Experiment on Pressure Wave Propagation (I)
The Result of Experiment on Branches and Bends

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Experiment on Pressure Wave Propagation

(1) The Result of Experiment on Branches and Bends

Makoto Hishida* and
Masao Hori**

Abstract

For the purpose of studying pressure wave propagation in the secondary loop of the prototype Fast Reactor MONJU, we have taken up branches and bends for study and carried out experiments on pressure wave propagation with respect to 2 kinds each of model specimens of branches and bends (Reduced scale of pipe diameter: About 1/12.5). The conditions for the experiments were as follows:

(1) Water was used as the medium for the pressure wave propagation.

(2) An input wave in which pulse rising time of pressure wave is about 1.5 msec and wave height is about 0.5 kg/cm^2 - 6.0 kg/cm^2 was used.

The findings that we obtained as a result of the experiments include the following.

(1) We studied in detail how the pressure wave propagates through the branch or bend parts, observing the wave form and height at the places near the branch part and near the bend part and have found that the results almost agree with the results obtained by

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* Japan Atomic Energy Research Institute at present.

** Fast Reactor Safety Laboratory, Sodium Engineering Department, Oarai Engineering Center, PNC.

the conventional one-dimensional, handling method.

(2) The energy loss of a pressure wave in a branch part can be almost ignored within the limit of this present experiment.

(3) As regards the bend, when a pressure wave passes the bend part, the wave is seemed to receive some effect by the bend, but this matter requires further study.

CONTENTS

1. Preface

When a sodium-water reaction (a large-scale, sodium-water reaction) takes place in the steam generator of a prototype fast breeder reactor, a pressure wave having a high pressure is generated and this pressure wave propagates to each components in the secondary loop (for example, the intermediate heat exchanger, reheater, pump, valves and piping) and may damage them.

Breakage of such a component may lead to outbreak of a sodium fire and decreases availability of the plant. Furthermore, should the intermediate heat exchanger break, allowing the activated sodium in the primary system to be mixed into the secondary system, it poses a problem on the safety of the nuclear reactor system.

Consequently, it is necessary to know how the pressure waves subsequent to an accident of sodium-water reaction propagate to each components in the secondary system.
(This report is organized as follows, that is, Section 2 presents an overview of the experiment on the pressure wave propagation and Section 3 onward are devoted to the results of tests with respect to bends and branches.)

2. Necessity for Experiment on Pressure Wave Propagation and Test Items

2.1 Necessity for Experiment on Pressure Wave Propagation

Experiments and theoretical handling of pressure waves propagating in a liquid have long been practiced in connection with the problem of water hammer generated by opening/closing valves or tripping a pump in water supply pipes in hydraulic power stations or in various kinds of water supply and feed pipes[(1)(2)(3)], or pressure wave propagation at the time of failure of the primary cooling system of a light water reactor[(4)] or at the time of a grounding accident in a hydraulic cable.[(5)(6)]

Also when a pressure wave generated as a result of an accident of sodium-water reaction in a steam generator propagates in the secondary loop, the phenomenon of propagation is substantially the same, although the cause of generation of the pressure wave is different, so that the same way of handling is thought applicable. However, it is mainly for the systems composed of rather simple piping elements including straight pipe, branches and valves that the experiments and theoretical calculations have been practiced up to date in connection with water hammer and so on. Furthermore, the experiments and theoretical calculations for these systems have been practiced only in the range of one-dimensional handling.

Consequently, when analyzing pressure wave propagation in the secondary loop of a prototype fast reactor, it can be thought that the following matters pose a problem (or experimental verification is required to be made).

(1) Whether pressure wave propagation in the components having rather complex forms including the intermediate heat exchanger,

steam generator and reheater in the secondary loop can be handled one-dimensionally? And to handle them one-dimensionally, what kind of model should be considered?

(2) In the secondary loop, there are a number of bends and branches. These bends and branches are installed close to one another. So, is it proper to think that they are a combination of a single-body bend and a single branch? In other words, do the bends and branches in the front not have any effect on the bends and branches in the rear?

(3) As to the component element of the secondary loop including bend, branch, valve and a junction with a stepwise change in diameter, if we consider reflection and transmission within the component, there can be some possibility of locally different pressures observed; that is there cannot be very high pressure generated through the reflection.

(4) What are the energy losses of the pressure waves at a bend part, branch part and the parts with the flow area suddenly expanded or contracted?

(5) It is not established yet as a friction loss coefficient in the straight pipe.

Since these problems need to be solved or verified experimentally, an experiment on pressure wave propagation was planned. (Besides, as it is already acknowledged in water hammer phenomenon, a negative pressure is generated locally as a result of reflection of pressure waves. When a pressure turns negative, water column separation (or sodium column separation) takes place.

When water column separation (or sodium column separation) takes place, high pressure waves may be generated at the time of the subsequent rebinding.[7]

It can hardly be said that handling of pressure wave in case water column separation takes place is established,[7] so that this also needs to be studied. However, the sodium column separation is not included in our present test items.)

2.2 Test Items

We think it is extremely difficult from the technical standpoint and also in view of the huge number of experiments to study all items of (1) through (5) in 2.1. Consequently, as a principle in carrying out a test, we decided to first, consider a model for the secondary loop (Refer to Fig. 2.1) (In deciding this model, it should be selected so that the items (1) through (5) in the preceding Section can be studied as much as possible) and compare the result of experiment using this model with the result of the conventional analytical method. However, in deciding the test items we considered that this secondary loop can be handled as a combination of each component element and wanted the comparative study with the result of experiment easy and furthermore, based on the way of thinking that the parts of which evaluation with the secondary loop is impossible should be tested separately from the loop. The following are the concrete items which was decided.

(1) To take up branches and bends out of the component elements of the secondary loop and carry out experiments with a branch and bend having typical dimensions and forms to obtain approximate ideas with respect to the following items (a) and (b).

(a) To locally check the propagation of pressure wave at the branch and bend and obtain approximate ideas with respect to items (2) and (3) of 2.1.

(b) To obtain approximate ideas of the energy losses at the branch and bend. (Part of (4) of 2.1)

(2) As to the intermediate heat exchanger and steam generator which are thought to have rather complex forms out of the components of the secondary loop, to conduct the experiment by using the IHX (or SG) model; that is without any other unknown or complex object. (items (1) and (2) of 2.1.)

(3) To carry out an experiment with respect to a model of the secondary loop of a reduced scale and to compare the result with the result of one-dimensional analytical method. (Evaluation of items (1) and (2) of 2.1 is the main object.)

The result of experiments that we performed for the purpose of studying item (1) is described in Section 3 onward.

3. Experiment Apparatus and Experiment Method

A rough system diagram of the experiment apparatus is illustrated in Fig. 3.1.

The experiment apparatus roughly consists of the following 3 parts.

(1) Feed Water System

(2) Pressure Generation System

(3) Testing Part

Designed to feed the testing part with properly deaerated water, the feed water system is composed of Water Heater, Deaerator and Cooler. Since it is thought that presence of even a small amount of air bubbles in the water will affect propagation of pressure wave[9], we exercised the utmost care for the deaeration of the feed water, before feeding the experiment apparatus with water.

The water heater is designed to heat the feed water (service water) to make deaeration easier and water is heated by an internal insertion type electric heater (Capacity: 12 kW) up to 60 $^{\circ}$C - 80 $^{\circ}$C at the outlet of the water heater.

The deaerator is designed to vacuum-deaerate the warm water coming from the heater. This deaerator is illustrated in Fig. 3.2. The warm water is sprayed through the funnel-shaped inlet on the top of the deaerator in the phase of water-drops and flows down the Rasich ring surface. During this period, the gas content in the warm water is removed and discharged by a vacuum pump. The water with the gas content reduced is accumulated in the bottom and sent to the experiment apparatus.

The cooler is provided for the purpose of cooling the warm water coming from the deaerator and sending the subsequent water to the testing apparatus. It is a double-tube type water cooler.

The vacuum pump is designed to discharge the separated gas from deaerator and make the testing part vacuous at the time of feeding the testing part with water.

The pressure generator is composed of nitrogen gas cylinder, nitrogen gas chamber, rupture disc, rupture disc breaking needle and pressure wave generating pipe. The rupture disc and rupture disc breaking needle are provided in the gas chamber, with their constructions as illustrated in Fig. 3.3. The pressure wave generating pipe is designed to obtain the input wave form to the testing part, with its approximate form as illustrated in Fig. 3.4. For generating pressure waves, a method for generating pressure waves in the water by applying a gas pressure on the water surface was adopted. That is to say, a nitrogen gas chamber partitioned with a rupture disc is filled with nitrogen gas (having the gas pressure in the range of 0.5 kg/cm^2G - 7 kg/cm^2G) in advance and by breaking the rupture disc with the needle, the gas pressure in the chamber is inflicted on the water surface at the upper part of the pressure-wave generating pipe, thereby causing a pressure wave. The pressure wave generated in the pressure-wave generating pipe is branched by the pipe near the bottom of the pipe and introduced into the testing part. It can be thought that the pressure wave applied on the water surface at the upper part of the pressure-wave generating pipe is of stepped form. But as to the pressure wave introduced into the testing part through the reflections on the bottom of the pipe and on the free surface, the first wave is of nearly pulse form. (Fig. 3.12)

To change the wave height of a pressure wave, the nitrogen gas pressure to be applied in the gas chamber is changed and at the same

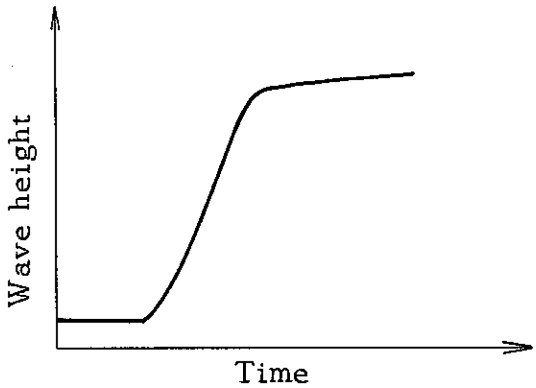


Fig. 3.11 Approximate form of pressure wave applied on the free surface of pressure wave generating pipe.

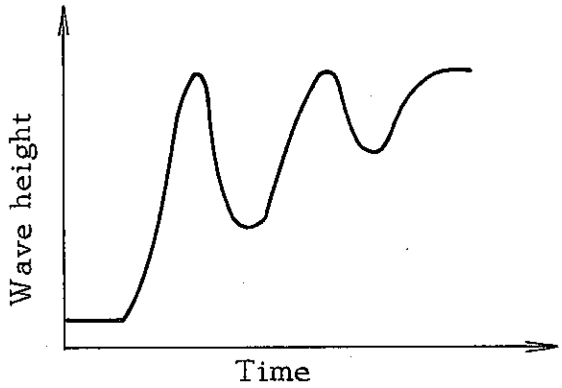


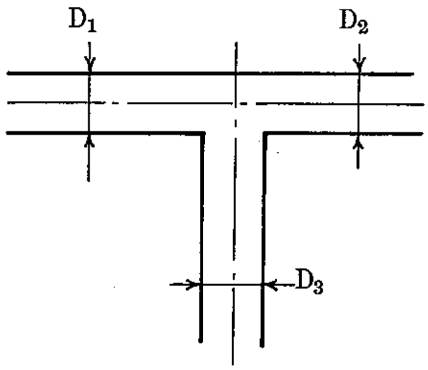
Fig. 3.12 Approximate form of pressure wave propagating to the testing part.

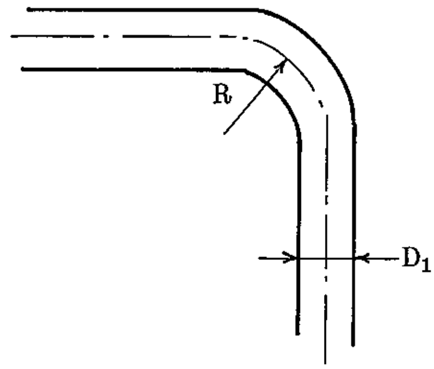
time a rupture disc which breaks near the required pressure is selected. (The breaking pressure varies with material and plate thickness.) For the purpose of controlling the time for breaking the rupture disc, a breaking needle is employed.

The testing part consists of a test object and necessary piping systems connected before and after it. A rough system diagram of the testing part with which we carried out a test with respect to the branch part is illustrated in Fig. 3.1. A round pipe of 3 inches called a pressure wave absorbing pipe was provided at the end of the testing part. Here, the pressure wave becomes a negative reflected wave and returns to the testing part. Our present tests were carried out Branch (I), Branch (II), Bend (I) and Bend (II). A block diagram of the testing part for the respective cases is shown in Fig. 3.4 and Fig. 3.5. The detailed dimensions of the test objects and the positions where pressure gauges were installed are illustrated in Fig. 3.6 through Fig. 3.9. Representative dimensions of the test objects are

Table 3.1 Test Objects

Test Object	Dimensions
Branch (I)	$D_1 = 42.6\phi$, $D_2 = 42.6\phi$, $D_3 = 42.6\phi$
Branch (II)	$D_1 = 42.6\phi$, $D_2 = 42.6\phi$, $D_3 = 22.2\phi$
Bend (I)	$D_1 = 42.6\phi$, $R/D_1 = 1.34$
Bend (II)	$D_1 = 42.6\phi$, $R/D_1 = 3.76$





illustrated in Table 3.1. Branch (I) consists of a $1\frac{1}{2}$ inch pipe with another pipe of the same diameter connected as a branch. Branch (II) consists of a $1\frac{1}{2}$ inch pipe with another pipe of $\frac{3}{4}$ inch in diameter connected as a branch. Bend (I) and (II) have the pipes of the same diameter, but they have different R/D, the ratio of radius of curvature (R) to the pipe diameter (D), that is, in the case of Bend (I), R/D = 1.34, while in the case of Bend (II), R/D = 3.76.

The pressure measuring system consists of pressure gauge sensor, strain amplifier, data recorder and electromagnetic oscillograph. As the pressure gauge sensor we used a pressure gauge of semiconductor strain gauge system manufactured by Toyoda Machine Works, Ltd. (Full scale 2.0 kg/cm^{2}G, 10 kg/cm^{2}G, Intrinsic frequency: More than about 40 kHz). The procedure for installing the pressure gauge sensor is illustrated in Fig. 3.10. To amplify the output signals from the pressure convertor, THA-2 Model DC amplifier manufactured by Toyoda Machine Works, Ltd. The output signals from the amplifier were recorded on Data Recorder (FR-1300 manufactured by AMPE or ANALOG-7 manufactured by TEAC) and regenerated by an electromagnetic oscillograph manufactured by Yokogawa Electric Works Co., Ltd.

4. Test Results

4.1 Test Conditions

The test conditions are shown in Table 4.1. In our present test, the branches and bends out of the piping elements composing the secondary loop were taken up and tests were performed with respect to 2 types each of branches and bends having representative dimensions and forms. The secondary loop that was chosen as the subject to the study is one provided by one of the companies who submitted proposals for the first conceptional design for the prototype fast reactor, MONJU. Branch (I) is the model for the T branch of the same diameter near the inlet/outlet of the steam generator. Branch (II) is the model for the branches of different diameters. In the preliminary design, the radius of curvature of the bend is not decided, therefore two types of R/D = 1.34 and R/D = 3.76 were selected arbitrarily. The dimension of the model was made about 1/12.5 in term of the pipe diameter. The positions for measuring pressure waves are illustrated in Fig. 4.2.1, Fig. 4.2.2, Fig. 4.3.1 and Fig. 4.3.2.

As the medium for propagating pressure waves water was selected, at normal temperature, instead of sodium. The differences of the physical property concerned with pressure wave propagation between water and sodium are shown in Table 4.1.1.

As to the input wave form of the pressure wave, a typical example of it is illustrated in 02 of Fig. 4.2.3 "Pressure Wave Form". That is to say, a wave form having the 1st pulse wave in which the rising time (the time up to the peak value) of the pressure wave is about 1.5 msec and the wave height is in the range, 0.5 kg/cm^2G through 7.0 kg/cm^2G followed by some pulse waves was

Table 4.1.1 Comparison of Physical Property between water (at normal temperature and sodium (at 300°C)

	Sodium (300 °C)	Water (20 °C)
Sonic velocity	2400m/sec	1480m/sec
Specific weight	880kg/m^3	998kg/m^3
Coefficient of dynamic viscosity	0.392x10^{-6}m^2/sec	1.01x10^{-6}m^2/sec
Coefficient of viscosity	0.3515x10^{-4}kg.sec/m^2	1.03x10^{-4}kg.sec/m^2

used as the input wave form.

There can be considered some differences in branch loss and bend loss at the branches and bends between the experiment apparatus with which the test was carried out under said conditions and the secondary loop in the real reactor. In other words, it can be thought that the test results obtained by our present experiment apparatus with respect to branch loss and bend loss show lower values mainly because of the different pressure value. Consequently, especially as to the results of tests concerning branch loss and bend loss using our present experiment apparatus, when the test result has exceeded the range of our present test conditions, consideration needs to be given to application of such result.

However, the result of the experiment[6][7] intended to obtain the branch loss using a pulse wave in which the peak value of the pressure pulse in oil is about 100 kg/cm^2 shows that even if the wave height is about 100 kg/cm^2, the branch loss is about 2 to 3%, so that the energy loss of the pressure wave due to branches is considered small even in the secondary loop of a real reactor.

4.2 Test Results and Discussion on Branches (I) and (II)

The pressure wave measuring points for Branch (I) are illustrated in Fig. 4.2.1 and those for Branch II in Fig. 4.2.2. Since it was not possible due to the limit in the number of pressure gauges to measure all the pressure waves at said measuring points at a time, we measured each of them separately and by comparing the result of measurement with the standard point, we made comparison among the measuring points. The measuring results with Branch (I) are illustrated in Fig. 4.2.3 through Fig. 4.2.8 and the measuring results with Branch (II) in Fig. 4.2.9 through Fig. 4.2.14.

The numbers shown at the left end in the diagram corresponds to the measuring points respectively. The manner in which a pressure wave propagates in the experiment apparatus is described with Fig. 4.2.3 as follows. First, the pressure measured at 01 is the result of measurement at a position about 40 mm to 45 mm below the free level in the pressure generating pipe and it can be thought that this pressure wave form is the input wave form to the pressure wave generating pipe. The pressure wave form measured at 02 is the pressure wave form affected by the reflections of the pressure wave given at 01 on the lower fixed end of the pipe and on the upper free surface. (Strictly speaking, the pressure wave form receives also the effect of reflection and transmission by the branch to the testing part at the lower part of the pressure generating pipe, but this effect is small.) The pressure wave form measured at 02 (or 03) is the wave form of the input wave to the testing part.

As to the wave form measured at 1 after the branch, for the period of 0 to 2 msec after the start of the rising of the pressure wave, the wave form of the input wave to the testing part is measured as it is, but 4.76 msec after that (ⓑ in the diagram), this reflected wave is further affected by the pressure wave reflected in the pressure wave generating pipe. Furthermore, 6.45 msec after that (ⓒ in the diagram), it receive the effect of reflection in the pressure wave absorbing pipe (1) and 7.2 msec after that (ⓓ in the diagram), it receives the effect of the pressure wave absorbing pipe (II). After that, it becomes a complex wave form as a result of receiving the effects of reflection and transmission at each place.

As to the pressure wave form measured at 9' in the rear of the branch, for the period, 0 to 4.5 msec, only the input wave form to the testing part having been transmitted through the branch is measured and after 4.5 msec (ⓔ in the diagram), it is affected by the reflected wave in the pressure wave absorbing pipe (II). After that, same as ①, it becomes a complex wave form as a result of receiving the effects of reflection and transmission at each place. The pressure wave forms in other places can be explained in the same manner.

Consequently, as to the pressure wave form measured at the testing part, for the period of about 2 msec from the start of the rising of the pressure wave (by the time the peak value of the 1st pulse wave has passed), a wave form having received the effect of at least only the branch which is the testing part but free of any effect of the reflected waves at other places is measured. In other words, if we arrange the result of experiment with respect to the 1st wave only, we can say that the result catches the effect of branches only.

4.2.1 Velocity of Pressure Wave Propagation in Piping

The velocity of pressure wave propagation in piping was obtained by measuring the time taken for the 1st peak of a pressure wave to travel between 2 points. As the distance between 2 points, the following were used, that is, (02) - ②, (03) - ⑥, ① - ⑧, (03) - ⑤, ① - ⑦, ① - ⑨, (02) - ⑨, ① - ⑨′ and (02) - ⑨′ for Branch I and (02) - ②, (02) - ⑥, ① - ②, ④ - ⑥, ① - ⑥, (02) - ① and ④′ - ⑥′ for Branch II. The results of measurements of propagation velocity are illustrated in Fig. 4.2.12.

In both cases of Branch I and II, each measuring value has the variance of ±5 around the calculation value 1387 m/sec, but this is thought ascribed to the measuring error at the time of reading the required time from the experiment data since the time taken for the pressure wave to travel the distance is very short due to the short distance between the two points. The values shown in the Table in Fig. 4.2.12 are the mean values for each data, that is, the values are 1384 m/sec for Branch I and 1390 m/sec for Branch (II). The calculated value is 1387 m/sec, showing a very satisfactory coincidence with the experiment value, with the error of the measured value being only -0.2%.

Used for the calculation was Allievi's equation in which modulus of elasticity of the piping material, fixing conditions of the piping and the ratio of wall thickness and diameter of piping which give effects on the propagation velocoty are taken into account.

$$Vtr = \sqrt{\frac{1}{\frac{w}{g}\left(\frac{1}{k} + \frac{C_1 D}{E e}\right)}} \qquad (4.2.1)$$

Vtr : Propagation velocity of pressure wave (m/sec) w : Specific weight of fluid (kgf/m^3)

g : Acceleration of gravity = 9.8 m/sec.

C_1 : Constant decided by the fixing conditions of piping. It was assumed as $C_1 = 0.95$. The value of C_1 varies with the fixed conditions of the piping as follows:

Ⓐ In case the upper end of the pipe is fixed and there is provided no expansion joint,

$C_1 = \frac{5}{4} - \mu$ μ : Poisson's ratio of the piping material

Ⓑ In case the pipe is fixed for the entire length so that no movement in vertical direction can be made,

$C_1 = 1 - \mu^2$

Ⓒ In the case of a duct where an expansion joint is provided,

$C_1 = 1 - \frac{\mu}{2}$

It is not clear which one out of said 3 cases of Ⓐ, Ⓑ and Ⓒ our experiment apparatus corresponds to. It may be in between Ⓐ and Ⓑ, but the effect due to the way of selecting the fixed conditions on the propagation velocity is so small that there is little difference between the results of calculation made using the case Ⓐ and Ⓑ.

D/e : Ratio of diameter to wall thickness of piping

K : Modulus of bulk elasticity of water (kg/m^2)

The modulus of bulk elasticity of water was obtained from the experiment equation of sonic velocity in water as follows:

$$u = 1402.736+5.03358T-0.0579506T^2+3.31636\times10^{-4}\times T^3 -1.45262\times10^{-6}\times T^4+3.0449\times10^{-9}\times T^5$$ (8)

(u: m/sec, T: °C)

E : Modulus of longitudinal elasticity of piping material (kg/m^2)

4.2.2 Reflection and Transmission of Pressure Wave at Branch Part and Pressure Wave Form in the neighborhood of Branch Part

The results of measurements in the neighborhood of a branch part (1D in front of the branch, branch point and 1D, 2D, 3D, 4D, 5D and 10D in the rear of the branch) in the case of Branch (I) are illustrated in Fig. 4.2.3 through Fig. 4.2.8. The results of measurements in the neighborhood of a branch part (1D in front of the branch, branch point and 1D and 10D in the rear of the branch) in the case of Branch (II) are illustrated in Fig. 4.2.9 through Fig. 4.2.11. As it can be seen from the diagrams, the pressure wave form at each measuring point shows almost the same form by the time it receives the effect of the reflected wave. (The mark ⓖ given at each measuring point represents the time when the pressure wave form receives the effect of a reflected wave from the bend in case there is assumed reflection of pressure wave at the bend and ⓗ represents the time when the pressure wave form receives the effect of a reflected wave from the pressure absorbing pipe (I) or (II). Even if there is assumed reflected waves from the bend, it can be thought that the quantity is very small, so that the wave form for the period from the rising time of the pressure wave till ⓗ is compared.)

Further, as described below, the wave height measured at each measuring point shows almost the same value as illustrated in Fig. 4.2.13 and Fig. 4.2.14. (within ±3%) Consequently, it can be thought that in the neighborhood of a branch, the pressure wave in propagated with the same wave form and wave height values.

In the branch, part of the pressure wave is reflected and the rest are transmitted. In Fig. 4.2.13 and Fig. 4.2.14 are illustrated the result of measurement of the peak value of the 1st pulse at each measuring point. The value is shown in term of the ratio to the peak value at ① in front of the branch. Consequently, at the measuring points after the branch (③ - ⑨, ④ - ⑨) it shows transmission factors. (s=Ftr/Fin, Ftr: Pressure wave having passed through the branch, Fin: Pressure wave coming into the branch, s: transmission factors.) The value at the measuring point ② is

$$\frac{\text{Fin} + \text{Fret}}{\text{Fin}} = 1 + r = \mathbf{r}$$

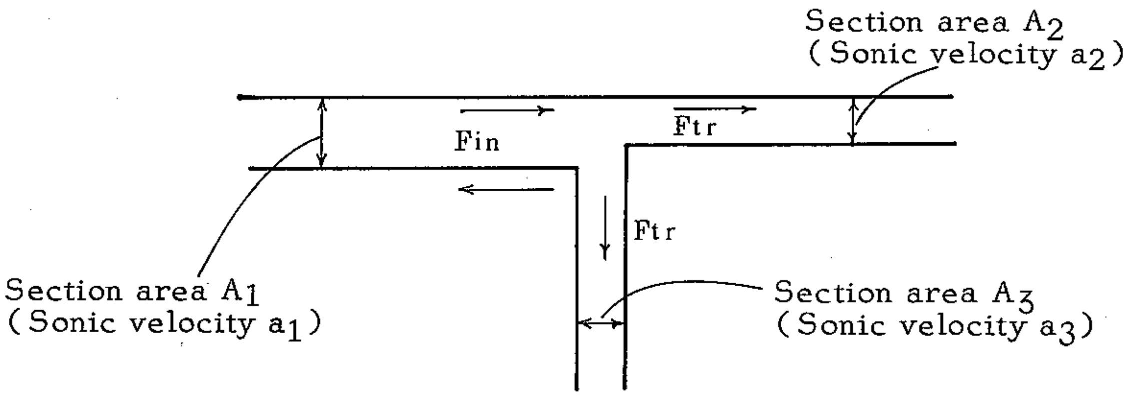
(Fret: Reflected wave, r: Reflection factor)

That is to say, at ② also, the value shows transmission factor. (If 1 is subtracted from the value in the diagram, reflection factor can be obtained.)

As to the measured values in Branch (I) and (II), almost all the calculated values (0.66 and 0.88 respectively) are within the range of ±3%. It can be said that there is a good agreement between the experimental result and the calculated one. Calculation was performed using the following equations for calculation giving the reflection factor and transmission factor of pressure wave at the branch point in case attenuation of pressure wave due to the friction of a fluid with wall and due to the branch loss at the branch point are ignored.

$$S = \frac{2A_1/a_1}{A_1/a_1 + A_2/a_2 + A_3/a_3} \qquad (4.2.2)$$

$$r = 1 - S \qquad (4.2.3)$$



From the fact that a quite satisfactory coincidence was shown between the value calculated using Equation (4.2.2) and the experiment value, we can see that the attenuation of the pressure wave at the branch point and the reflection of the pressure wave subsequent to branch loss can be ignored almost entirely.

As a result of the experiments with Branches (I) and (II), the following matters have become known.

(1) When the pressure waves propagates in a branch, its wave form and wave height are almost same regardless of places. Consequently, even if another piping element is provided near the branch, it can be handled as a simple body with respect to the branch.

(2) Even when evaluating pressure wave propagation paying attention to a branch and the neighborhood of a branch, it can be thought that one-dimensional handling of it is available as the difference of two-dimensional (or three-dimensional) pressure wave form need not be considered.

(3) Attenuation of the pressure wave in a bend or reflection of the pressure wave as a result of a branch loss can be ignored almost entirely in the range of our present experiment.

(4) Further, since the pressure wave forms in the neighborhood of a branch are almost the same, even in the case of a branch where the branch angle is any other than 90°, it can be thought that the pressure wave propagate in the same manner as in the case of a 90° branch.

4.3 Test Results with Bends (I) and (II) and Discussion thereof

The pressure wave measuring points in the case of Bend (I) are illustrated in Fig. 4.3.1 and the pressure wave measuring points in the case of Bend (II) are illustrated in Fig. 4.3.2. Since measurement of the pressure wave at all the measuring points at a time cannot be performed, same as the case of branches, due to the limit in the number of pressure gauges, they were measured separately and by comparing the results of measurements with the standard point, comparison among the measuring points was made.

The results of measurements in the case of Bend [I] are illustrated in Fig. 4.3.3 through Fig. 4.3.8. The results of measurements in the case of Bend [II] are illustrated in Fig. 4.3.9 through Fig. 4.3.12.

The numbers shown at the left end of the diagram correspond to the measuring position Nos. respectively.

Taking up Fig. 4.3.3 as an example, the pressure wave form at each measuring point in case it is assumed that the pressure wave receives the effect at the bend part (partly reflected) as described later is examined as follows. First, the pressure wave at ⑮05 shows the same wave form as that at the measuring point ⓪02 in the test conducted with a branch and this wave form is the input wave form to the testing part.
The wave form measured at ① is the pressure wave form at a position about 1400 mm after the branch.
If a pressure wave is reflected at a bend, up to about 2 msec after

the start of the rising of the pressure wave (ⓐ in the diagram), the input wave form to the testing part will be measured as it is, but after 2 msec, the wave form receives the effect of the reflected wave at the bend and after about 4.2 msec (ⓑ in the diagram), the wave form receives the effect of the reflected wave at the bend part in the rear. Further, after 5.97 msec (ⓒ in the diagram), it receives the effect of the pressure wave subsequent to re-reflection in the pressure wave generating pipe of the wave reflected in the forward bend (the test bend). After that, it receives the effect of the pressure wave reflected at each place to become a complex wave form. As to the pressure wave form at ⑥ in the rear of the bend, for the period from 0 to 2.1 msec, only the pressure wave form which has passed the test bend out of the pressure wave having propagated from the pressure wave generating pipe to the testing part is measured and after 2.1 msec (ⓓ in the diagram), it receives the effect of the bend in the rear and after 3.12 msec (ⓔ in the diagram), it becomes the pressure wave form affected by the reflected wave in the pressure wave absorbing pipe at the final end of the testing part.

The description provided above concerns the case where a pressure wave is reflected at a bend part, but in case a pressure wave is not affected at all at the bend part, the pressure wave form at each measuring point first receives the effect of the reflected wave in the pressure wave absorbing pipe at the final end of the testing part. The time the pressure wave starts receiving said effect varies with each measuring point (In each measurement, the pressure wave starts receiving the effect at the time shown at ⓖ in the diagram.) It is at the measuring point ⑩ that the pressure wave starts receiving the effect earliest, that is, it starts receiving the effect 3.12 msec after the start of the rising of the pressure wave. It is at the measuring point ① that the pressure wave start receiving the effect latest, that is, it starts receiving the effect 7.14 msec after the start of the rising of the pressure wave. Consequently, in case it is assumed that there are reflections of pressure waves at the bend part, the 1st pulse is of a wave form free of the effect of the reflected wave.

4.3.1 Velocity of Pressure Wave Propagation in Piping

Same as the case of branches, the velocity of pressure wave propagation in piping was obtained by measuring the time taken for the 1st peak value of the pressure wave to travel between 2 points. As the distance between the 2 points, the following were used, that is, (05) - ①, (05) - ②, (05) - ⑩, (05) - ⑦, ⑥ - ⑩, ① - ⑩, ① - ⑦, (05) - ⑧, ① - ② for Bend I and (05) - ②, (05) - ⑯, (05) - ㉖, ① - ②, ① - ⑯, ① - ㉖, ① - ⑤, ① - ⑥, ① - ⑦ for Bend II. The measuring results of propagation velocity are illustrated in Fig. 4.2.12.

In both cases of Bend (I) and Bend (II), each measuring point has the variance of ±5% around the calculation value 1387 m/sec, but this is thought ascribed, same as the experiment result with brands, to the measuring error at the time of reading the required time from the experiment data since the time taken for the pressure wave to travel the distance is very short due to the short distance between the two points. The values shown in the Table in Fig. 4.2.12 are the mean values for each data, that is, the values are 1384 m/sec for Bend (I) and 1354 m/sec for Bend (II). The calculated value is 1387 m/sec, with the error of the measured value being +0.2% for Bend (I) and -2.4% for Bend (II), showing a very satisfactory coincidence between measured value and calculated one Equation (4.2.1) was used for calculation.

4.3.2 Pressure Wave Form in the neighborhood of Bend Part

The results of measurements in the neighborhood of the bend part with respect to Bend (I) are illustrated in Fig. 4.3.3 through Fig. 4.3.8.

(In the cases of Fig. 4.3.4 and Fig. 4.3.5, the pressure scale at each measuring point is almost same, but in the cases of other diagrams, the pressure scale varies with each measuring point.)

The term "Neighborhood of Bend" used here refers to the measuring points, ②, ③, ④, ⑤, ⑥, ⑦ and ⑧. As it can be seen from the diagrams, the pressure wave forms at these measuring points are almost the same up to the time (g in the diagram) they starts receiving the effect of the reflected waves from the pressure wave absorbing pipe. Further, as it can be seen from Fig. 4.3.5 through Fig. 4.3.8, the pressure waves are of the same wave form regardless of the input wave form. In Fig.4.3.13 are illustrated the peak values of the 1st pulse wave at each measuring point as described later. In the neighborhood of the bend, these values are almost within the range of ±5% of the mean value.

Consequently, in the neighborhood of the bend, it can be thought that pressure wave is propagated with the same values of wave form and wave height.

Examples of the measuring result of pressure wave forms in the neighborhood of the bend part with respect to Bend (II) are illustrated in Fig. 4.3.9 through Fig. 4.3.12. (In each diagram, the pressure scale varies with the measuring point.) The term

"Neighborhood of the bend part" refers to the measuring points, ②, ⑤, ⑥, ⑦, ⑪, ⑫, ⑬, ⑮, ⑯ and ⑰. As it can be seen from the diagrams, the pressure wave at these measuring points has almost the same form. However, in the case of Bend (II), with the exception of the measuring point ②, the pressure wave forms are almost identical, even after 5.1 msec (ⓖ in the diagram) when pressure wave starts receiving the effect of reflected waves from the pressure wave absorbing pipe at the final end of the testing part, but as to the measuring point ②, the wave pressure after 5.4 msec (g in the diagram) when the pressure wave starts receiving the effect of reflected waves show a wave form rather different from other wave forms measured. This can be thought ascribed to the difference in the time when a pressure wave receives the effect of reflected waves, but further study of it needs to be made. In any case, by the time the pressure wave receives the effect of reflected waves, it can be thought that it is of almost the same wave form. As it is described later, in Fig. 4.3.14 are illustrated the peak values of the 1st pulse at each measuring point, and in the neighborhood of the bend, almost all values are within ±3% of the mean value. Consequently, as to Bend (II) also, it can be thought that pressure wave in the neighborhood of a bend is propagated with the same wave form and wave height.

In Fig. 4.3.13 and Fig. 4.3.14 are illustrated the peak values of the 1st pulse wave out of the pressure wave propagated in the bend part. The measured values are shown in term of the ratio to the peak value at ① before the bend. As it can be seen from the diagrams, in each case of Bend (I) and Bend (II), the wave height in the neighborhood of the bend is constant regardless of the measuring point, showing the value about 0.92 to 0.93 times the wave height value at ① before the bend. Consequently, as described above, it can be thought that when the pressure wave is propagated in a bend part, it is propagated with almost the same pressure wave form and wave height regardless of the measuring position.

Incidentally, in both cases of the experiment result with Bends (I) and (II), the wave height value in the neighborhood of a bend shows a value lower than the wave height value measured before the bend, that is, the former is about 0.92 to 0.93 of the latter. So far, in connection with water hammer and so on, the bend part has been handled same as a straight pipe. But the result of our present experiment shows that unlike the case of a straight pipe, when the pressure wave is propagated in the bend part, it receives some effects there.

What sorts of effects the pressure wave receive in the bend part is not yet known at the present stage, but in view of the fact that the wave height values immediately before and after the bend are identical, it can be thought that the pressure wave does not suffer any energy loss in the bend part but part of the pressure wave is reflected in the bend part. As to the problem that the pressure wave receives some effects in the bend part, the phenomenon that the measured values immediately before the bend in the rear of the branch (at the measuring points ⑥ and ⑥' in the Figure 4.2.7) are rather lower than the measured values immediately after the branch as shown in the experiment result in the case of Branch (II) also suggests that the pressure wave receives some effects. However, the fact that in Fig. 4.3.13, the measured value at the measuring point ⑩ shows the same value as the values measured at other points (Since at the measuring point ⑩ , the pressure wave must receive the effect of the bend in the rear, the value measured ought to be rather lower.) is contradictory to the fact that the pressure wave receives the effect in the bend part. We think, therefore, this requires further study in future.

The following matters have become known from the results of tests with Bends (I) and (II).

(1) When the pressure wave propagate in a bend part, its wave form and wave height are almost constant regardless of places in the neighborhood of the bend part. Consequently, even if another piping element is provided near the bend, it can be handled as a simple body with respect to the bend.

(2) Even when evaluating pressure wave propagation paying attention to a bend part or the neighborhood of the bend part, it can be thought that one-dimensional handling of it is available as the difference of two-dimensional (or three-dimensional) pressure wave form need not be considered.

(3) It can be thought that the energy loss of the pressure wave in a bend part can be ignored almost entirely within the range of our present experiment.

(4) It can be thought that when propagating in a bend part, the pressure wave receives certain effects (for example, part of it is reflected.), but further study is required of it.

5. Conclusion

As a result of our experiments on pressure wave propagation using an input wave in which the rising time is about 1.5 msec and the wave height is 0.5 kg/cm^2 - 7.0 kg/cm^2 with respect to the respective models of a branch and bend having typical dimensions and forms out of the component piping element of the secondary loop of the prototype fast reactor, MONJU, the following matters have been known.

(1) We studied in detail the wave forms and wave heights of the pressure wave propagating in a branch part and bend part at various measuring points in the neighborhood of the branch and bend and found that the values are almost identical regardless of the measuring point, showing an agreement with the result of the conventional handling method.

Consequently, even when considering the pressure wave propagation paying attention to the places quite near the branch part or bend part, two-dimensional (or three-dimensional) pressure wave propagation difference need not be considered.

(2) Consequently, even if another piping element is provided close to the branch or bend, the branch or bend can be handled as a simple body.

(3) The energy loss of the pressure wave in the branch part can be ignored almost entirely within the range of our present experiment. As to the bend part also, it can be thought that the energy loss of the pressure wave can be ignored almost entirely within the range of our present experiment.

(4) As to the bend, when the pressure wave propagates in the bend, it is thought that the pressure wave receives certain effects, but further study is required of it.

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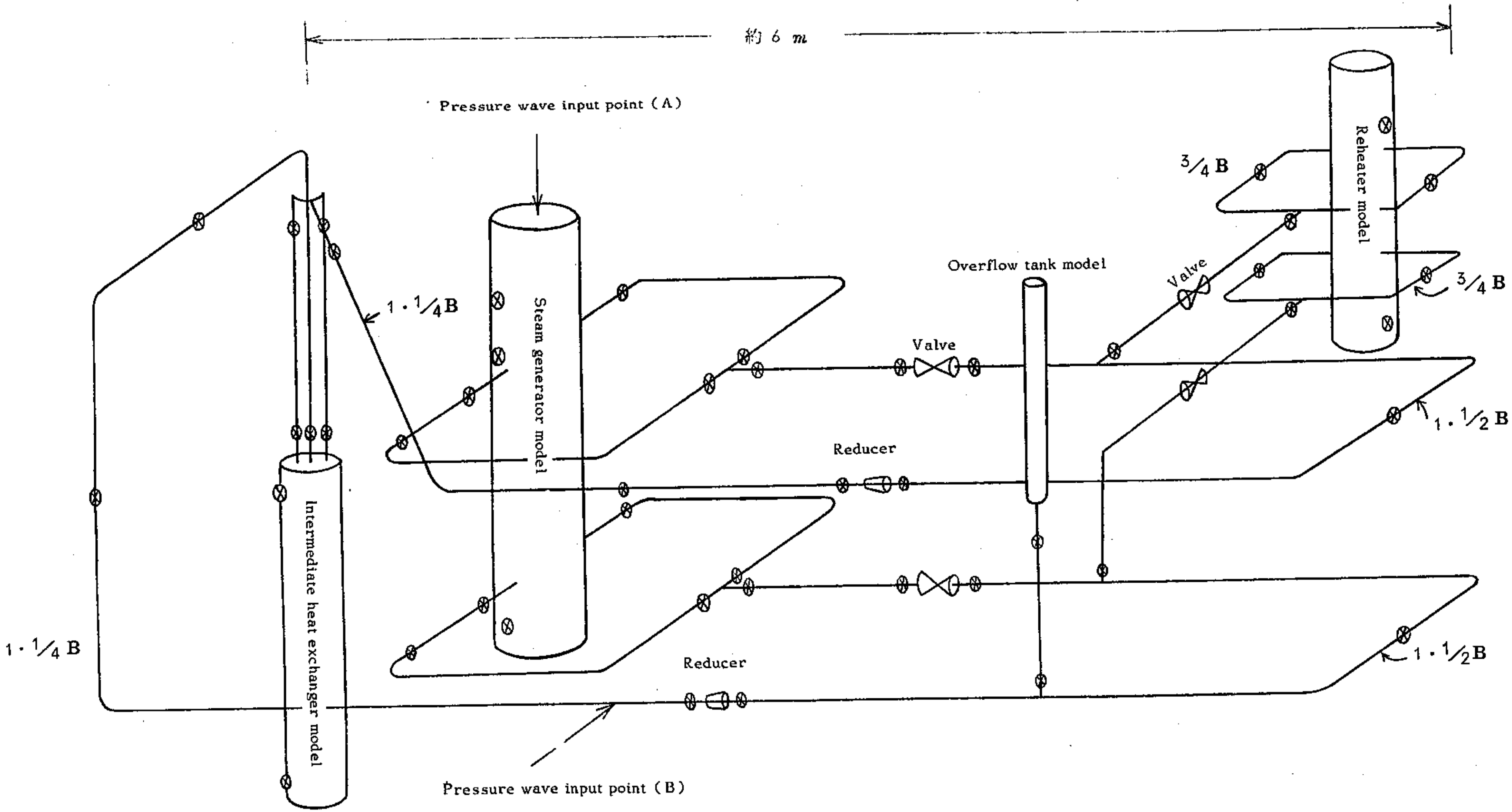


Fig. 2.1 Rough Diagram of A Reduced Model of Secondary Loop of Prototype Reactor

⊗ mark ... Pressure measuring point

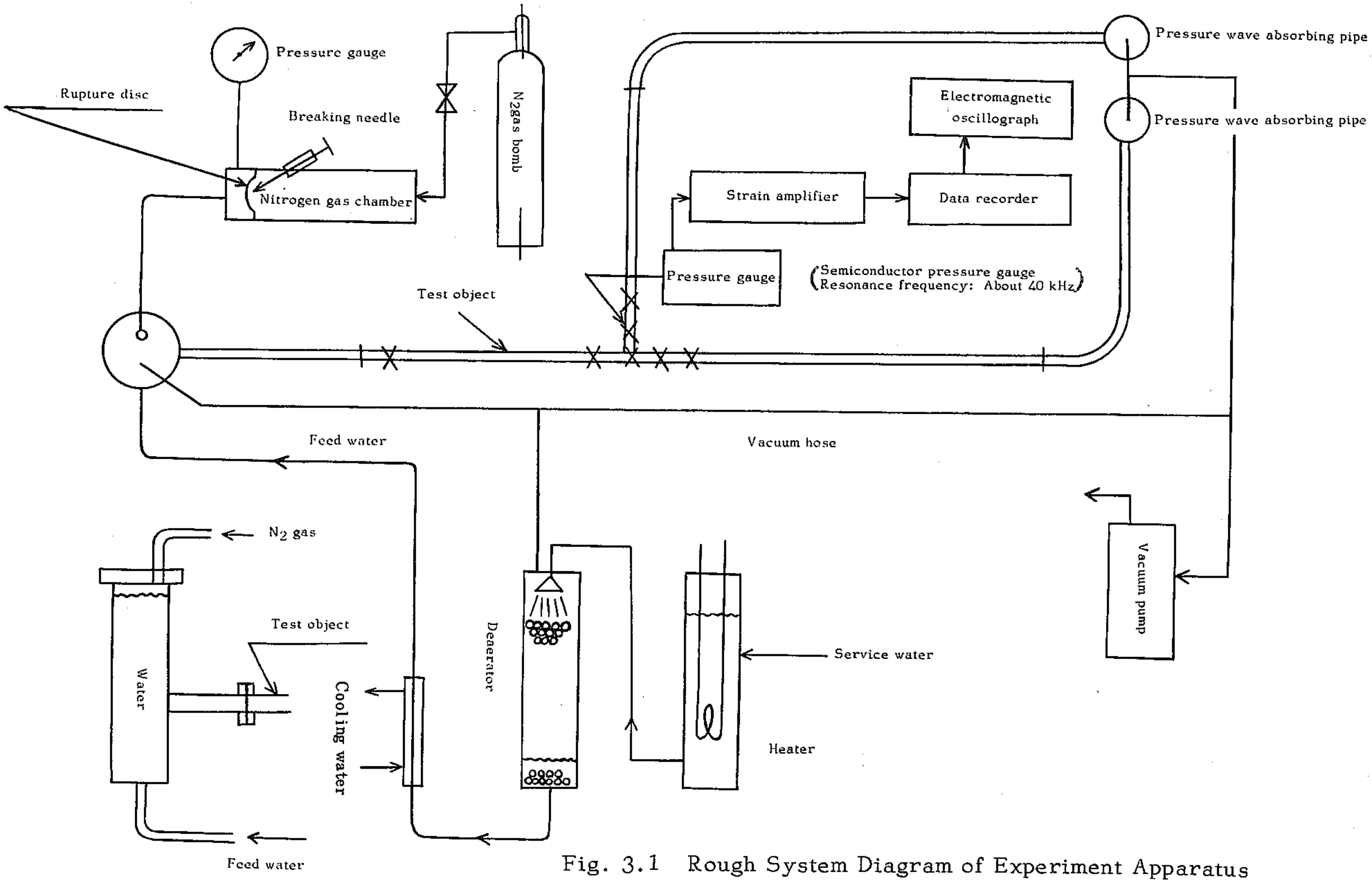


Fig. 3.1 Rough System Diagram of Experiment Apparatus

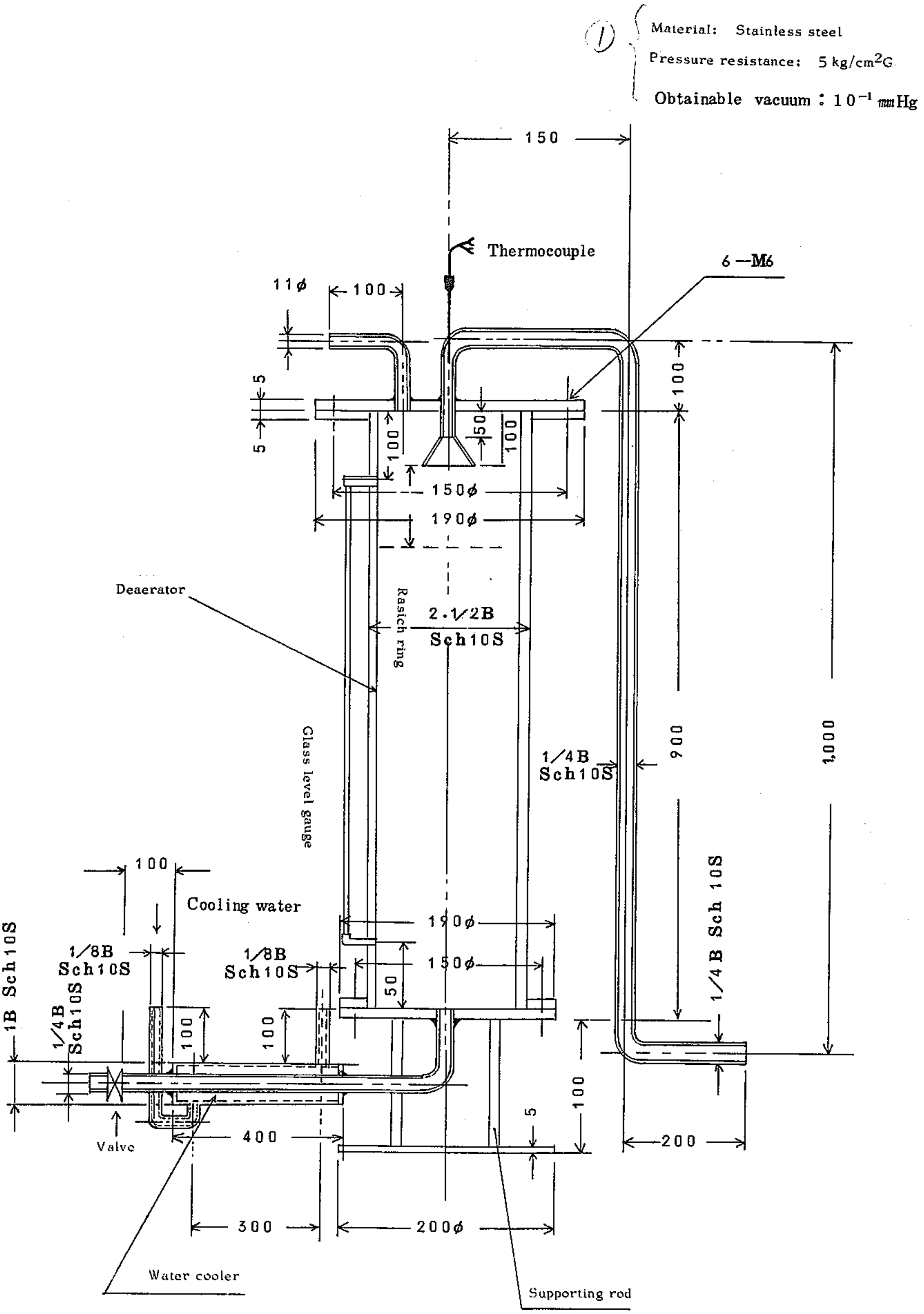


Fig. 3.2 Deaerator

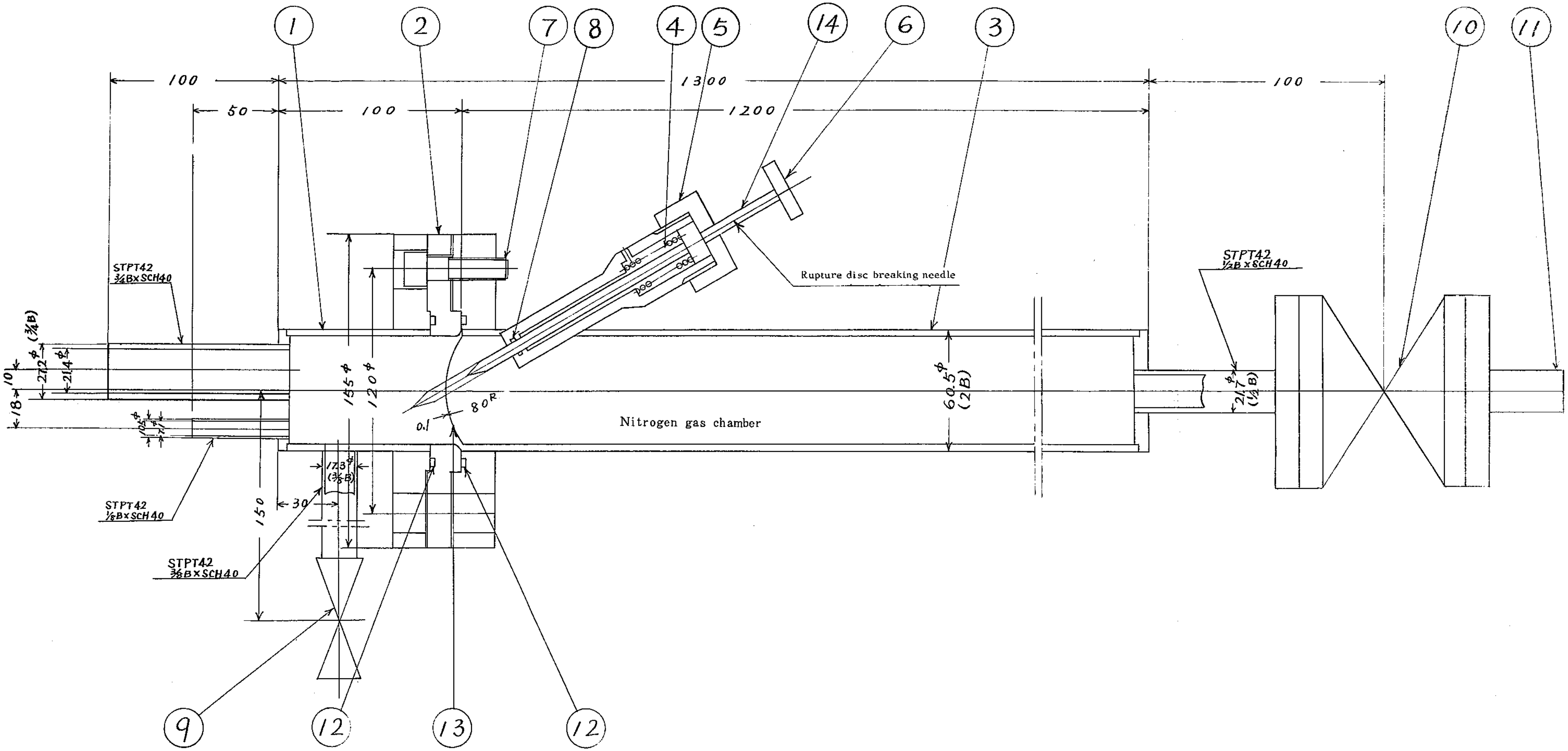
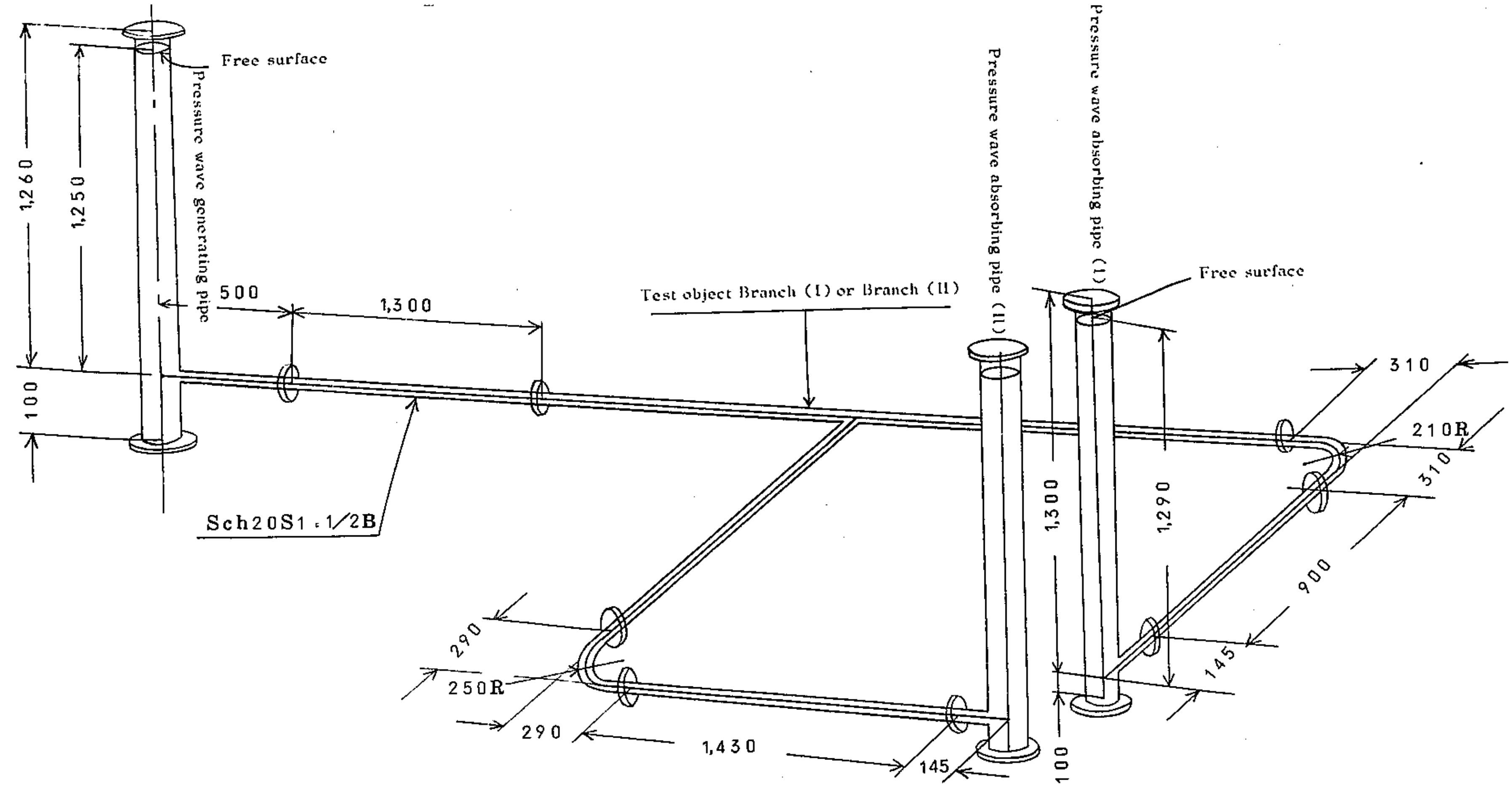


Fig. 3.3　　pressure wave generator



Pressure wave generating pipe	SUS 27	4B Sch 20 S
Pressure wave absorbing pipe (I)	SUS 27	3B Sch 20 S
Pressure wave absorbing pipe (II)	SUS 27	3B Sch 20 S
Other pipes	SUS 27	1.1/2B Sch 20 S

The pressure wave absorbing pipe (I) and (II) have the same dimensions

Fig. 3.4 Sketch of Testing Part for Branches (I) and (II)

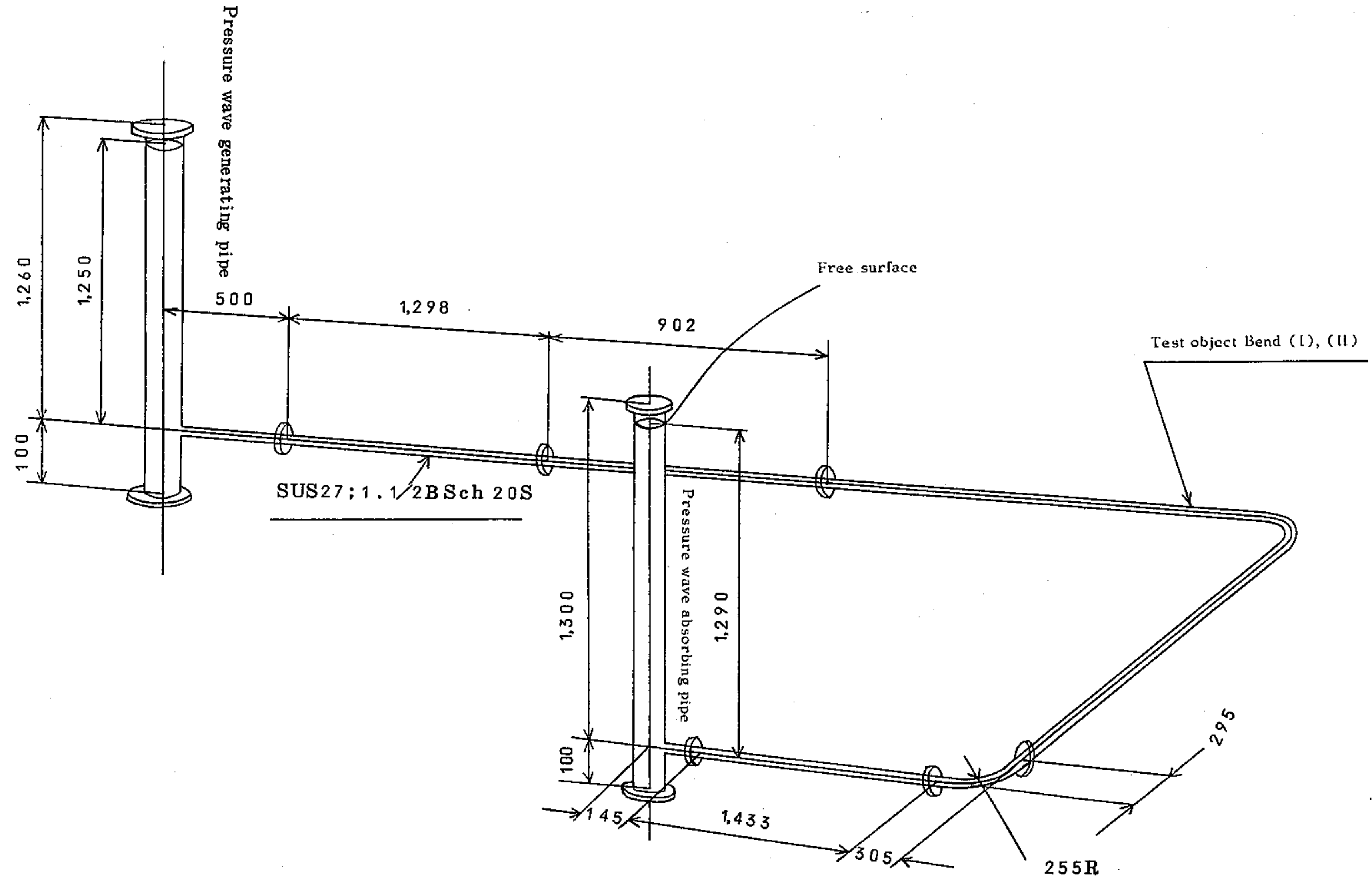


Fig. 3.5 Sketch of Testing Part for Bend (I), (II)

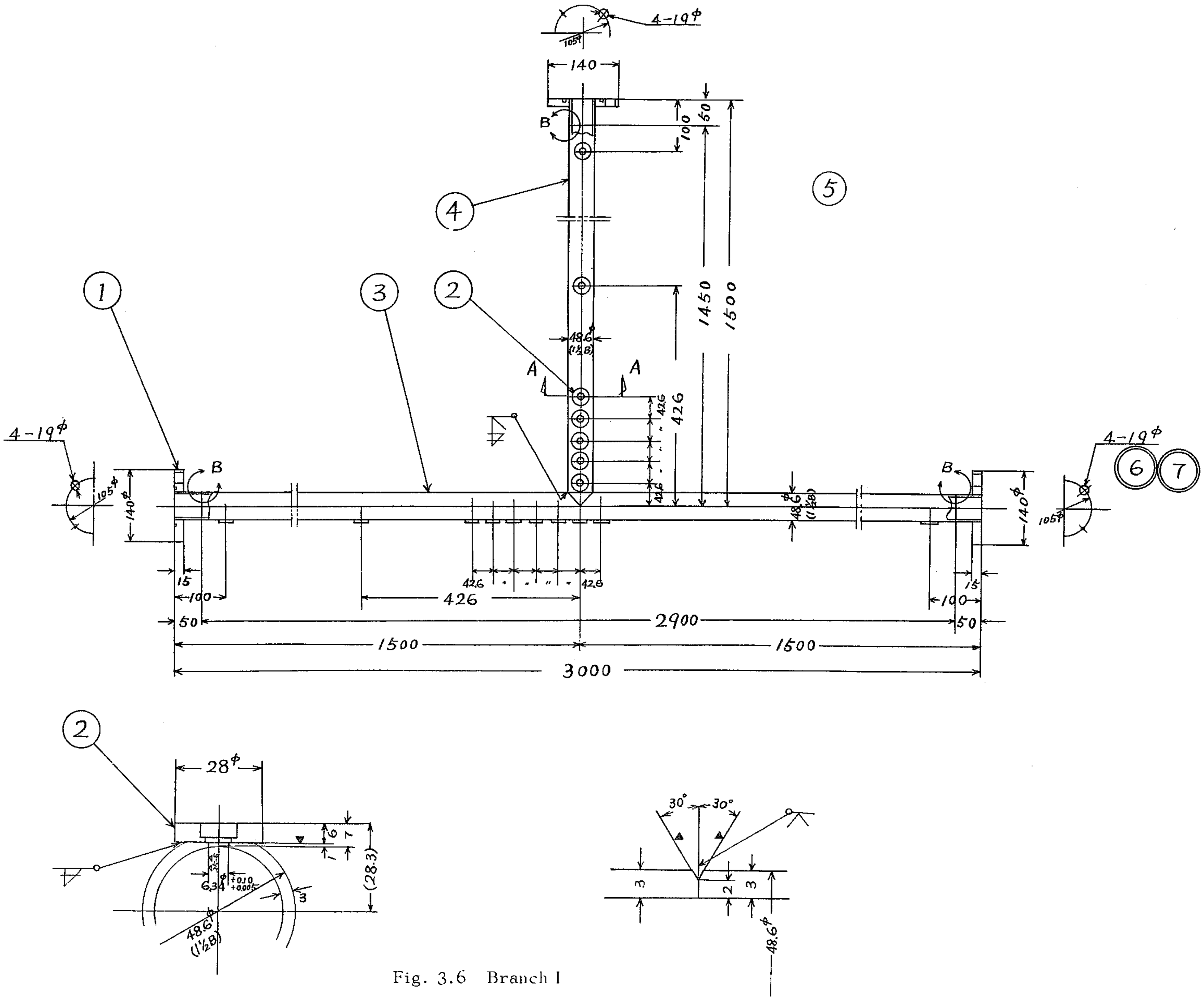


Fig. 3.6 Branch I

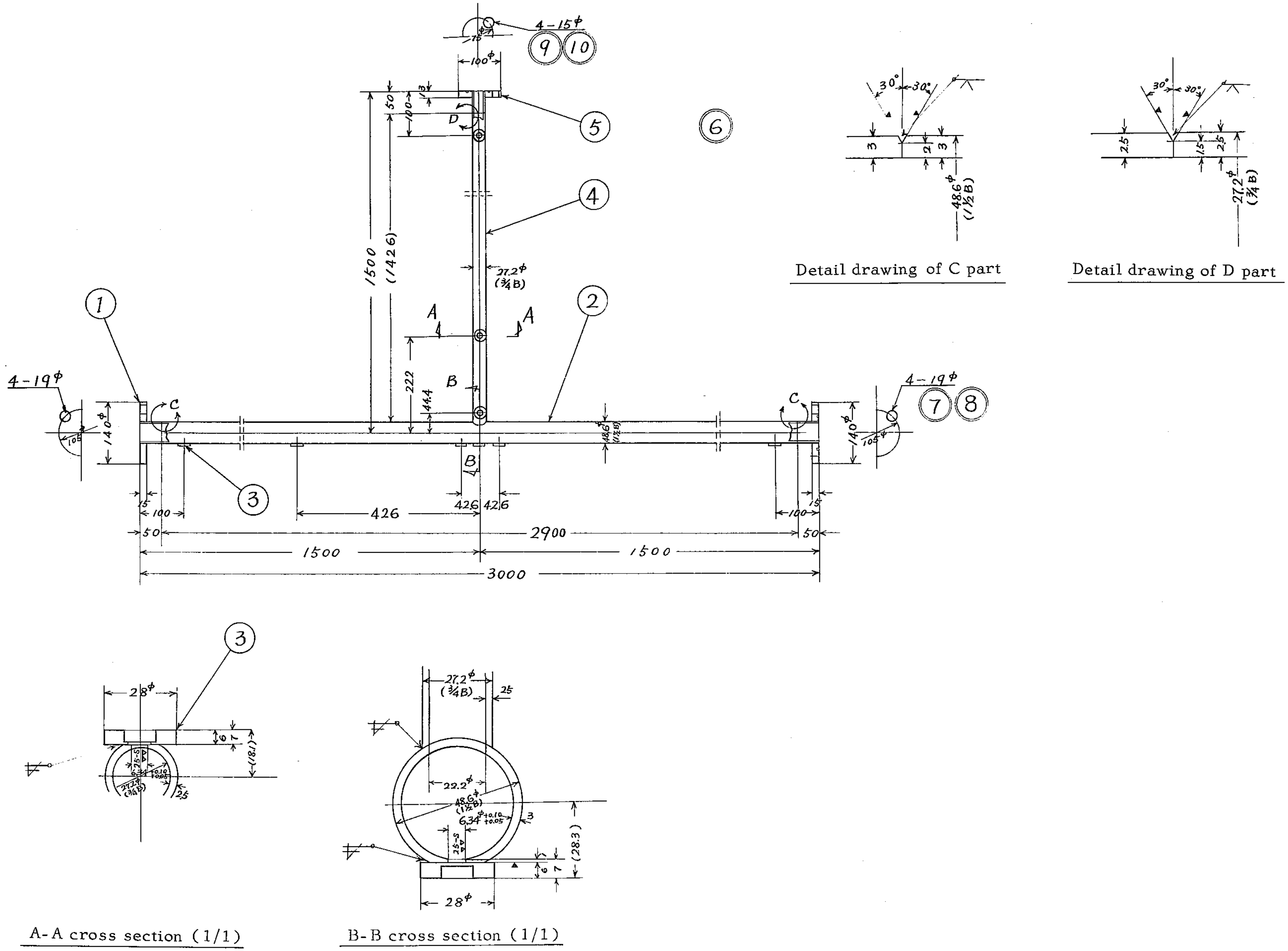


Fig. 3.7 Branch (II)

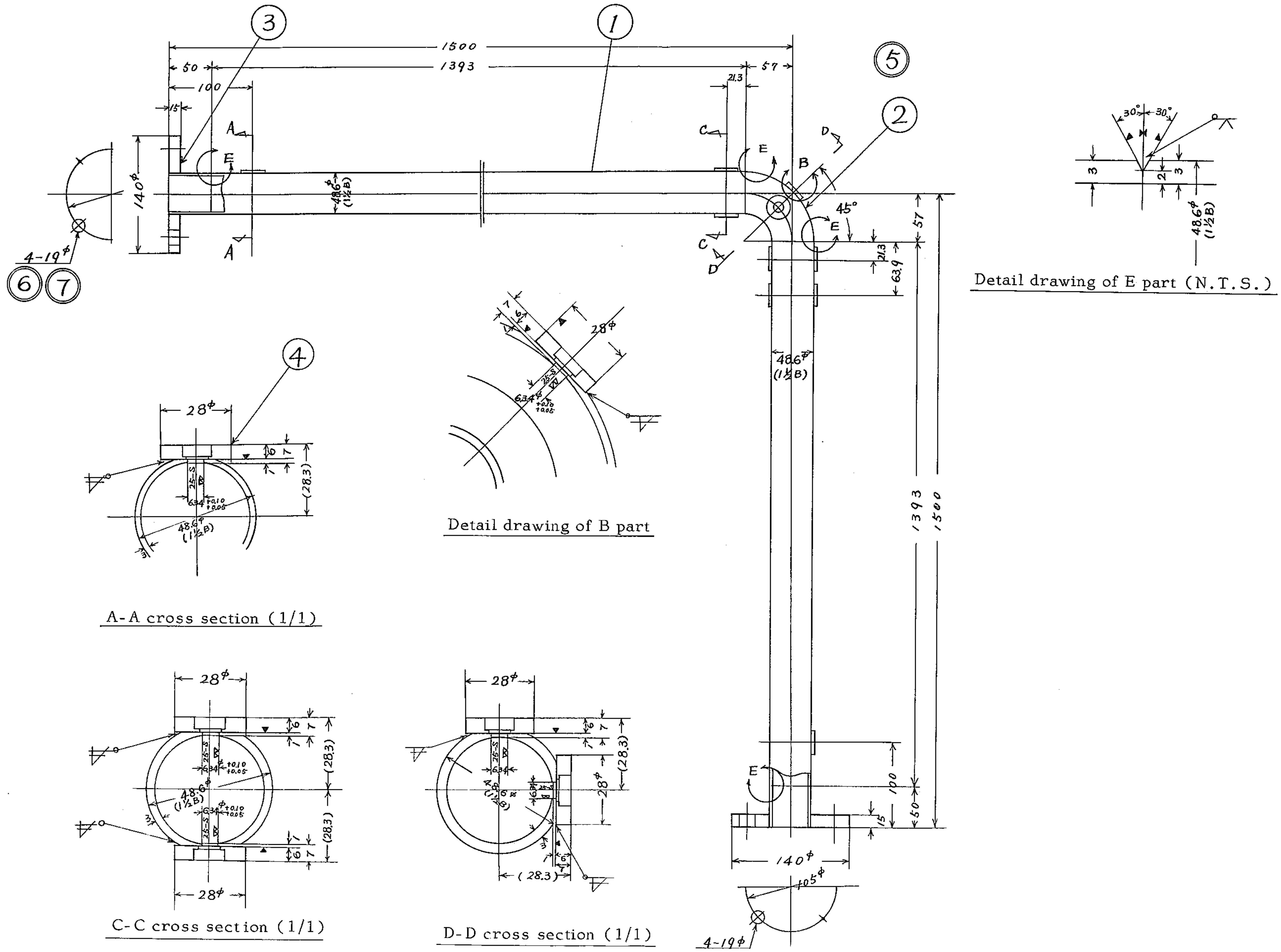

1500
1393
50
100
15
57
21.3
A
C
D
E
B
45°
48.6φ (1½B)
140φ
4-19φ
105φ
63.9
28φ
25-S
(28.3)
Detail drawing of E part (N.T.S.)
30°
Detail drawing of B part
A-A cross section (1/1)
C-C cross section (1/1)
D-D cross section (1/1)

Fig. 3.8 Bend (1)

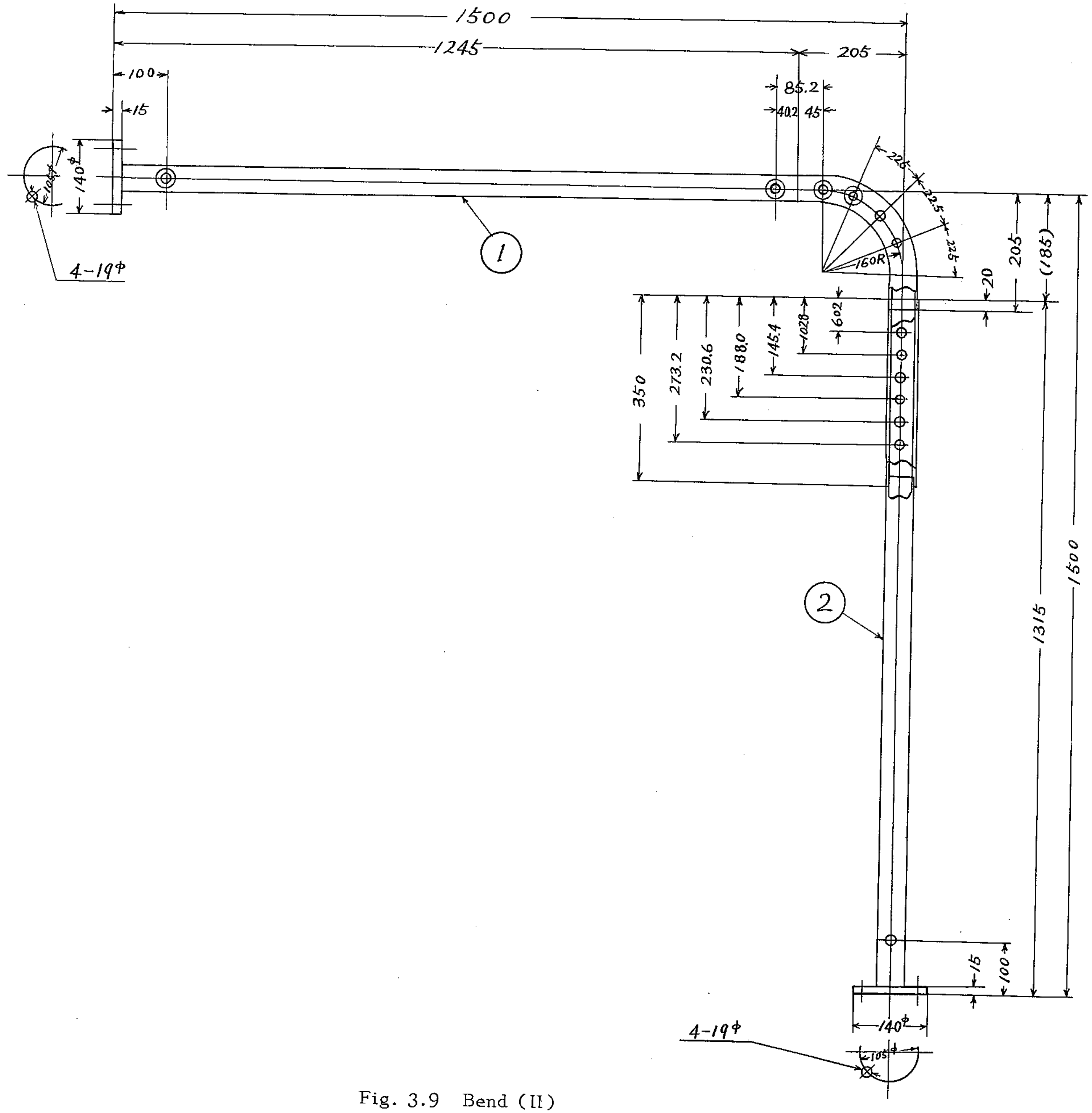


Fig. 3.9 Bend (II)

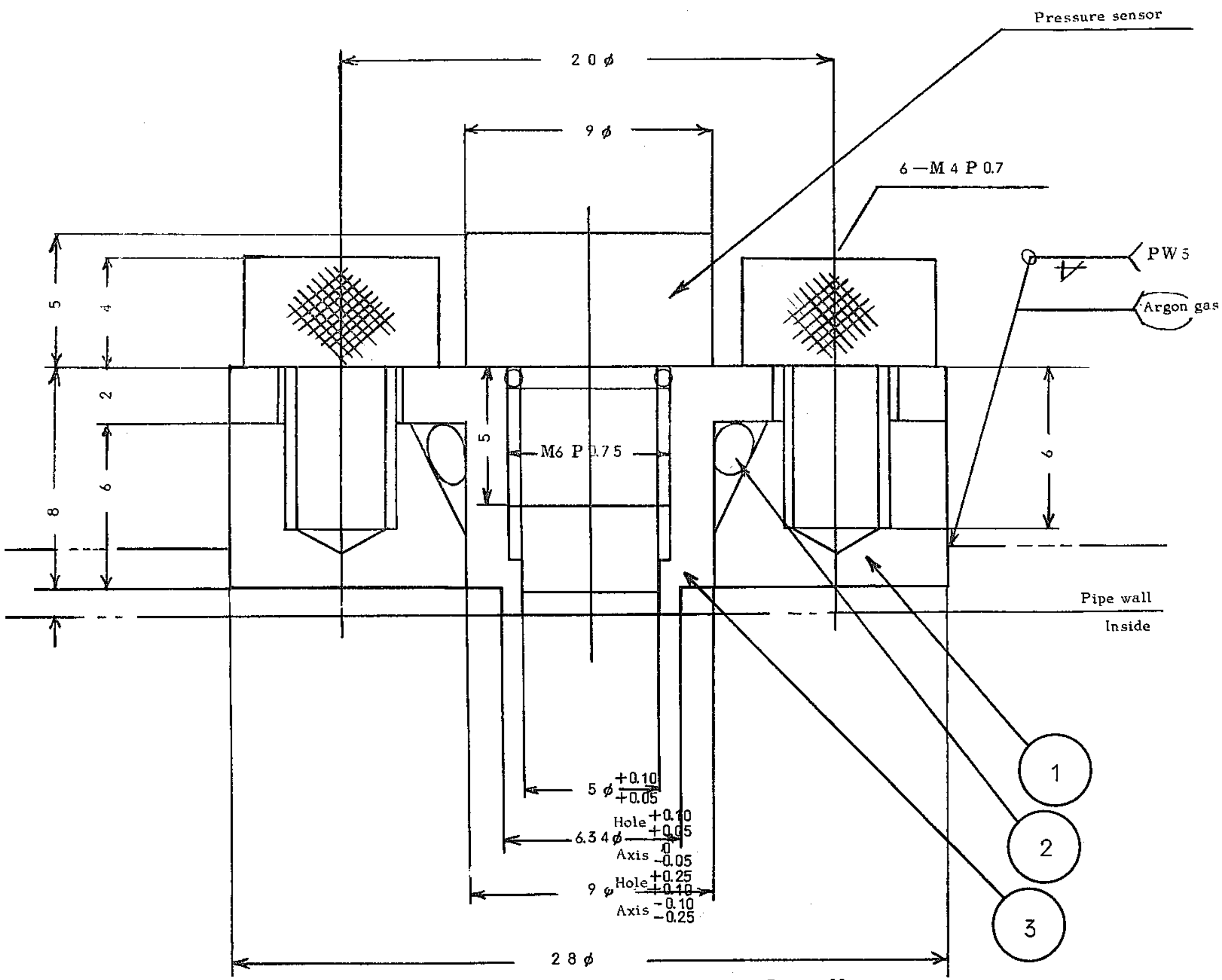


Fig. 3.10 Pressure Gauge Installation

Table 4-1-1 Table of Test Conditions

Test Object	Pipe Diameter	Water Temperature	Pressure Range	Pressure Pulse Rising Time
Branch I	42.6φ 42.6φ 42.6φ	25.5°C	0.5Kg/cm² ~ 3.0Kg/cm²	About 1.5 msec
Branch II	42.6φ 42.6φ 22.6φ	25.5°C	0.8 Kg/cm² ~ 3.5 Kg/cm²	About 1.5 msec
Bend I	42.6φ R = 57 mm	25.5°C	0.7 Kg/cm² ~ 4.7 Kg/cm²	About 1.5 msec
Bend II	42.6φ R = 160 mm	25.5°C	0.7 Kg/cm² ~ 6.0 Kg/cm²	About 1.5 msec

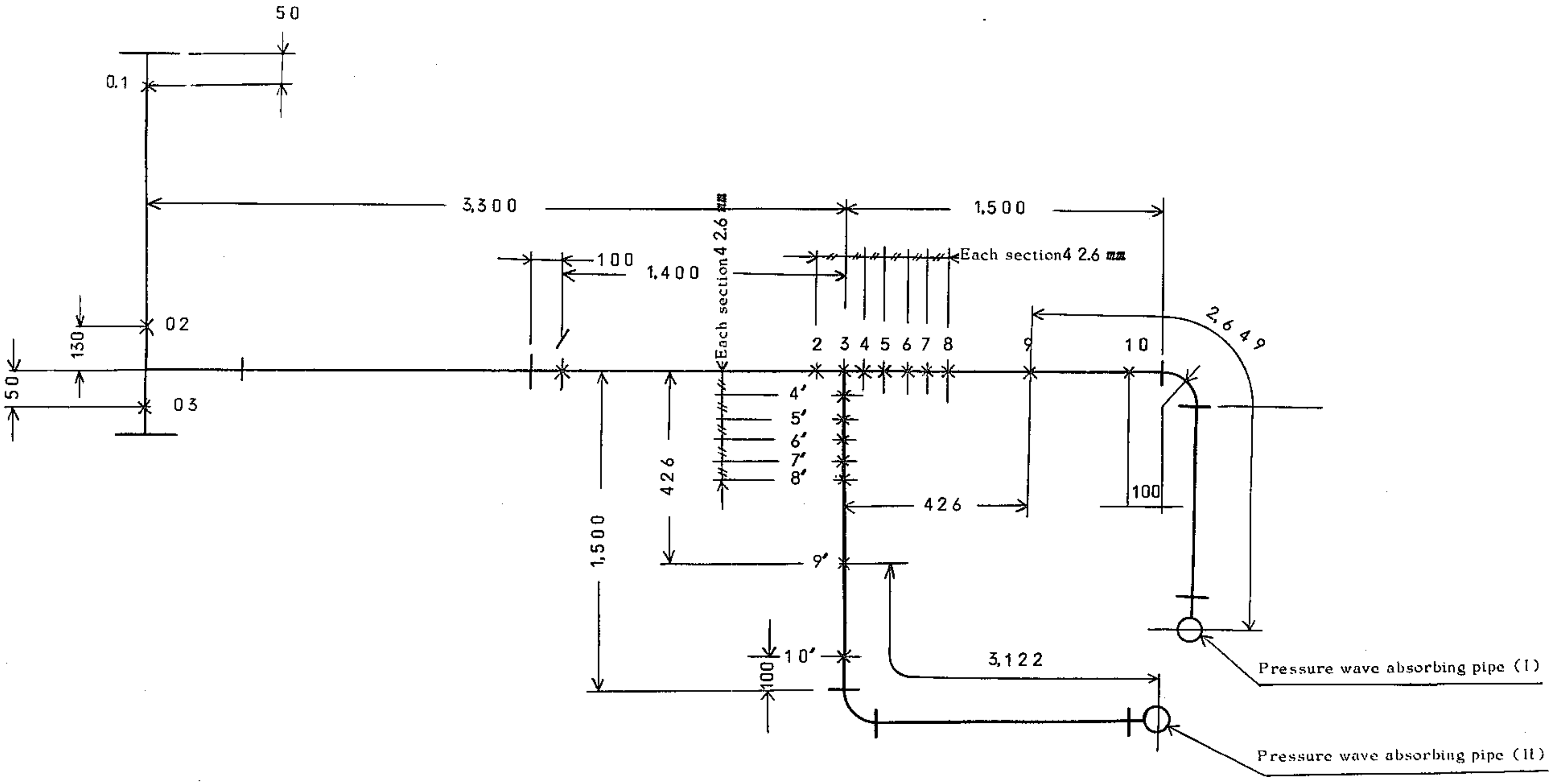


Fig. 4.2.1 Pressure Wave Measuring Positions in Branch (I)

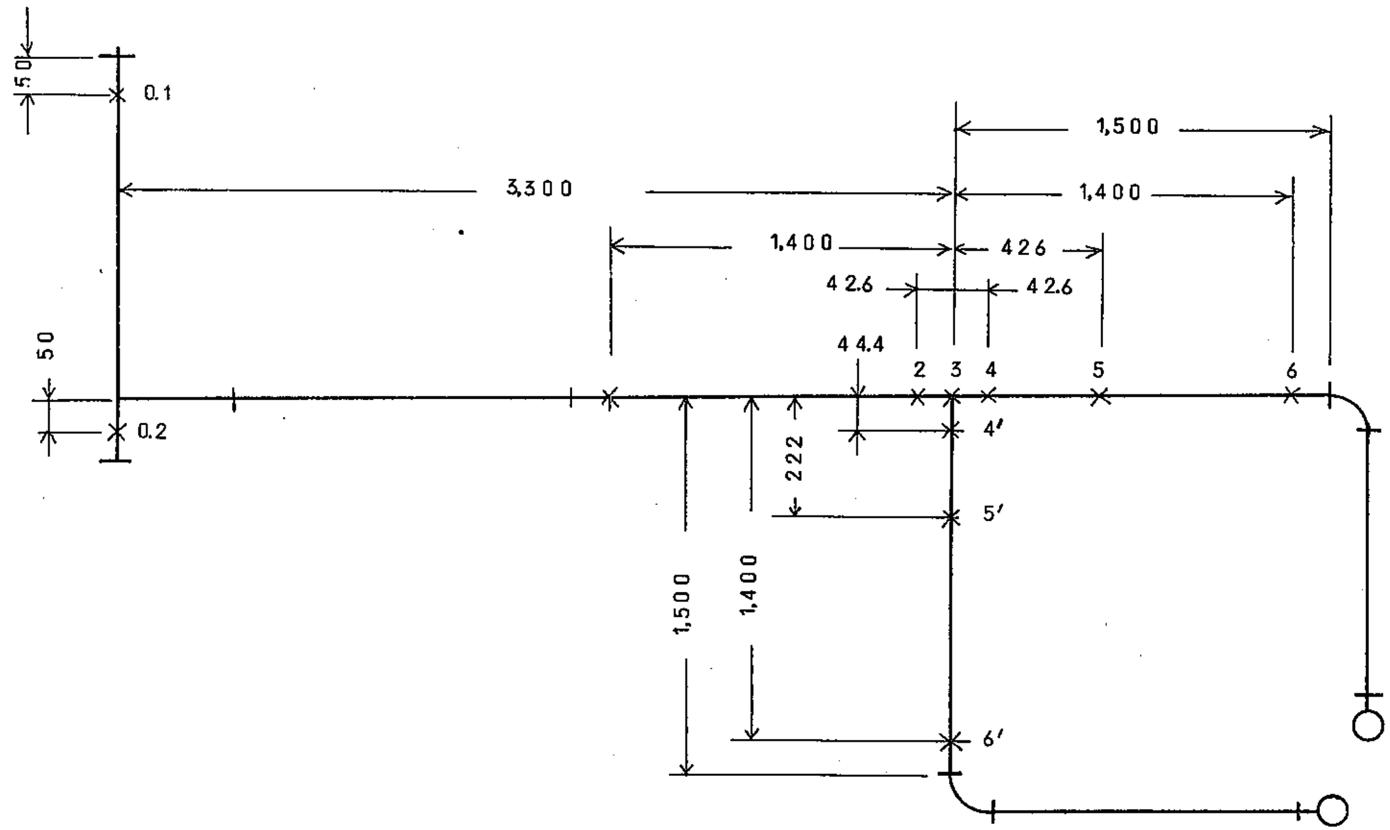


Fig. 4.2.2 Pressure Wave Measuring Positions in Branch II

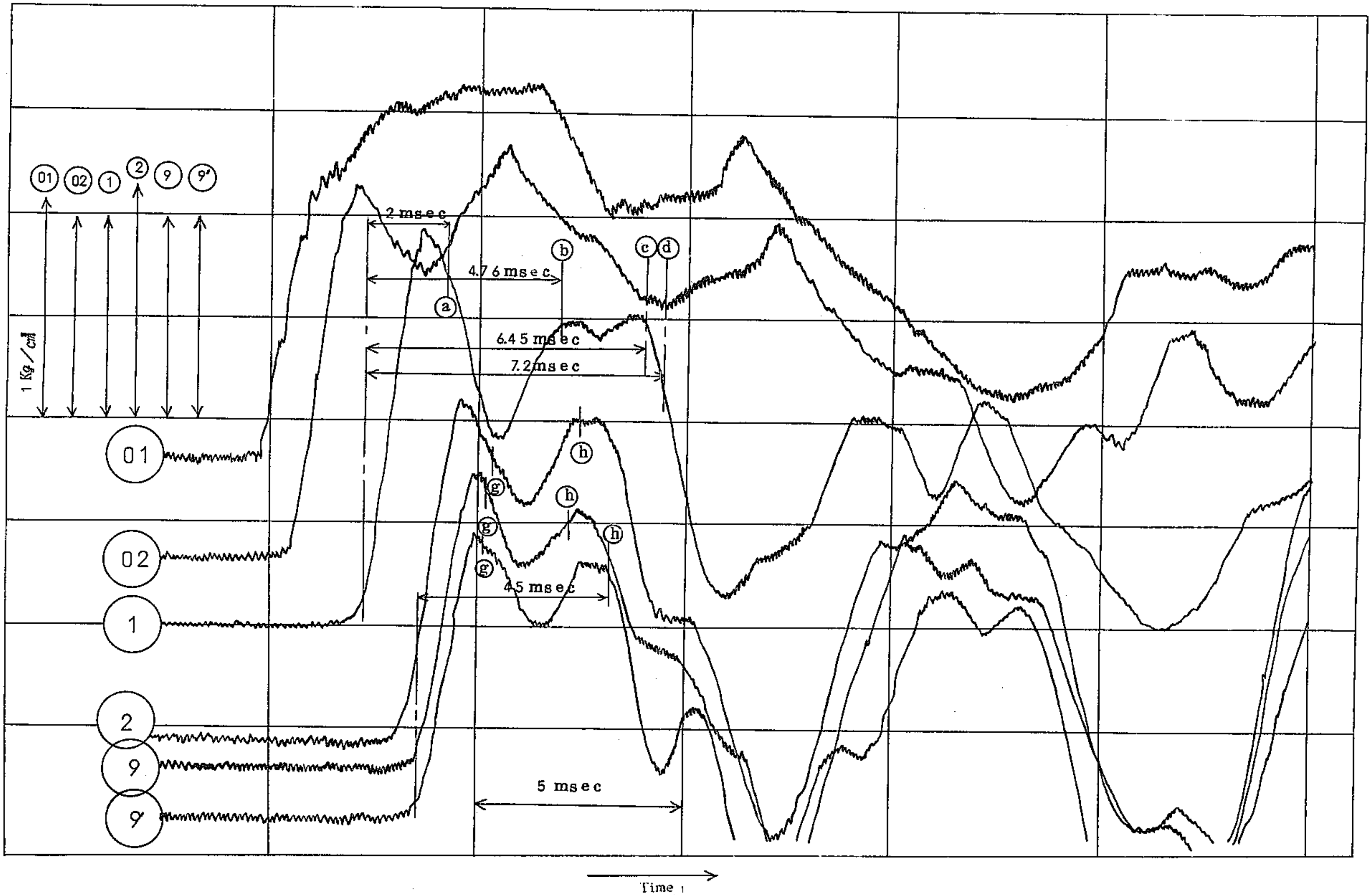


Fig. 4.2.3 Result of Measurement with Branch (I)

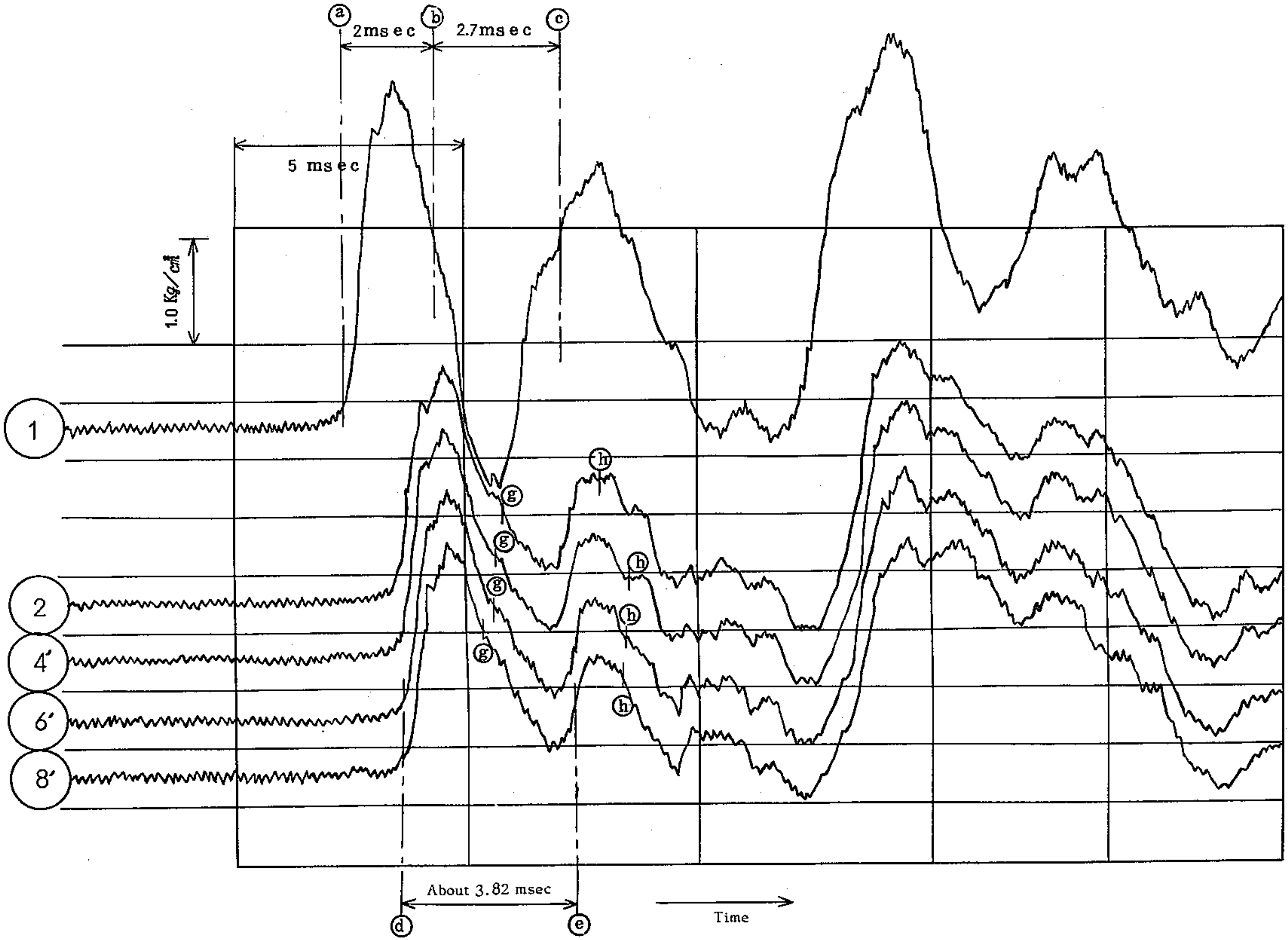


Fig. 4.2.4 Result of Measurement with Branch (I)

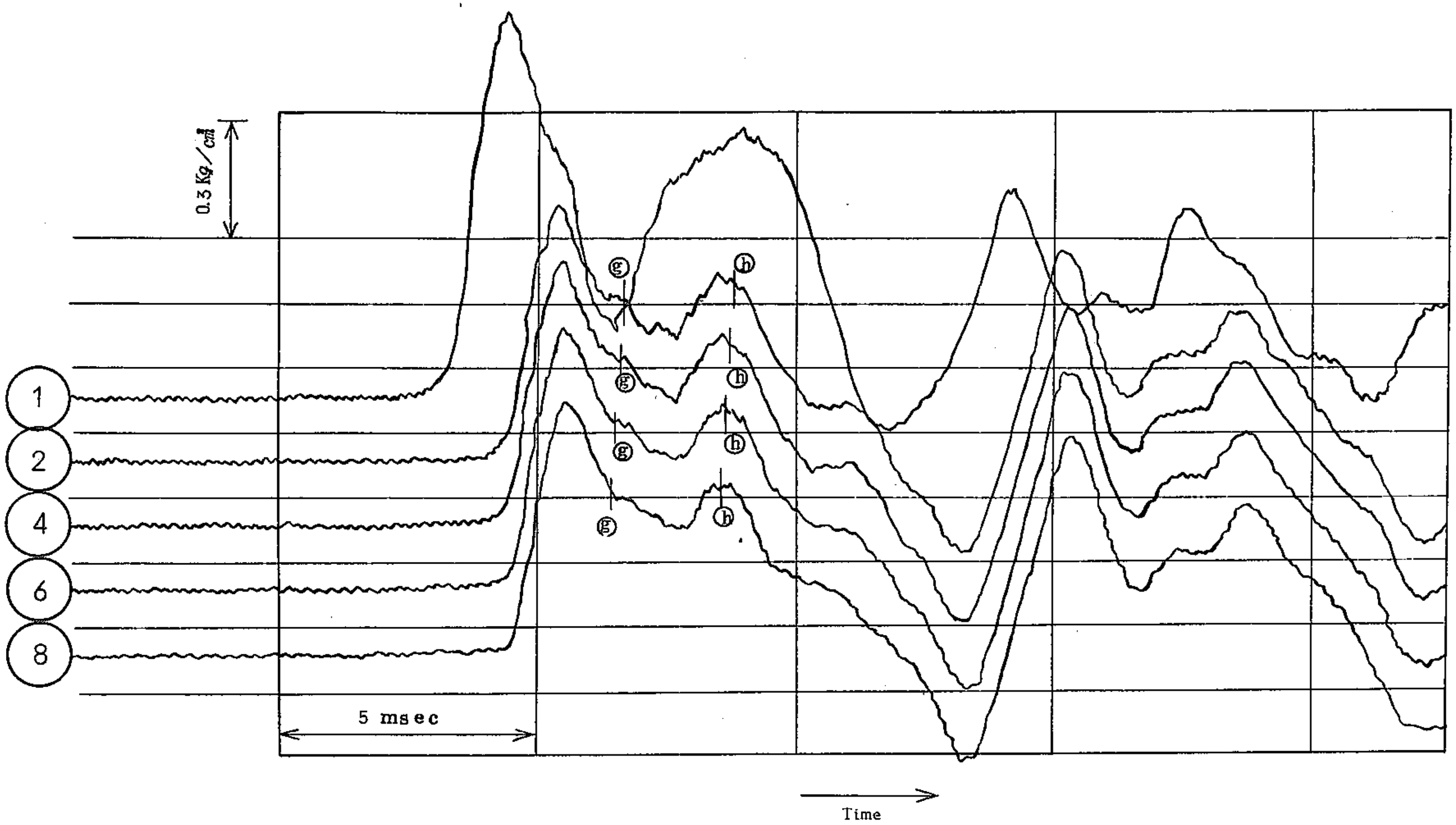


Fig. 4.2.5 Result of Measurement with Branch (I)

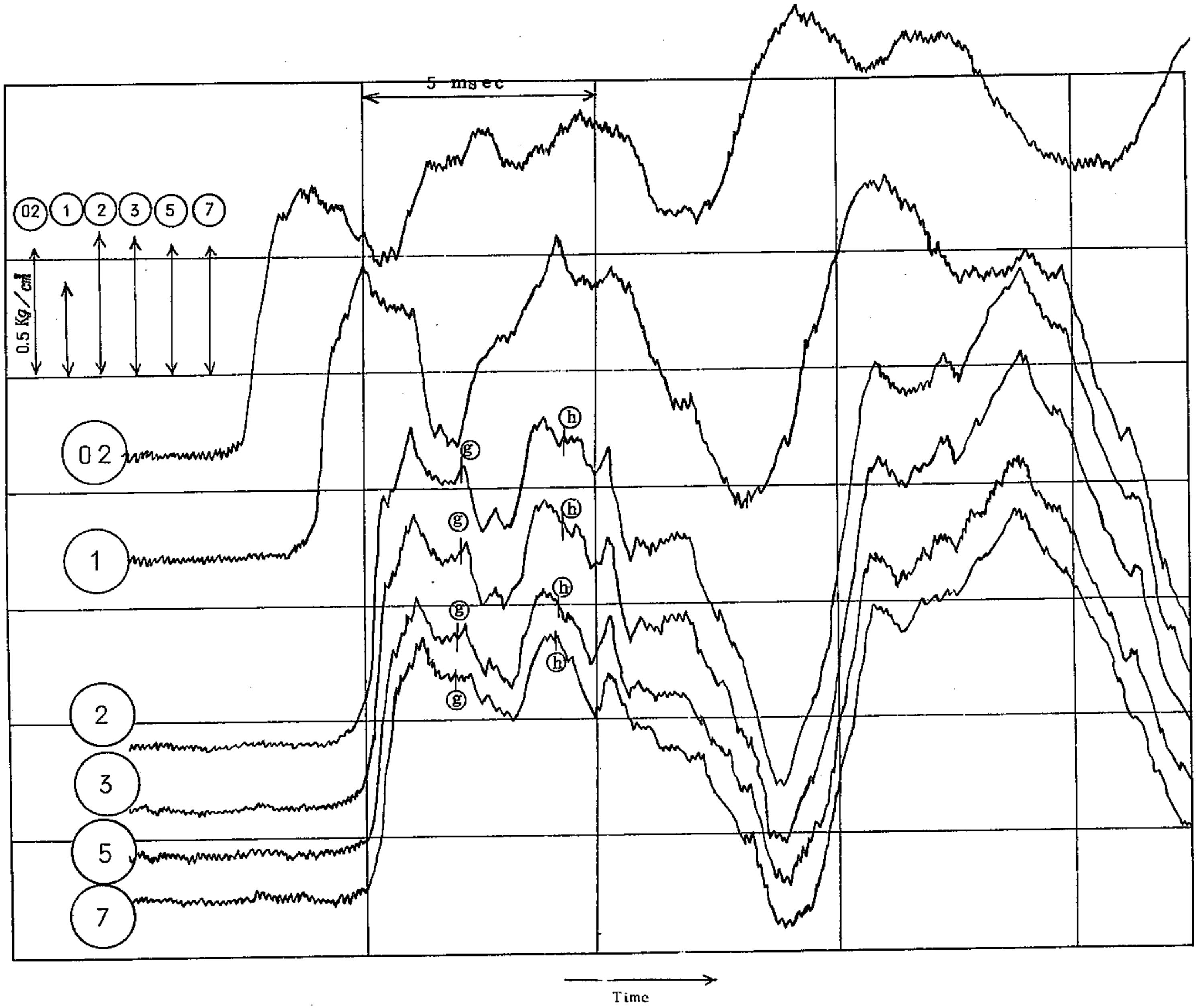


Fig. 4.2.6 Result of Measurement with Branch (I)

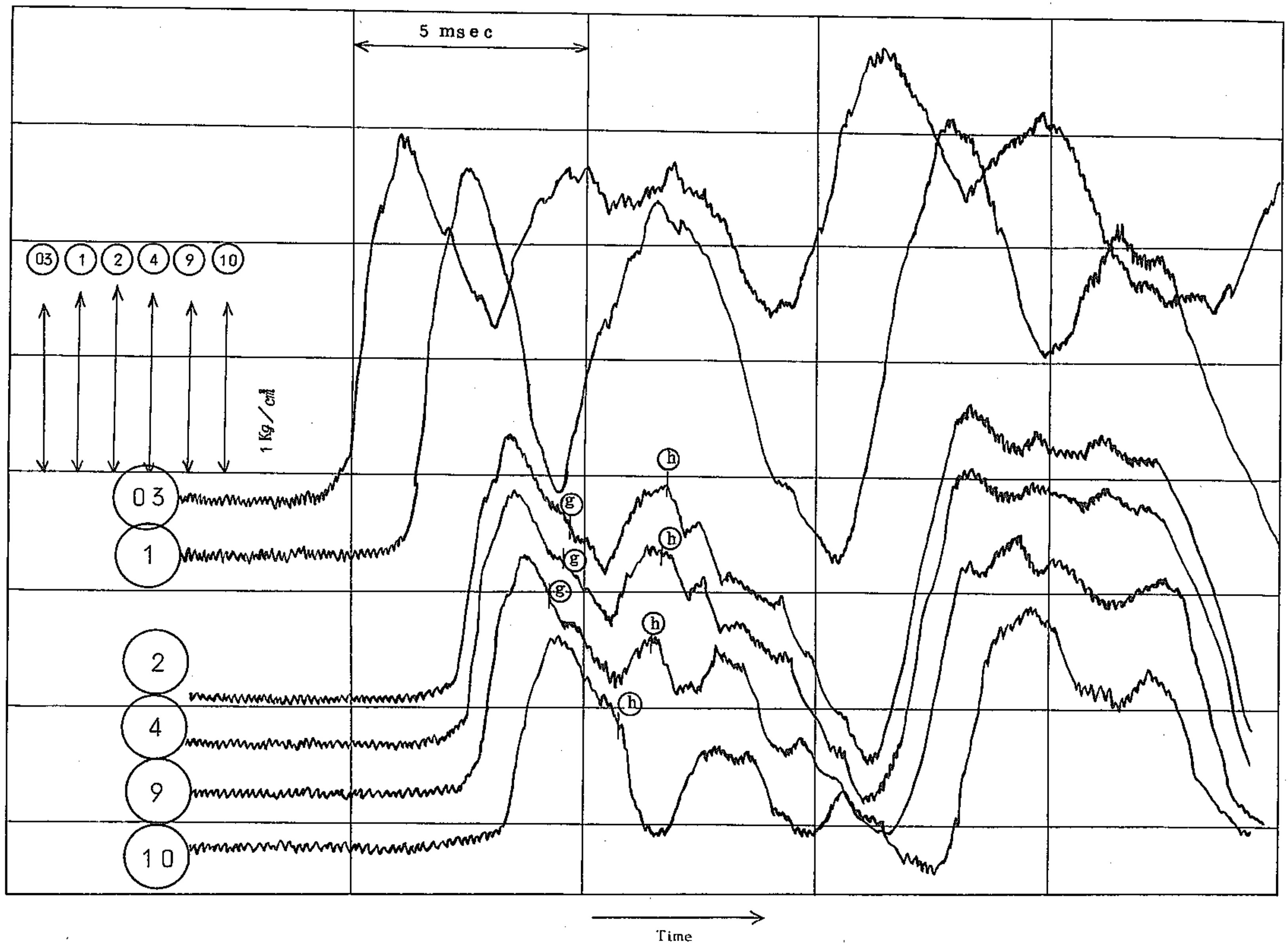


Fig. 4.2.7 Result of Measurement with Branch (I)

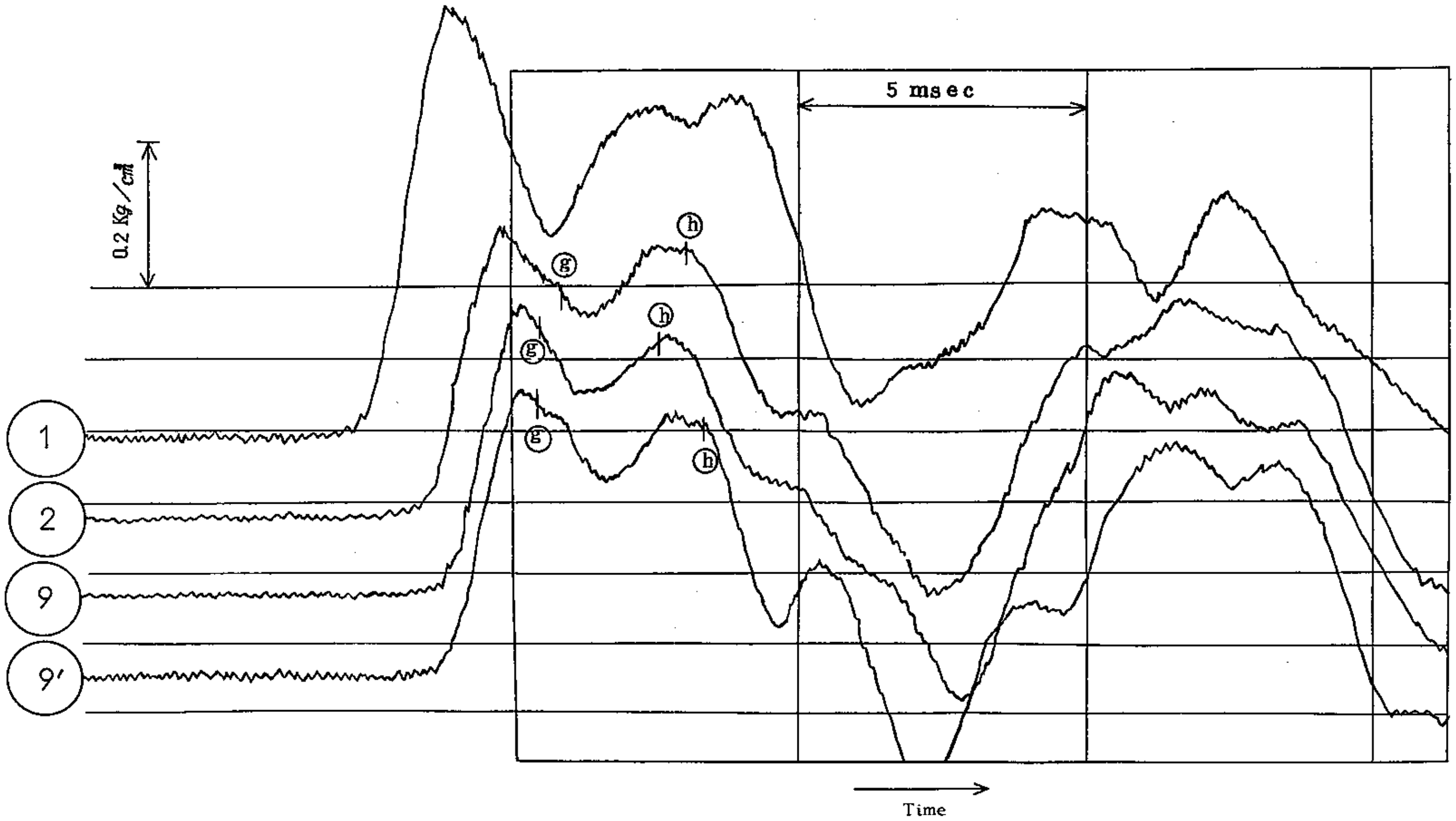


Fig. 4.2.8 Result of Measurement with Branch (I)

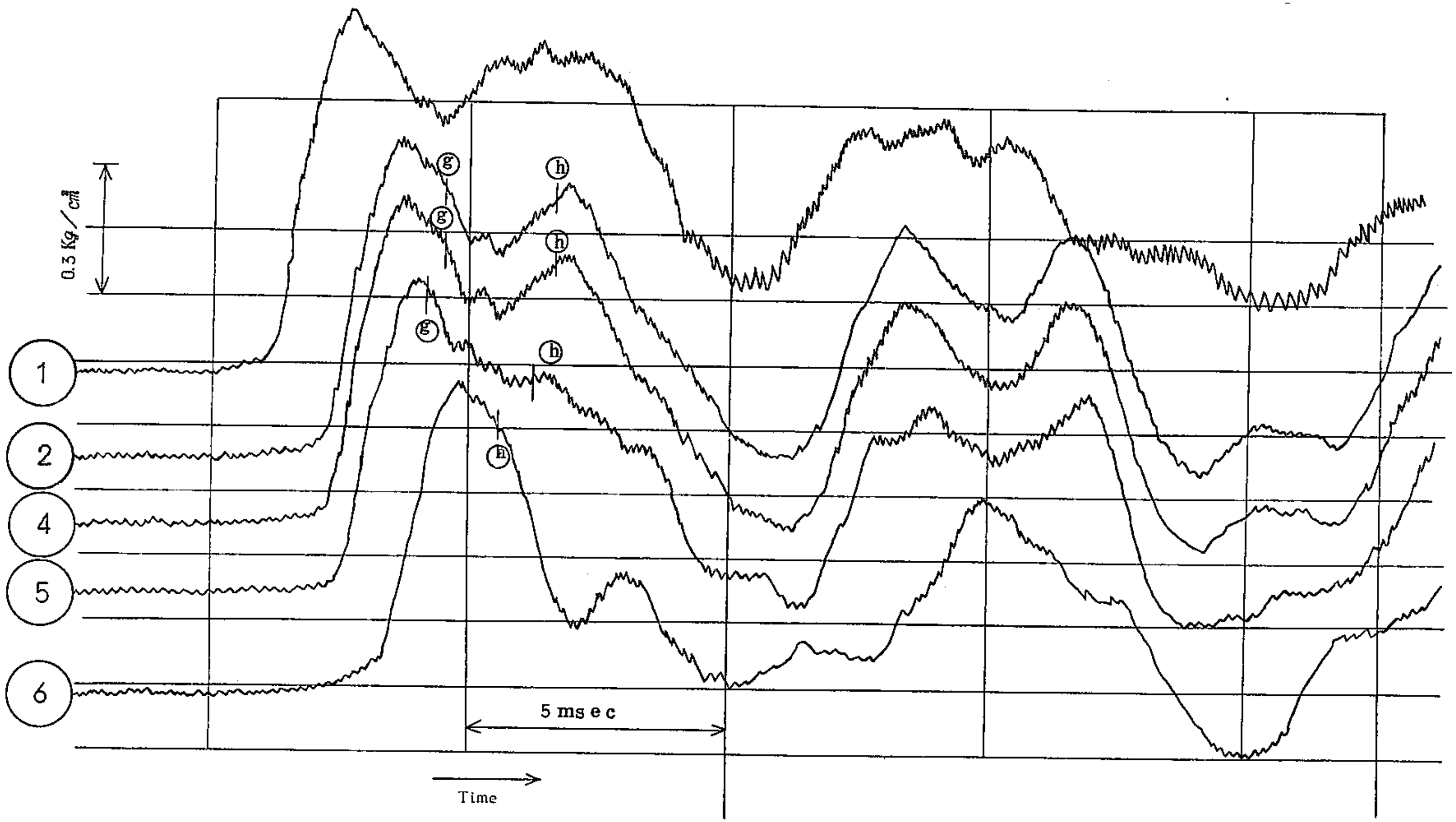


Fig. 4.2.9 Result of Measurement with Branch (II)

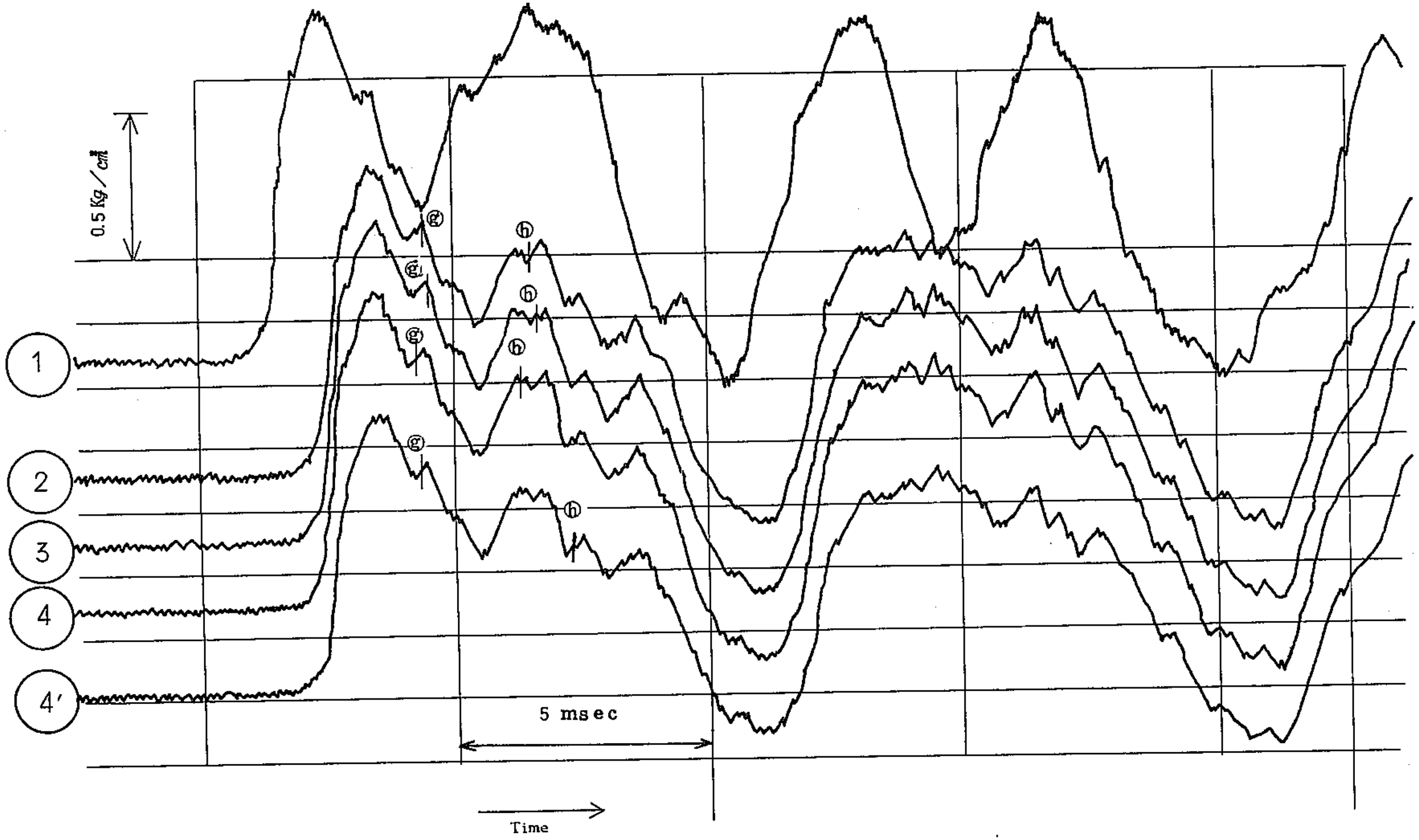


Fig. 4.2.10 Result of Measurement with Branch (II)

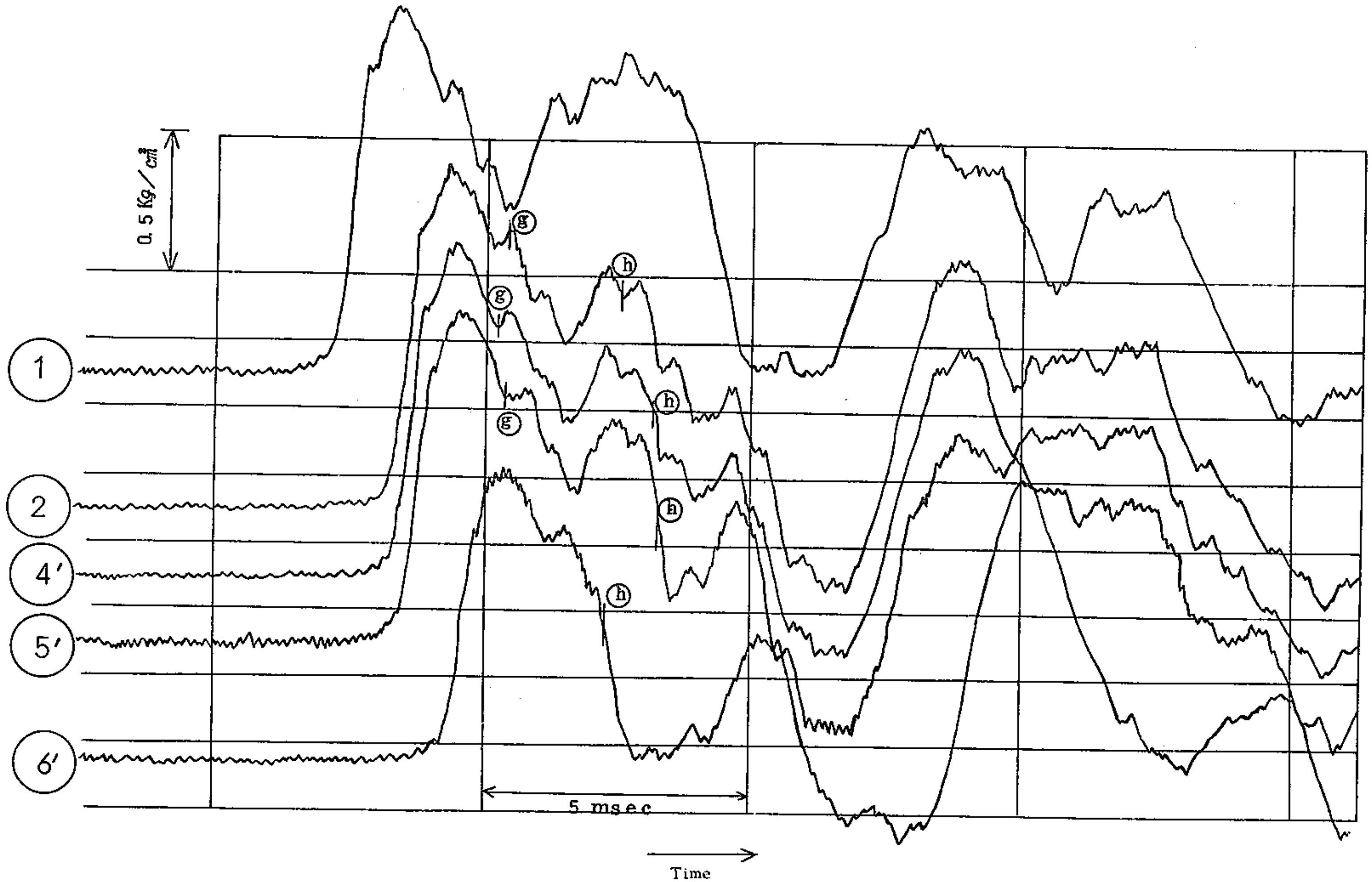


Fig. 4.2.11 Result of Measurement with Branch (II)

Object of Experiment	Measured Value	Calculated Value	Error
Branch (I)	1,384 m/s	1,387 m/s	− 0.2%
Branch (II)	1,390 m/s	1,387 m/s	+ 0.2%
Bend (I)	1,384 m/s	1,387 m/s	+ 0.2%
Bend (II)	1,354 m/s	1,387 m/s	− 2.4%

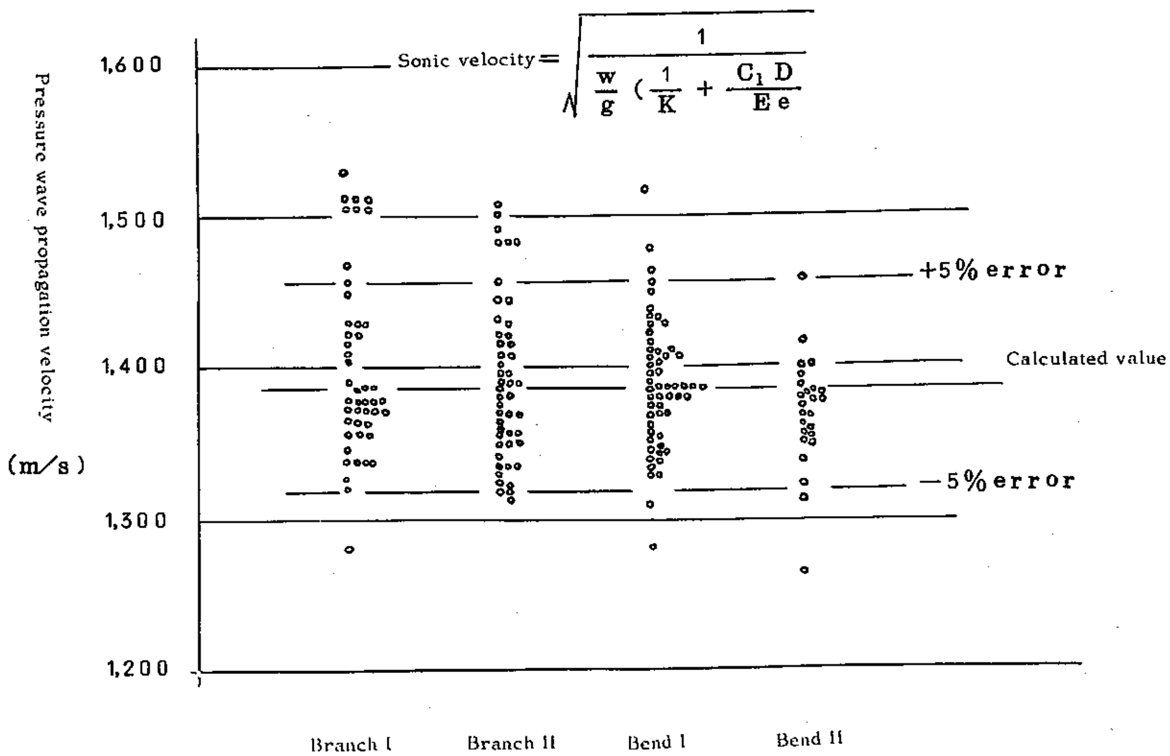


Fig. 4.2.12 Measuring Result of Pressure Wave Propagation Velocity

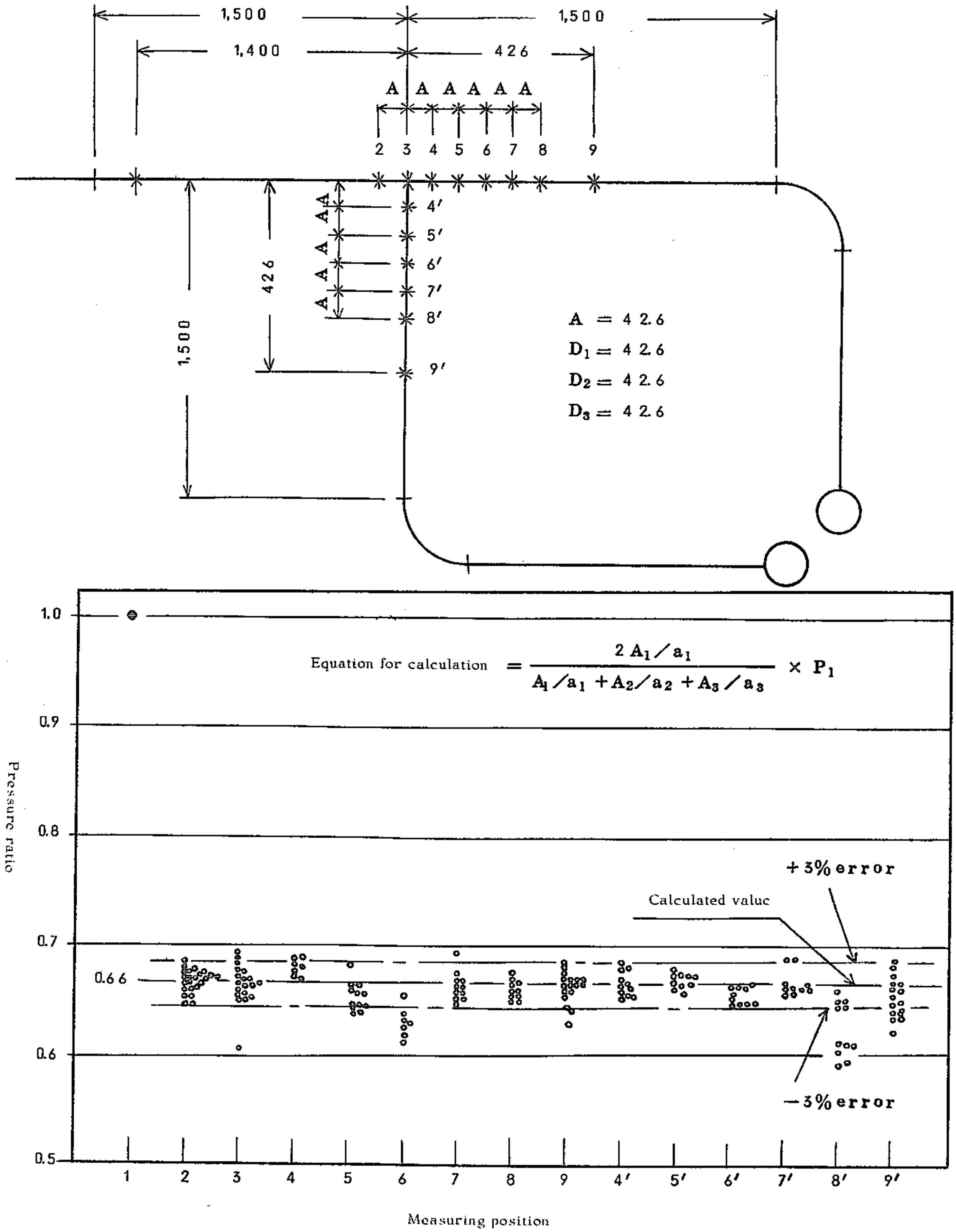
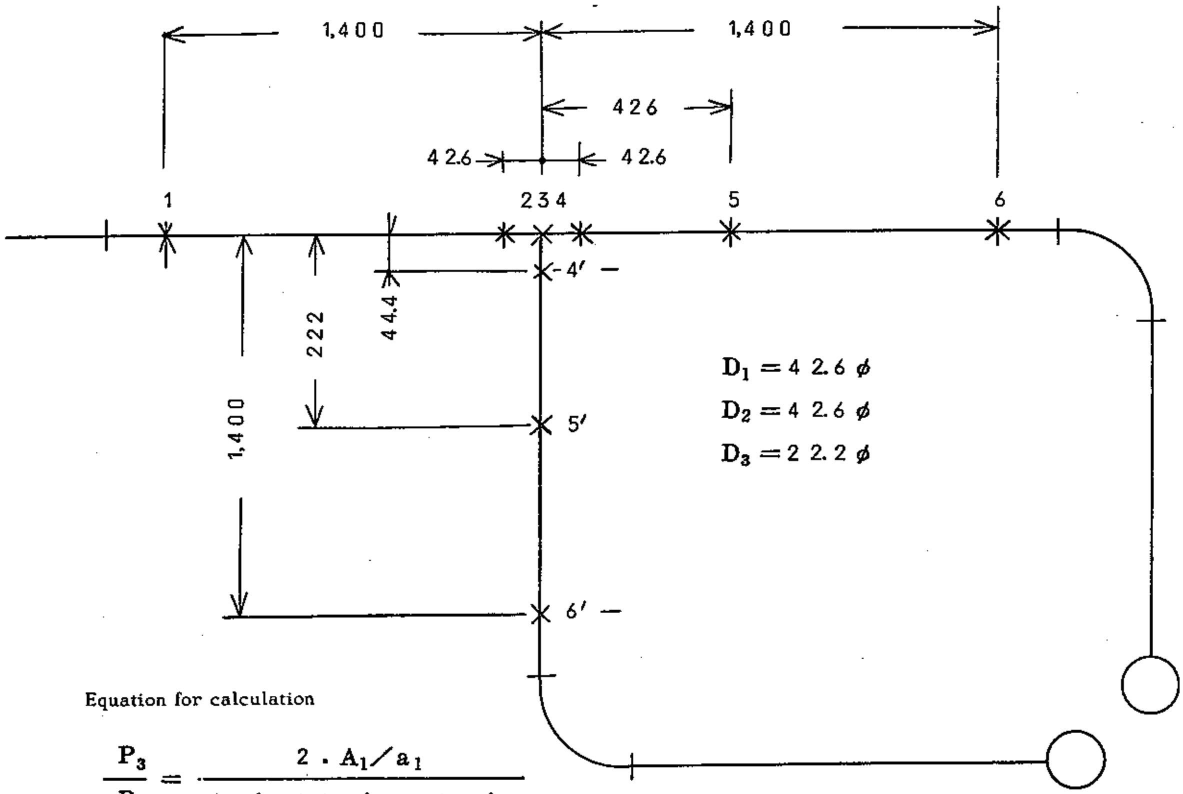


Fig. 4.2.13 Result of Experiment with Branch (I)



Equation for calculation

$$\frac{P_3}{P_1} = \frac{2 \cdot A_1/a_1}{A_1/a_1 + A_2/a_2 + A_3/a_3}$$

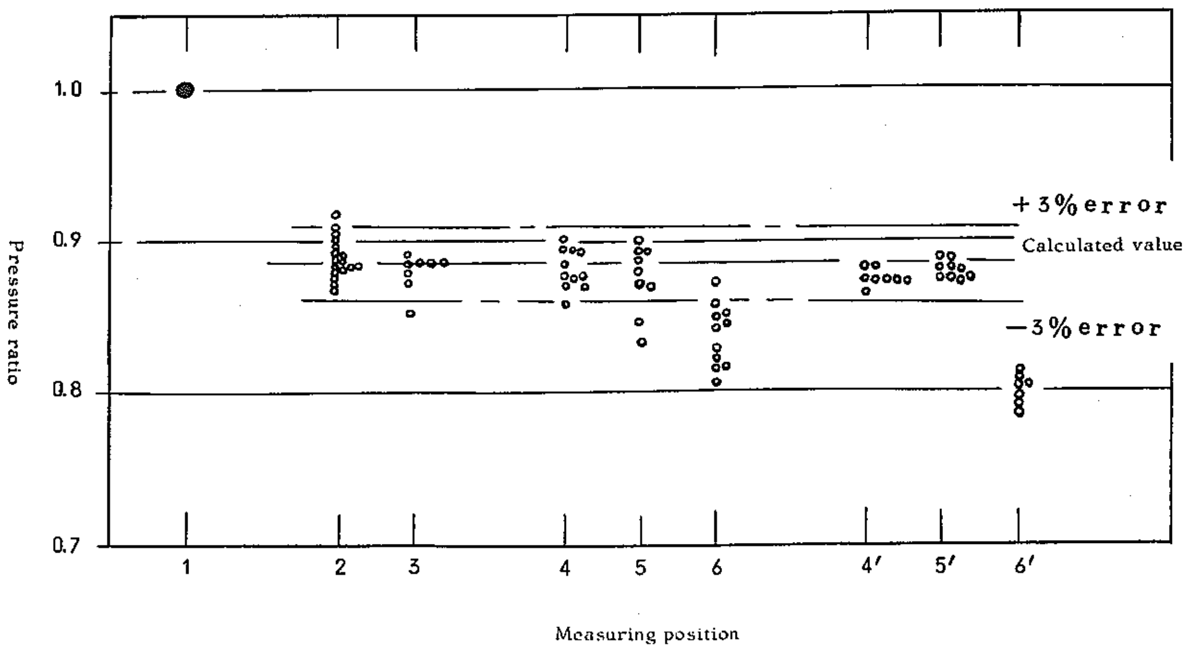


Fig. 4.2.14 Result of Experiment with Branch (II)

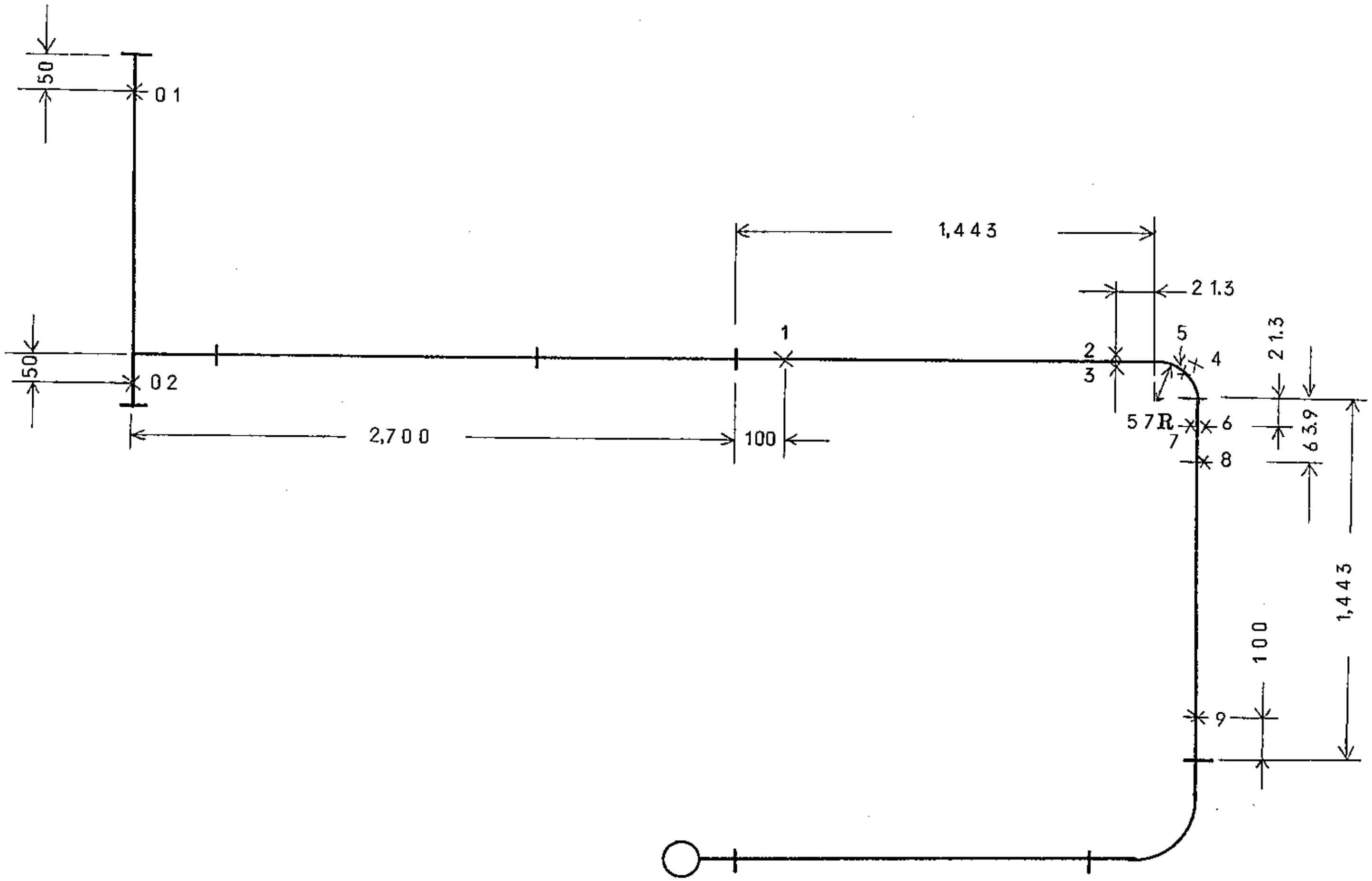


Fig. 4.3.1 Pressure Measuring Positions in Bend (I)

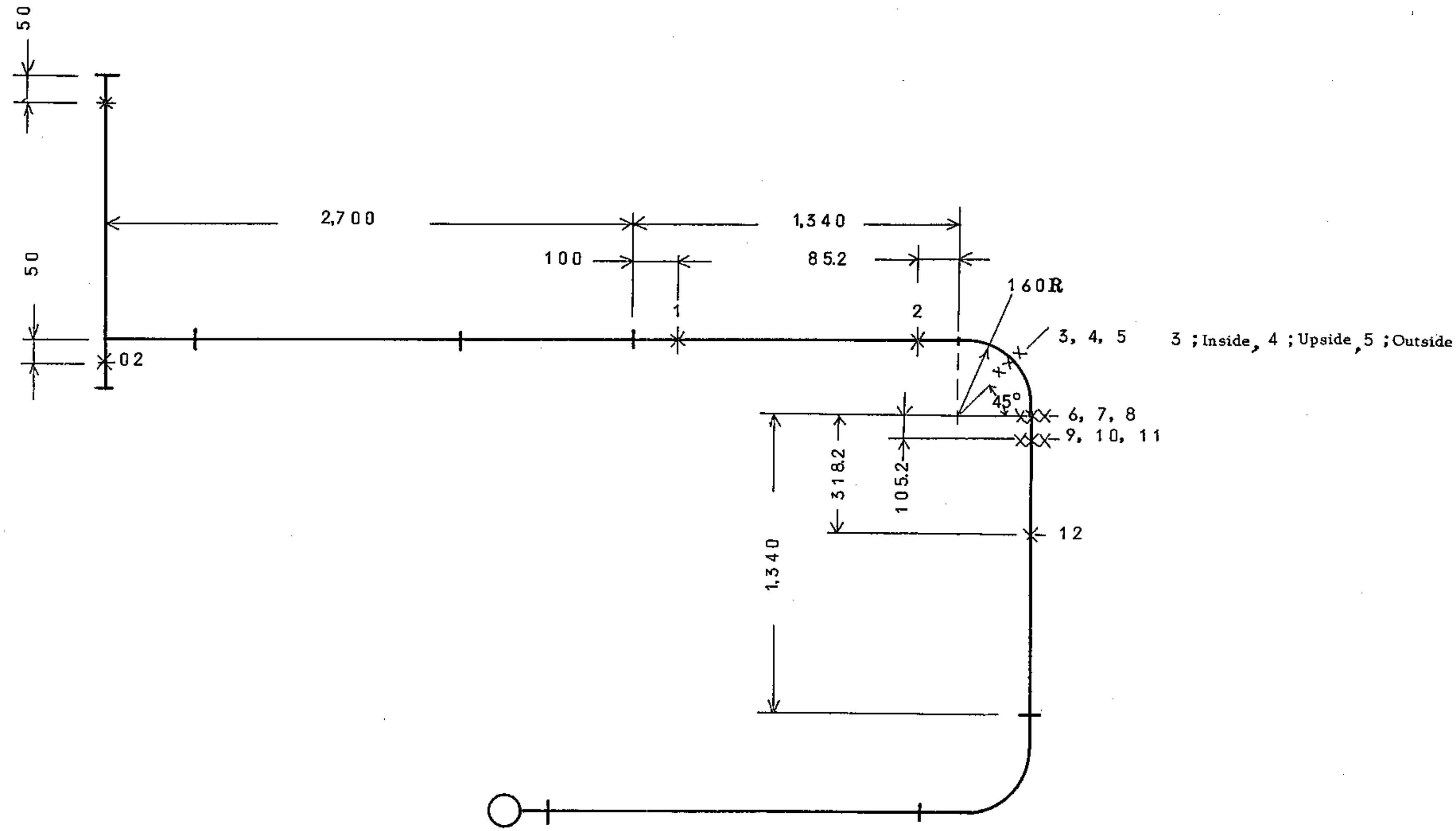


Fig. 4.3.2 Pressure Measuring Positions in Bend (II)

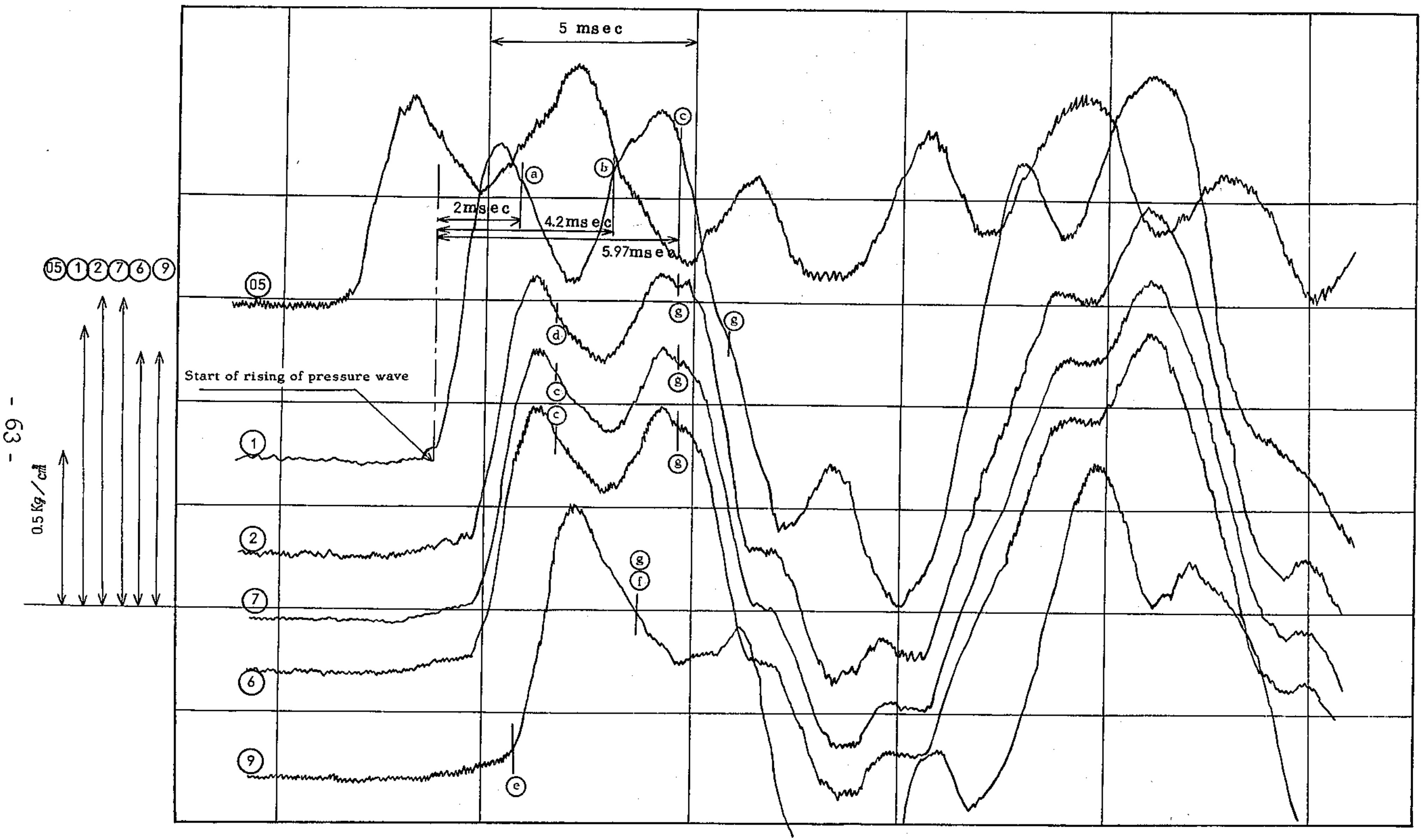


Fig. 4.3.3 Result of Measurement with Bend (I)

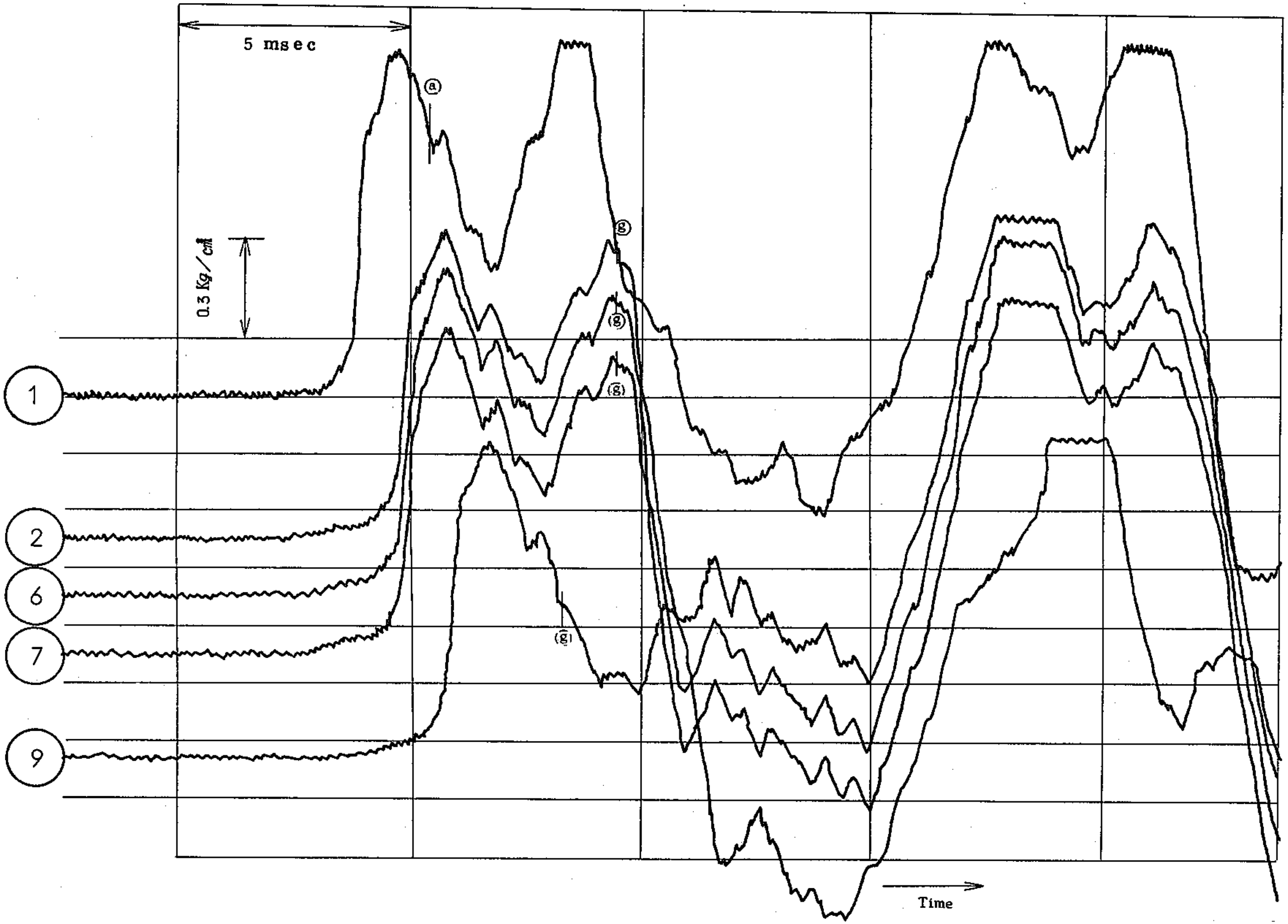


Fig. 4.3.4 Result of Measurement with Bend (I)

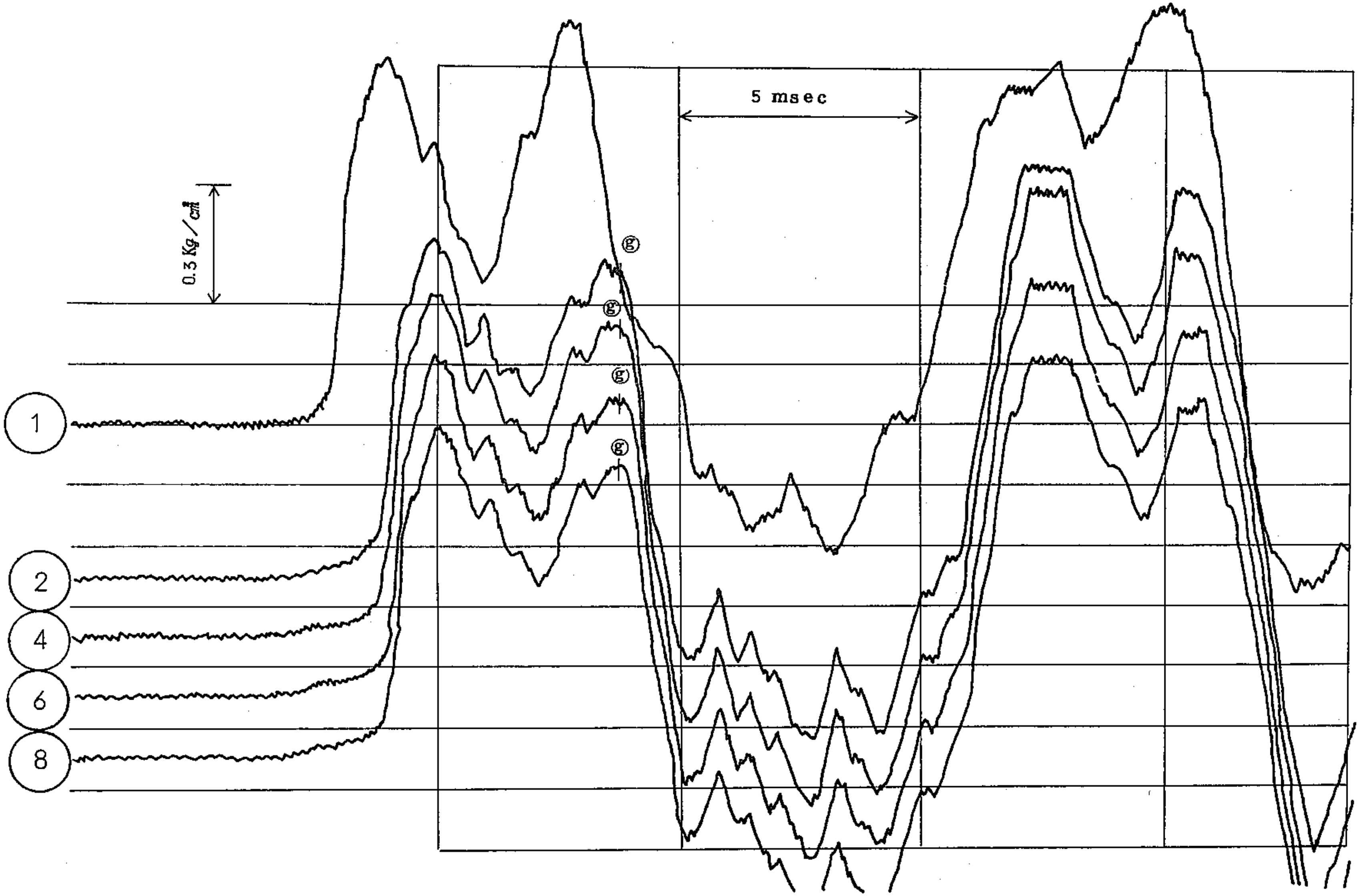


Fig. 4.3.5 Result of Measurement with Bend (I)

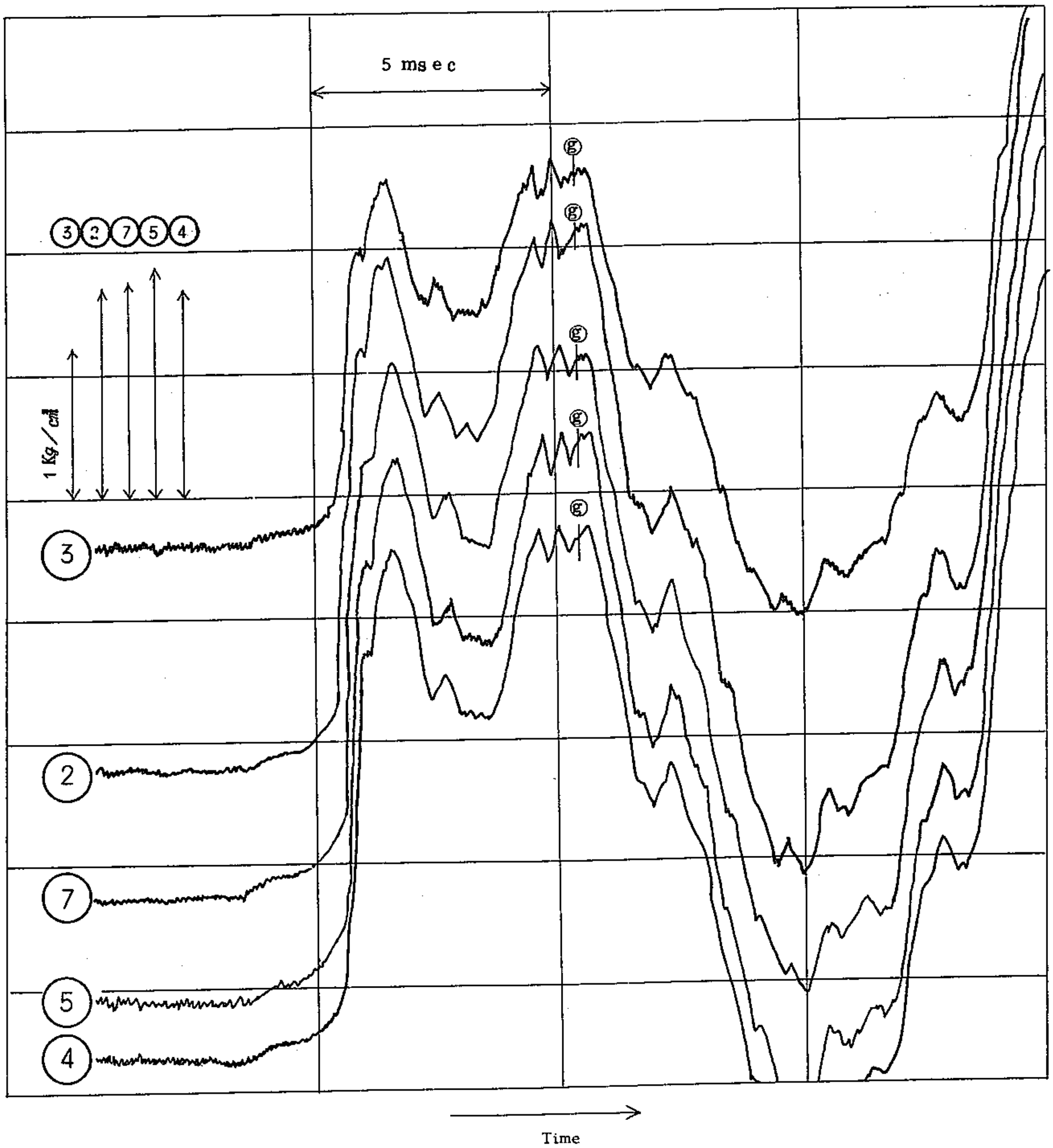


Fig. 4.3.6 Result of Measurement with Bend (I)

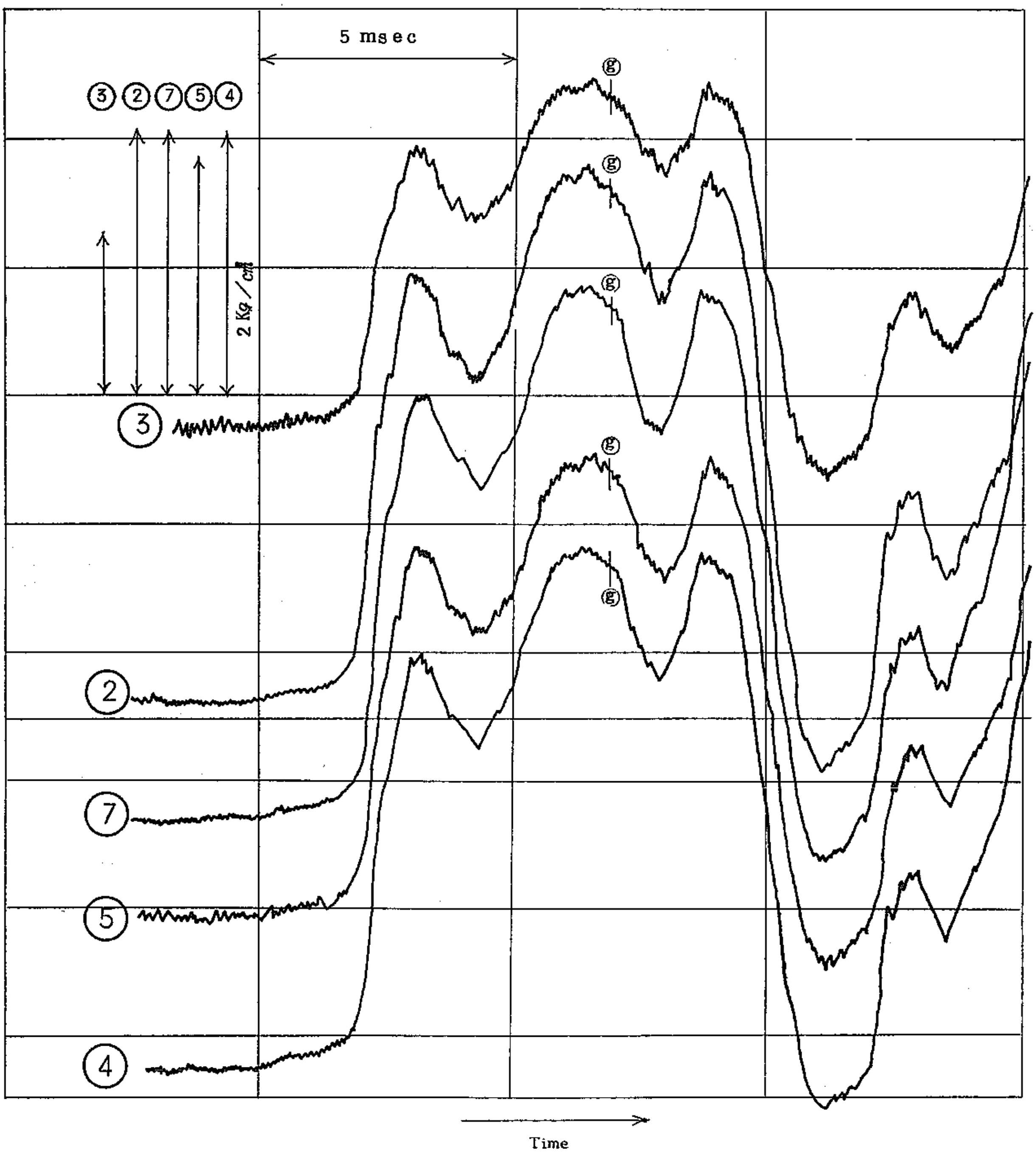


Fig. 4.3.7 Result of Measurement with Bend (II)

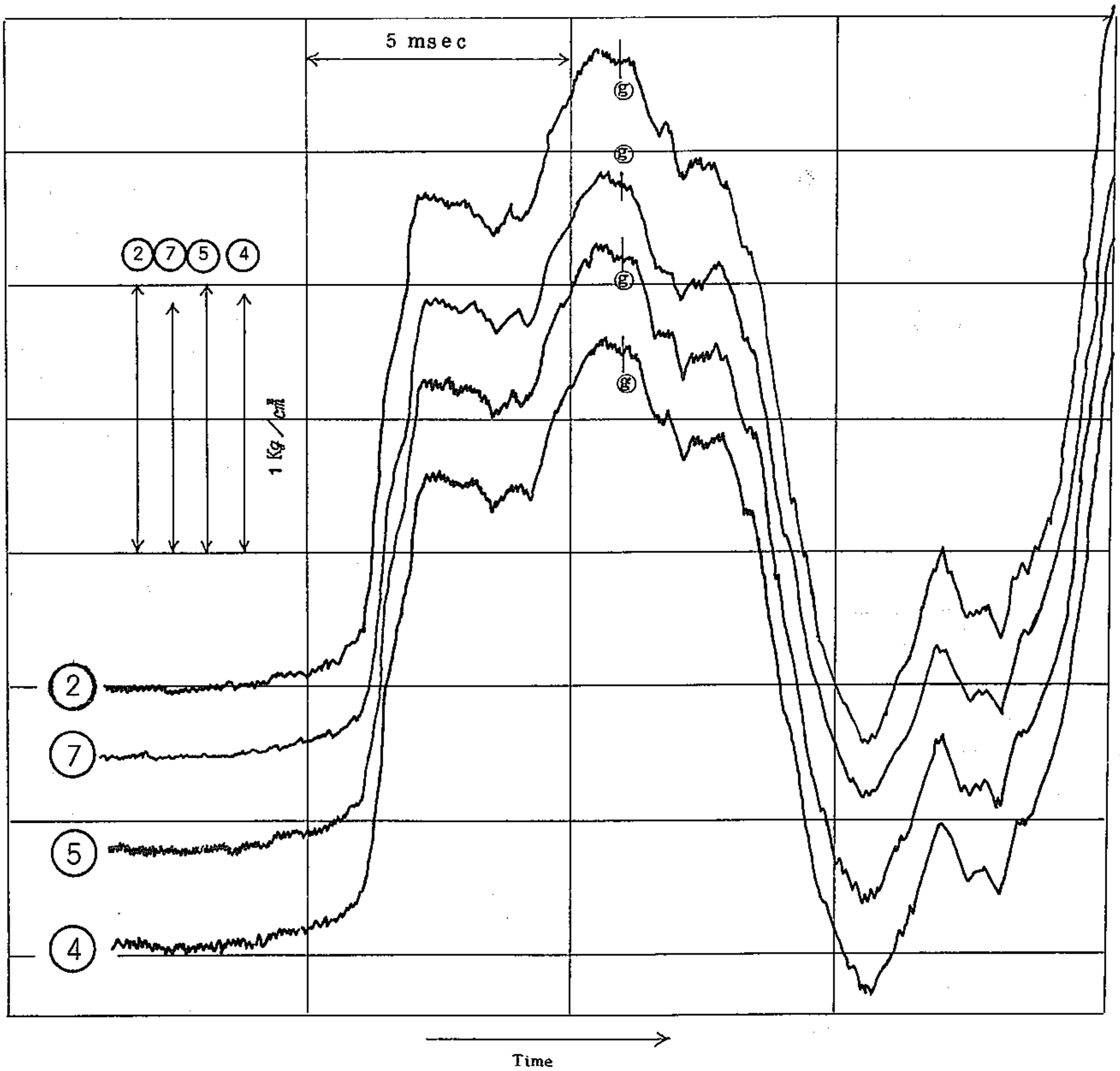


Fig. 4.3.8 Result of Measurement with Bend (II)

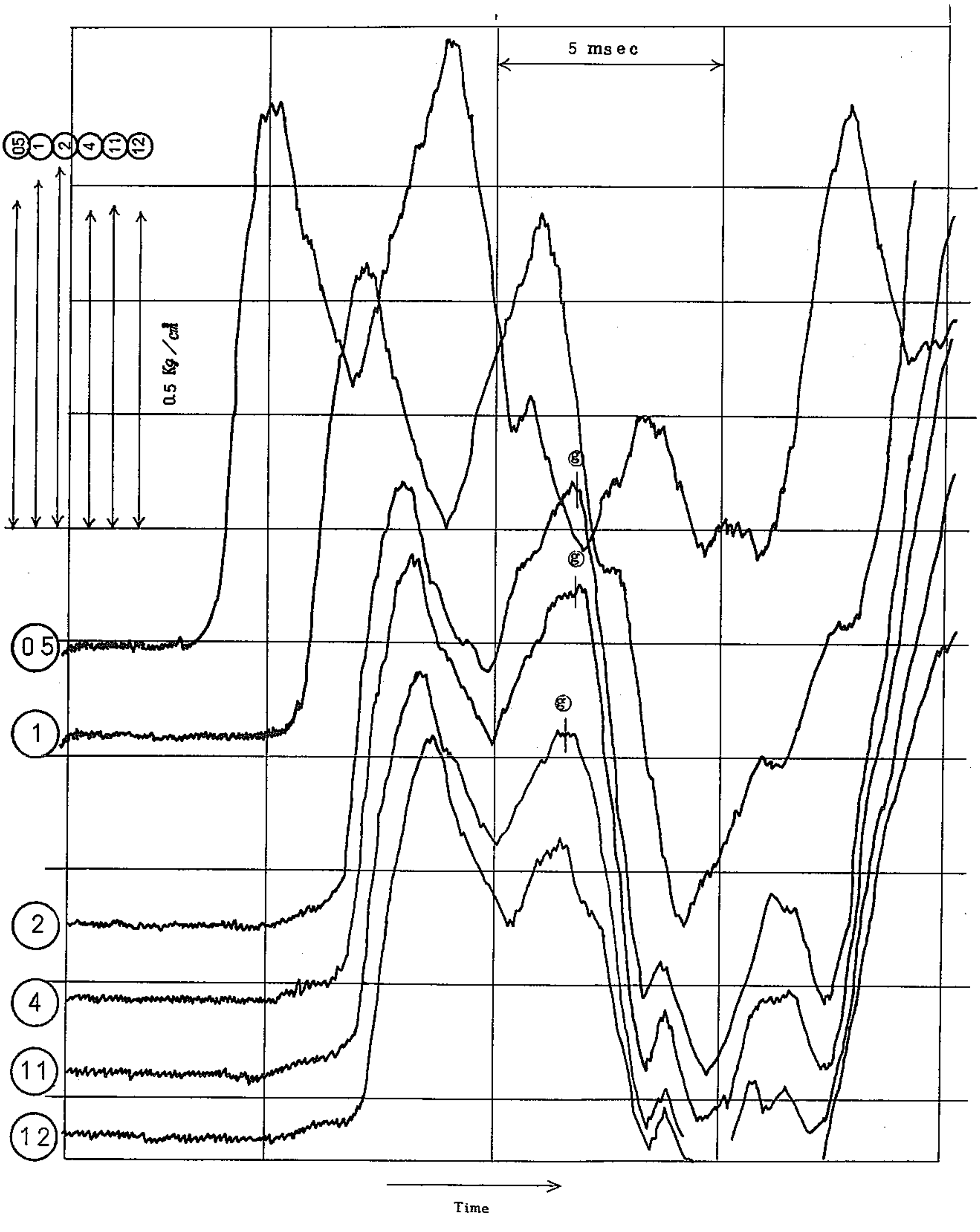


Fig. 4.3.9 Result of Measurement with Bend (II)

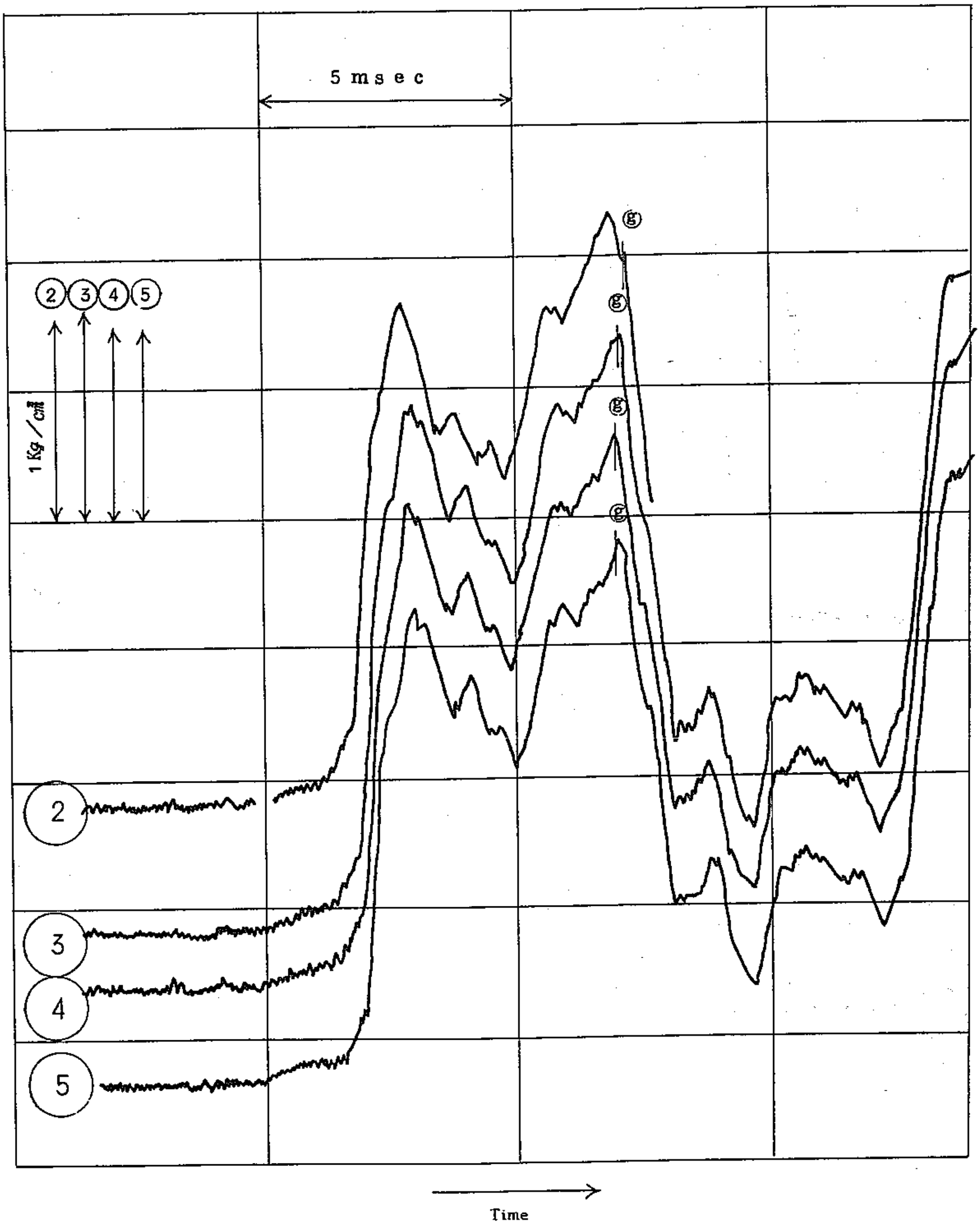


Fig. 4.3.10 Result of Measurement with Bend (II)

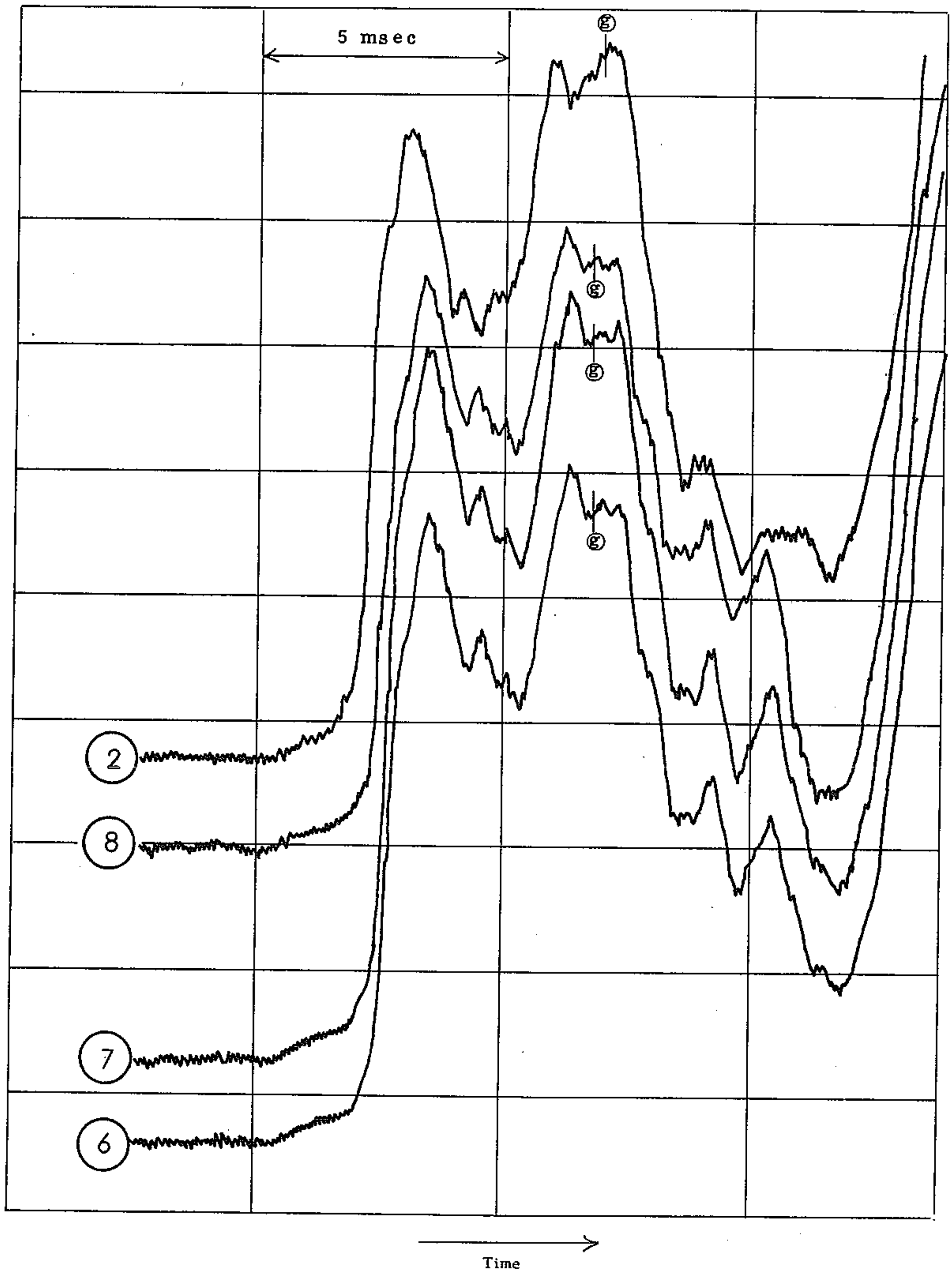


Fig. 4.3.11 Result of Measurement with Bend (II)

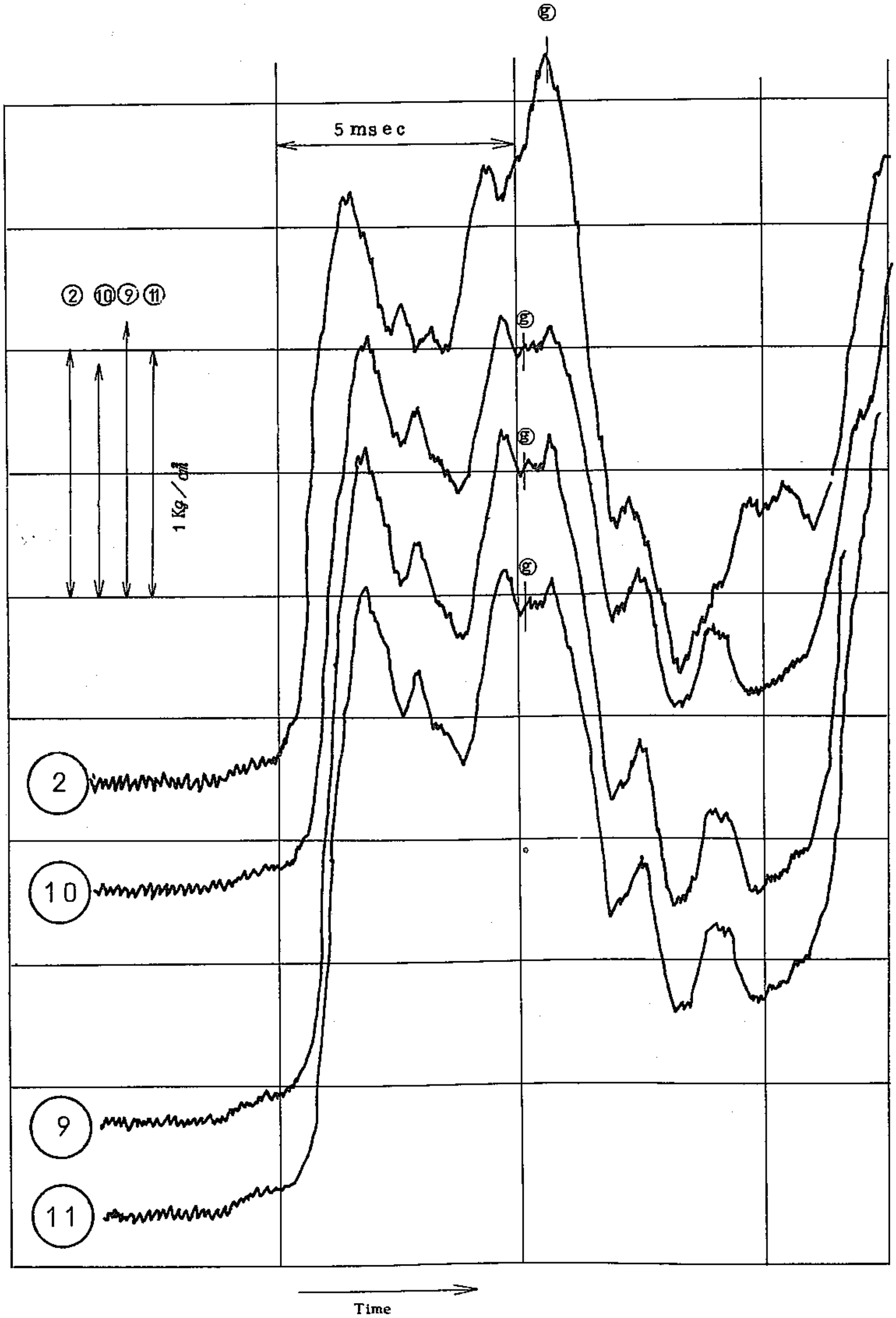
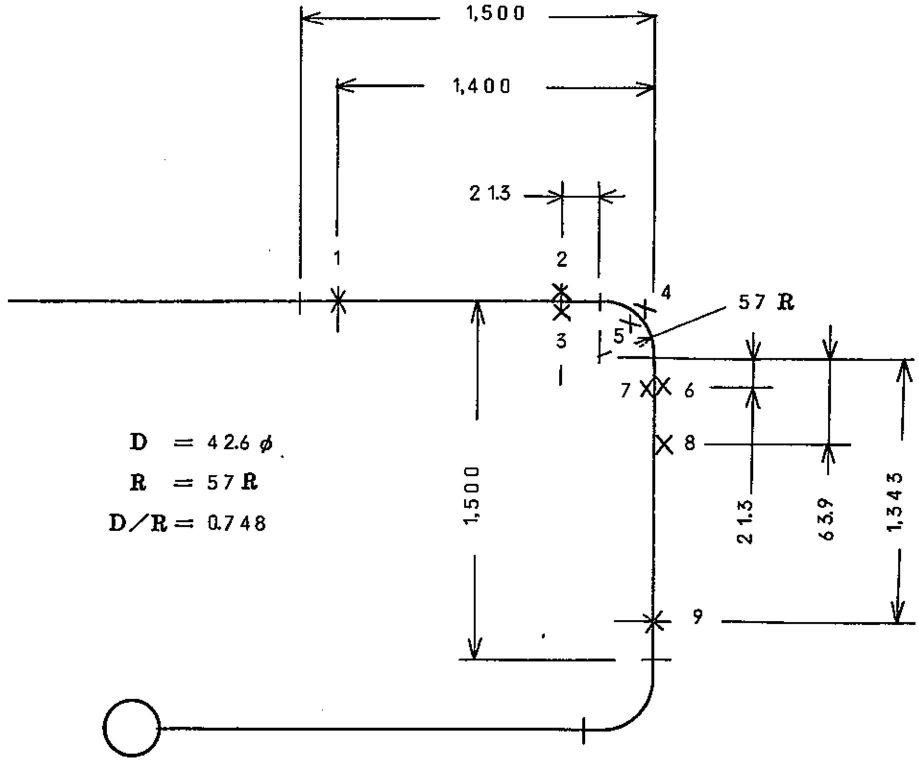


Fig. 4.3.12 Result of Measurement with Bend (II)



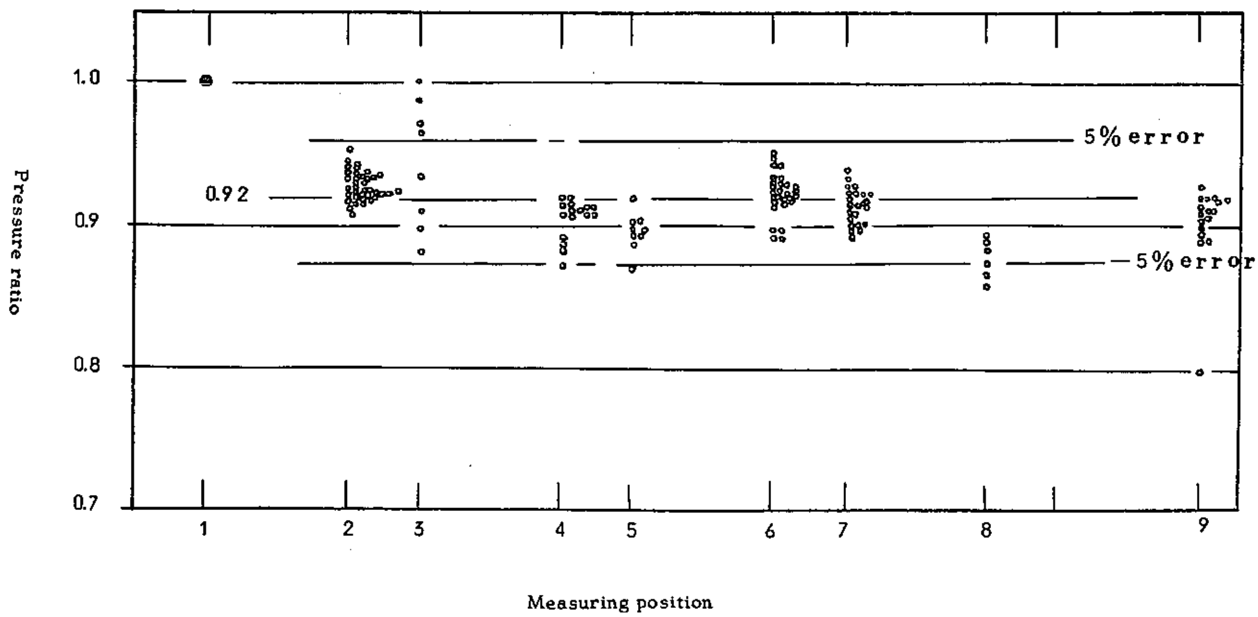
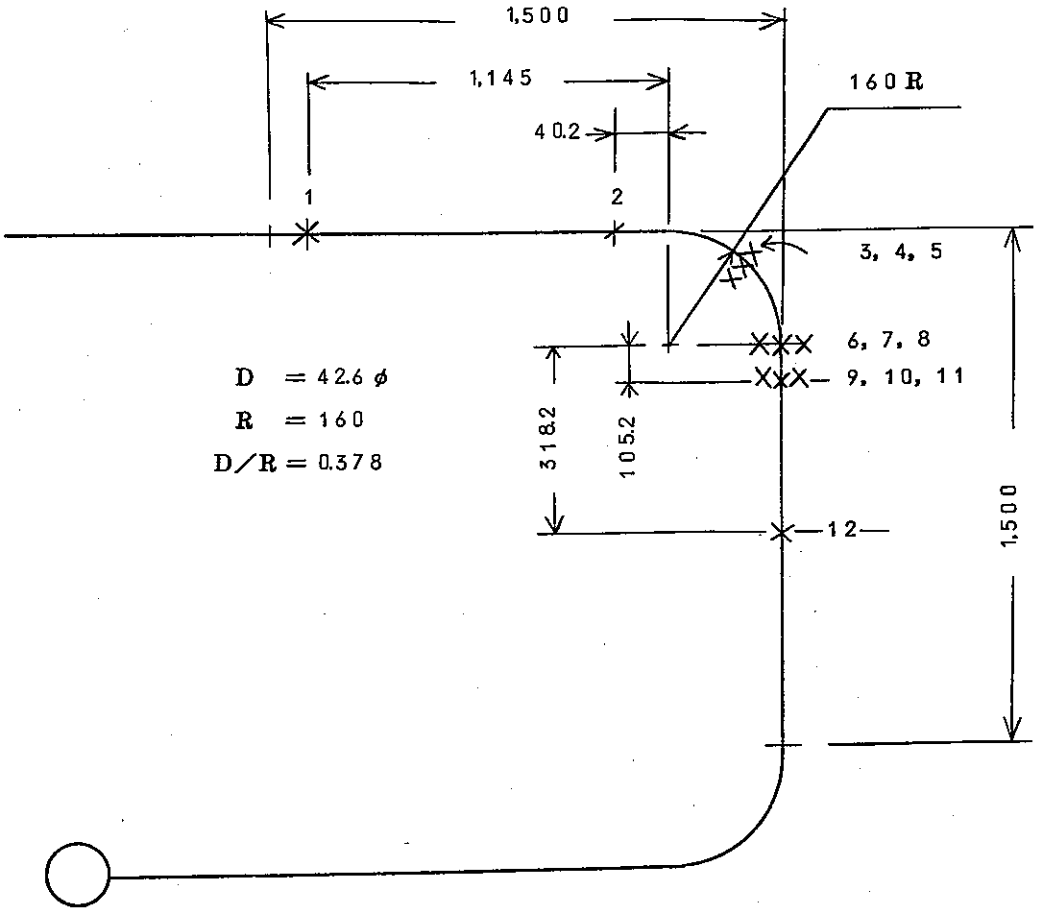


Fig. 4.3.13 Result of Measurement with Bend (I)



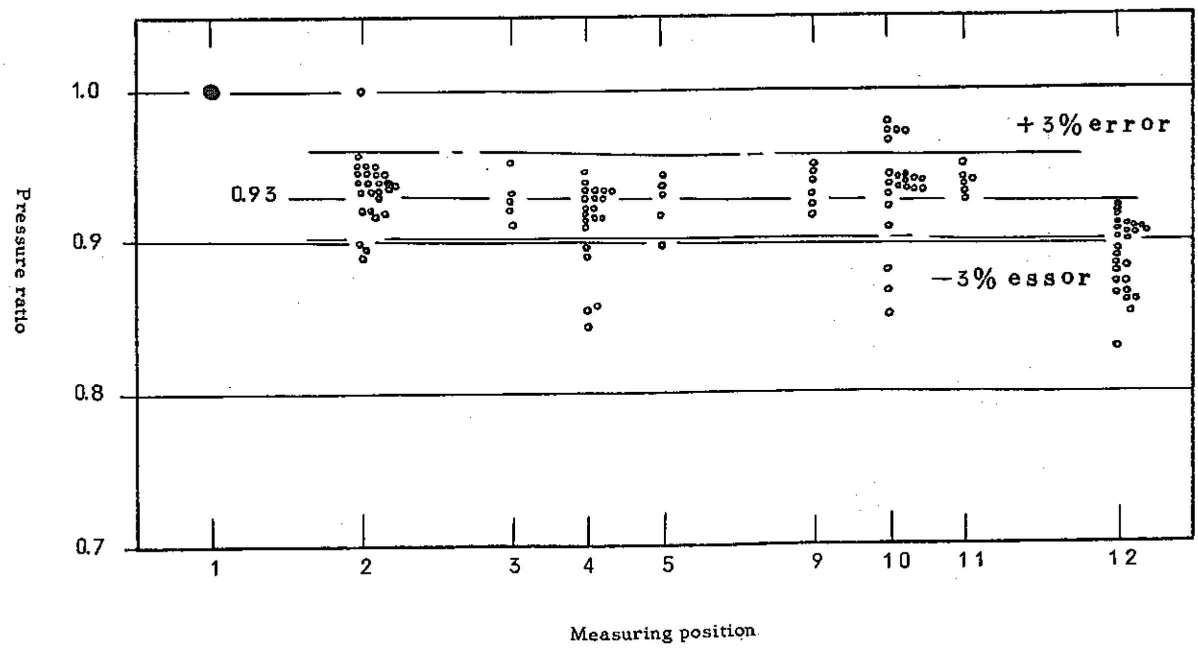


Fig. 4.3.14 Result of Measurement with Bend (II)