University of Michigan
Department of Mechanical Engineering
Cavitation and Multiphase Flow Laboratory

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"Assisted Research and Analysis of the Wave Phenomena and the Associated Pulse Periods Due to Cavitating Bubbles"

by
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Mechanical Engineering
Fluid Theory Concepts 490

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Abstract

This report contains information on the characteristics of bubble collapse especially the periods of oscillations and some aspects of bubble dynamics. A general definition of cavitation is presented so as not to exclude artificially produced phenomena of the same nature but occurring under different circumstances. Cavitation is understood as a phenomenon of its own and not merely as some kind of nonlinearity. Some further thoughts are presented in the future development of basic cavitation research.

Purpose

As in the past similar aspects of this nature have been documented for the purpose of recording experimental findings and assisting in continued research.

Introduction: General and Basic Aspects of Cavitation

A general description of cavitation may consist of the study and research of the occurrence of cavities in matter under special circumstances. Cavitation is a group of phenomena which are associated with the occurrence of cavities in a liquid, especially their formation, motion, and the physical, chemical, and biological effects thereby produced. A cavity in a liquid (often called a cavitation bubble) is any bounded volume in space being empty or containing vapor and/or gas with a defined physical boundary at least part of which must be made up of liquid.

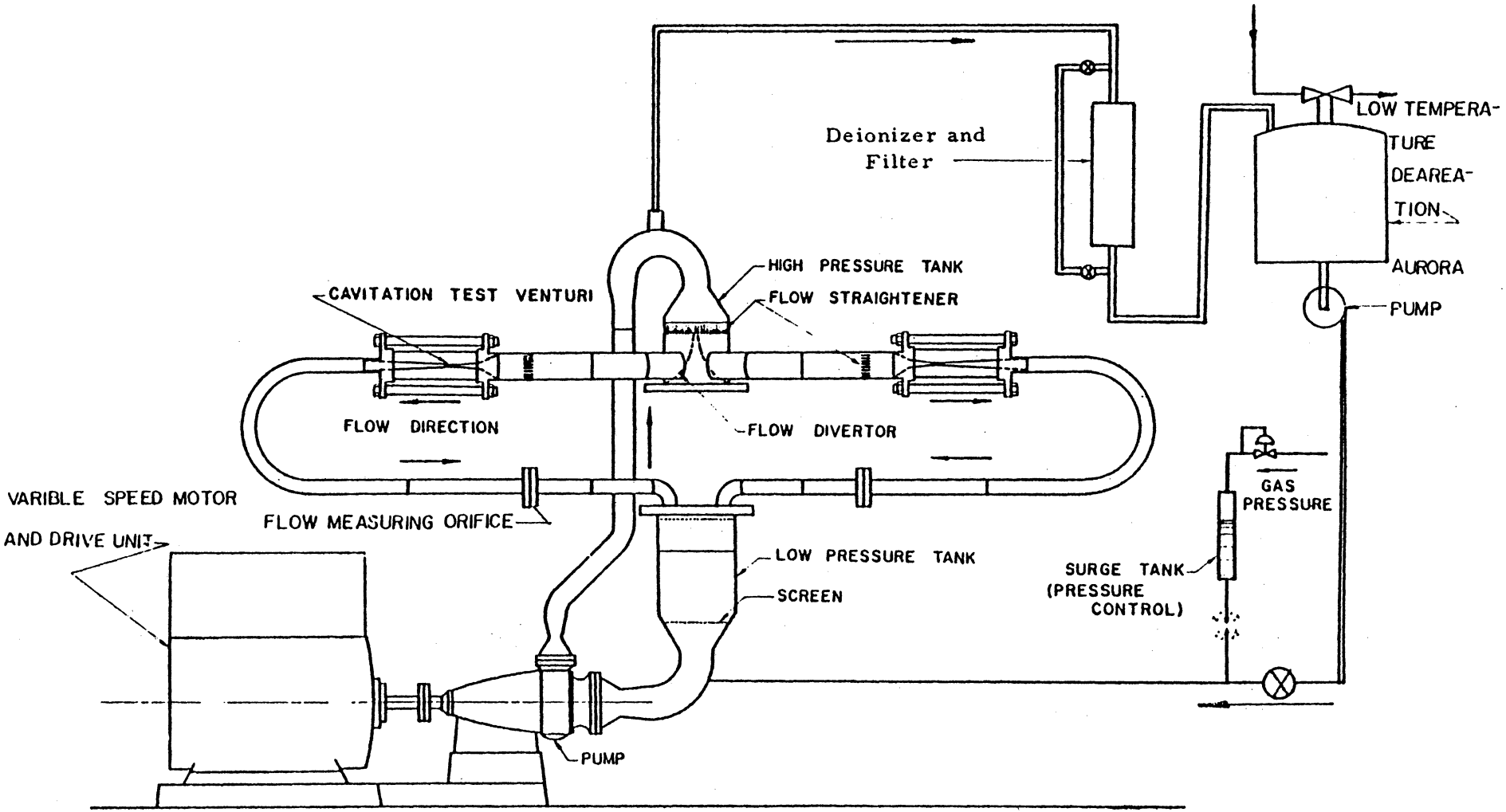
Some special cases involve the cavities in a liquid obtained by pressure reductions in flowing systems or by the underpressure in sound fields. In the first case cavitation is the result of a localized pressure reduction in a flowing system. It is characterized by the formation of vapor bubbles in a localized region sustaining a pressure below the vapor pressure of the fluid at the local temperature and pressure.

Cavitation is introduced in this definition as a group of phenomena. The definition contains implicitly that cavitation is not simply a nonlinear phenomenon of some kind but is a phenomenon of its own. The notice of this will greatly influence the manner of attacking problems and

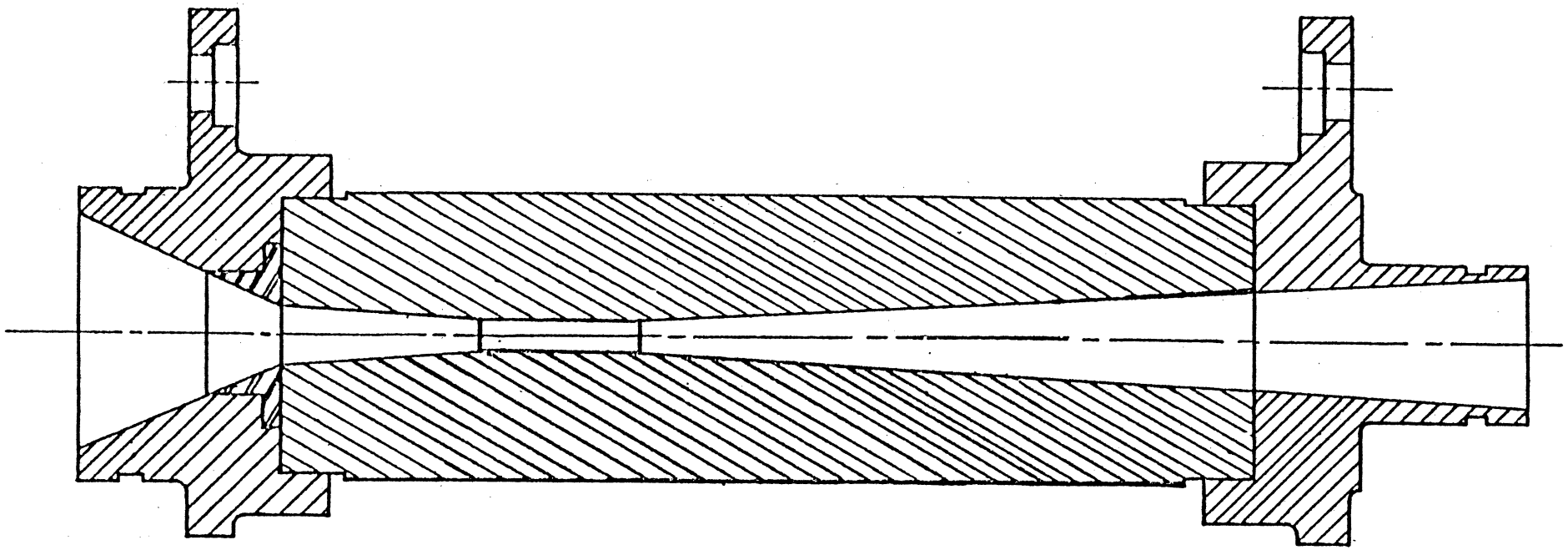
may also be used as a guideline where the usual nonlinear approaches may fail in describing the phenomena observed.

There are two main areas of research: hydraulic cavitation and acoustic cavitation. Hydraulic cavitation is associated with all kinds of hydraulic systems: for example, ship propellers, turbine blades, hydrofoils, and pumps. The occurrence of cavitation lowers the efficiency, often leads to a quick destruction of the parts being exposed to cavitation and can be the source of intense noise radiated into the liquid. Acoustic cavitation appears in sound fields at sufficiently high sound pressure amplitudes. It is unwanted in underwater acoustics where signals are to be transmitted over a long range, and in ultrasonic diagnostics, where, for example, the interior of the human body is scanned with the aid of sound waves. In industry acoustic cavitation has found some application in cleaning complex parts, in emulsification, and disintegration.

To do research work on cavitation a few standard facilities have been developed. In hydraulic cavitation most research work has been done using cavitation tunnels as they are called. These facilities are capable of producing a flow of liquid with adjustable parameters such as flow velocity, pressure in the liquid, gas content of the liquid and so on. A schematic of this equipment is shown in diagrams 1 and 2. With the



Dia. 1. Schematic of Water Tunnel Facility.

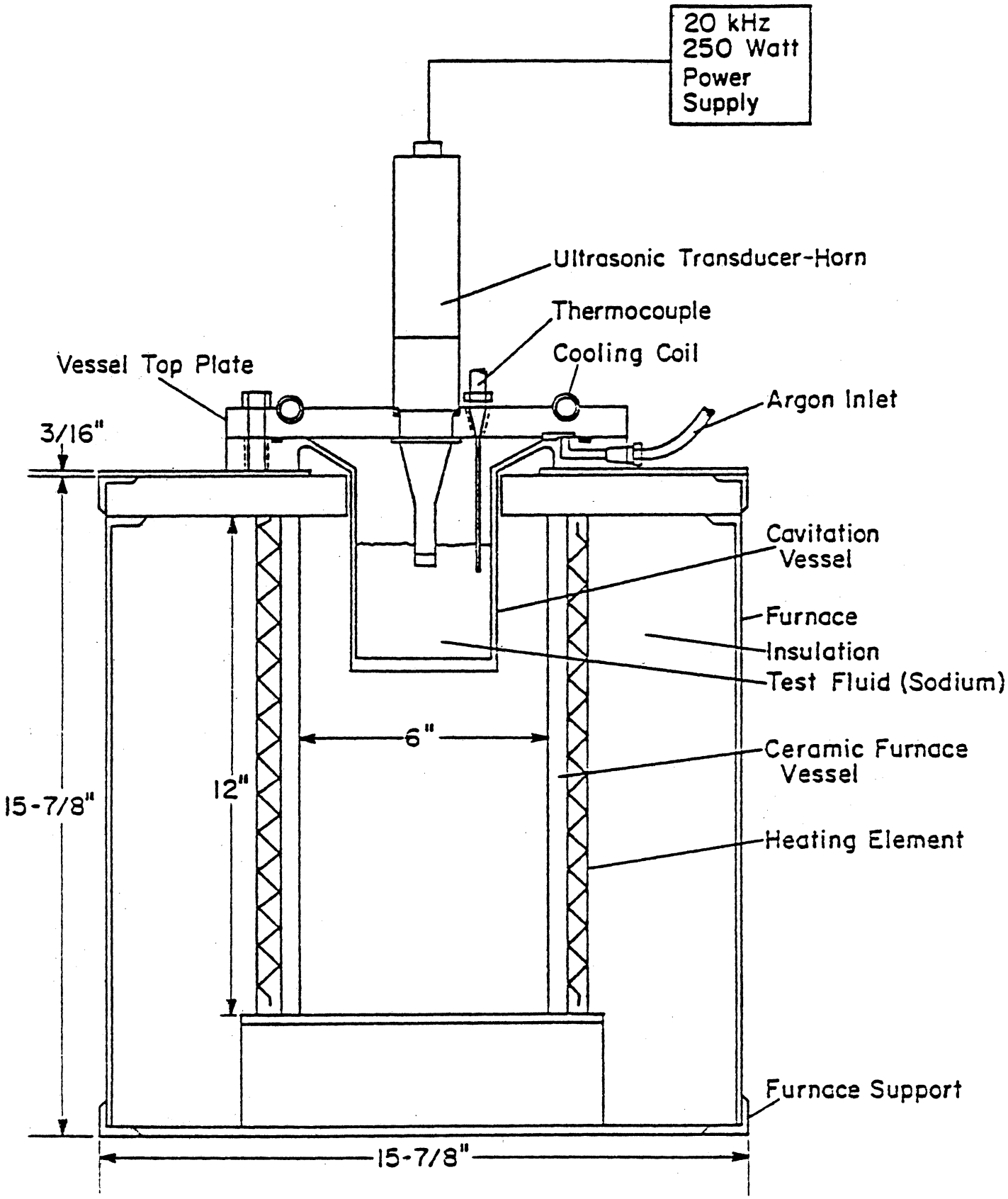


Dia. 2. The Plexi-glass 3/4 in. Diameter Venturi Test Section

aid of a pump a liquid flow is generated through a test section where cavitation on submerged bodies can be studied.

In acoustic cavitation a variety of devices exist. An example of one such device is shown in diagram 3. The device is mainly used for cavitation erosion tests. The probe to be tested forms the tip of an amplitude transformer dipped in the liquid and driven by a transducer on the other end. The transducer is usually made up of a series of nickel plates (using magnetostriction) or a cylinder of piezoelectric material like $BaTiO_3$ or PZT ceramics. The probe is sometimes put at some distance opposite to the tip of the amplitude transformer to eliminate the large accelerations encountered during the vibration of the transformer.

Cavitation damage and noise can be said to be the most important cavitation phenomena. We now know a lot about these phenomena, but are far from being sure about the details. However, to understand the action of cavitation the dynamics of the produced cavitation bubbles or cavitation bubble fields must be looked at. Thus cavitation bubble dynamics is the fundamental area of research in cavitation. Explanation of observed phenomena can only be expected with bubble dynamics as a basis. But theoretical studies as well as experiments in this field of cavitation research are difficult because of the many parameters and aspects involved which cannot be



Vibratory Facility Cavitation Erosion Study In SODIUM.

Dia. 3

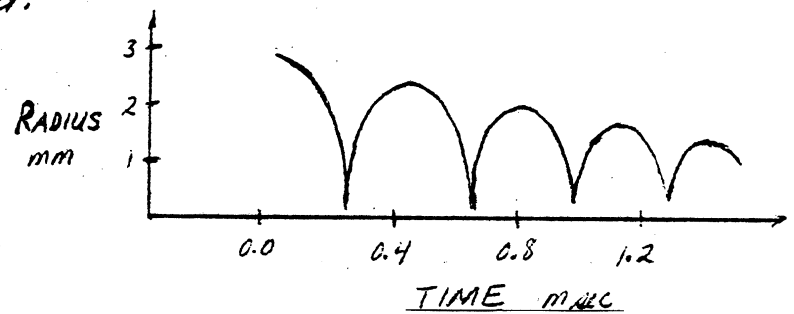
suitably taken into account (like non-spherical bubbles) or controlled (like the formation of spherical bubbles in experiments). The first step in attacking the problem has of course been to put aside the real cavitation bubble fields and to start with models of single cavitation bubbles looking at their properties and comparing them with known phenomena.

The R.N.N.P. (Rayleigh - Noltingk - Neppiras - Poritsky) bubble model is a nonlinear differential equation which includes the effects of gas content, surface tension, and viscosity.[1] The differential equation is of the form

$$\ddot{R} + \frac{3}{2R}\dot{R}^2 = \frac{1}{\rho R}\left[P_n\left(\frac{R_n}{R}\right)^{3K} + P_0 - \frac{2\sigma}{R} - P_s - \frac{4\mu}{R}\dot{R} + P(t)\right] \quad [2]$$

where $P_n = \frac{2\sigma}{R_n} + P_s - P_0$

It is not known what value might be inserted for K as almost nothing is known about the gas content inside the bubble. It may lie between 1.00 and 1.67 and may alter during bubble oscillation. The curve shown in the diagram below was calculated for a constant intermediate value ($K = 1.33$). The R.N.N.P. - model seems to give an appropriate description of the bubble investigated.



Discussion

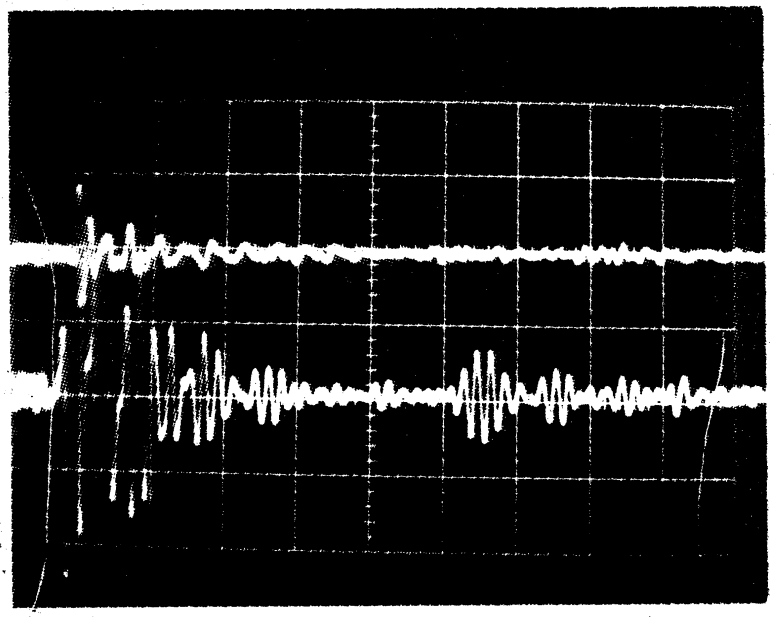
Several high speed films have been analyzed along with previously recorded data on bubble oscillations and the results were recorded as graphs in the following figures.

In figures 1 and 2 the maximum period of oscillation for a given number of occurrences is depicted. The venturi system parameters are as follows: system pressure 4 psi., venturi inlet pressure 17 psi., venturi outlet pressure 12 psi., water temperature 62°F, and the manometer read 3 in. Hg. Likewise in figures 3 and 4 the maximum period of oscillation for a given number of occurrences is represented. The system parameters are as follows: system pressure 1 atm., venturi inlet pressure 7.5 psi., venturi outlet pressure ≈ 0 psi., water temperature 60°F, and a manometer reading of 42 in. Hg.

For the figures 5 and 6 the maximum period of oscillation for a given number of occurrences is shown where the data was obtained from a static spark in a spark generator. Period number 1 represents the first period having a maximum amplitude and period number 2 corresponds to the second period (rebound) and second maximum amplitude.

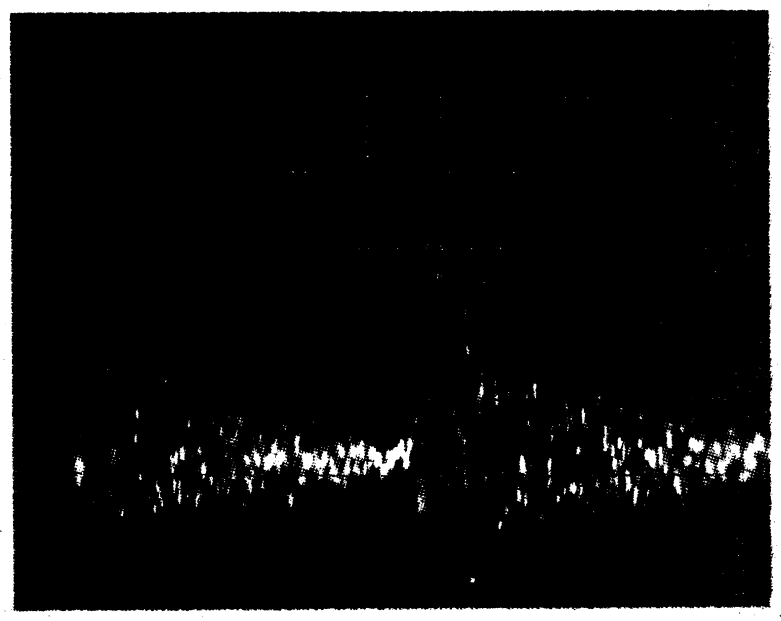
The graphs were obtained by recording the average period of bubble oscillation for a given number of occurrences. This entailed analysis of photographic pictures of bubble oscillations as recorded

on film from an oscilloscope. Events of bubble oscillation were detected by use of two pressure sensitive probes (the U.M. probe and the Kistler probe). The signal produced by the probes was then monitored on an oscilloscope. Shown in the pictures below are examples of these bubble oscillations as recorded from a flowing system as in the case of the venturi tunnel and as in a static system of a spark generator.



VENTURI
OUTPUT PULSE
50μsec/div

SPARK
GENERATOR
PULSE
1m sec/div



High speed film analysis enabled the discovery of bubble behavior once the film speed was secured. Calculation of bubble collapse and its corresponding period was possible by analysis of individual frames. The results are tabulated on pages and of this report.

It is interesting to note the result of combining the graphs in figures 1, 2, 3, 4, 5 and 6. The graph of figure 7 depicts this result. The graph shares much similarity with the behavior of the R.N.N.P. bubble model theory.

42-381 50 SHEETS 5 SQUARE
42-382 100 SHEETS 5 SQUARE
42-389 200 SHEETS 5 SQUARE
NATIONAL

Concluding Remarks

Both aluminum and plexiglass represent extreme material behavior. They have not been in use for long as parts of a machine which have been damaged by imploding bubbles. It is very useful to study the behavior and the different stages of damage of model materials when subjected to imploding cavitation bubbles.

Of special interest in bubble dynamics is the final stage of bubble collapse. Due to the sufficiently good repeatability of bubble size, bubble collapse could be filmed with picture repetition rates of 8000 f.p.s. (refer to figure 8). The pictures taken confirm that bubble collapse in its final stages is an extremely fast event. In the case shown the jet formation is evident. Jet speed can be estimated to lie between 100 m/sec and 200 m/sec.

When extrapolating results from one material to another we must not only look at the structures, which surely have an influence on the behavior of the materials under this special loading, but also the change in mechanical properties. This is of great importance especially if we want to find out something about the cavitation resistance of heterogeneous materials with their different mechanical properties in particular phases.

These particular phases often differ very much in their cavitation-resistance. It is not sufficient to know only the

resistance of each single phase to predict the cavitation-resistance of the whole material, because of the change in the surface of each phase may have a great influence on the behavior of the other phases.

Differences in the shape of the damage caused by a single bubble implosion and a single liquid jet impact result from different test conditions. The cavitation test specimen will alwa be covered with a liquid layer, so that the jet, formed when the bubble implodes, cannot reach the surface directly. The liquid layer subdues the effect of the jet, and its thickness ha an influence on the damage.

Possibilities in basic cavitation research are promising. There is neither a lack of ideas nor methods to go on (refer to figures 9 and 10). An interesting subject is exhibited here, cap tured by a movie camera having a film speed of 8000 f.p.s. This phenomena is duly deserving of future study in that the understanding of its behavior might be more than simply random coincidence.

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A.S.M.E. - FILM ANALYSIS

No. Oscillations	Period No. 1 (No. Frames)		Period No. 2 (No. Frames)		Period No. 1 (No. cm)		Period No. 2 (No. cm)	
	Grow	Collapse	Grow	Collapse	Grow	Collapse	Grow	Collapse
2	2	1	2	3+	4/3	2/3	$\underbrace{2/3 + 4/5}_{22/15}$	$\underbrace{4/3 + 4/5}_{32/15}$ +

Film Speed - 8000 fps

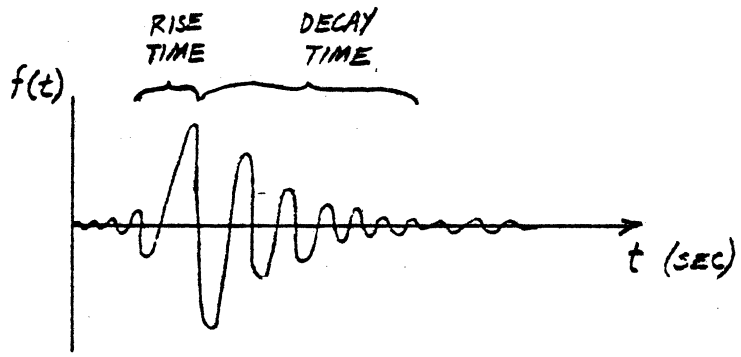
CHARLES KLING - FILM ANALYSIS

No. Oscillations	Period No. 1 (No. Frames)		Period No. 2 (No. Frames)		Period No. 3 (No. Frames)		Period No. 4 (No. Frames)	
	Grow	Collapse	Grow	Collapse	Grow	Collapse	Grow	Collapse
4	?	50	25	20	12	8	8	12 ?

Period No. 1 (No. cm)		Period No. 2 (No. cm)		Period No. 3 (No. cm)		Period No. 4 (No. cm)	
Grow	Collapse	Grow	Collapse	Grow	Collapse	Grow	Collapse
?	2	4/3	1/3	2/3	1/6	1/4	1/4 ?

(16 fps x 1.57×10^4 time magnification = 2.512×10^5 fps)

NOTE: A PERIOD CONSISTS OF A SHORT RISE TIME FOLLOWED BY A LONGER DECAY TIME.



A.S.M.E. Film Analysis (8000 fps)

No. of Oscillations	Collapse Period (Frames)	Collapse Period (m sec)
1	8	1.000
1	9	1.125
1	6	0.750
1	6	0.750
1	8	1.000
1	5	0.625
1	6	0.750
1	6	0.750
1	5	0.625
1	4	0.500

Film Analysis of Bubble Growth and Collapse in Water in a 2-Dimensional Venturi by R. D. Ivany (8000 fps)

No. of Oscillations	Collapse Period (Frames)	Collapse Period (m sec)
1	4	0.500
1	7	0.875
1	7	0.875

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A.S.M.E. FILM - CALCULATIONS

PERIOD No. 1

GROW : 1/8000 fps X 2 FRAMES = 0.250 m sec

COLLAPSE : 1/8000 fps X 1 FRAME = 0.125 m sec

total 0.375 m sec

PERIOD No. 2

GROW : 1/8000 fps X 2 FRAMES = 0.250 m sec

COLLAPSE : 1/8000 fps X 3 FRAMES = 0.375 m sec

total 0.625 m sec

The combination of the two periods is 1.000 m sec and this represents the entire bubble life from inception to anihilation.

CHARLES KLING FILM - CALCULATION

PERIOD No. 1

GROW : $1/2.512 \times 10^5$ fps X ? = ⊕

COLLAPSE : $1/2.512 \times 10^5$ fps X 50 FRAMES = 0.199 m sec

total 0.199⊕ m sec

PERIOD No. 2

GROW : $1/2.512 \times 10^5$ fps X 25 FRAMES = 0.0995 m sec

COLLAPSE : $1/2.512 \times 10^5$ fps X 20 FRAMES = 0.0796 m sec

total 0.179 m sec

PERIOD No. 3

GROW : $1/2.512 \times 10^5$ fps X 12 FRAMES = 0.0478 msec

COLLAPSE : $1/2.512 \times 10^5$ fps X 8 FRAMES = 0.0318 msec

total 0.0796 msec

PERIOD No. 4

GROW : $1/2.512 \times 10^5$ fps X 8 FRAMES = 0.0318 msec

COLLAPSE : $1/2.512 \times 10^5$ fps X 12 FRAMES = 0.0478 msec

total 0.0796 msec

The combination of the four periods is 0.5372 ⊕ msec and this is not representative of the total bubble life since the inception of the bubble was not observed.

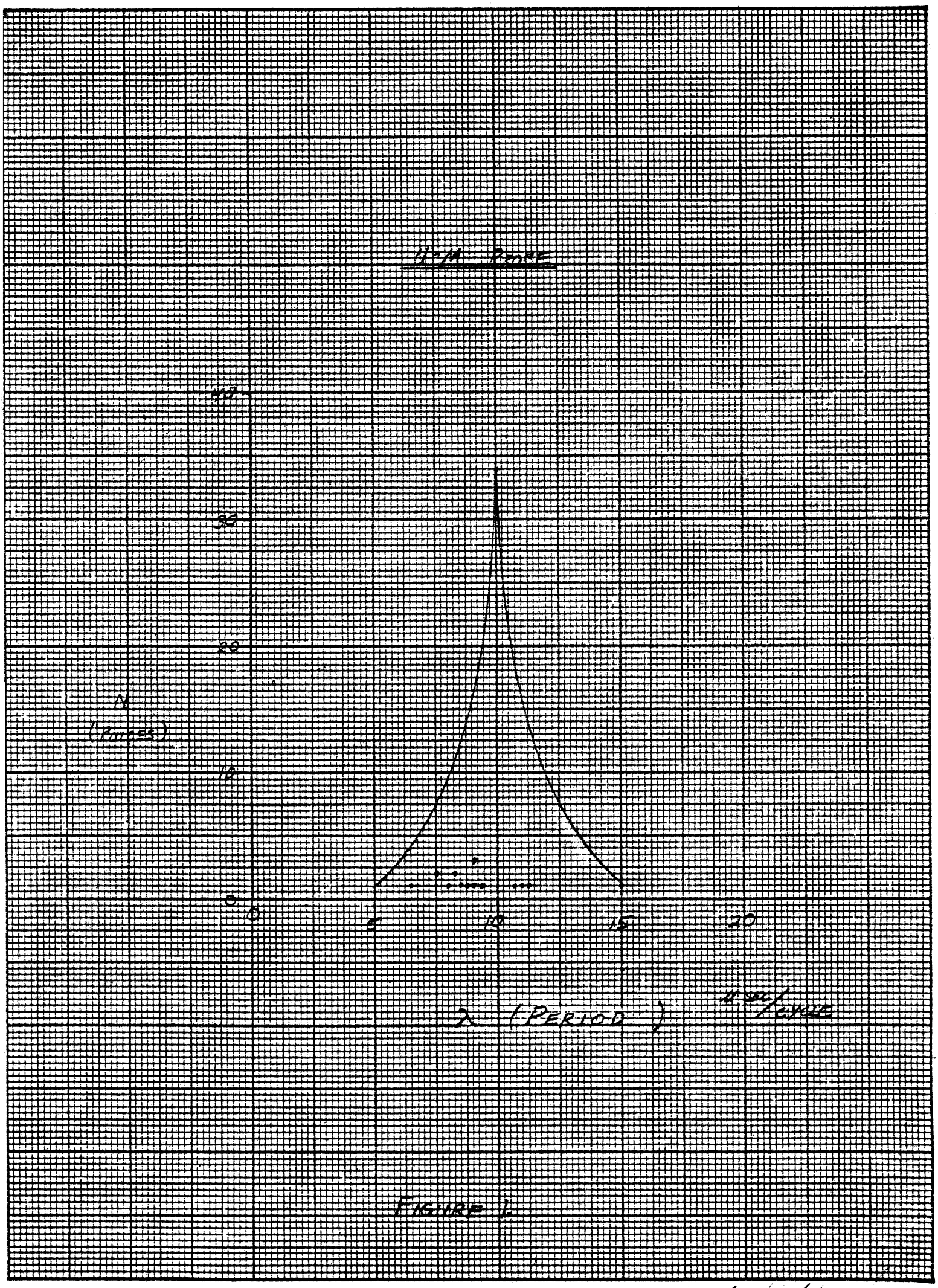


FIGURE 1.

Charles Schoenak

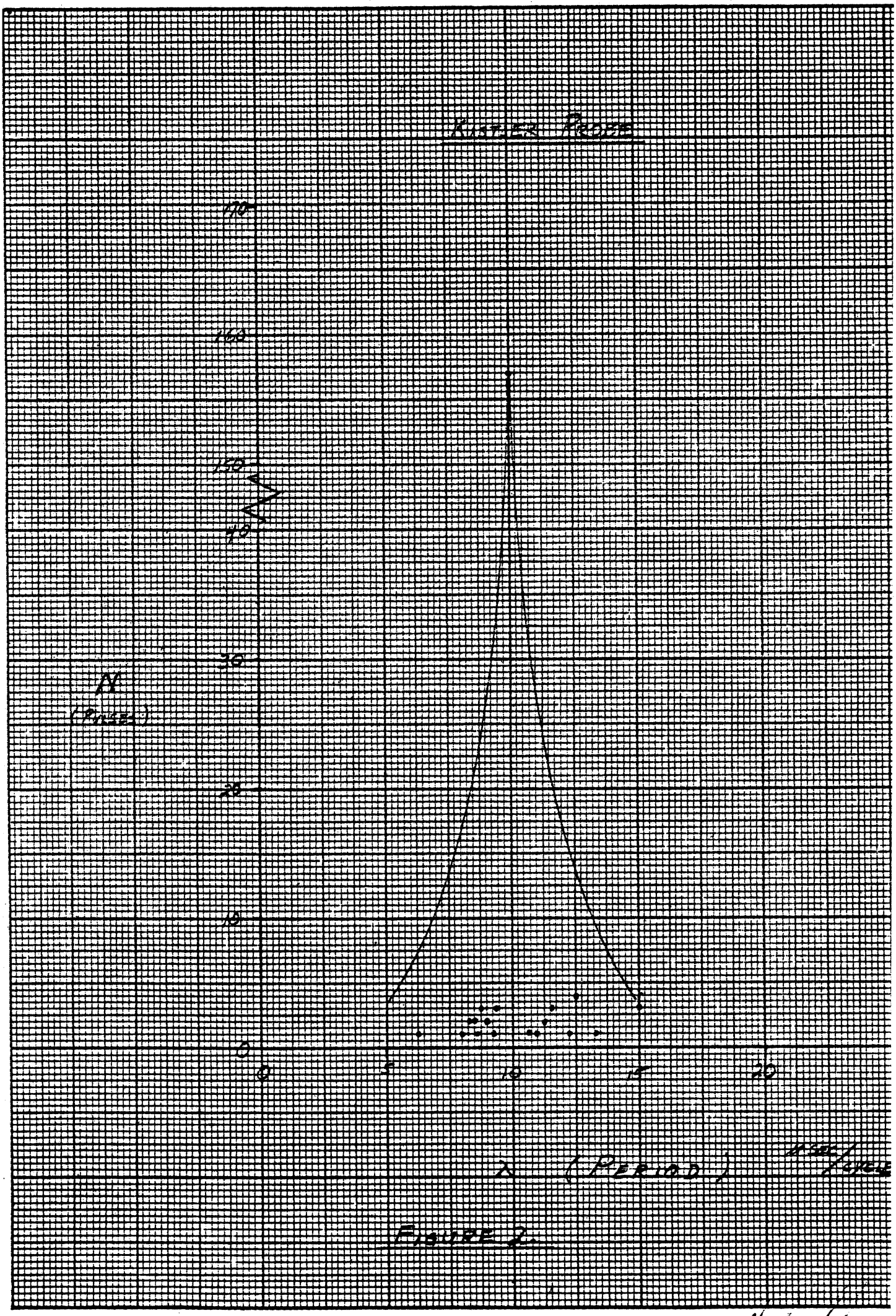


FIGURE 2

Charles Schorne

U-M PROBE

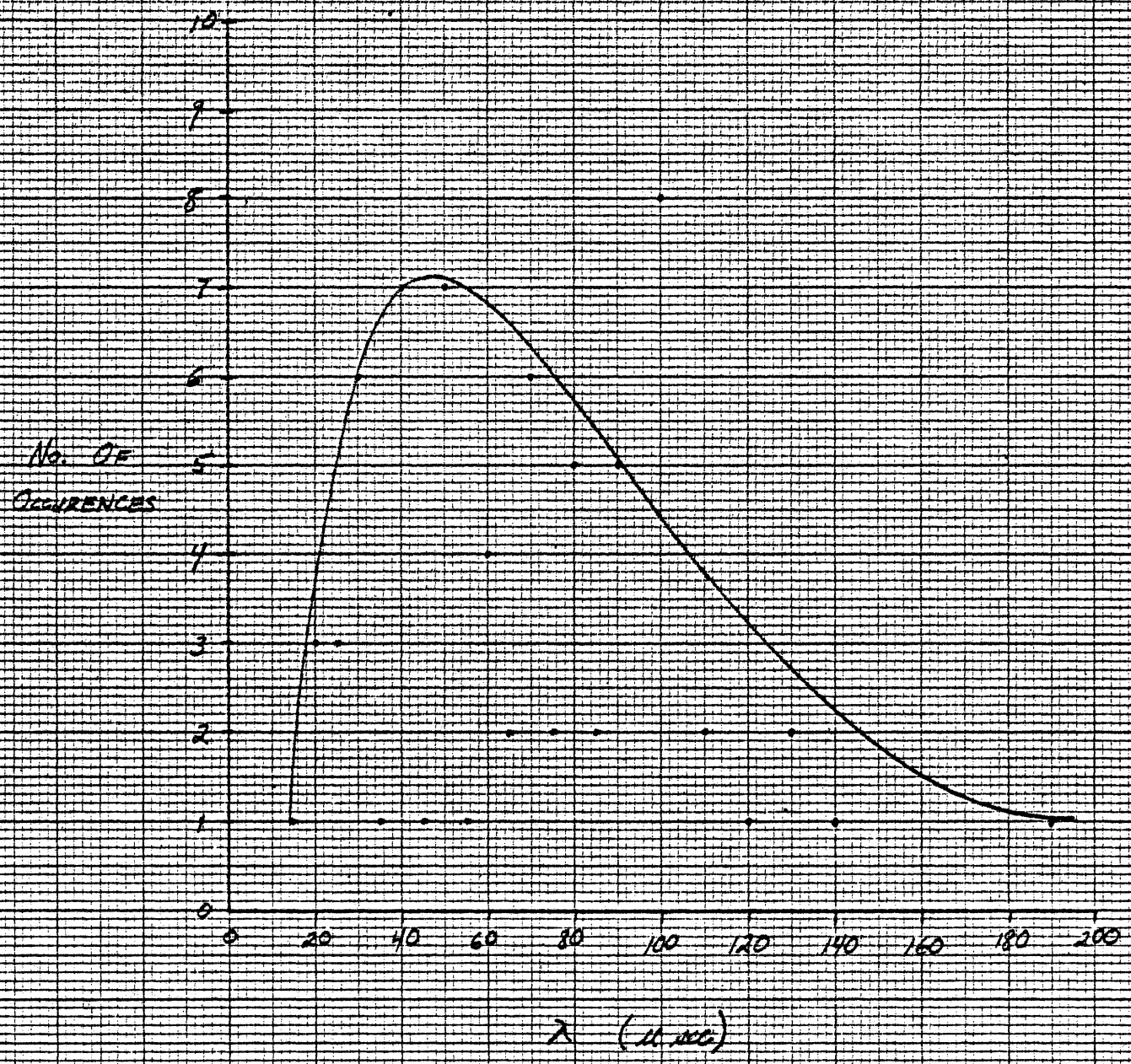


FIGURE 3.

Charles Dicerrate

5/30/77

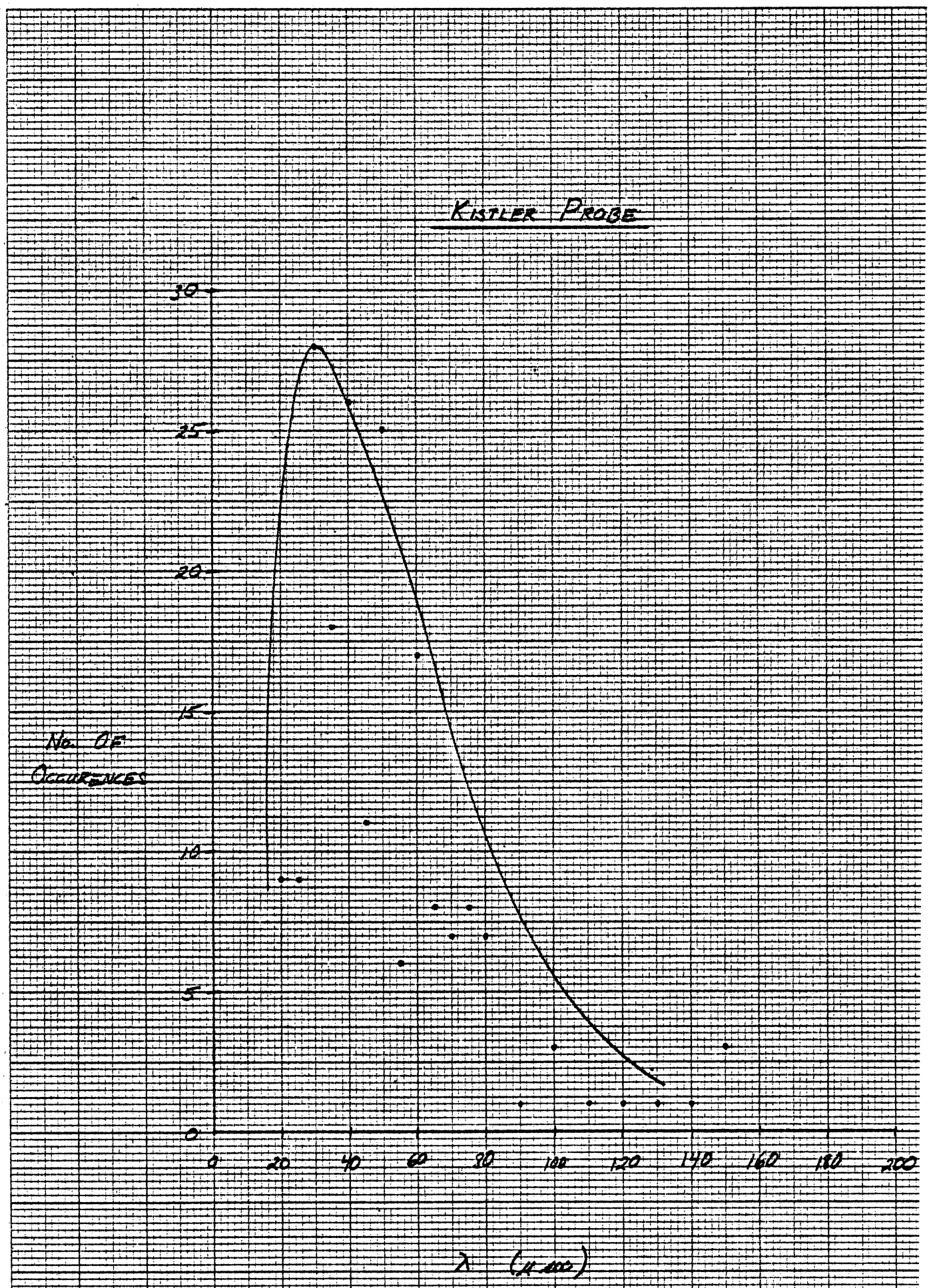


FIGURE 4.

Charles Schannon
5/30/[illegible]

SPARK GENERATOR – PERIOD No. 1

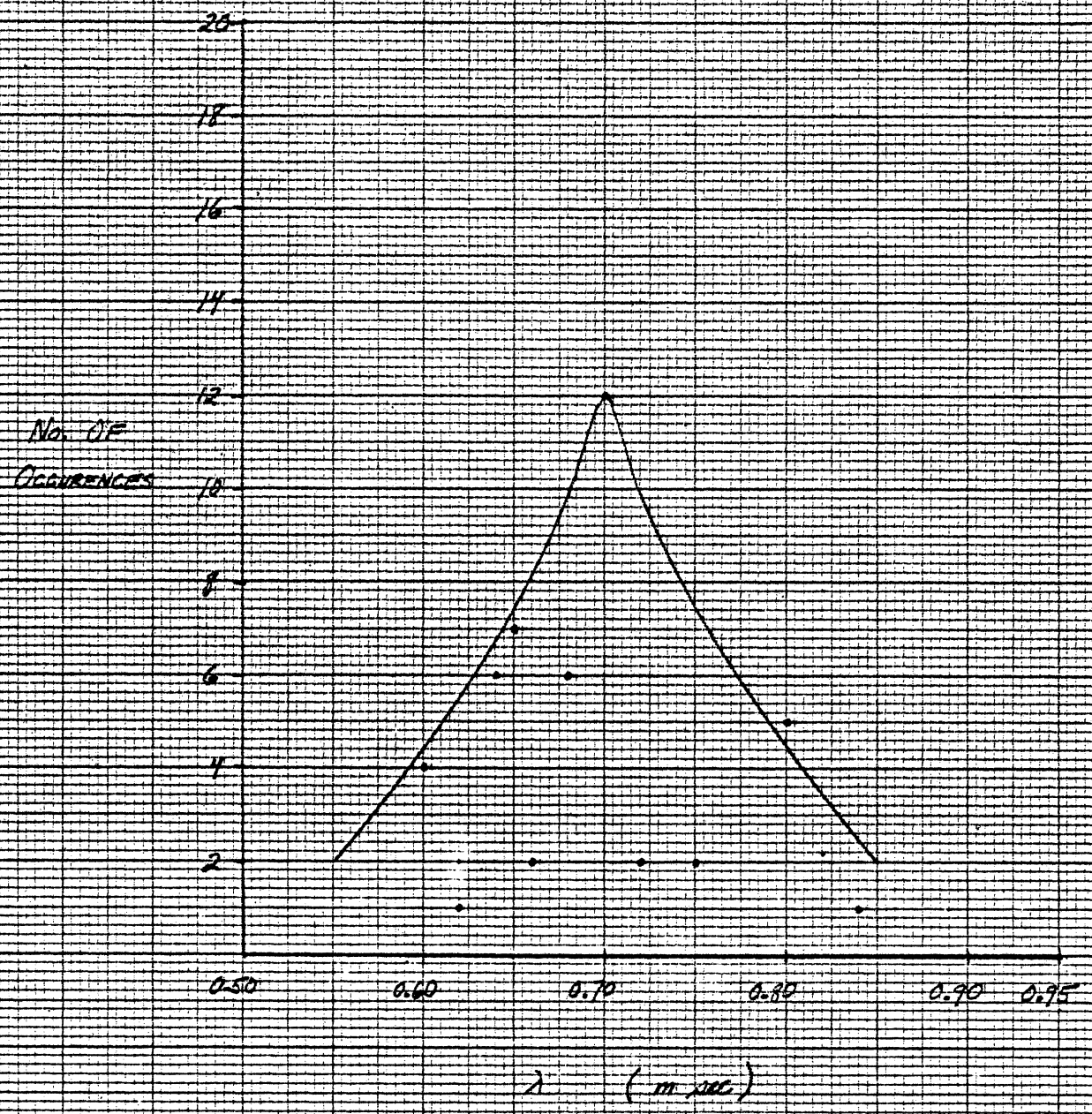


FIGURE 5.

Charles Schomaker

SPARK GENERATOR – PERIOD No. 2

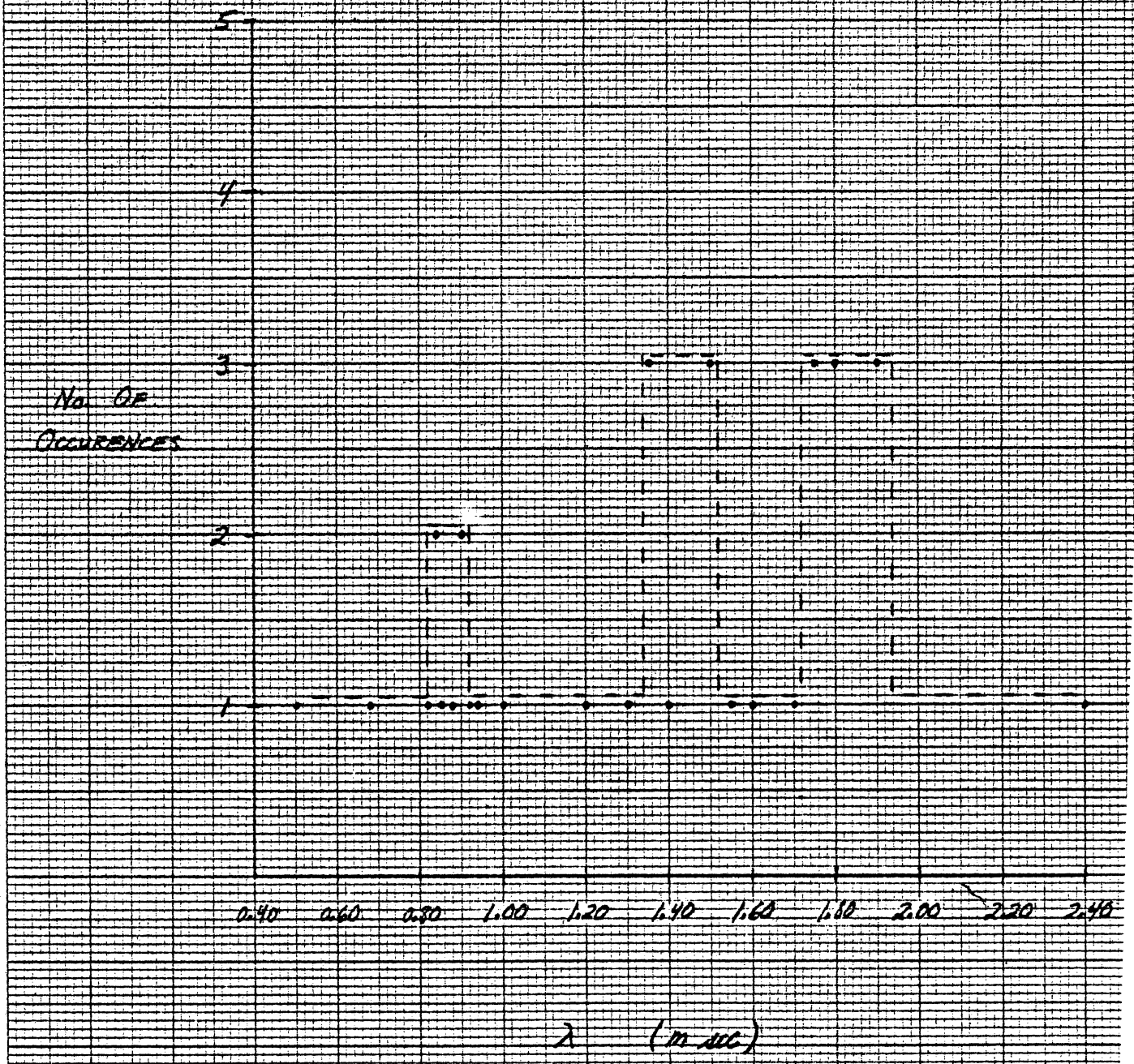


FIGURE 6.

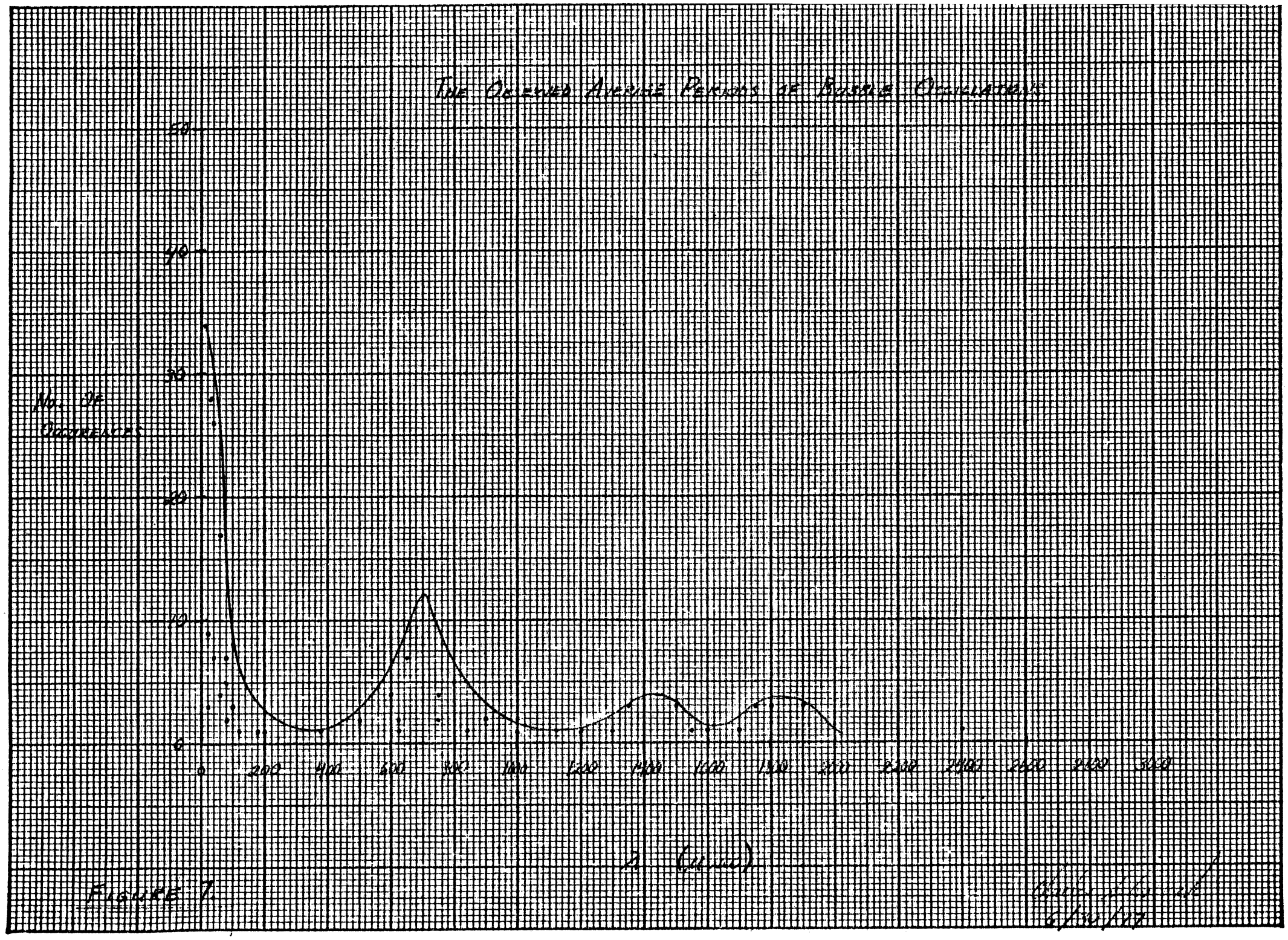
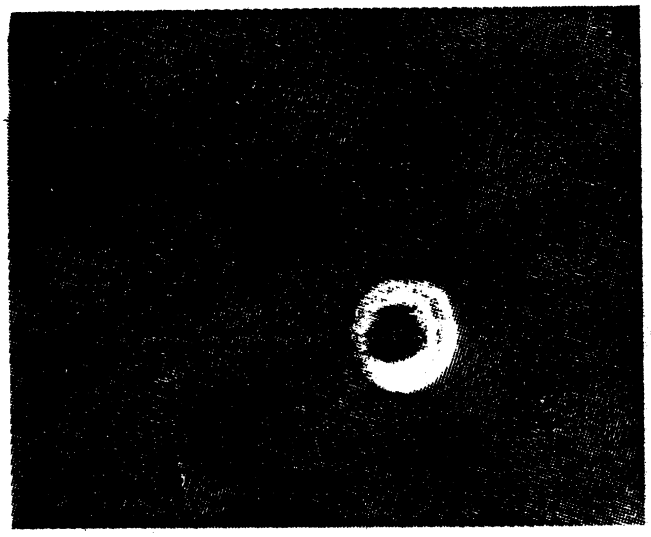

THE OBSERVED AVERAGE PERIODS OF BURSTS OF OSCILLATIONS
No. OF OCCURRENCES
50
40
30
20
10
0
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
λ (cm)

FIGURE 7.

Figure 8. Dynamics of a spherical cavitation bubble in water in the vicinity of a plane solid boundary after collapse. The picture repetition rate is 5000 f.p.s.

1.



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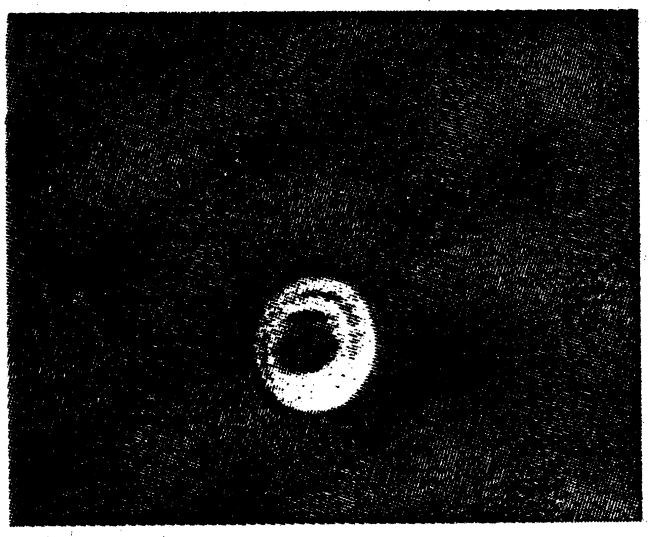

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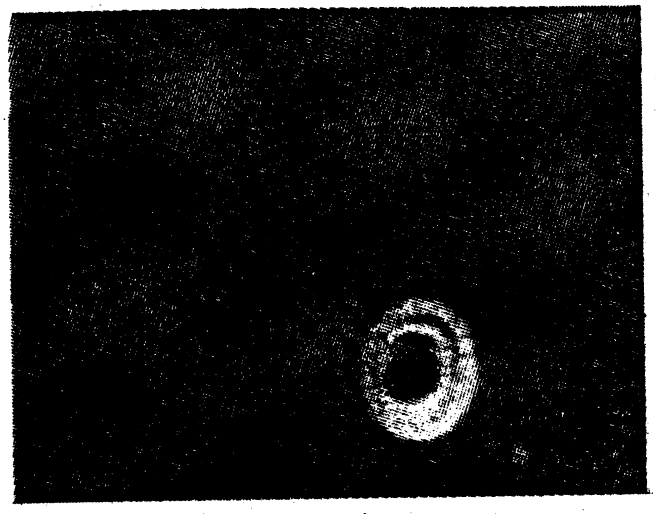

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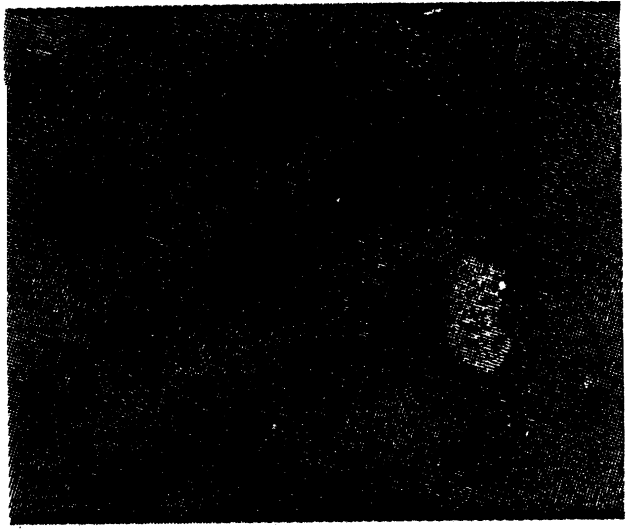
5.



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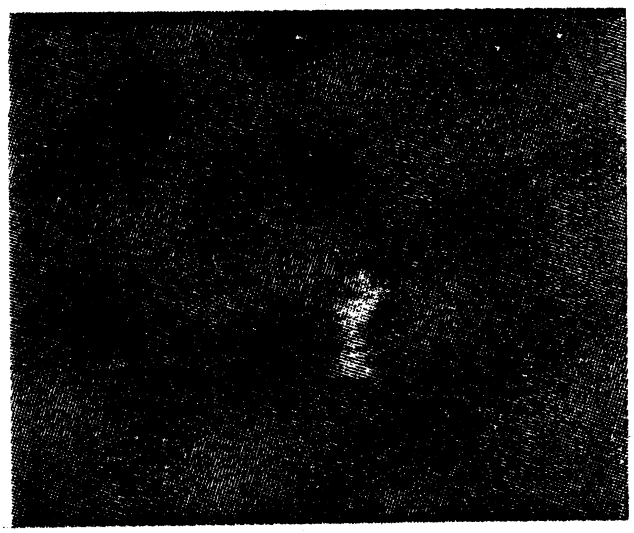
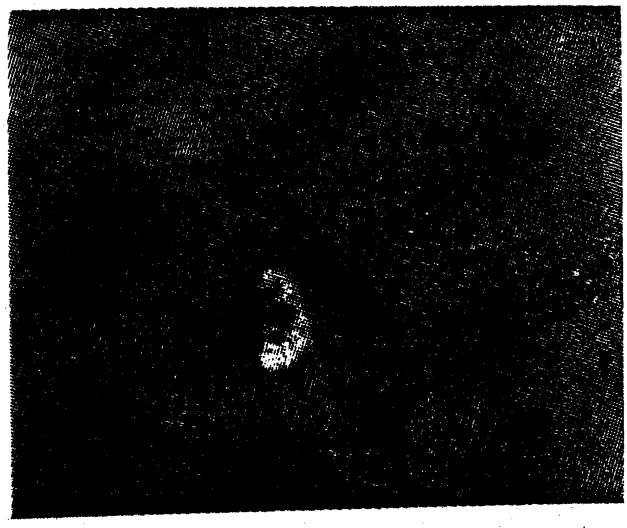


7.



8.

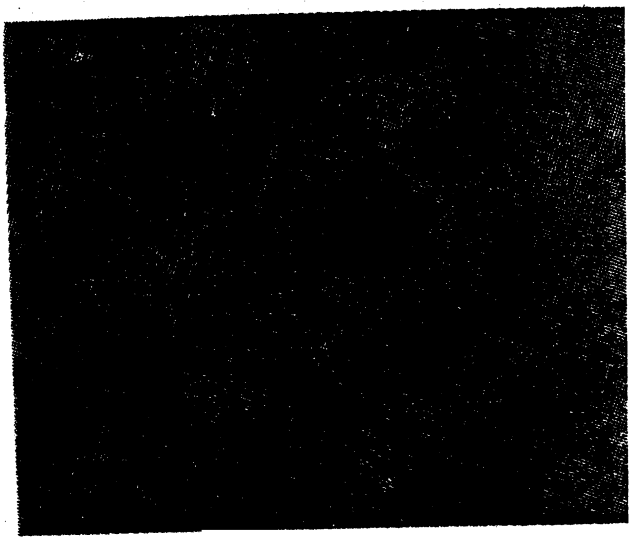
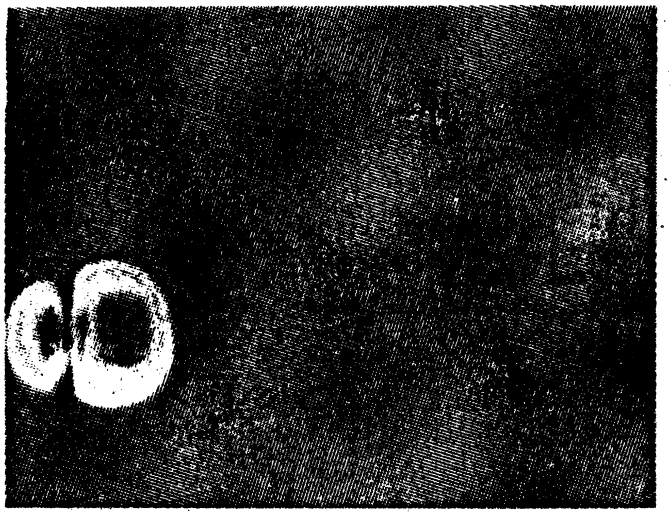


Fig. 8

Figure 9. and 10. exhibits two bilateral non-spherical cavitation bubbles

1.



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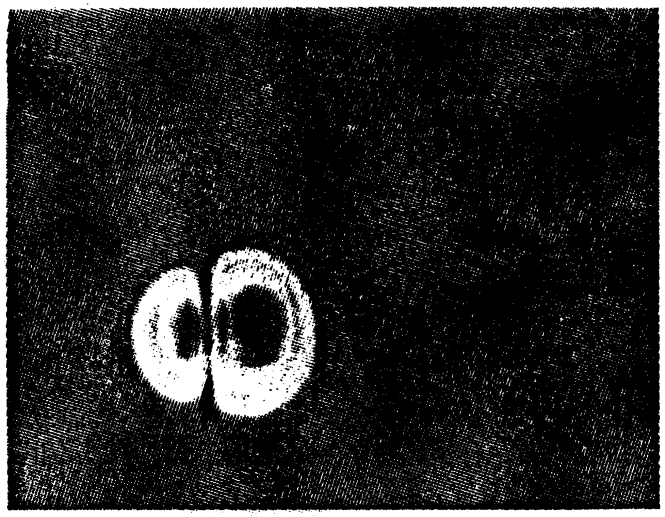

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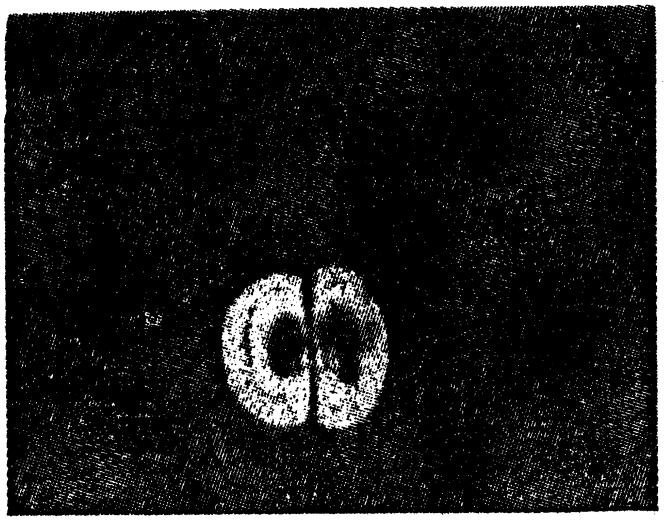

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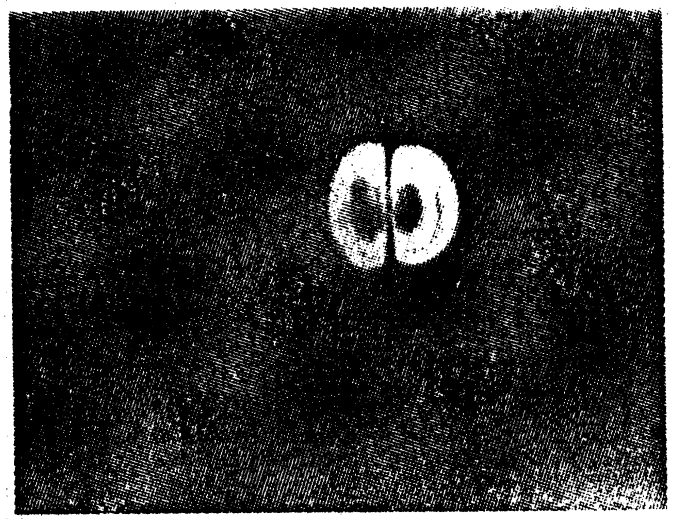

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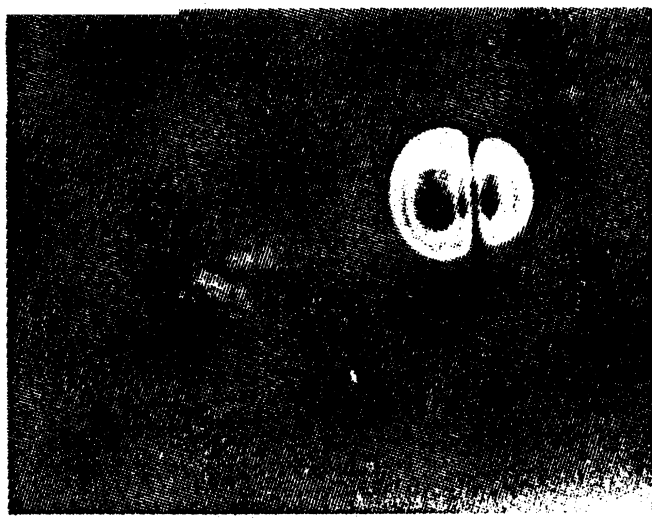
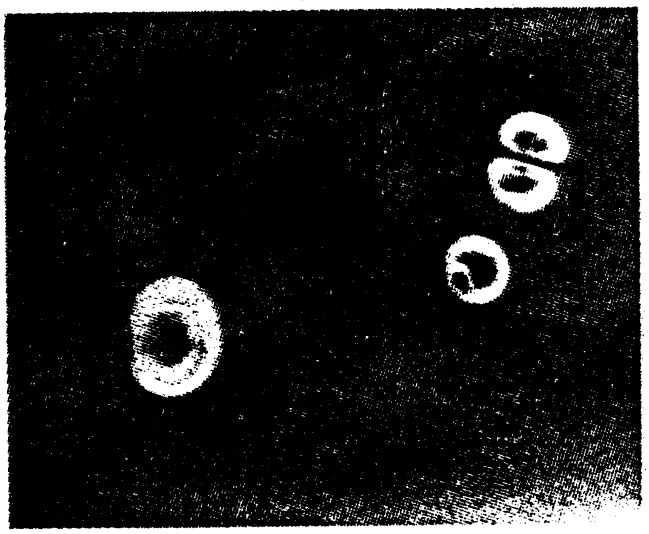


6.

Fig. 9

A.



B

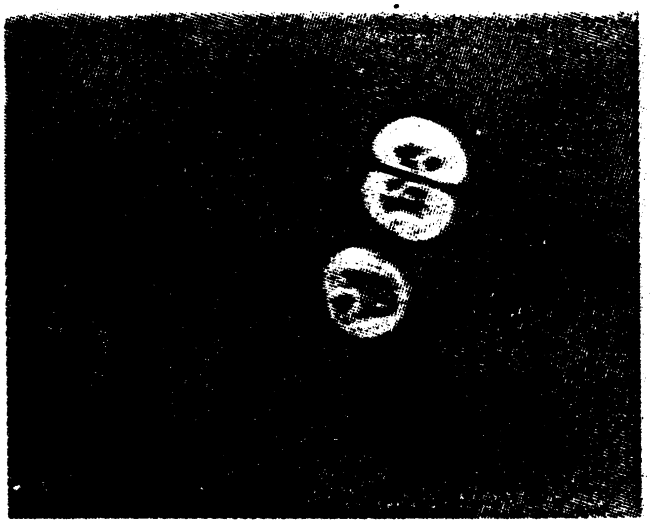


FIG. 10.

Bibliography

1. Finite Wave Effects in Fluids, Proceedings of the 1973 Symposium, Copenhagen, Session 3, Cavitation: General and Basic Aspects, Section 5.1 Nonlinear Spherical Bubble Oscillation, p.198

2. R is the radius of the spherical bubble, ρ the density of the liquid, R_n the radius of the bubble at rest, P_n the gas pressure inside the bubble for $R = R_n$, $K = C_p/C_v$ the ratio of the specific heats inside the bubble, P_0 the vapor pressure of the liquid, σ the surface tension of the liquid, P_s the hydrostatic pressure at the location of the bubble, μ the viscosity of the liquid, and $P(t)$ an arbitrary time varing pressure.

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