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AN ANALYSIS FOR JET DISCHARGING TESTS WITH STOP VALVE BY PRTHRUST-JI CODE

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An analysis was made by PRTHRUST-J1 code for the jet discharging tests with stop valve performed in the preliminary pipe rupture test. In this analysis, the stop valve which was installed between the first elbow and the discharging end was assumed to open linearly with time. The time required for valve opening was decided from the time variation of pressure in the discharging nozzle. The analysis was performed for the jet discharging tests using the discharging nozzles of 2 in. and 3 in. in diameter by varying the value of discharging coefficient. The analytical blowdown thrust force and pressure in the discharging nozzle were compared with experimental results. Qualitative agreement was found between both of the blowdown thrust forces. It was also found that generally speaking the blowdown thrust forces obtained from the experiments were between the analytical results of discharging coefficient of 1.0 and 0.6. The discharging coefficient which was best coincident with experimental results could not, however, be obtained from this analysis.

Keywords: PRTHRUST-J1 Code, Jet Discharging Tests, Pipe Rupture Test, Stop Volve, Discharging Nozzle, Discharging Coefficient, Blowdown Thrust Force

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*) On leave from Ishikawajima Harima Heavy Industries Co., Ltd.

PRTHRUST－J 1コードによる急速遮断弁を用いたジェット放出試験の解析

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（1981年3月6日受理）

ブローダウンスラスト力解析コードPRTHRUST－J 1を用いて配管破断予備試験として実施した急速遮断弁を用いたジェット放出試験を解析した。解析に際しては，放出口に隣接した第1エルボと放出口の間にある急速遮断弁の開度が時間とともに線形に変化するものと仮定した。この弁が全開するのに要する時間は，放出ノズル部の圧力の時間変化から決定した。2インチおよび3インチ口径のジェット放出について放出係数をパラメータとして解析を実施し，ブローダウンスラスト力および放出ノズル部の圧力を実験結果と比較した。この結果，ブローダウンスラスト力の定性的な傾向は実験結果と解析結果で比較的良く一致していること，および実験から得られたブローダウンスラスト力はおおむね放出係数が0.6から1.0の場合の解析結果に入っていることがわかった。しかし，実験結果を最も良く表わす放出係数値については結論が得られなかった。

本報告書は，電源開発促進対策特別会計施行令に基づき，科学技術庁から日本原子力研究所への委託研究，昭和53年度配管信頼性実証試験のうち，ブローダウンスラスト力解析コードPRTHRUST－J 1による急速遮断弁を用いたジェット放出試験の解析結果についてまとめたものである。

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1. Introduction

The facilities for the pipe rupture tests, FRPC-II,(*) were completed in March, 1978. The first blowdown tests of high pressure and high temperature water were performed as the preliminary tests in October to November, 1978, prior to the main tests, which will be carried out by using the test pipes with larger diameter. The preliminary tests consisted of the jet discharging tests(1) with a pneumatic stop valve and the pipe whip test.(2) The discharging nozzles of 1 in.(1B), 2 in.(2B) and 3 in.(3B) in diameter were used for the jet discharging tests (RUN No.5301 ~ 5316). The blowdown thrust force resulted from discharging jet was measured in these tests.

This report presents the analytical results of these jet discharging tests implemented with the computer code PRTHRUST-J1(3) for calculating the blowdown thrust force. PRTHRUST(**) code which was the original version of PRTHRUST-J1 code was mounted in the JAERI's computer system in order to estimate the blowdown thrust force obtained from the jet discharging tests and the driving force of the pipe whipping. This code could not, however, deal with preliminary jet discharging tests, because this had a few limitations in modelling the analytical system.(***) Therefore, PRTHRUST code was modified into PRTHRUST-J1 code so that it could analyze the preliminary jet discharging tests. Analytical abilities of PRTHRUST-J1 code were examined by comparing its analytical results with the experimental data obtained from a series of jet discharging tests.

(*) FRPC-II = Facilities for Reliability Study of Pressure Boundary Components

(**) PRTHRUST code was developed by Quadrex Corporation in USA.

(***) After submitting the manuscript of this paper, the authors were informed by Quadrex Corporation that the original PRTHRUST version 1.0 code introduced into JAERI has been modified into the PRTHRUST version 1.2.1 code in which most of the limitations were eliminated.

2. Outline of Preliminary Jet Discharging Tests

The preliminary jet discharging tests were performed with the system shown in Fig.1. The pneumatic stop valve was installed between the first elbow(*) and the discharging nozzle in order to control discharging jet with its opening and closing operation. Sixteen cases of jet discharging tests were performed with the discharging nozzles of 1 in., 2 in. and 3 in. in diameter. Table 1 shows the main test conditions of these tests. Fig.2 shows the details of this piping system. The stop valve used in these tests was the Y-pattern globe valve whose stem had the inclination of 50 degrees from flow path.

The blowdown thrust force induced by discharging jet was measured by the load cell (WU111) attached to the first elbow. The pressure in the discharging nozzle by the pressure sensors of PU112, PU113 and PU114 was also measured in addition to the pressures and temperatures in the remainder of this system.

(*) In this report, the elbow adjacent to the discharging end is called "the first elbow".

3. Outline of PRTHRUST-J1 Code

In the preliminary jet discharging tests, three reducers of 4B × 3B, 3B × 2B and 2B × 1B and the stop valve were located between the first elbow and the discharging end as shown in Fig.2. It is impossible that PRTHRUST code makes a model of the above components used in the preliminaly jet discharging tests, because in this code the region between the first elbow and the discharging end must be modeled by only one control volume. Therefore, PRTHRUST code was modified into PRTHRUST-J1 code so that it could analyze the preliminaly jet discharging tests. The main modifications in PRTHRUST-J1 code are as follows:(*)

(1) The region from the first elbow to the discharging end can be divided into suitable number of control volumes.

(2) The blowdown thrust force at the arbitrary elbow in the pipe line can be calculated and obtained in the form of plotter output.

(3) The blowdown thrust force at the first elbow can be obtained in the form of three separate terms of acceleration force, momentum force and pressure force and each term can be obtained in the form of plotter output.

(4) The ramp characteristics of valve operation are included to the control valve so that it can model the stop valve used in the preliminary jet discharging tests.

(5) New options are added to the discharging coefficient and the procedure for calculating the acceleration force.

(*) The authors were informed by Quadrex Corporation that PRTHRUST version 1.2.1 and subsequent versions incorporated the items of modification (1), (2) and (4) described here.

4. Analytical Model

Table 1 shows sixteen cases of the jet discharging tests including 1B, 2B and 3B jet discharging tests. Any useful data could not, however, be obtained in the transient region of 1B jet discharging tests, because the blowdown thrust forces for these cases were relatively small in comparison with the capacity of the load cell WU111. Therefore, the numerical analyses were carried out for 2B and 3B jet discharging tests.

The pipings of 2B and 3B jet discharging tests were divided into twelve and eleven volumes, respectively, as shown in Fig.3. In both cases, the position of stop valve is Junction 9.

As stated before, discharging jet was controlled by the pneumatic stop valve. The valve opening time influences directly the transient blowdown thrust force, so that the ramp characteristics of valve operation were used in these analyses. Namely, the stop valve was assumed to open linearly with time. The valve opening time was decided from the time history of pressure (PU112) in the discharging nozzle as shown in Fig.4(a) through Fig.4(g). For instance, Fig.4(f) shows how to decide the valve opening time in case of RUN No.5314. From this figure, the followings are found in relation to the time history of valve operation. The electrical signal was sent to the stop valve to open it at the time of 0.0 sec. Then, this valve opened slightly at the time of 0.2 sec but it did not open moreover for a little while. At the time of 0.45 sec, it opened rapidly and pressure increased approximately linearly with time to 0.57 sec. Therefore, it was assumed for the analyses by PRTHRUST-J1 code that the stop valve started to open at the time of 0.45 sec, opened linearly with time and was completely open at the time of 0.57 sec. For other jet discharging tests, the valve opening time was determined in the same way described above. These times are written in Fig.4(a) through Fig.4(g). On the other hand, the flow area versus time at the break junction which is Junction 12 for 2B discharge and Junction 11 for 3B discharge was assumed to open instantaneously at the time of 0.0 sec.

The pressure and temperature measured by the detectors prior to discharging jet may be used for the initial conditions of the control volumes between the pressure vessel and the stop valve. On the other hand, it is reasonable to assume the two-phase state with certain quality as the initial state of the control volumes between the stop valve and the discharging end, because this valve was partially open prior to rapid opening. However, it is difficult to know accurately this two-phase state. According to the analyses presented in Ref.(3), the transient blowdown thrust force is not strongly dependent on the initial state in the control volumes between the stop valve and the discharging end, after the fluid filled in these control volumes is completely discharged. Therefore, it was assumed in these analyses that the control volumes between the stop valve and the discharging end were filled up with the saturated steam of 100 °C.

There are some pressure drop due to the friction of pipe wall, valve and other fittings. In PRTHRUST-J1 code, the pressure drop in a control volume is calculated by the following equation

$$\Delta P = \frac{K W^2}{\rho} \tag{1}$$

where

ΔP = Pressure drop, ($\ell b\,f\,/\,in^2$) [kg/cm^2]
ρ = Fluid density, ($\ell b\,m\,/\,in^3$) [kg/m^3]
W = Mass flow rate, ($\ell b\,m\,/\,sec$) [kg/sec]
K = Friction coefficient, ($\ell b\,m\,/\,sec$) [kg/sec]

The friction coefficient K is calculated from the following Darcy-Weisbach equation

$$K = \frac{f_D\,(\frac{L}{D})}{(2g_c)(C)(\frac{\pi}{4}D^2)^2} \tag{2}$$

in which

f_D = Darcy friction factor, dimensionless
L = Equivalent pipe length, (ft)[m]
D = Pipe diameter, (ft)[m]
g_c = ($32.5\ ft/sec^2$)[$9.81\ m/sec^2$]
C = 144 (British units)
= 10,000 [Metric units]

The friction coefficient K calculated from eq.(2) must be input into PRTHRUST-J1 code. Crane's handbook(4) was used to determine the equivalent length of the stop valve and various fittings. Supposing that the flow in the piping is complete turbulent flow and the piping is composed of drawn tubings, the Darcy friction factor may be estimated to be 0.0085 from Fig.5. According to the Crane's handbook, the ratios L/D are estimated to be 13 for the long radius elbow and 145 for the stop valve, respectively. Then, the Darcy friction factor K of the elbow and the stop valve can be calculated from eq.(2) by using the above values of f_D and L/D. The friction coefficient of each reducers was calculated as sudden contractions.

5. Analytical Results and Discussion

The numerical analyses were performed for RUN No.5306, 5307, 5311, 5312, 5313, 5314 and 5315 in which the useful blowdown thrust forces were measured. In these analyses, the discharging coefficient C_D was taken as equal to 1.0, 0.8 and 0.6 in order to find out the most appropriate value of C_D representing the experimental data. The analytical results obtained from PRTHRUST-J1 code were compared with the experimental data of pressure (PU112 and PU113) in the discharging nozzle, pressure (PU111) in the 4B pipe and blowdown thrust force (WU111). The above measuring locations are shown in Fig.1.

For the 2B jet discharging tests, Fig.6(a) through Fig.6(d) show the comparison between the average pressure of Volume 12 in Fig.3(a) obtained from PRTHRUST-J1 code and the experimental data of PU113 attached to the 2B pipe. For the same tests, Fig.7(a) through Fig.7(d) show the comparison between the average pressure of Volume 11 in Fig.3(b) obtained from PRTHRUST-J1 code and the experimental data of PU111 attached to the 3B pipe. For the 3B jet discharging tests, the same comparison as shown in Fig.7(a) through Fig.7(d) is given in Fig.8(a) through Fig.8(c). The analytical results for C_D of 1.0 and 0.6 are shown in these figures. These figures show that the differences between the analytical results of C_D of 1.0 and 0.6 are rather small. Therefore, from the transient pressure change within less than one second, it seems to be difficult to choose the most appropriate value of C_D representing experimental data, even if the analytical results of pressures at the discharging nozzle are in good agreement with the experimental ones by assuming the characteristics of valve operation correctly. Comparing the analytical results with the experimental ones, both are comparatively in good agreement for RUN No.5311 5312 and 5313, but for other cases the analytical results are greater than the experimental ones. This may be due to the reason that the characteristics of valve operation are not appropriately assumed. Namely, the valve opening time may be assumed to be short. Furthermore, the valve may open nonlinearly with time. Considering that the stem of the stop valve moves gradually from halt state, it may be more appropriate for this valve to assume to open nonlinearly than linearly with time.

Fig.9(a) through Fig.9(c) show the comparison between the average pressure of Volume 8 obtained from PRTHRUST-J1 code and the experimental data of PU111 attached to the 4B pipe. The experimental data show the steep pressure drop resulting from the propagation of decompression wave generated by opening the stop valve. The qualitative agreement is found between the analytical and experimental results in the pressure change of PU111.

In Fig.10(a) through Fig.10(g), the analytical results of blowdown thrust force are compared with experimental ones presented by the broken lines which are drawn by linking the experimental peak values of blowdown thrust force. Analytical results are given for the discharging coefficients of 1.0, 0.8 and 0.6. For all cases, the first peak is found between 0.05 sec and 0.15 sec because of acceleration force. It is also found that the larger the discharging coefficient is, the larger the blowdown thrust force is. This is due to the reason that as shown in Fig.12(b) the momentum force in the blowdown thrust force increases with discharging coefficient. It can be concluded from these figures that qualitative agreement is found between the analytical and experimental results and that the experimental results lie between the discharging coefficient of 1.0 and 0.6. However, the discharging coefficient which is best coincident with experimental results can not be obtained from these figures.

In Fig.11(a) through Fig.11(c), the blowdown thurst forces calculated for RUN No.5312 are separated into the three terms, i.e. acceleration force, momentum force and pressure force. It is found from these figures that the oscillation of blowdown thrust force is caused by the acceleration force. It is also found that the momentum force and the ratio of momentum force to blowdown thrust force decrease with increasing discharging coefficient.

Fig.12(a) through Fig.12(c) show the variations of acceleration, momentum and pressure terms of blowdown thrust force calculated for the three discharging coefficients of RUN No.5312. For all discharging coefficients, the acceleration force in Fig.12(a) have the positive peaks around 0.05 sec and 0.1 sec and the negative peak around 0.15 sec. The acceleration force is dependent on mass flow rate. Therefore, this force has a positive value when the mass flow increases with time, while it has negative one when the mass flow decreases with time. This is made clear from Fig.13 which shows the time history of mass flow rate at each junction for $C_D = 1.0$ of RUN No.5312. It is found from Figs.12(a) and 13 that the positive and negative values of acceleration force in Fig.12(a) are respectively corresponding to the increase and decrease of the mass flow rate shown in Fig.13. It seems that the change of mass flow rate is resulted from the propagation of decompression wave generated by the opening stop valve. The momentum forces shown in Fig.12(a) show the large difference among the discharging coefficients. This is because discharging rate of momentum becomes small by multiplying the critical mass flow rate by discharging coefficient. On the other hand, the discharging coefficient has little effect on the pressure force. This is expected from the reason that the pressure in the break volume is relatively insensitive to the discharging coefficient as shown in Fig.6(a) through Fig.6(d) and Fig.8(a) through Fig.8(c).

6. Concluding Remarks

An analysis was made by PRTHRUST-J1 code for the jet discharging tests with a stop valve performed in the preliminary pipe rupture test. The following conclusions are obtained by comparing analytical results with experimental ones.

(1) Analytical and experimental results of the pressure in the discharging nozzle are in good agreement for RUN No.5311, 5314 and 5314, while for the other cases the former is larger than the latter. This is because the assumption of valve operation is still imperfect.

(2) The steep decrease of pressure in the upper stream of the stop valve caused by the propagation of decompression wave is also obtained from the analysis.

(3) Qualitative agreement is found between the analytical and experimental results of blowdown thrust force. It is also found that, generally speaking, the blowdown thrust forces obtained from experiment lie between the results of discharging coefficient of 1.0 and 0.6.

(4) The discharging coefficient which is best coincident with experimental results can not, however, be obtained from this analysis.

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The authors wish to make their grateful acknowledgement to Dr. M. Nozawa, Head of Division of Reactor Safety in JAERI for his support through this work. Thanks are given to Dr. S. Miyazono, Chief of the Mechanical Strength and Structure Laboratory in JAERI for his valuable advices.

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(3) Miyazaki, N., Kogo, J., "PRTHRUST and PRTHRUST-J1 — Computer Codes for Calculating Blowdown Thrust Force", JAERI-M 9137, (1980).

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(4) Crane, "Flow of Fluids through Valves, Fittings, and Pipe", Technical Paper No.410, (1969).

Table 1 Test Conditions for Jet Discharging Test

TEST ITEM	RUN NO.	TEST MODE	BREAK LOCATION	BREAK DIA. (mm)	PRESSURE IN PRESSURE VESSEL (kg/cm^2g)	TEMPERATURE IN PRESSURE VESSEL (°C)	WATER LEVEL BEFORE DISCHARGE (m)	WATER LEVEL AFTER DISCHARGE (m)	DURATION OF DISCHARGE (sec)	NOTE
Jet Test	5301	BWR	Lower Nozzle	21.2 (1B,Sch 160)	20	214	4.8	3.85	128	RUN NO. 5305: Water in Pressure Vessel was fully discharged. Stop valve was not fully opened.
	5302				20	214	4.8	2.90	290	
	5303				40	251	4.8	2.90	190	
	5304				70	286	4.8	2.90	136	
	5305				99	310	4.8			
	5306	BWR	Lower Nozzle	43.1 (2B,Sch 160)	22	219	4.8	2.86	65	RUN NO. 5308, 5309: Stop valve was not fully opened.
	5307				44	257	4.8	2.83	45	
	5308				70	286	4.8	4.69	31	
	5309				70	286	4.8	4.70	27	RUN NO. 5312: Water in Pressure Vessel was fully discharged.
	5311				70	286	4.8	4.19	10	
	5312				99	310	4.8			
	5313	BWR	Lower Nozzle	66.9 (3B,Sch160)	20	214	4.8	3.57	18	RUN NO. 5316: Water in Pressure Vessel was fully discharged. Stop valve was not fully opened.
	5314				64	280	4.8	2.93	16	
	5315				99	310	4.8	3.19	10	
	5316				110	317	4.8			

Pressure, temperature and water level in pressure vessel before and after discharge are measured by process instruments.

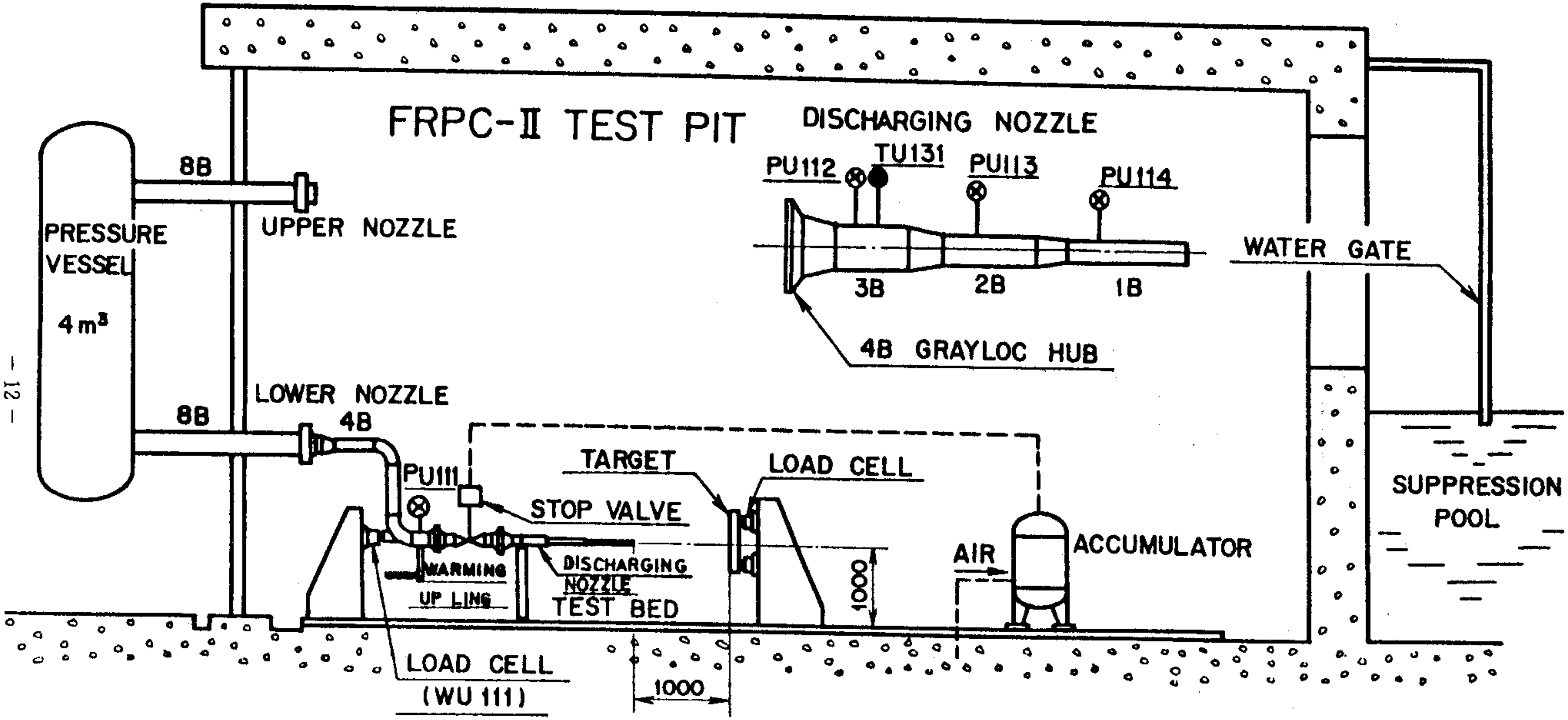


Fig.1 Schematic Diagram of Jet Discharging Test

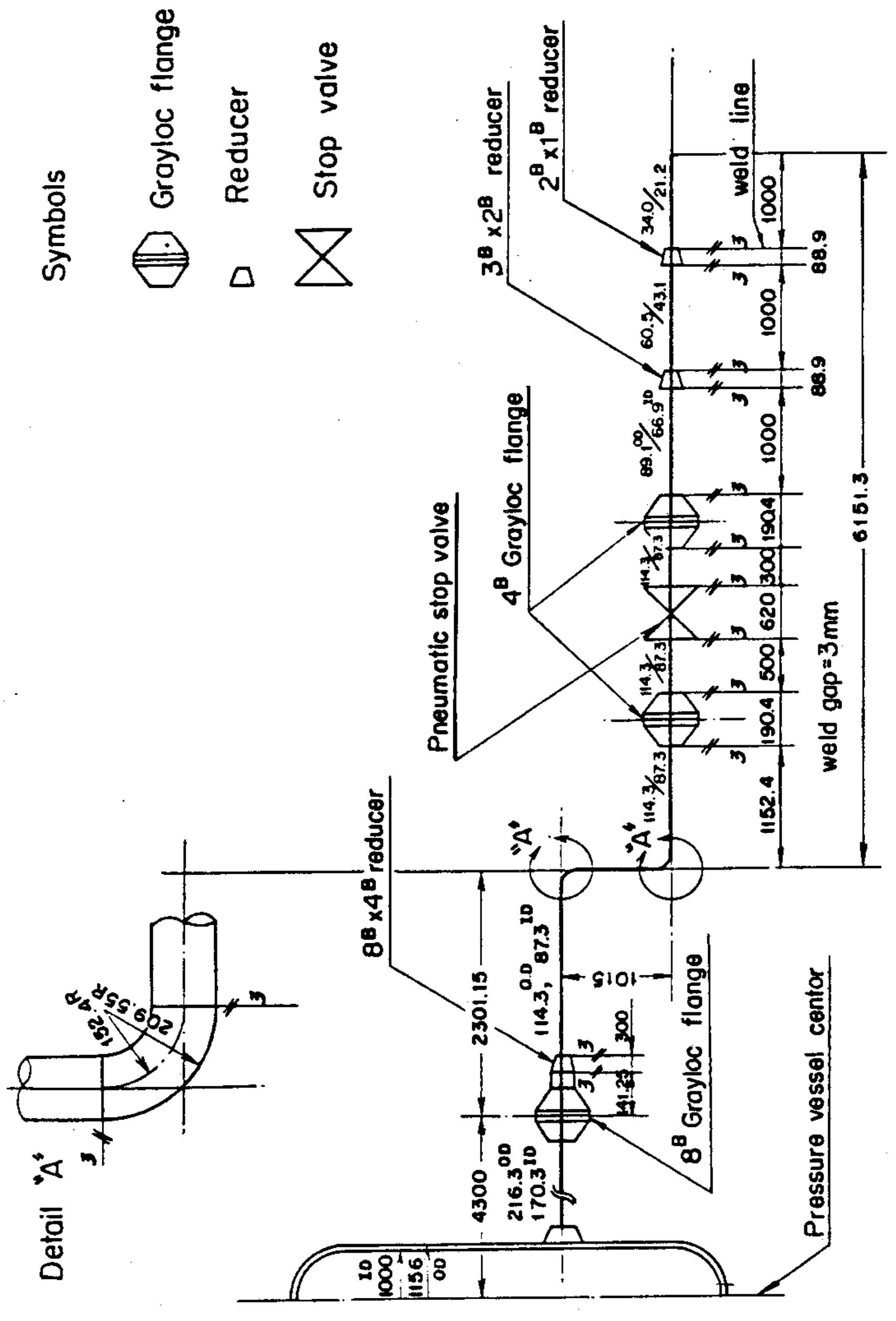
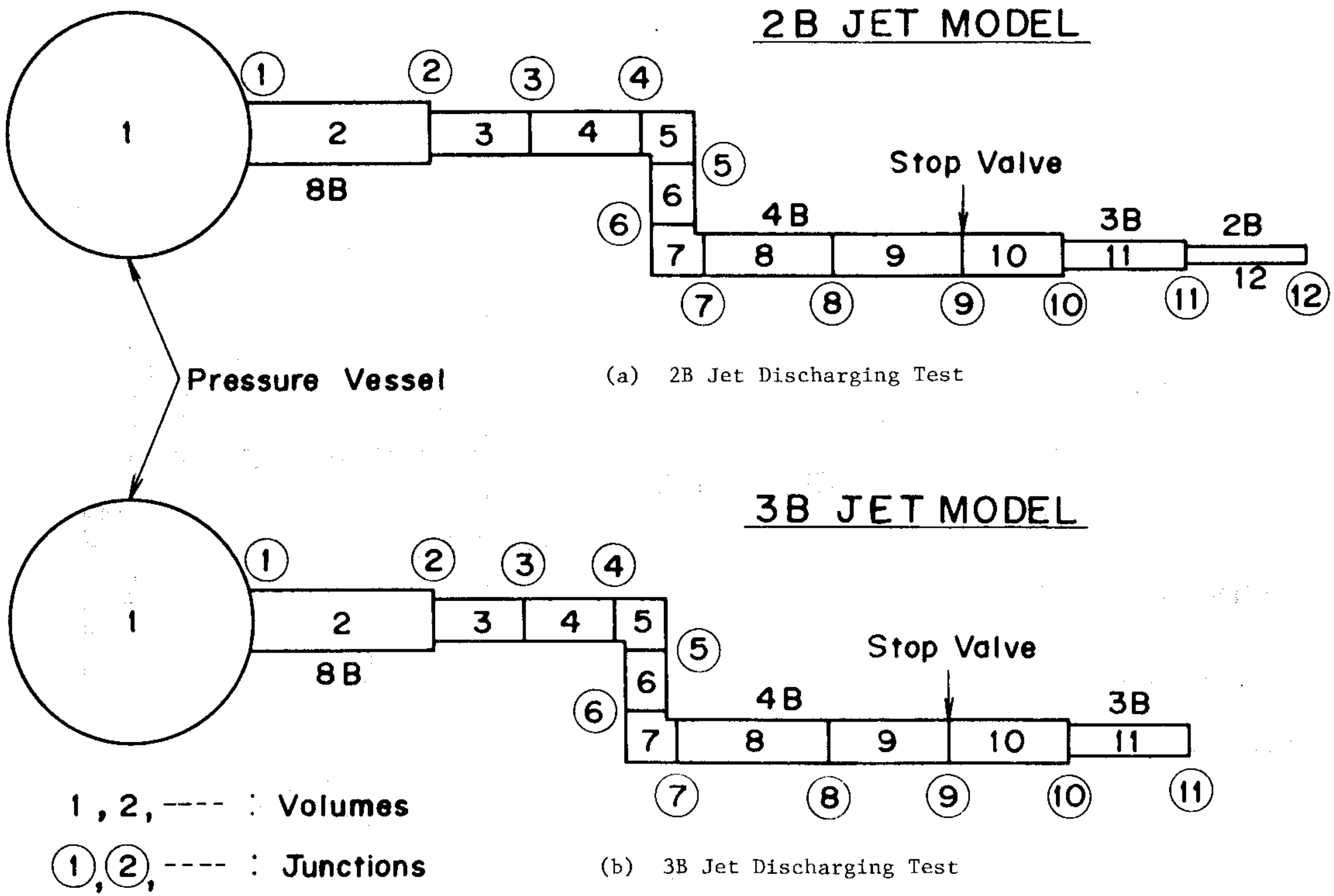


Fig.2 Pipe Line Layout of Jet Discharging Test



(a) 2B Jet Discharging Test

(b) 3B Jet Discharging Test

Fig.3 Volume Division of Pipe Line.

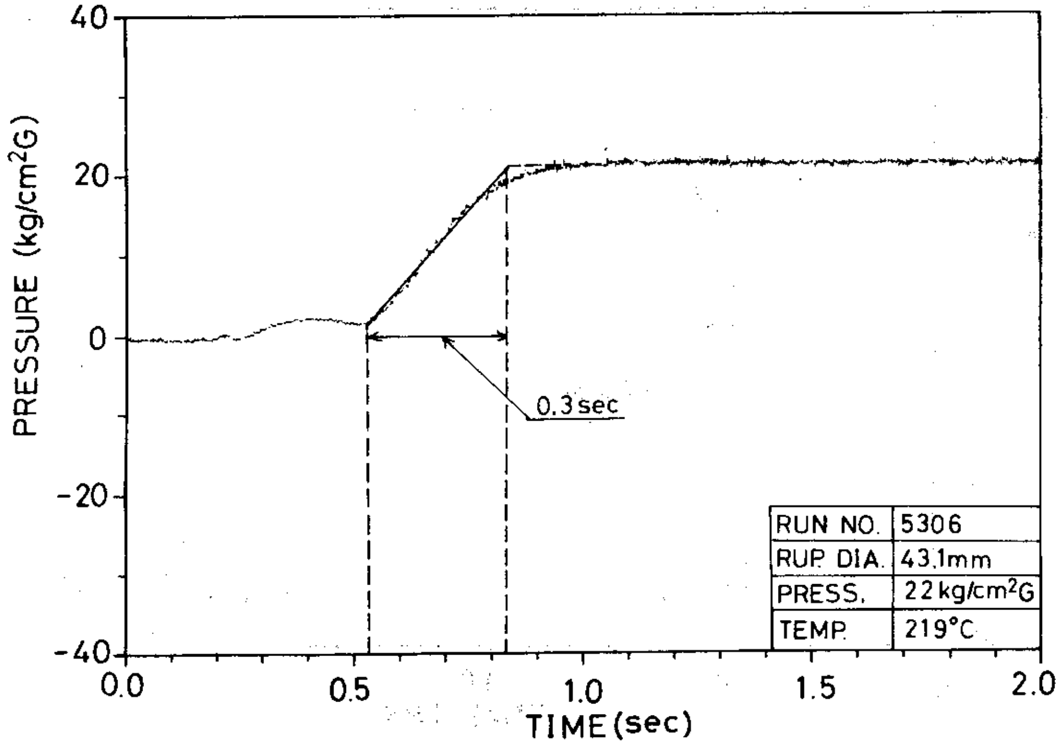


Fig.4(a) Variation of Pressure in Discharging Nozzle (PU113) for RUN NO.5306 and its Approximated Line.

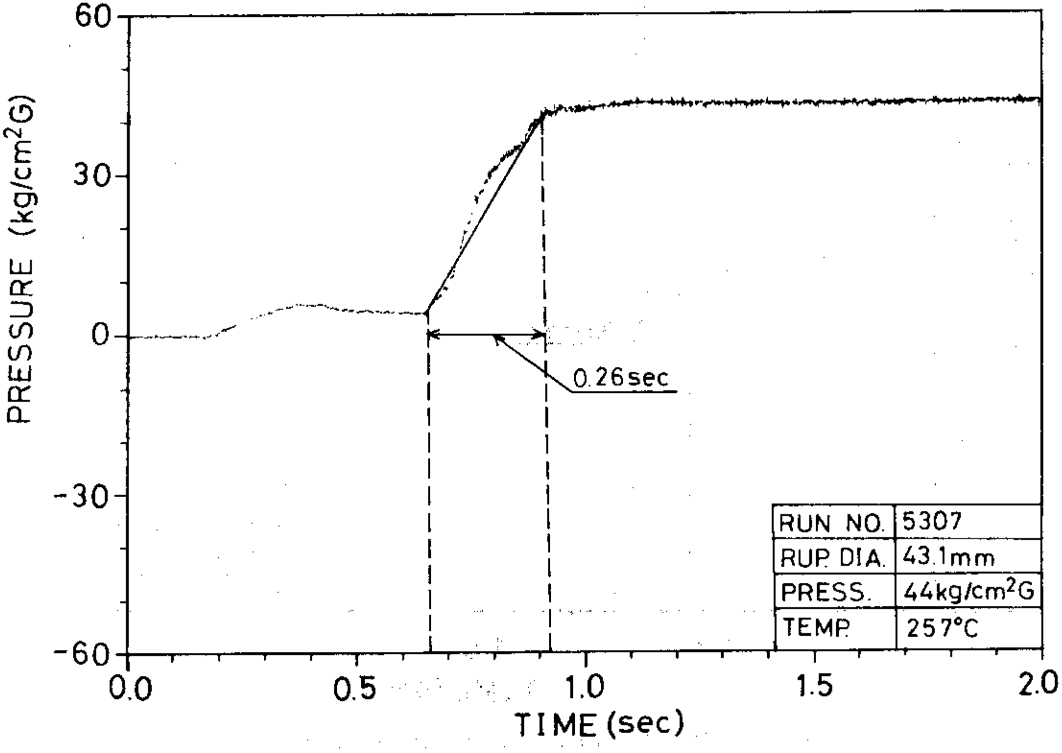


Fig.4(b) Variation of Pressure in Discharging Nozzle (PU113) for RUN NO.5307 and its Approximated Line.

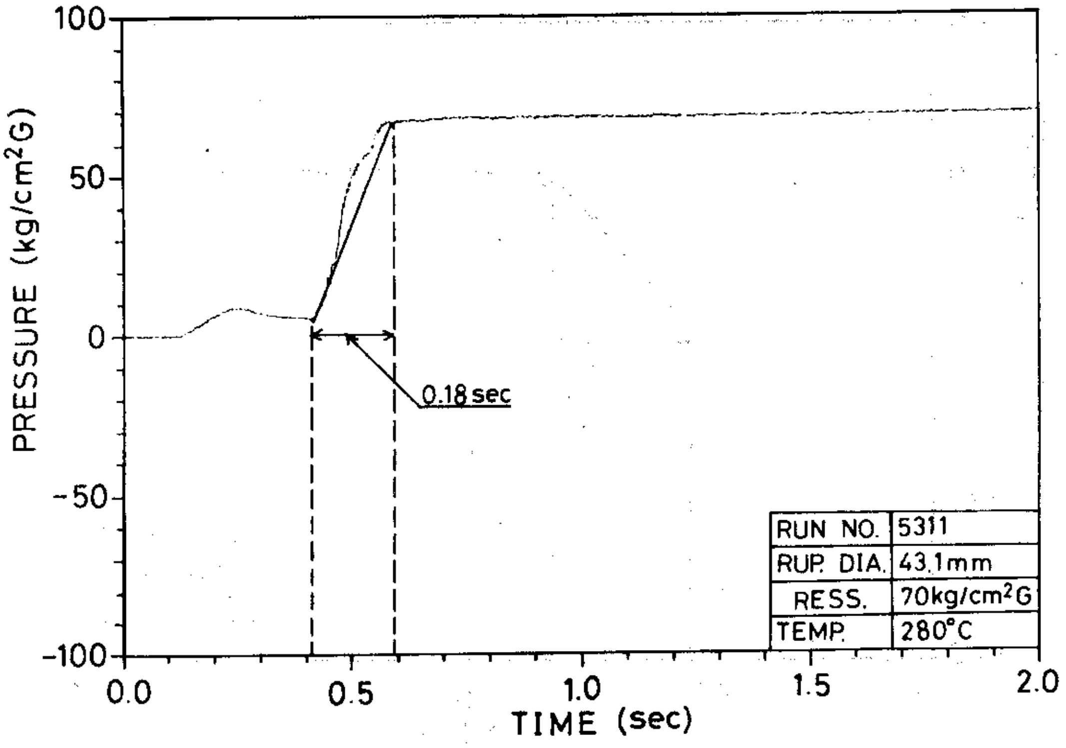


Fig.4(c) Variation of Pressure in Discharging Nozzle (PU113) for RUN NO.5311 and its Approximated Line.

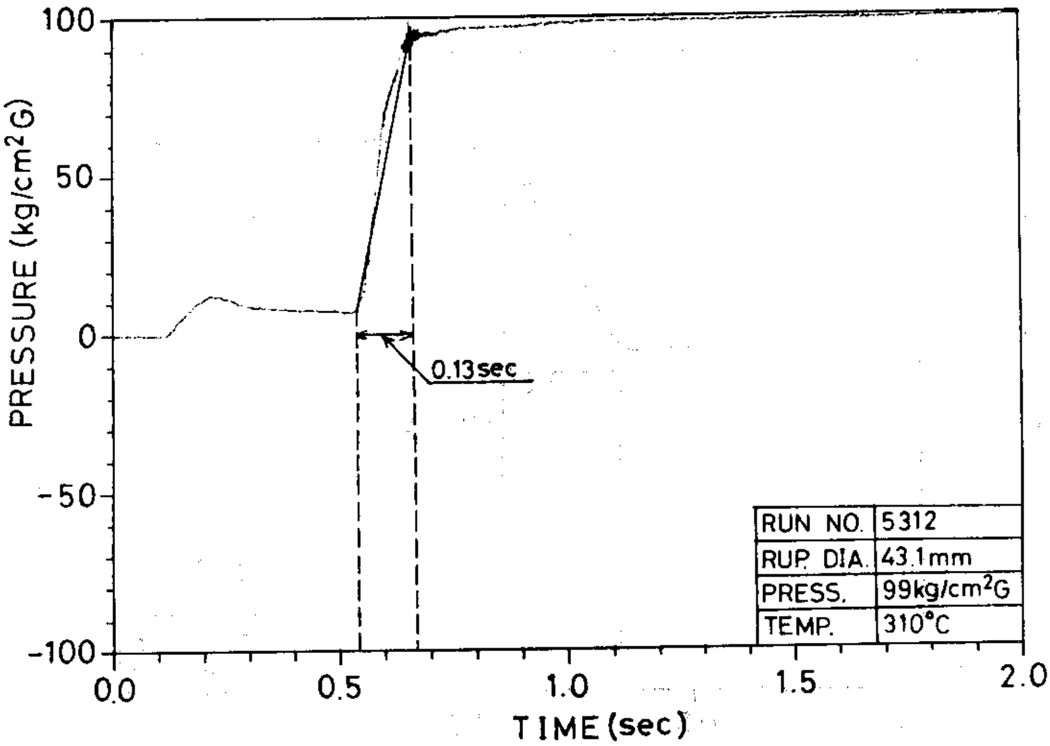


Fig.4(d) Variation of Pressure in Discharging Nozzle (PU113) for RUN NO.5312 and its Approximated Line.

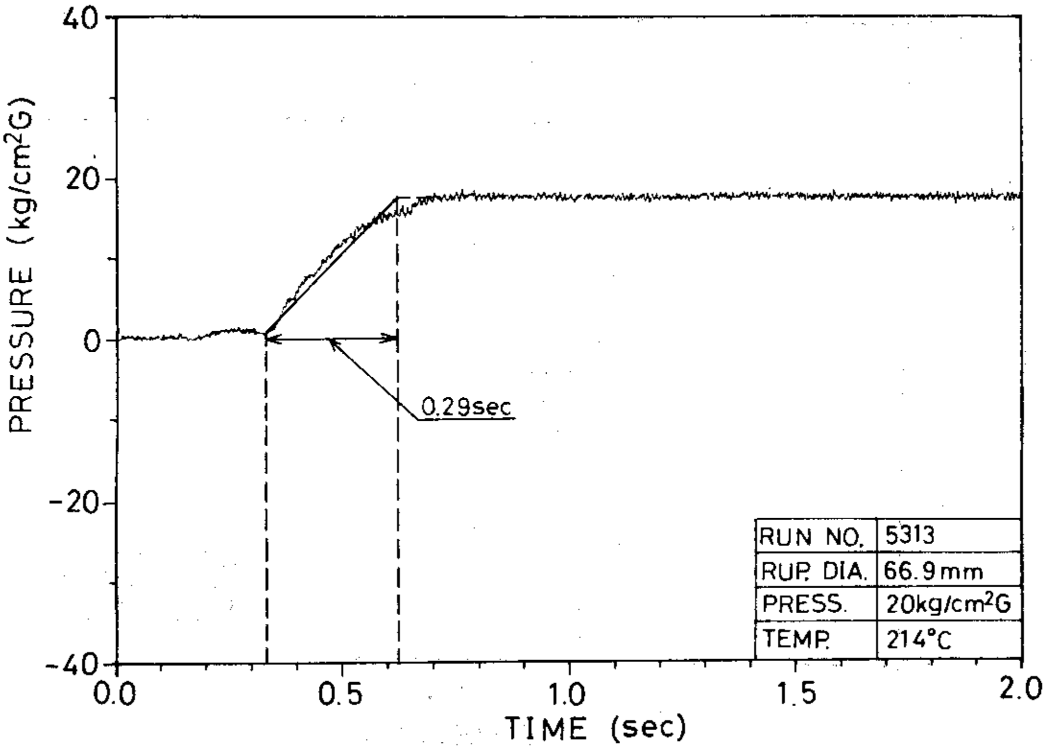


Fig.4(e) Variation of Pressure in Discharging Nozzle (PU112) for RUN NO.5313 and its Approximated Line.

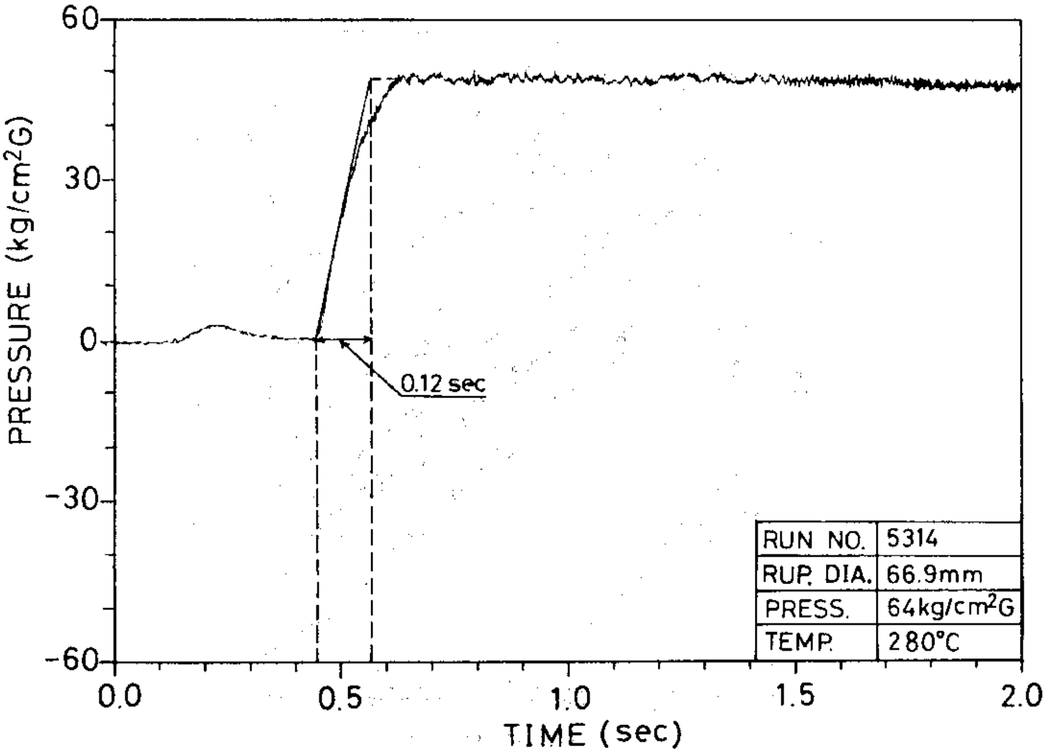


Fig.4(f) Variation of Pressure in Discharging Nozzle (PU112) for RUN NO.5314 and its Approximated Line.

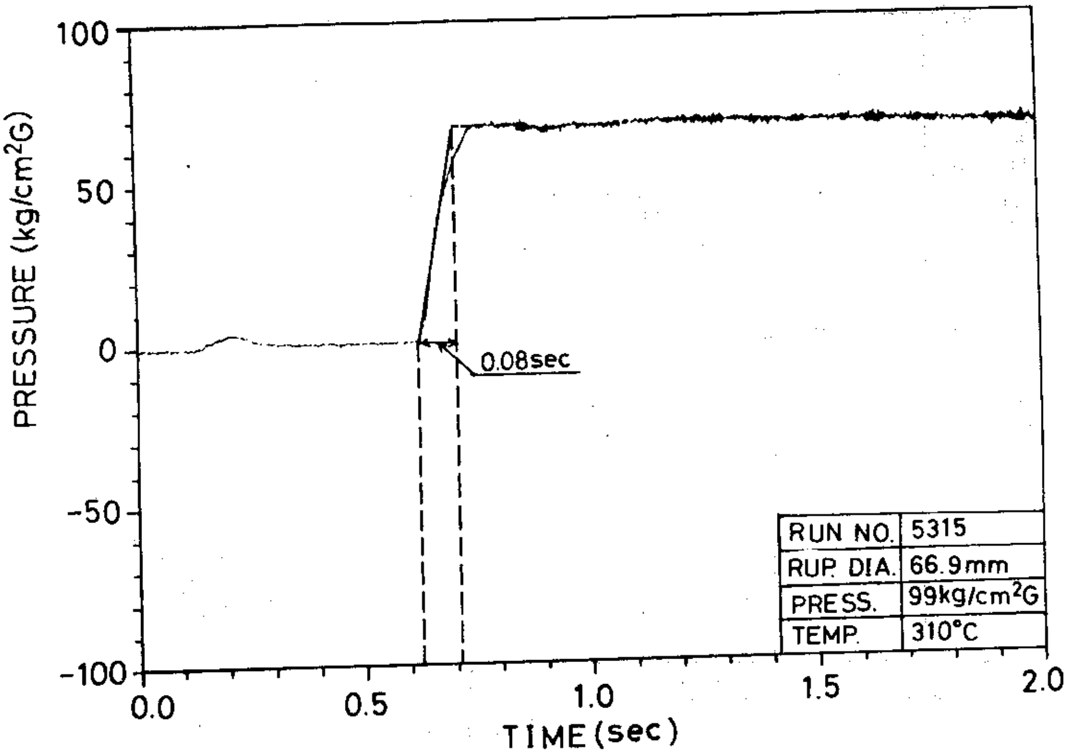


Fig.4(g) Variation of Pressure in Discharging Nozzle (PU112) for RUN NO.5315 and its Approximated Line.

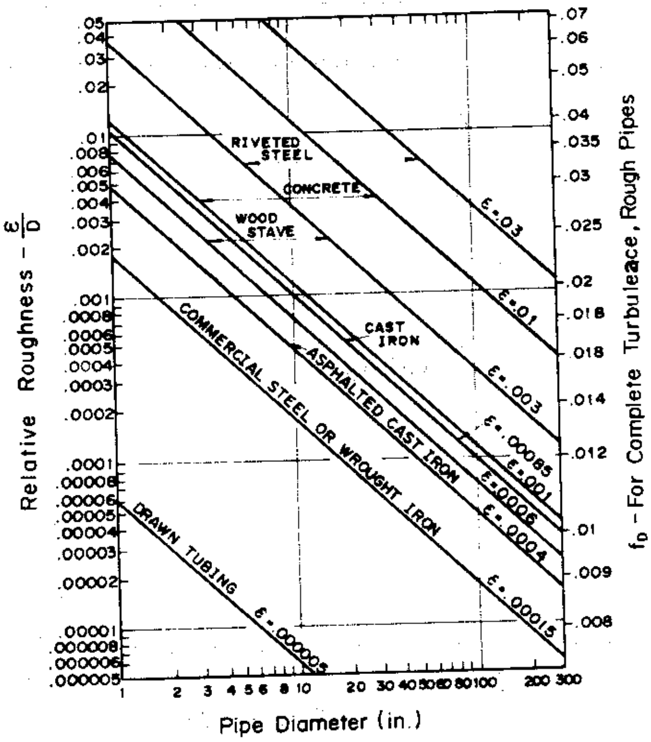


Fig.5 Darcy Friction Coefficient Given in Crane's Handbook(4).

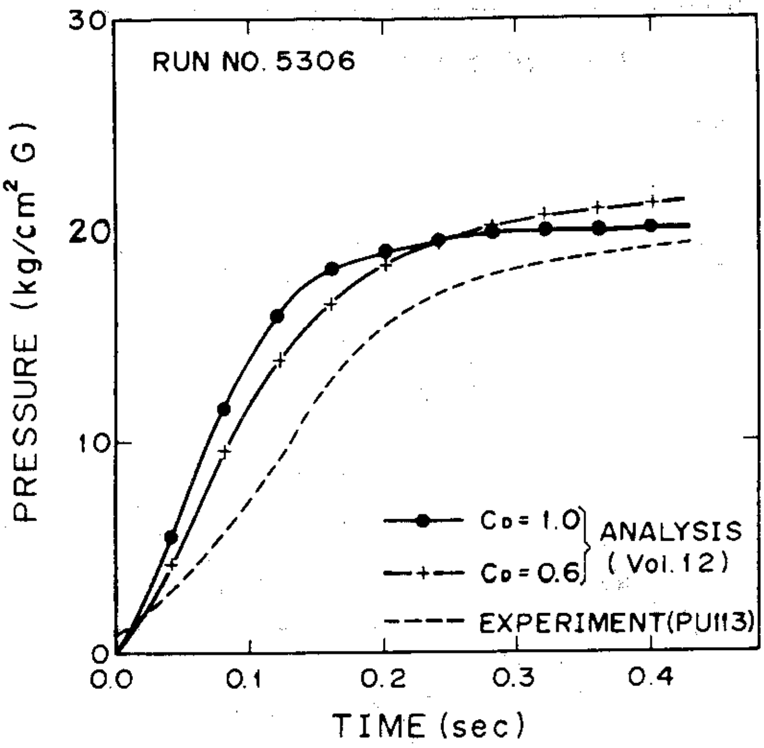


Fig.6(a) Comparison between the Analyzed Pressure at Vol.12 and the Experimental Data of PU113 in Case of RUN NO.5306.

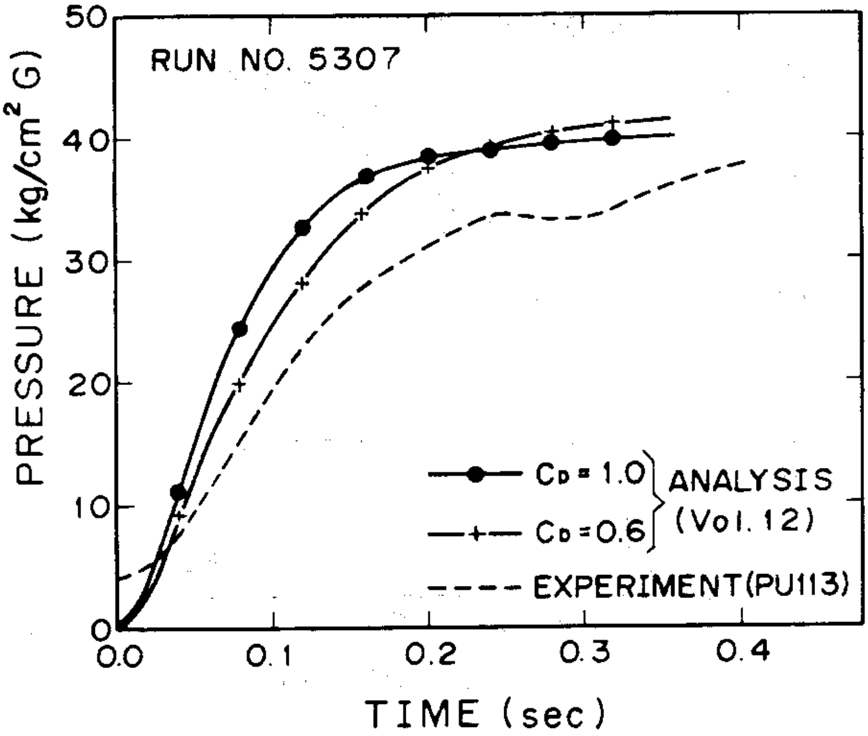


Fig.6(b) Comparison between the Analyzed Pressure at Vol.12 and the Experimental Data of PU113 in Case of RUN NO.5307.

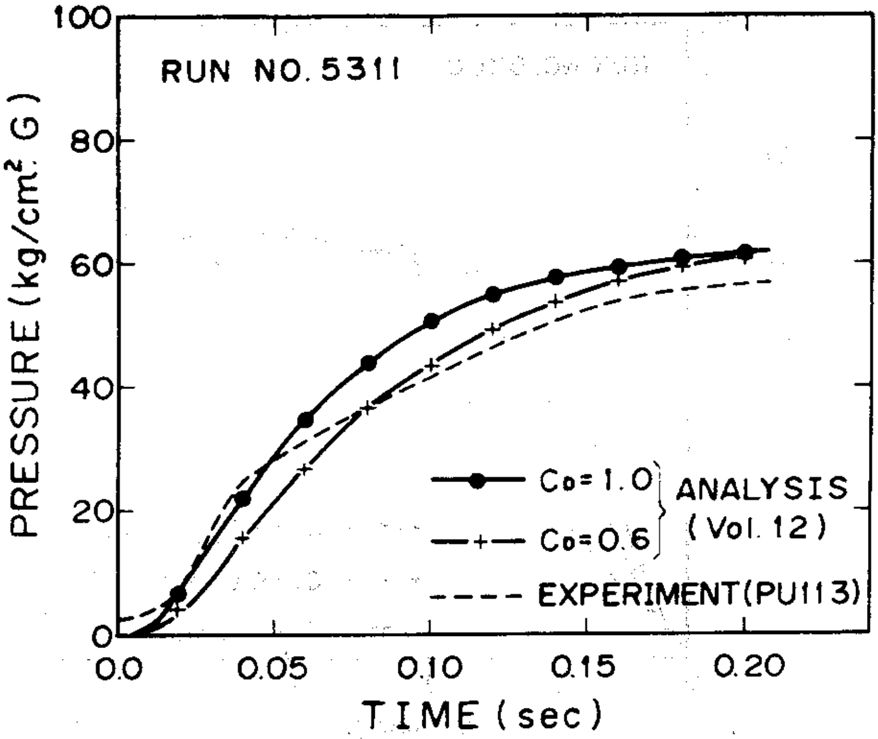


Fig.6(c) Comparison between the Analyzed Pressure at Vol.12 and the Experimental Data of PU113 in Case of RUN NO.5311.

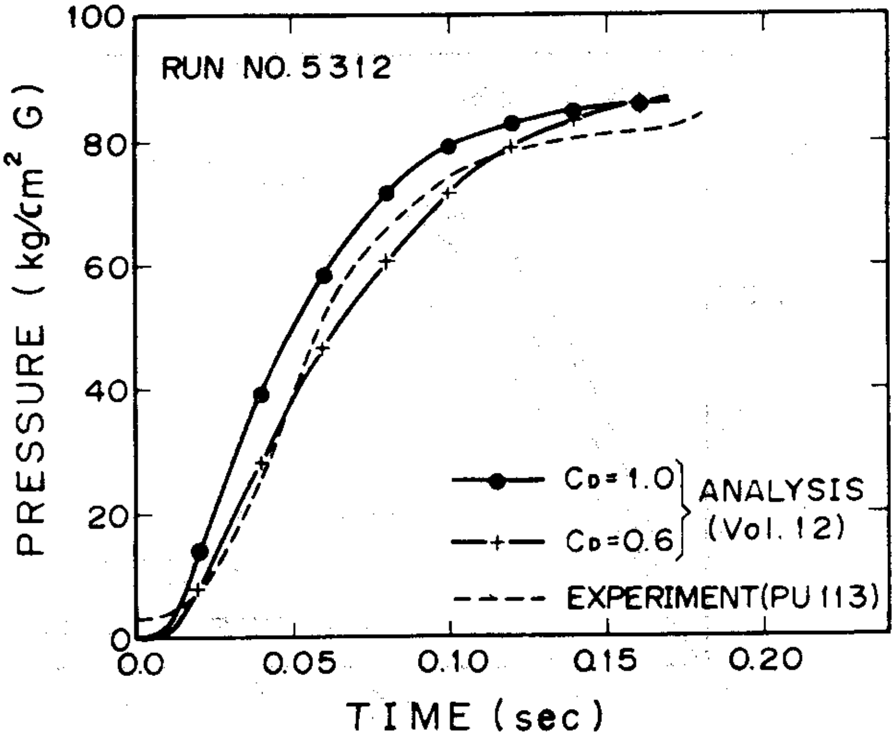


Fig.6(d) Comparison between the Analyzed Pressure at Vol.12 and the Experimental Data of PU113 in Case of RUN NO.5312.

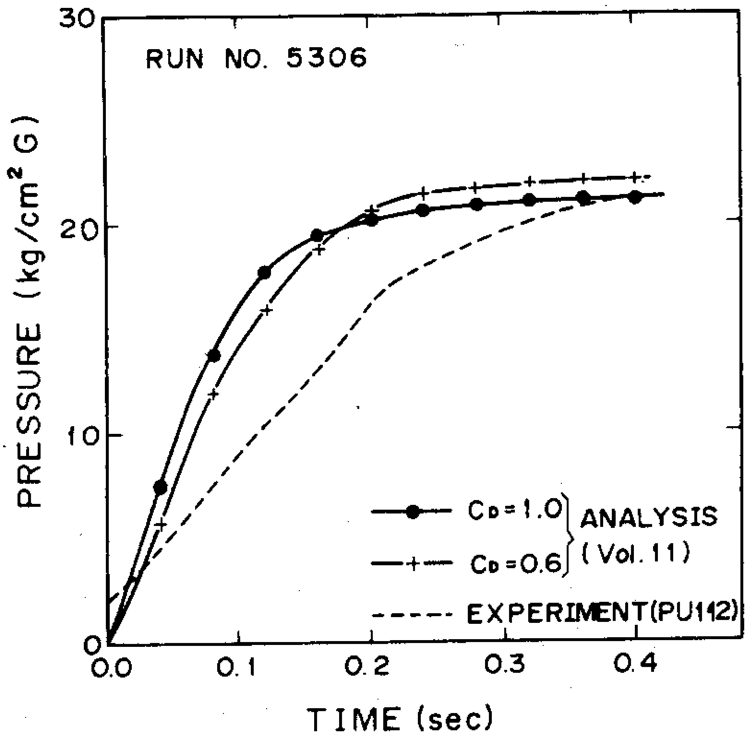


Fig.7(a) Comparison between the Analyzed Pressure at Vol.11 and the Experimental Data of PU112 in Case of RUN NO.5306.

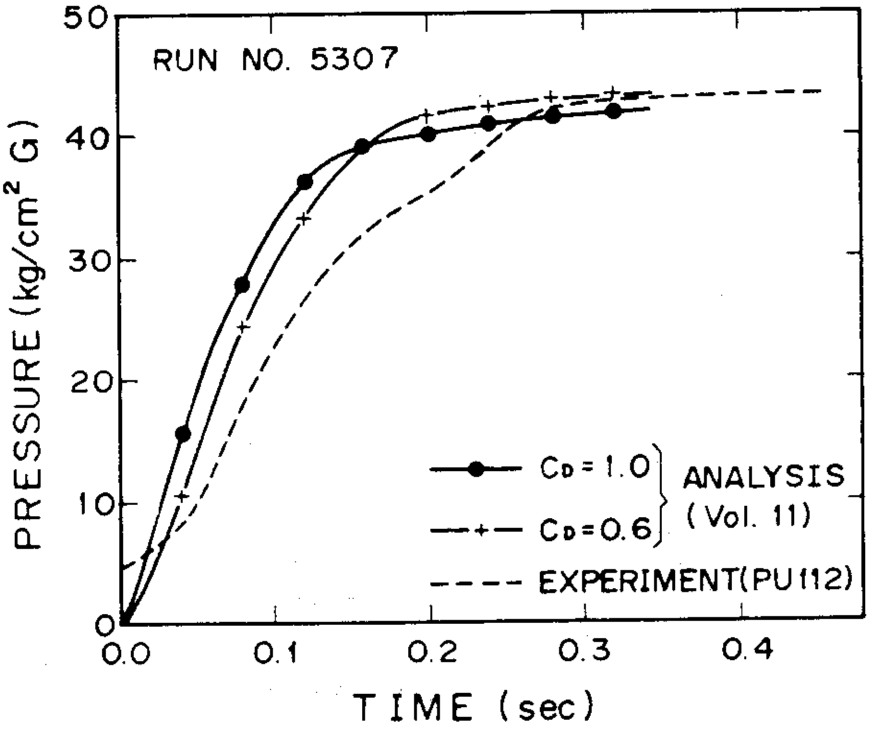


Fig.7(b) Comparison between the Analyzed Pressure at Vol.11 and the Experimental Data of PU112 in Case of RUN NO.5307.

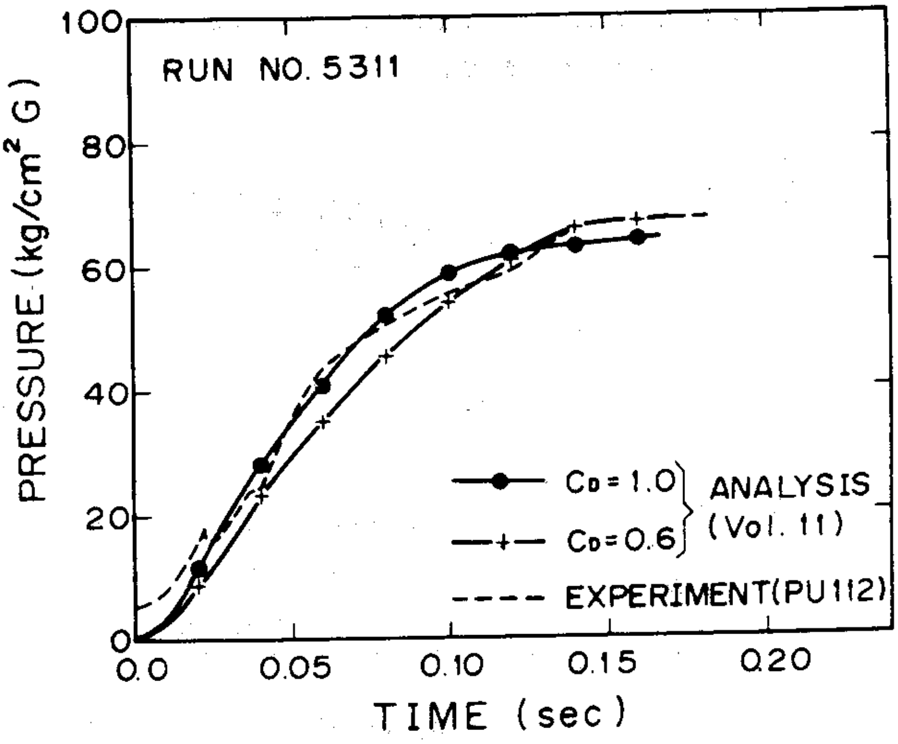


Fig.7(c) Comparison between the Analyzed Pressure at Vol.11 and the Experimental Data of PU112 in Case of RUN NO.5311.

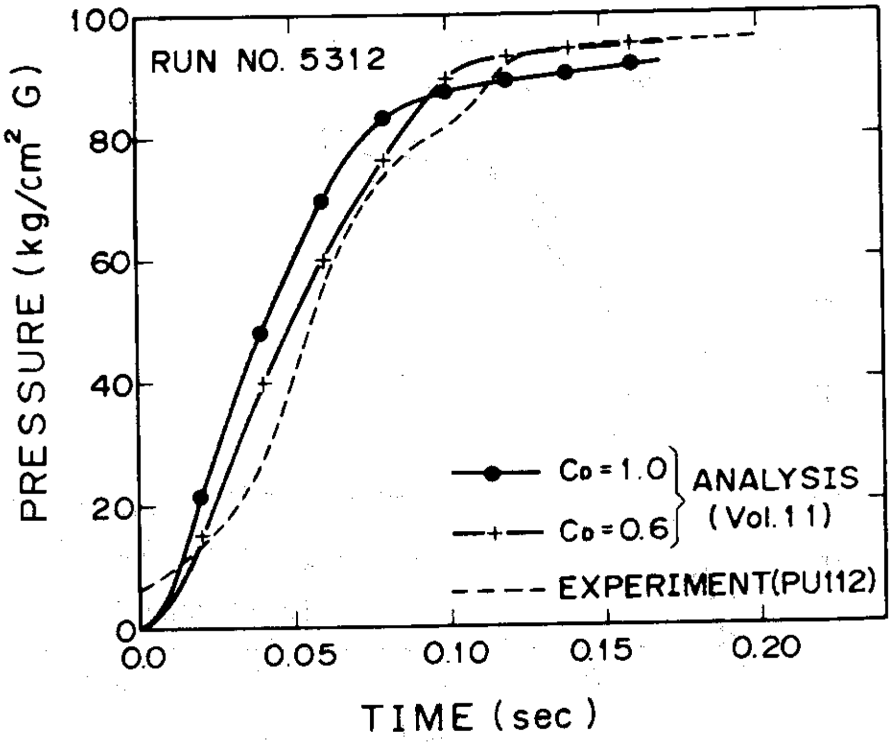


Fig.7(d) Comparison between the Analyzed Pressure at Vol.11 and the Experimental Data of PU112 in Case of RUN NO.5312.

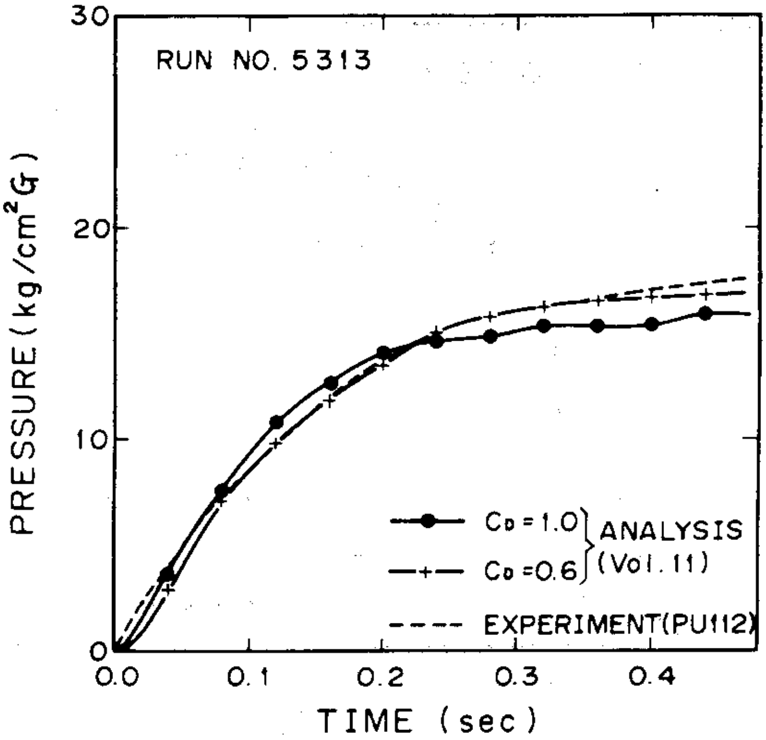


Fig.8(a) Comparison between the Analyzed Pressure at Vol.11 and the Experimental Data of PU112 in Case of RUN NO.5313.

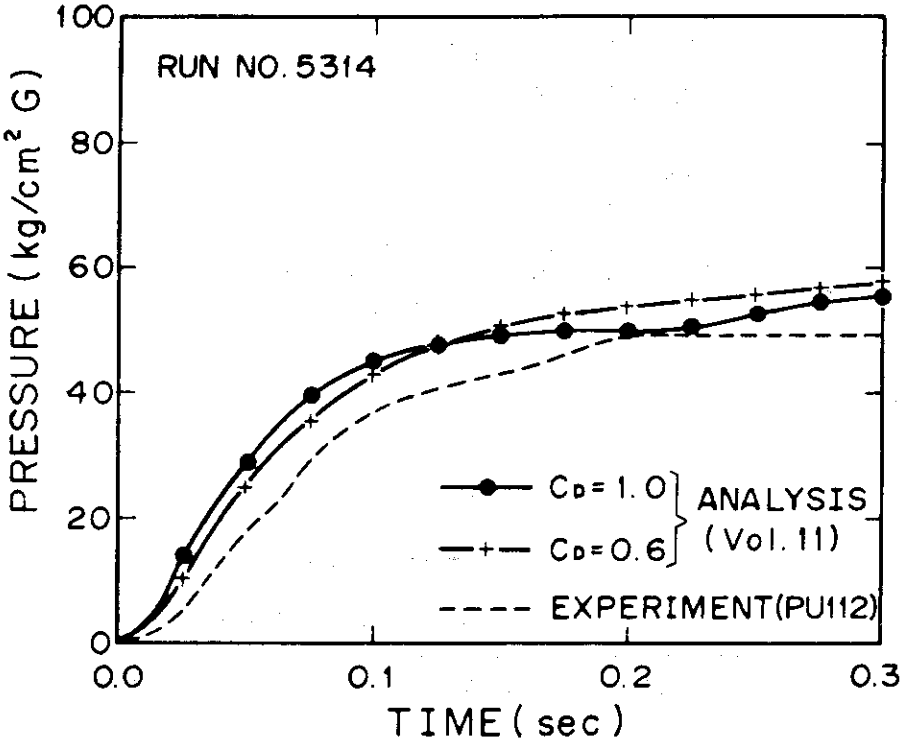


Fig.8(b) Comparison between the Analyzed Pressure at Vol.11 and the Experimental Data of PU112 in Case of RUN NO.5314.

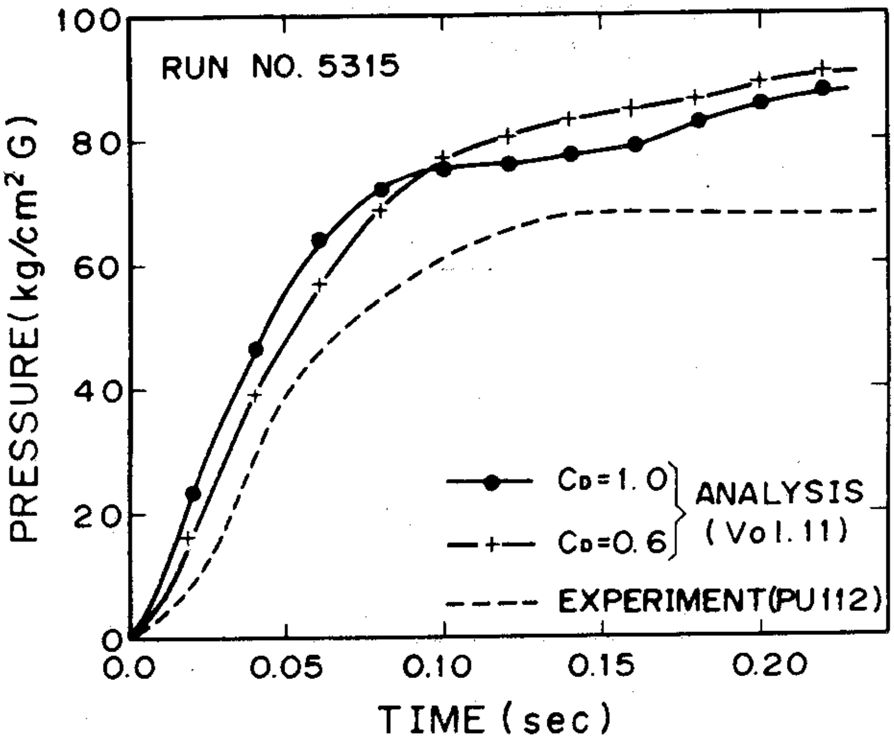


Fig.8(c) Comparison between the Analyzed Pressure at Vol.11 and the Experimental Data of PU112 in Case of RUN NO.5315.

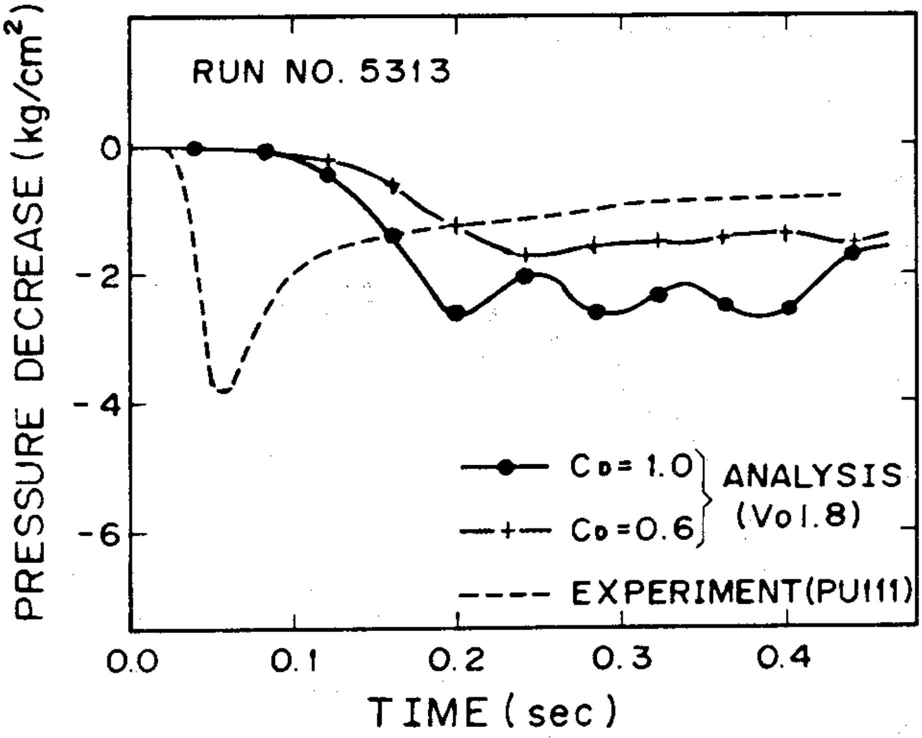


Fig.9(a) Comparison between the Analyzed Pressure at Vol.8 and the Experimental Data of PU111 in Case of RUN NO.5313.

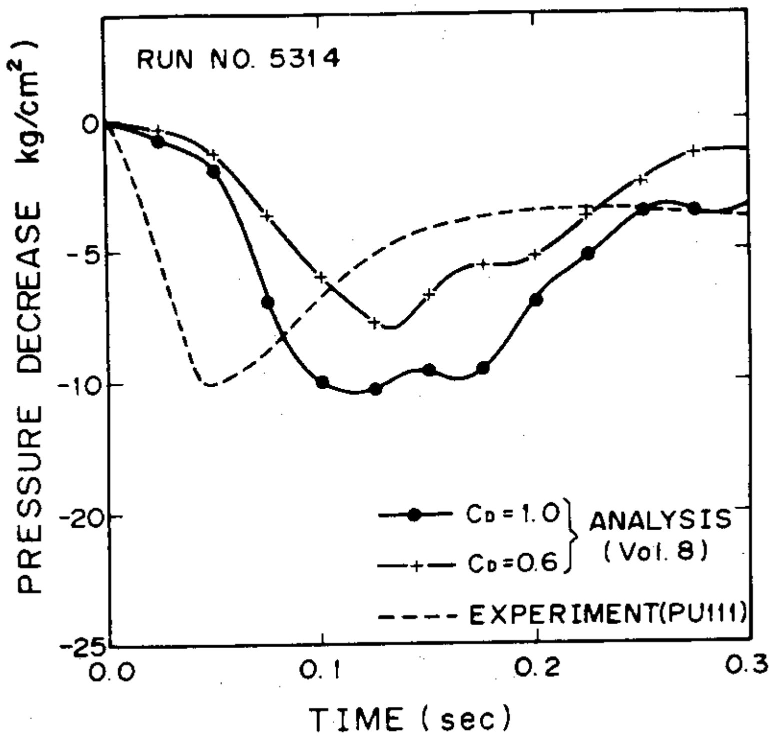


Fig.9(b) Comparison between the Analyzed Pressure at Vol.8 and the Experimental Data of PU111 in Case of RUN NO.5314.

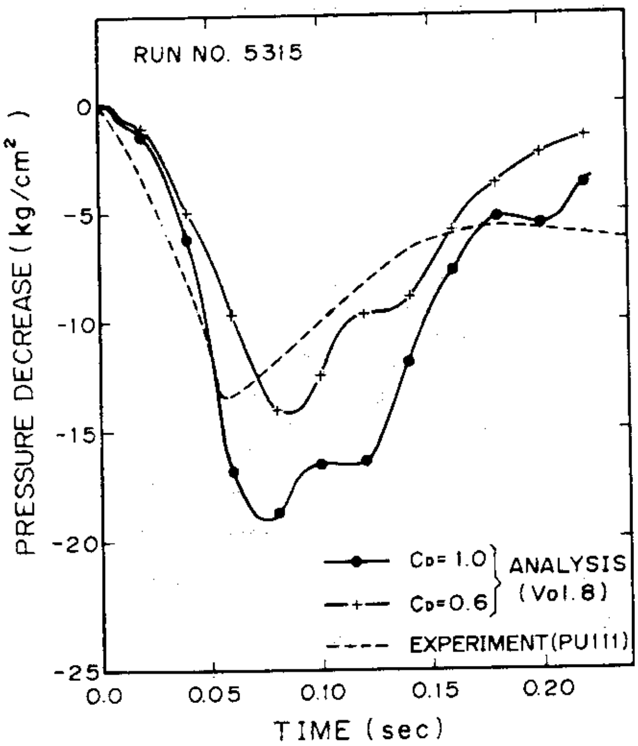


Fig.9(c) Comparison between the Analyzed Pressure at Vol.8 and the Experimental Data of PU111 in Case of RUN NO.5315.

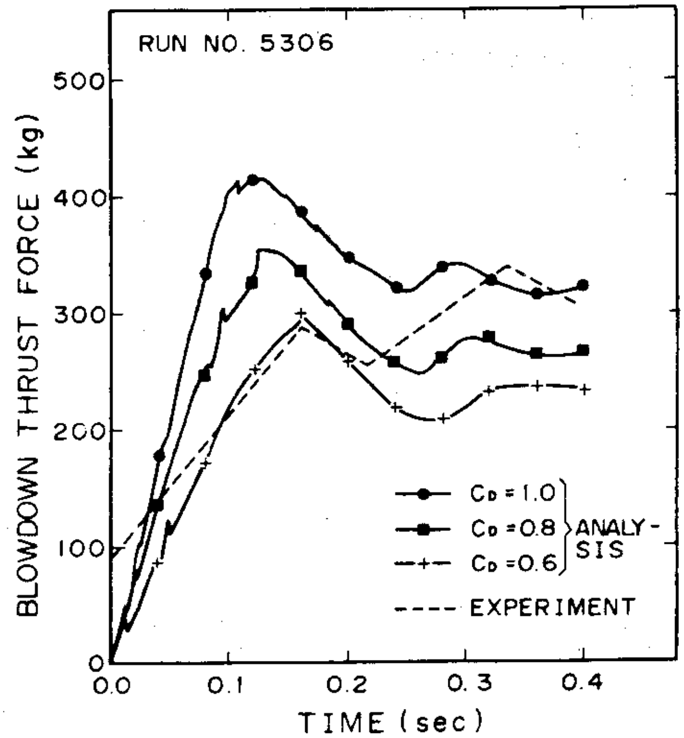


Fig.10(a) Comparison between the Analyzed Blowdown Thrust Force and the Experimental Data of WU111 in Case of RUN NO.5306.

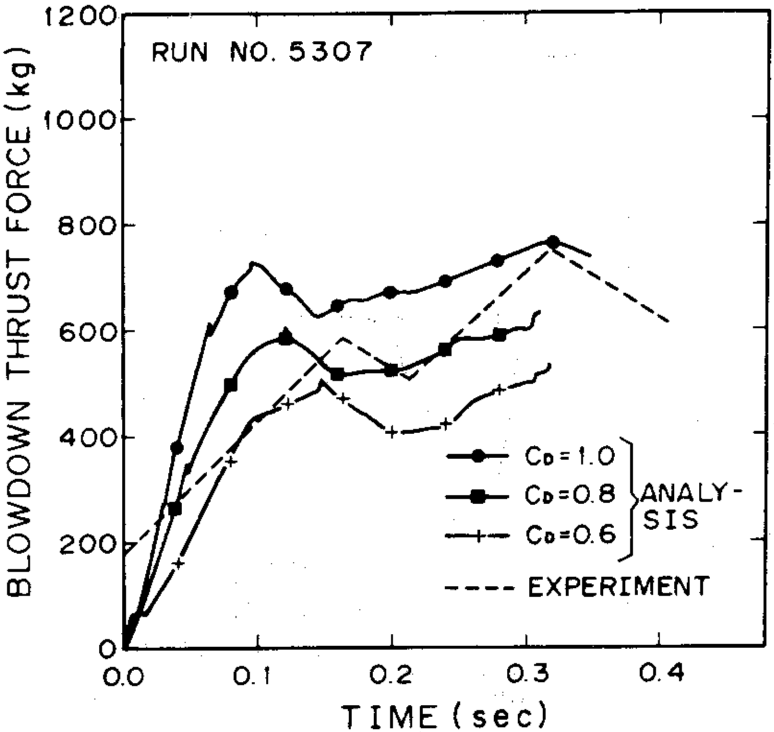


Fig.10(b) Comparison between the Analyzed Blowdown Thrust Force and the Experimental Data of WU111 in Case of RUN NO.5307.

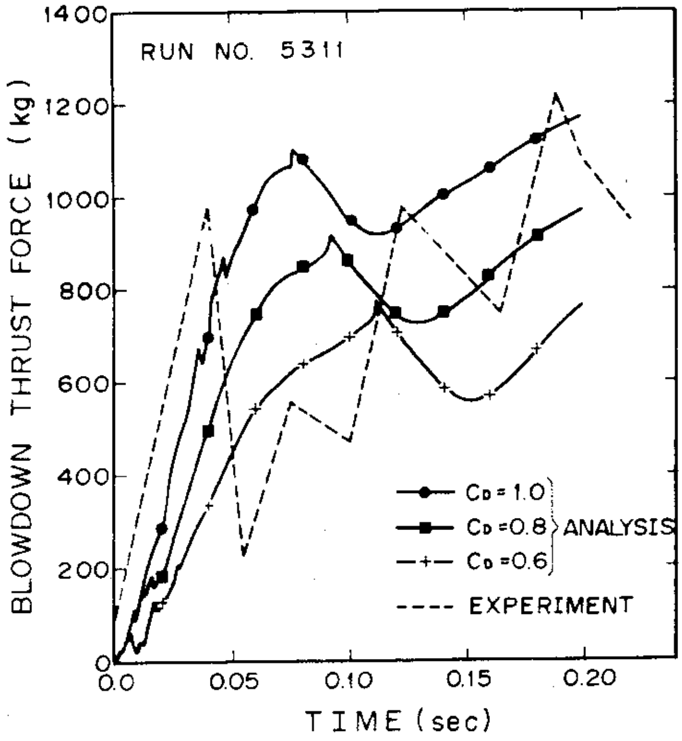


Fig.10(c) Comparison between the Analyzed Blowdown Thrust Force and the Experimental Data of WU111 in Case of RUN NO.5311.

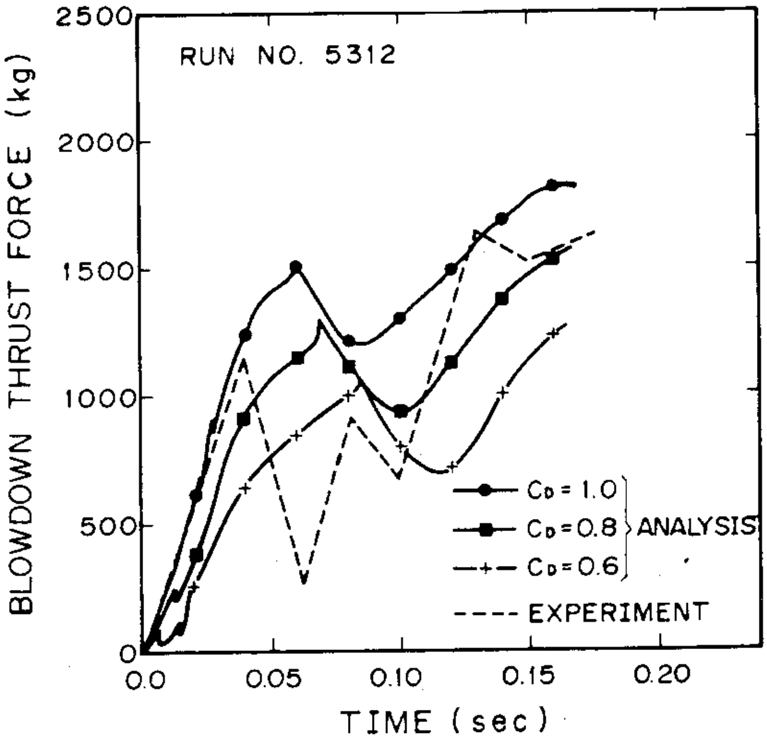


Fig.10(d) Comparison between the Analyzed Blowdown Thrust Force and the Experimental Data of WU111 in Case of RUN NO.5312.

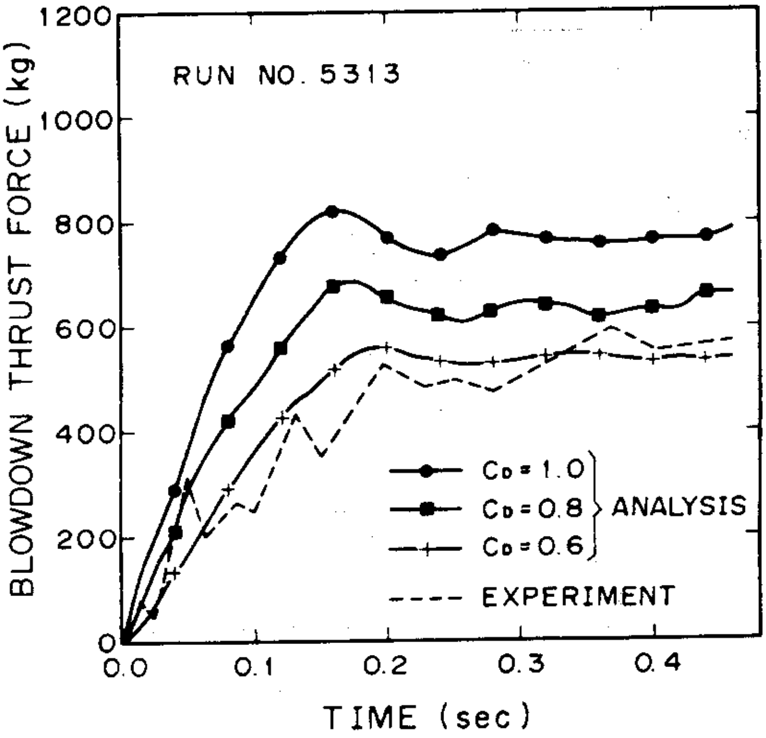


Fig.10(e) Comparison between the Analyzed Blowdown Thrust Force and the Experimental Data of WU111 in Case of RUN NO.5313.

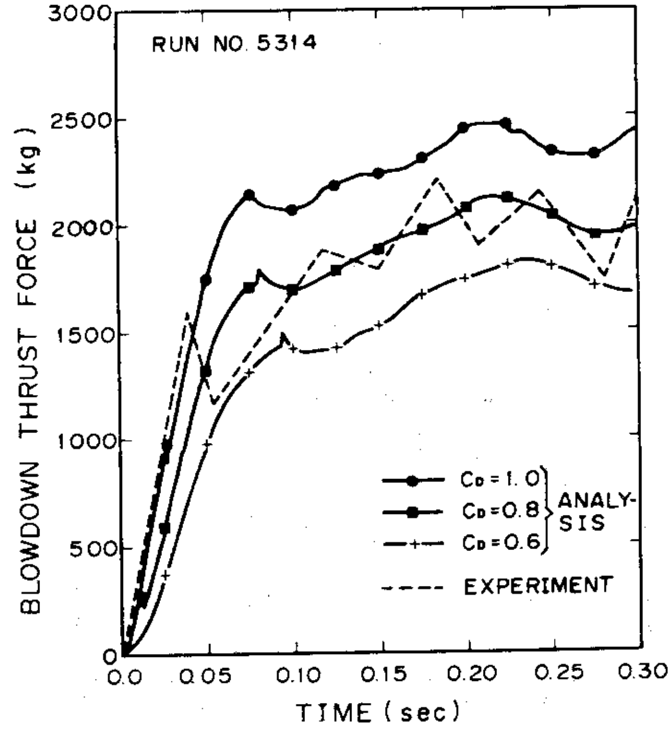


Fig.10(f) Comparison between the Analyzed Blowdown Thrust Force and the Experimental Data of WU111 in Case of RUN NO.5314.

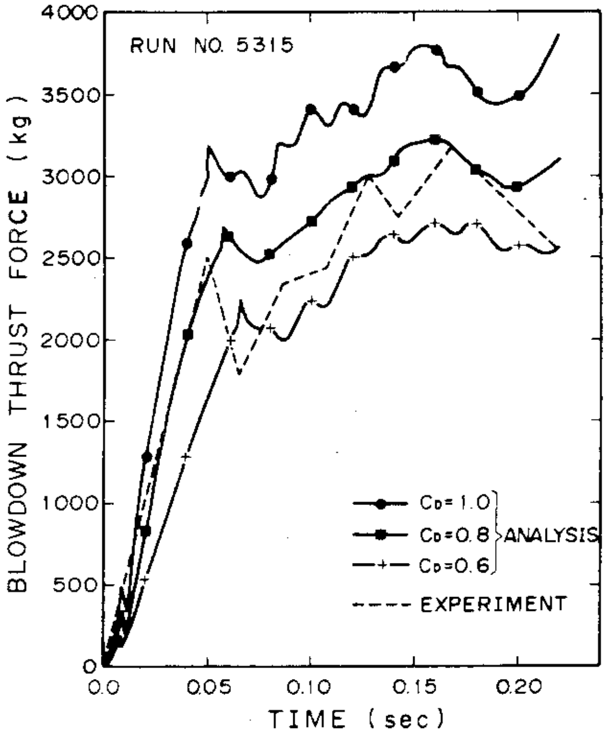


Fig.10(g) Comparison between the Analyzed Blowdown Thrust Force and Experimental Data of WU111 in Case of RUN NO.5315.

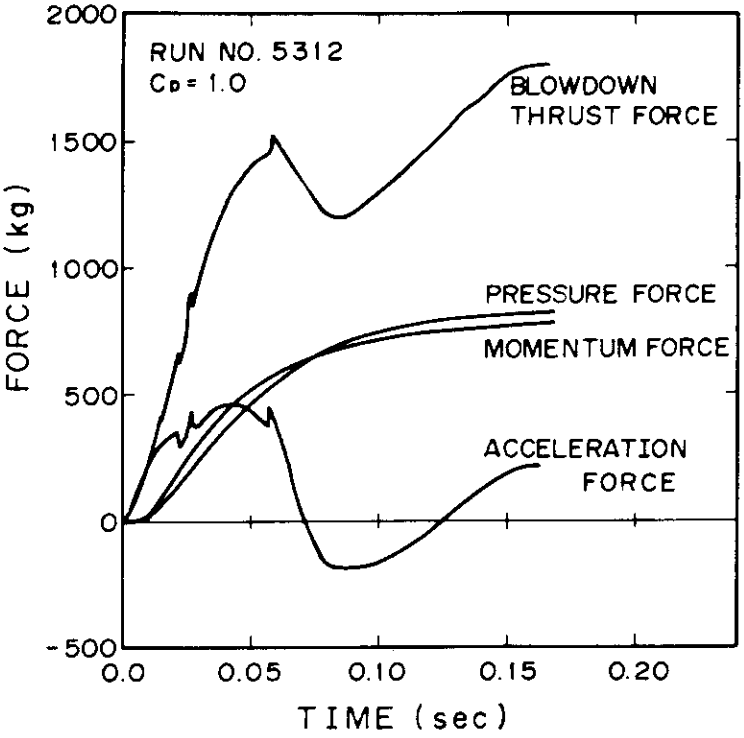


Fig.11(a) Comparison among Three Components of Analyzed Blowdown Thrust Force in Case of RUN NO.5312,C_D=1.0.

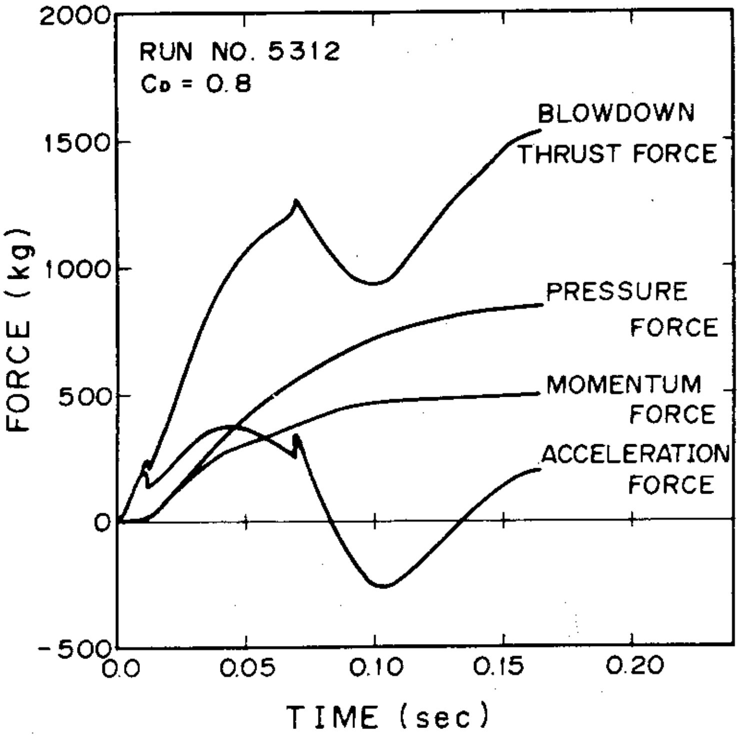


Fig.11(b) Comparison among Three Components of Analyzed Blowdown Thrust Force in Case of RUN NO.5312,C_D=0.8.

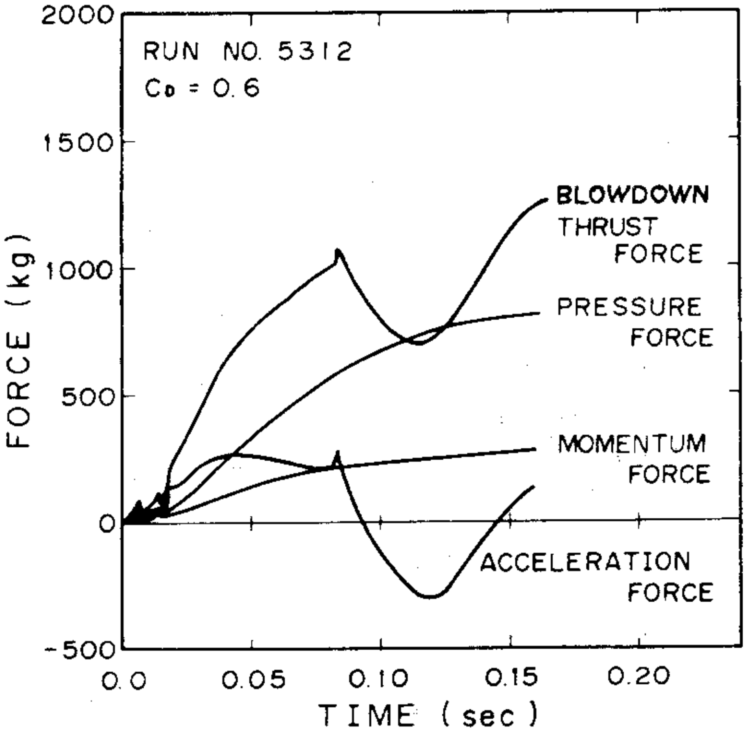


Fig.11(c) Comparison among Three Components of Analyzed Blowdown Thrust Force in Case of RUN NO.5312,C_D=0.6.

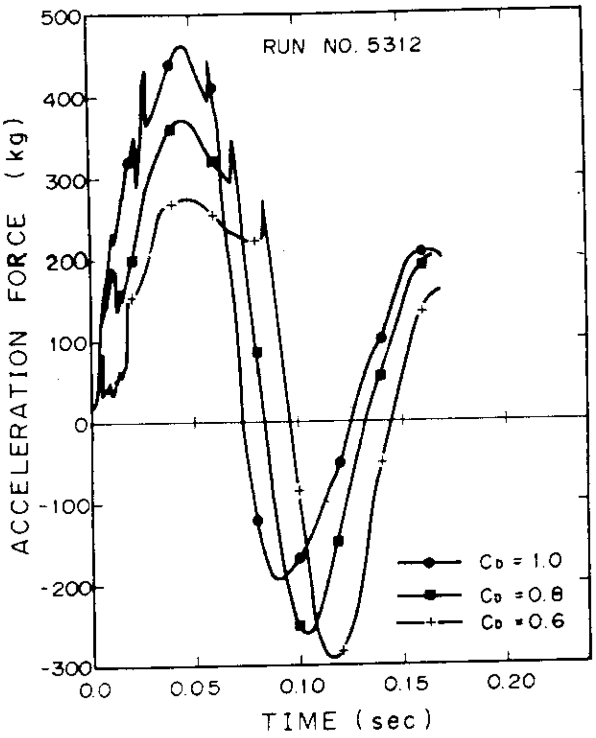


Fig.12(a) Time History of Analyzed Pressure Force for Each Discharging Coefficient in Case of RUN NO.5312.

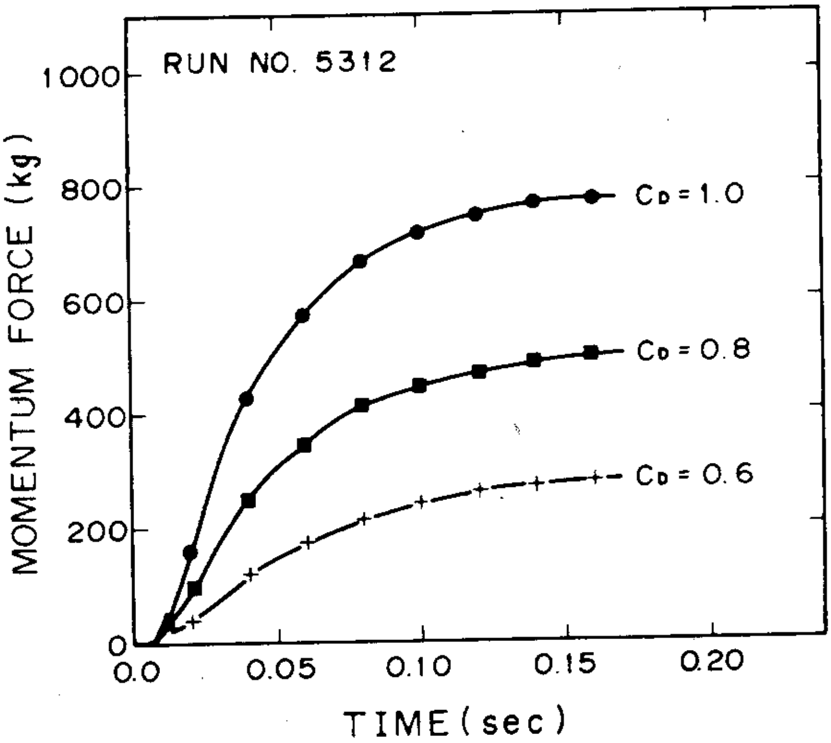


Fig.12(b) Time History of Analyzed Momentum Force for Each Discharging Coefficient in Case of RUN NO.5312.

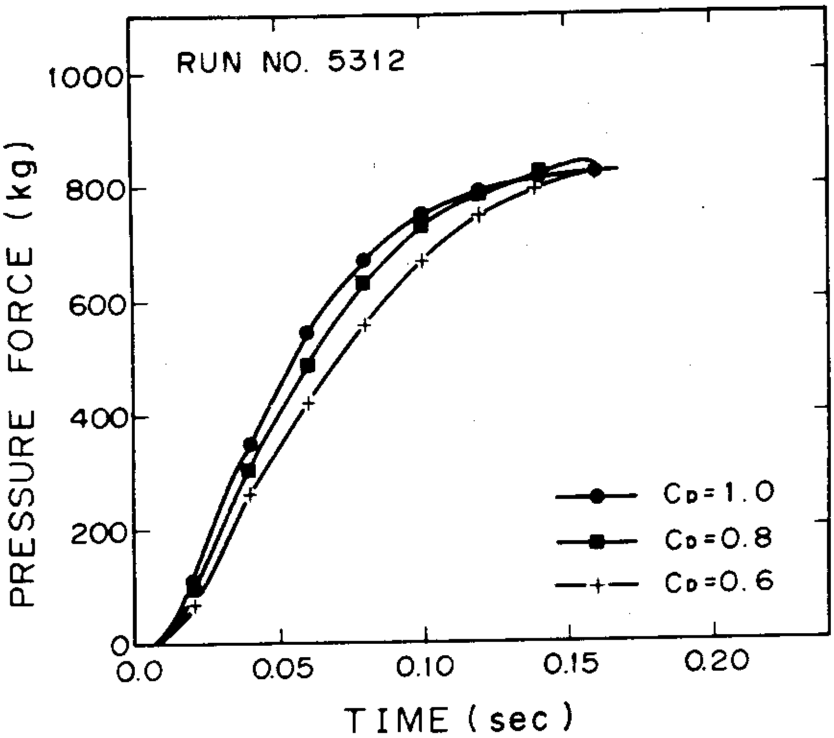


Fig.12(c) Time History of Analyzed Acceleration Fofce for Each Discharging Coefficient in Case of RUN NO.5312.

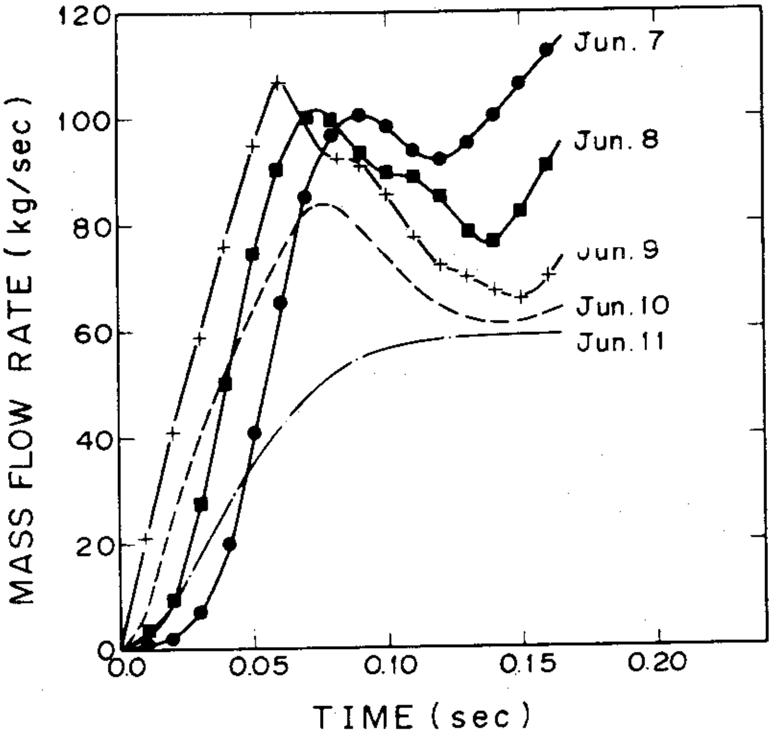


Fig.13 Time History of Mass Flow Rate at Each Junction in Case of RUN NO.5312,C_D=1.0.