03424-2
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ANALYSIS OF PROFILOMETER DATA

FOR CAVITATION PITS

Project 03424

Internal Report 2

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I. Introduction

Three stainless steel wear samples, with surfaces pitted from exposure to a cavitation field, were tested with a profilometer to determine the profiles of the pits. These tests were conceived and supervised by Mr. V. F. Cramer. They were conducted using equipment very kindly loaned by Micrometrical Mfg. Co. of Ann Arbor, with the assistance of their Mr. Charles Good.

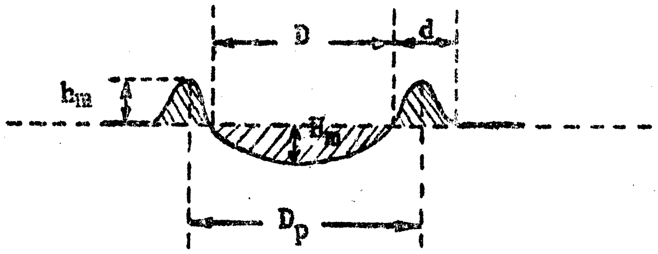
A profilimeter is a mechanical-electric instrument which provides a permanent magnified chart record of the height, shape, and spacing of surface irregularities. The pit profiles were traced by using a 0.001 inch diameter diamond stylus which is capable of detecting surface irregularities of less than a millionth of an inch. For our purposes, the instrument was limited to those pits which were either large enough for the 1 mil diameter stylus to fit into or were shallow enough to accommodate the hemispherical stylus tip. Fortunately, all pits tested were very shallow and most of the pits greater than 1/2 mil in diameter yielded meaningful traces.

The profilometer tracings were compared with high magnification photographs of the surfaces tested to aid in making an estimate of the overall shapes of the pits involved. In most cases, only 2 or 3 sweeps were traced across each pit and the photographic information was very helpful.

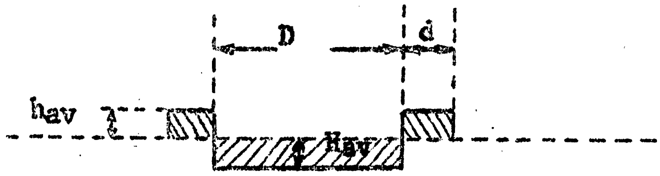
II. Analysis Procedure

The proficorder charts traced approximately 50 pits, but in many cases the information was not useful due to small pit sizes, inadequate profile information, etc. However, 14 pits were found whose tracings gave reliable information. Each of these pits was closely investigated and its overall shape and volume loss estimated. The 14 pits selected showed a surprising similarity and several generalities could be made.

A typical pit may be considered to consist of two parts - a "pit" and a "ridge." A vertically exaggerated sketch of a "typical" pit is given below:



For purposes of calculation, the following model was assumed:



The following quantities are defined:

D = Average pit diameter

d = Average ridge width

H_m = Maximum pit depth

h_m = Maximum ridge height

H_{av} = Average pit depth

h_{av} = Average ridge height

The quantities (D, d, H_m, H_{av}, h_m, h_{av}) were estimated and tabulated for each of the 14 pits used.

It should be noted that the pit diameter, D, differs from the apparent average pit diameter (D_p) as seen visually or photographically. D_p, the observed diameter, is measured from ridge peak to ridge peak.

III. Observations

A. All pits abserved were very shallow; $H_m \approx (1/13)D$.

B. Ridges account for a large amount of the volume lost at the pit.....Between $\sim$ 10-50%.

C. Average pit depth $\approx$ 2/3 x Maximum pit depth; $H_{av} \approx (2/3)H_m$.

D. Many pits are circular and many are heart-shaped.

E. The ridges generally extend only $\sim$ 1/2 way around the holes.

F. For a given surface area, the ridges occur on the same sides of the pits; about 90% of the observed ridges occur on the downstream side of the pits; the 10% which occur on the upstream side are relatively small ridges.

G. Pit shapes appear to be relatively uniform, whereas ridge shapes appear to be quite random.

H. Photographs provide the best method for estimating the average pit diameters but are useless for estimating pit depths or ridge heights. Often, what appears to be a deep pit photographically turns out to be very shallow, and vice versa.

IV. Calculations

Volume of pit $\approx \frac{\pi D^2}{4} \times H_{av}$

$H_m \approx 1/13\ D$; $H_{av} \approx 2/3\ H_m$

$\therefore$ Volume of pit $\approx (2/3)(1/13\ D)(\frac{\pi D^2}{4})$

Volume of pit $\approx \frac{\pi D^3}{78}$

..... Where D is the average pit diameter

(Average ridge thickness, $d \approx 0.56\ D$)
( )
(Maximum ridge height, $h_m \approx 0.54\ H_m$) Conclusions from profilometer
( ) charts
(Average ridge height, $h_{av} \approx 1/3\ h_m$)

Ridge volume, $V_R \approx$ Circumference x Average cross-sectional area x 1/2

Since ridges only extend about half way around.

$V_R \approx (\pi D_p) \times (0.56\ D \times 1/3 \times 0.54 \times D/13) \times 1/2$

Volume of ridge $\approx \frac{\pi\ D^2 D_p}{260}$

$D_p \approx 5/4\ D$ (From profilometer traces)

$V_R \approx \frac{\pi D^3}{208}$

Total wt. loss per pit $\approx V_{pit} - V_{Ridge} \approx \pi D^3(1/78 - 1/208)$

Total wt. loss per pit $\approx 0.008\ \pi D^3$

$V_R/V_p \approx \frac{(1/176)}{(1/66\ )} = 0.375$

Ridges account for ~ 3/8 of the pit volume loss.

In terms of the apparent pit diameter, D_p .....

Volume loss per pit $\approx 0.008 \pi D^3 = 0.008 \pi (4/5\ D_p)^3$

For n pits occurring on a surface:

Total wt. loss $\approx \rho \times 0.008 \pi (4/5)^3 \sum_{i=1}^{n} (D_p)_i^3$

where ρ = density of the metal.

Presently, only the pits on the polished surfaces of the metal samples have been measured, counted, etc. However, weight is also lost from the non-polished surface areas which project into the cavitating region. One possible solution would be to assume the weight loss (per unit area) from both surfaces to be equal. Unfortunately, this appears to be a poor assumption since the polished surfaces themselves exhibit great variations in the pitting tendency along the various regions of a given surface. We have no assurance that the pitting rate of an unpolished surface is similar to that of a polished surface on the same specimen. The polished surface constitutes only 15% of the total area exposed to cavitation.

A much better, but less comprehensive assumption would be that the rates of pitting of the two surfaces are directly proportional to each other. For example, if the weight loss from the polished surface is doubled, the weight loss from the sides would also be doubled.

For n pits occurring on the polished surface.....

Total weight loss of the sample $\approx k \sum_{i=1}^{n} (D_p)_i^3$

Where $(D_p)_i$ is the apparent diameter of the i^{th} pit

k is a constant for a given material and cavitation field.

It would be nearly impossible to tabulate the average D_p for each pit over the entire polished surface of a sample and compute $\sum_{i=1}^{n}(D_p)_i^3$, since in most cases there are hundreds of pits and each is unique. The following method of analysis is suggested: Consider the spectrum of pits to be separated into 3 major divisions ....."Small"pits, "Large" pits, and "Very Large" pits with the following definitions:

$$\begin{pmatrix} 0.3 \text{ mils} < \text{Small pits} < 1.5 \text{ mils} \\ 1.5 \text{ mils} < \text{Large pits} < 3.0 \text{ mils} \\ 3.0 \text{ mils} < \text{Very Large pits} < 10 \text{ mils} \end{pmatrix}$$

The pits smaller than 0.3 mils are considered negligible for the consideration of weight loww, although there usually are thousands of them. No pits larger than 10 mils have been observed to the present.

$$(D_p)_i^3 = C_1A + C_2B + C_3C$$

Where A = Number of small pits

B = Number of large pits

C = Number of very large pits

C_1, C_2, and C_3 are unvarying constants for a given material and represent the average D_p^3 of the regions involved. From photographic evidence (See Appendix pp 11-12)..... $C_1 \approx 0.455$

$C_2 \approx 11.5$

$C_3 \approx 238$

The equation becomes.....

$$\sum_{i=1}^{n}(D_p)_i^3 \approx 0.455\,A + 11.5\,B + 238\,C$$

If a given region contains less than ~ 10 pits, the statistics of the method become poor and $\sum_{n=1}^{n}(D_p)_i^3$ for that region should be calculated termwise.

Example A: Consider a typical surface with the following data:

- 20 Large pits
- 150 Small pits
- 1-6.5 mil pit
- 1-7.0 mil pit

$$\sum (D_p)_i^3 = (0.455)(150) + 11.5(20) + (6.5)^3 + (7.0)^3$$
$$= 68.3 + 230 + 275 + 343$$
$$= 916.3$$

In the example above, which may be considered typical.....the two "very large" pits accounted for 68% of the weight loss; the "large" pits represent 25%; and the "small" pits only 7% of the total. All of the pits less than 0.3 mils in diameter can be shown to have a negligible effect. Assuming a $(D_p)_{av}^3$ of ~6 x 10^{-4} $mils^3$ for this region, over 300,000 pits would be needed to cause a 10% change in the weight loss.

Example B: Consider a sample with the following data:

- 230 Small pits
- 67 Large pits
- 20 Very Large pits

$$\sum_{i=1}^{n}(D_p)_i^3 \approx 0.455(230) + 11.5(67) + 238(20)$$
$$\approx 104 + 771 + 4760$$
$$\approx 5635$$

In this case the weight distribution was:

- 84.4% Very Large pits
- 13.7% Large pits
- 1.9% Small pits

Again, the pits smaller than 0.3 mils are negligible with regard to weight loss -- Over 1 million pits in this region would be needed to alter the total weight loss by 7%.

The general equation for the total weight loss of a sample is:

$$W = k\sum_{i=1}^{n} (D_p)_i^3 = k(0.455\ A + 11.5\ B + 238\ C)$$

The only unknown in this equation is k, which may be estimated in three different ways:

1. Comparison with direct weighing results
2. Observation of pitting behavior on the sample sides
3. Comparison with radioactive test results (Standard solution, etc.)

As a first approximation of k, the assumption of equal pitting rates on both surfaces may be used.

$$W = \rho \times 0.008\,\pi(4/5)^3 \sum_{i=1}^{n} (D_p)_i^3 \times (1/0.15)$$

$$W = 0.086\,\rho \sum_{i=1}^{n} (D_p)_i^3$$

$$W = 0.086 \times 7.86\ \text{gm/cm}^3 \sum_{i=1}^{n} (D_p)_i^3\ \text{mils}^3 \times \left(\frac{1\ \text{inch}}{10^3\text{mils}}\right)^3 \times \frac{16.39\ \text{cm}^3}{1\ \text{inch}^3}$$

$$W = 1.11 \times 10^{-8}\ (0.455\ A + 11.5\ B + 238\ c)\ \text{grams}$$

The weight loss predicted by this equation is probably low. A large part of the pitting occurs on the edges of the samples. This pitting is such that the pit count at the edge would underrate the weight loss. At many places on the edge, the area is so heavily pitted that the entire edge is worn down.....Also in many instances the corners are battered to the extent that the depths of the pits are very large compared to that of the typical shallow pit for which this correlation was derived. For any degree of accuracy, one of the three methods of estimating k (listed on page 8) should be used.

V. Summary

From profilometer traces and photographic evidence, the geometry of a typical cavitation pit has been postulated and several methods of estimating the sample weight loss suggested. With our present information, only a rough approximation can be made. Three methods of improving the weight loss equation are listed: Comparison with direct weighing results, observation of the pitting behavior at the sample sides, and comparison with radioactive test results. All of these methods should probably be attempted.

The profilometer data was very limited and more profilometer traces are recommended. These should include more sweeps across each pit and an expanded horizontal scale. Also, a recheck of the same pits after additional cavitation would be desirable to yield information on the development and growth of pits.

APPENDIX

Estimation of C_1

Size range, mils	n = # of pits	$(D_p)_{av}^3$	$n(D_p)_{av}^3$
0.3-0.4	100	0.0430	4.300
0.4-0.5	79	0.0911	7.200
0.5-0.6	61	0.1663	10.20
0.6-0.7	48	0.2750	13.20
0.7-0.8	37	0.422	15.60
0.8-0.9	30	0.613	18.40
0.9-1.0	25	0.857	21.40
1.0-1.1	20	1.160	23.20
1.1-1.2	16	1.52	24.32
1.2-1.3	12	1.95	23.40
1.3-1.4	9	2.46	22.14
1.4-1.5	6	3.04	18.24
	$\Sigma n =$ 443		$\Sigma n(D)_{av}^3 = +\ 201.6$

$$(D_p)_{av}^3 = \left(\frac{\sum n(Dp)^3}{\sum n} \right) = \frac{201.6}{443}$$

$$(D_p)_{av}^3 = 0.455 \quad \text{mils}^3$$

ROOT MEAN CUBE $\approx$ 0.77 mils

$C_1 \approx 0.455$ mils^3

Estimation of C_2 and C_3

Size range, mils	n = # of pits	$(D_p)_{av}^3$	$n(D_p)_{av}^3$
1.5-2.0	100	5.36	500.4
2.0-2.5	88	11.40	1003.0
2.5-3.0	70	20.80	1457
	$\sum n$ = 258		$\sum n(D_p)^3$ = 2960.4

$$(D_p)_{av}^3 \approx \frac{\sum n(D_p)^3}{\sum} = \frac{2960.4}{258} = 11.5$$

$C_2 \approx 11.5$......ROOT MEAN CUBE $D_p \approx 2.25$ mils

Estimation of C_3:

In the calculation of C_1 and C_2 the root mean cube D_p was found to be slightly less than the average diameter. We will assume the same behavior to exist in this region;

For estimation of C_3..... $D_{av} = \dfrac{3\text{ mils} + 10\text{ mils}}{2} = 6.5$ mils

Assume: $(D_p)_{av}^3 \approx (6.2\text{ mils})^3 \approx 238$

$C_3 \approx 238$ ..... ROOT MEAN CUBE $D_p \approx 6.2$ mils.

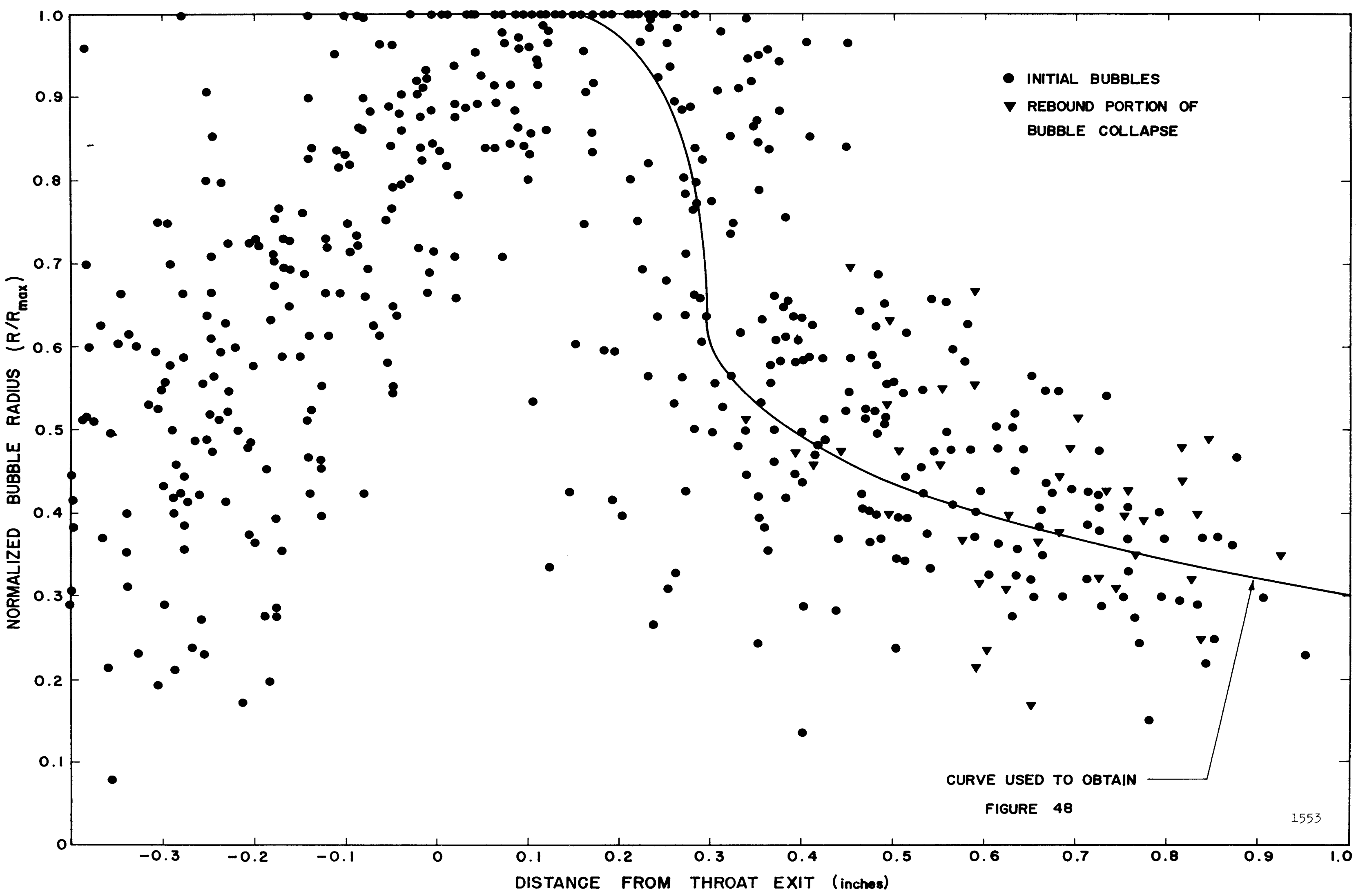


Figure 10. Normalized Observed Bubble Radius vs Distance from Throat Exit, 73 Bubbles

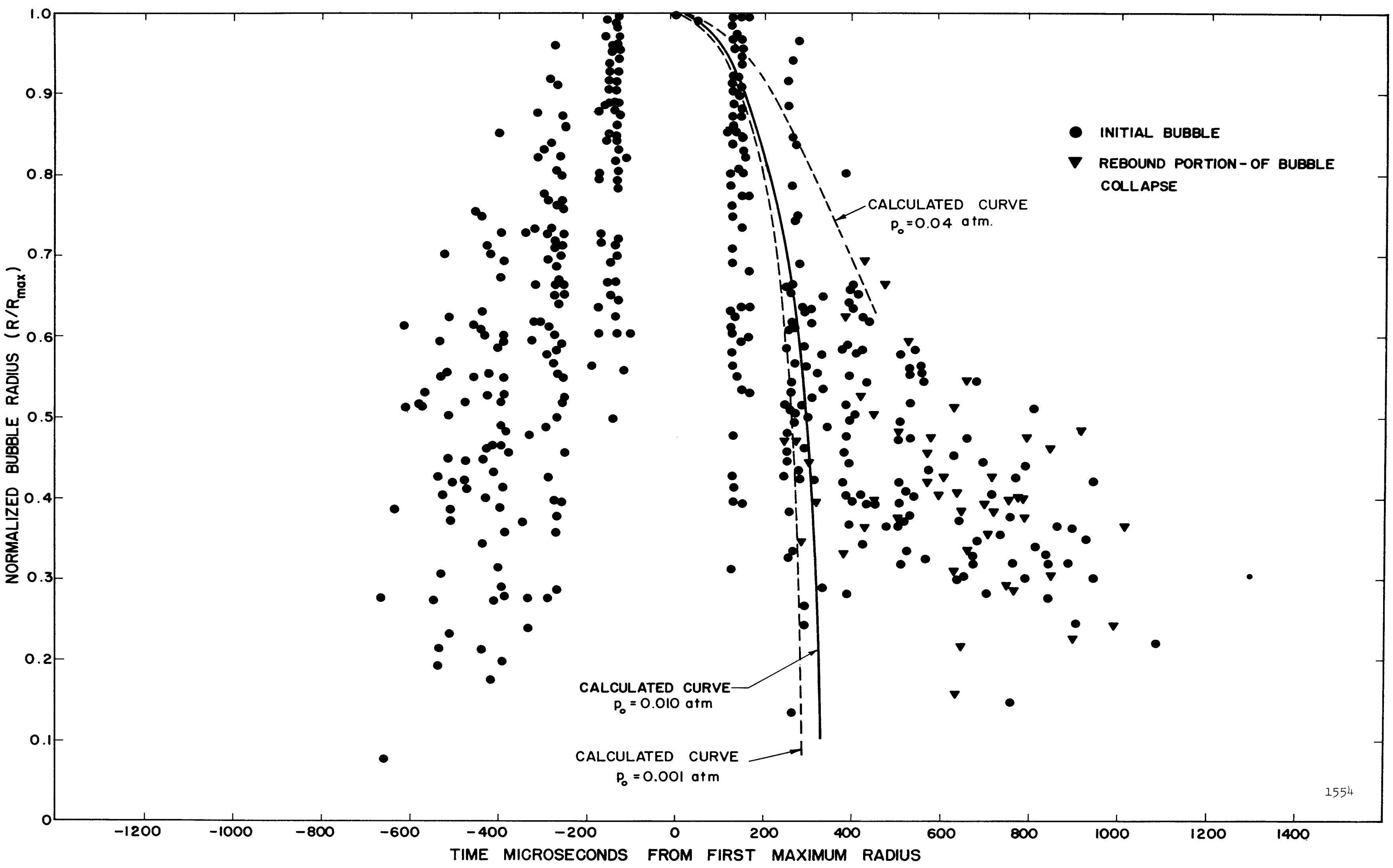


Figure 11. Normalized Observed Bubble Radius vs Time from the First Observed Maximum Radius, 73 Bubbles

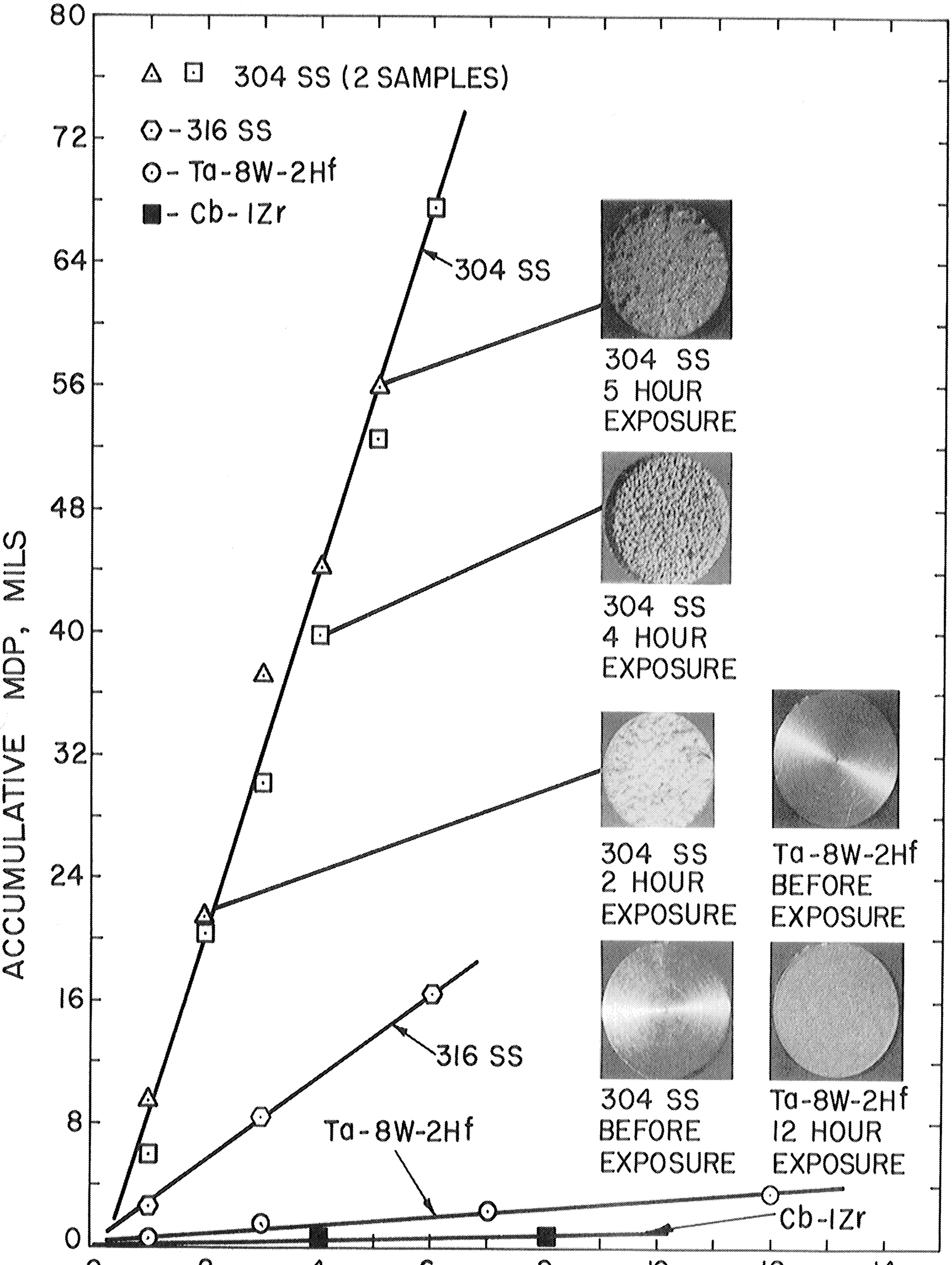


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FIGURE 1. CAVITATION IN LEAD-BISMUTH AT 1500° F