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Author
Ishikawa, N.

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Observation Of Flow Characteristics In A Model I.C. Engine Cylinder

Nobuhiko Ishikawa and John W. Daily

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Lawrence Berkeley Laboratory University of California/Berkeley

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OBSERVATION OF FLOW CHARACTERISTICS IN A MODEL I.C. ENGINE CYLINDER

Nobuhiko Ishikawa and John W. Daily

Department of Mechanical Engineering
University of California, Berkeley

ABSTRACT

A study of fluid mechanical effects on unburned hydrocarbon generation has been made in a single compression expansion model automobile engine. Full optical access has allowed the color schlieren observations of various gas motion alongside the engine cylinder. Motion pictures of the gas motion and flame propagation have been taken at a rate of seven thousand frames per second for the following cases:

1) intake stroke
2) exhaust stroke
3) compression power stroke with combustion and blow-down with appropriate exhaust valve opening.

Unburned fuel concentrations were measured by means of a gas chromatograph. The results show that turbulent motion of the mixture increases the amount of unburned fuel. It is implied that the rolled-up vortices play an important role on wall flame quenching processes in an engine.

I. INTRODUCTION

Unburned hydrocarbons remain in an automobile engine due to incomplete chemical reactions within the cylinder, along the cylinder walls [1,2,3], and in any small gaps in the piston crevices [4,5] where the flame quenches and the fuel is left unburned. The flow patterns within the engine cylinder that affect the combustion process are extremely complicated. Both the intake process and the compression stroke introduce turbulence into the flow field, the former by the jet action from the intake valve, and the latter due to the vortex roll-up phenomena [6,7]. The flame must propagate through this flow field and the nature of the turbulence and its location within the cylinder can have a profound effect on the degree to which reactions are completed [8,9,10]. That flame wall quenching and crevice quenching depend upon local aerodynamics with time was first observed experimentally by Daniel and Wentworth [11]. Tabazynski, et al., [6], reported that the unburned hydrocarbons exit the cylinder in two distinct peaks, one at the blow-down process, and the other at the end of the exhaust stroke, which coincides with the rolled-up vortex arriving at the exhaust valve. Wentworth demonstrated the relative importance of the piston crevice and was able to reduce exhaust hydrocarbons by 47-74% with revised designs of the engine piston. These designs consisted of piston crowns in which the top land was significantly narrowed. Experiments, however, do not directly imply that crevice quenching is responsible for such a large fraction of unburned hydrocarbons, a conclusion we will discuss below. The revised piston of Wentworth has been tapered at an angle of 45° so that the interface of the piston and the cylinder is no longer at a right angle in the vicinity of the cylinder wall. This may change the nature of the vortex roll-up in its interaction with the flame and also effect exhaust aerodynamics.

In the present work we have attempted to visualize gas motion in a model engine under a variety of operating conditions. Our goal has been to break the intake, compression, expansion and exhaust stroke into separate processes in the engine, and thereby simplify the flow field under study at each stage. Previous work reporting visualization of the engine combustion process has been done under conditions in which only a top view of the piston was possible [1,12]. Our single compression-expansion engine has a square cross-section which allows a side view of the engine chamber so that the flow patterns which exist during the intake and exhaust strokes and the vortex roll-up and the compression stroke are able to be seen clearly. Our engine has another advantage in that it may be operated such that we simulate only the intake stroke or only the compression stroke or only the compression and expansion stroke, etc. Optical observations are made by taking high-speed movies of a Schlieren image of the test section. Both color Schlieren and black-and-white Schlieren are utilized.

In addition to the flow visualization experiments reported below, a number of experiments were conducted in which total unburned methane was measured by means of a gas chromatograph. These experiments demonstrate the effect of various operating conditions on unburned hydrocarbons in a more direct way than the visualization experiments.

In the following we describe the experimental apparatus and procedures that are used in Section II. In Section III the experimental results are presented in the form of movies for the flow visualization experiments, and gas chromatograph results for the hydrocarbon experiments. In Section IV the results are summarized and conclusions drawn.

II. APPARATUS AND PROCEDURE

The single compression-expansion engine system has been described in detail in references 7 and 13. The engine has a stainless steel test section with square cross-section, 3.81 x 3.81 mm, with side windows of quartz. The pneumatically driven piston is designed to simulate constant angular velocity crank shaft rotation. The electronic control system can operate the engine in a variety of modes such as single compression stroke, single expansion stroke, and single compression-then-expansion stroke. The engine is equipped with a simulated exhaust valve and a burned gas sampling device which are illustrated in Figures 1 and 2. The valve is made of aluminum to minimize inertia, and is operated by a fast-acting solenoid valve. The opening stroke is 1.3 mm, which is fully executed in about 3 milliseconds. The valve angle is 50° and its diameter is 15.875 mm, with a gap width of 0.88 mm. The burned gas sampling device consists of two rubber bags attached to the exhaust valve so that the burned gas is collected into the sampling collector at atmospheric pressure. It has an adapter for a hypodermic needle which is used to extract the gas sample from the bags and inject it into a gas chromatograph. The sample device can be evacuated to .5 inches of mercury, which eliminates possible interference due to leakage of fresh charge through the exhaust valve. The sampling bags can be disconnected from the exhaust valve and the exhaust let out to atmospheric pressure when simulating actual engine operating conditions.

A new igniter has been installed in the engine [14]. It is a line igniter and provides an extremely two-dimensional flame front so that analysis of the Schlieren image is simplified considerably. The gas mixture, which is methane air, is provided by a mixing device as reported in reference 15. The fresh gas mixture is introduced into the engine chamber through a pinto valve which is pneumatically operated. The pinto valve is designed so as to be flush with the wall surface and to eliminate any possibility of unburned hydrocarbons remaining in the valve assembly.

The engine is run under two conditions. For concentration measurements the experiment is operated and the burned gases allowed to soak in the engine for a period of several minutes. The burned gases are then collected by manually opening the exhaust valve and forcing the piston to move to top dead center. The sample is then collected via the syringe and transferred to the gas chromatograph. In the other mode of operation the exhaust valve is opened at typical exhaust timing, and the Schlieren movies used to observe the flow patterns which result.

The Schlieren system is essentially the same as that reported in Reference 13. It is a two mirror Schlieren with a Fastex camera to take the movies. The only change is that of a new color stop which is illustrated in Figure 3. In order to improve the color resolution the neighboring colors are separated by black ribbons, which eliminate all light which is not of a pure color. The Schlieren image is much clearer with better definition of the colors. This change has been helpful in making quantitative measurements.

Figure 4 shows the modified piston which is designed to investigate the effect of a bevel at the edge of the piston crown. The piston has the same top land as the regular flat piston head that is originally used in the engine. The only modification involves the attachment of an additional piece having a thickness of .635 cm, the edges of which are tapered to an angle of 45°. Once the modified piston was installed, it was noticed that the crevice volume associated with the piston had actually increased inadvertently. The effect of this increase in crevice volume is demonstrated in Section III.

III. EXPERIMENTAL RESULTS AND DISCUSSION

As discussed in the Introduction, the experimental results may be divided into two classes: (a) flow visualization experiments, and (b) unburned methane experiments.

A. Flow Visualization Experiments

The results of the flow visualization studies consist of a series of films in which first the intake flow without combustion is observed, secondly the compression-expansion stroke as a continuous sequence with combustion is observed, both for a conventional piston and for the Wentworth-type piston, and finally the exhaust stroke is observed.

In Figure 5, a sequence of frames from a typical Schlieren movie of the intake flow field is shown. For the purposes of Schlieren observation, the cylinder was filled with helium and the piston located at top dead center. As the intake stroke proceeded, the valve opened and air was entrained through the intake valve. It is seen from the movies that air enters the cylinder in the form of a strong jet. The strength of the jet is not uniform around the gap. However, this is due to some extent to the nature of the Schlieren imaging process. The jet eventually impinges on the cylinder head and circulates back into the undisturbed region below the valve. The strength of the jet flow decreases as the piston reaches bottom dead center and the dispersion of the turbulence flow field throughout the cylinder is seen. It should be noticed that there is still appreciable jet flow after the piston reaches bottom dead center. The directional characteristic of the intake flow can also be recognized in Dent and Salama's experiment [9]. They investigated turbulent characteristics in an engine with two different chamber configurations, using a hot-wire anomometer. Because of the length of time between the closing of the intake valve in a typical engine and ignition, it is felt that the turbulence introduced by the intake process often diffuses homogeneously throughout the cylinder during the compression process. Of course, in the case of swirl-inducing piston and cylinder head shapes, the intake-caused turbulence may not be as important. In general it appears that the intake induced turbulence has attained a fairly small scale by the time ignition would occur.

Figures 6 and 7 show the flow patterns observed during the compression and expansion strokes with combustion taking place. Figures 6 and 7 correspond to early and late ignition, respectively. In both cases the vortex roll-up occurs in what was initially a quiescent environment. The size of the vortex keeps increasing, even after top dead center. The boundary layer, which grows along the wall due to the bulk motion induced by piston movement, may be seen clearly. Interesting to note that as the vortex diverges after top dead center, the boundary layers along the walls become turbulent almost instantly. This may be caused by the interaction of the boundary layer and reverse flow that is induced by the growth of the vortex. The essential difference between the early ignition and late ignition cases is that with early ignition the flame propagates throughout the chamber in a turbulent free environment, with the exception of the vortex region, and consequentially, the wall quenching process is laminar over most of the cylinder. In the late ignition case, a substantial fraction of the cylinder is highly turbulent, which substantially modifies the flame wall quenching process. Furthermore, in the late ignition case, the cylinder pressure has begun to drop due to piston withdrawal, and the flame must propagate at a lower overall pressure than for early ignition. As will be demonstrated in the next subsection, this has a significant effect on the total unburned hydrocarbons present after combustion is completed. Although it is speculation at best, it may be that the formation of moisture on the cylinder walls as the piston withdraws is an indication of the degree to which combustion has been completed. In the late ignition case, it may be observed that near the piston no water condenses on the walls, indicating the presence of a quenched region.

In Figure 8 we show a movie frame sequence at the same conditions as in the previous paragraph, except for the piston configuration. The modified piston head is similar to that utilized by Wentworth [4]. However, our modified piston has a thickness of 6.35 mm for the tapered portion, as contrasted with that of only 1.58 mm for Wentworth's piston. The quantitative results, however, are extremely interesting. The main feature of the modified piston is that the vortex roll-up size is limited by the size of the triangular region defined by the cylinder wall and the wedge. Regardless of operating conditions, the vortex never leaves the wedge region. It is therefore much smaller than that of the normal piston. Unlike the normal piston, the rolled-up vortex does not grow once the cylinder has come to top dead center. One interesting aspect of the movie is that during the expansion stroke, gas that was entrained in the piston wall crevice feeds out into the vortex that remains in the wedge area. This implies that with the wedge piston, the majority of unburned hydrocarbons remain in the crevice and vortex region. The conclusion that we reach from these observations is that the large reduction in unburned hydrocarbons observed by Wentworth for his modified piston crown is not entirely due to a reduction in the crevice volume, but may in part be caused by a substantial reduction in the level of turbulence at the piston end of the cylinder due to the wedge-shaped crown modifying the nature of the vortex roll-up.

In Figure 9 the exhaust gas motion is shown. For this experiment, the mixture was burned before the compression process. Shortly after combustion is completed, the piston is moved forward and the valve opened. It can be seen that the exhaust process is similar to that described by Tabazynski, et al. [6], in that first gas from the bulk of the cylinder enters the exhaust system, followed by the rapid exiting of gas from the vortex region nearest to the exhaust valve. The vortex far from the valve still remains in the chamber and gradually disperses. The boundary layers along the walls seem to remain in the cylinder. The size of the rolled-up vortex is larger than in the case of compression.

The effect of operating conditions on the vortex size is illustrated in Figure 10, in which the longitudinal and lateral dimensions of the vortex are compared for the compression stroke and the exhaust stroke with the regular and modified piston crowns. As can be seen, the vortices are longer in the lateral dimension in each case. At top dead center the vortex sizes are measured every one millisecond after the piston stops. As noticed above, it is remarkable that the vortex created by the modified piston does not flow after top dead center, unlike that formed over the normal piston crown. Also note that the vortex is somewhat larger for the exhaust stroke.

B. Unburned Methane Measurements

Experiments in which unburned methane was measured consisted of two types. The first was that of piston withdrawal with combustion. This condition was similar to that discussed previously by Ishikawa and Daily [13], and it was hoped that the qualitative interpretation of the previous photographic results would be borne out by the methane measurements. The second set of experiments consisted of combining the compression and expansion stroke similar to that discussed in the previous subsection.

In the piston withdrawal experiments, the cylinder was first filled with the premixed methane air charge, and the piston brought top dead center and the mixture allowed to depressurize to 1 atmosphere. The piston was then withdrawn with various degrees of ignition timing. The burned gases were analyzed by means of the gas chromatograph, as discussed in Section II. The results are shown in Figure 11. In the previous work of Ishikawa and Daily [13], it was shown that the degree of turbulence present in the combustion chamber depended strongly on the time in the cycle. It was anticipated therefore that ignition timing would have an effect on the unburned hydrocarbon concentration, that being greater the later the ignition. Furthermore, the later the ignition, the lower the pressure in the cylinder and therefore the thicker the quench layer along the walls. As may be seen from Figure 11, however, no such effect is observed, and therefore no conclusion can be reached. This may be because the influence of wall turbulence is small for this case of piston withdrawal, and because the total amount of unburned methane is dominated by other effects. The figure shows that about 50% of the initial methane is not burned. This high concentration of unburned fuel can not be explained by quenching arguments alone, and thus must be related in some way to bulk quenching phenomena at these low pressures. An analysis of bulk flame quenching may be found in reference 14. Also shown on Figure 11 is the effect of stoichiometry on total unburned methane, and as may be seen, there is little effect. This may be explained by qualitative arguments in that as the equivalence ratio becomes leaner, the quench layers become thicker, while at the same time the total concentration of methane is decreasing. The two have a counter-balancing effect.

In the second set of experiments, the compression-expansion cycles were coupled. Figure 12 shows unburned methane percentages as a function of ignition timing, with equivalence ratio, piston design, and engine speed allotted parametrically. As a general trend early ignition timing produces less unburned fuels than late ignition timing. This is in agreement with our qualitative interpretation of the Schlieren movies in the previous section. It is interesting to note that the unburned fuel concentration reaches a constant value for ignition timing later than five milliseconds after top dead center. This may be because the flame must propagate through less turbulence but at a lower pressure than in the early ignition case. This trend appears to be more appreciable for the stoichiometric mixtures than lean mixtures. This may be attributed to their difference in burning velocity.

In comparing the effects of piston designs, the modified piston generates higher concentrations of unburned methane than the regular piston. This may be caused by the additional crevice volume that was inadvertently present in our modified piston head. It should be noted that the modified piston shows a similar effect of ignition timing as in the conventional piston. This seems to indicate the importance of turbulence near the corners, at the interface of the piston and cylinder, and that in both cases, the flame may not reach the corner region during the period when significant combustion is taking place.

Only two data points are shown in Figure 12 for an equivalent engine speed of 2,000 RPM. Although both of them lie below the average curve for the 1,000 RPM case, the results are not clear and it is hoped that we will be able to obtain more data before the final version of the paper is due.

IV. SUMMARY AND CONCLUSIONS

Both the color Schlieren cinemagraphic study of fluid mechanical conditions in a model automobile engine and unburned methane measurements for similar conditions have been presented. Flow characteristics were examined for the case of intake flow, exhaust flow, and compression-expansion, with both a normal and a modified piston crown configuration. From the Schlieren photographs, the role of the rolled-up vortex has been shown to be an important one in determining overall turbulence characteristics within the cylinder. It has been observed that the vortex may induce boundary layer turbulence shortly after top dead center. It has also been observed that the modified piston crown controls the size of the vortex and that the growth of the vortex after top dead center observed with a normal piston crown does not occur with the modified crown. Unburned methane measurements were made for a number of conditions paralleling those observed by Schlieren cinemagraphy. The results have shown appreciable effects of turbulence, mainly due to the rolled-up vortex. Turbulence effects appear to be more significant for stoichiometric mixtures than for lean mixtures. The modified piston is less sensitive to turbulent effects than the regular piston crown.

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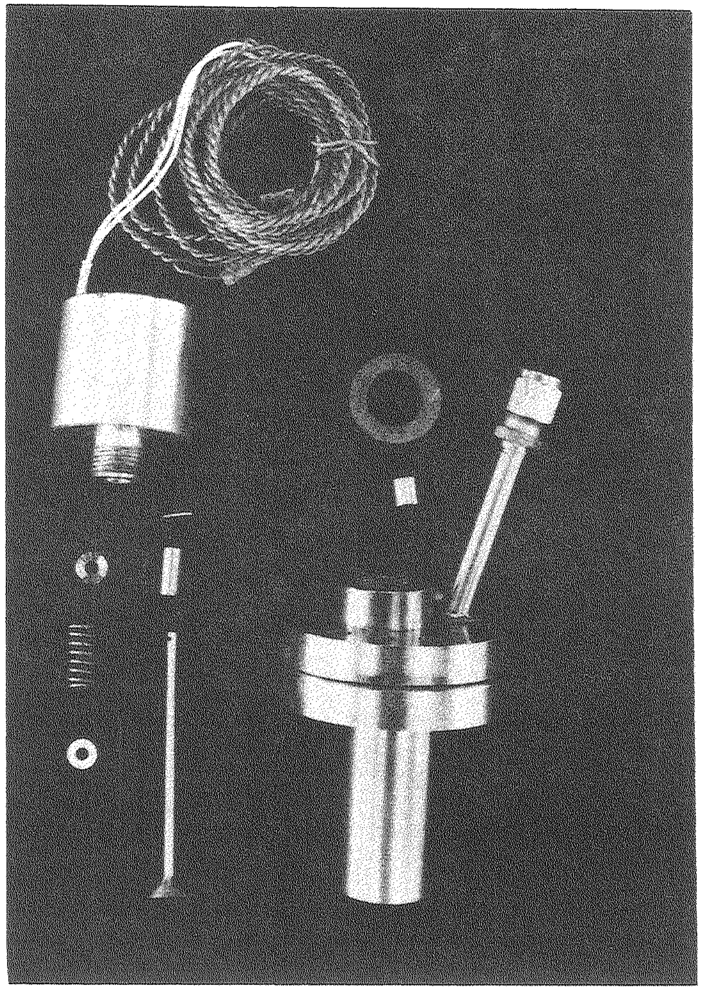

Fig. 1 Exhaust Valve

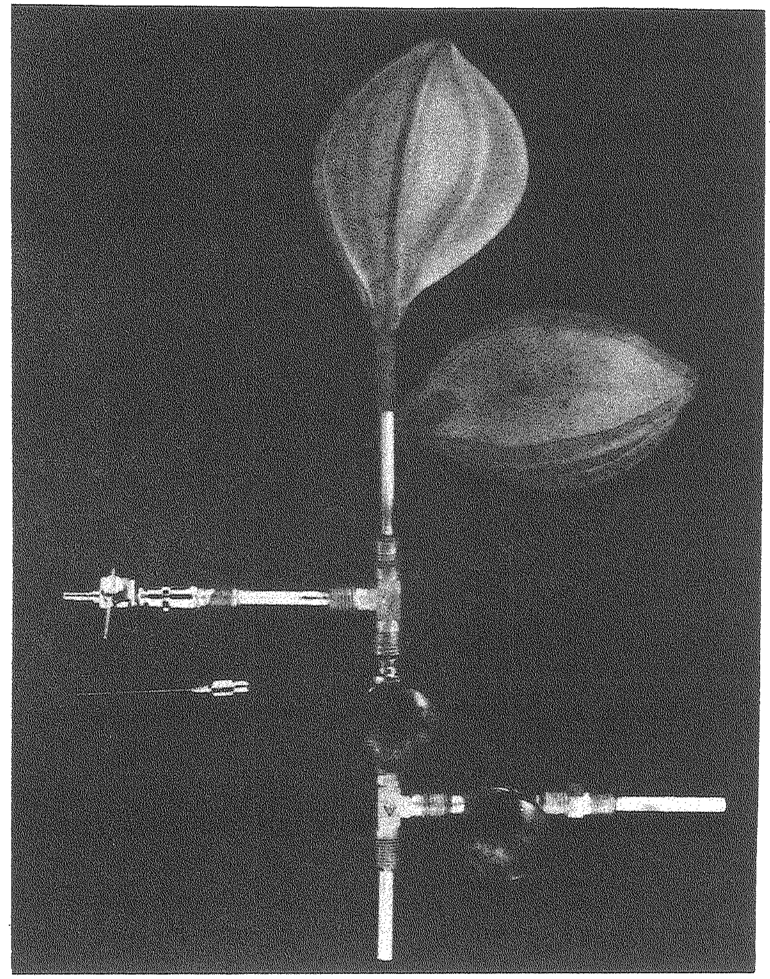

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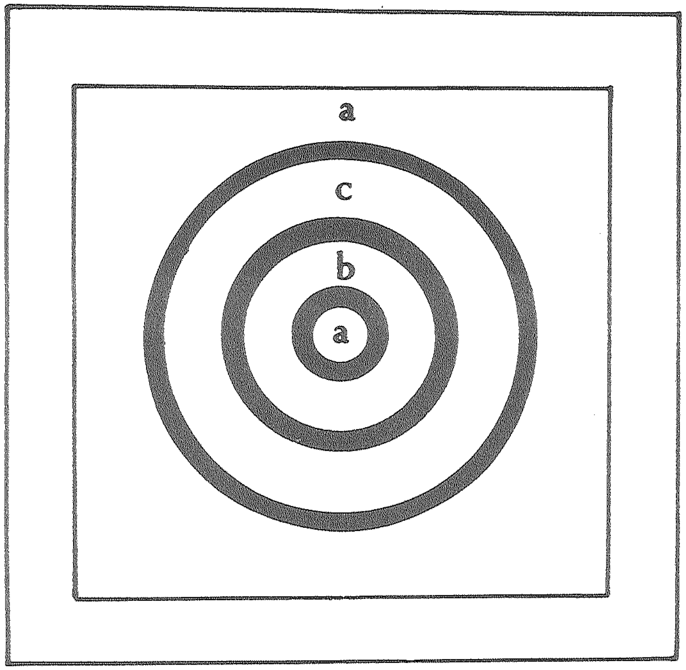
Fig. 2 Gas Sampling Device



(a) blue (b) red (c) yellow

Fig. 3 Color Schlieren Stop
with Black Ribbons

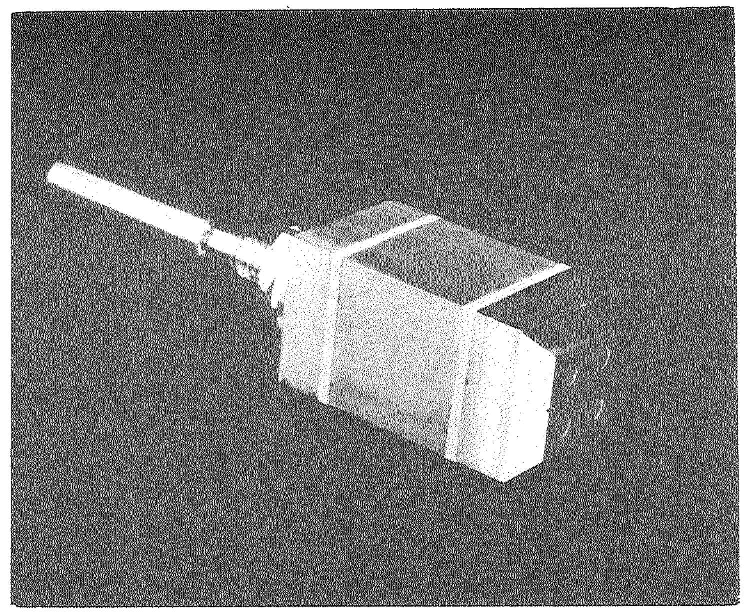


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Fig. 4 Modified Piston Head

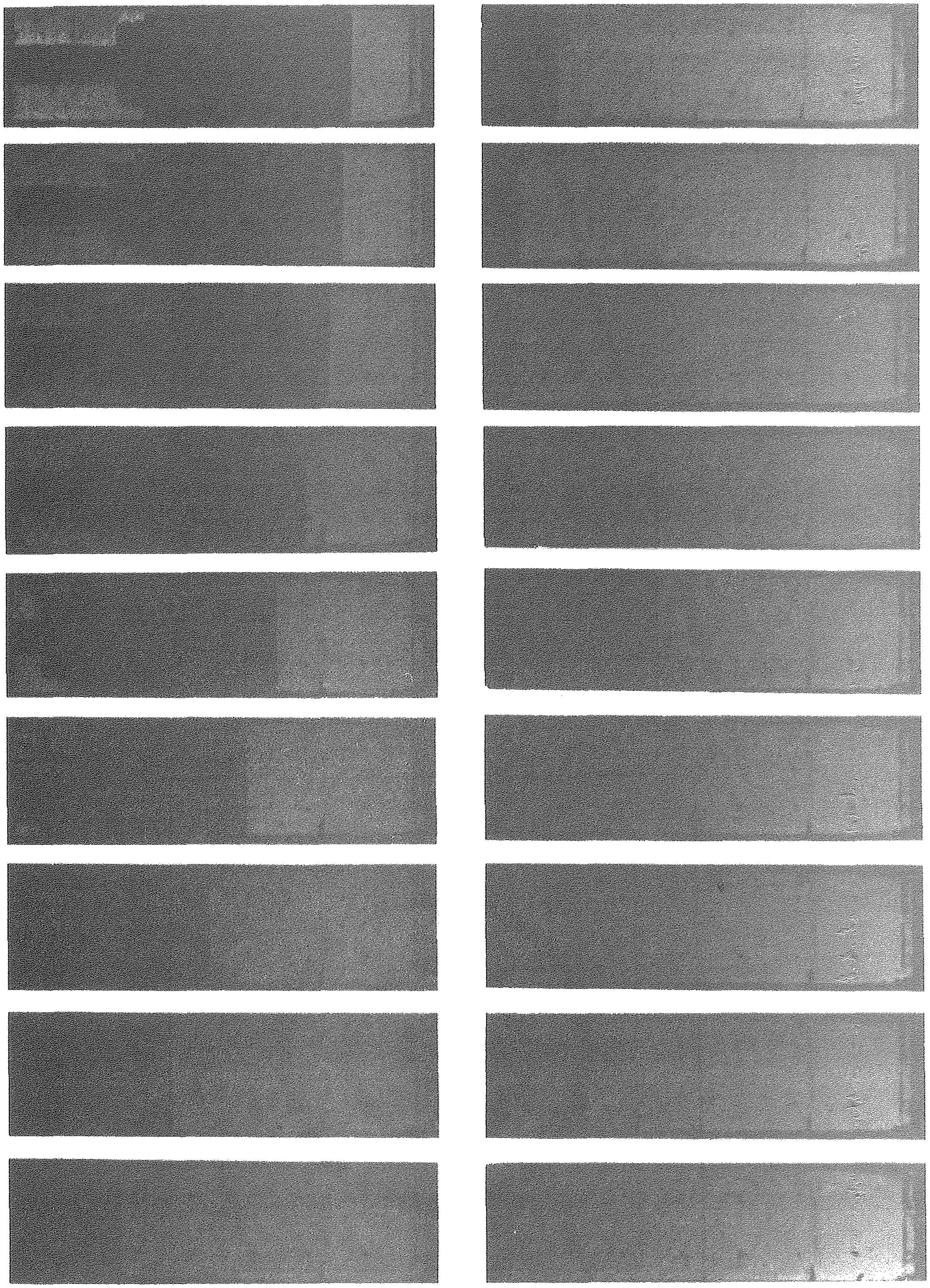

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Fig. 5

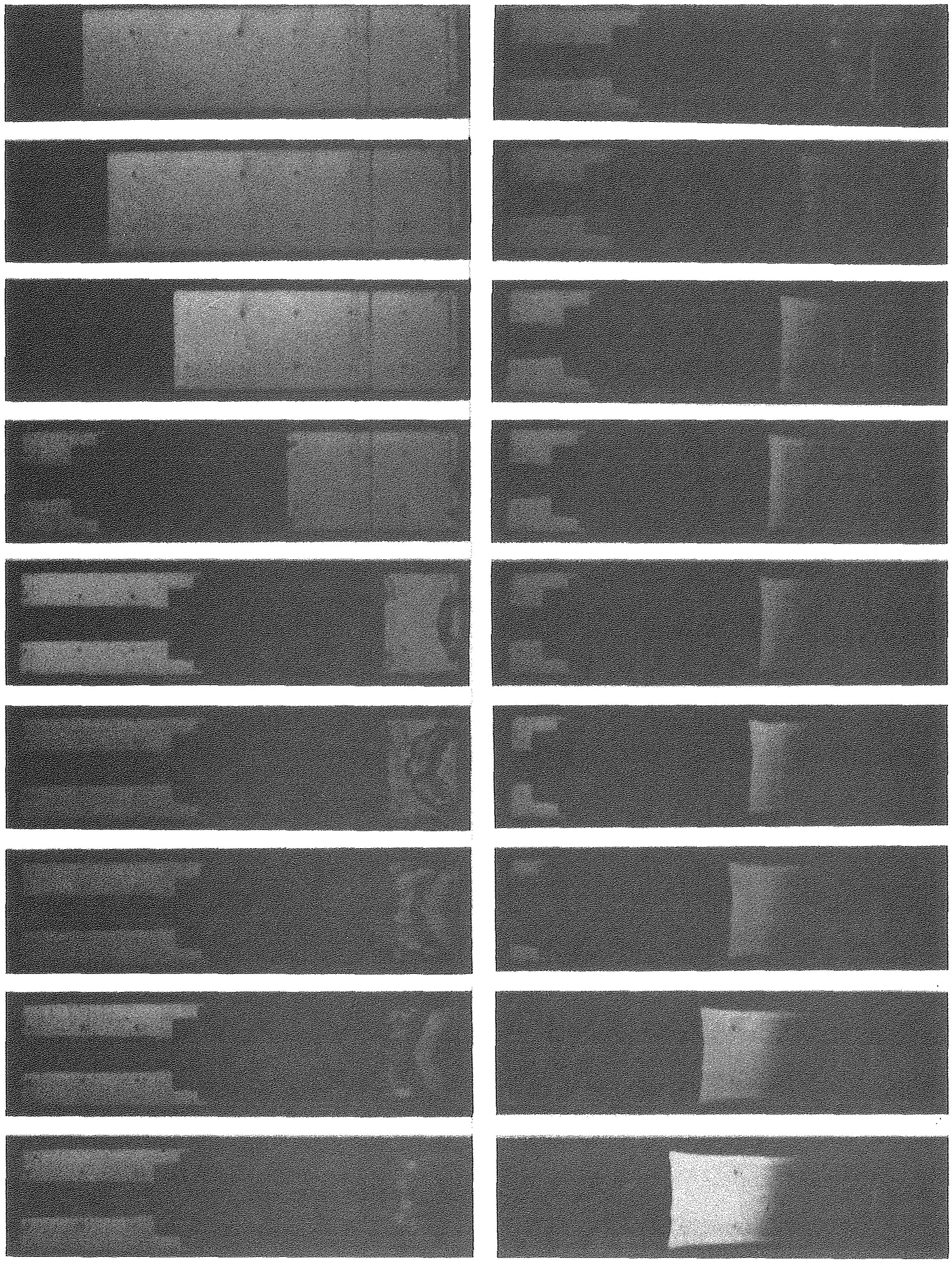

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Fig. 6

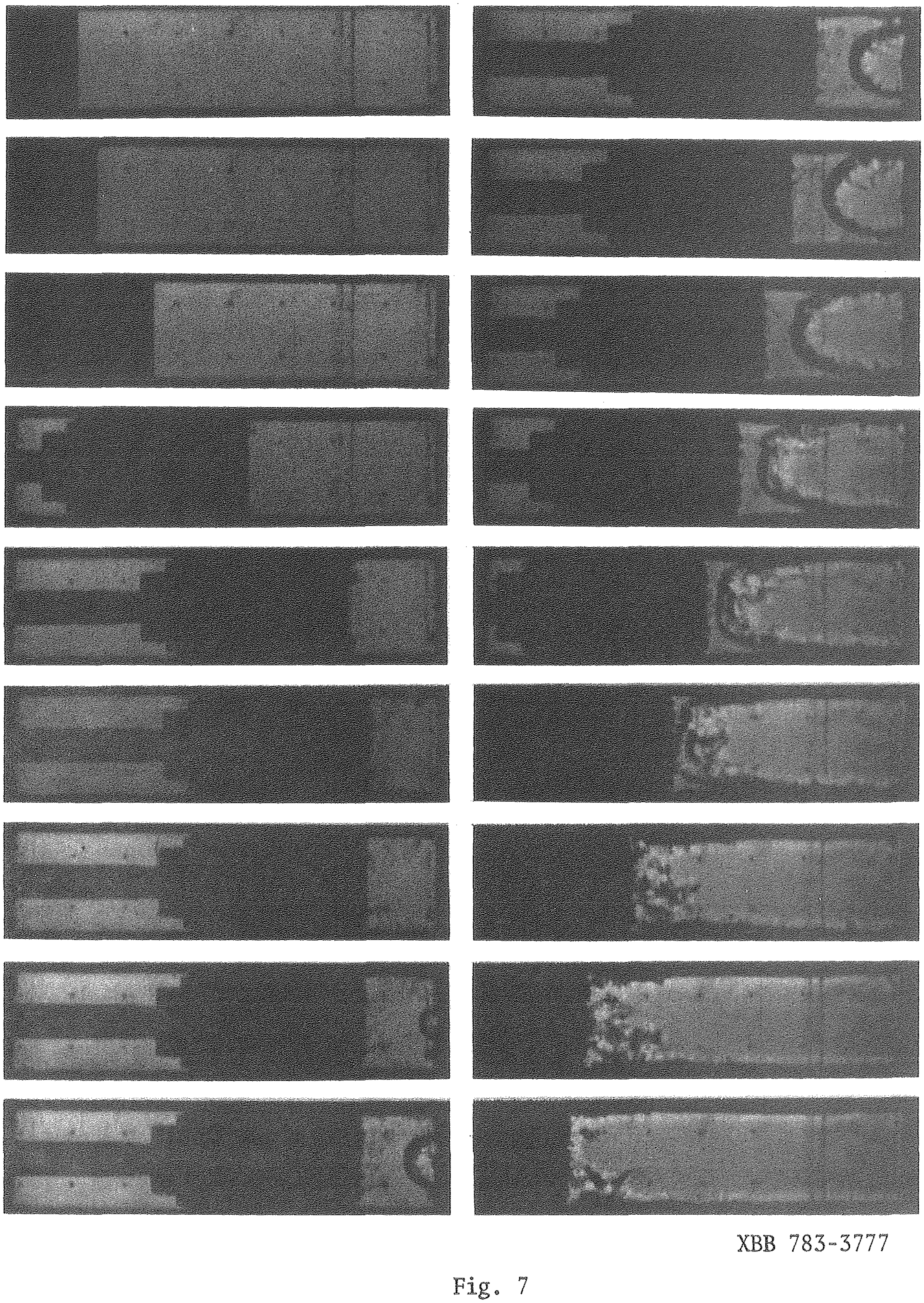

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Fig. 7

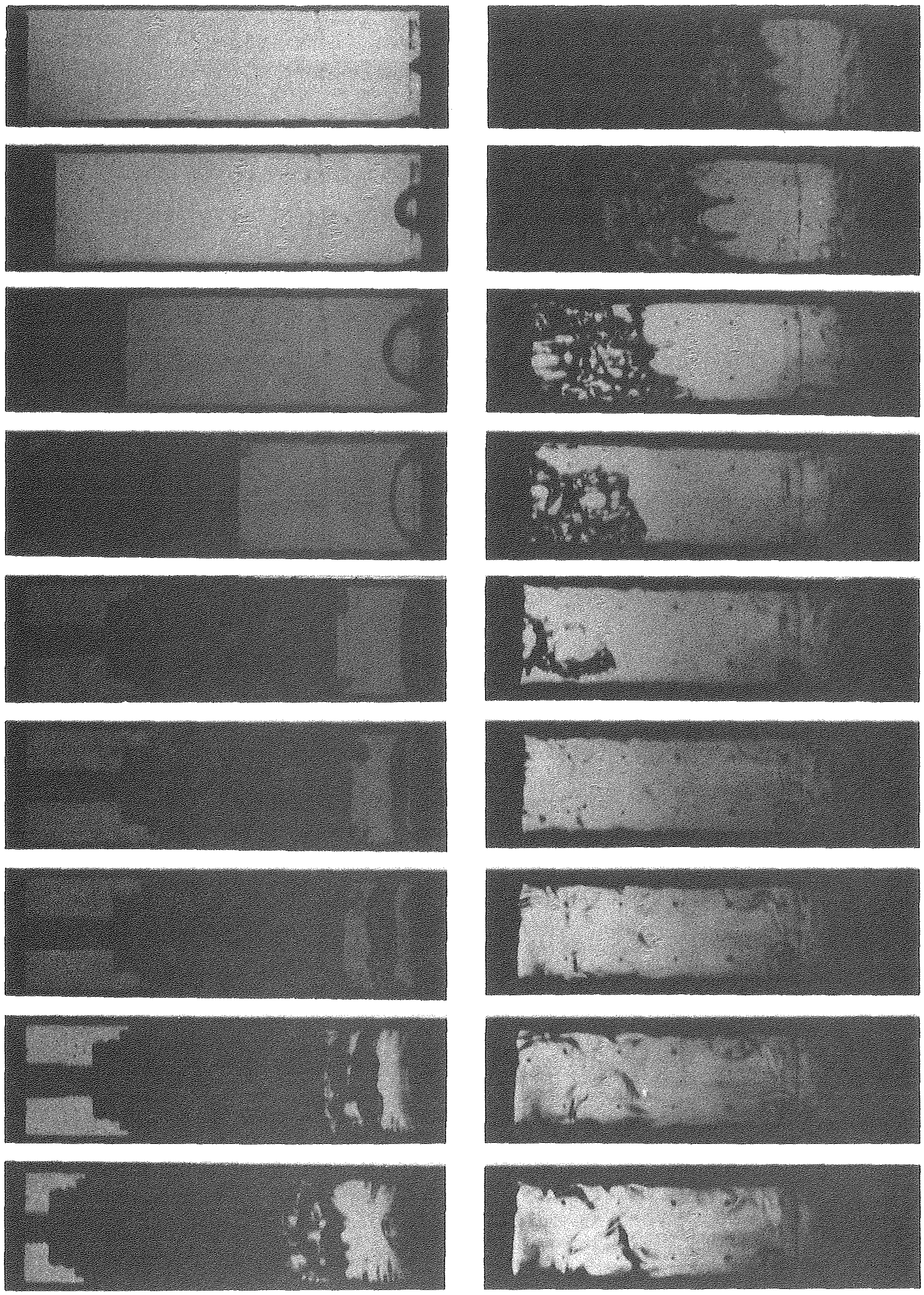

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Fig. 8

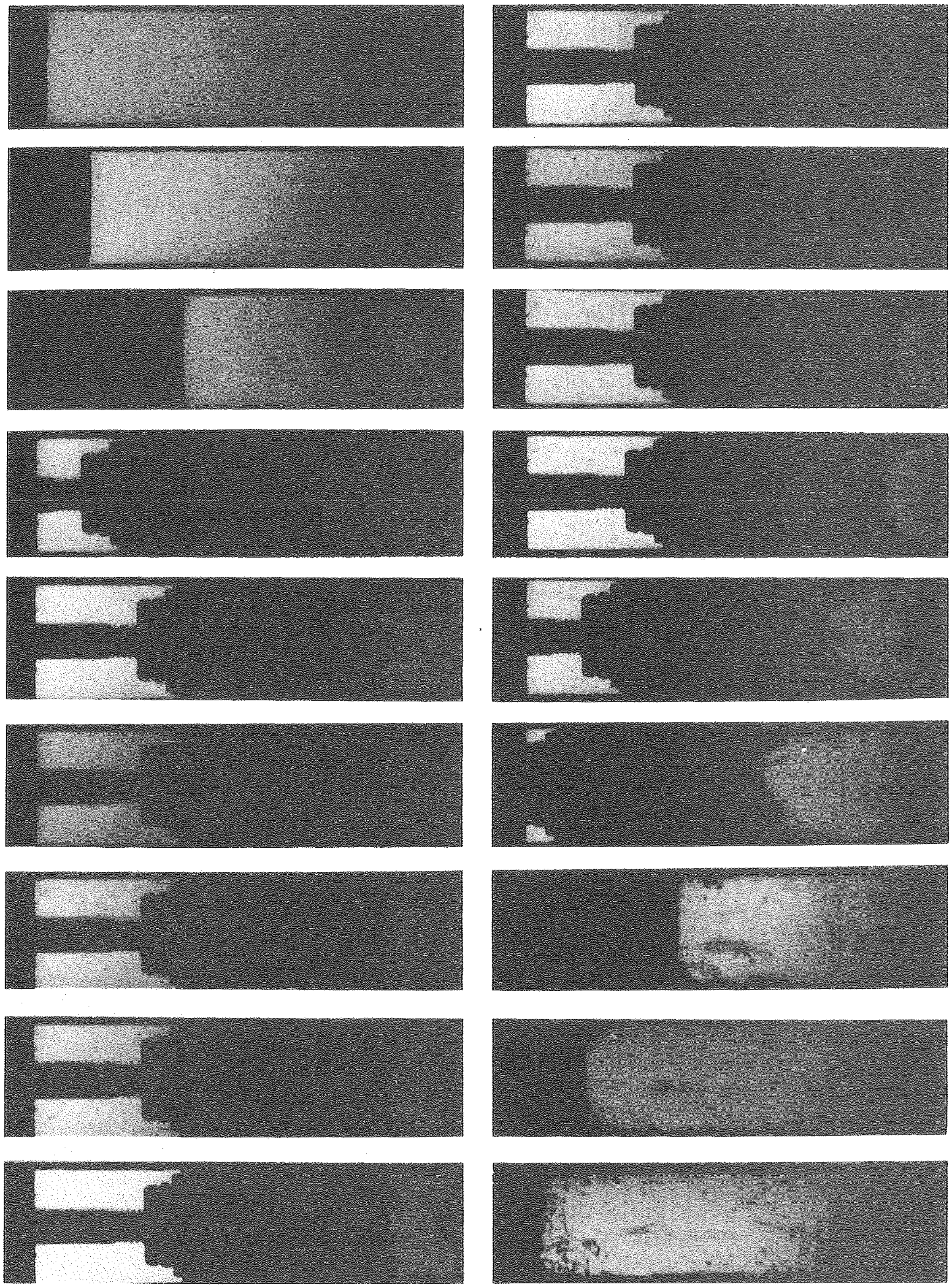

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Fig. 9

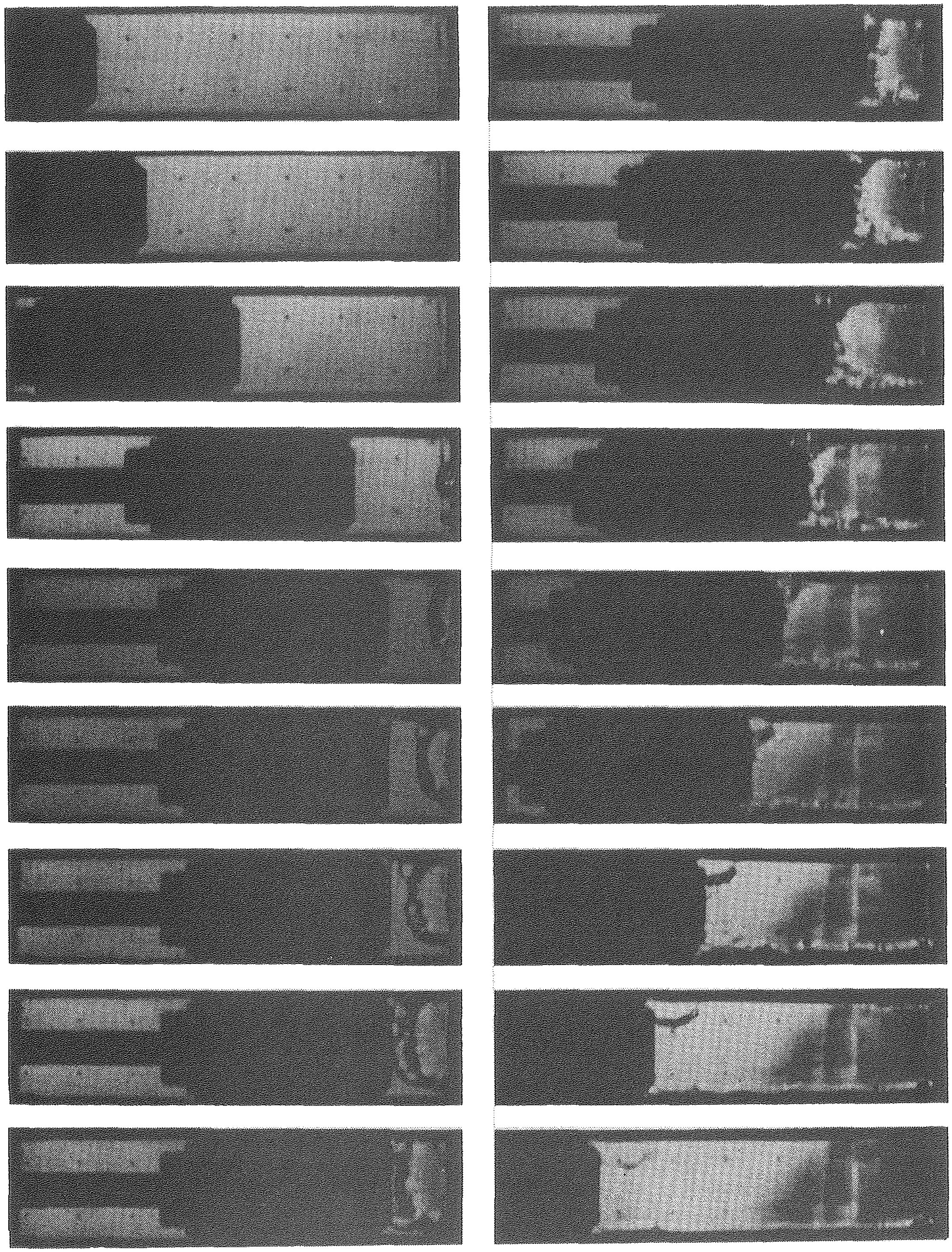

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Fig. 10

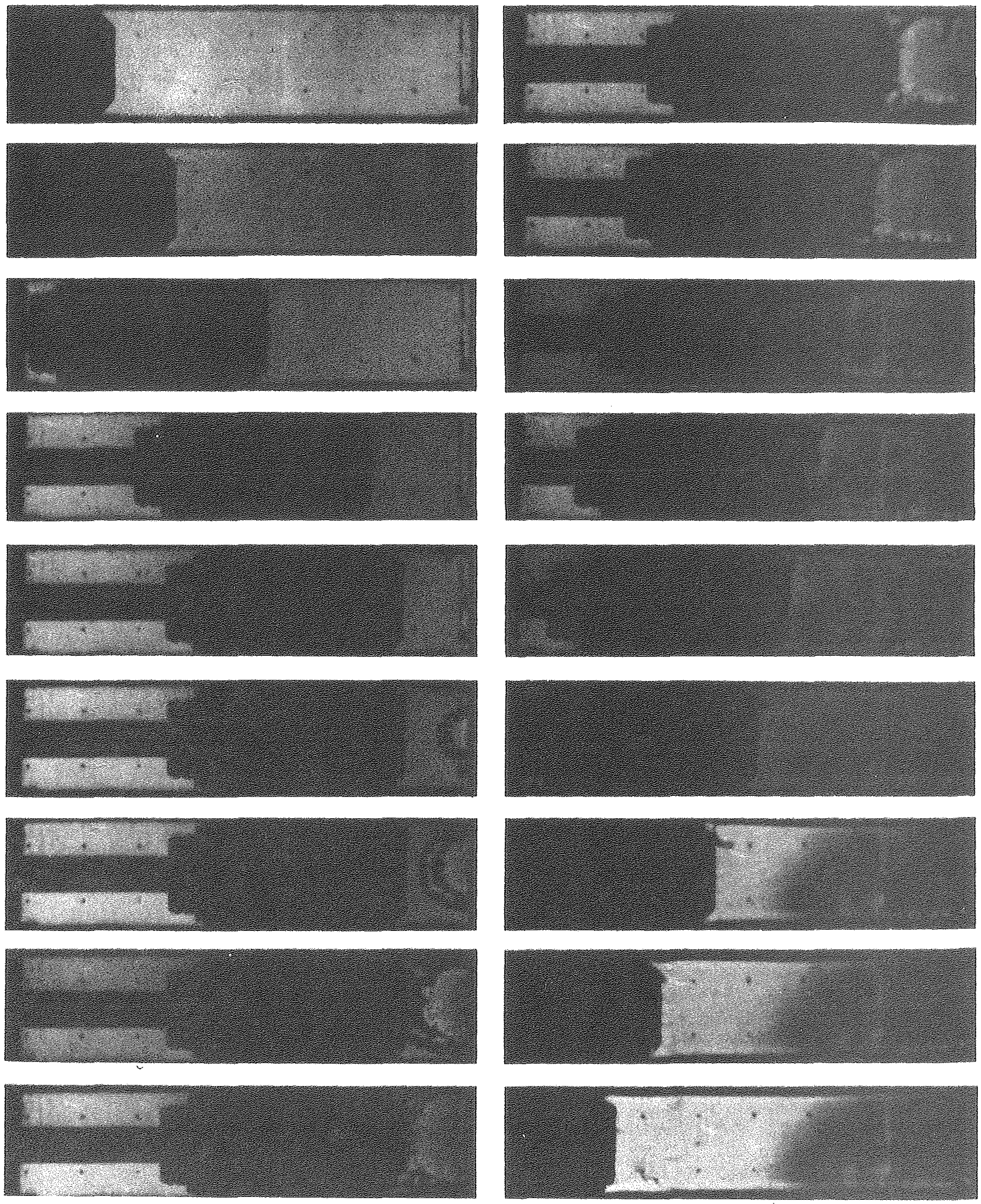

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Fig. 11

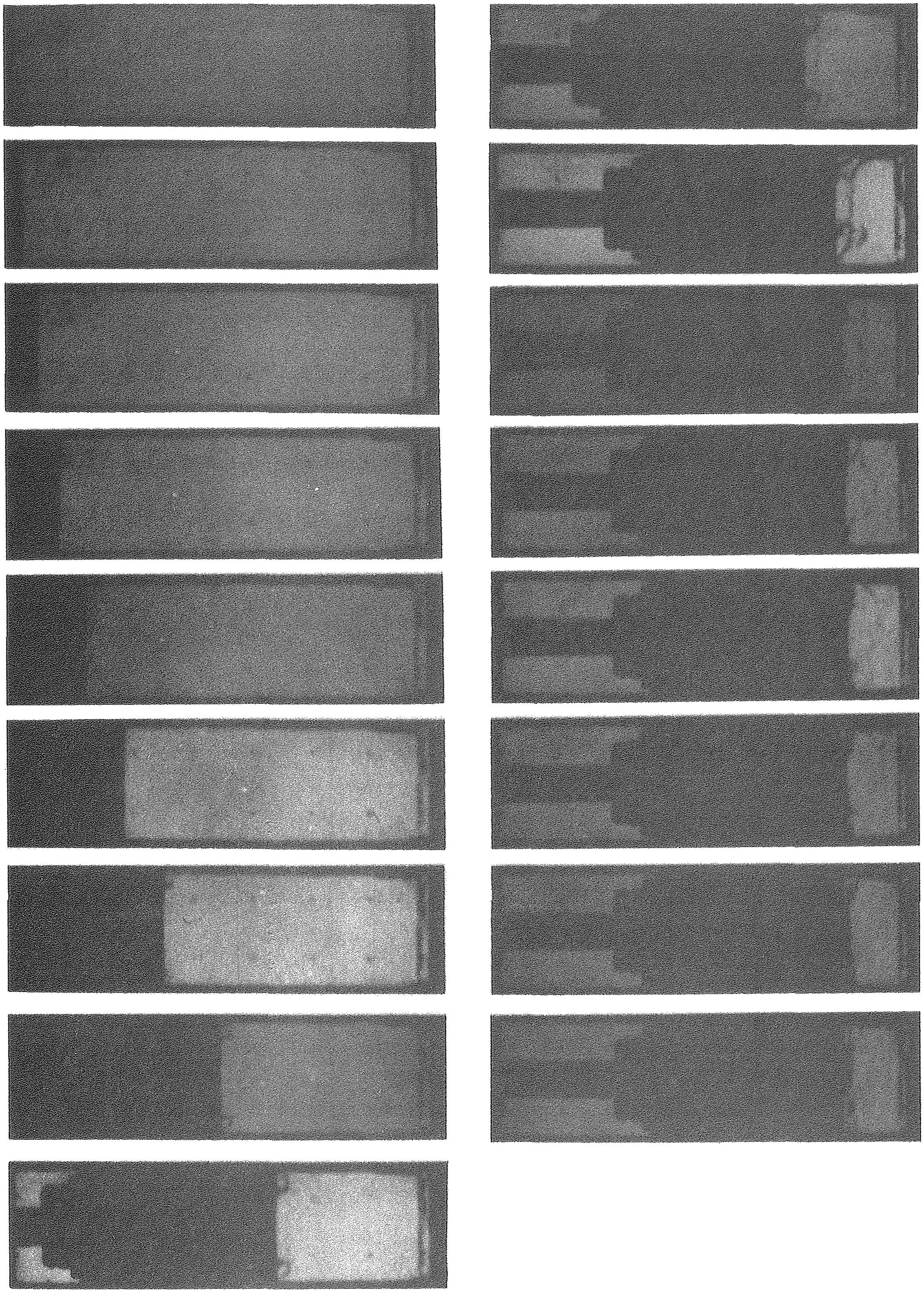

Fig. 12

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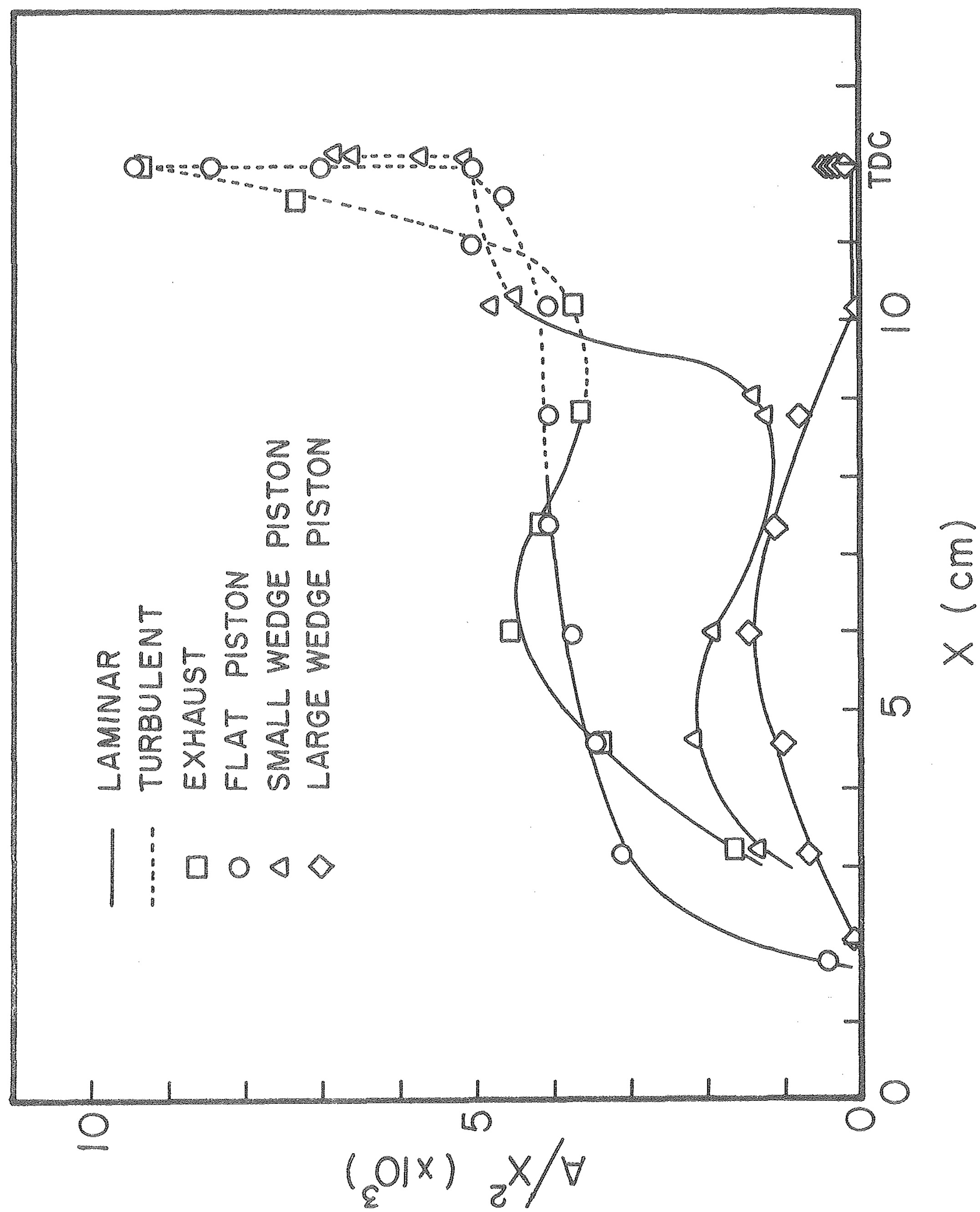

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Fig. 13

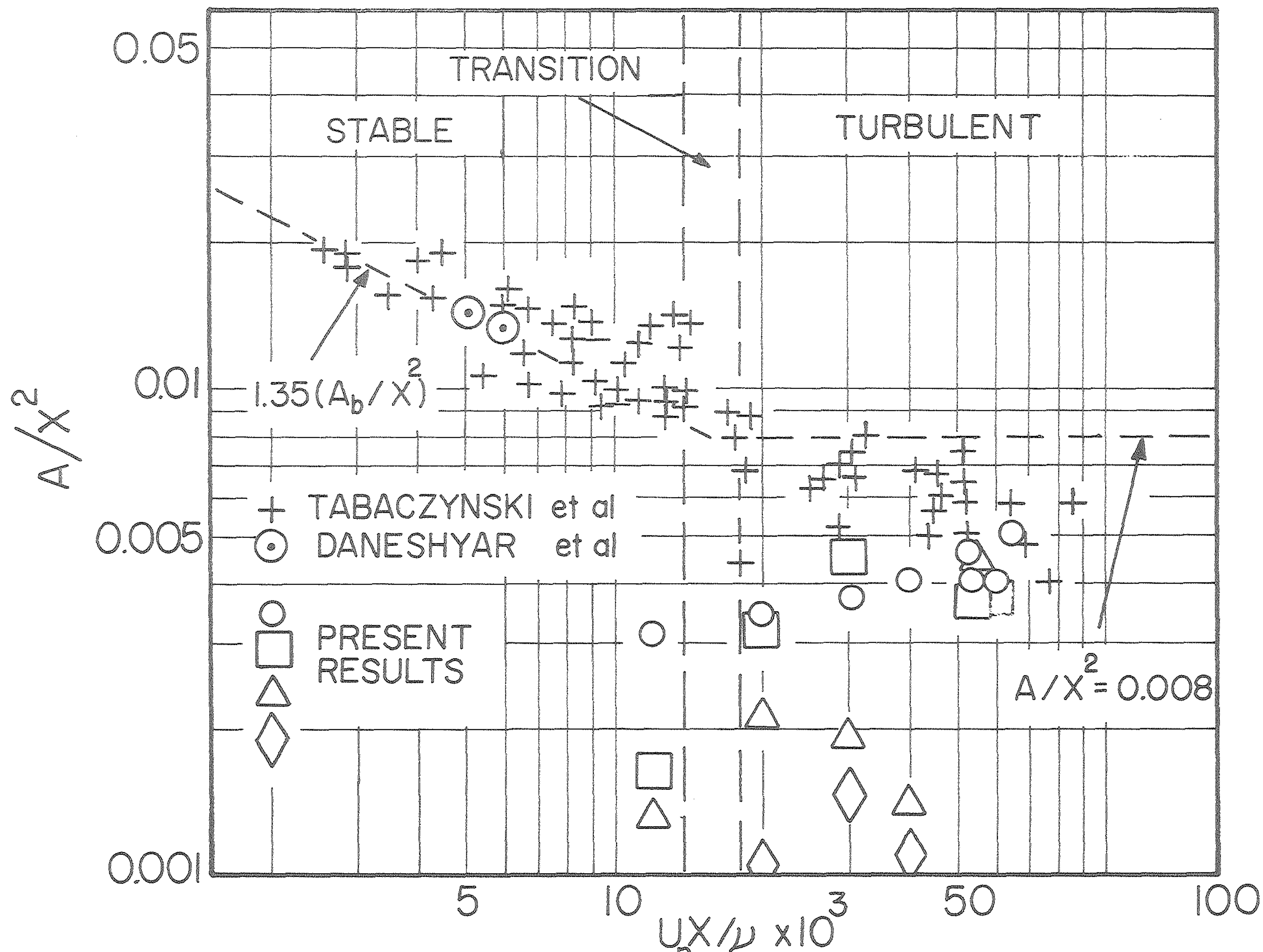

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Fig. 14

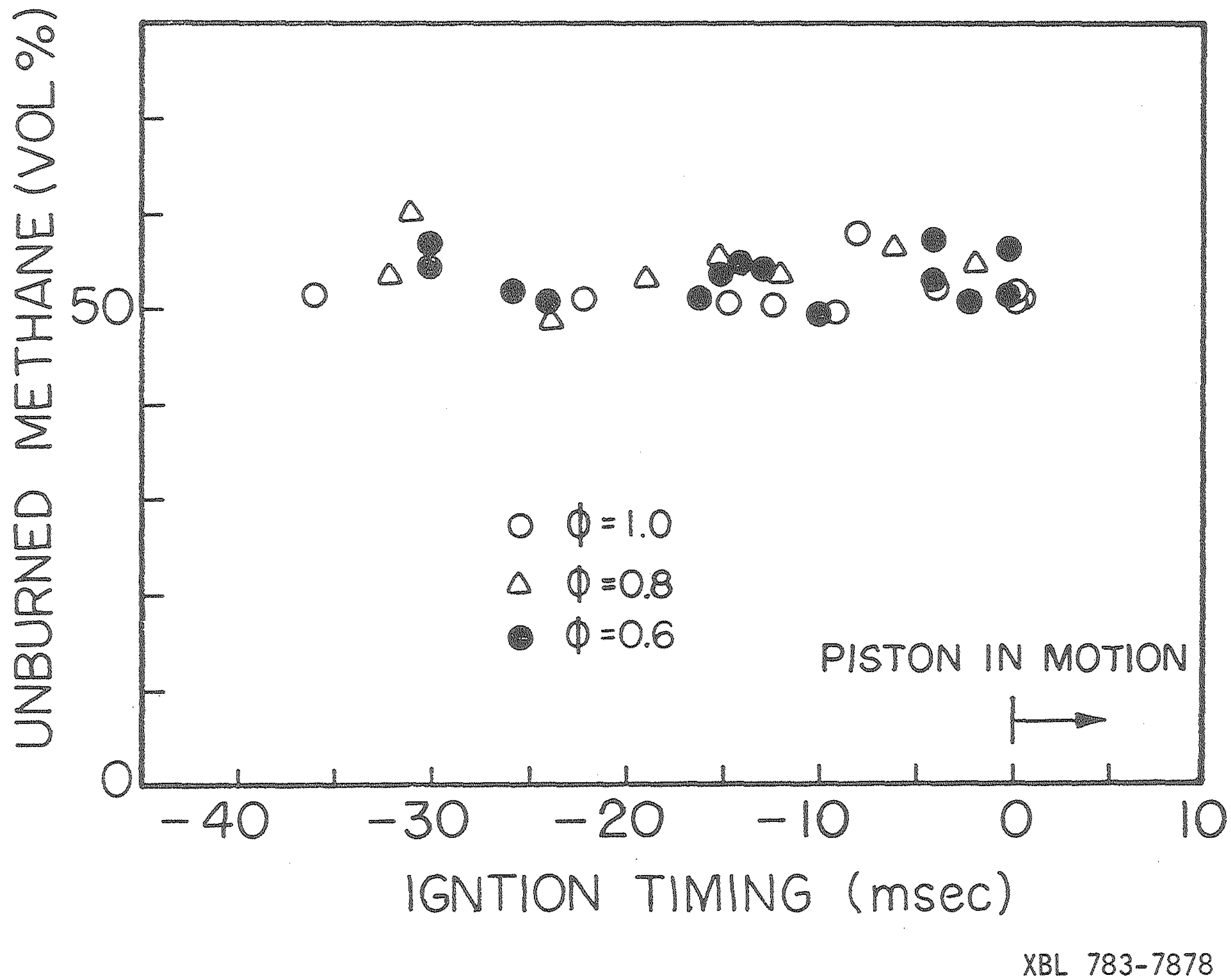
UNBURNED METHANE (VOL %)
50
0
−40
−30
−20
−10
0
10
IGNTION TIMING (msec)
φ = 1.0
φ = 0.8
φ = 0.6
PISTON IN MOTION
XBL 783-7878

Fig. 15

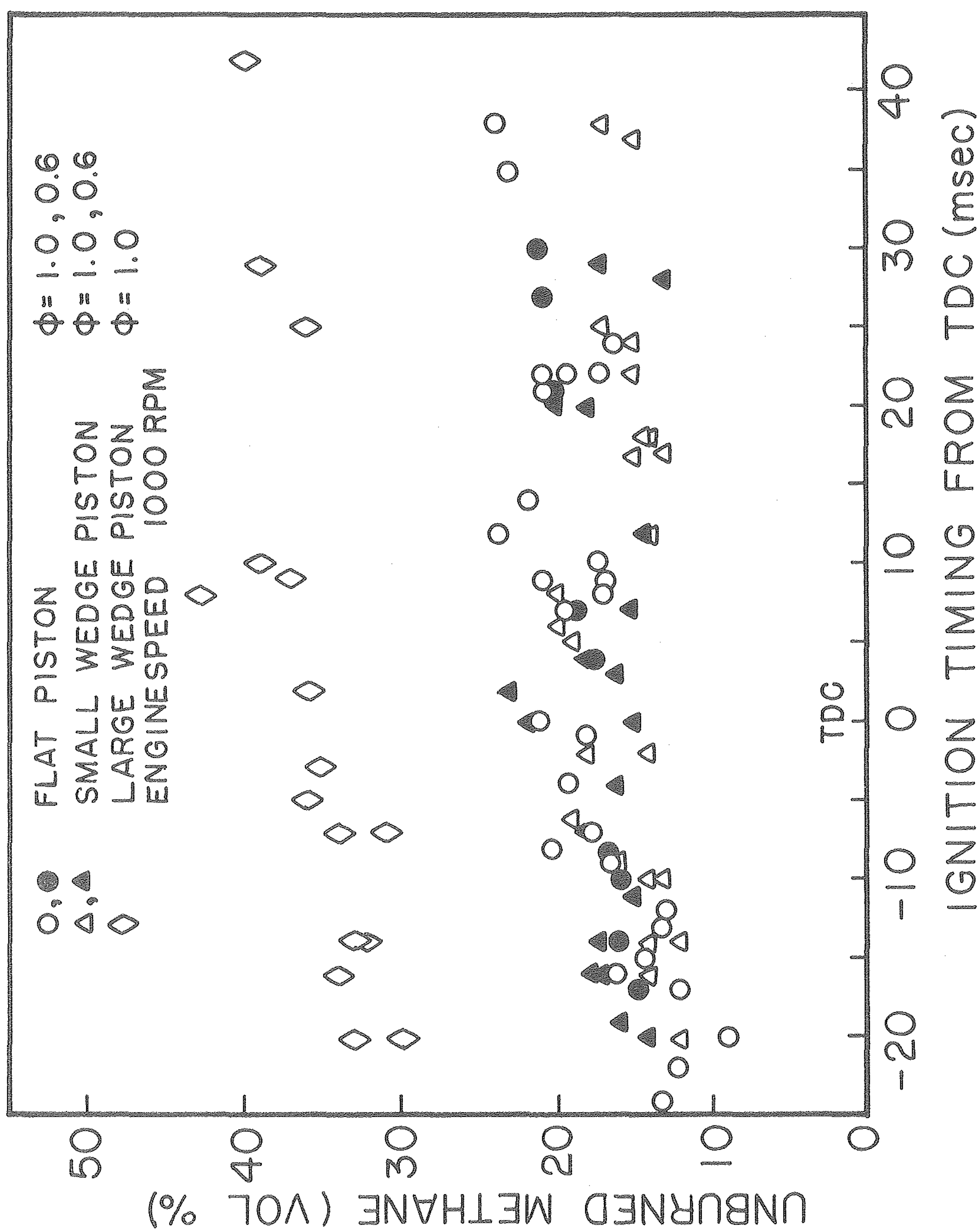

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Fig. 15

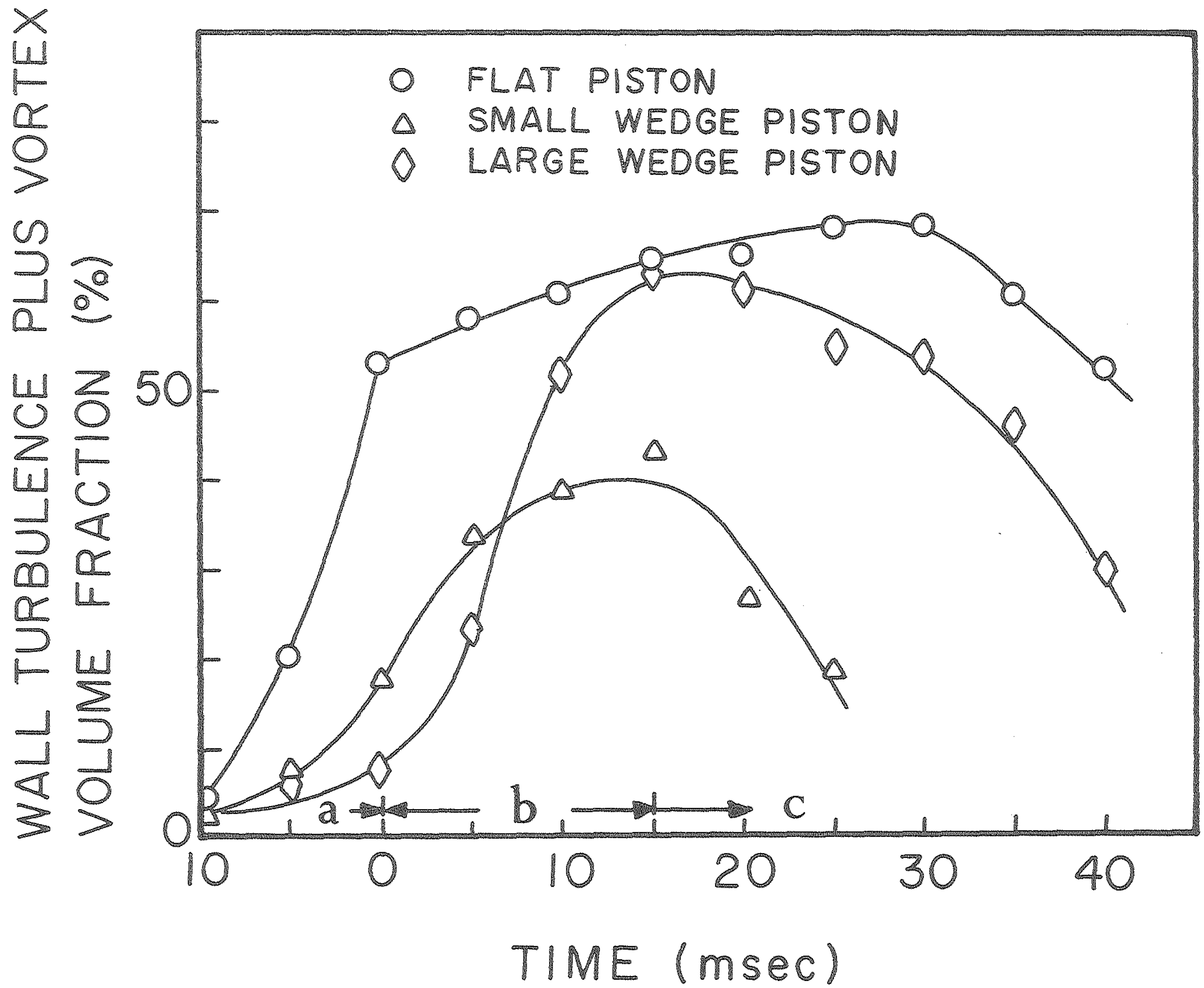

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Fig. 17

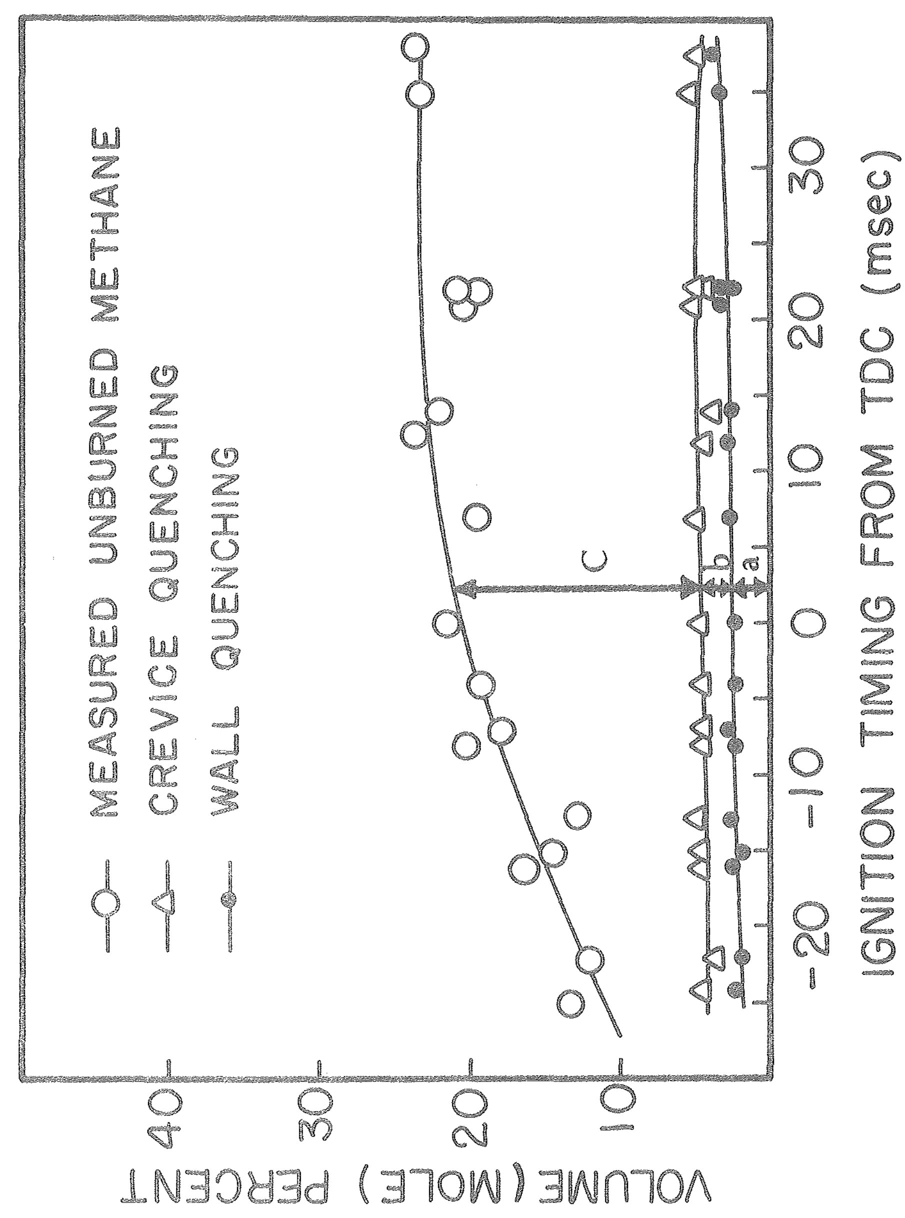

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Fig. 18

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