07738-TR-1

THE UNIVERSITY OF MICHIGAN

College of Engineering

epartment of Nuclear Engineering

or Fluid Flow and Heat Transport Phenomena

Technical Report No. 1

BUBBLE COLLAPSE BEHAVIOR AROUND A SHARP WEDGE IN A DIFFUSER

Terry M. Mitchell
Charles L. Kling
Frederick G. Hammitt

Financial Support Provided by:

The National Science Foundation under Grant No. GK-730

July, 1966

TABLE OF CONTENTS

Page

ABSTRACT

Two theoretical models attempting to explain the damaging potential of collapsing bubbles are explored. The "shock" theory assumes that high pressures produced during collapse in the liquid adjacent to the bubble are sufficient to cause damage to nearby solid surfaces. The "jet" theory assumes that bubbles near solid surfaces collapse asymmetrically into a torus containing a central jet. This jet when properly oriented in the direction of solid surface is assumed to be the cause of damage.

Experimental data consists of high speed photographs of the cavitating field in the vicinity of a solid boundary. Results of bubble collapse analysis support the "jet" theory of collapse by showing predominantly asymmetrical collapse.

LIST OF FIGURES

I. INTRODUCTION

The primary goal of this investigation is to theoretically and experimentally study the collapse behavior of bubbles in various liquid systems in order to be able to predict more accurately their capacity for damaging adjacent solid material, as well as to obtain a better basic understanding of the collapse behavior itself in cases where spherical symmetry may not apply.

Two lines of thought have been developed to explain the damage mechanism, the "shock" theory and the "jet" theory. The former is based on Lord Rayleigh's classical analysis showing that a spherically symmetric void collapsing in an incompressible inviscid liquid produces infinite pressure in the liquid adjacent to the bubble wall when the bubble has collapsed to zero volume. Later more complete analyses[2,3,4, etc.] which include such effects as compressibility, viscosity, surface tension, and internal gas content confirm the existence of a high pressure wave in the liquid for spherical collapse of a bubble. The two more recent analyses[3,4] one done at this laboratory, however, show that the pressure in the liquid during the collapse, at a distance from the center of the collapse equal to the original radius of the bubble is not sufficient to cause the observed damage although pressures during the subsequent rebound were sufficiently high.

The possibility of the spherical collapse being the damaging mechanism is strengthened by the results of Herring's[5] analysis which shows that a bubble moves toward a solid surface during collapse and hence that a bubble's damaging potential may be increased substantially over the stationary-centered bubble case. However, it is questionable that bubbles which are close enough to a wall to cause damage can even approximate a spherical collapse. There is rather the strong likelihood of an asymmetric collapse. These questions have been recently discussed in some detail by Ellis[6] as well as in our own proposal to NSF[7] from which this grant originated. Earlier, Rattray[8] indicated the asymmetrical nature of the collapse as well as the migration of the bubble center toward the surface using a perturbation technique for an ideal fluid.

The second hypothesis, the "jet" theory, states that bubbles collapse by flattening on one side, finally involuting into a torus with a liquid jet penetrating the disc-shaped void and striking the surface. Naude and Ellis[9] experimentally observed such collapses using spark-generated bubbles in a static field as well as the existence of a high pressure pulse below the impact point of the jet on a photoelastic material on which the bubble collapsed. Shutler and Mesler[10] later observed in an experiment, similar but not identical to that of Naude and Ellis, that material damage did not occur under the jet but under the torus around the jet. Ivany's work[11] shows asymmetrical collapse and possible torus formation for bubbles collapsing in a high pressure gradient away from solid surfaces. Recent work in this laboratory by Olson[12] shows good pictures of toroidal collapses in the cavitation field of a vibrating horn.

Further significant support for the "jet" theory is obtained from the recent pictures by Ellis[6] showing bubbles collapsing adjacent to a solid boundary in a static liquid. High speed motion pictures of hydrogen gas bubbles collapsing in water show asymmetrical collapse with the formation of jets sufficiently energetic to cause pitting. Ellis further pointed out that pitting depends on a crucial combination of conditions; bubble size and position, timing, etc. The same arguments have been independently advanced by the present group.[13] This is consistent with the observation that only about one bubble in 10,000 collapsing adjacent to the surface will cause damage in most cavitating systems made in recent studies in this laboratory[12,14] and previously reported by Plesset.[15]

II. RESULTS OBTAINED TO DATE

The experimental data obtained so far in this investigation consists primarily of high speed motion pictures taken of cavitation bubbles growing and collapsing in water flowing through a two-dimensional venturi in the vicinity of a fixed solid surface. The venturi has an 0.25 inch by 3.0 inch throat opening. It then widens at a 3° half-angle from the 0.25 inch dimension with no change in the 3.0 inch dimension. An 0.205 inch long arrow is marked in the plexiglas for scaling purposes with its tip at the throat exit. Top view of the venturi is shown in Figure 1.

A stainless steel wedge (Figure 2) was inserted 0.25 inches downstream from the throat exit. The wedge is located midway between the parallel plexiglas sideplates in the venturi diffuser, while in the other direction perpendicular to the flow, it occupies the full width of the diffuser section of the venturi. The wedge extends in the direction of the flow from 0.25 inches to 6.75 inches downstream of the throat exit. The wedge is designed so that one surface is flat and parallel to the flow while the other surface diverges at about 5.5^{o} from a sharp point to a thickness of 0.1875 inches two inches downstream. The wedge was designed in this manner to make the flow across the top as uniform and unchanged as possible.

Unfortunately, as the sequence of photographs in Figures 3 and 4 reveal, either or both the boundary layer effects and roughness of the leading edge caused a wake to form on the flat surface. Redesigning the assembly to allow for an adjustable angle of attack did not alleviate the problem. Further redesign of the wedge may help solve the problem.

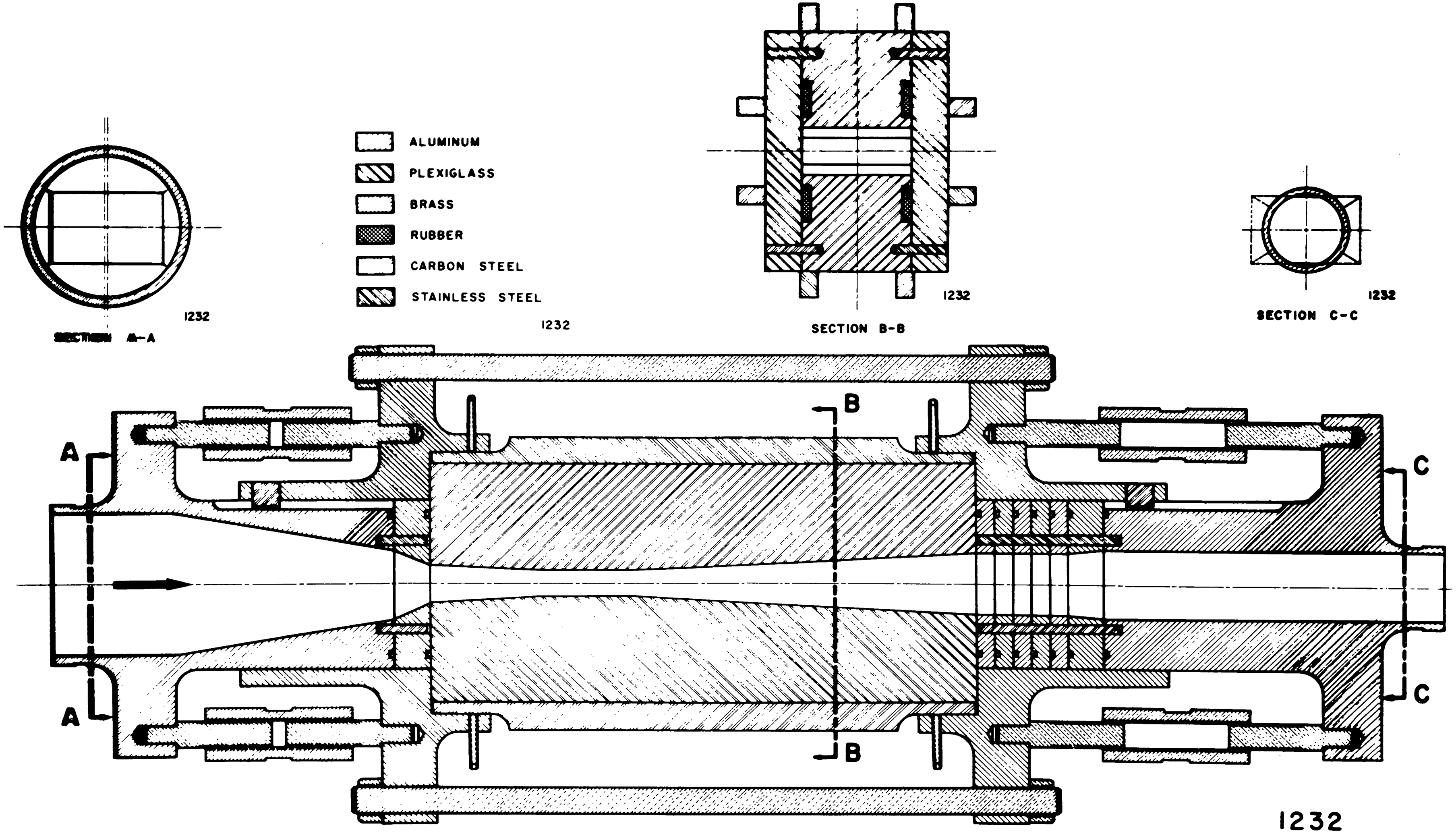
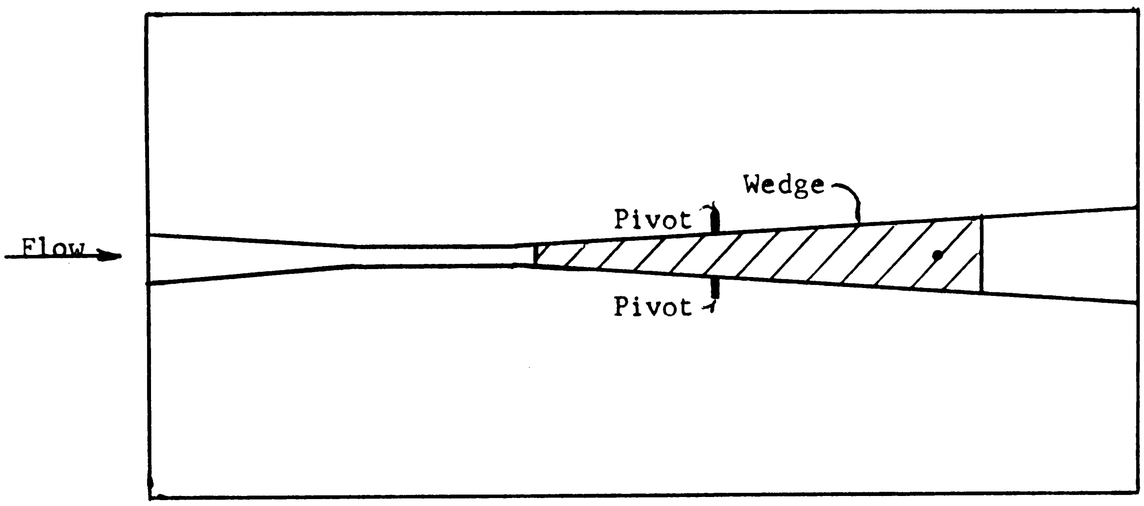
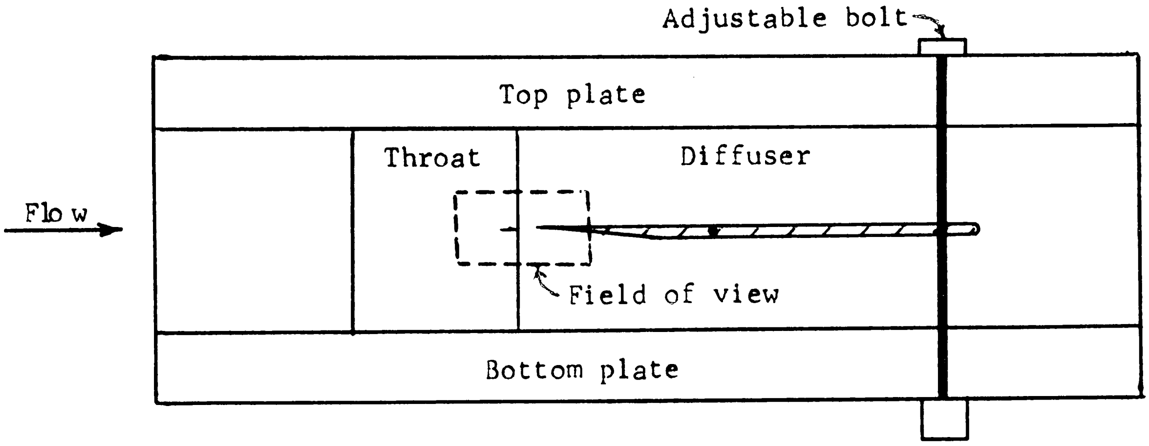


Figure 1. Schematic of Two-Dimensional Venturi.



TOP VIEW



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SIDE VIEW

Figure 2. Wedge in Plexiglas Section of 2-Dimensional Venturi

Although the flow regime was not as desired, high-speed motion pictures were taken with a Wollensak Fastax camera and an Edgerton, Germerhauson & Grier strobe. In analysing the pictures, the primary question is how a fixed surface affects collapsing bubbles in a flowing system. As discussed in the Introduction, if the collapse is reasonably symmetrical the collapsing bubble should migrate toward the nearest fixed surface. This, of course, would allow the pressure forces arising in the bubble's vicinity to exert damaging forces on the surface during collapse or subsequent rebound. For the asymmetrical collapse model one would expect flattening of the bubble and formation of a jet to cause pitting. Ivany's pictures[11] indicate flattening of the bubble on the high pressure side in a flowing system and suggested torus-jet formation. If such behavior is repeated in the present film, along with the favorable orientation of the assumed jet with respect to the specimen, we would have some of the best evidence confirming the "jet" theory.

Flow conditions for the film were 1.3% air content and a throat velocity (assuming 100% liquid) equal to 83.5 feet per second. The camera speed, determined by a 60 cycle timing light on the film, varied from 5800 to 7700 frames per second. The time between corresponding points on consecutive images, therefore, varies between

174 and 132 microseconds. However, the duration of the light flash for each frame is only 1.2 microseconds. For the first analysis 72 separate bubbles were examined giving 586 separate bubble images. The only bubbles examined were those which gave no indication of contact with the walls of the venturi, i.e., no streamers or extremely irregular collapse. Also no bubble was examined whose collapse was altered obviously by the presence of other bubbles nor any bubble whose center was more than four times its maximum diameter from the wedge. This last restriction was imposed arbitrarily to restrict the number of bubbles to be examined to those of primary interest. It appeared from preliminary viewings that bubbles more than a diameter or two from the wedge showed no effect of the wedge's presence. Finally, bubbles traveling below the wedge or striking its sharp leading edge were not examined in the analysis. An example of a bubble striking the leading edge is shown in Figure 4. Note that the bubble appears to flatten and bend around the tip, then totally disappears much more quickly than the non-"pierced" bubbles shown in Figures 3 and 4. Briefly then, the bubbles examined in this analysis were those growing and collapsing regularly although not necessarily spherically, above the wedge, but within 4 diameters thereto.

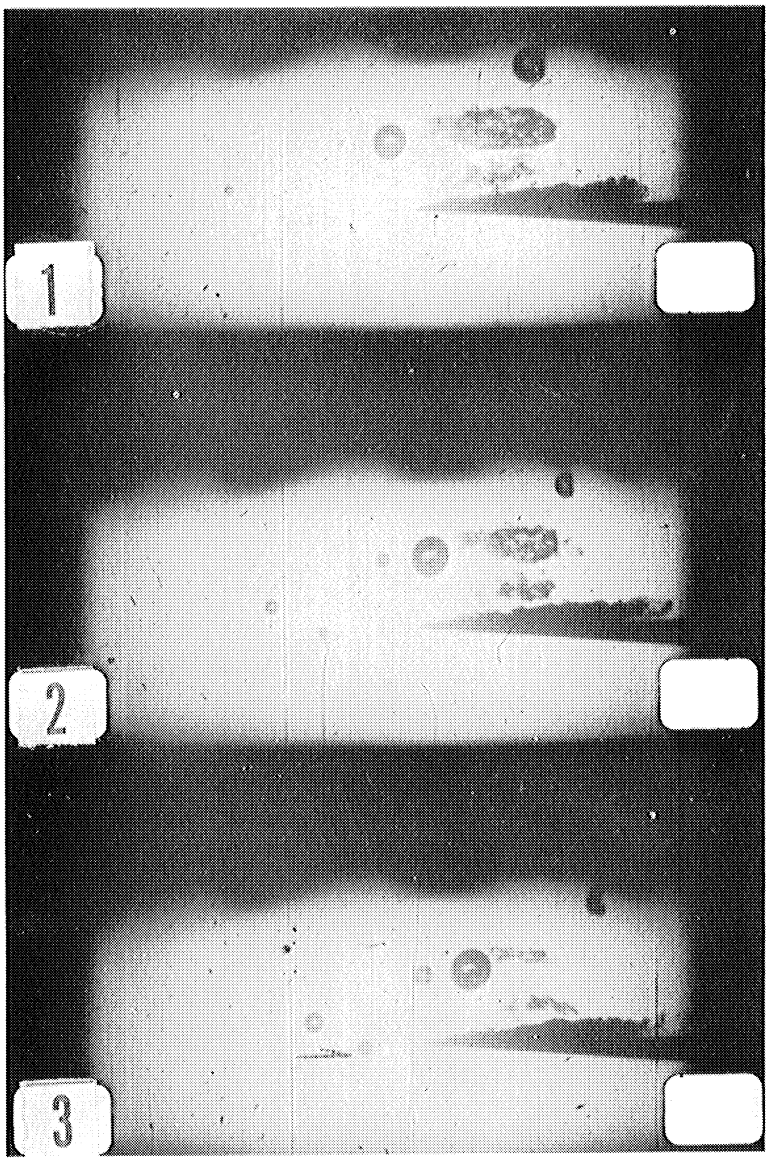

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Figure 3. High Speed Photographs, Velocity 83.5 ft/sec, Air Content 1.3%, 139 Microseconds per frame, Scale Length (Arrow) 0.205 in.

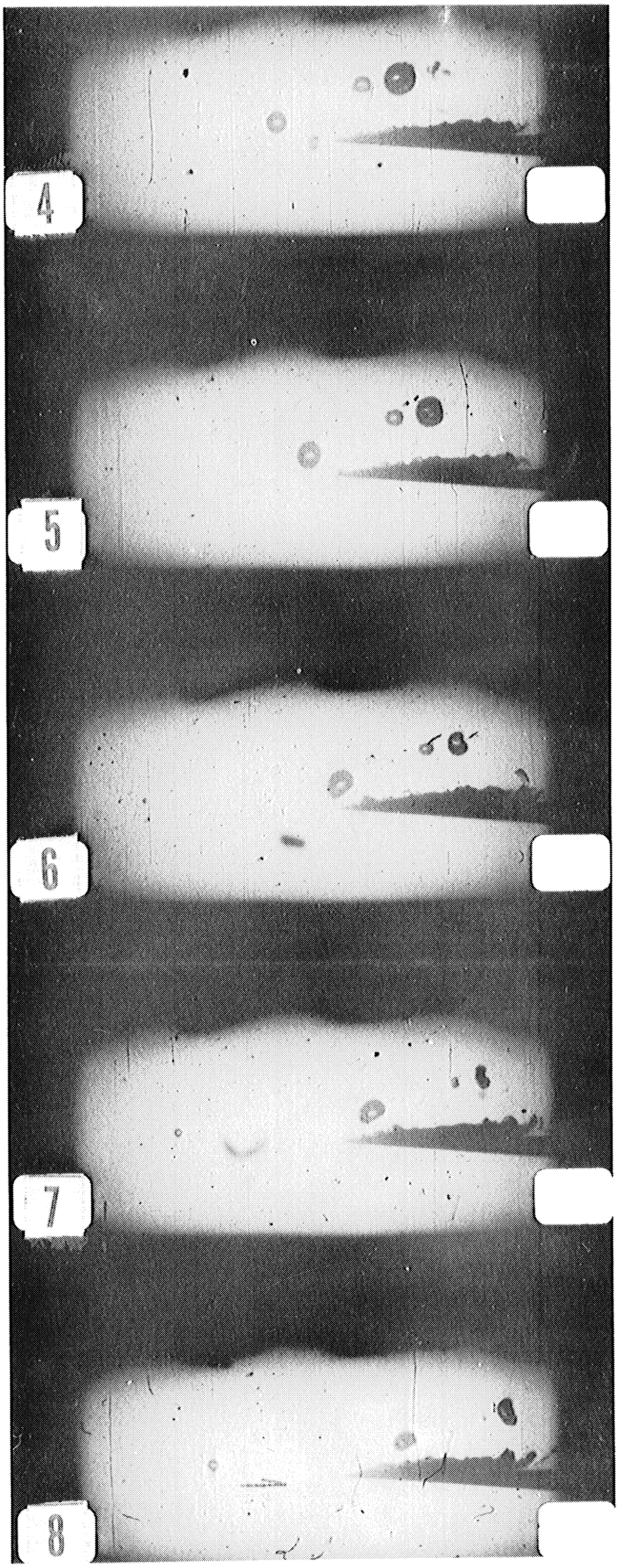

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Figure 3. (Cont.)

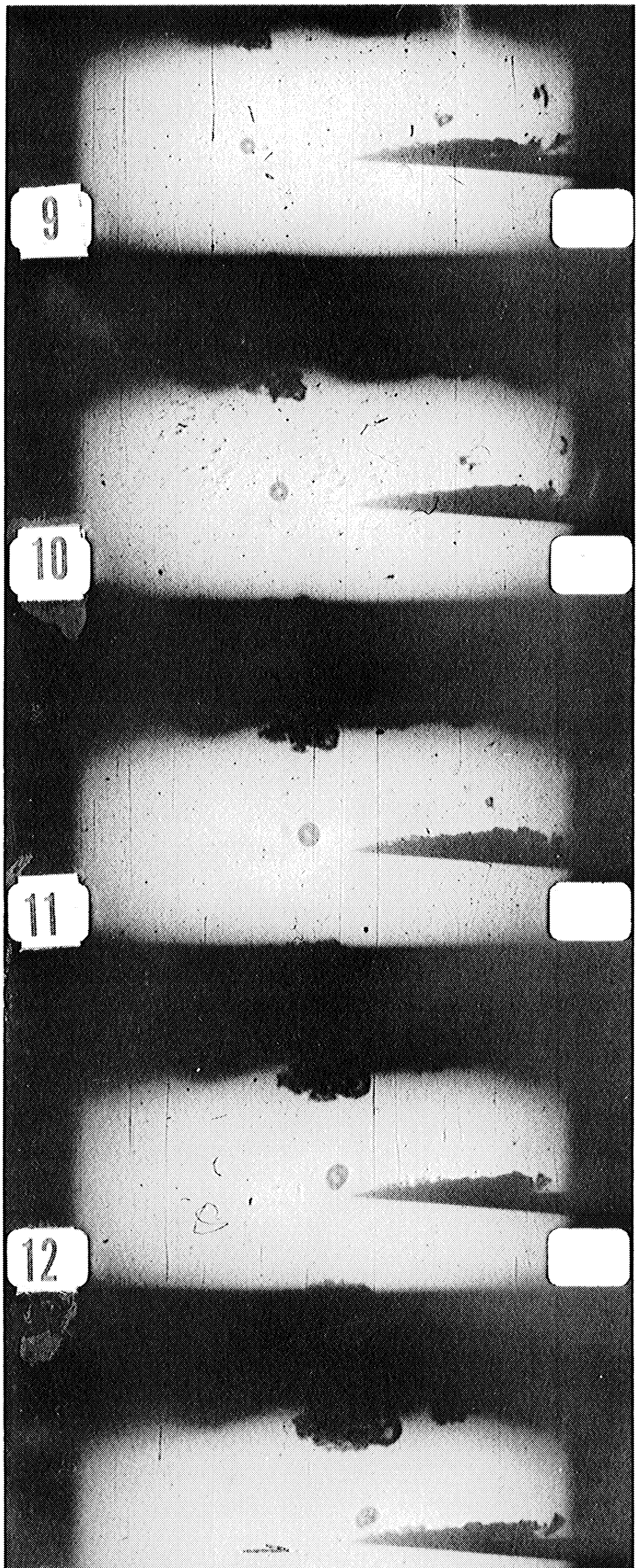

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Figure 3. (Cont.)

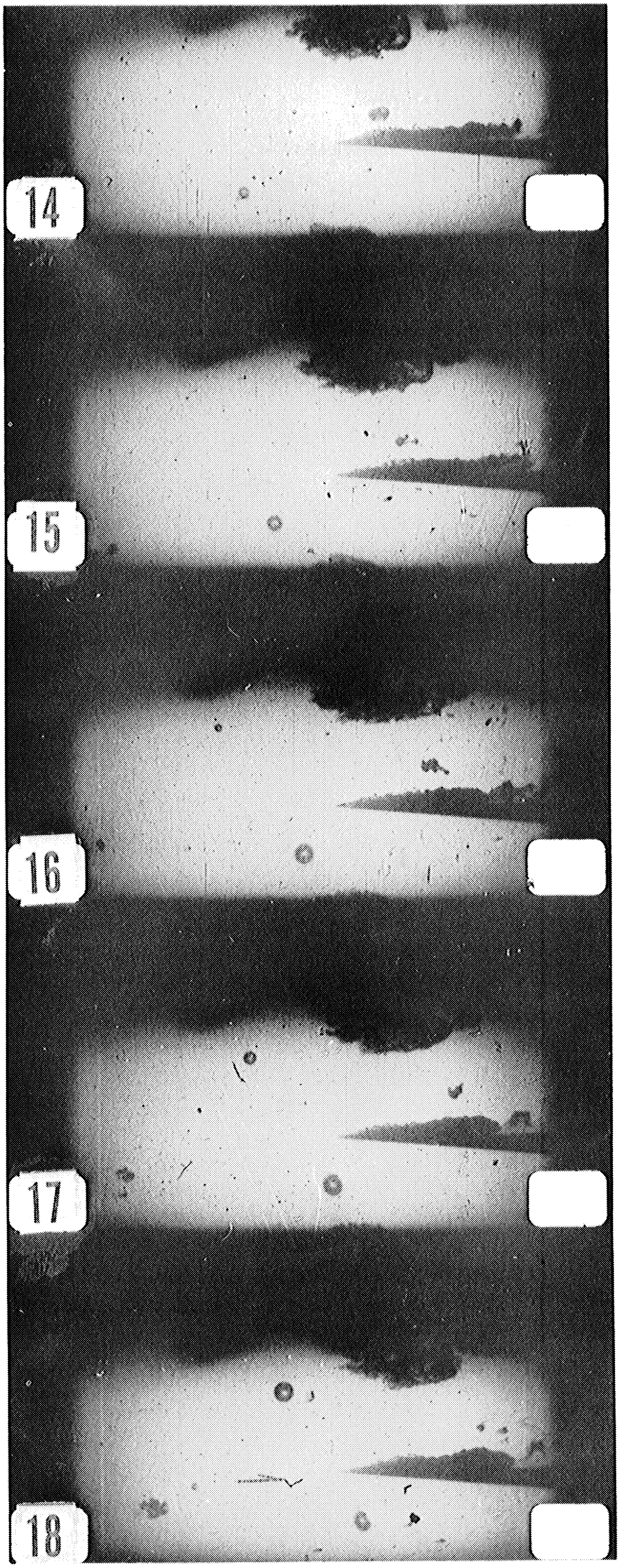

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Figure 3. (Cont.)

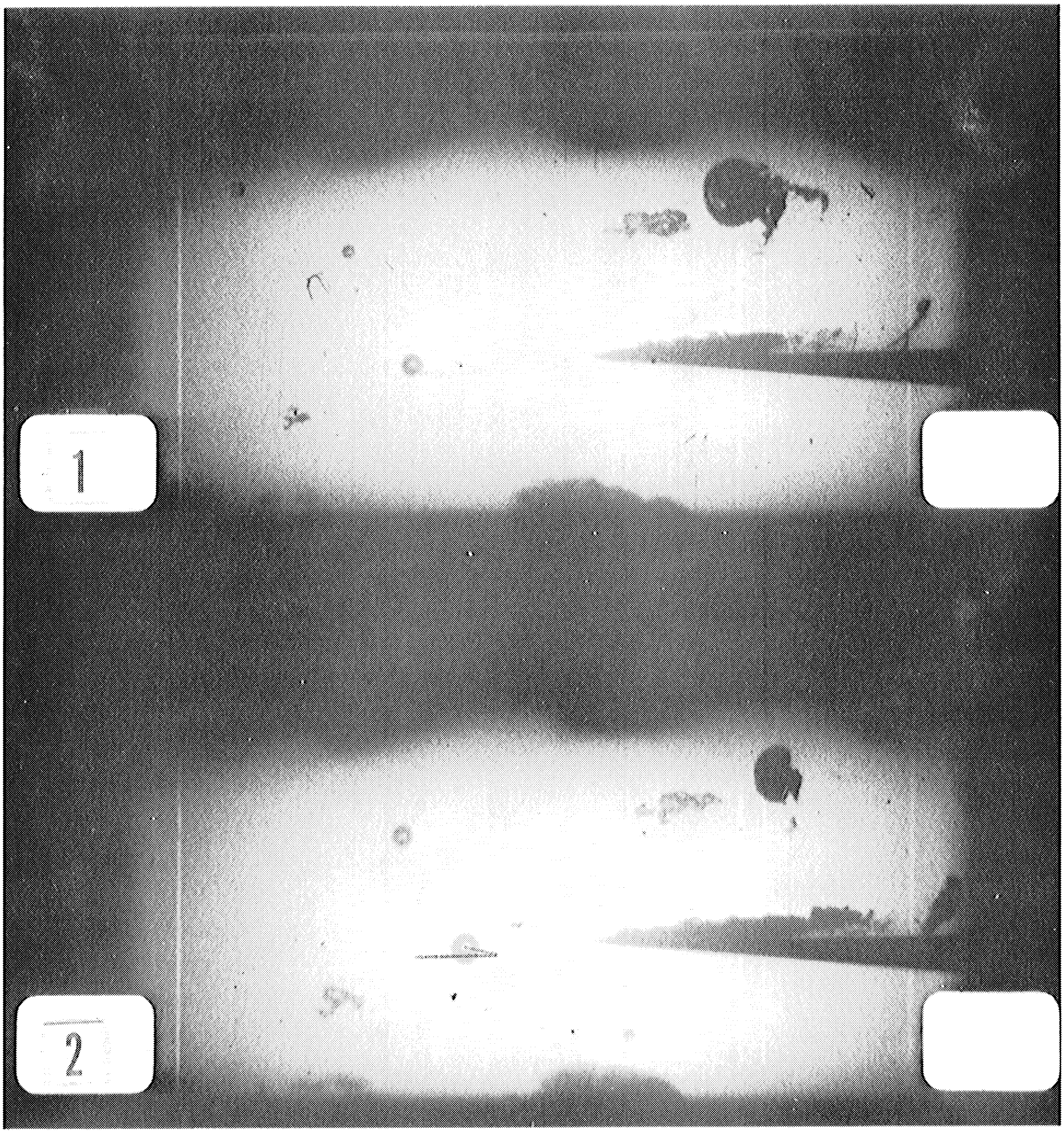

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Figure 4. High Speed Photographs, Velocity 83.5 ft/sec., Air Content 1.3% 132 Microseconds per frame, Scale Length (Arrow) 0.205 in.

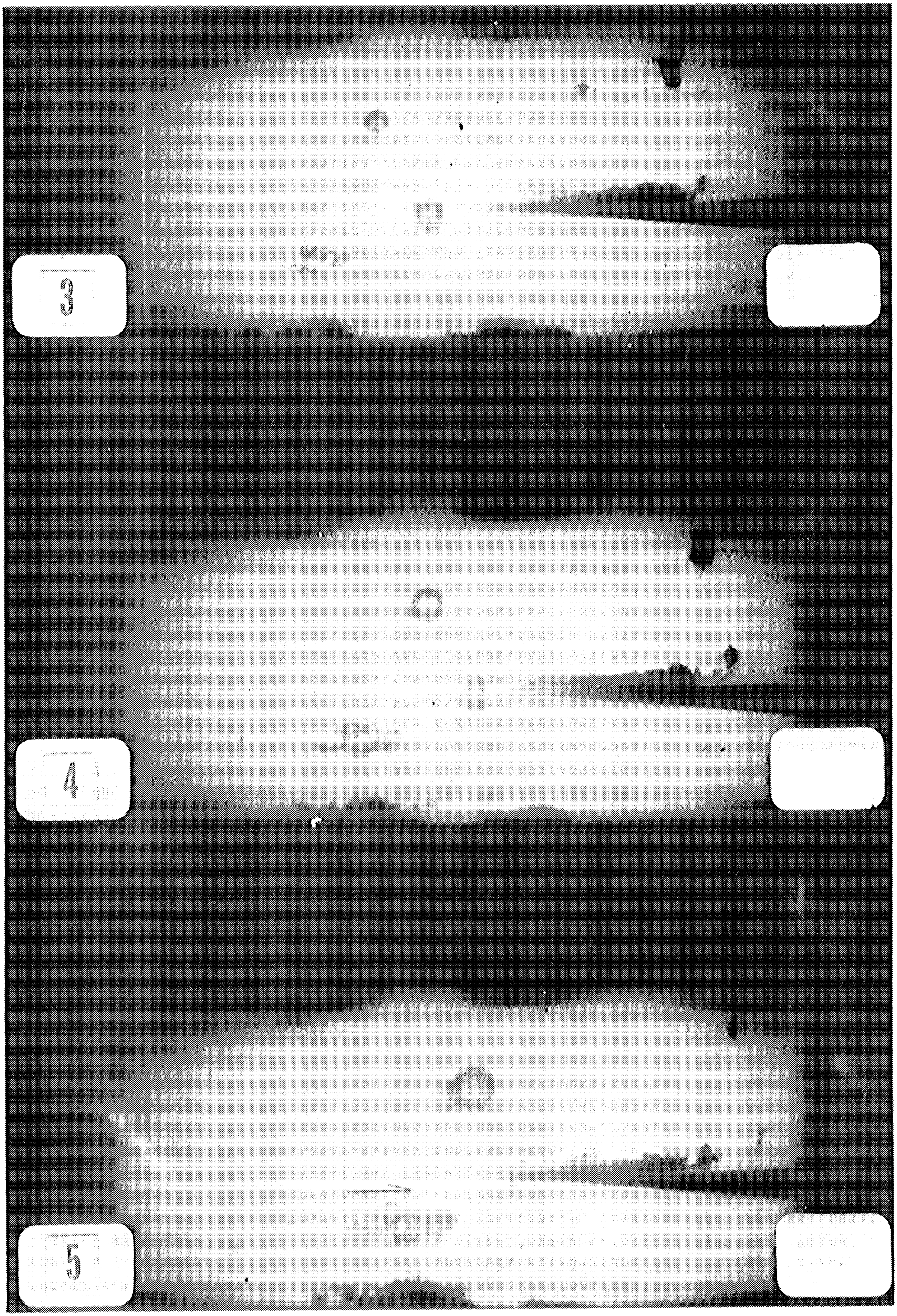

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Figure 4. (Cont.)

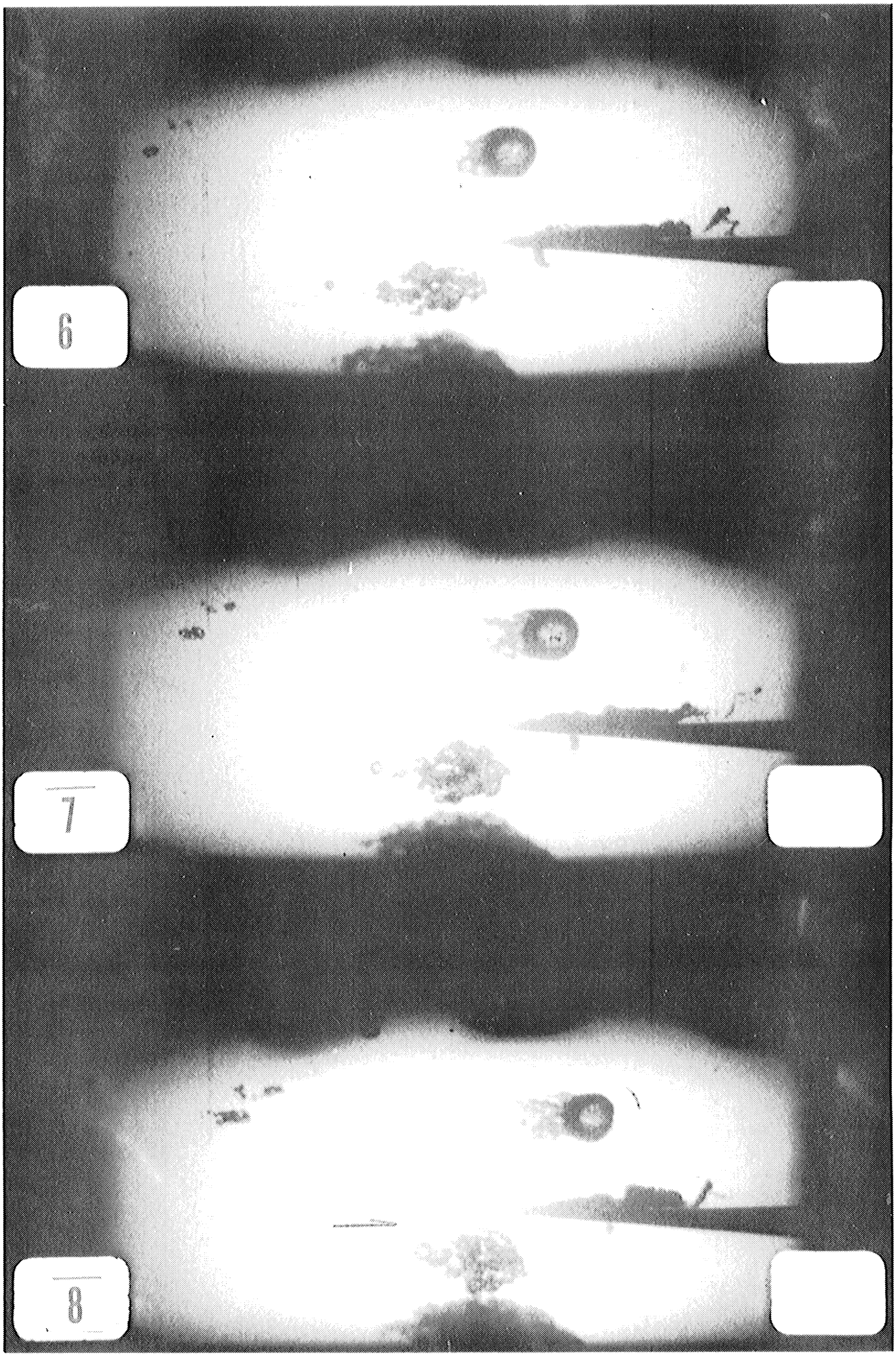


Figure 4. (Cont.)

The bubbles photographed ranged in diameter from 20 mils, the smallest observable, to 190 mils. Data taken for each image included horizontal (in direction of flow) and vertical distances of the bubble centroid from the tip of the wedge, longest (A) and shortest (B) dimensions of the bubble (A=B for spherical bubbles) and the angle of inclination (θ), if any, of the flat side of the bubble with respect to the horizontal. Ivany's pictures[11] indicated 90° inclinations for almost all of his bubbles. Ellis' pictures[16] of bubbles flowing over an ogive showed varying inclinations which he attributed to the bubbles' flattening along the constant pressure lines.

All 72 bubbles studied collapsed asymmetrically. There appeared to be two regions in the flow with quite separate pressure gradients. All the bubbles whose centers were more than 2½ times their maximum diameters away from the wedge flattened similarly to those shown by Ivany[11] i. e. with the flat side perpendicular to the flow. All bubbles less than one diameter from the wedge flattened on the side nearest the wedge indicating the predominence of the pressure distribution around that body as compared with that due to the divergence of the diffuser. About half of the bubbles between 1 and 2½ diameters from the wedge collapsed in the latter orientation, the remainder in the former. Figure 3 shows a typical sequence from the film, with bubbles collapsing in both orientations. In frames 6, 7, and 8, for example, the large bubble to the right collapses apparently under the diffuser pressure gradient only, while the bubble in the middle is obviously distorted by the wedge's pressure gradient. The influence of the wedge can also be seen in frames 12, 13, and 14 of the same figure.

Figure 5 shows a comparison of theoretical constant pressure lines for the experimental set-up and inclination of the flat side of bubbles as a function of bubble positions. The constant pressure lines were found by a potential flow mapping of the stream lines and equipotential lines for ideal (one-phase, one-dimensional) flow over the wedge and the steady cavity which formed along the flat side of the specimen nose. Using this technique the velocity of the water can be approximated (correcting the area of the stream-tube for the diffuser angles) as a function of position. The pressure is then found from the velocity by Bernoulli's equation. It is clear that the region adjacent to the observed cavity cannot by easily treated in this manner since the theoretical boundary condition of vapor pressure over the cavity surface may not be consistent with other geometry conditions. This paradox suggests that the 40, 50, 55, and 60 isobars must extend almost parallel to the cavity surface and pass around the tip of the wedge if this experimentally

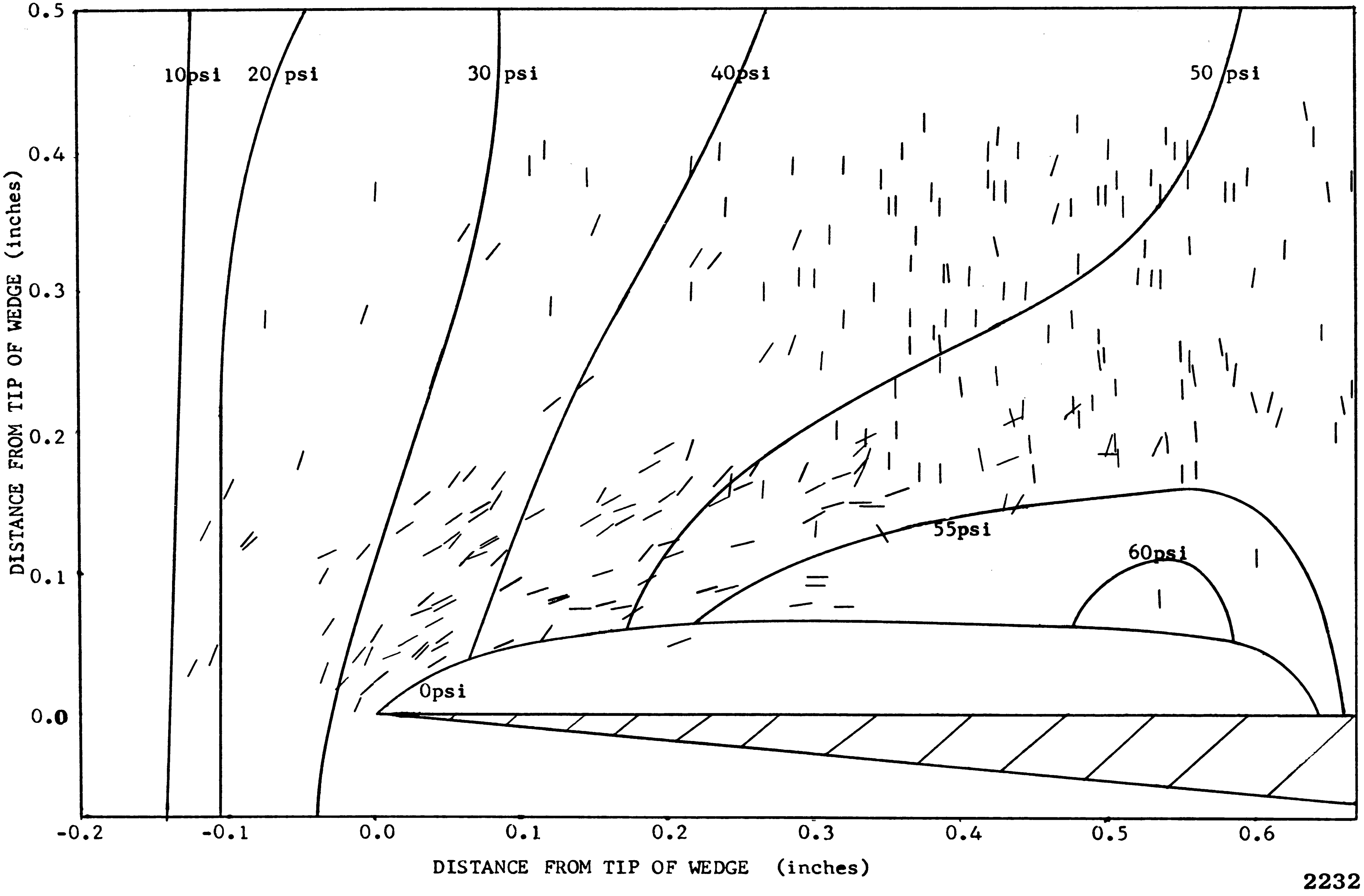
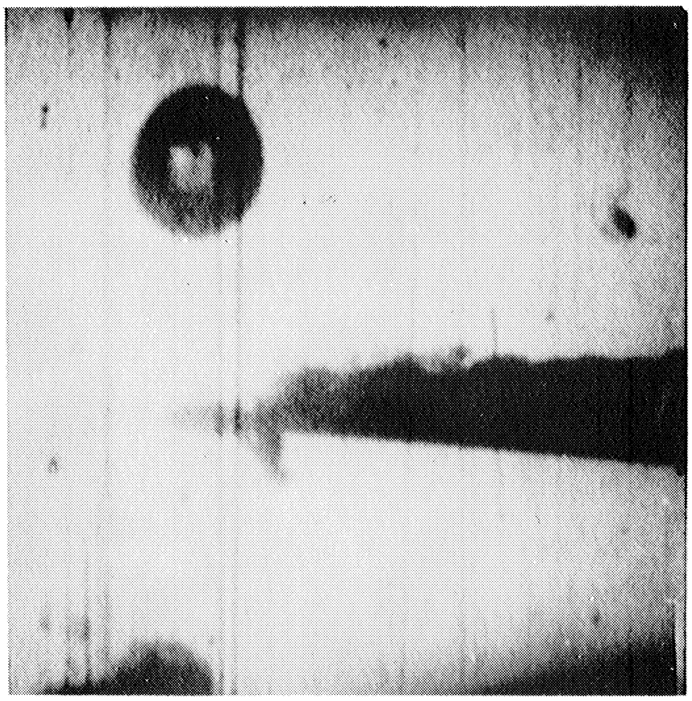


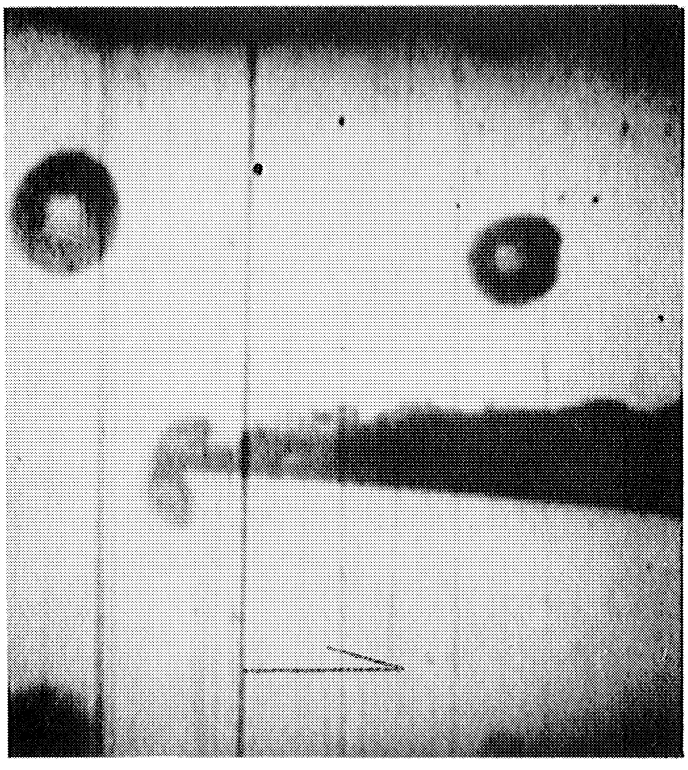
Figure 5. Orientation of Flattened Side of Bubble vs Distance from Tip of Wedge and Relation to Constant Pressure Lines.

observed cavity (or wake) is assumed to exist. The inclinations of the flat sides of the bubbles near the cavity in Figure 3 seem to confirm this last hypothesis. Another possible future step in the investigation suggested here is to make a more accurate flow mapping using electrical analog techniques. In conclusion, from Figure 5, it appears that the pressure gradients in a flowing system do act to cause flattening on the high pressure side of a bubble during collapse. With proper flow geometry, this effect could orient the bubble properly to allow jet pitting of the fixed wall.

A second analysis of the film was made in order to determine some model for bubble collapse near a solid boundary. Several factors greatly limited the number of bubbles studies in this analysis. Although initial perturbation of the bubbles, noted by the progressive flattening on the high pressure side , would persist through several frames, the final collapse and initial rebound invariably occurred in the time between frames. Therefore the general picture of a bubble collapse shows the bubble flattened on one side in one frame and the somewhat amorphous rebound bubble in the next frame. In those frames when a bubble was near its smallest volume, such as the second frame of Figure 6, bubble wall motion was too rapid and bubble size too small for the resolution of the film. Since bubbles at minimum volume could not



FRAME 2



FRAME 1

2233

Figure 6. High Speed Photographs, Velocity 83.5 ft/sec., Air
132 Microseconds per frame, Scale length (Arrow) 0.205 in.

be observed, this analysis attempted to obtain information from the initial phases of bubble rebound when the rebound shape would hopefully represent the shape at minimum volume.

Before discussing the results of the photographic analysis will be discussed. Shutler and Mesler's[10] work, among others, shows that the collapse of a bubble attached to a surface in a static field forms a jet during collapse which impinges on the surface as shown in part one of Figure 7. Bubbles collapsing in a free stream subjected to a positive pressure gradient present a different problem. Pictures taken by Ivany[4] show an initial flattening on the high pressure side; however, the final collapse mode of the bubbles is beyond the resolution of the film. Two models of the final collapse have been proposed. The first model shown in part two of Figure 7 assumes the flattened portion of the bubble continues the collapse to form a torus with a jet oriented in the upstream direction. The second model shown in part three of Figure 7 assumes jet formation in the downstream direction. This formation occurs when the upstream face of the bubble is pushed in by the force of the moving fluid in the downstream direction as the bubble slows down with respect to the fluid due to drag forces and "slip". This mode of collapse assumes that the initial flattening of the downstream side of the bubble is a slow process compared to final collapse.

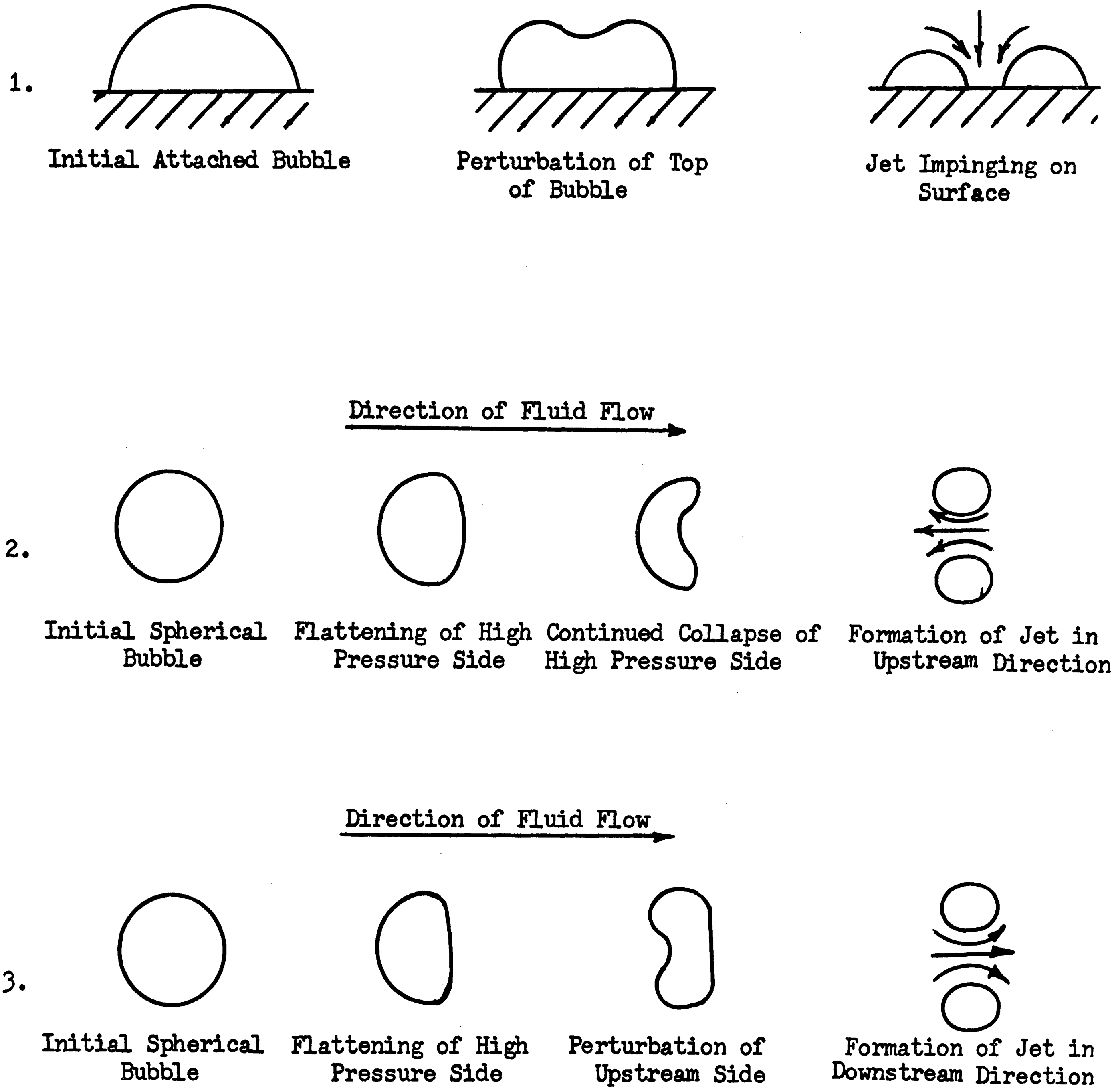


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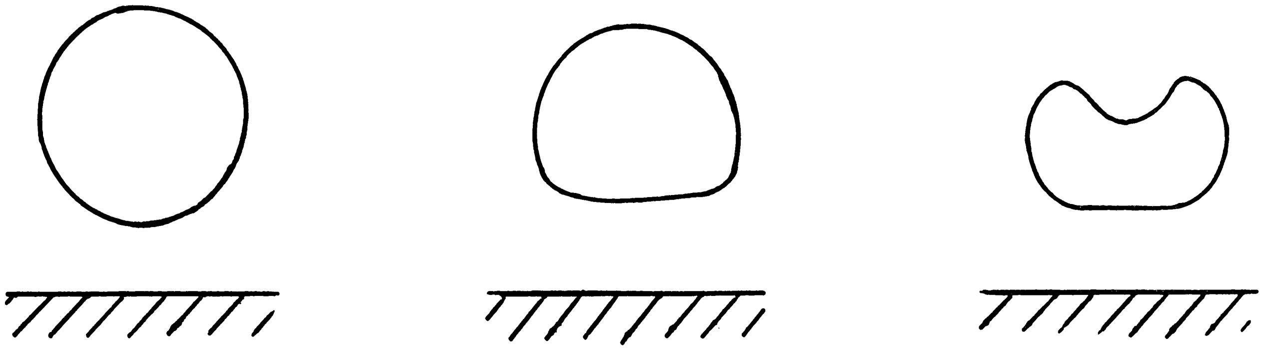
Figure 7. Bubble Collapse Models

4.



Initial Spherical Bubble

Flattening of High Pressure Side

Perturbation of Side Away from Surface

Jet Penetrating Flattened Side of Bubble

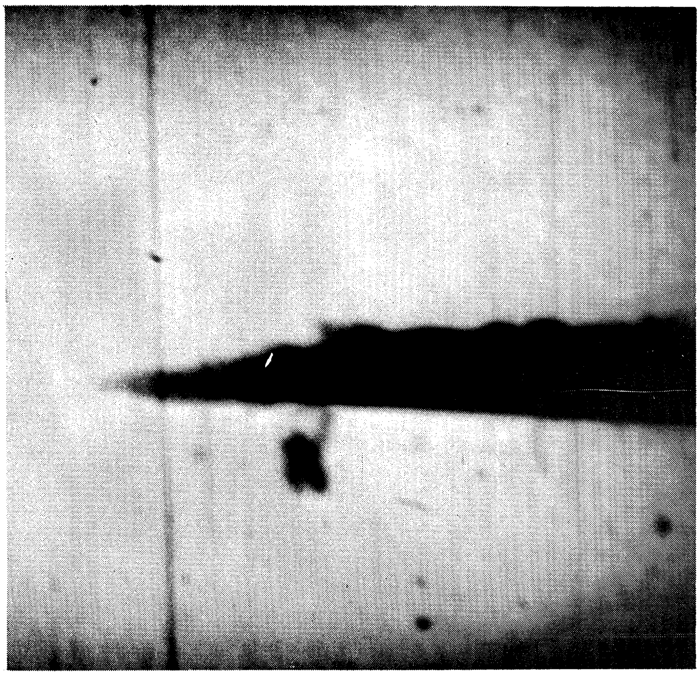
Formation of Jet

2234b

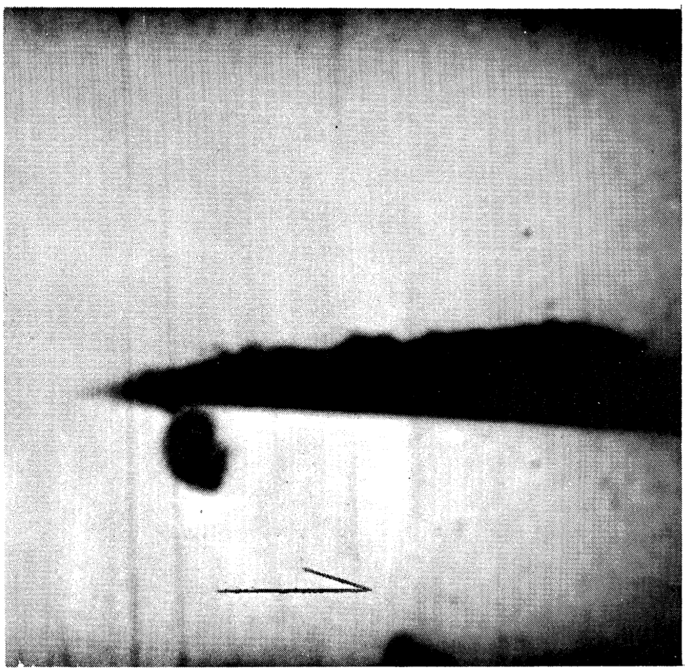
Figure 7. (Cont.)

The model assumed for this analysis for bubble collapse near a solid boundary is shown in part four of Figure 7. The initial flattening is on the high pressure side toward the wall while the final collapse is much like a bubble attached to the surface. There are two reasons why the flattened side is not assumed to continue collapsing thereby forming a jet in the wrong direction. First because of the inertia of the water between the flat side of the bubble and the wall and second because the water would have to rapidly flow into the region between the bubble and the wall and would slow this form of collapse allowing the surface away from the wall to collapse toward the wall. The fact that the flattened bubble persists for several frames while the actual collapse occurs in the time between frames shows that the flattening on the high pressure side is a comparatively slow process.

Experimental results for this last model are sparce because of the framing rate and film resolution available. Also the wake which formed on the flat surface of the wedge makes the analogy of collapse near a solid boundary a difficult one. Therefore the best pictures were obtained for bubble collapsing near the solid boundary of the angled surface of the wedge where no wake was present. Several bubbles of the type shown in Figure 8 were obtained. The first frame shows the bubble with initial flattening oriented partially toward the surface. The second frame



FRAME 2



FRAME 1

2235

Figure 8. High Speed Photographs, Velocity 83.5 ft/sec., Air Content 1.3% 132 Microseconds per frame, Scale length (Arrow) 0.205 in.

shows the bubble in the rebound mode. There is quite evidently cavitation left by a jet which has impinged on the surface. Figure 9 shows a bubble above the surface. The first frame shows the bubble with the flattened side oriented toward the surface while the next frame shows the bubble just after the surface away from the wall has penetrated the flattened surface. A model very similar to this one with appropriate experimental evidence from pictures taken in the cavitating field around an ultrasonic horn has recently been completed at this laboratory.[12]

The collapse center migration hypothesis did not encounter such positive results. There was no evidence for the bubbles observed, i.e., in the size range 20-200 mils, of any detectable migration toward or away from the wedge during collapse or rebound. Figure 3 shows this quite well. Such migration might exist at the end of collapse when the bubbles are too small to be visible, but the positions of the rebound bubbles did not confirm that such migration had occurred. Thirty-nine of the 72 bubbles showed apparent rebounds.

In summary of the present results, then, it has been found that our experimental evidence supports the toroidal jet collapse theory quite well, but gives little support to the bubble center migration postulated in convection with the spherical shock hypothesis for cavitation damage,

FRAME 2

FRAME 1

2236

Figure 9. High Speed Photographs, Velocity 83.5 ft/sec., Air Content 1.3% 132 Microseconds per frame, Scale length (Arrow) 0.205 in.

in that this would probably require substantial migration of the bubbles toward the wall and a collapse more spherically symmetric than observed to be significant.

III. PRESENT THEORETICAL INVESTIGATIONS

In addition to the experimental results already discussed, some effort has been devoted toward constructing a mathematical model of bubble collapse. Two approaches are suggested here:

1. A direct numerical solution of the fluid equations starting with a spherical bubble in an axial pressure gradient;
2. Solution for the collapse of a toroidal vortex in an infinite fluid first with later inclusion of wall effects and/or a pressure gradient oriented parallel to the center line of the torus.

The first approach was used with limited success by Rattray[8] and by Walters and Davidson.[17] Rattray used a Legendre polynomial expansion and small perturbations to model several simple flow problems similar to ours, although asymmetries similar to our experimental pictures arose, his series expansion blows up very quickly and no significant confirmation of the jet theory was possible. Walters and Davidson encountered the same difficulty. However, with the greater computing capacities now available more complete results can be obtained.

The second approach is really the analysis of the dynamic behavior of a "smoke ring." However, this too is not simple.

IV. CONCLUSIONS

1. The toroidal jet theory has been strengthened as the best explanation for the cause of cavitation damage on the basis of our preliminary experimental evidence.
2. Pressure gradients may be very crucial in determining the damaging capability of bubbles by controlling orientation of jets as well as closeness of approach of collapsing bubbles.

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