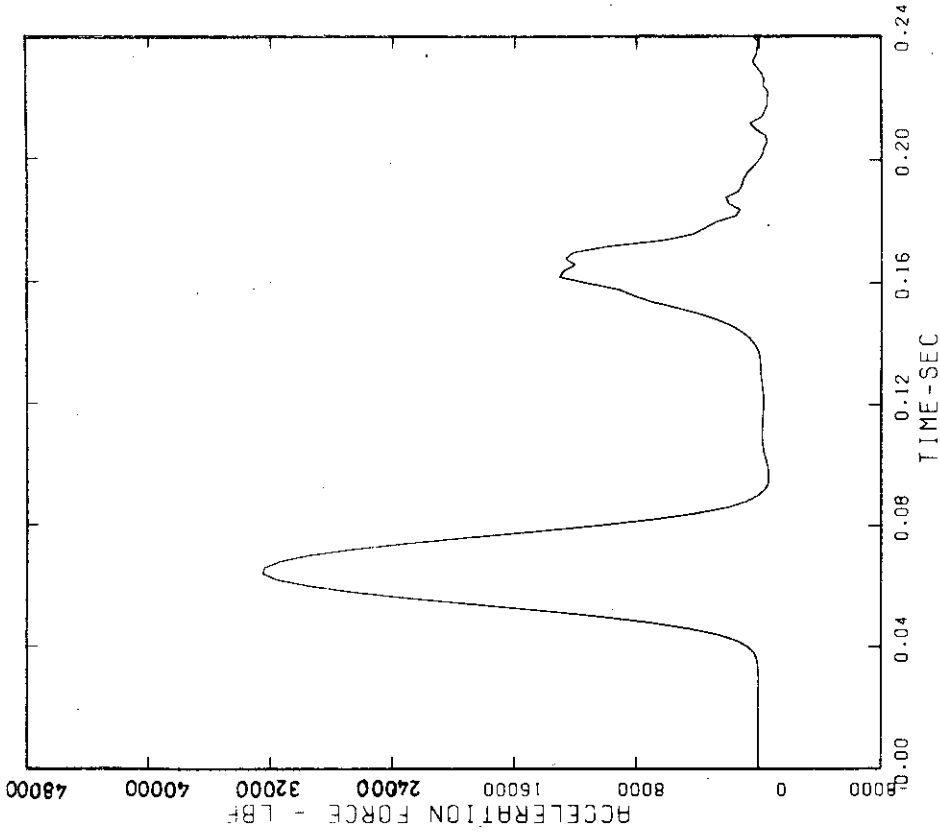


Fig.11-6 Time History of Wave Thrust, F₂, for Sample Problem of Steam Blowdown Analyzed by PRTHRUST-J1 ----- FA is taken equal to zero and the option of smoothing the output of plotter is used.

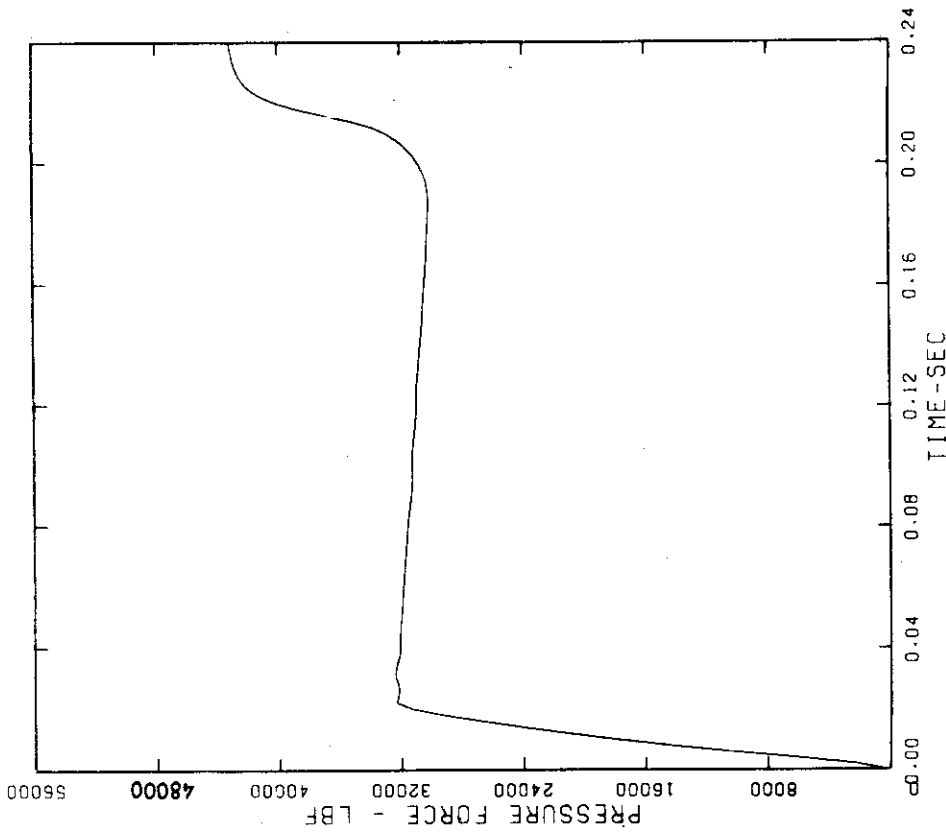


Fig.11-5 Time History of Pressure Force of F₁ for Sample Problem of Steam Blowdown Analyzed by PRTHRUST-J1 ----- FA is taken equal to zero and the option of smoothing the output of plotter is used.

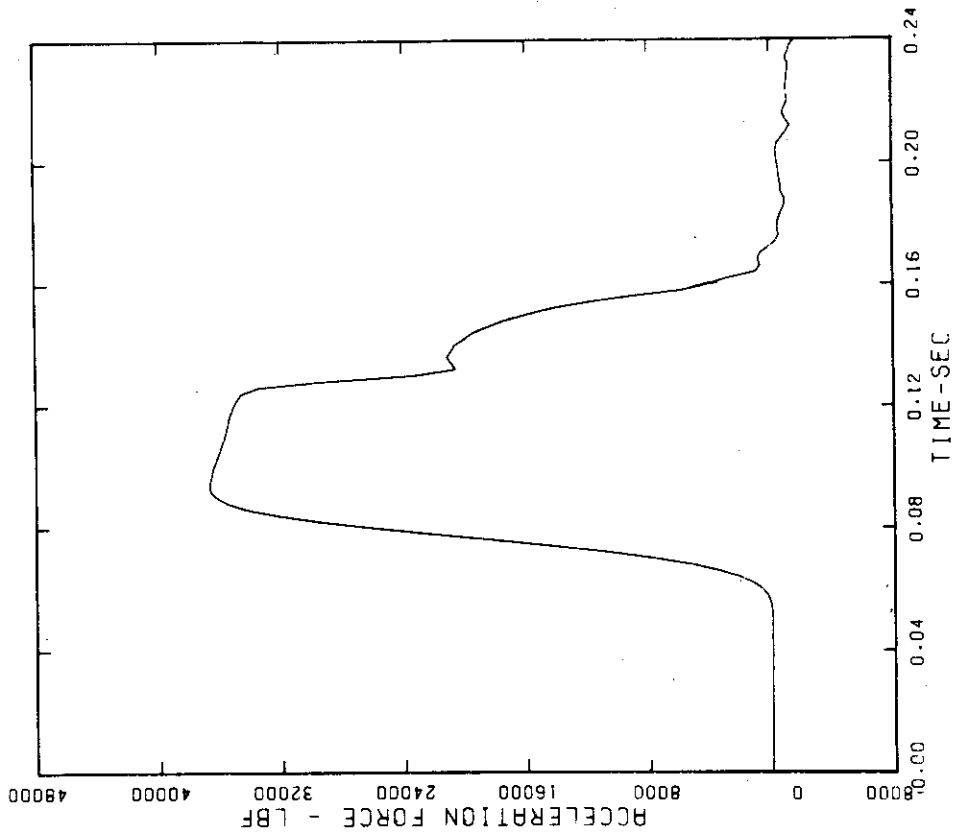


Fig.11-7 Time History of Wave Thrust, F₃, for Sample Problem of Steam Blowdown Analyzed by PRTHRUST-J1 ----- FA is taken equal to zero and the option of smoothing the output of plotter is used.

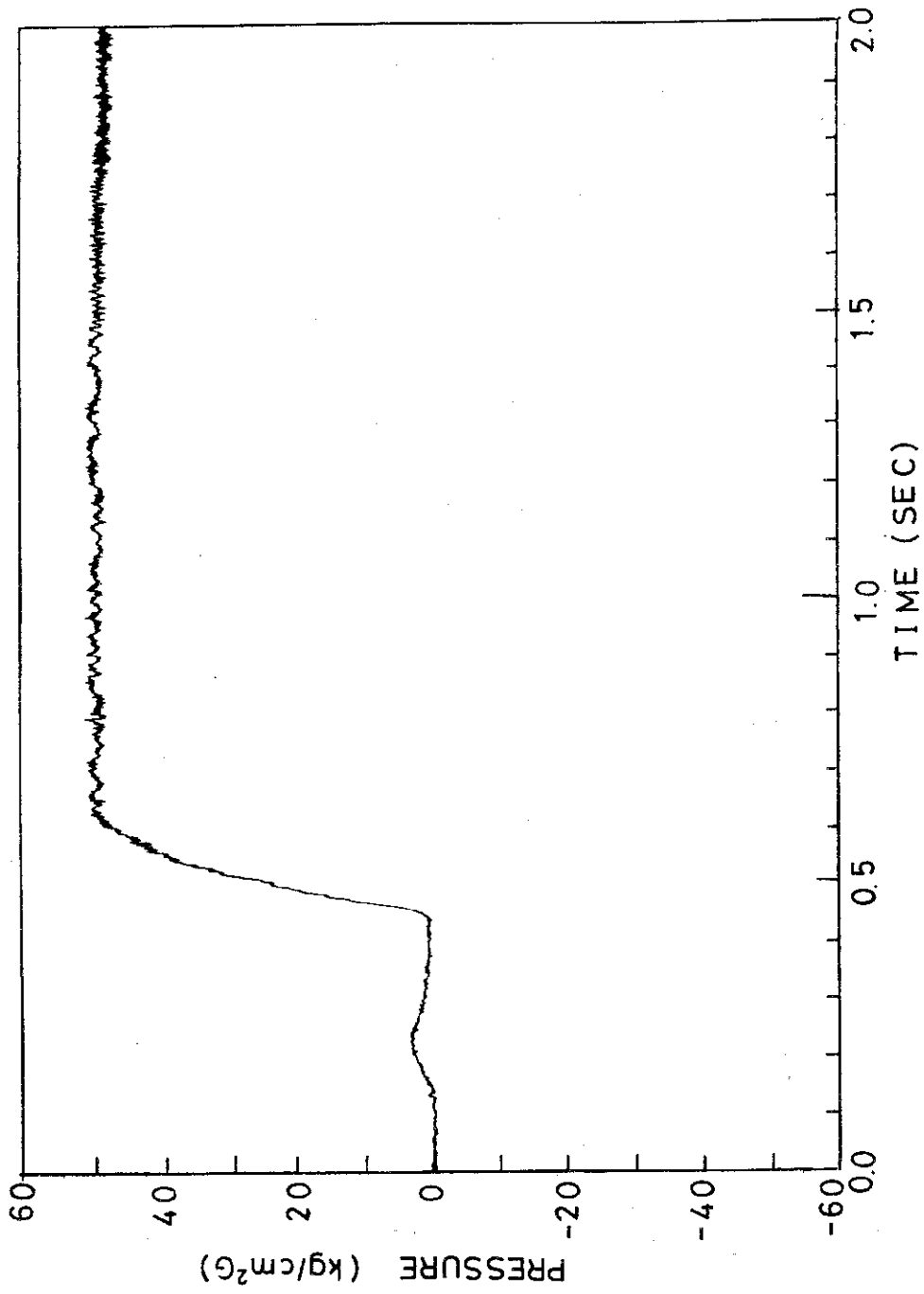


Fig. 12 Pressure at Discharging Nozzle for RUN NO. 5314 of Preliminary Jet Test.

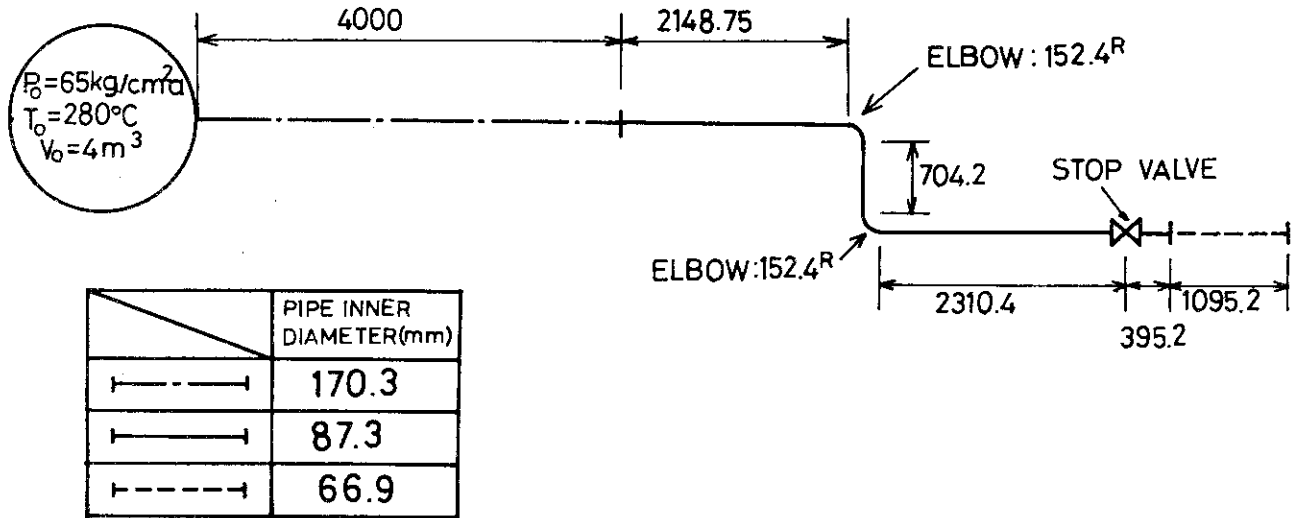


Fig. 13 Pipe Line Layout for RUN NO. 5314 of Preliminary Jet Test.

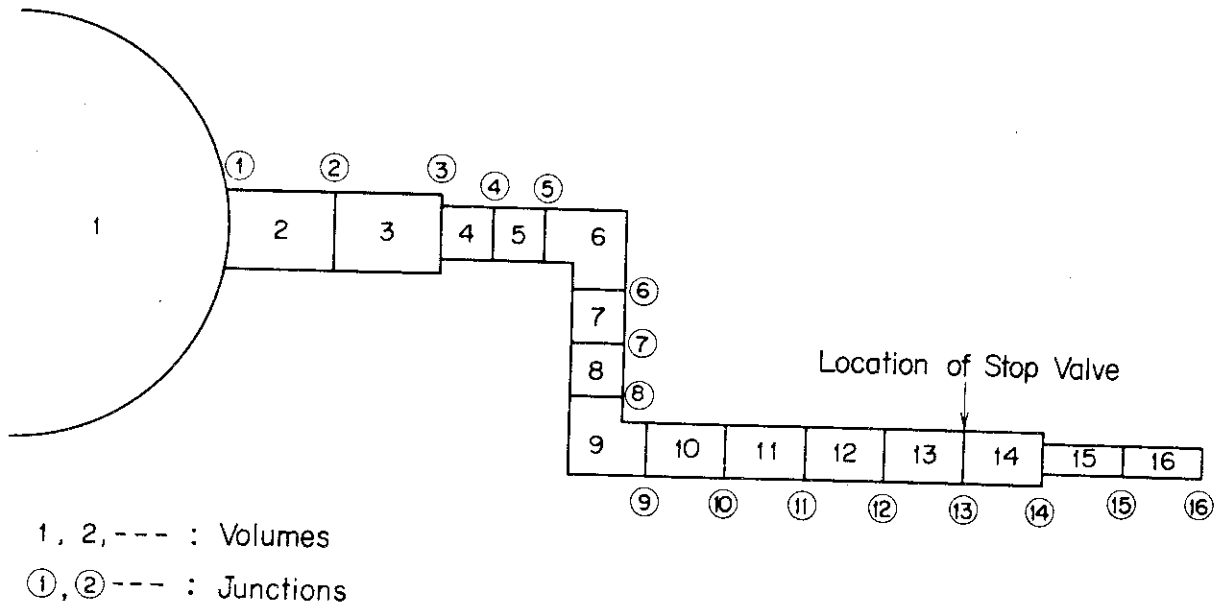


Fig. 14 Volume Division of Pipe Line.

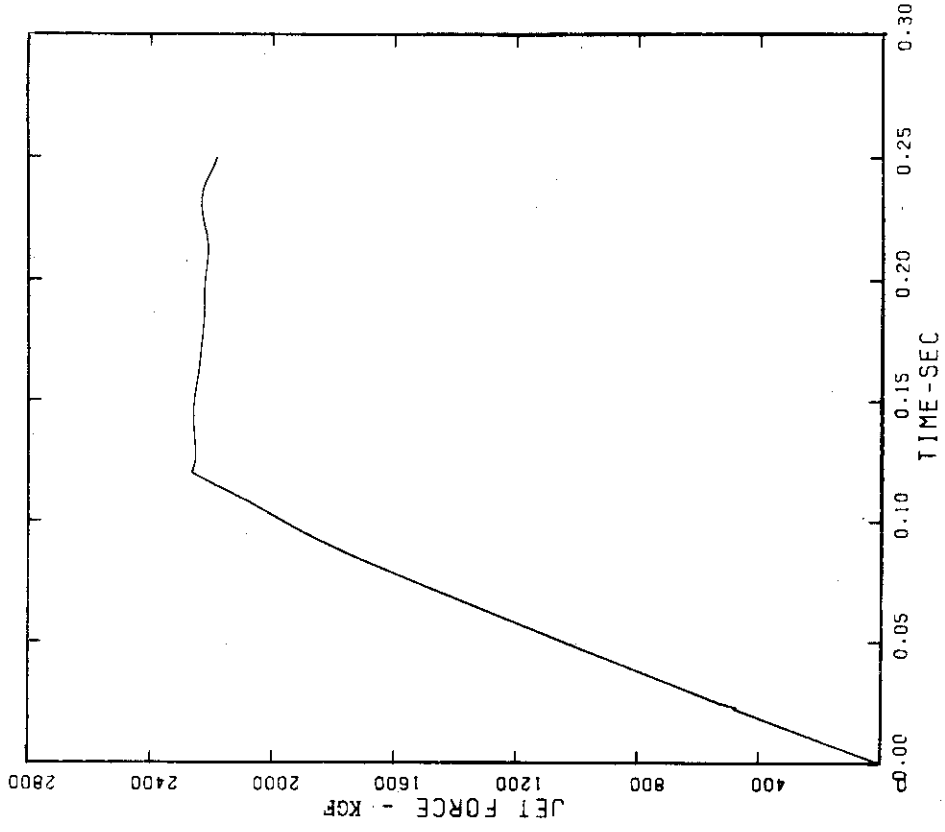


Fig.1.5-2 Time History of Jet Impingement Force for Model 1.

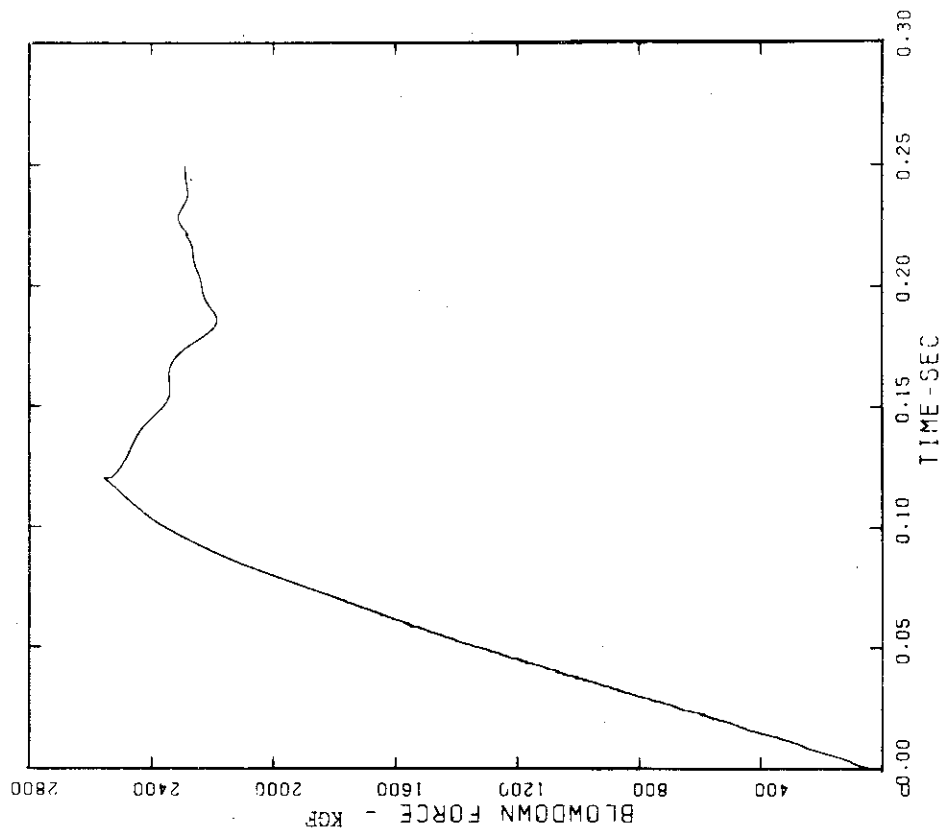


Fig.1.5-1 Time History of Thrust Force, F_1 , for Model 1.

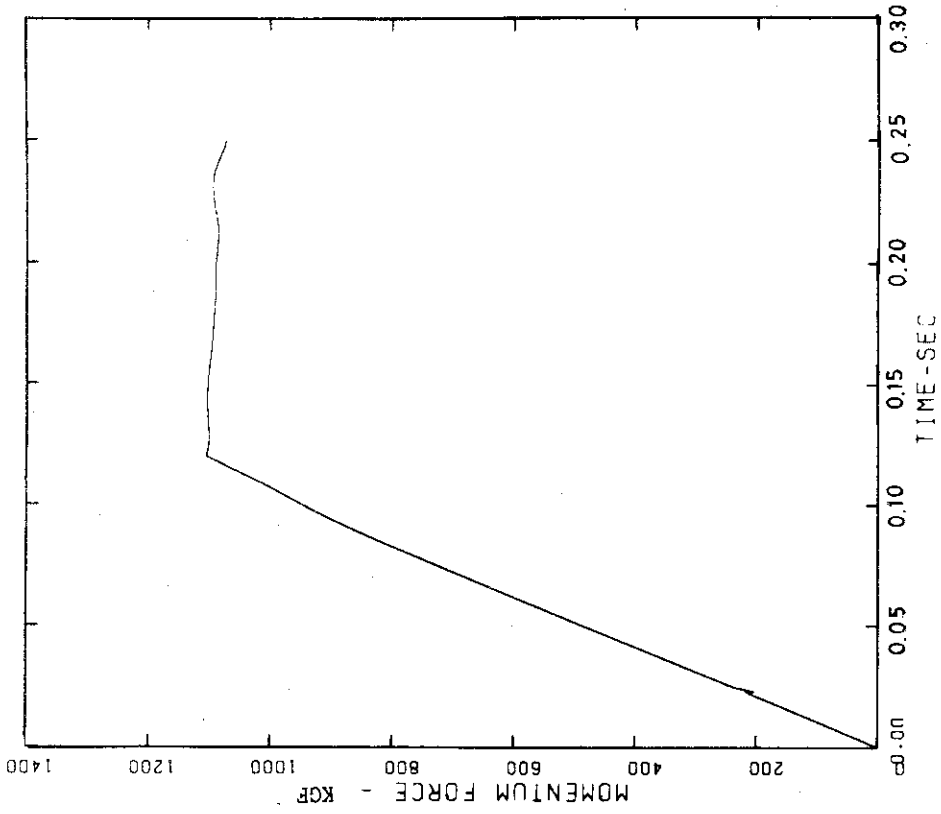


Fig.15-4 Time History of Momentum Force of F_1 for Model 1.

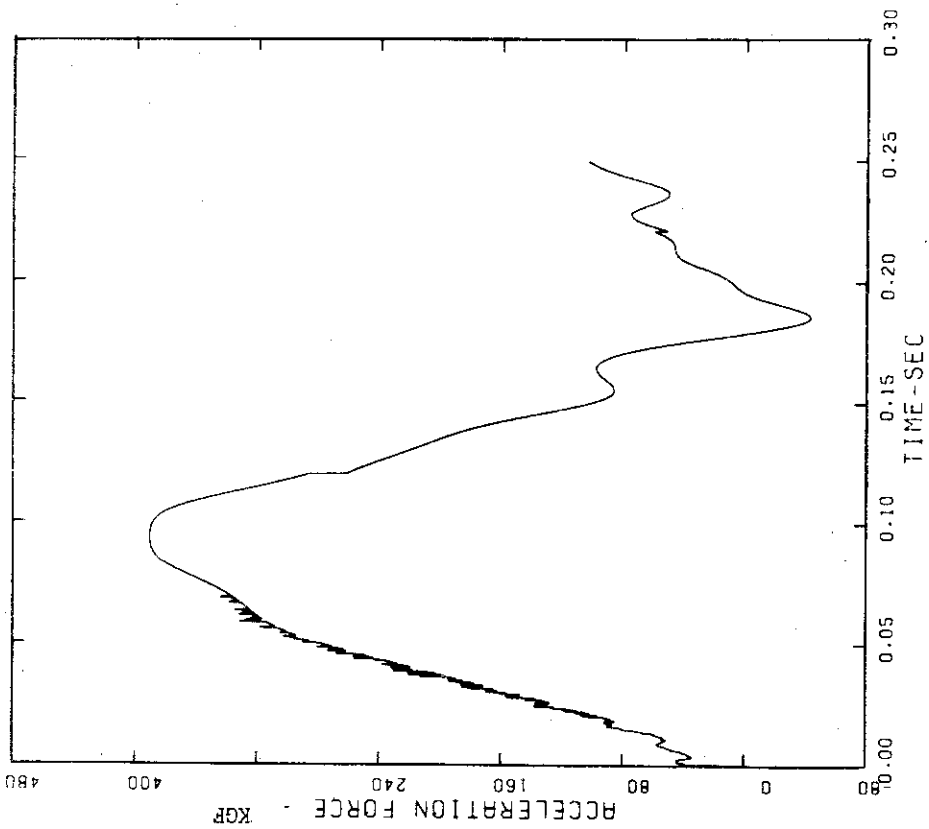


Fig.15-3 Time History of Wave Thrust of F_1 for Model 1.

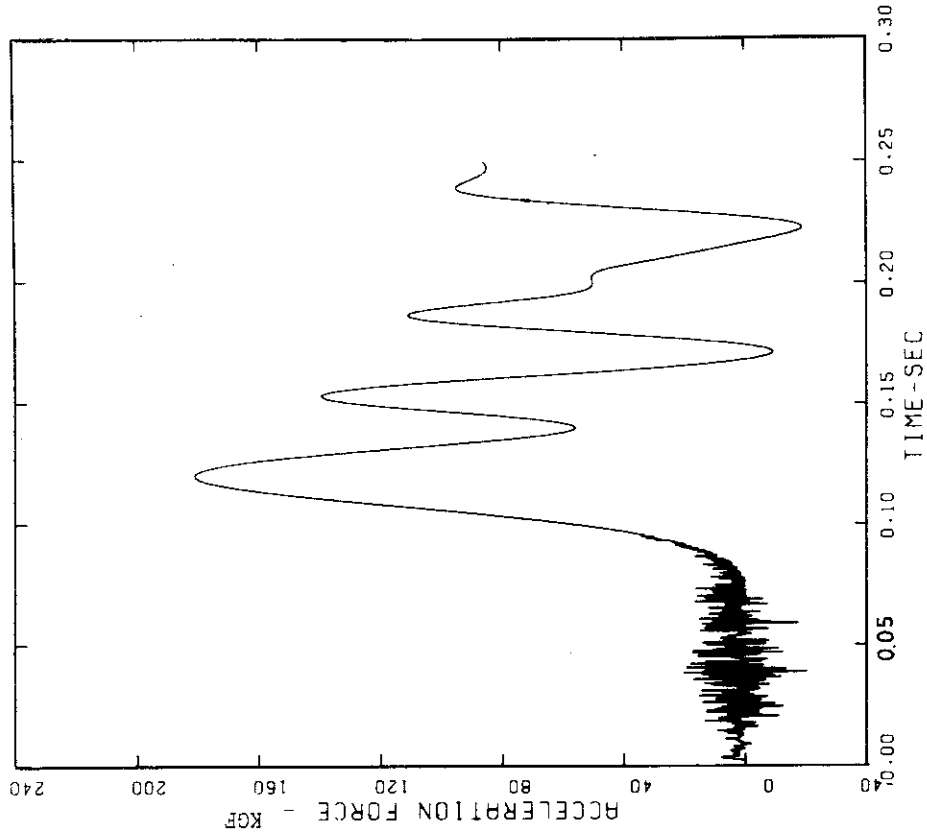


Fig.15-6 Time History of Wave Thrust, F_2 , for Model I.

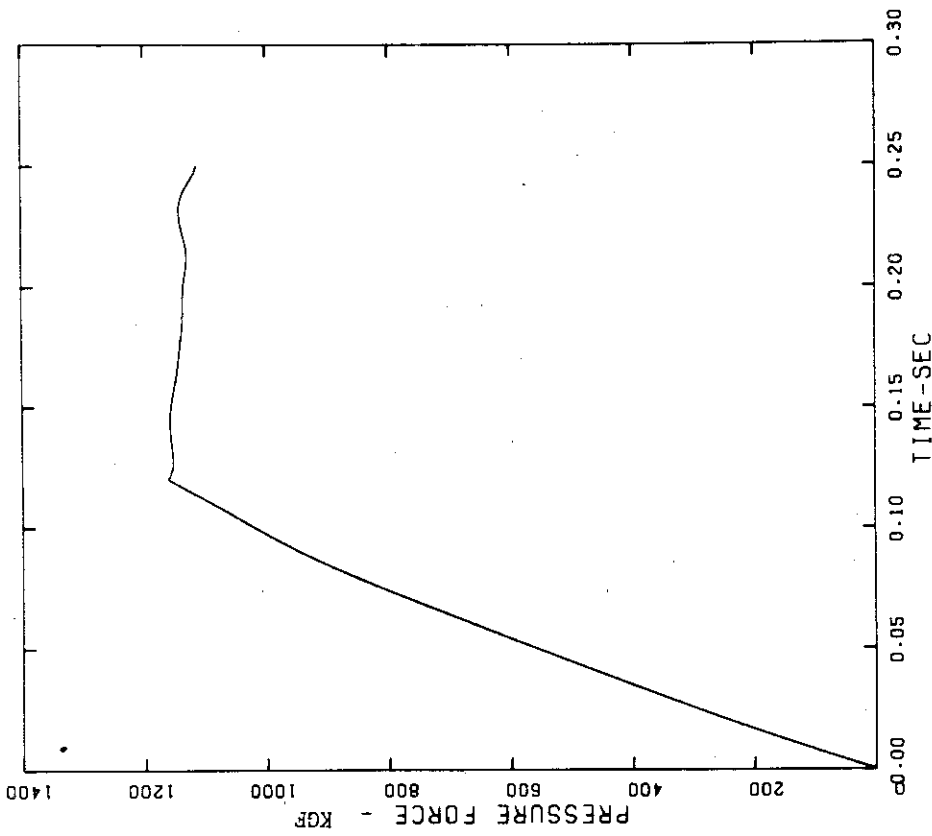


Fig.15-5 Time History of Pressure Force of F_1 for Model I.

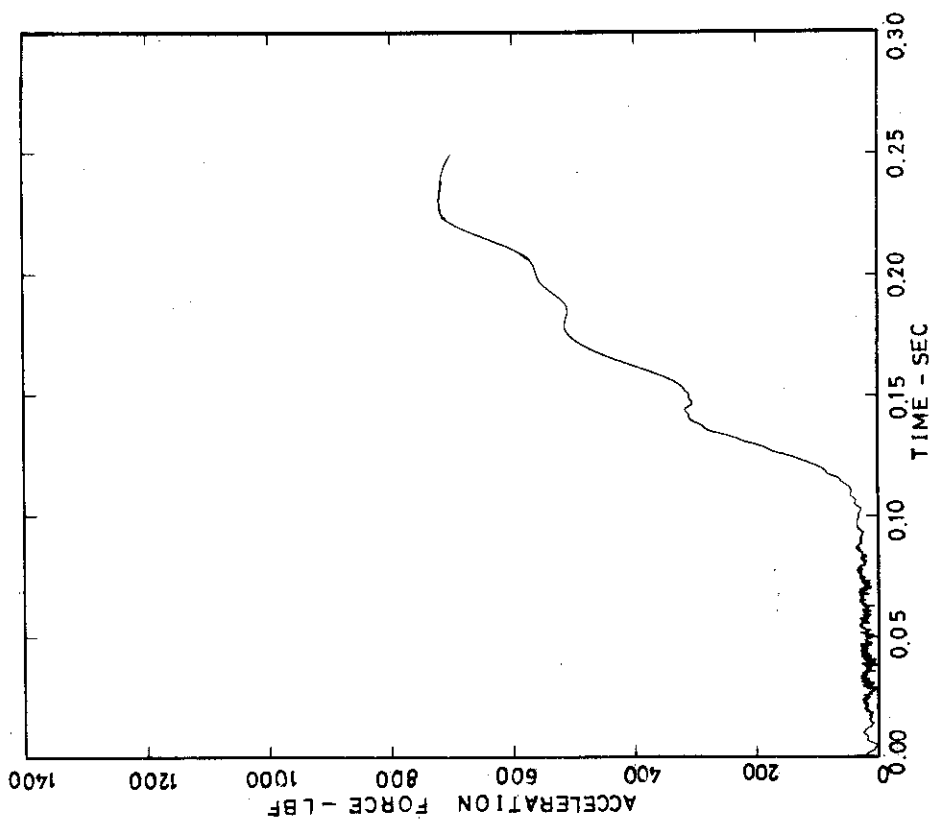


Fig.15-7 Time History of Wave Thrust, F₃ for Model 1.

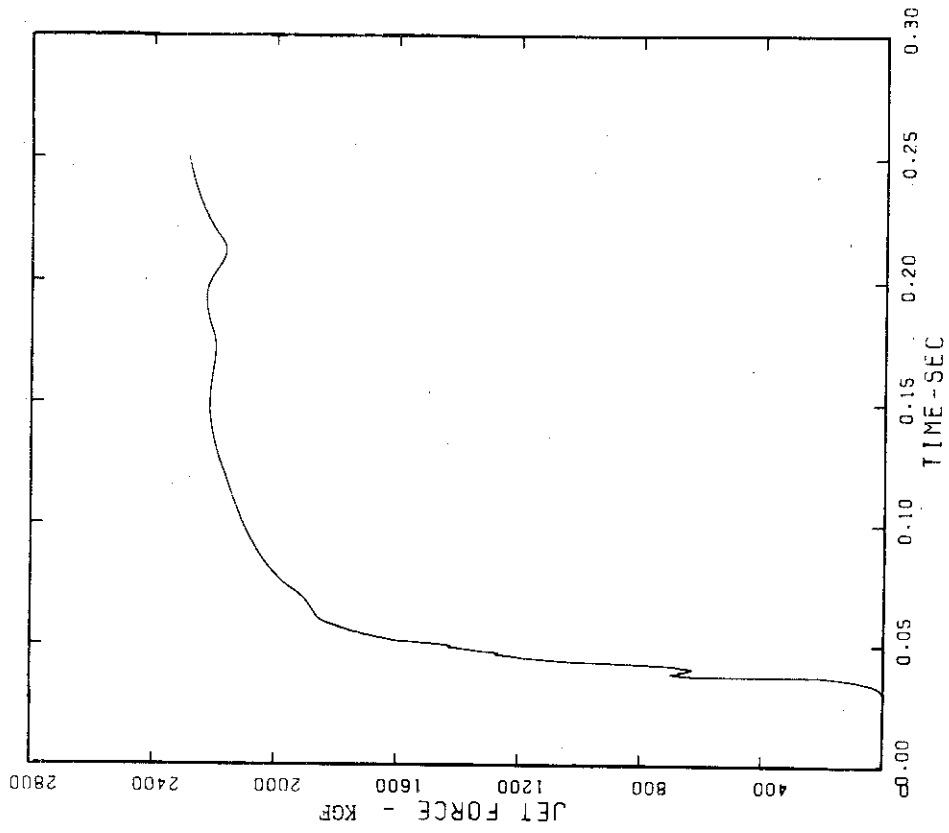


Fig.16-2 Time History of Jet Impingement Force for Model 2-1.

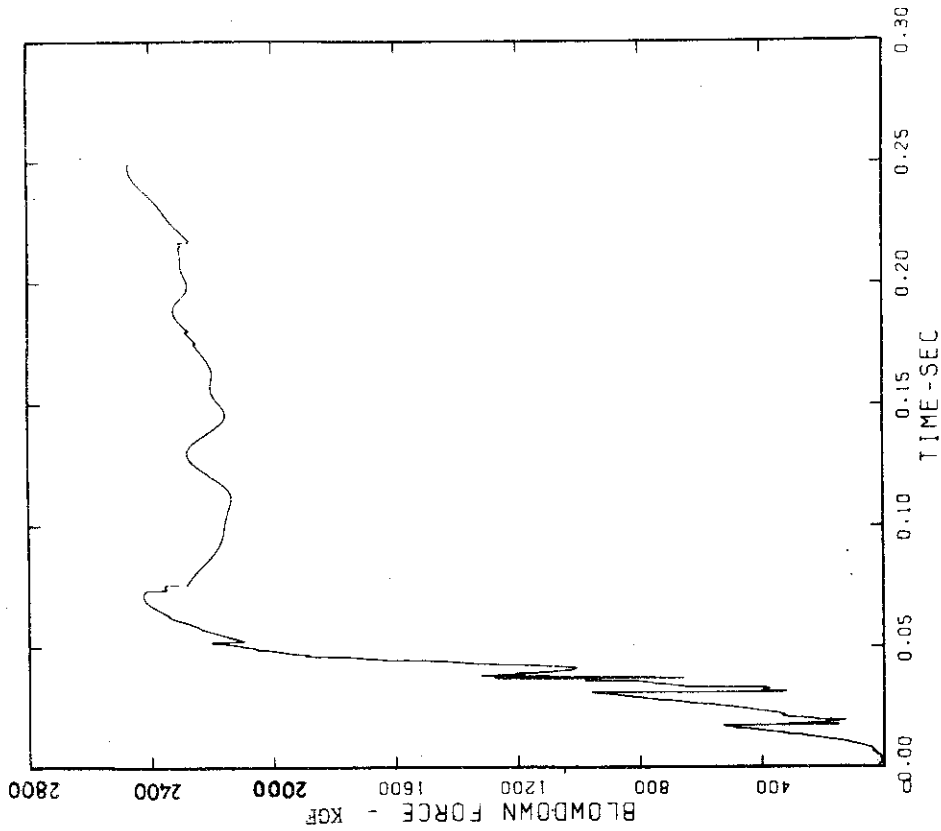


Fig.16-1 Time History of Thrust Force, F_1 , for Model 2-1.

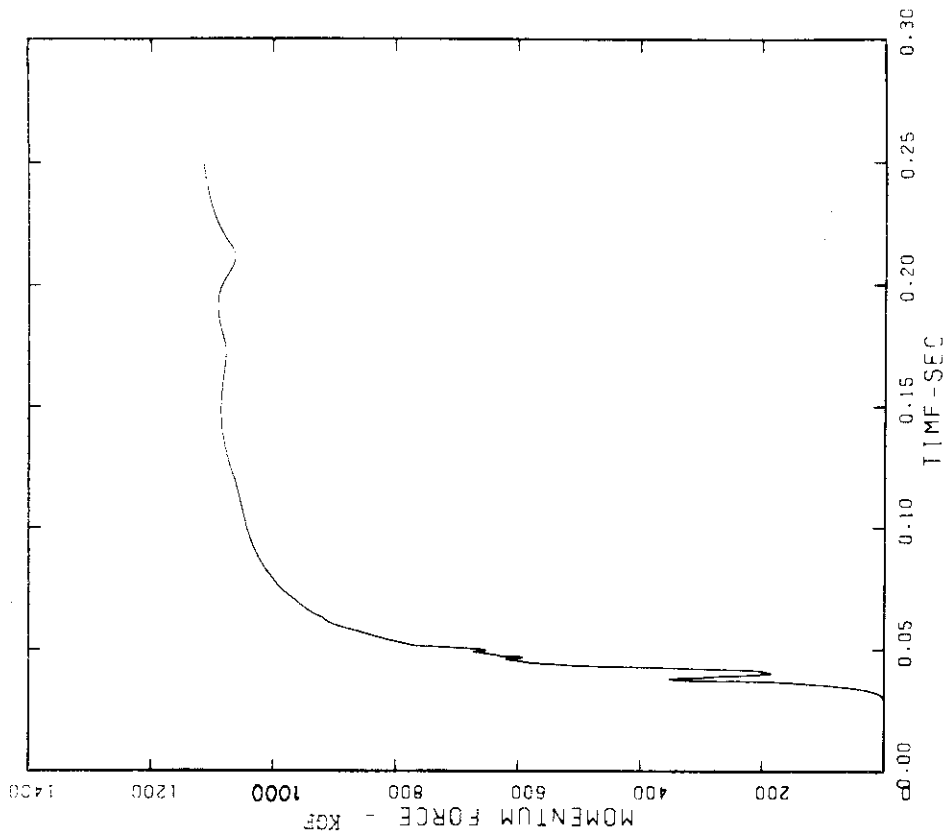


Fig.16-4 Time History of Momentum Force of F1 for Model 2-1.

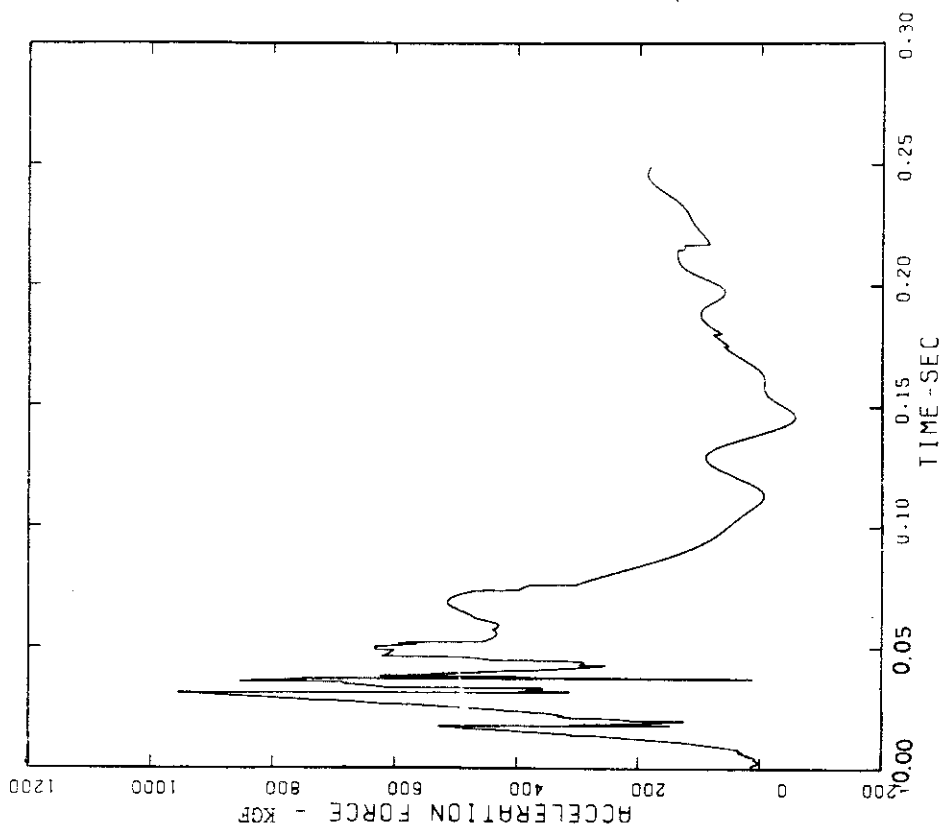


Fig.16-3 Time History of Wave Thrust of F1 for Model 2-1.

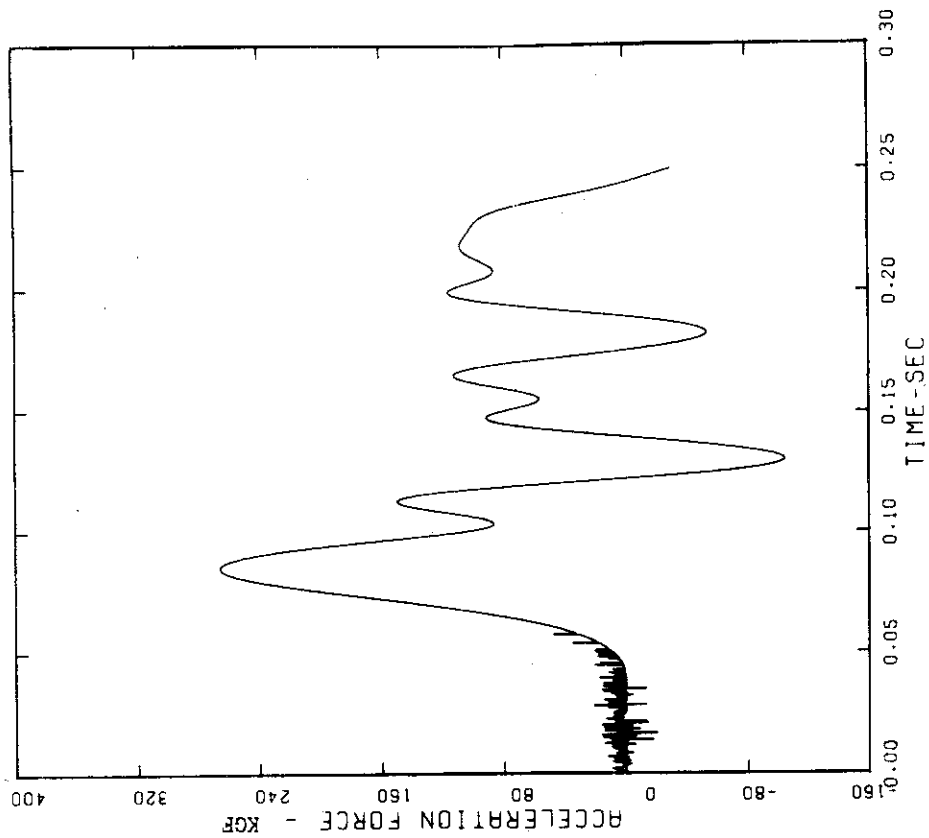


Fig.16-6 Time History of Wave Thrust, F_2 , for Model 2-1.

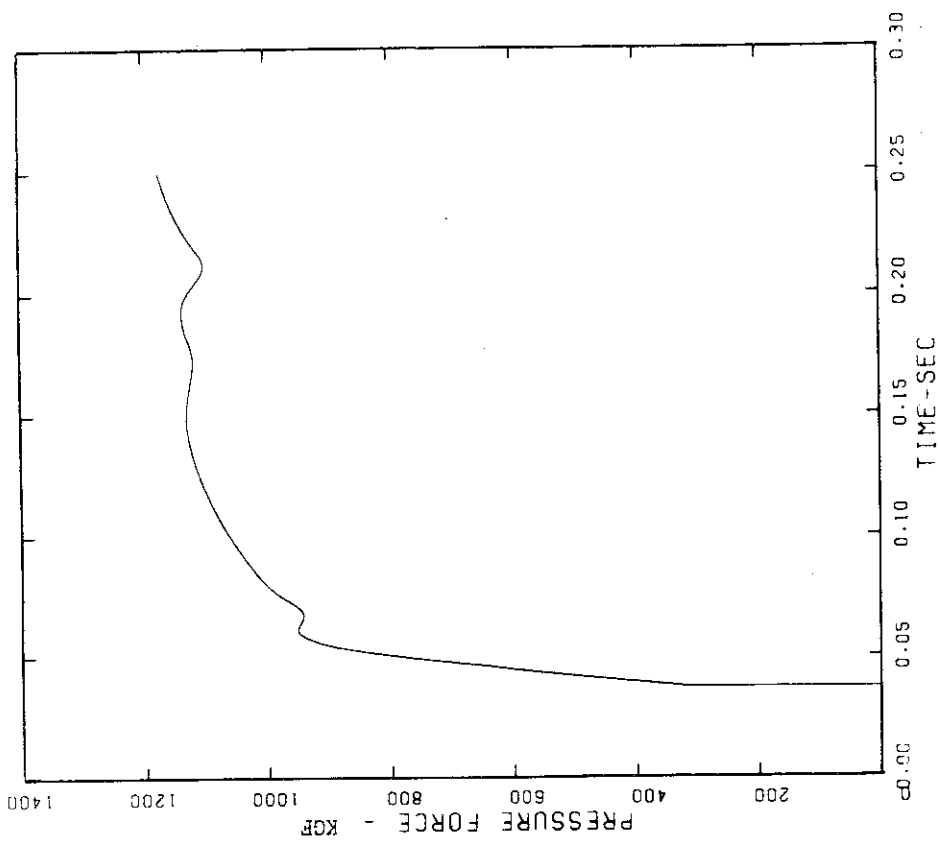


Fig.16-5 Time History of Pressure Force of F_1 for Model 2-1.

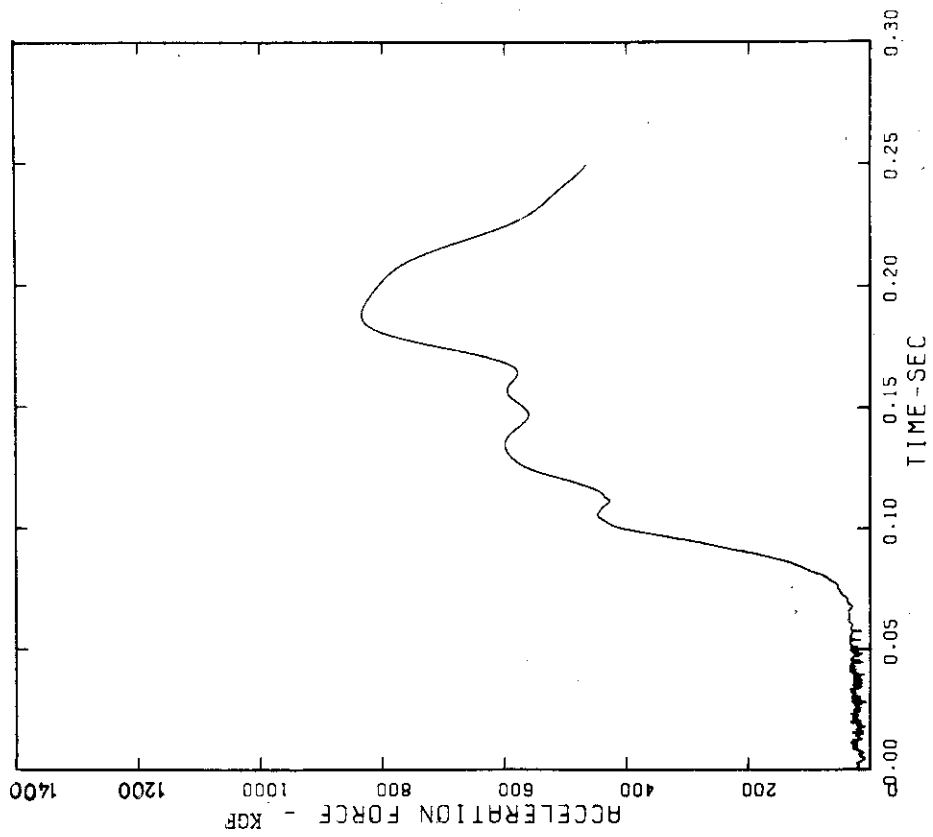


Fig.16-7 Time History of Wave Thrust, F_3 ,
for Model 2-1.

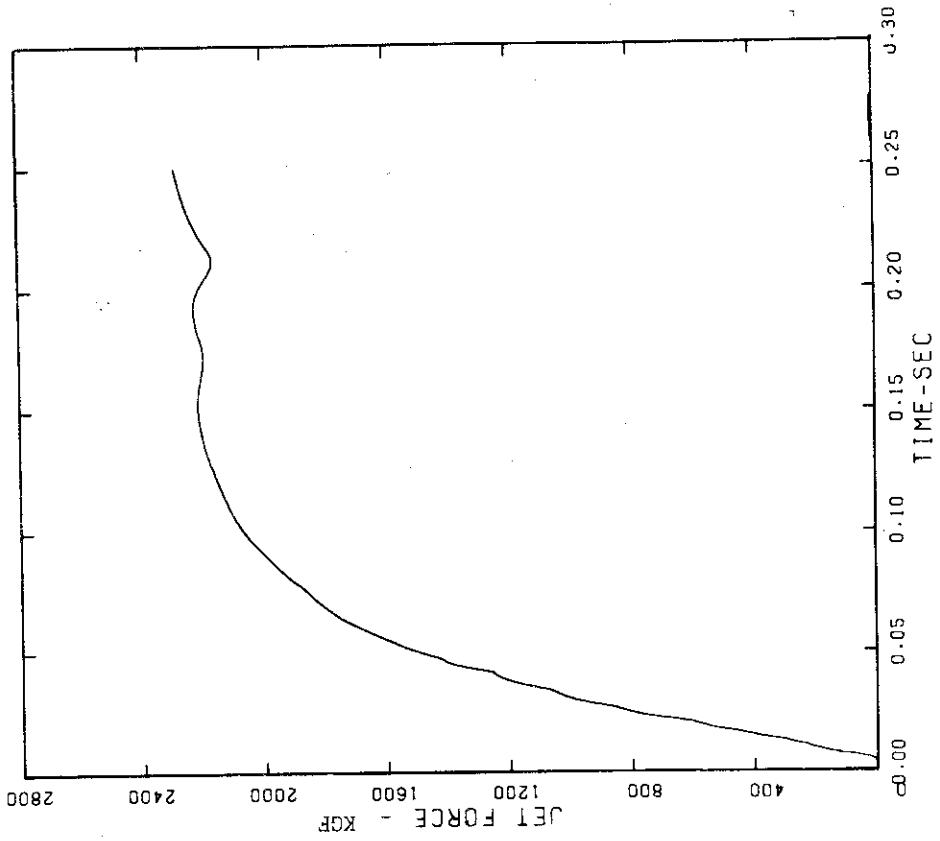


Fig.17-2 Time History of Jet Impingement Force for Model 2-2.

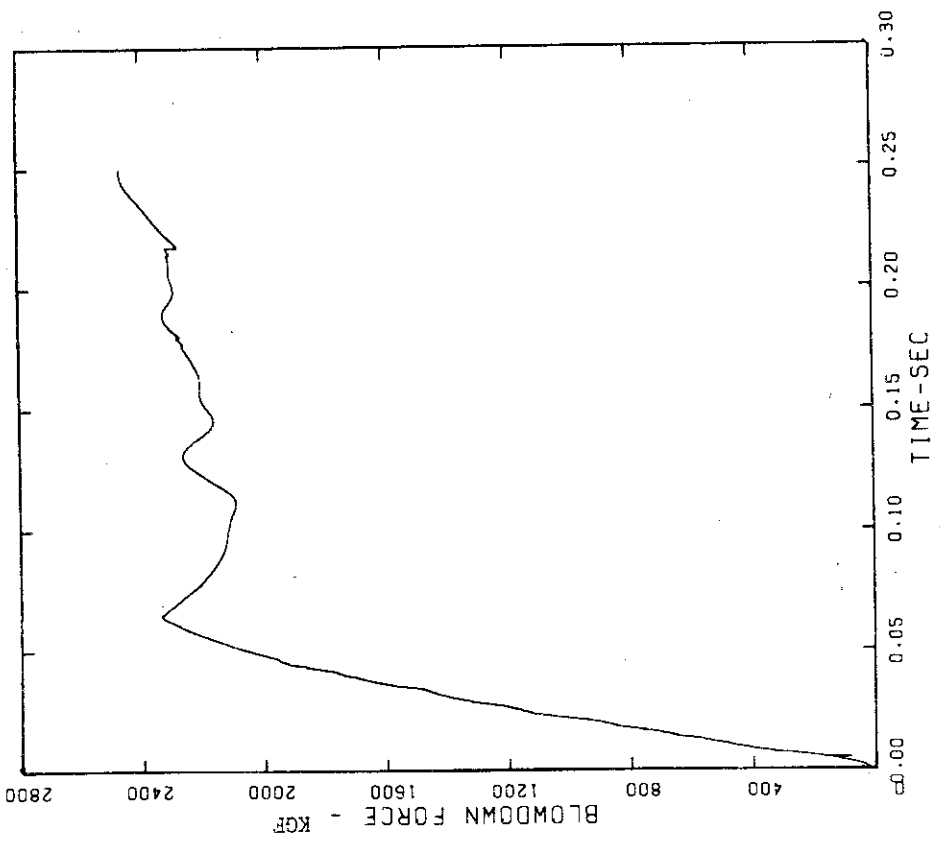


Fig.17-1 Time History of Thrust Force, F_1 , for Model 2-2.

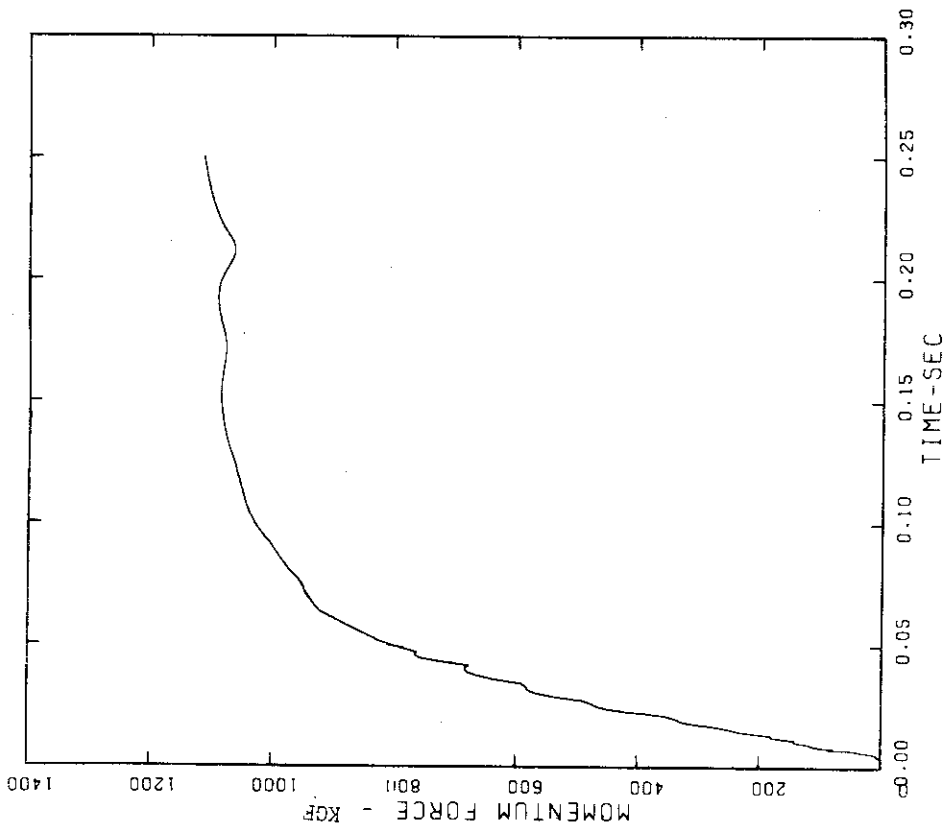


Fig.17-4 Time History of Momentum Force of F₁ for Model 2-2.

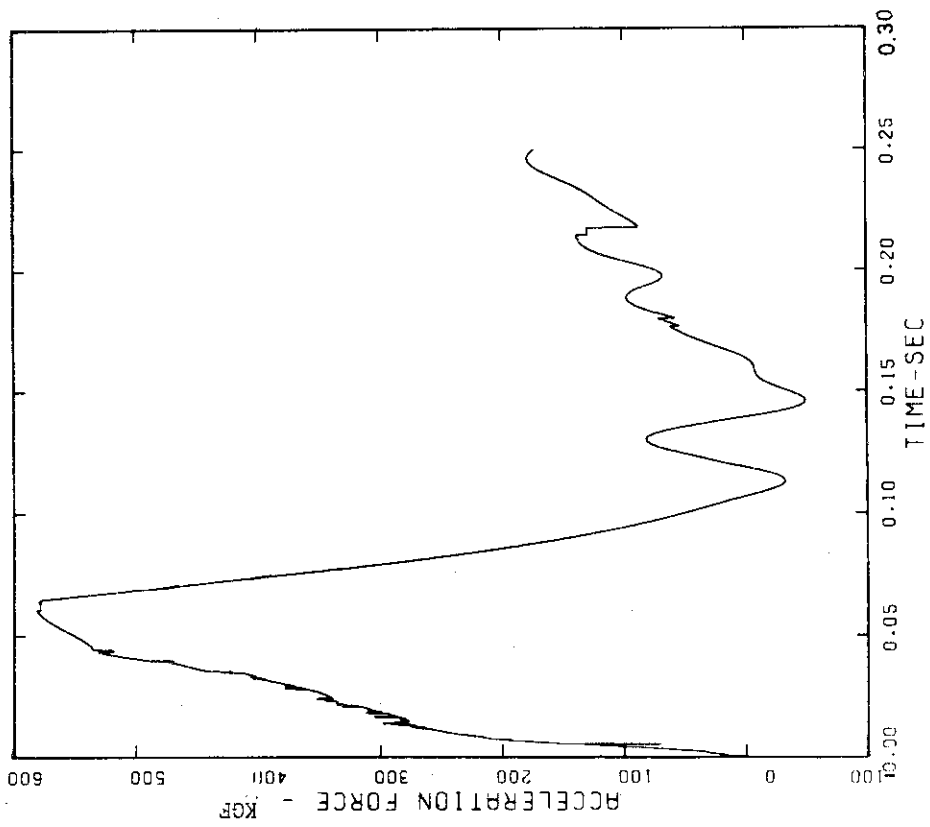


Fig.17-3 Time History of Wave Thrust of F₁ for Model 2-2.

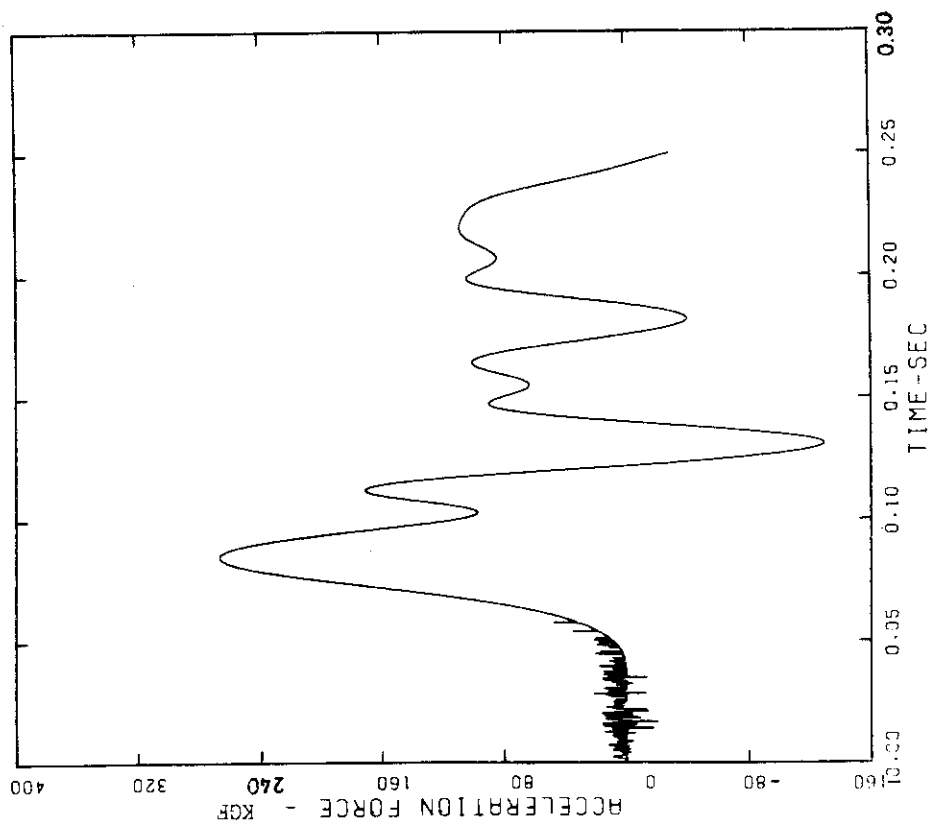


Fig.17-6 Time History of Wave Thrust, F2, for Model 2-2.

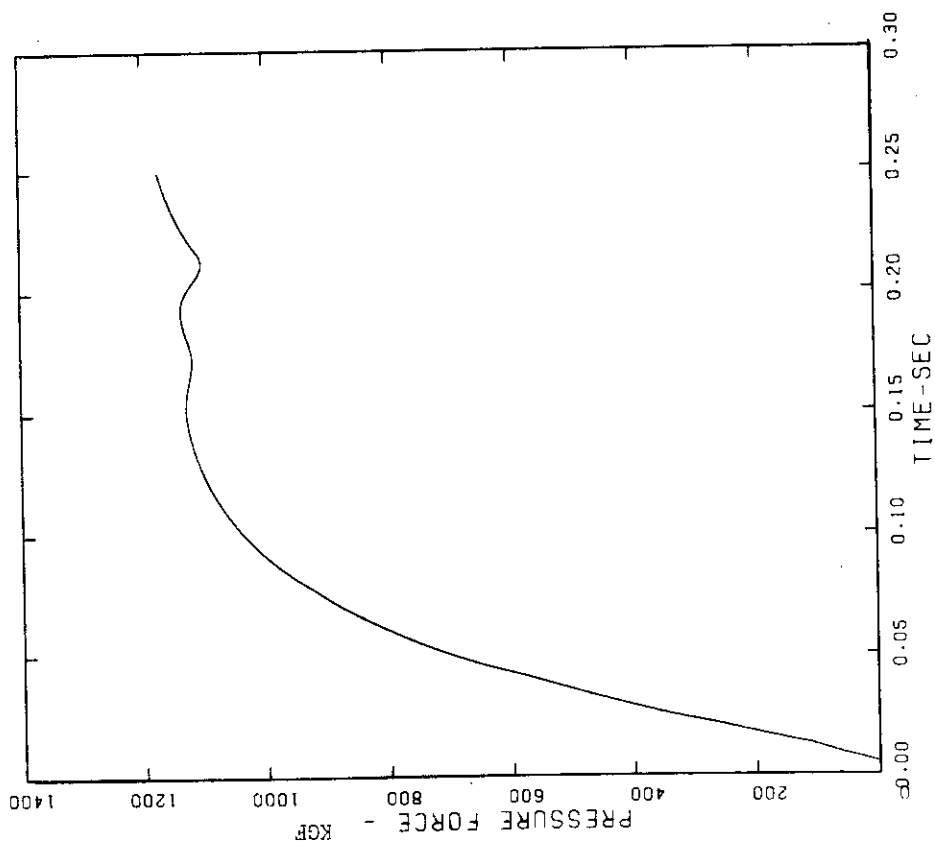


Fig.17-5 Time History of Pressure Force of F1 for Model 2-2.

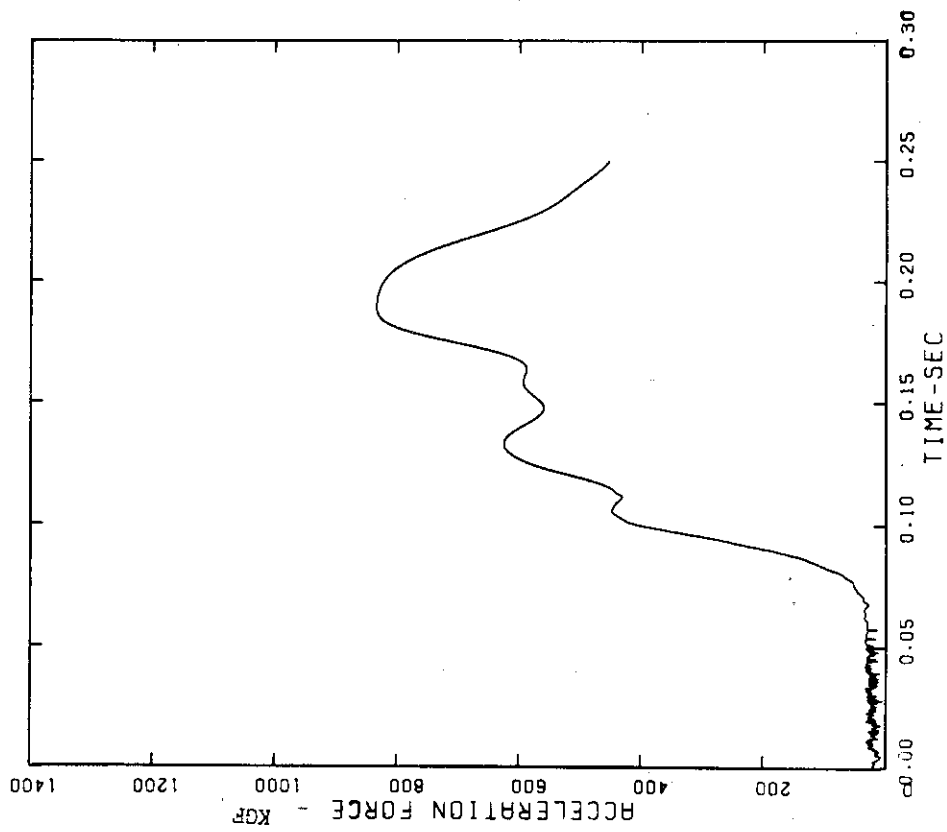


Fig.17-7 Time History of Wave Thrust, F₃,
for Model 2-2.

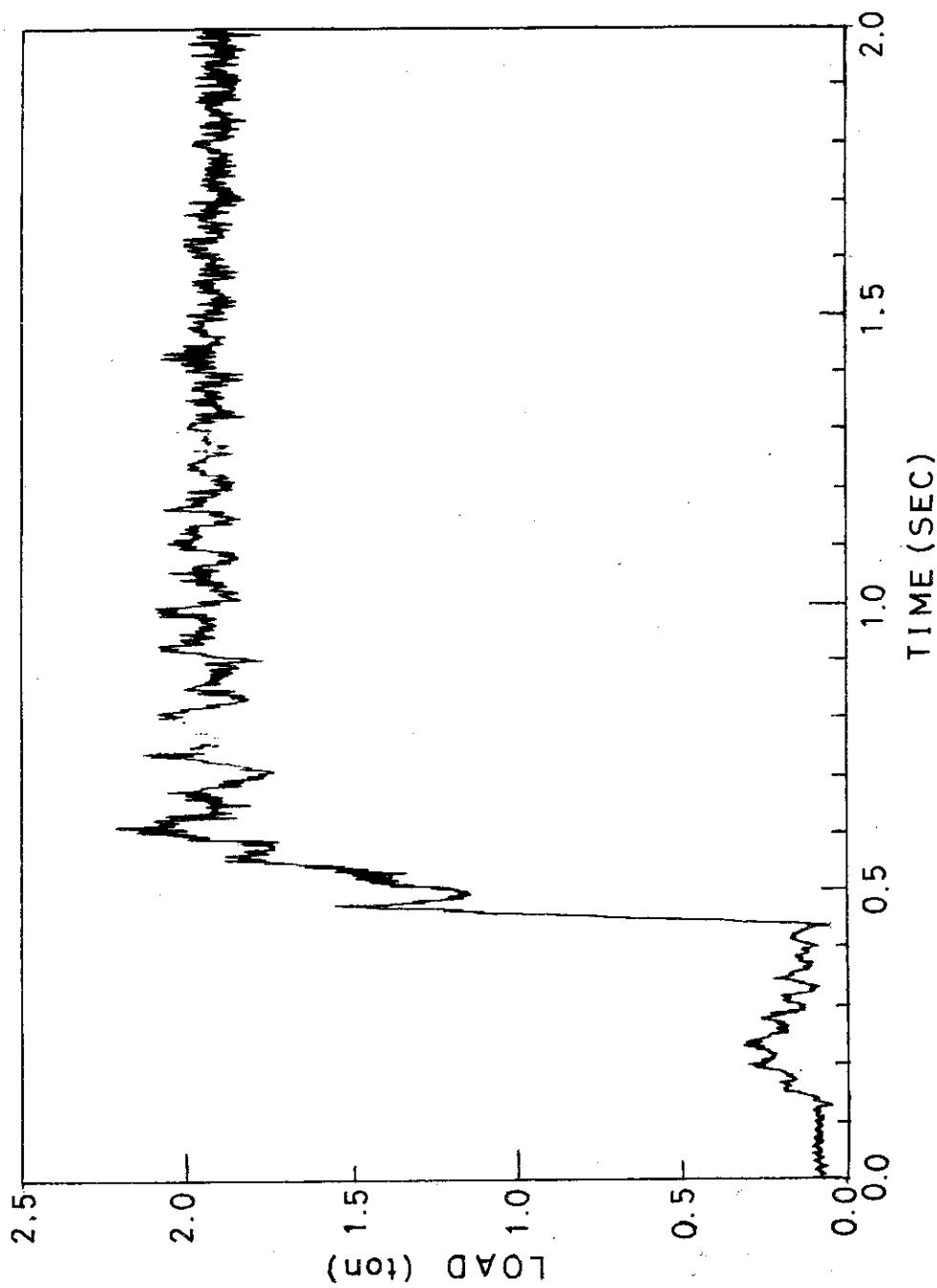


Fig. 18 Thrust Force Measured by Load Cell WU111 for RUN No. 5314 of Preliminary Jet Test.

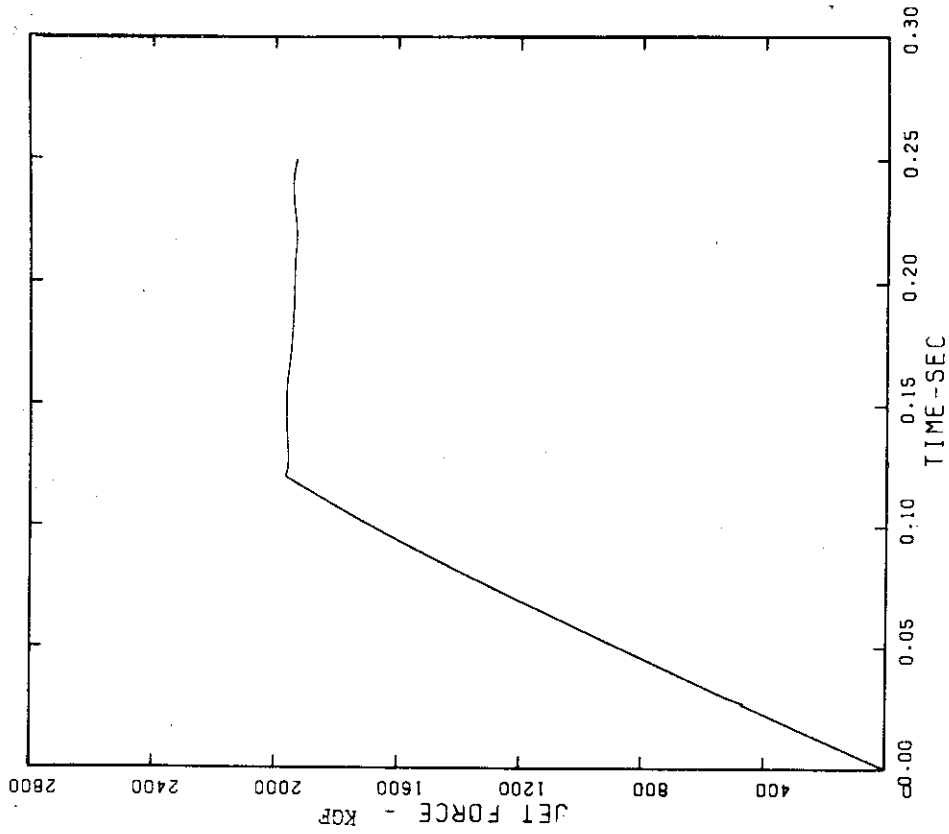


Fig.19-2 Time History of Jet Impingement Force for Model 1 ----- Discharging Coefficient = 0.8.

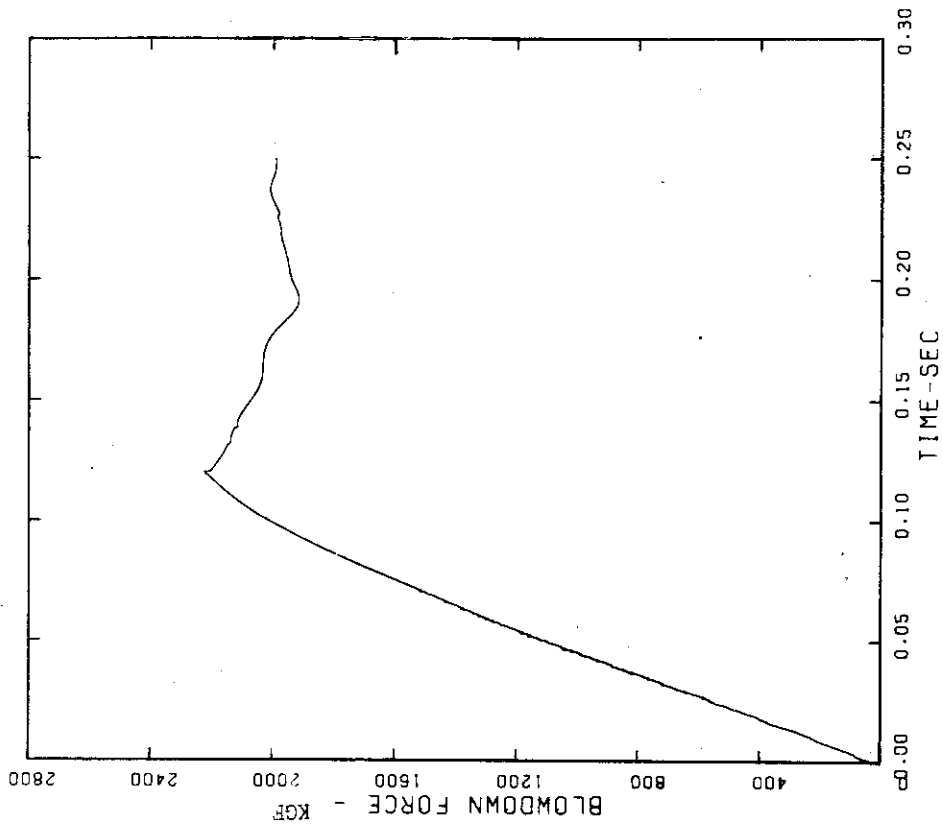


Fig.19-1 Time History of Thrust Force, F_1 , for Model 1 ----- Discharging Coefficient = 0.8.

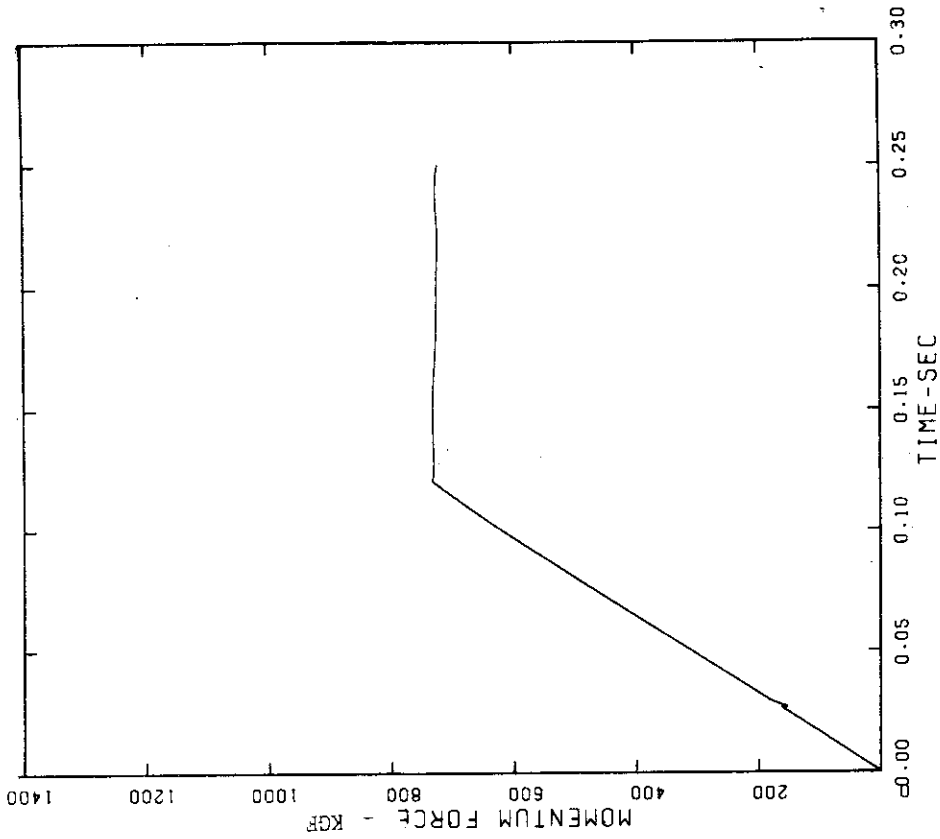


Fig.19-4 Time History of Momentum Force of F₁ for Model 1 ----- Discharging Coefficient = 0.8.

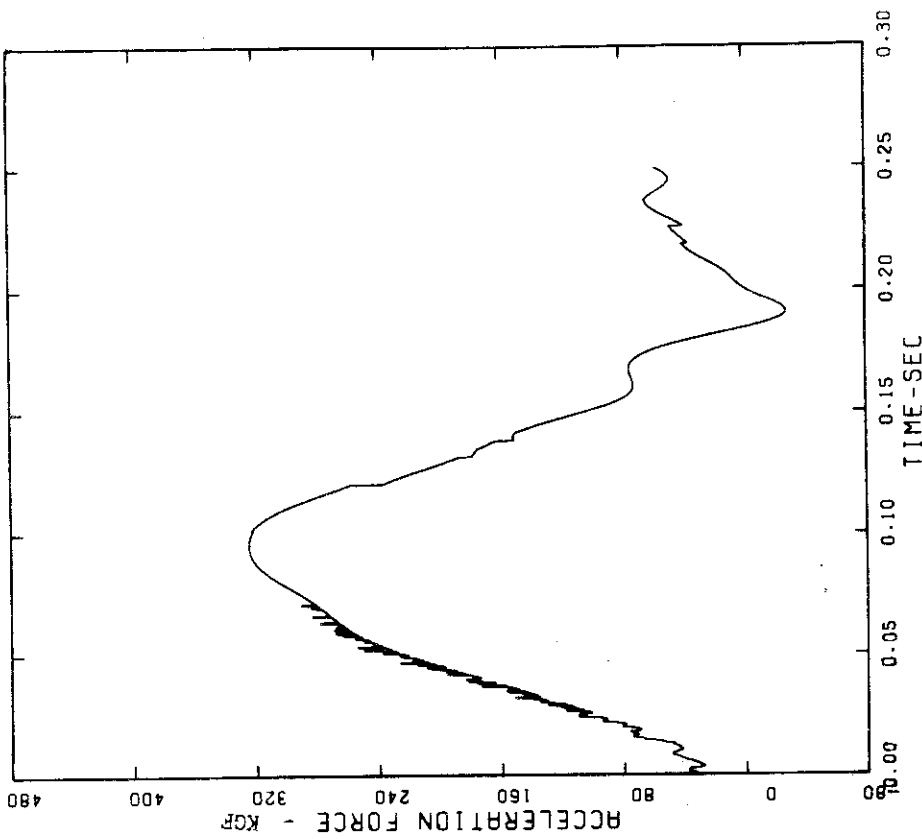


Fig.19-3 Time History of Wave Thrust of F₁ for Model 1 ----- Discharging Coefficient = 0.8.

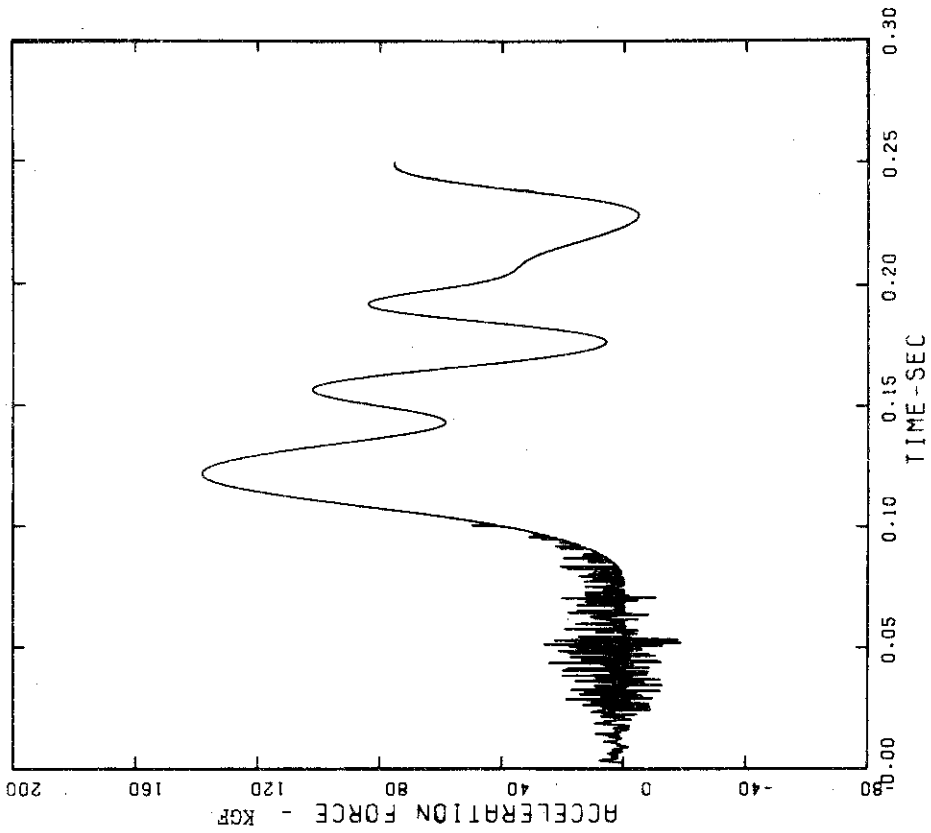


Fig.19-6 Time History of Wave Thrust, F_2 , for Model 1 ----- Discharging Coefficient = 0.8.

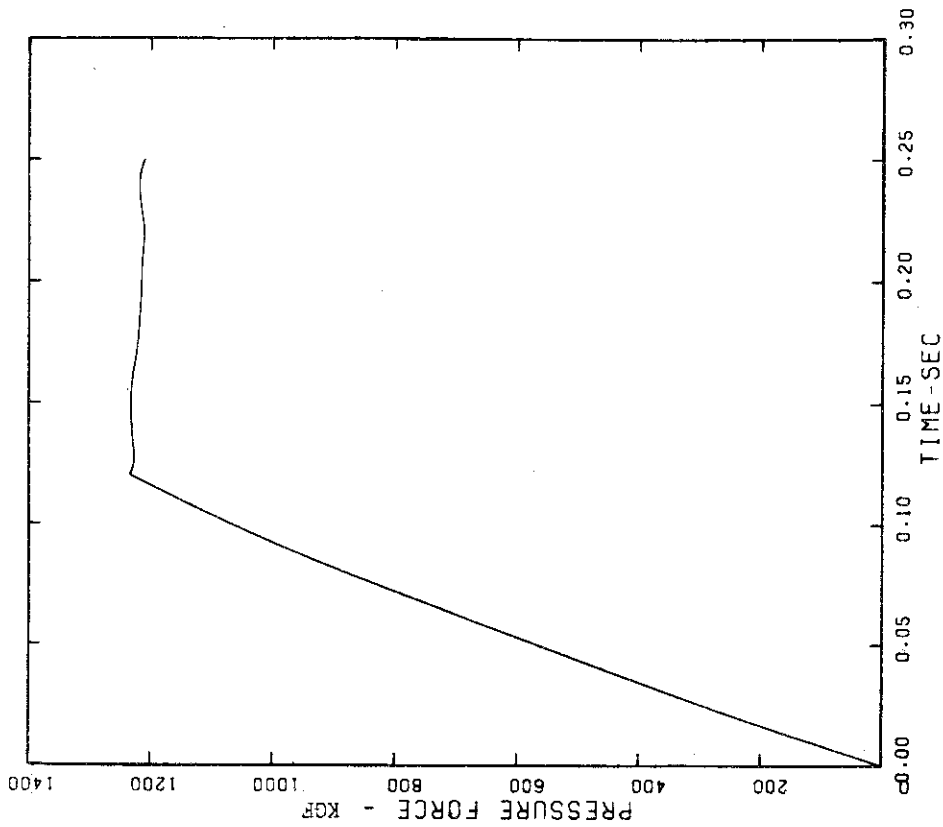


Fig.19-5 Time History of Pressure Force of F_1 for Model 1 ----- Discharging Coefficient = 0.8.

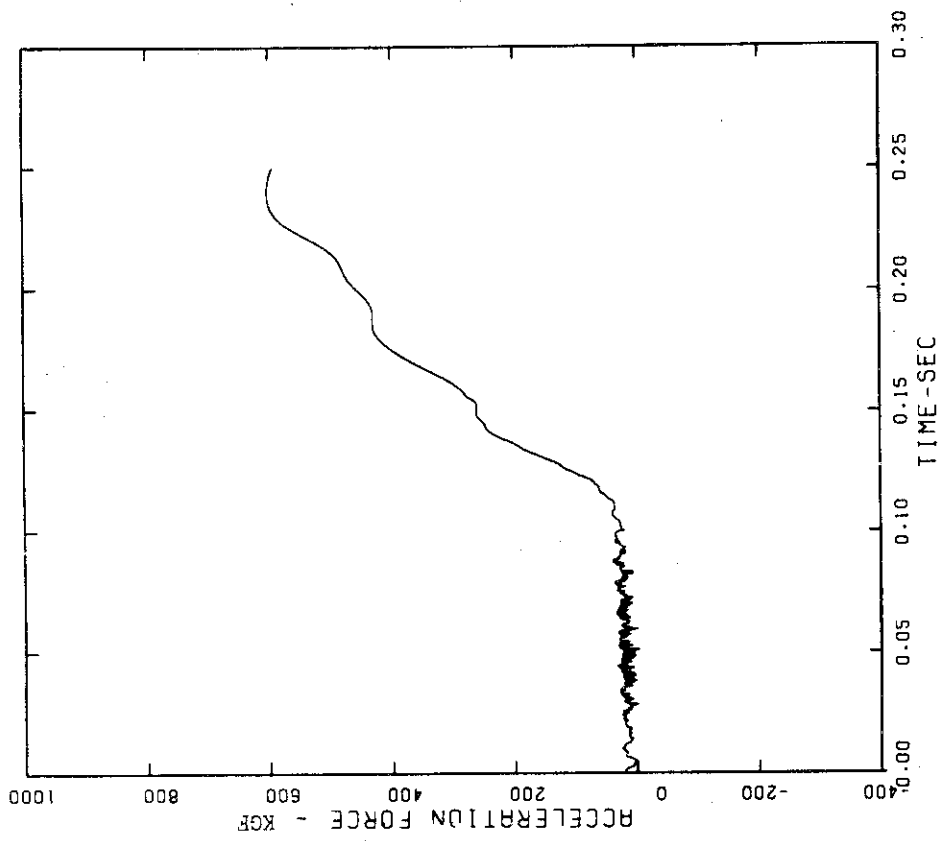


Fig.19-7 Time History of Wave Thrust, F₃, for Model 1 ----- Discharging Coefficient = 0.8.

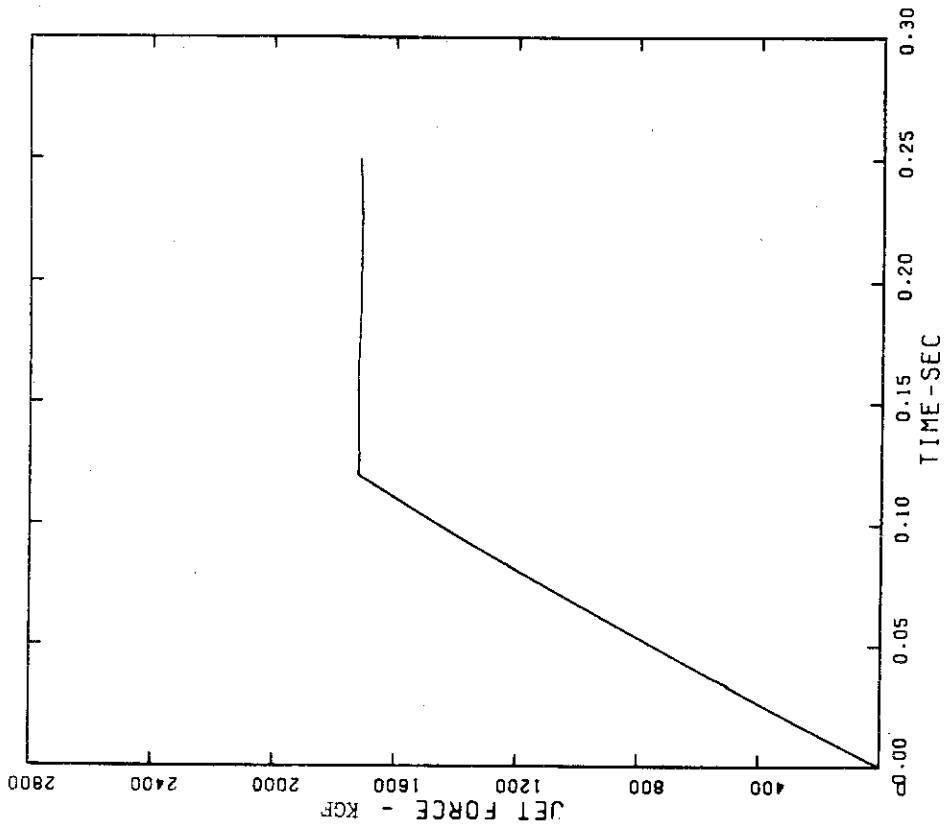


Fig.20-2 Time History of Thrust Force, F_1 , for Model 1 ----- Discharging Coefficient = 0.6.

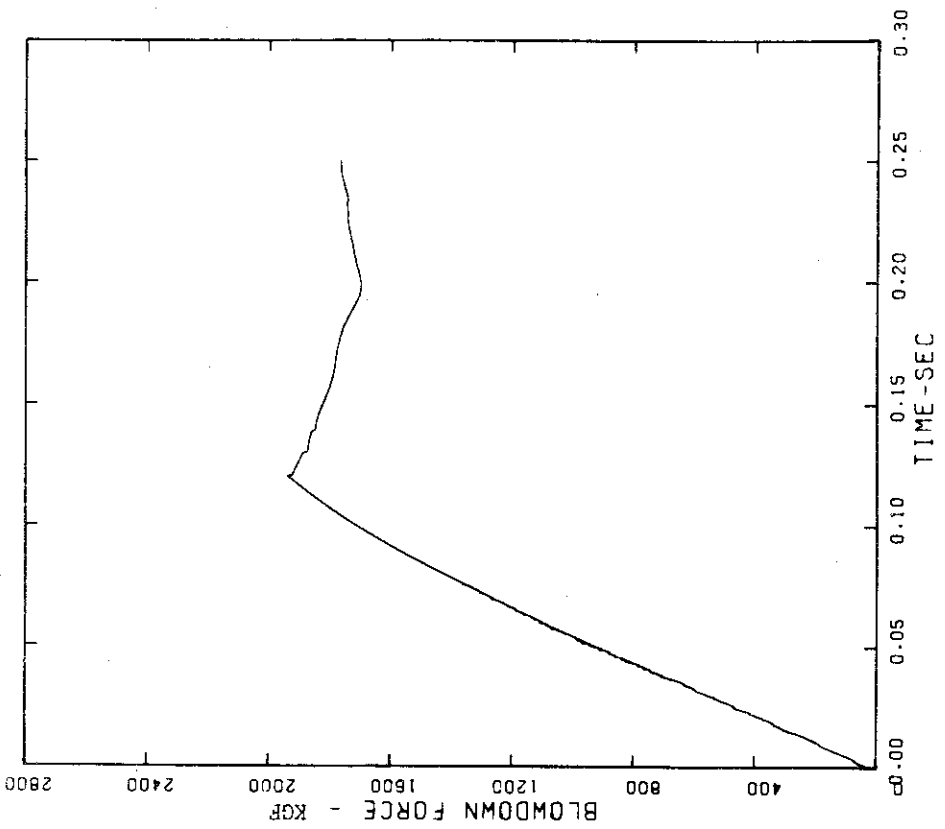


Fig.20-1 Time History of Thrust Force, F_1 , for Model 1 ----- Discharging Coefficient = 0.6.

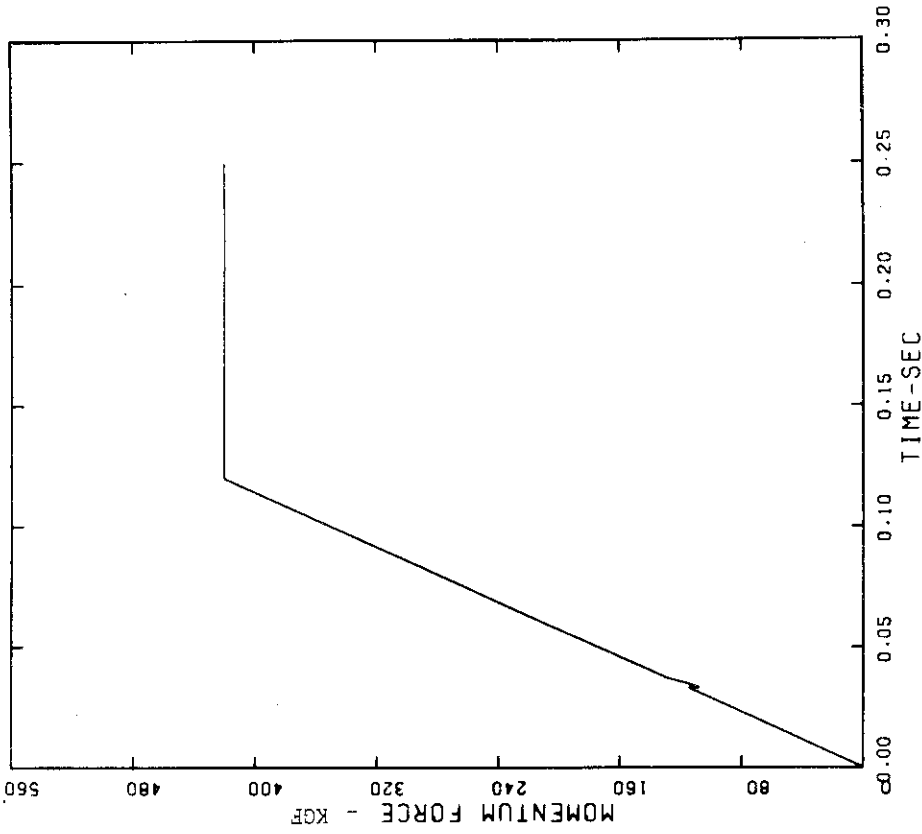


Fig.20-4 Time History of Momentum Force of F₁ for Model 1 ----- Discharging Coefficient = 0.6.

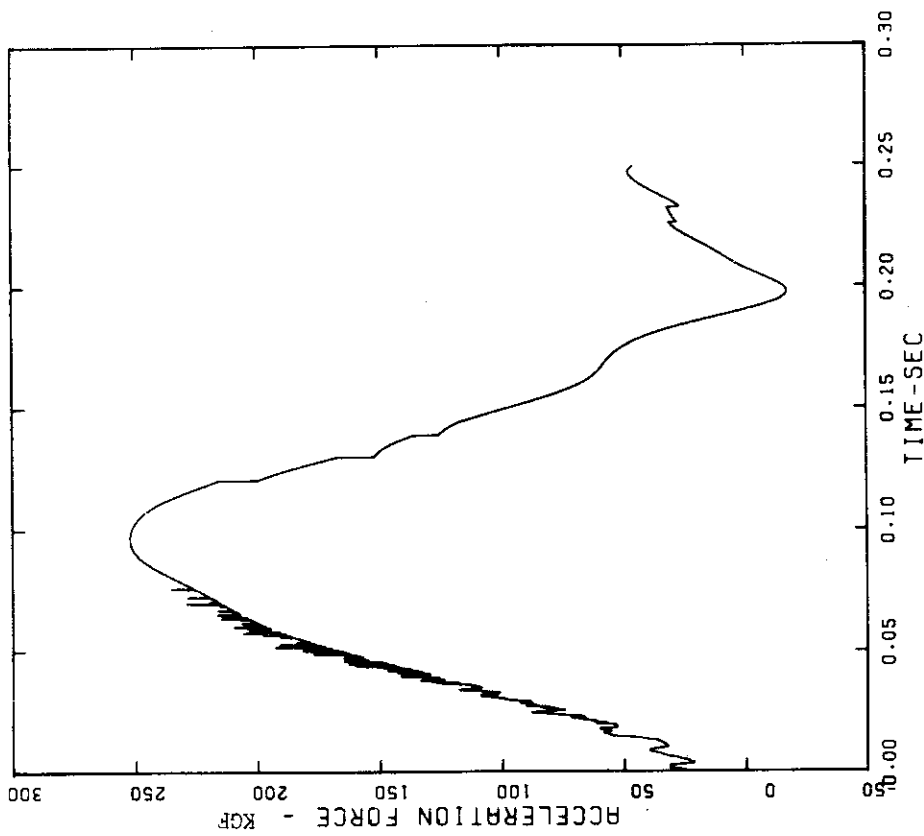


Fig.20-3 Time History of Wave Thrust of F₁ for Model 1 ----- Discharging Coefficient = 0.6.

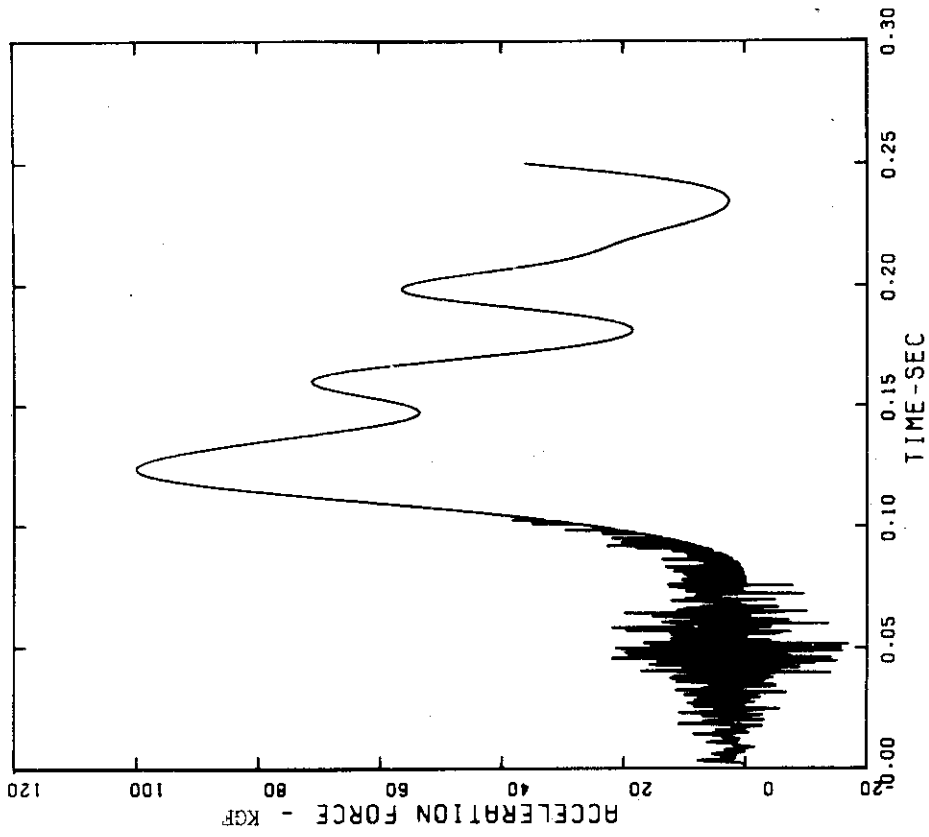


Fig.20-6 Time History of Wave Thrust, F₂, for Model 1 ----- Discharging Coefficient = 0.6.

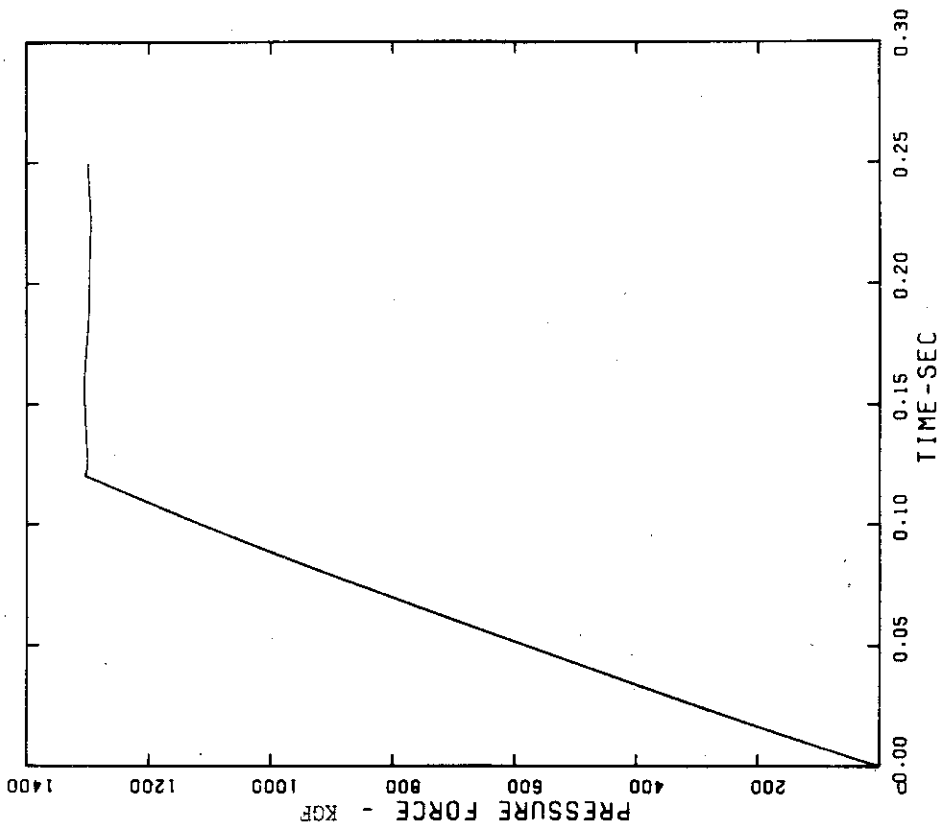


Fig.20-5 Time History of Pressure Force of F₁ for Model 1 ----- Discharging Coefficient = 0.6.

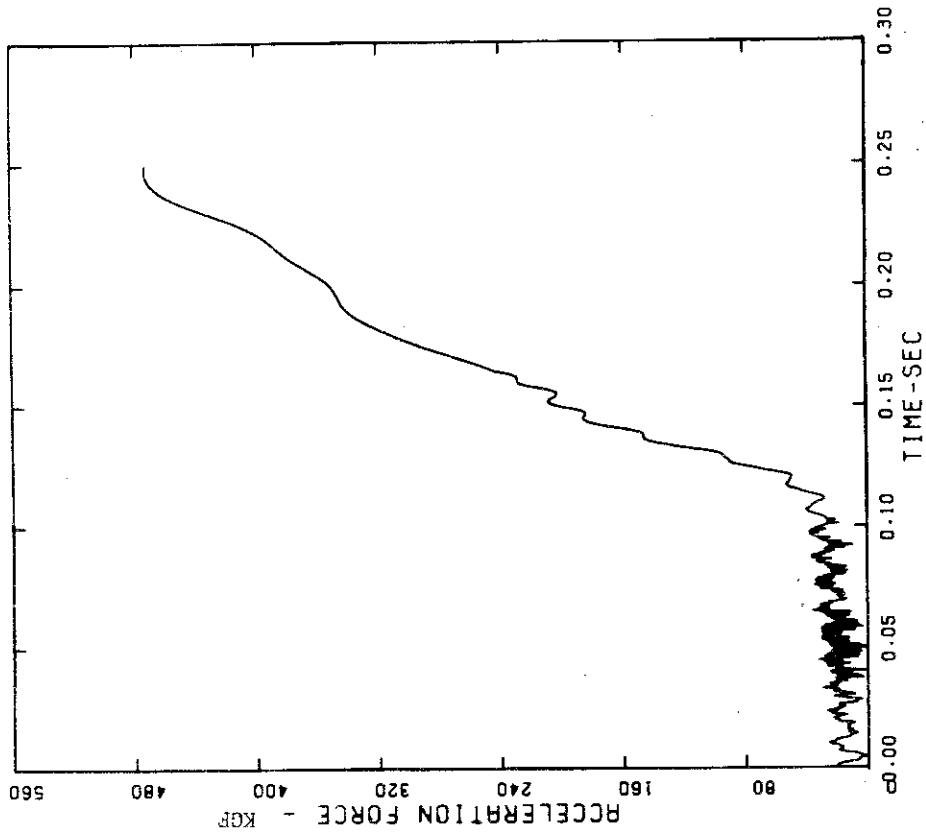


Fig.20-7 Time History of Wave Thrust, F₃, for Model 1 ----- Discharging Coefficient = 0.6.

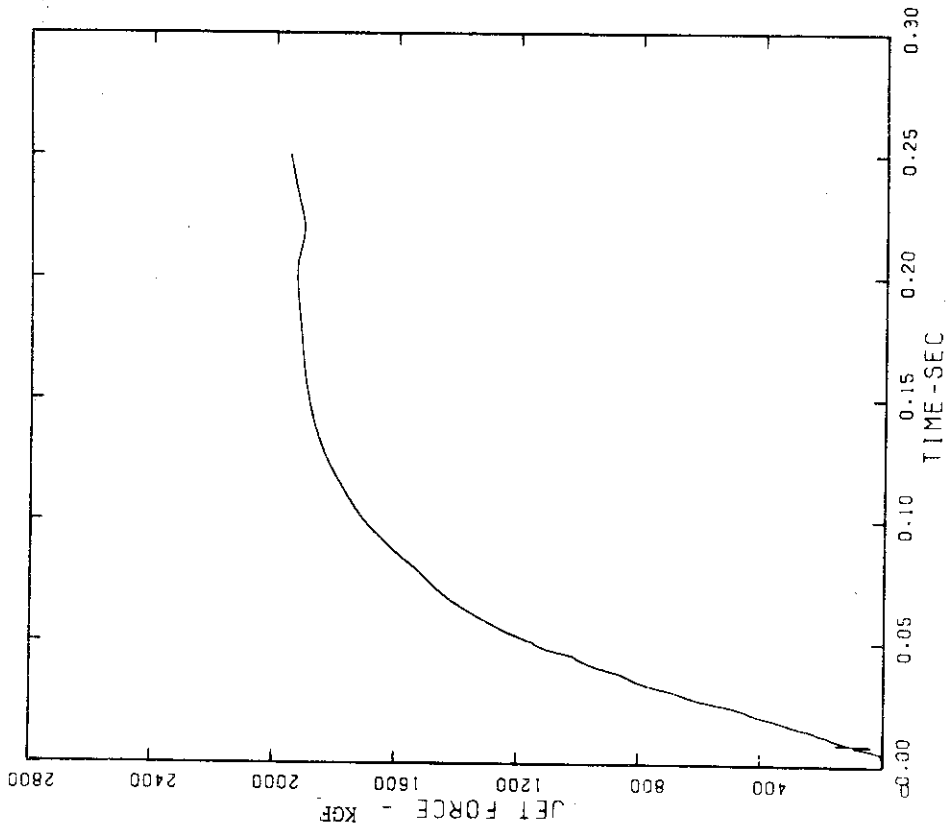


Fig.21-2 Time History of Jet Impingement Force for Model 2-2 --- Discharging Coefficient = 0.8.

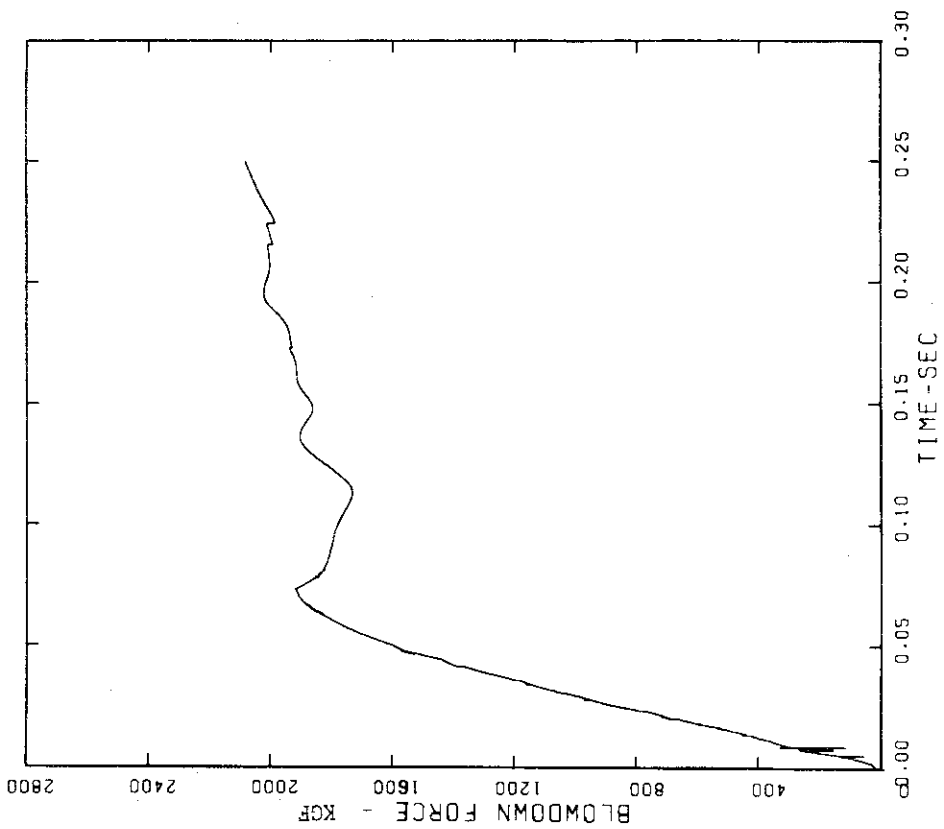


Fig.21-1 Time History of Thrust Force, F_1 , for Model 2-2 --- Discharging Coefficient = 0.8.

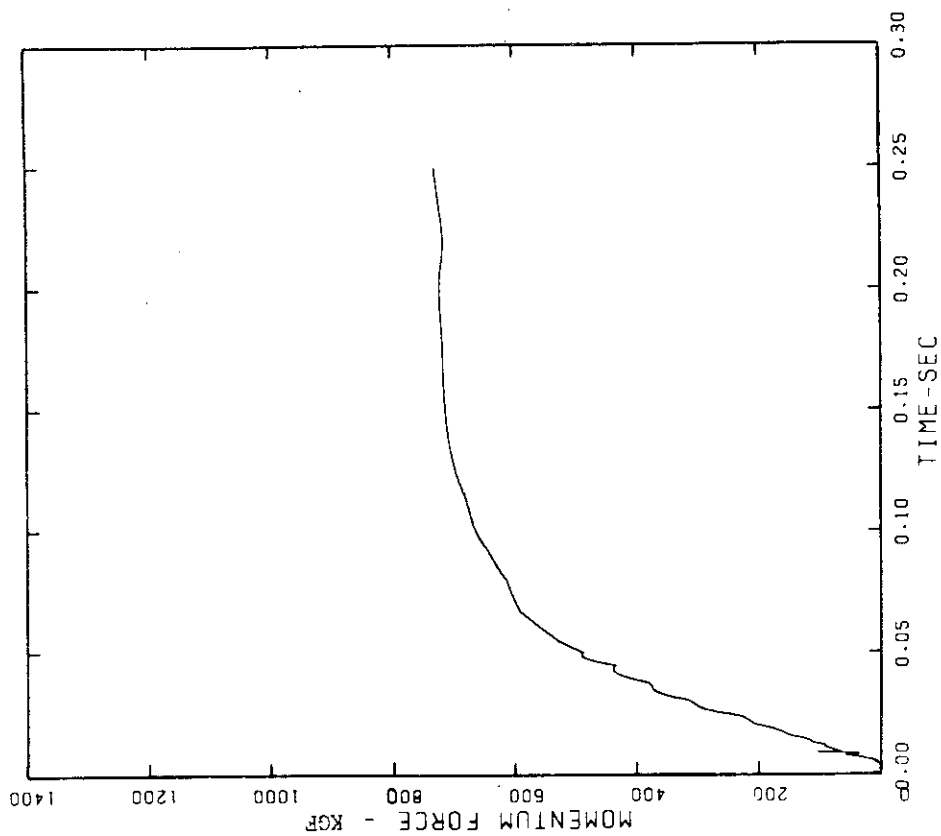


Fig. 21-4 Time History of Momentum Force of F1 for Model 2-2 ---- Discharging Coefficient = 0.8.

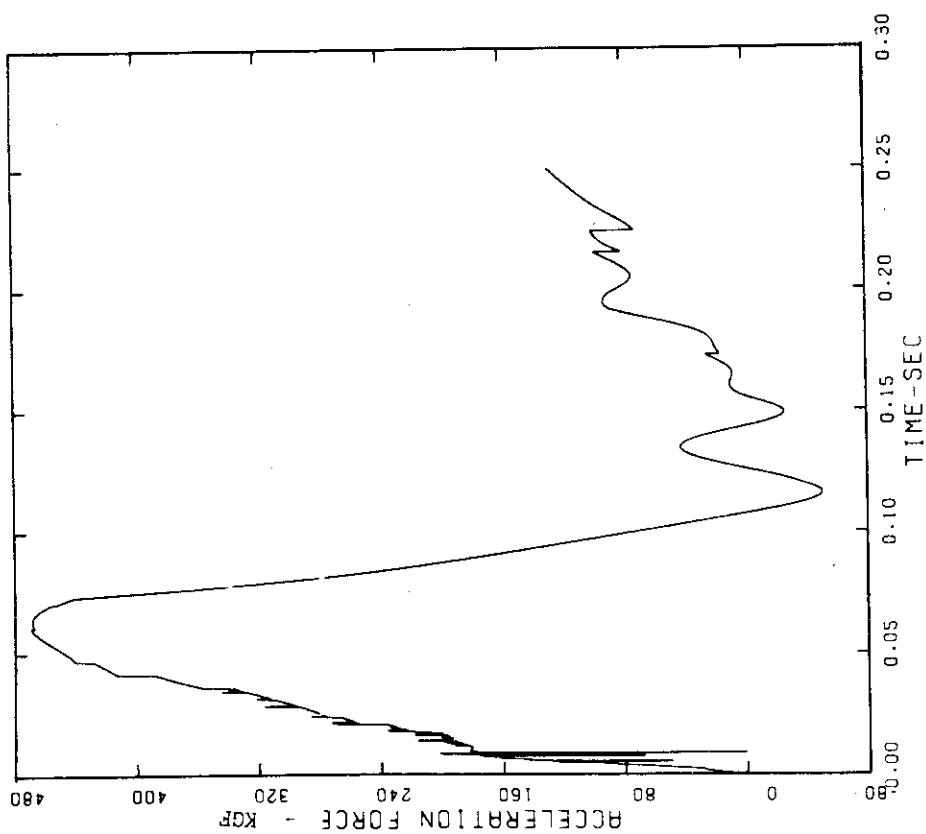


Fig. 21-3 Time History of Wave Thrust of F1 for Model 2-2 ---- Discharging Coefficient = 0.8.

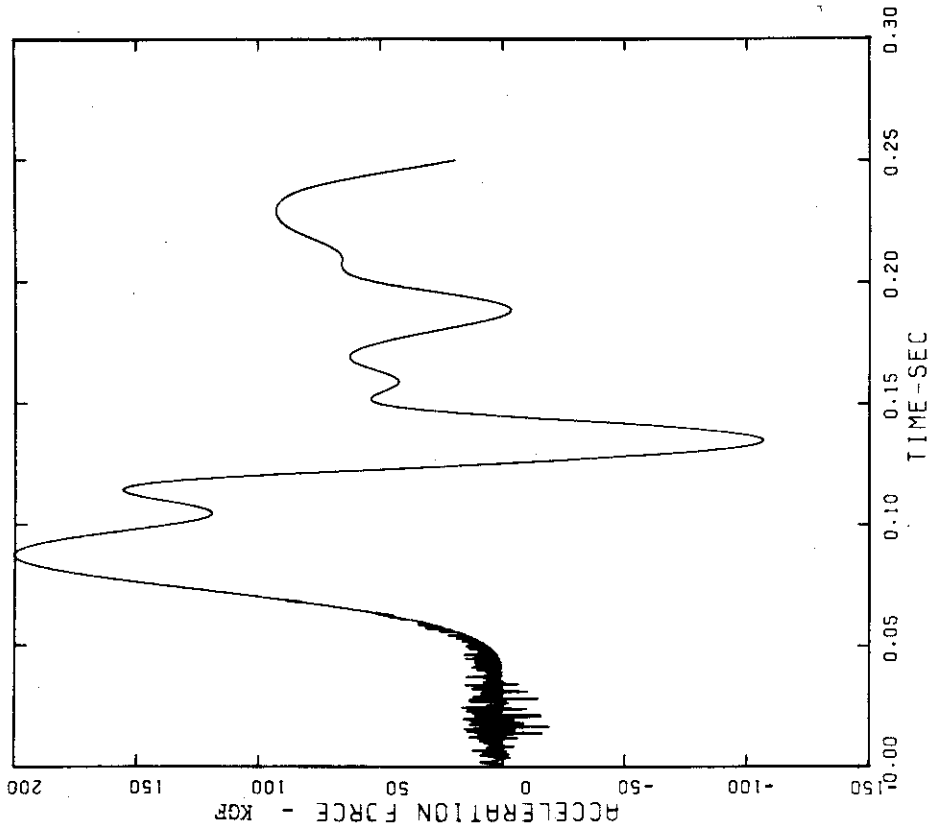


Fig.21-6 Time History of Wave Thrust, F_2 , for Model 2-2 ----- Discharging Coefficient = 0.8.

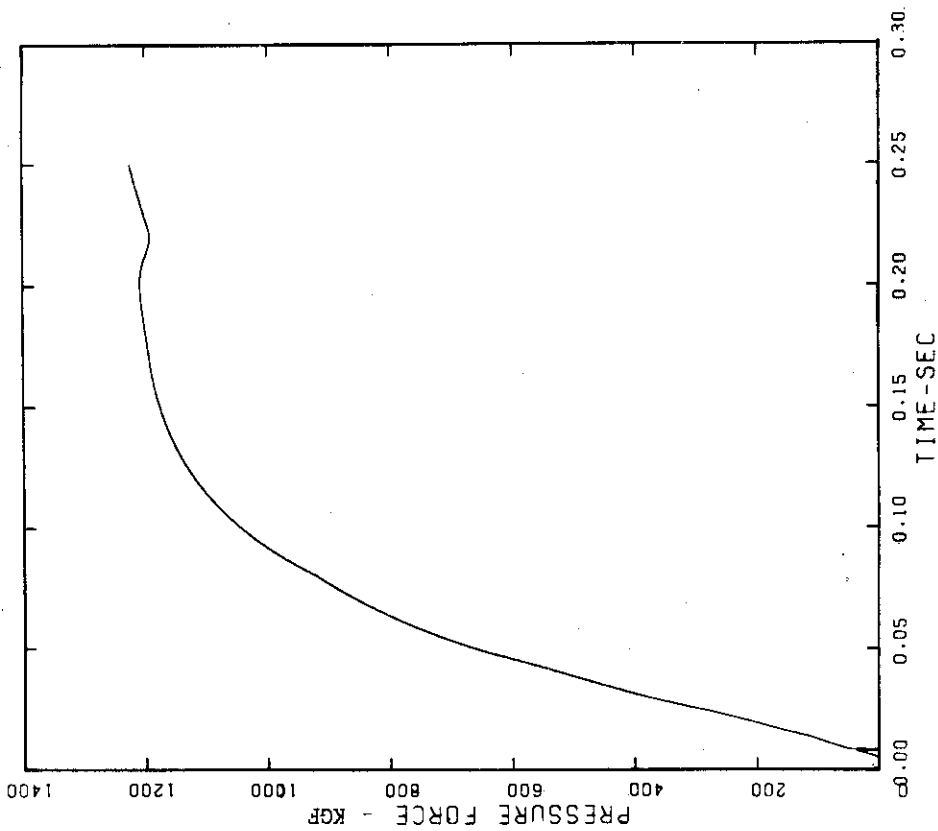


Fig.21-5 Time History of Pressure Force of F_1 for Model 2-2 ----- Discharging Coefficient = 0.8.

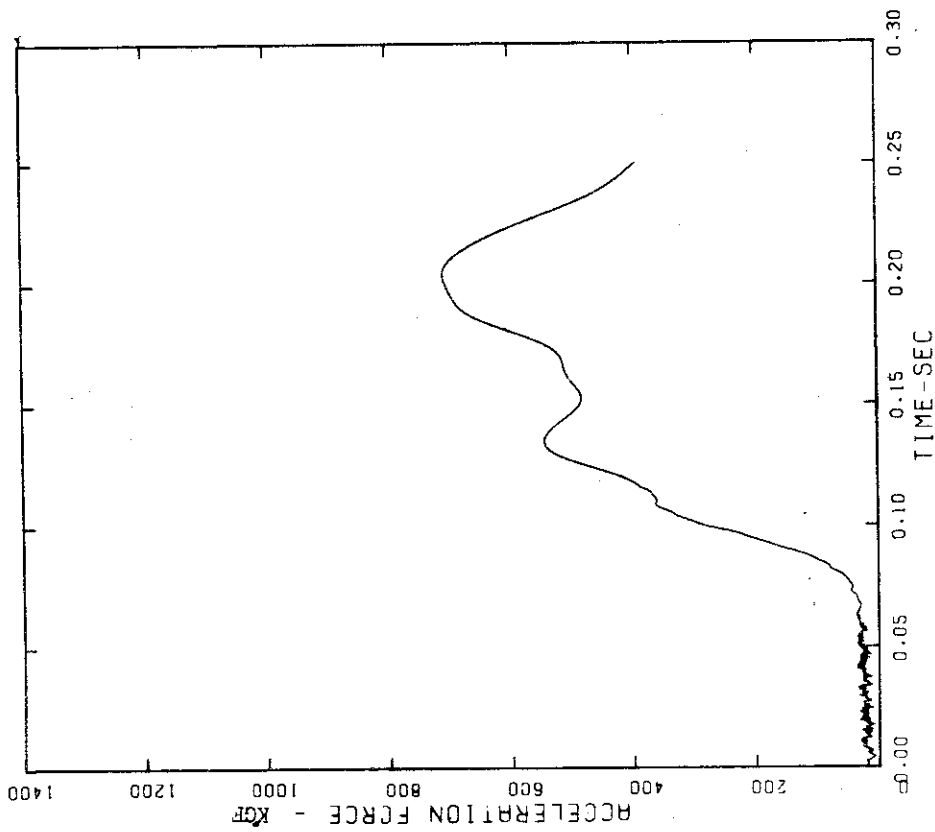


Fig. 21-7 Time History of Wave Thrust, F₃, for Model 2-2 μ --- Discharging Coefficient = 0.8.

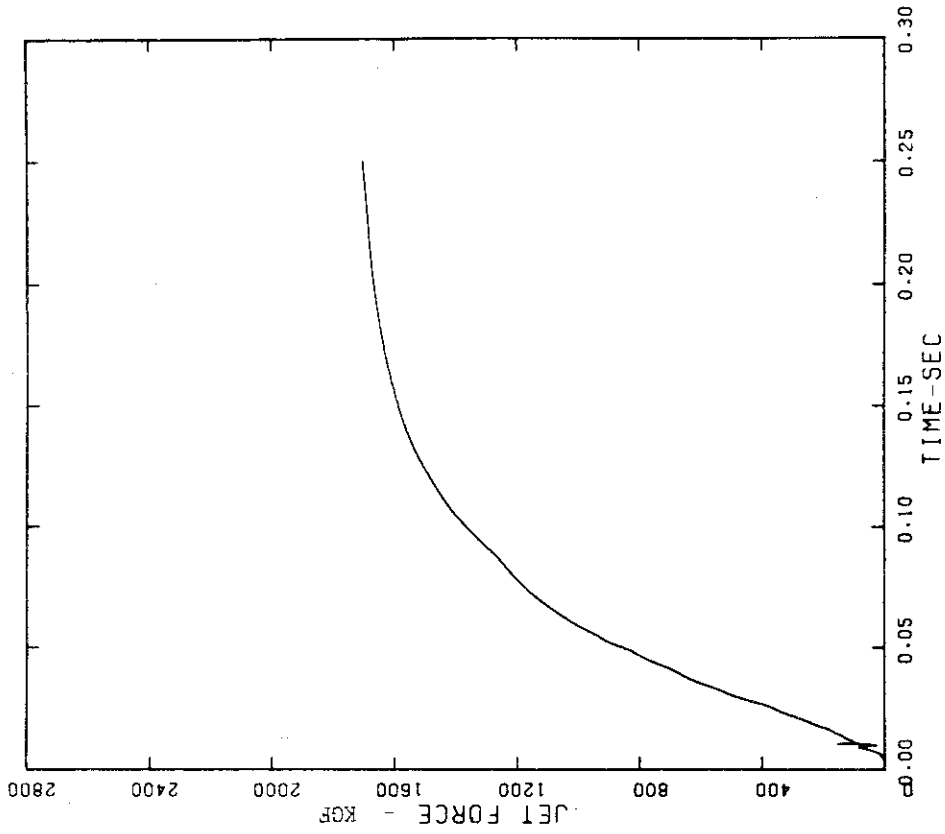


Fig.22-2 Time History of Jet Impingement Force for Model 2-2 ----- Discharging Coefficient = 0.6.

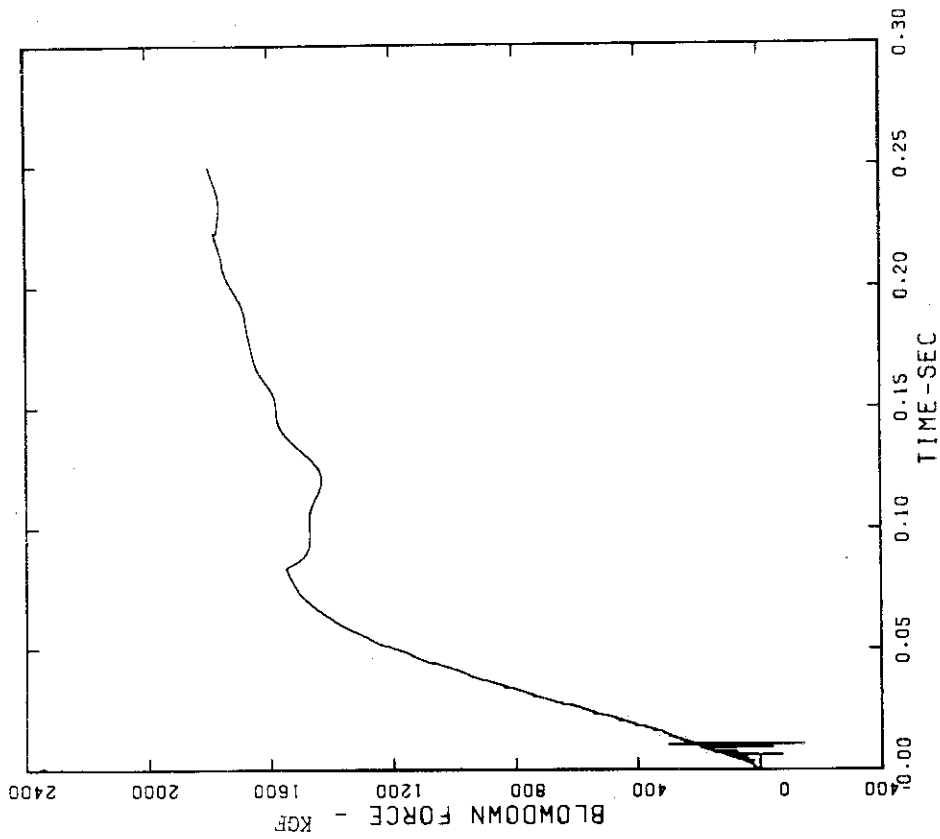


Fig.22-1 Time History of Thrust Force, F_1 , for Model 2-2 ----- Discharging Coefficient = 0.6.

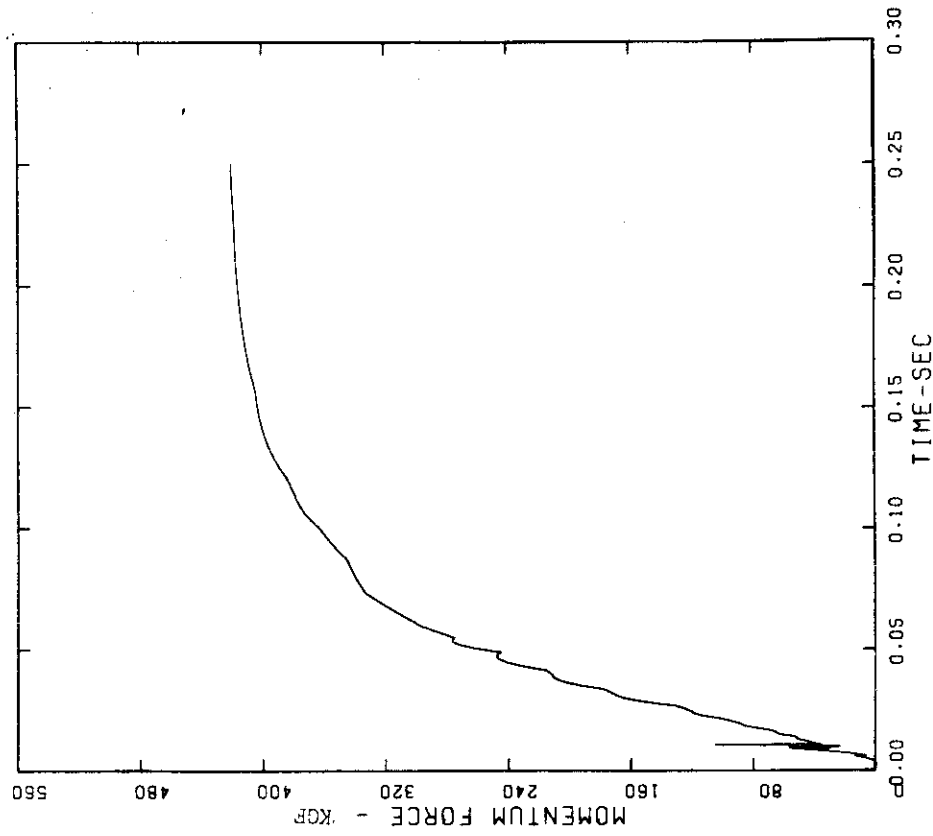


Fig.22-4 Time History of Momentum Force of F1 for Model 2-2 ----- Discharging Coefficient = 0.6.

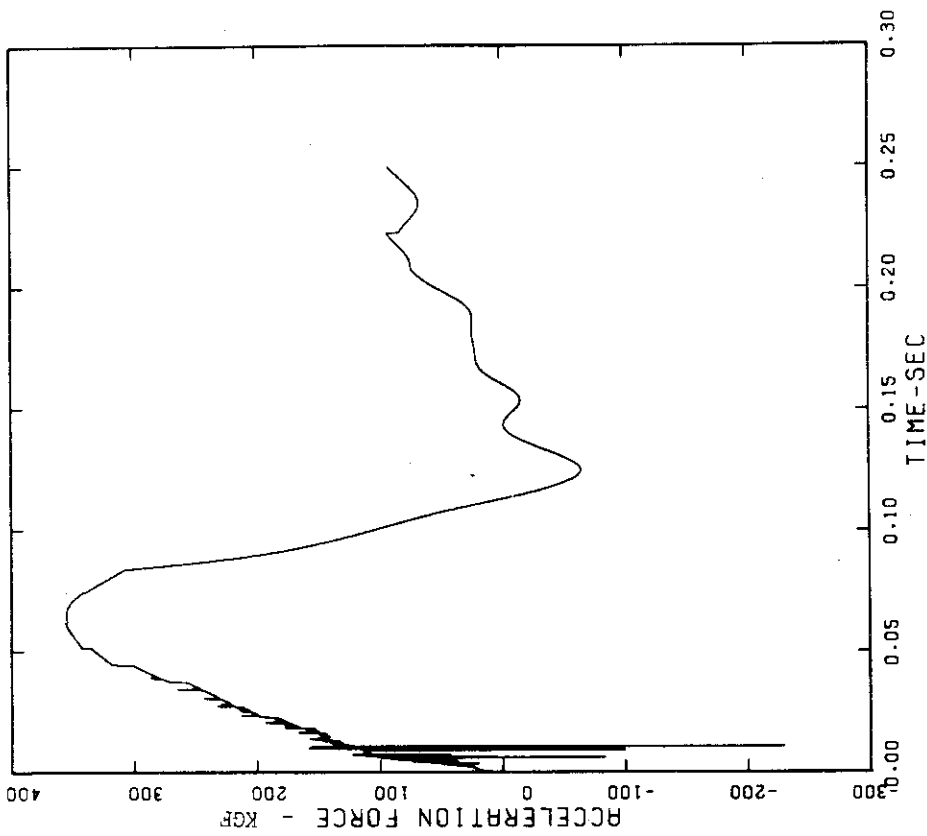


Fig.22-3 Time History of Wave Thrust of F1 for Model 2-2 ----- Discharging Coefficient = 0.6.

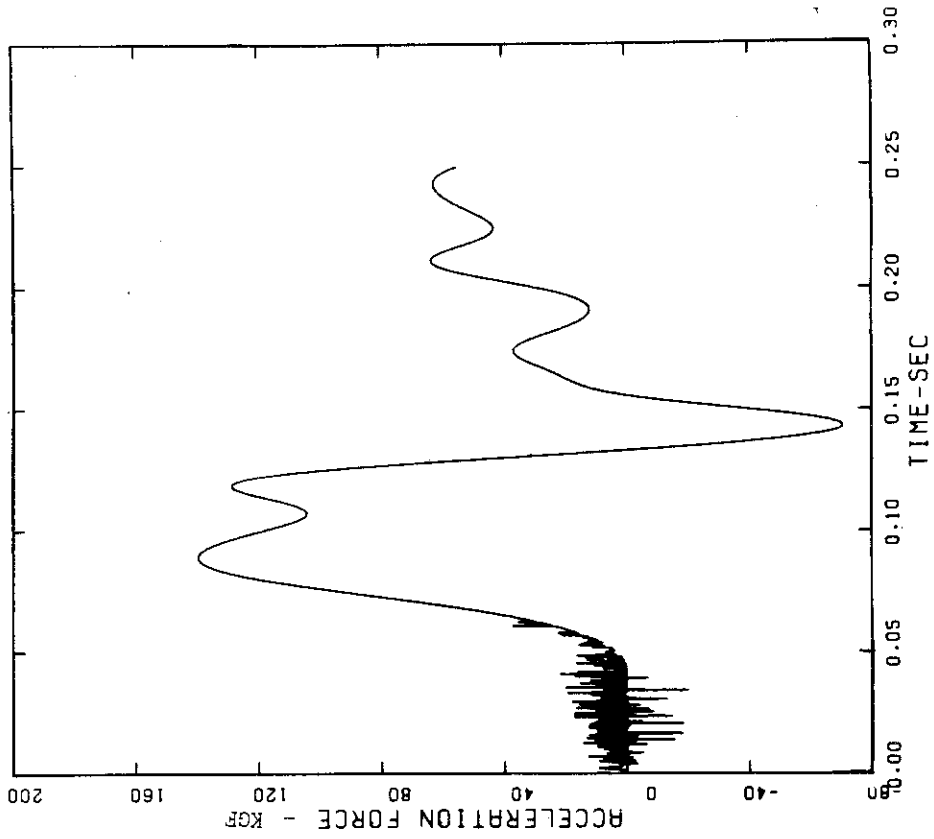


Fig.22-6 Time History of Wave Thrust, F_2 , for Model 2-2 ----- Discharging Coefficient = 0.6.

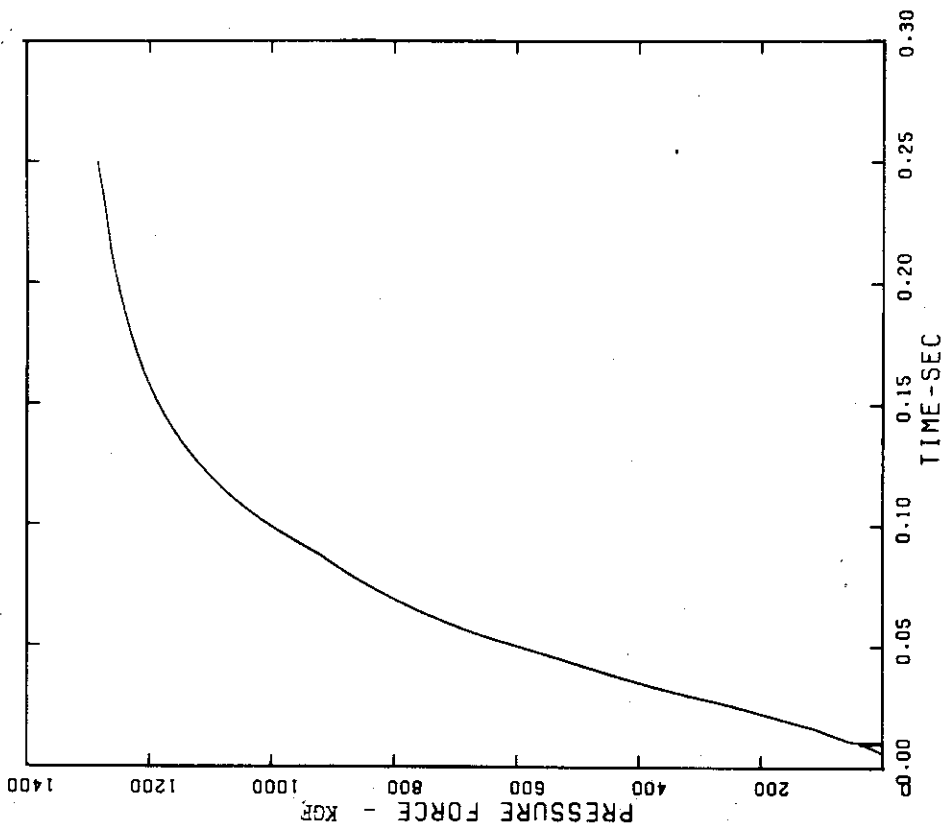


Fig.22-5 Time History of Pressure Force of F_1 for Model 2-2 ----- Discharging Coefficient = 0.6.

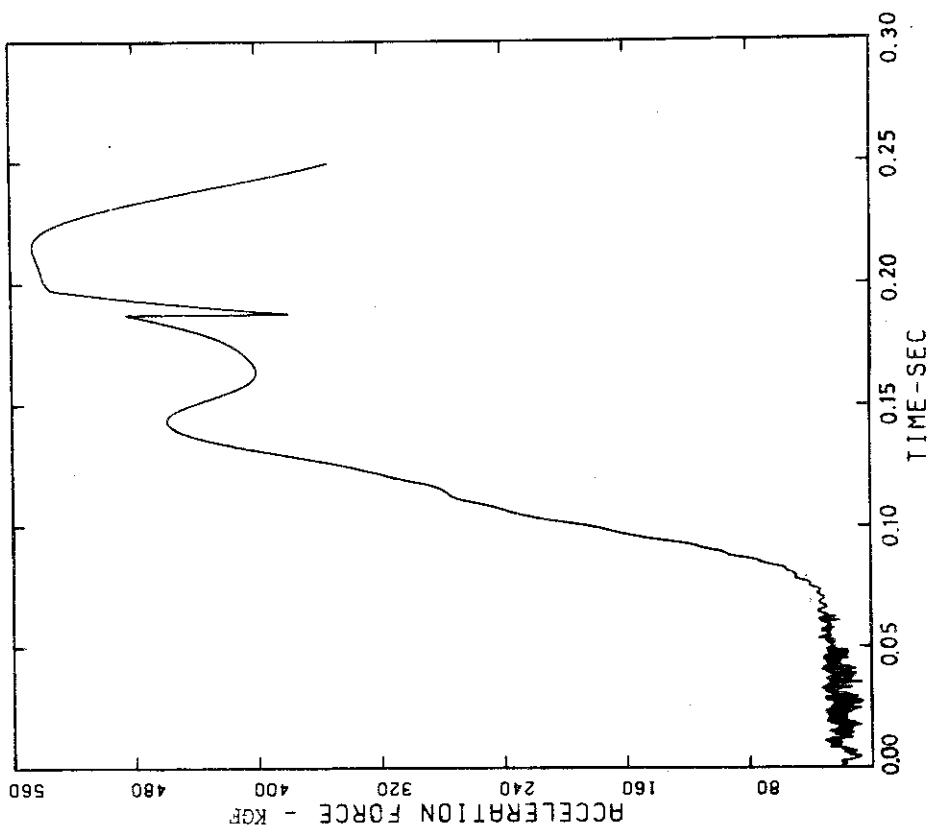


Fig.22-7 Time History of Wave Thrust, F_3 , for Model 2-2 ---- Discharging Coefficient = 0.6.

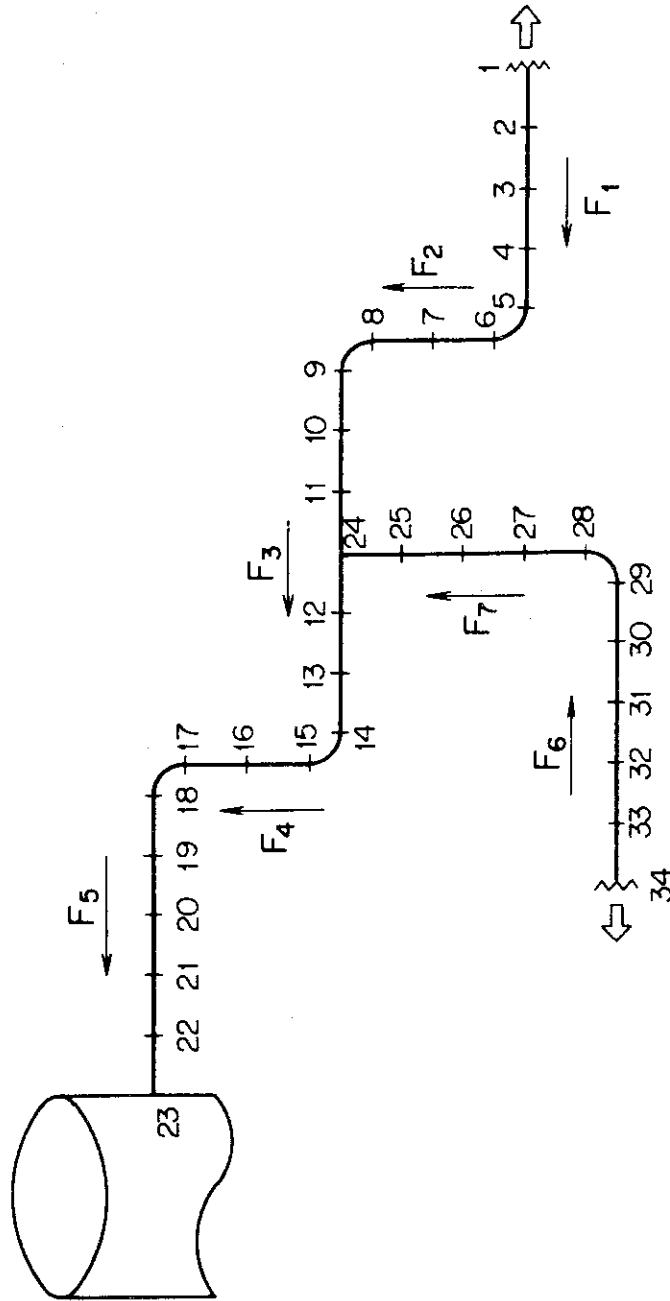


Fig. A-1 Volume Division of Example Problem.