THE UNIVERSITY OF MICHIGAN

College of Engineering

Department of Mechanical Engineering

Cavitation and Multiphase Flow Laboratory

Report No. UMICH-324490-1-T

LIQUID IMPINGEMENT AND CAVITATION STUDIES OF EROSION RESISTANCE OF RUBBER-COATED MATERIALS FOR B.F. GOODRICH

by

F.G. Hammitt

N.R. Bhatt

T.M. Mitchell

N. Orlandea

J.M. Stifel

E.E. Timm

V.M. Wild

December 1970

ABSTRACT

High-speed motion picture sequences of liquid jet impact at 500 MPH with 6 rubber-coated materials supplied by B. F. Goodrich and also with Epon-828 and Plexiglas have been obtained, showing in good detail the portion of the impact believed responsible for damage. Some conclusions on favorable characteristics of the splash pattern for superior damage resistance are made.

The erosion resistance of the same materials has been measured with repeated impacts with the same water jet at 500 MPH and with a cavitation test. It was found that the erosion resistance measured with the water jet is quite similar to that measured on the Goodrich propellor arm at the same speed, and is also quite closely related to the cavitation resistance. Thus the water gun could be utilized for tests up to Mach 2 as has been done with materials such as Astrocoat for NADC. The best correlation with material mechanical properties or splash parameters was that with hardness.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

I. INTRODUCTION

An initial contract of one year between the B. F. Goodrich Co. and the Cavitation and Multiphase Flow Laboratory of the Mechanical Engineering Department of the University of Michigan had a three-fold objective:

1. Obtain high-speed motion pictures of the impacts of 500 MPH water jets generated by our water gun device upon 6 rubber-coated materials supplied by Goodrich to observe the details of this collision and attempt to ascertain possible differences in the response of materials that might be related to their droplet impact erosion resistance. The framing rates for these pictures should be such that as many frames as possible be available during the critical part of the impact process. The pictures were taken with our Beckman-Whitley framing camera capable of producing up to 80 framesper run at 2 million frames per second. Due to the short time which can be sampled, optimum information in this case is obtained with less than maximum framing rate as will be explained later. Pictures have also been taken under the same impact conditions for two harder materials for comparison, Epon-828 and Plexiglas.

2. Investigate utility of this water gun device for the testing of rubber-coated materials for liquid droplet erosion resistance. Test data on the water gun device for the 6 materials supplied by Goodrich can be directly compared with results on the same materials at the same velocity generated by Goodrich using their propellor arm device. If a reliable relationship between results from these two devices could be shown at 500 MPH, data could then be obtained on the same or other materials of interest to Goodrich at velocities up to about 1200 MPH with the gun device (which has such a capability). A possibly significant difference between the two types of test at the moment is the fact

that the gun device impacts repeatedly in the same location on the specimen whereas the propellor arm provides a random distribution of impacts as does an actual rain storm. The capability of random distribution of impact could be added at moderate expense to the jet gun.

3. Investigate utility of our vibratory cavitation device for testing of the same materials for droplet impingement erosion resistance. Obviously, cavitation erosion data for these same materials are of interest per se, but their relation to impact data was to be investigated.

All of the above tasks have been completed as will be explained in considerable detail in the body of the report. These preliminary results suggest the desirability of additional investigations covering at least another year of effort as will also be explained later.

II. PHOTOGRAPHIC AND EXPERIMENTAL OBSERVATIONS

A. Experimental Facilities Utilized

1. Impact Facility. For the liquid jet impact tests, a repeating water gun (Fig. 1) was utilized.[1] This device produces liquid jets with velocity up to about 600 m/s, emanating from an orifice of 1.61 mm. dia. The repetition rate is up to about 50 per minute. The actual jet shape depends upon various parameter settings. For the present tests, wherein the impact velocity was ~223 m/s (500 MPH) its appearance is as shown in Fig. 2 - 9. The initial stage of the impact is with a "precursor jet" of diameter somewhat smaller than that of the main jet. Precursor jet diameter in these tests is ~ 1/3 mm. and main jet diameter is ~1.2 mm. It is believed that the important part of the impact from the viewpoint of damage production is the initial part during which high transient pressures and velocities are possible. The pressure and velocity across the surface of a "steady-state" jet of the present impact velocity would be much smaller and probably not damaging during the short time of the collision.*

The six rubber-coated materials supplied by B. F. Goodrich Co. (Table 1) were tested at 500 MPH impact velocity, angle of impact perpendicular. Photographic sequences of the collisions were then obtained (Fig. 2 - 7) using the high-speed framing camera described in the next section. Collisions with two relatively non-elastic materi als (Epon-828 and Plexiglas) were also photographed (Fig. 8, 9) under the same conditions for purposes of comparison. Damage data (weight loss) were obtained for all these materials with repeated impact under the same conditions for which the photographs were made. (Table 1 and 3, and Fig. 19-28).

2. High Speed Motion Picture Facility. The motion picture sequences of the water jet impacts (Fig. 2 - 9) were made with a Beckman-Whitley framing camera capable of a maximum framing rate

---

*A modification to the device to provide a stripper plate allowing only the precursor portion of the jet to pass can be made in the future to obliviate this difficulty.

of 2 million frames / second, with a total of 80 of frames/run. To obtain maximum information per run, a framing rate of 0.66 million frames per second was used.

As will be observed in Fig 2 - 9, it is quite possible to estimate the radial and axial velocities of the liquid during the collision utilizing the times from initial impact noted on the individual photos. Note also that the flow patterns are well-developed by about 40 μs, and that there are considerable differences in flow patterns generated between the materials. These matters will be discussed in more detail later. Unfortunately it is not possible in these photos to observe the deflection of the specimen surface during the impact. However, from the steep angle of splash-back, it may be inferred that in some cases this deformation is considerable. A possible method for future tests for measuring the deformation during the impact and correlating it to photos such as these is discussed later in the report.

3. Cavitation Damage Facility. All the previously mentioned materials were also tested in cold water (70^{o}F) in our vibratory stationary specimen set-up (Fig. 10) where the specimen is held 20 mils from the tip of the vibrating horn[1]. The double amplitude is 2 mils and the frequency 20 kHz. The resultant maximum damage rates are listed in Table 1 along with those from the impact tests. Generally it is noted that the correlation between impact resistance and cavitation resistance for these rubber-coated materials is not good, especially when compared with the less elastic materials (Epon-828 and Plexiglas).

B. Liquid Impact Photographic Results

Fig. 2 - 9 respectively show high-speed motion picture sequences of impacts at 500 MPH (732 m/s = 233 m/s = 0.67 Mach at STP) for the rubber-coated materials supplied by Goodrich and for the more rigid materials, Epon-828 and Plexiglas. Fig. 2 - 7 show the Goodrich materials in ascending rank according to the Goodrich numbers; Fig. 8 and 9 are for Epon and Plexiglas respectively. The times in microseconds

are shown in each frame. Though approximately 80 frames were exposed per run, only selected frames are shown to indicate the significant features of the impact. The portion of the overall impact shown by the figures is that with the "precursor" portion of the main jet which has a diameter of about 1/3 mm. The main jet of about 1.2 mm diameter follows, but since this latter portion of the collision is a roughly steady-state impingement, as compared to the first portion, it is not thought to be important to the damage process.

Though the impact phenomenon is quite similar for all the materials, there are significant differences in the velocity and direction of splash-back. This is minimal in the more rigid materials (Epon and Plexiglas), and quite pronounced in all of the rubber-coated materials, except for the natural rubber (Goodrich #1) which is similar in this respect to the rigid materials. It is maximal for Goodrich #4. Another difference which may be significant is the velocity with which the splash-back plume moves out radially from the center of the collision. This is maximal for Goodrich #4 and minimal for Goodrich #5 and 6 of the rubber-coated materials, but is considerably greater for the rigid materials. These trends are discussed in further detail below.

Fig. 11 - 18 are plots of the velocity components taken from the photographs, Fig. 2 - 9. Some of the pertinent numbers from these plots are listed in Table 2. It is noted that typically both radial* and axial splash-back velocity achieve a maximum very near the time of impact (0-1.7 μs). In some cases both of these velocities are greater than the actual impact velocity, In all cases, the maximum radial velocity is greater than the actual impact velocity. In most cases, the maximum splash-back velocity is less than the impact velocity, ranging from about 1/2 for Goodrich #4 to ~1.3 x for Goodrich #5 and Epon-828. The initial radial velocity (which is also the maximum) is largest for Goodrich #3, being 2.3 x the impact velocity for this material, and 2.0 x

*When measured from actual point of impact, the radial splash appears to be quite symmetrical.

the impact velocity for Goodrich #10. It ranges from 1.1 - 1.3 x impact for the other materials. A large radial velocity may be significant in that Goodrich #3 and 10 were also most erosion resistant in the gun tests (Tables 1 and 3). It has previously been reported by other investigators, Brunton[2 e.g.] that radial velocities of 4 -5 x impact velocity are observed sometimes for impact of spherical drops upon materials such as Plexiglas (in our present tests the maximum radial velocity only slightly exceeded the impact velocity for this material). The reduced radial velocity in the present tests may be due to the fact that the jet nose is not perfectly spherical, and perhaps also to differences in impact velocity and drop diameter which would affect the surface deformation. The fact that the radial and axial velocities quickly decrease substantially tends to confirm the previously stated assumption that the significant damaging mechanisms exist only during the very early part of the collision, so that the remainder of the impact which occurs after the portion of the photographic sequences shown, is not important in this regard.

Another significant difference between materials which can be observed in the photographs themselves, in the curve sheets, and in Table 2 is the degree of outward (radial) motion of the splash-back plume after the initial impact. For the rubber-coated materials this outward motion is minimal for the natural rubber, Goodrich #1, and maximal for Goodrich #4, 3 and 10 in that order. It thus appears that a large outward motion of the plume is desirable for erosion resistance (Table 1 and 3).

Although the initial splash-back velocity is reasonably large for all materials tested, rubber-coated and otherwise, the photographs and Table 2 show that the actual height of plume attained is considerably the greatest for # 10, 4 and 3, so that this type of behavior is apparently desirable. Since the splash-back is presumably due to deformation of the surface under the impact guiding the velocity away from the surface, it is reasonable that it should be large for more flexible materials. Although no actual observations of surface deformation during the impact were possible in these tests, a careful analysis of the photographs, with some assumptions, could allow its estimation. In further work, this might advantageously be done along with an attempt to measure the deformation, perhaps using ultrasonic or laser beam interference techniques.

III. EROSION OBSERVATIONS

A. Impact Erosion Tests

The 6 rubber-coated Goodrich materials as well as Epon-828 and Plexiglas have been tested at the same velocity for which the impact photographs were taken (223 m/s). The weight and volume loss vs. number of impact curves are shown in Fig. 19 - 28, and the results are summarized in Tables 1 and 3.

Prior to this initial set of tests, little knowledge of the behavior of materials of this type in the gun device and in this range of velocity existed. Consequently the tests were performed with the general objective of generating the full curve of weight loss vs. number of impacts until the coating had been eroded down to the substrate. Fig. 19 - 26 show such curves for the rubber-coated materials. Since the impacts occur repeatedly at very nearly the same spot when using the gun device, as opposed to the Goodrich propellor arm device where the impacts are random across the specimen surface as in an actual rain environment, a given degree of local attack upon the specimen corresponds to a much smaller total weight loss in the gun than in the propellor arm. Thus no direct comparison is possible at a given weight loss between the Goodrich propellor arm curve (Fig. 29), and the water gun curves for the same material. However, for a rough comparison, we have assumed that a given gun weight loss is equivalent in terms of local damage to either 10 or 100 x that weight loss for the propellor arm data. For the present however, the factor of 10 allows an extrapolation of the Goodrich data for comparison with the gun data and will be used. If the factor of 10 were approximately correct, the gun tests correspond approximately to the propellor arm tests up to a weight loss of about 0.2 gms (2.0 gms for 100 x). The effect of both of these assumptions upon the relative ranking of materials by the propellor arm and gun devices is shown in Table 3, and will be discussed later.

Once the general shape of the water gun test curves for these various materials is known, it becomes apparent that time to initial failure rather than maximum weight loss rate (commonly used as the figure of merit for cavitation and impact tests on metals) is probably of primary importance. This could be characterized as the "incubation period", i.e., number of impacts to cause measurable weight loss. It could be measured by extrapolating to zero that portion of the weight loss vs. time curve which corresponds to an accelerated rate of weight loss. Examination of Fig. 19 - 26 shows that this is an uncertain procedure because of the substantial differences in detailed curve shapes. Nevertheless, incubation period as so estimated is listed in Table 1. Since there was no direct method for measuring the number of impacts to cause an initial failure of the coating (probably the most important figure of merit), an alternative approach has been adopted. The number of impacts necessary to cause a small but measurable weight loss is estimated directly from the weight loss vs. number of impacts curves. Table 1 lists the number of impacts necessary to cause 3 mm^3 and 1 mm^3 volume losses, as well as the "incubation periods" as defined above.

Examination of Table 1 shows that the relative rankings of materials is much the same according to incubation period of impacts to either of the small volume losses used. However, the rankings according to maximum weight loss rate once gross failure has occurred (WLR of Table 1) are quite different. For example, according to any of the definitions of incubation period, Goodrich #10 is best and #3 next. According to maximum damage rate, #10 is still best, #6 is next and #3 is fifth. As will be discussed later, the cavitation resistance rankings of the materials according to maximum damage rate is again somewhat different from the gun rankings with #4 being best, #3 the next, and #10 second from the worst. However, the rigid materials, Epon-828 and Plexiglas are far worsethan any of the rubber-coated materials. Examination of Table 3-c shows all Goodrich materials, with the exception of #4 and 10, hold the same ranking for cavitation and water gun.

As indicated above, after initial tests had been completed on all materials, it became apparent that much greater detail in the early part of the test would be desirable, since the impacts to initial failure are probably much more important than the rate of failure once this occurs. This suggests the desirability for future work of a more precise method for measuring initial failuresuch as might be provided with an ultrasonic probe, which conceivably could also measure deformation of the surface during the impact. This is discussed in more detail later. Though such an instrument was not available for the present tests, still a second run was made on the two materials appearing best in the first run, i.e. #10 and 3, with more numerous examinations and weighings. These results are shown in Fig. 27, where data from the initial portion of the tests for two specimens of both materials is shown. Average values for these materials are then used in Table 1. Fig. 27 indicates the considerable divergence between different specimens of the same material. Fig. 28 shows in more detail the results from the early portion of the tests for the other rubber-coated materials, so that comparison can be made. Fig. 29 is the Goodrich curve for the same materials from their propellor arm, also at 500 MPH.

Fig. 30 - 33 are photographs of each material from both the water gun and the cavitation test after completion of the test. In all cases little or no damage can be seen in the photos from the cavitation tests, though slight damage could be seen in careful examination of the specimens. The damage from the gun tests is substantial and obvious. There is considerable difference in the damage pattern between materials. As previously mentioned more detailed probing of the very early portions of failure in future tests mightbe extremely rewarding.

B. Correlation of Impact Damage with Mechanical and Collision Parameters

Fig. 34 - 39 plot impacts to 1 mm^3 volume loss (selected as the most meaningful figure of merit) against various parameters dependent upon the material properties, i.e., hardness, tensile strength, maximum radial velocity after impact, and maximum splash-back axial velocity. It is noted that the correlation is not particularly good with any of these, although those with either Shore-A hardness or microhardness seem best. Fig. 38 and 39 shows the correlations between "incubation period" and impact to 1 mm^3 and 3 mm^3 volume loss both of which are quite good since the impacts to "initial" failure seems of most basic importance, this parameter has been used for the remainder of this report.

C. Cavitation Erosion Results

Fig. 40 - 47 are plots of weight loss vs. time for the 6 Goodrich materials, Epon-828 and Plexiglas in the cavitation test. Since the rubber-coated materials are all very resistant to cavitation damage in this test as compared with more rigid materials (even metals), the weight losses in feasible test time are not sufficient to obtain closely reproducible cavitation damage curves. However, two specimens of each material were tested. Two separate curves for each specimen are shown on the curve-sheets, an averaged smoothed curve is then constructed, and finally a straight line from the origin to the average final weight loss. The slope of this straight line is then used as the figure of merit for the cavitation test for the particular material. Fig. 48 shows all these resultant straight lines without data points to allow an easy comparison between materials. The slopes of these weight loss lines are then converted into volume loss rates (MDPR) for Table 3.

As shown on Fig. 48 and in Table 3, the rigid materials Epon-828 and Plexiglas are very much less resistant to this relatively mild cavitation field than are the rubber-coated materials. This was also true for the impact tests, but the differentiating factor was much less.

IV. OVERALL COMPARISONS

Table 3 compares the erosion resistance data from the water gun and cavitation tests with that achieved with the same materials and velocity using the Goodrich propellor arm. In Table 3-A the actual numerical data from each type of test for each material is presented. This table including Astrocoat for comparison, which was tested with our water gun for NADC at a much higher velocity,(approximately 600 m/s). While the cavitation resistance of this material is not outstanding, its resistance to impact damage is very great compared to the Goodrich rubber-coated materials or the others tested (Epon-828 and Plexiglas), since no weight loss was obtained after 20,000 impacts even at 600 m/s (vs. 223 m/s for the other materials).

Table 3-B lists all the same results as Table 3-B as erosion resistances. These are normalized in such a way as to assign unity to Goodrich #1, i. e., all values are divided by the value applying in that particular test to Goodrich #1. Table 3-C gives the relative ranking of each material according to that particular test, with the most resistant material being assigned the highest numerical ranking. The rankings are presented with and without inclusion of Epon-828, Plexiglas, and Astrocoat which were not included in the Goodrich propellor arm test.

Fig. 51-55 show the degree of correlation between the water-gun and the propellor arm; cavitation and the propellor arm; and water-gun and cavitation, respectively. The propellor arm data is shown both for time to 10 mm^3 volume loss and time to 100 mm^3 volume loss, as previously discussed. As shown in Table 3-C, the relative ranking of materials between the water gun and the propellor arm for 100 mm^3 or for 60 minutes is nearly identical, the only difference being the interposition of materials #3 and #5 in the rankings. However, there is somewhat greater difference between the gun tests and the propellor arm time to 10 mm^3 volume loss. This situation is also illustrated in Fig. 51 and 52.

Thus it appears that the damage intensity caused by the water gun at 1 mm^3 volume loss is similar to that for the propellor arm to 100 mm^3 loss. As previously explained, the ratio between comparable volume losses is presumably the result of the fact that water gun impingement is closely upon the same spot, while that for the propellor arm is randomly distributed across the entire facial area of the specimen.

Fig. 53, 54, and 55 show that for the rubber-coated materials there is a relatively good positive correlation between liquid impact and cavitation resistance with either the water gun or the propellor arm. As previously reported by this laboratory[1], this was not the case when comparing cavitation with the rocket sled (at Mach 2), or the gun (at Mach 2) with the rocket sled, although the gun and cavitation test correlated closely. Hence the correlation between water gun and cavitation is further confirmed by the present tests, although apparently neither device correlates well for elastomeric materials with the much more intensive erosion environment provided by the Mach 2 rocket sled. However, the correlation with ceramics or laminates was relatively good. The discrepancy for elastromerics could be partly due to aerodynamic heating of the specimens in the rocket test, to which elastomerics could be more sensitive.

There are exceptions in the present test to the correlation discussed above between the water gun and cavitation test. Of particular note in this regard is Astrocoat which was extremely resistent to impingement damage but only mediocre with respect to cavitation. It is the somewhat intuitive belief of the first author that the relative ranking of materials will change considerably with the intensity of the erosion environment and that this is particularly the case for elastomerics. This is illustrated by the fact that there is good correlation between the cavitation test, water gun and Goodrich propellor arm at 500 MPH, whereas the correlation between either cavitation or water gun (which correlated well together) and rocket sled at Mach 2 was inverse.

V. RECOMMENDED FUTURE WORK

Obviously the work completed in this one-year contract is only a beginning in many areas, so that desirable and significant new work can be postulated in many areas. Two possible areas of major importance are suggested below.

A. Prevention or Reduction of Cavitation Damage by Surface Flexibility

It is theoretically expected and has been shown by past tests, some of which were just recently completed in this laboratory[3], that, while a rigid surface will attract a collapsing bubble and cause the orientation of the resultant microjet to be toward the surface, the inverse is the case with a sufficiently flexible surface, so that cavitation bubbles are actually repelled, and the microjet oriented away from the surface of the material. Thus a material with a suitably-designed flexible surface might be virtually immune to cavitation damage. Preliminary tests,[3] which we have completed with spark-induced bubbles collapsing adjacent to a rubber diaphragm stretched across an air space, indicate that the theoretically postulated mode of collapse described above actually occurs. Hence, a further investigation of this phenomenon using our relatively unique high-speed photographic facilities with tests in both our venturi and beaker set-ups could point the way to the rational design of rubberized materials to take advantage of this facet of bubble dynamics.

B. Detailed Material Behavior in Liquid Impact to Initial Failure

A complete understanding of the actual material behavior under impact, and the mechanism for the initial failure, would be most desirable to aid in the more rational design of better materials. The presently completed tests show in detail the motion of the water during the significant portion of the impact from the viewpoint of damage. However, it is not possible to view the motion of the surface during this time. It may be possible to infer this motion from the observed fluid motion, but this would involve a rather intricate and lengthy analysis which has not yet been done. The continuation of a computerized calculation of velocity and pressures on the surface of a rigid surface during impact to include the effect of surface deformation would allow the predication of these splash velocities and a check of the analysis against the present photographs. This essentially analytical approach should be continued, but further significant experimental information should be obtained as explained below.

It may be possible to at least obtain a rough estimate of surface motion during impact by an ultrasonic probe. Initial investigation of this concept is fairly hopeful, so that a more detailed feasibility investigation should be pursued. Another possible approach is through the use of laser interferometry with a transparent surface. This appears feasible but would involve a fairly major effort. However, at least a preliminary evaluation of the concept would be worthwhile.

Further use of ultrasonic techniques would be made for detection of initial flaws in the surface after a few impacts. The present tests, based only upon visual observation and measurement of weight loss, are not sensitive enough to detect the initiation of failure, and the form which it takes. Since it is believed that more detailed information on the actual failure mechanism would be highly desirable, it is recommended that an ultrasonic probe be employed in this regard. This probe could also at least provide some information on the deflection of the surface during impact. The precision of the latter data might be limited because of the difficulty of obtaining sufficient resolution of the ultrasonic beam. Such should not be the case with the laser beam technique mentioned above.

VI. CONCLUSIONS

The major conclusions which can be drawn from this work follow.

1. It has been proven feasible to obtain detailed motion pictures of the impact from the water gun jet at 500 MPH upon 6 rubber-coated materials supplied by Goodrich as well as upon 2 relatively rigid materials, and this has in fact been done. The details of the resultant splash-back, velocities and their directions, have been taken from these photos and listed in the report. The characteristics of the splash differ considerably between the rubber-coated materials, and between these and the more rigid materials. Comparing these photographic sequences with the measured erosion resistance of the materials to repeated impacts of the same form, it appears that a large radial and axial splash velocity, with the splash plume moving radially outward from the initial point of impact is desirable for superior erosion resistance. It appears that these velocity patterns would be the characteristics of a large surface deformation under impact, hence large effective surface elasticity, thus minimizing "water-hammer" pressures. The above remarks apply both to rubber-coated and more rigid materials (which in this case were less erosion resistant).

2. Results from both the water gun at 500 MPH and the cavitation device for the rubber-coated materials correlate quite closely with results from the Goodrich propellor arm (also at 500 MPH), if erosion resistance for the propellor arm is taken as the time to erode 100 mm^3 from the surface. Erosion resistance for the water gun is then taken to be the number of impacts necessary to erode 1 mm^3 from the surface, and the cavitation test erosion resistance is taken as the reciprocal of the maximum MDPR. The rational for comparing 100 mm^3 volume loss for the propellor arm with 1 mm^3 for the water gun is that the impacts are distributed randomly across the surface for the propellor arm but are concentrated at one point for the water gun. As previously reported[1]

the correlation is inverse between the Mach 2 rocket sled and the water gun at Mach 2) for this type of material. This indicates that the ranking of materials depends upon the intensity of the erosion environment. No detailed comparison of maximum volume loss rates in the impact tests has been made since this does not seem a good figure of merit.

3. For both impact tests, rated as described above, Goodrich #10 was uniformly the best material, Goodrich #4 was next for the water-gun, followed by Goodrich #6 and #5. For the Goodrich propellor arm, the second best material is Goodrich #4, followed by Goodrich #3 and #5. In both cases Goodrich #1 (natural rubber) is worst, followed by Goodrich #4. Thus the correlation between results from the two devices is quite close. The cavitation results are somewhat similar, but #10 is worst for cavitation and #3 is best. Thus a good material for impact may not be good in cavitation. This is also illustrated by the behavior of Astrocoat.

4. Since the water gun and propellor arm results match reasonably closely at 500 MPH, the gun would be a useful device for extrapolating results for materials of interest to the 1500 MPH range of which it is capable. In this range, it was found in previous tests for Naval Air Development Center (NADC), that various materials* were not eroded substantially a 20,000 impacts (major damage with the present materials occurs $\lesssim$ 1000 impacts). However, Astrocoat, shown in Table 3, was better than the best of the present materials.

5. Correlations of damage resistance with characteristics of the splash and with material hardness and tensile strength have been made. It is found that the best correlation is with hardness.

*Brunswick Cross-Linked Polyethylene and Hughson Elastomeric, CD-1154-G4, e.g. See UMICH Report 02643-PR-5, December, 1970 F. G. Hammitt, et al.

VII. BIBLIOGRAPHY

1. F. G. Hammitt, J. B. Huang, T. M. Mitchell, D. O. Rogers, E. E. Timm, "Cavitation and Droplet Impingement Damage of Aircraft Rain Erosion Materials", Proc. 3rd International Conference, Rain Erosion and Assoc. Phenomena, Farnborough England, 1970; also available as Report UMICH 02643-5-I, May 1970.

2. J. H. Brunton, "High Speed Liquid Impact", Phil. Trans., Roy. Soc., A, 1110, 260, July 1966, 78-85.

3. E. E. Timm, Unpublished Data, 1970.

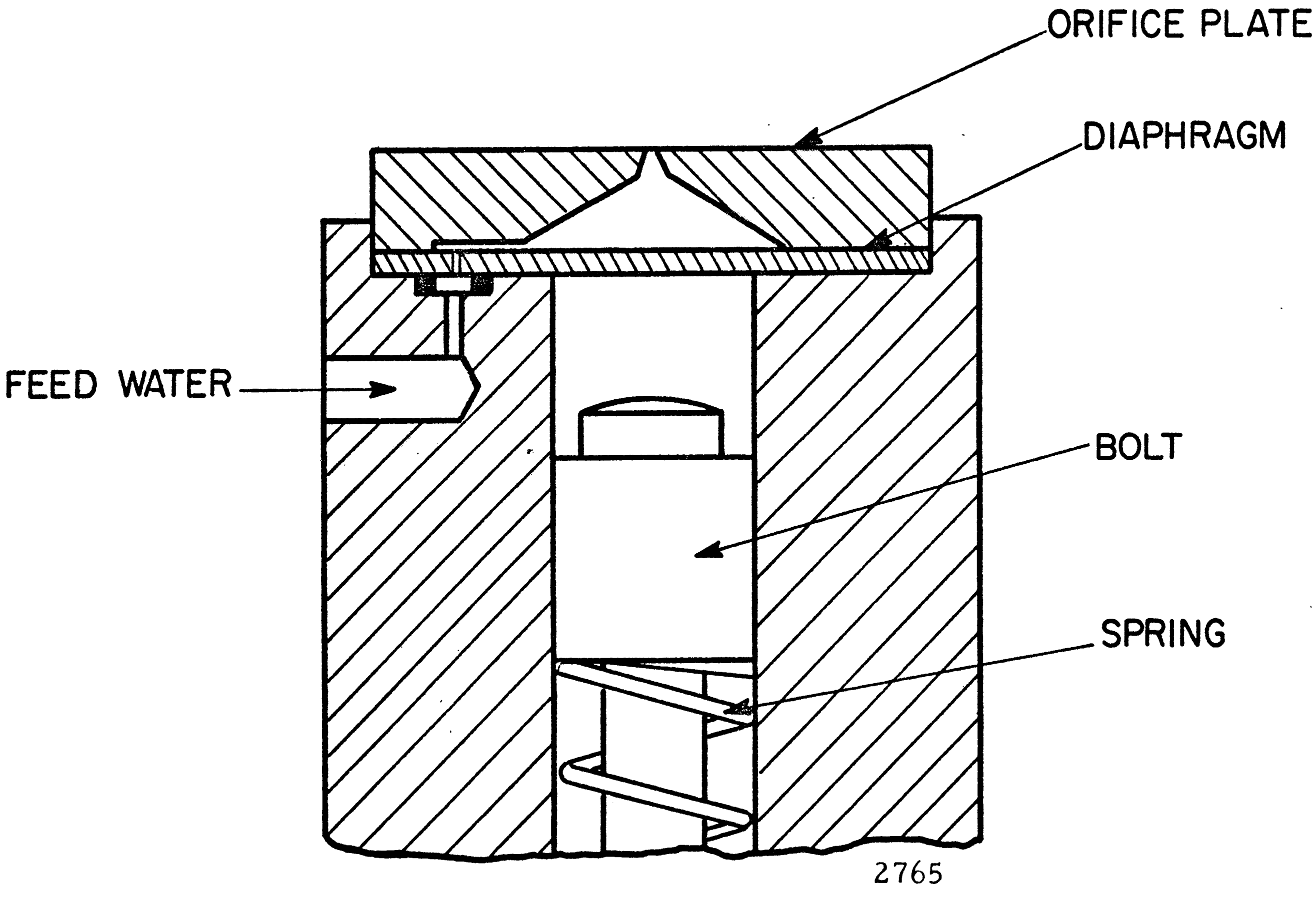


Figure 1. Schematic of Water Gun Device

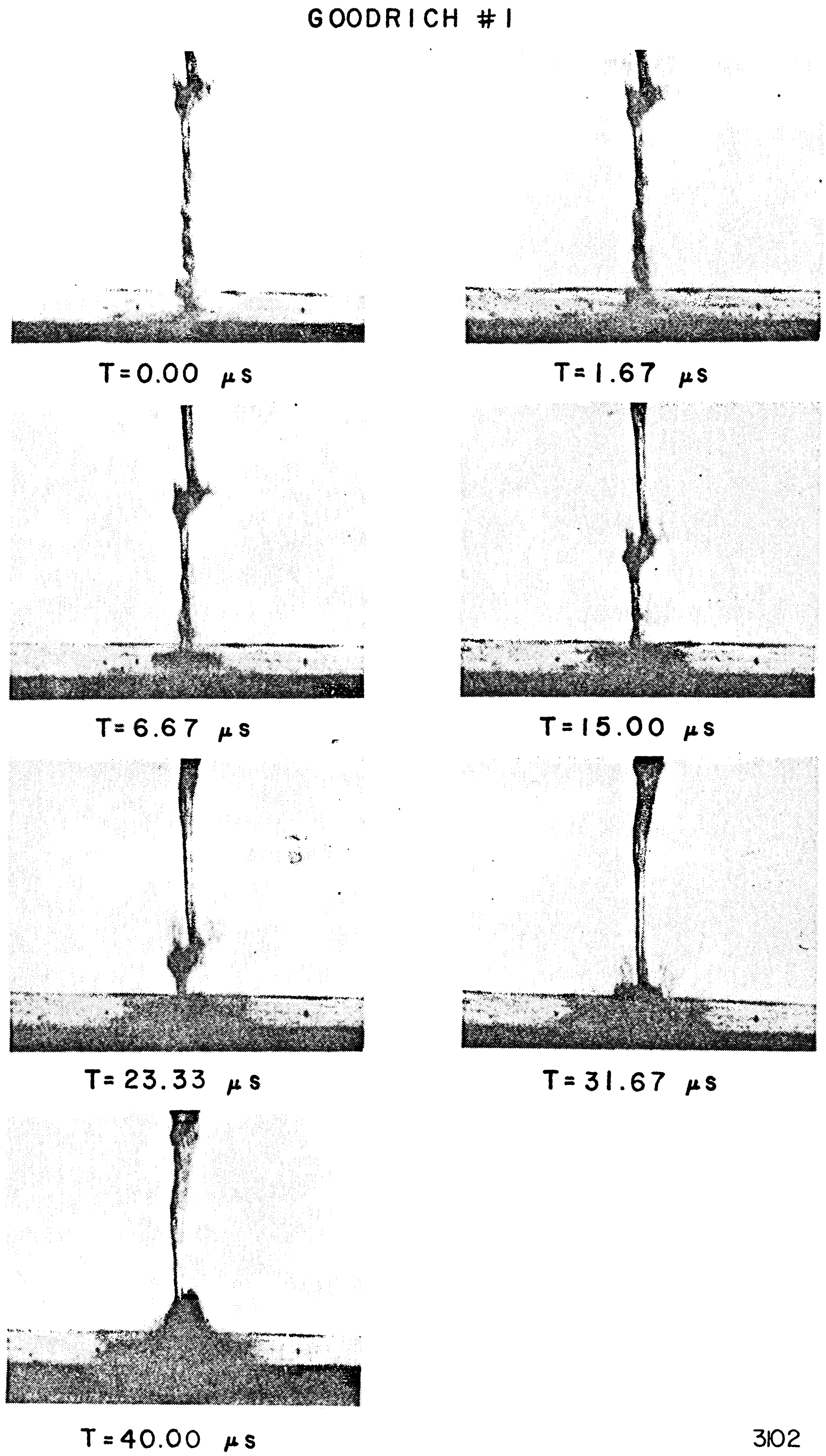


Figure 2. High-Speed Motion Picture Sequence of Jet Impact - Goodrich #1

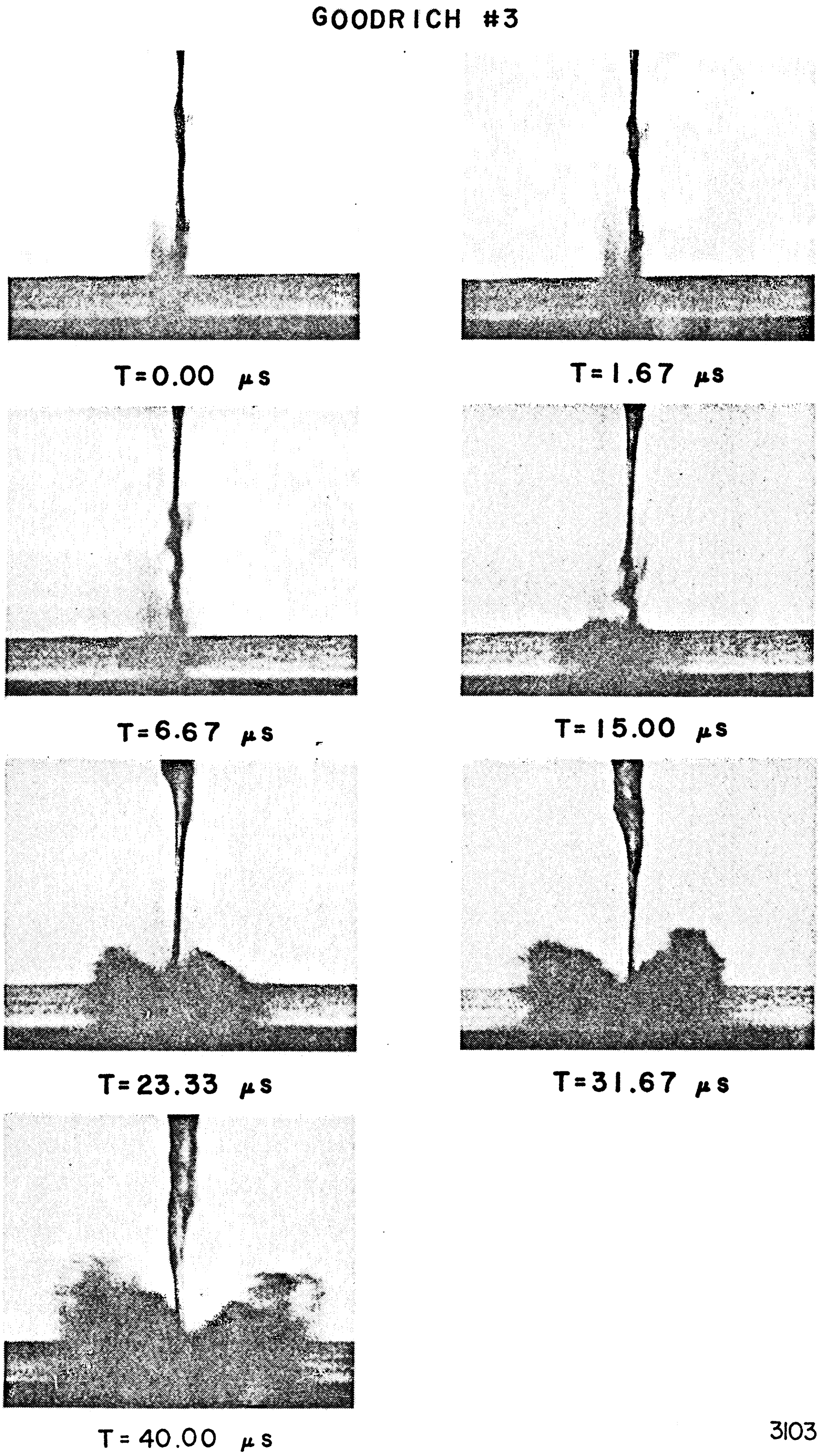


Figure 3. High-Speed Motion Picture Sequence of Jet Impact - Goodrich #3

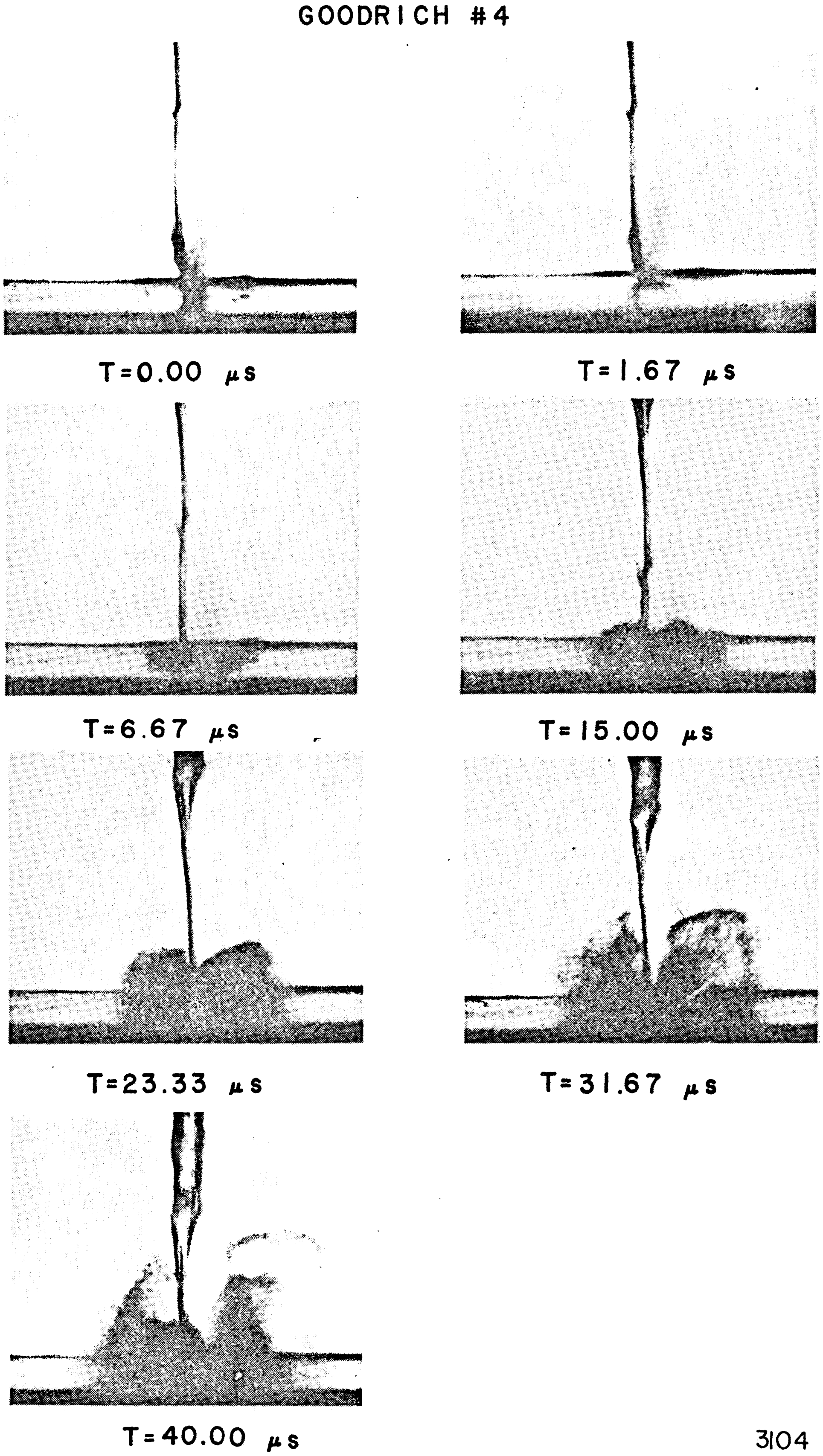


Figure 4. High-Speed Motion Picture Sequence of Jet Impact - Goodrich #4

GOODRICH #5

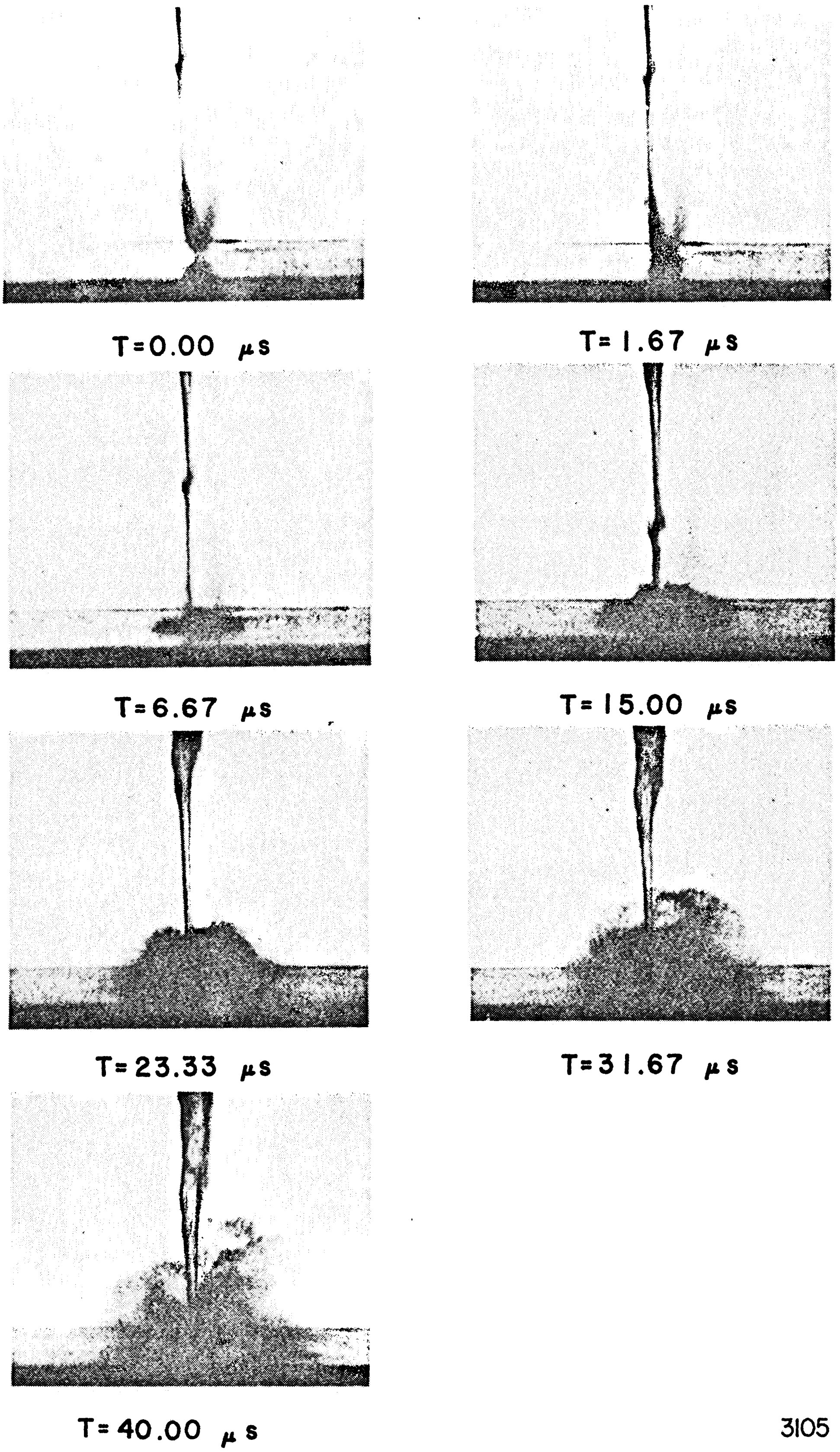


Figure 5. High-Speed Motion Picture Sequence of Jet Impact - Goodrich #5

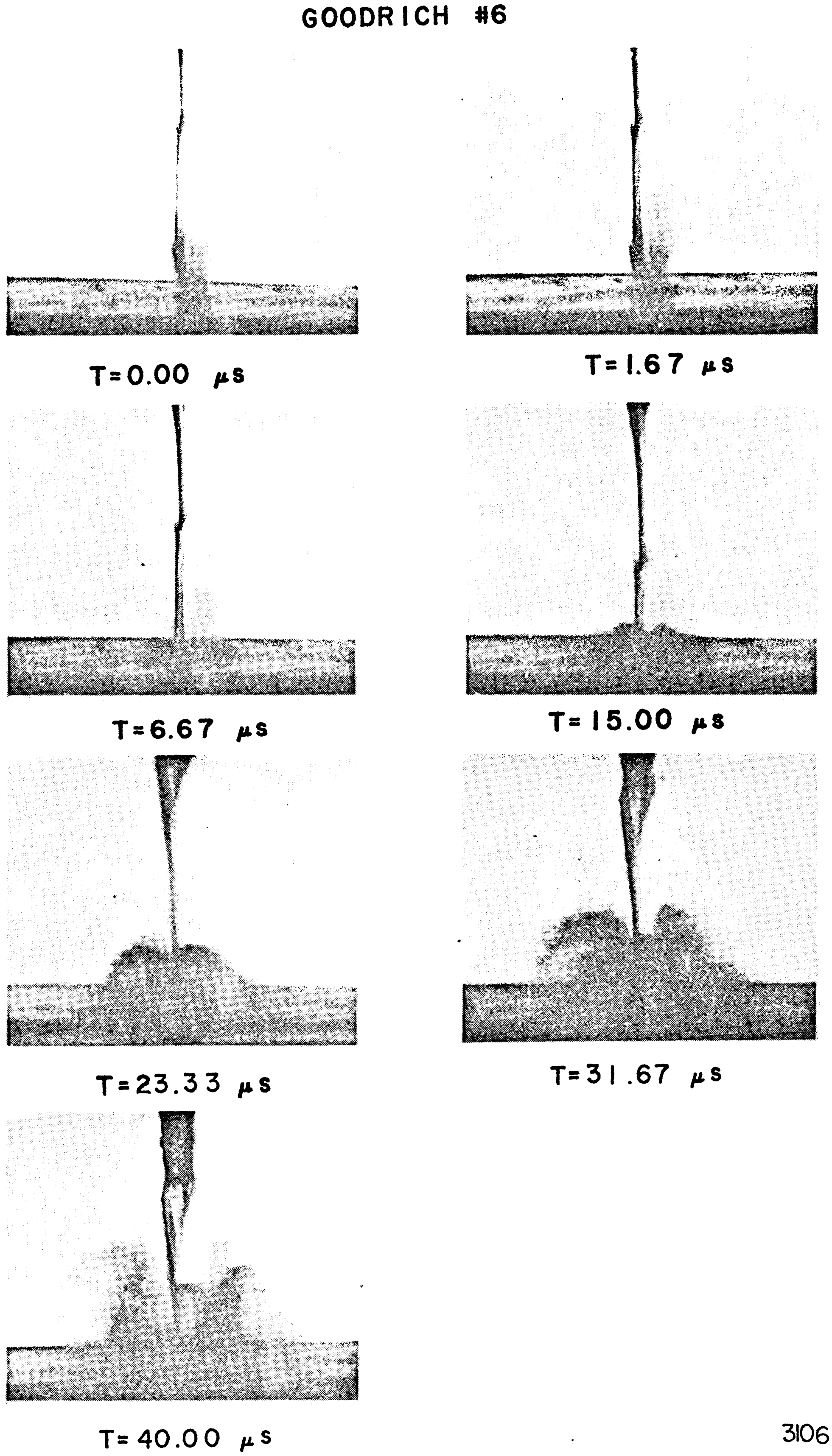
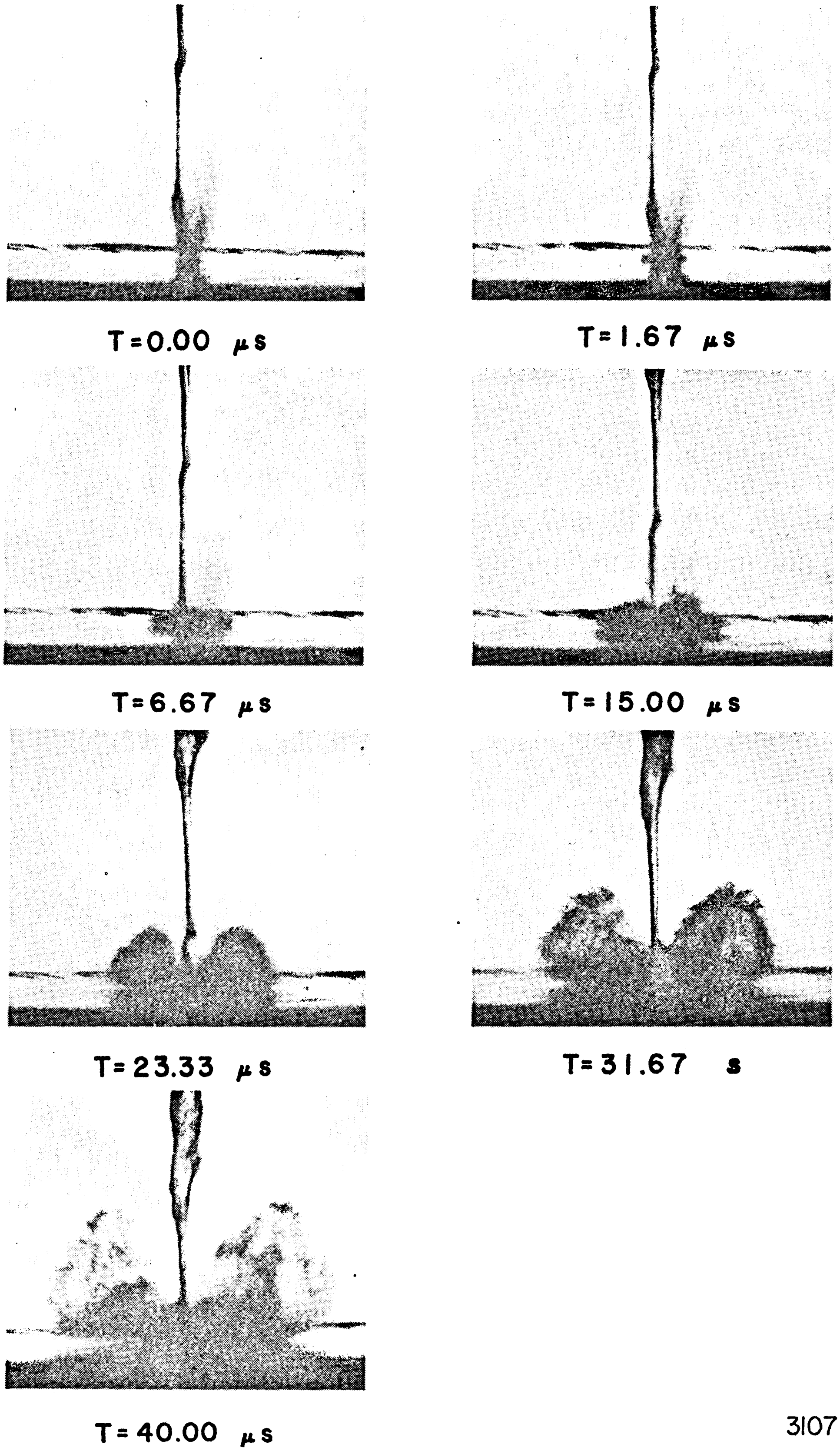


Figure 6. High-Speed Motion Picture Sequence of Jet Impact - Goodrich #6

GOODRICH #10



3107

Figure 7. High-Speed Motion Picture Sequence of Jet Impact - Goodrich #10

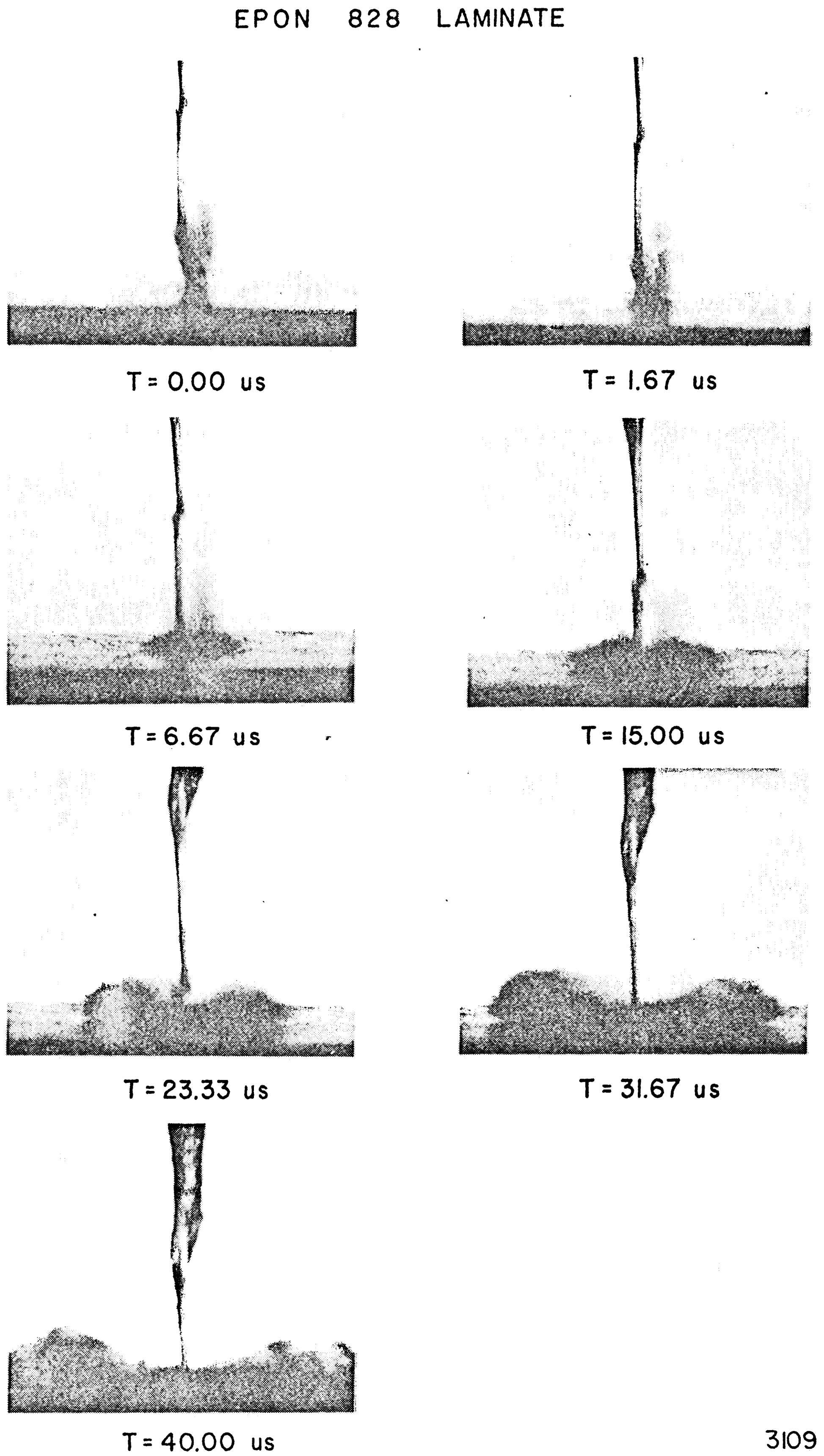


Figure 8. High-Speed Motion Picture Sequence of Jet Impact - Epon-828

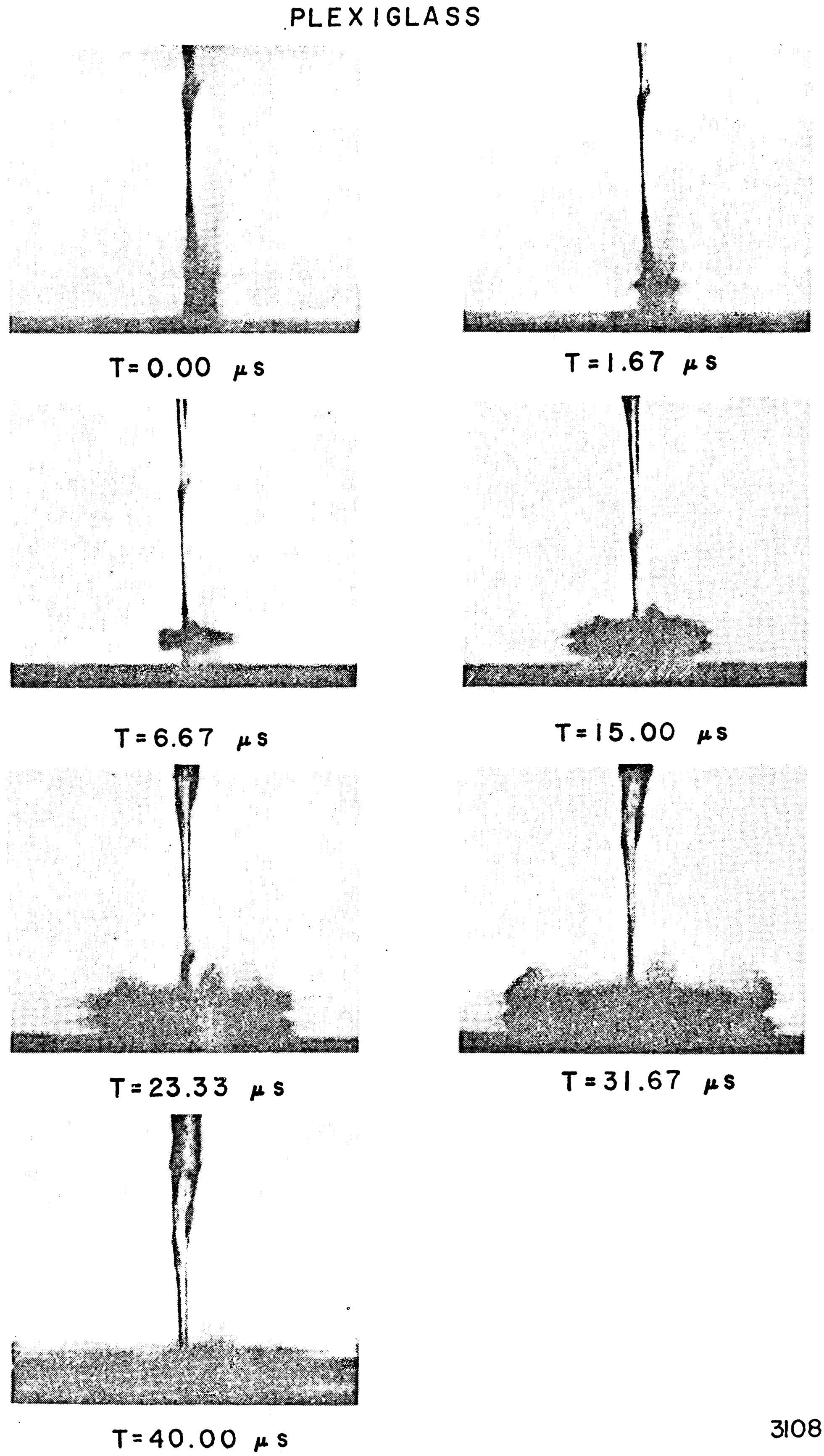


Figure 9. High-Speed Motion Picture Sequence of Jet Impact - Plexiglas

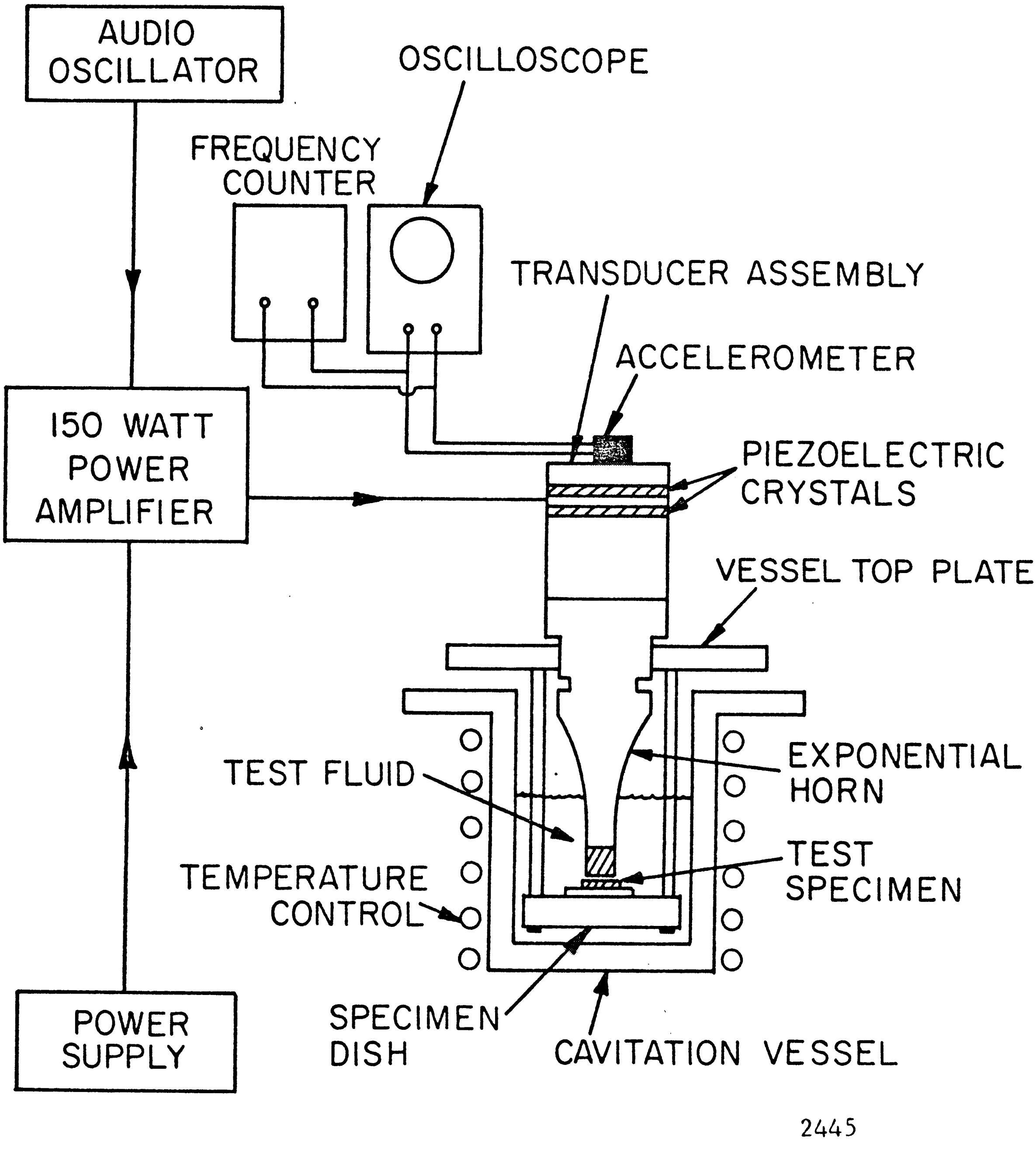


Figure 10. Schematic of Cavitation Stationary Specimen, Vibratory Set-Up

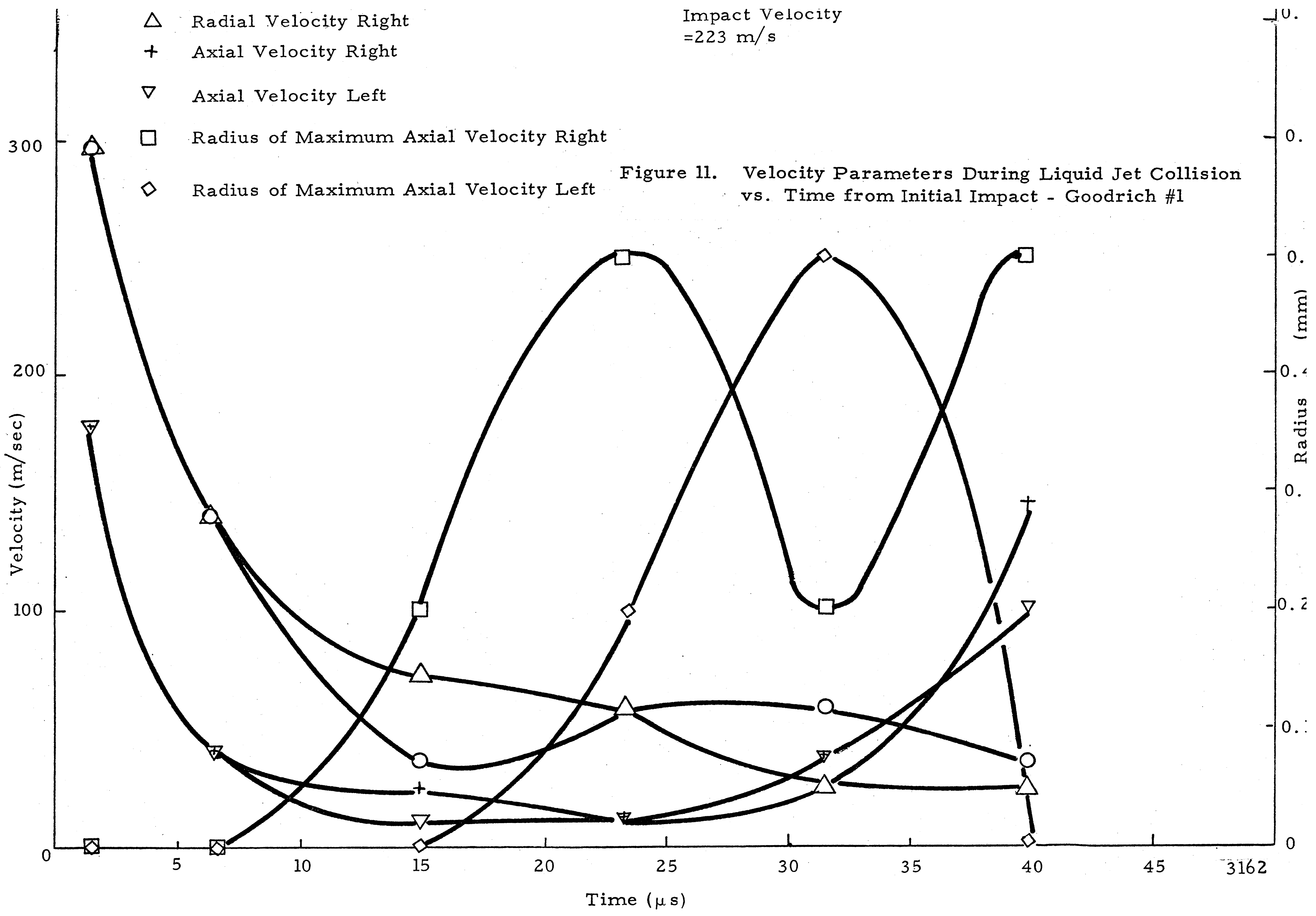


Figure 11. Velocity Parameters During Liquid Jet Collision vs. Time from Initial Impact - Goodrich #1

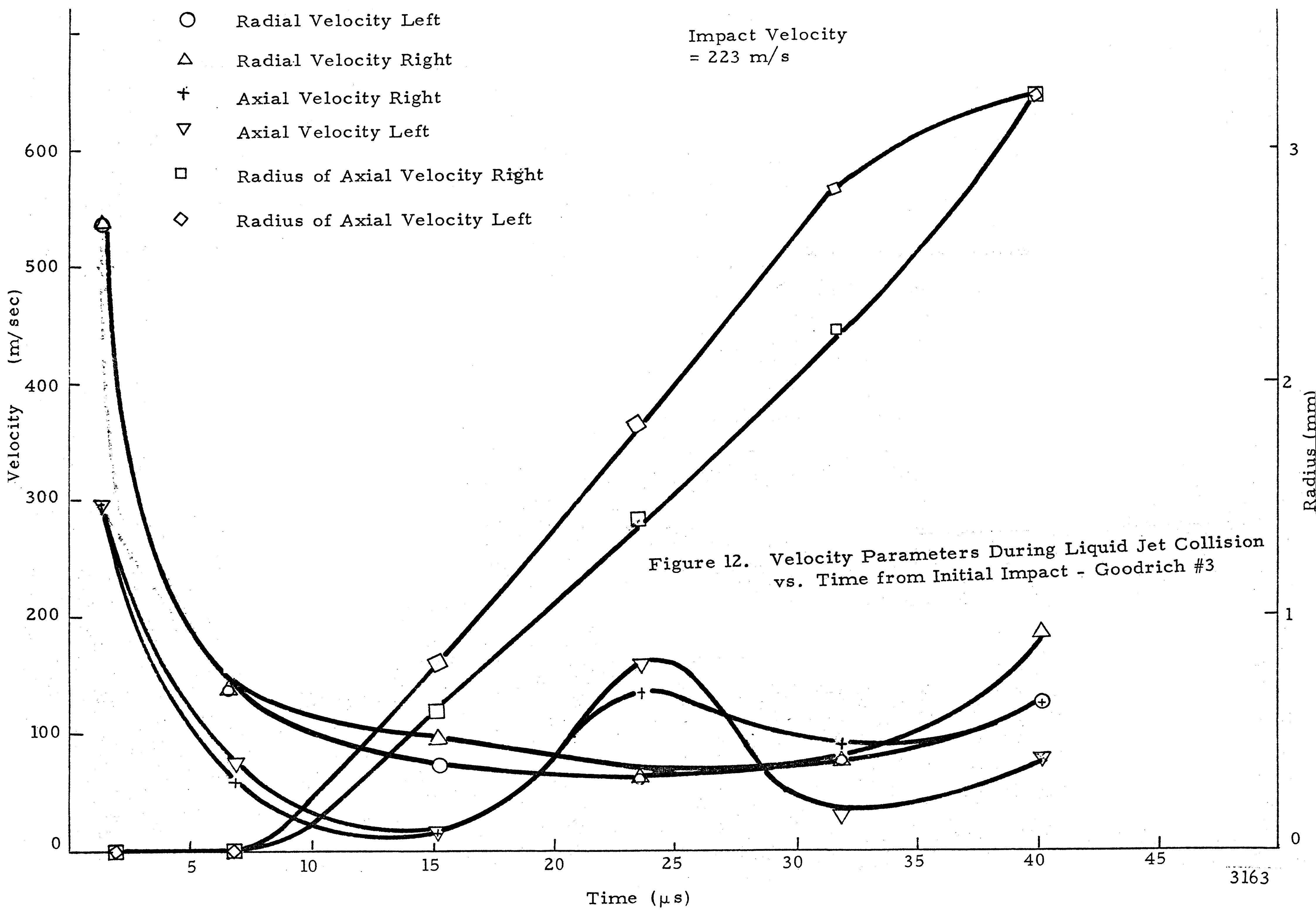


Figure 12. Velocity Parameters During Liquid Jet Collision vs. Time from Initial Impact - Goodrich #3

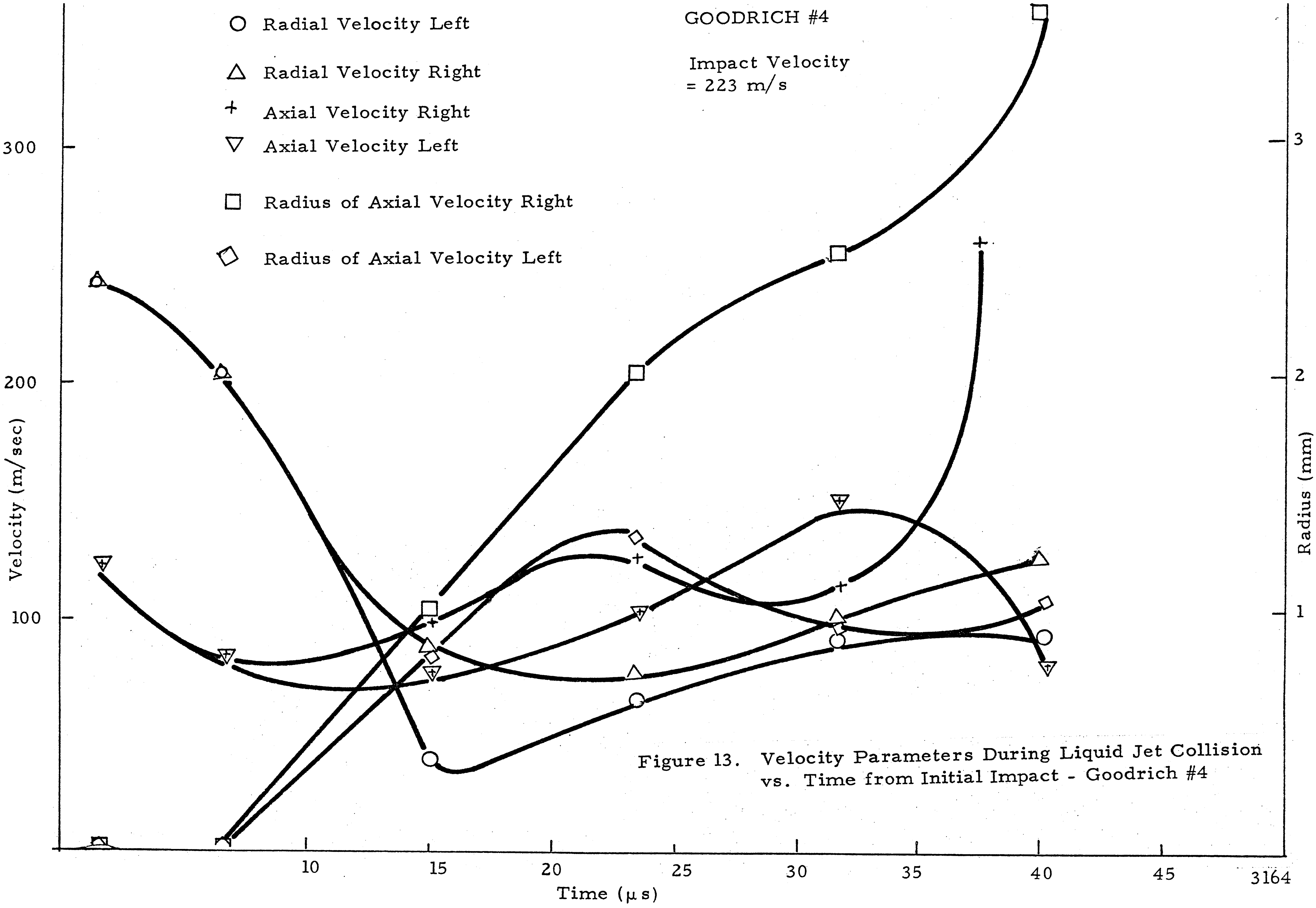


Figure 13. Velocity Parameters During Liquid Jet Collision vs. Time from Initial Impact - Goodrich #4

3164

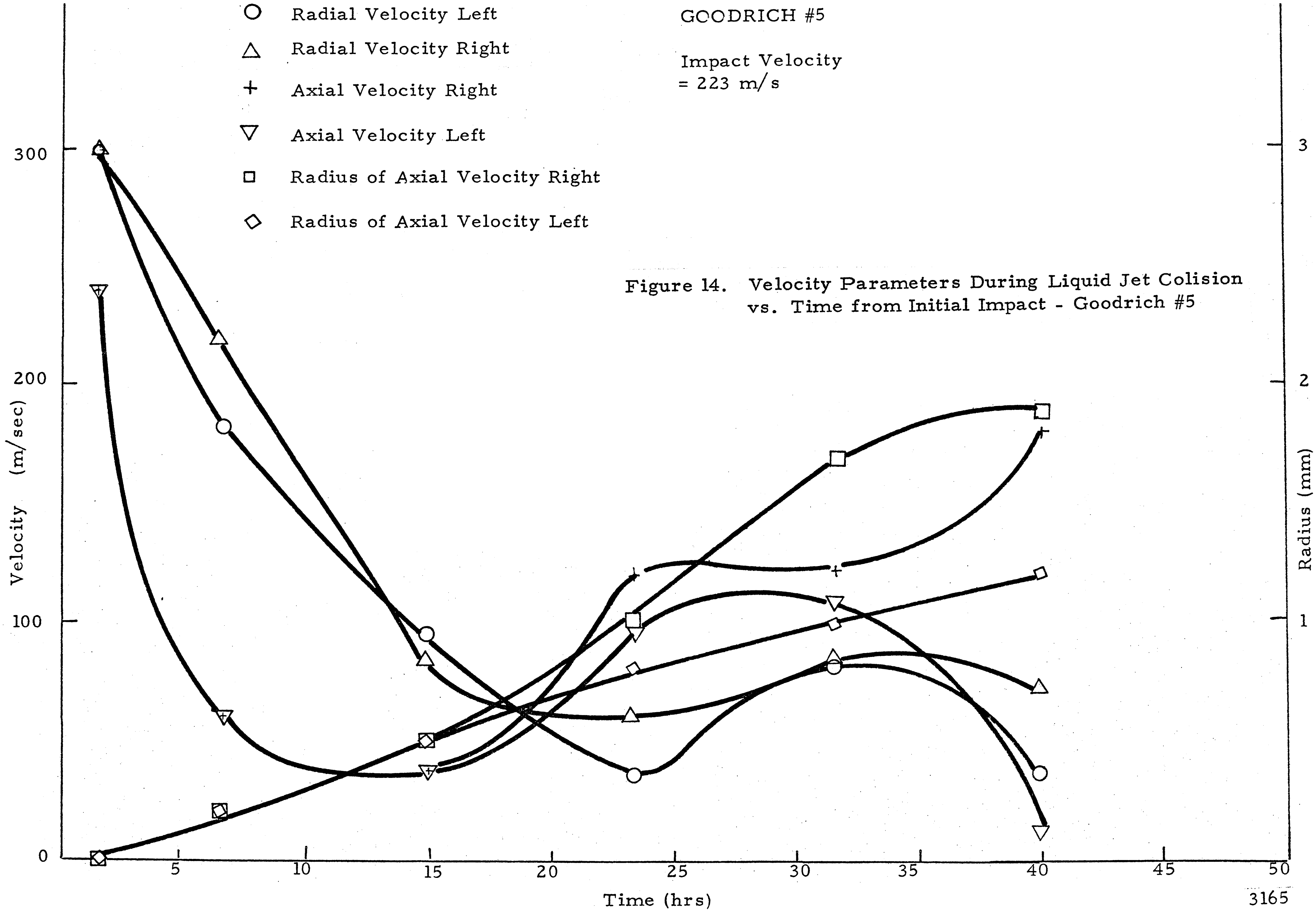


Figure 14. Velocity Parameters During Liquid Jet Colision vs. Time from Initial Impact - Goodrich #5

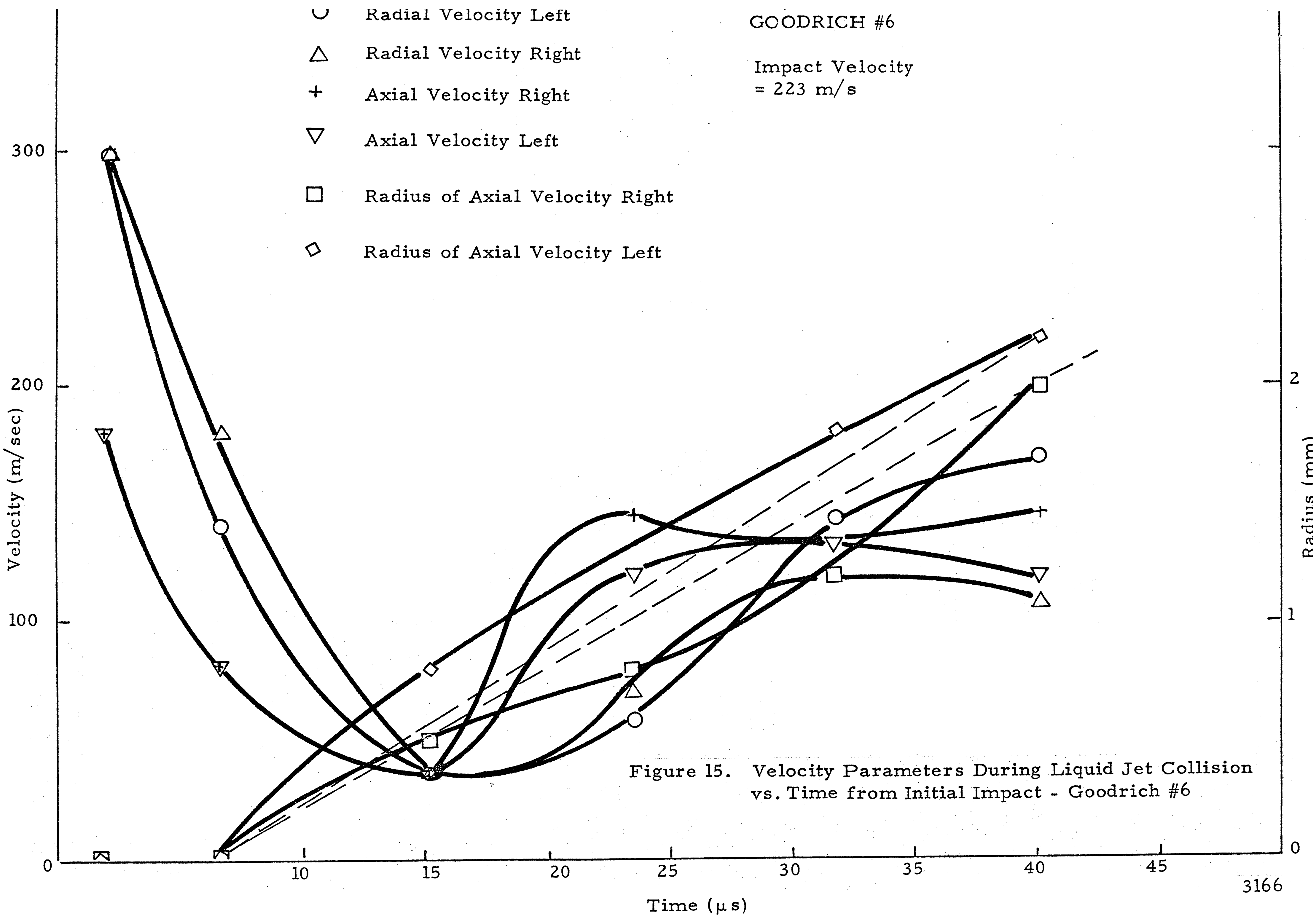


Figure 15. Velocity Parameters During Liquid Jet Collision vs. Time from Initial Impact - Goodrich #6

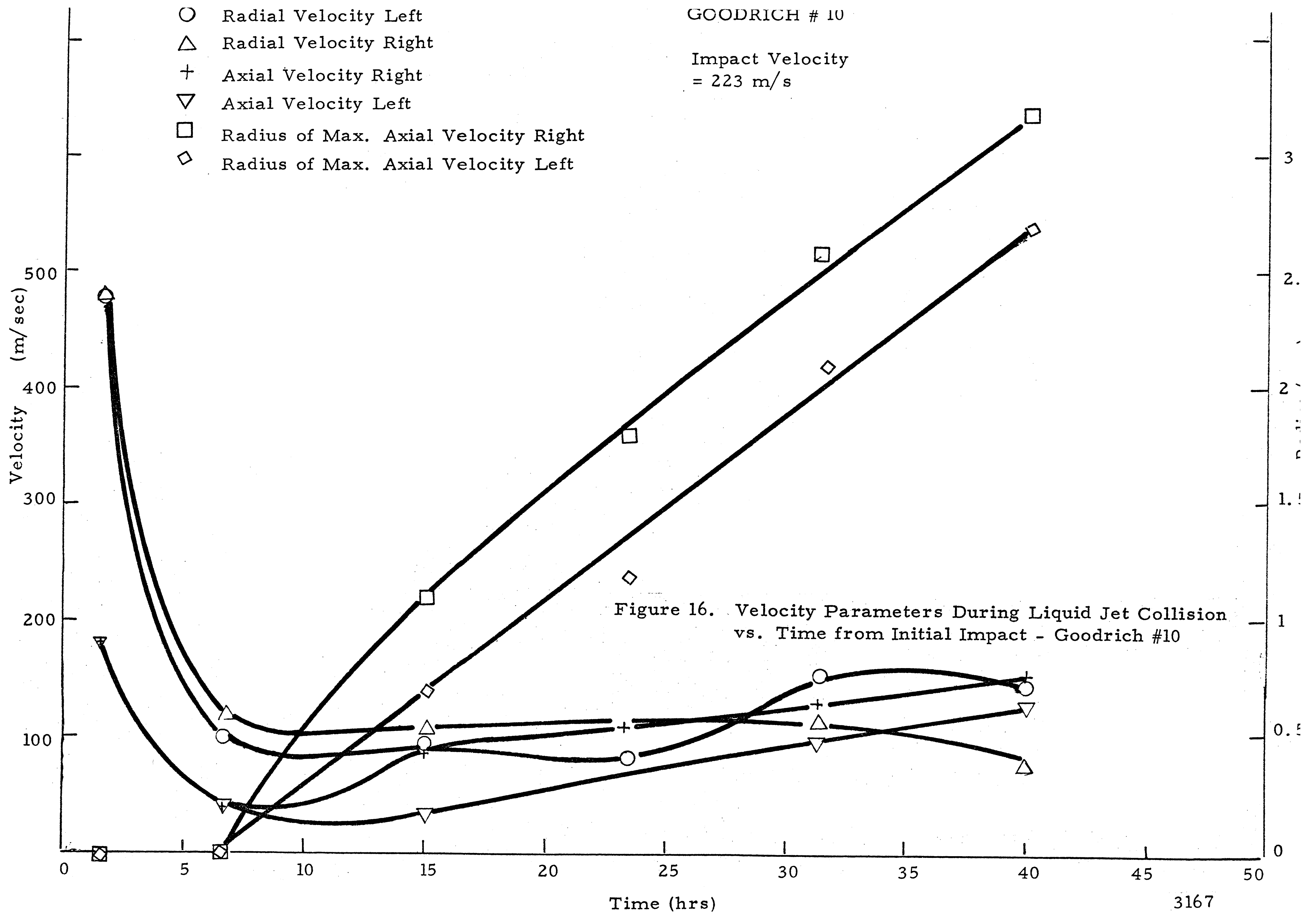


Figure 16. Velocity Parameters During Liquid Jet Collision vs. Time from Initial Impact - Goodrich #10

3167

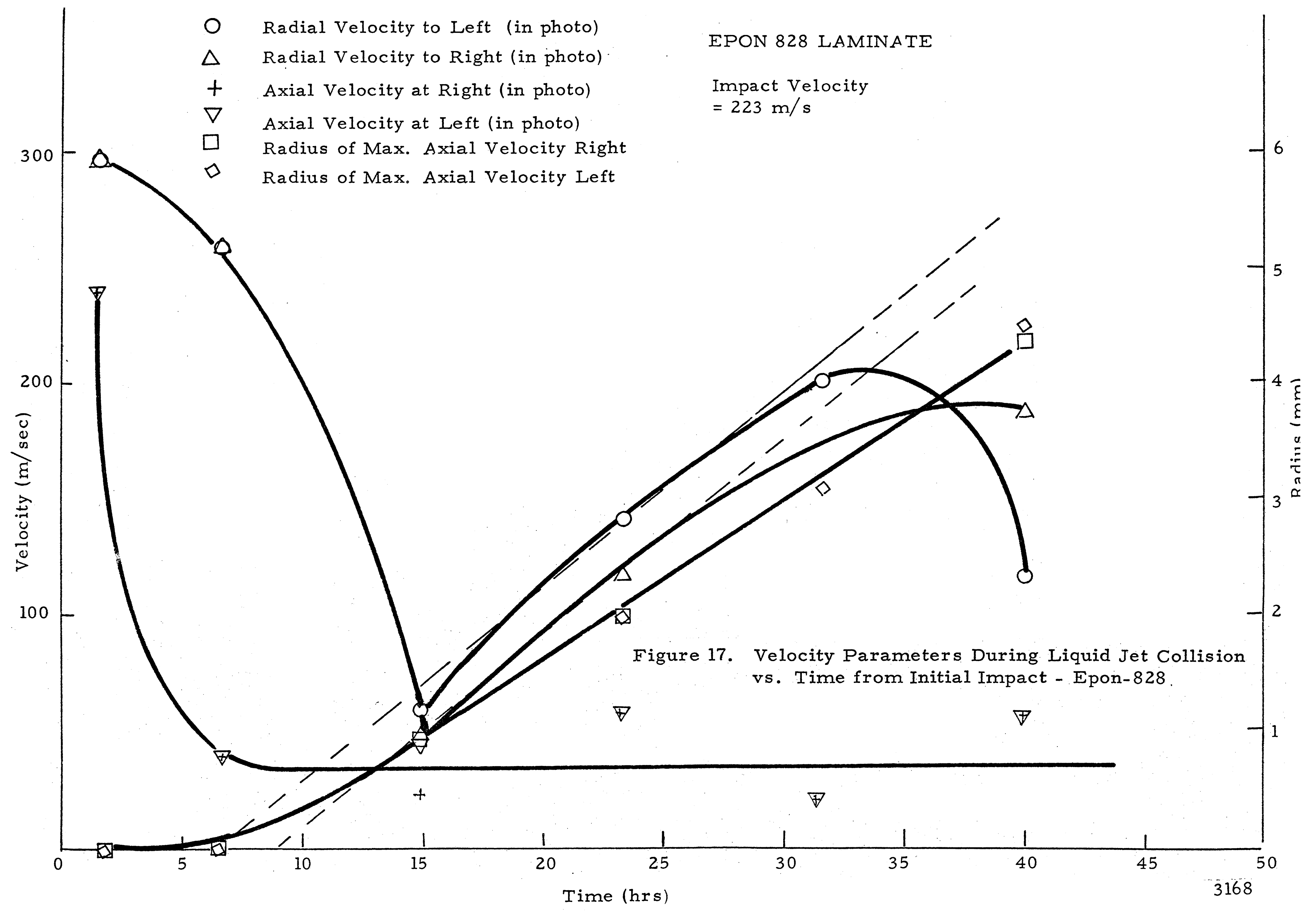


Figure 17. Velocity Parameters During Liquid Jet Collision vs. Time from Initial Impact - Epon-828

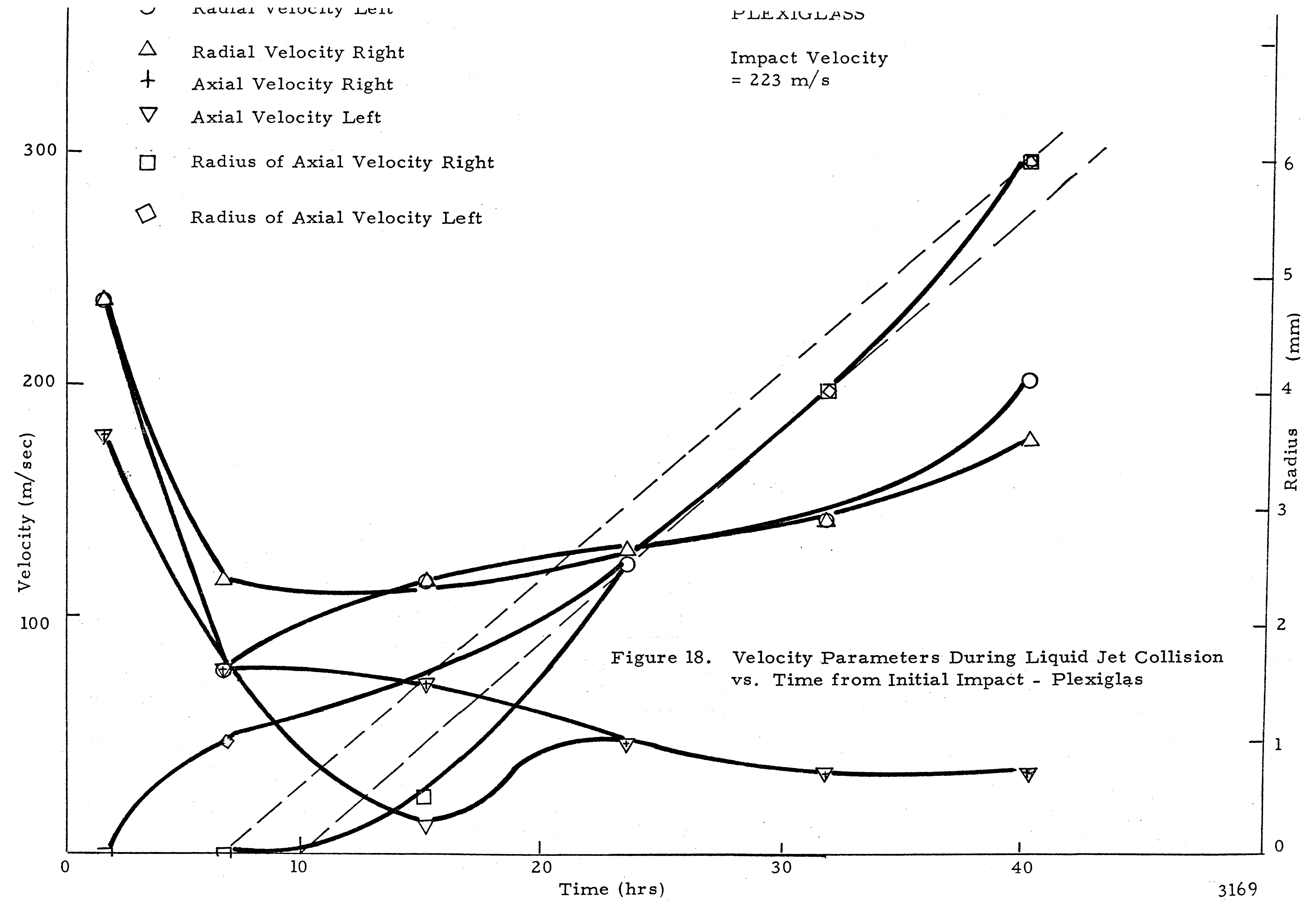


Figure 18. Velocity Parameters During Liquid Jet Collision vs. Time from Initial Impact - Plexiglas

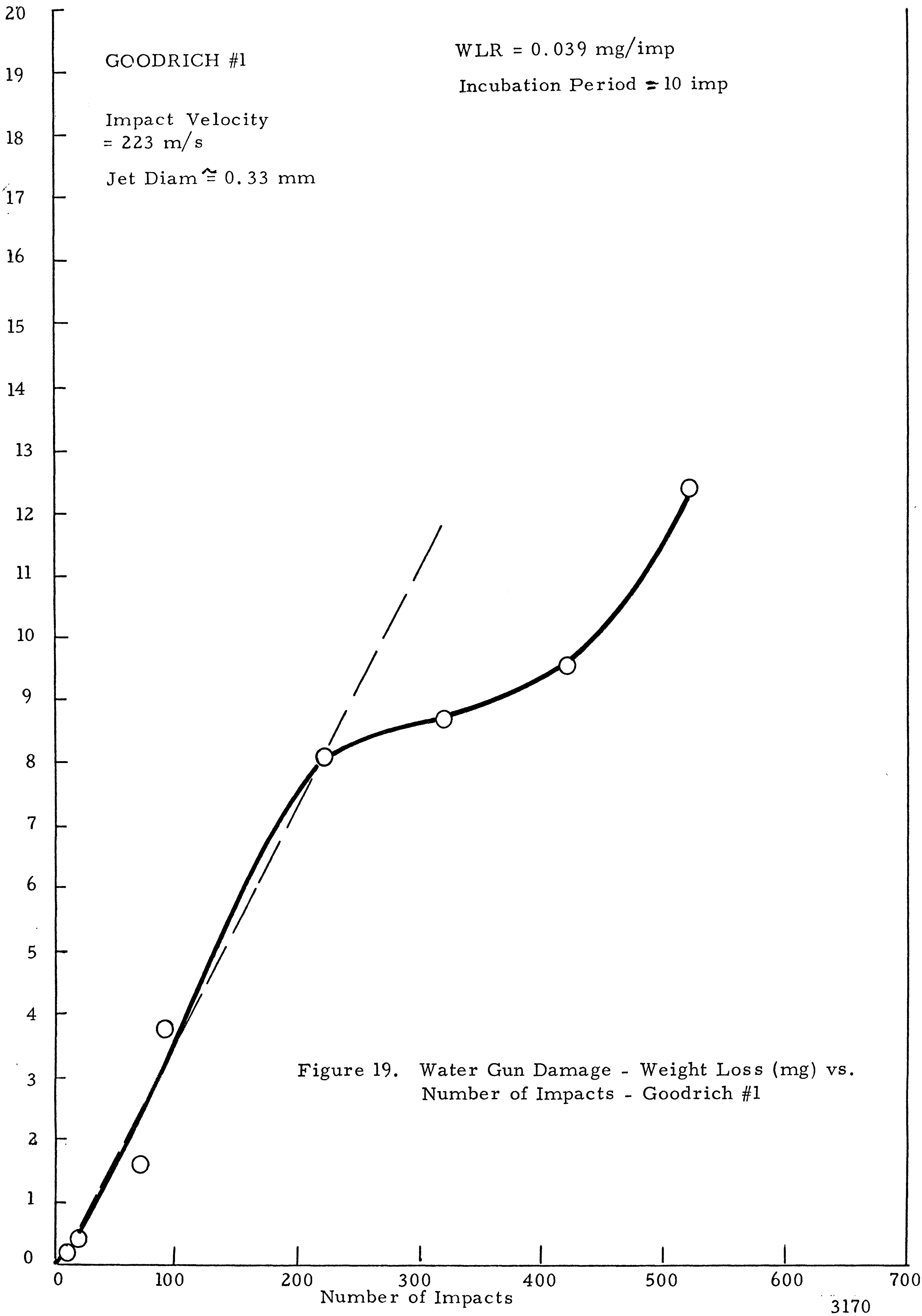


Figure 19. Water Gun Damage - Weight Loss (mg) vs. Number of Impacts - Goodrich #1

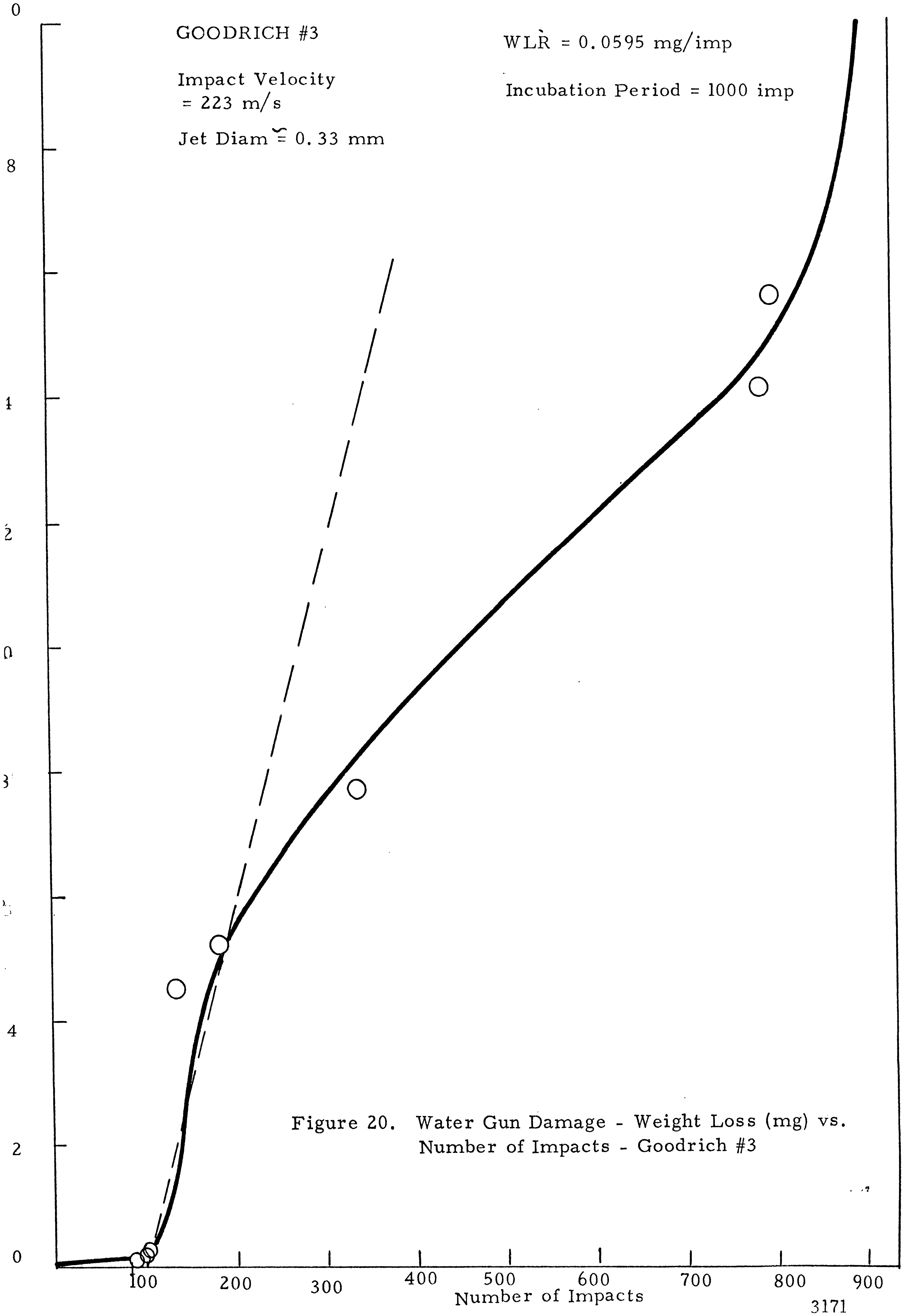


Figure 20. Water Gun Damage - Weight Loss (mg) vs. Number of Impacts - Goodrich #3

3171

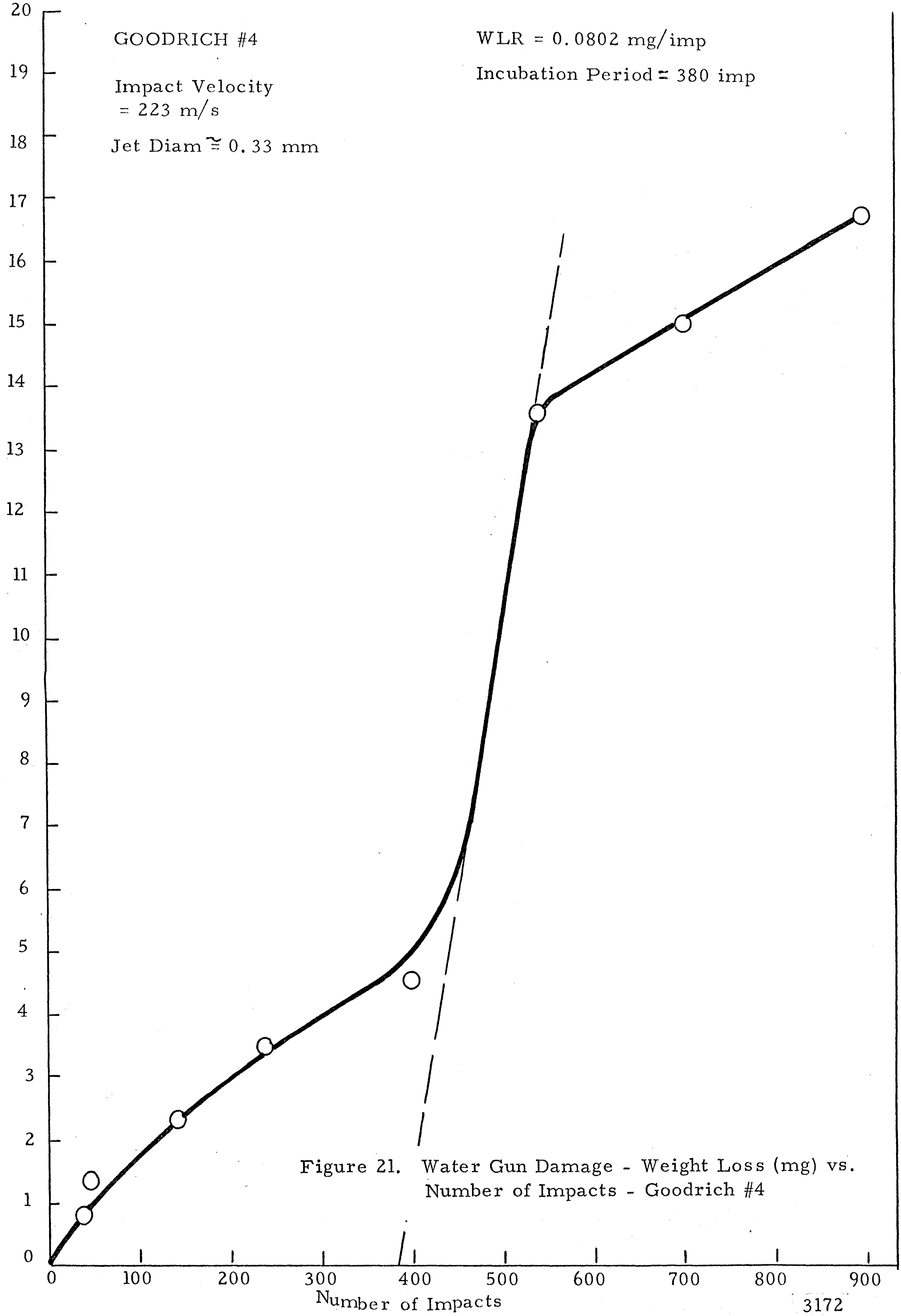


Figure 21. Water Gun Damage - Weight Loss (mg) vs. Number of Impacts - Goodrich #4

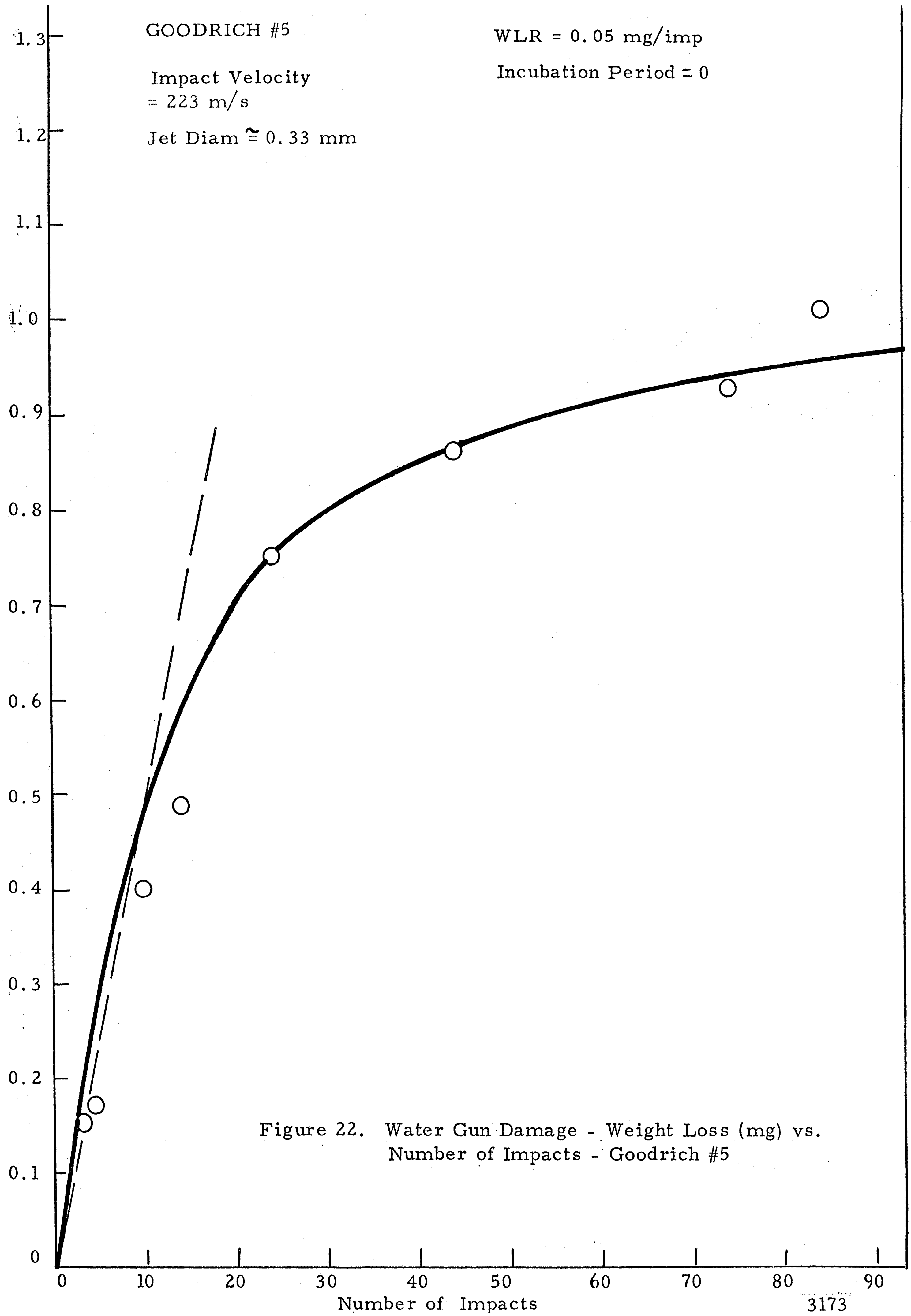


Figure 22. Water Gun Damage - Weight Loss (mg) vs. Number of Impacts - Goodrich #5

3173

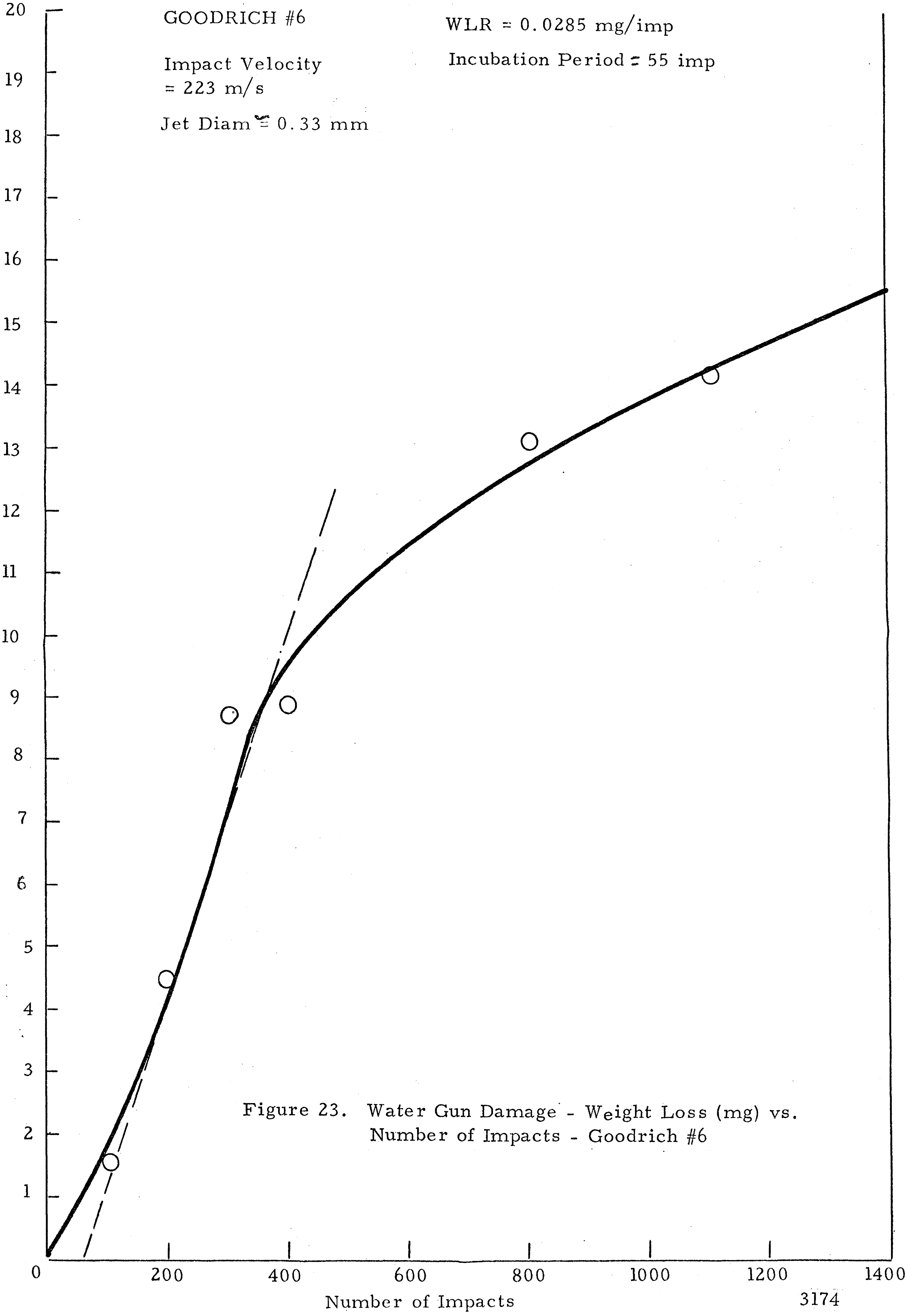


Figure 23. Water Gun Damage - Weight Loss (mg) vs. Number of Impacts - Goodrich #6

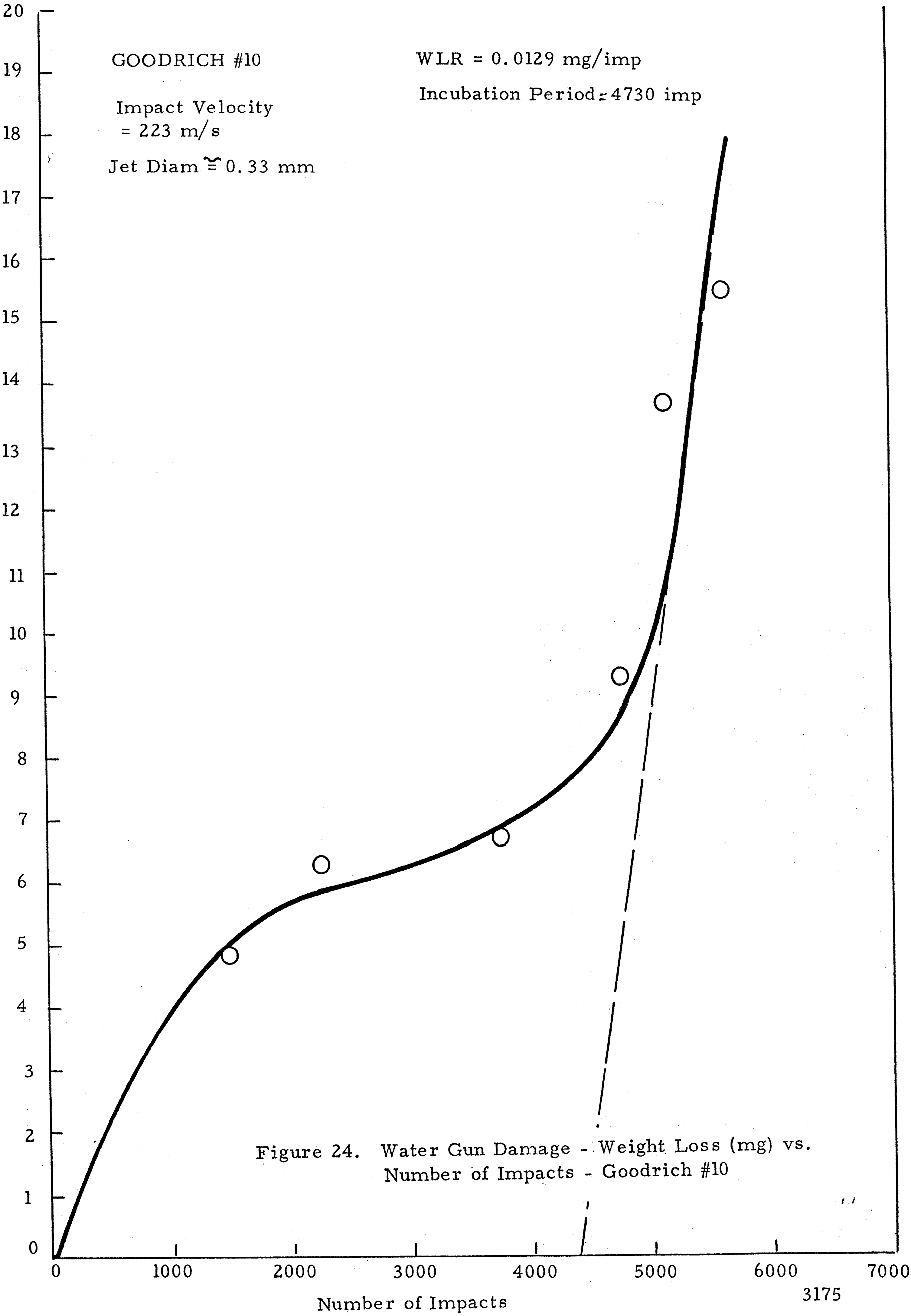


Figure 24. Water Gun Damage - Weight Loss (mg) vs. Number of Impacts - Goodrich #10

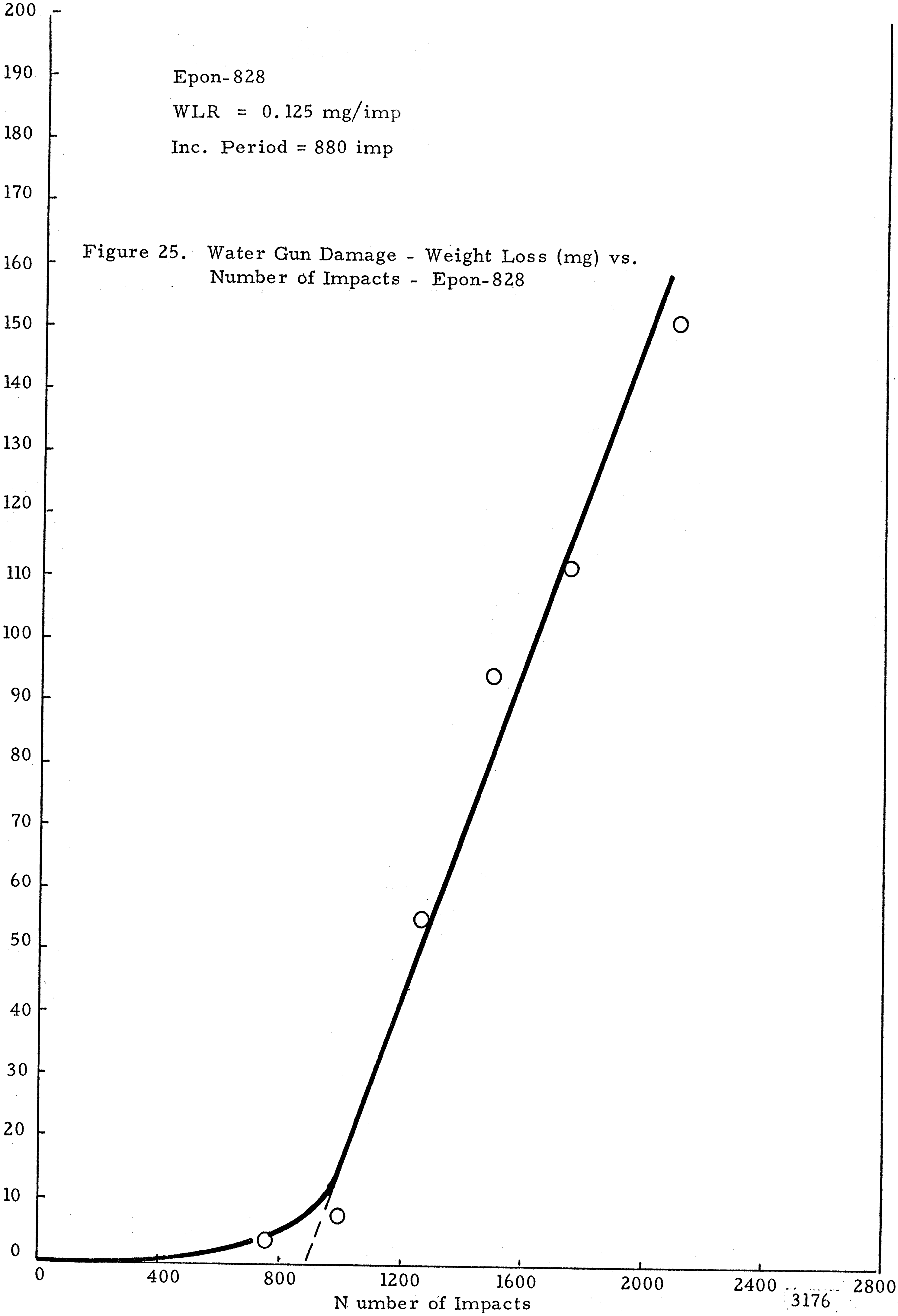


Figure 25. Water Gun Damage - Weight Loss (mg) vs. Number of Impacts - Epon-828

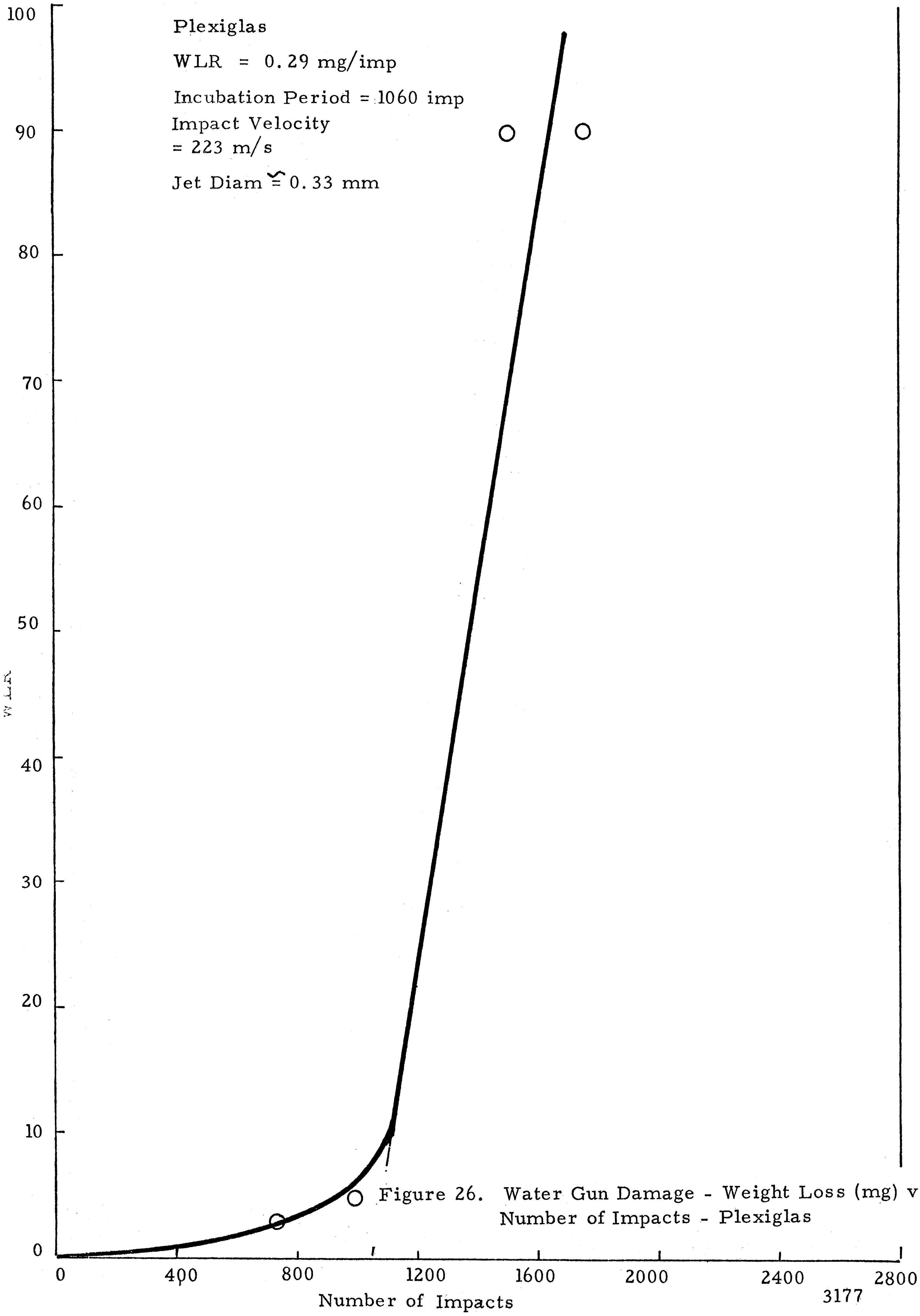


Figure 26. Water Gun Damage - Weight Loss (mg) vs. Number of Impacts - Plexiglas

3177

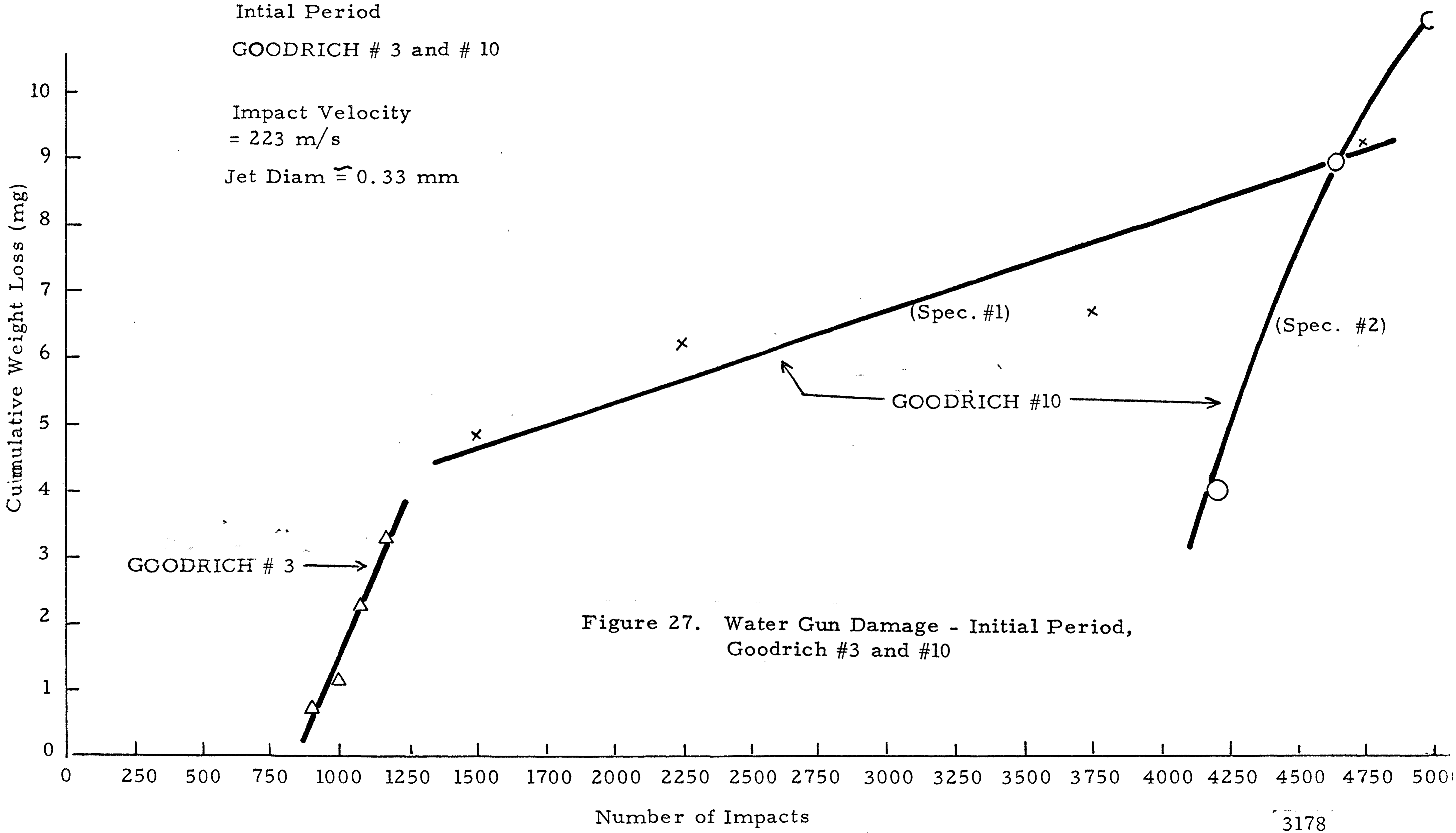


Figure 27. Water Gun Damage - Initial Period, Goodrich #3 and #10

3178

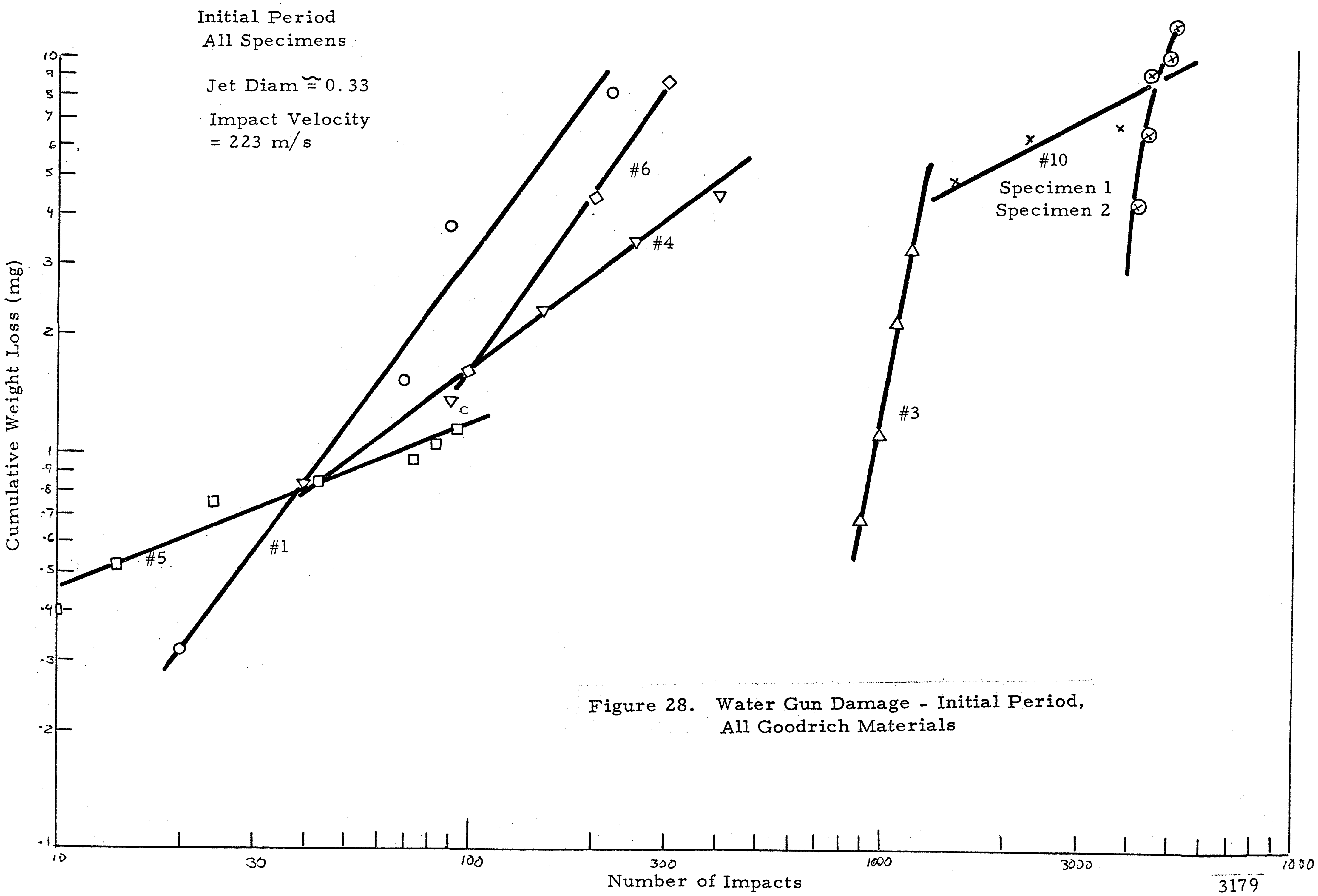


Figure 28. Water Gun Damage - Initial Period, All Goodrich Materials

3179

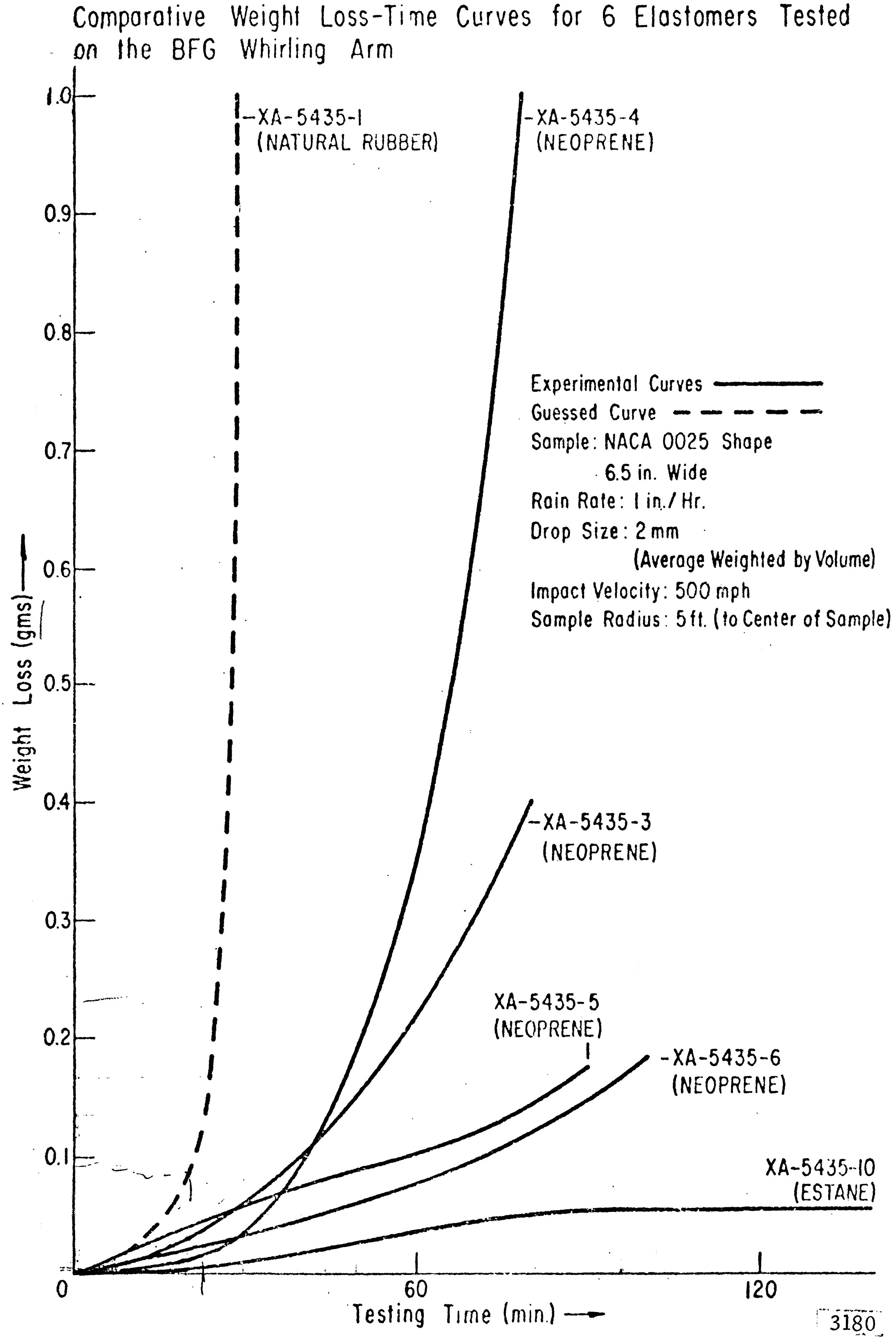
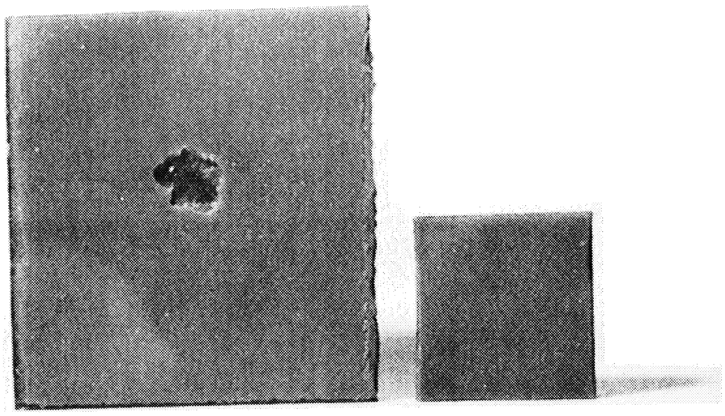


Figure 29. Goodrich Propellor Arm Weight Loss (500 MPH)

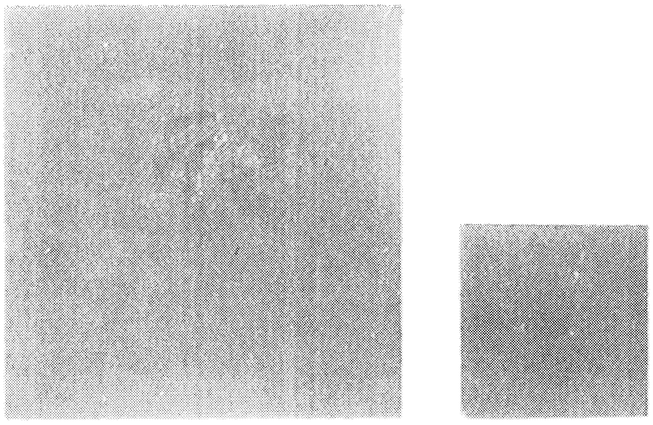


(a)

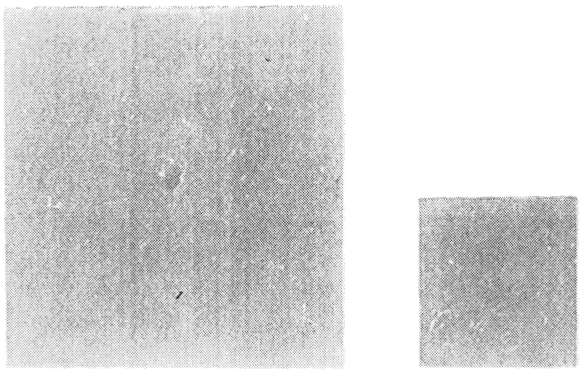
(b)

3181

Figure 30. Damaged Specimen Photos, Impact to Left, Cavitation to Right - a) Goodrich #1, b) Goodrich #3



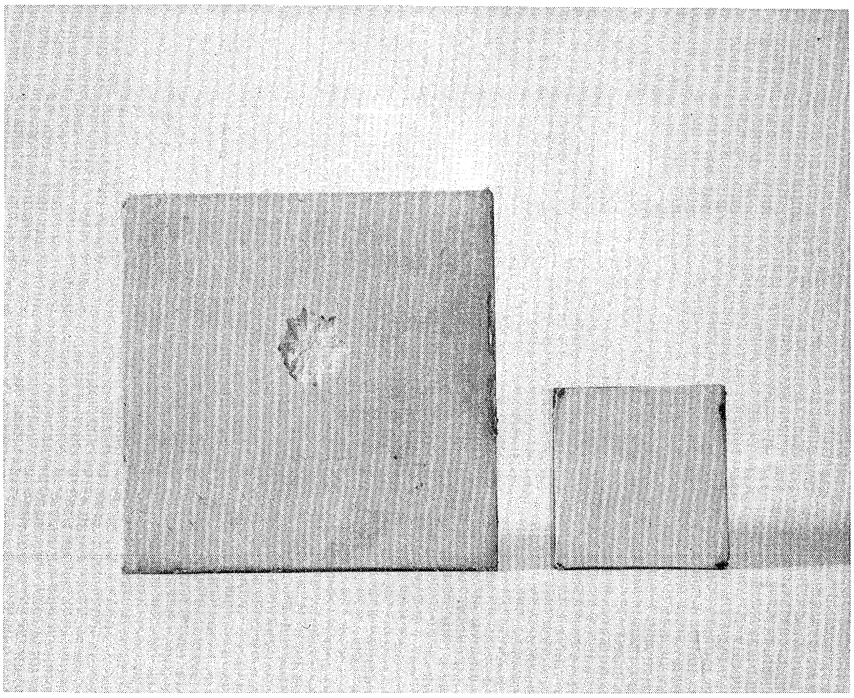
(a)



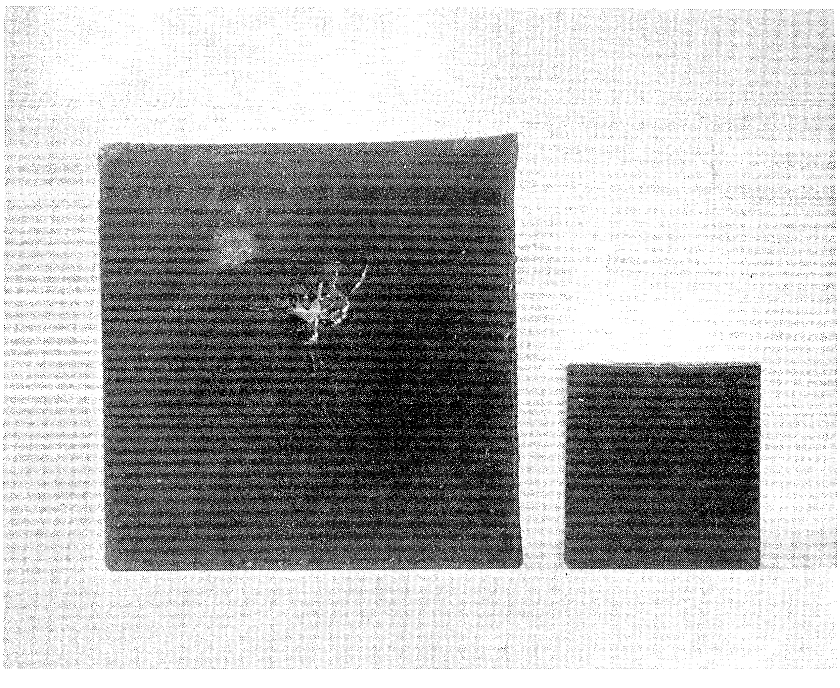
(b)

3182

Figure 31. Damaged Specimen Photos, Impact to Left, Cavitation to Right - a) Goodrich #4, b) Goodrich #5

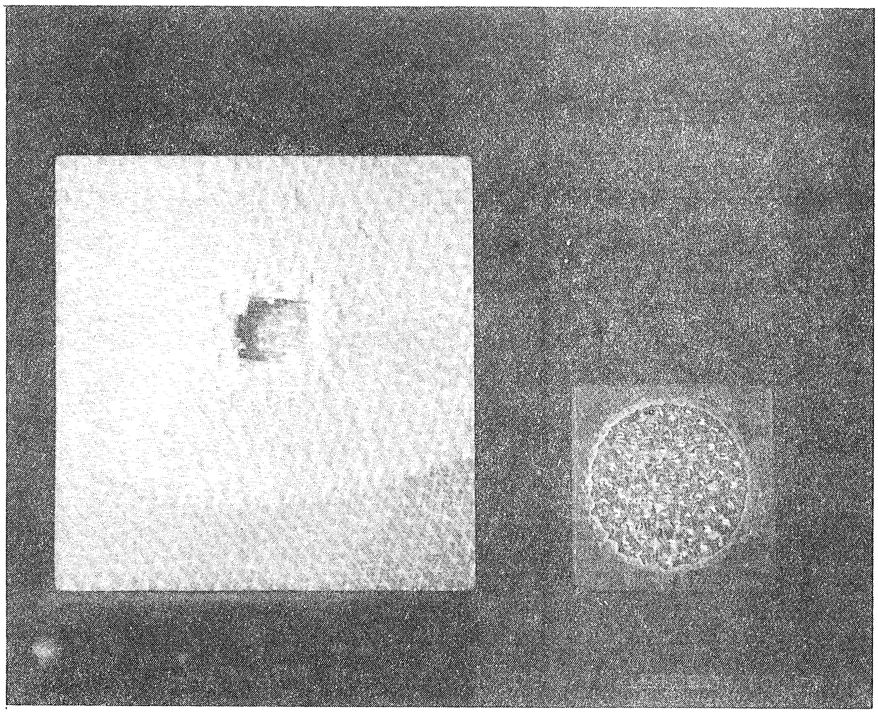


(a)

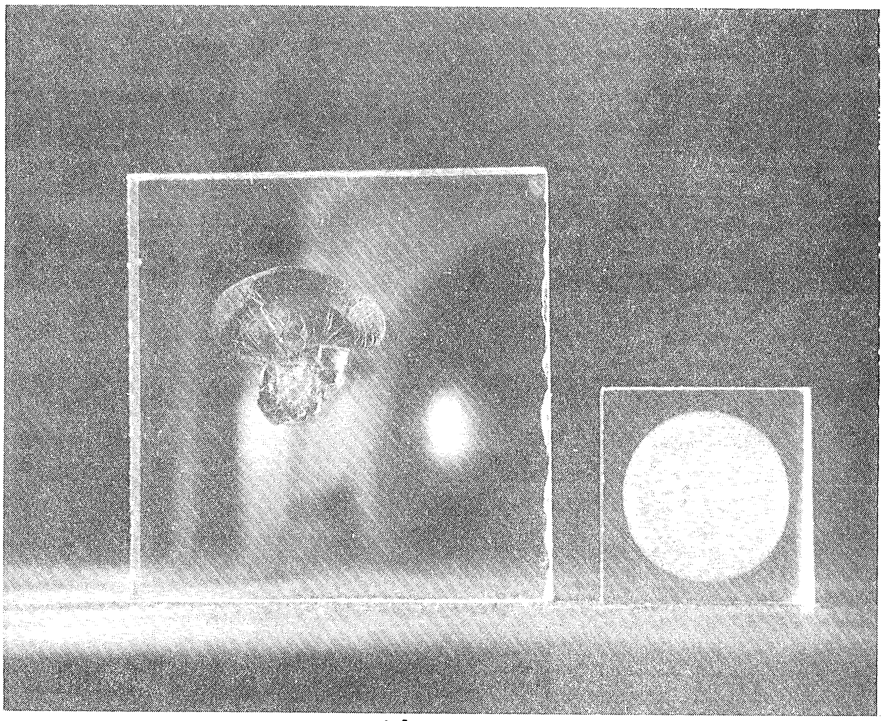


(b) 3183

Figure 32. Damaged Specimen Photos, Impact to Left, Cavitation to Right - a) Goodrich #6, b) Goodrich #10



(a)



(b)

3184

Figure 33. Damaged Specimen Photos, Impact to Left. Cavitation to Right - a) Epon-828, b) Plexiglas

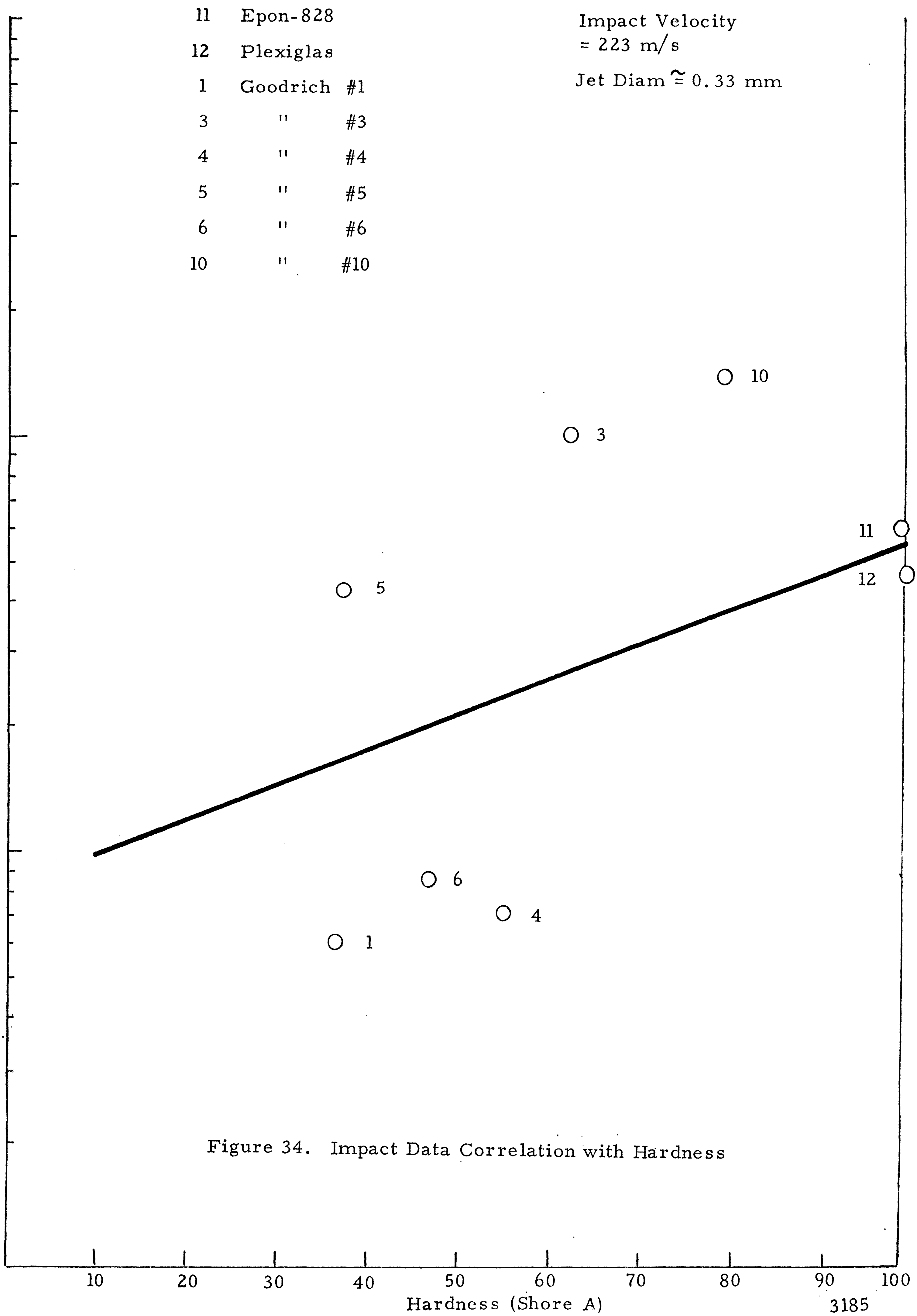


Figure 34. Impact Data Correlation with Hardness

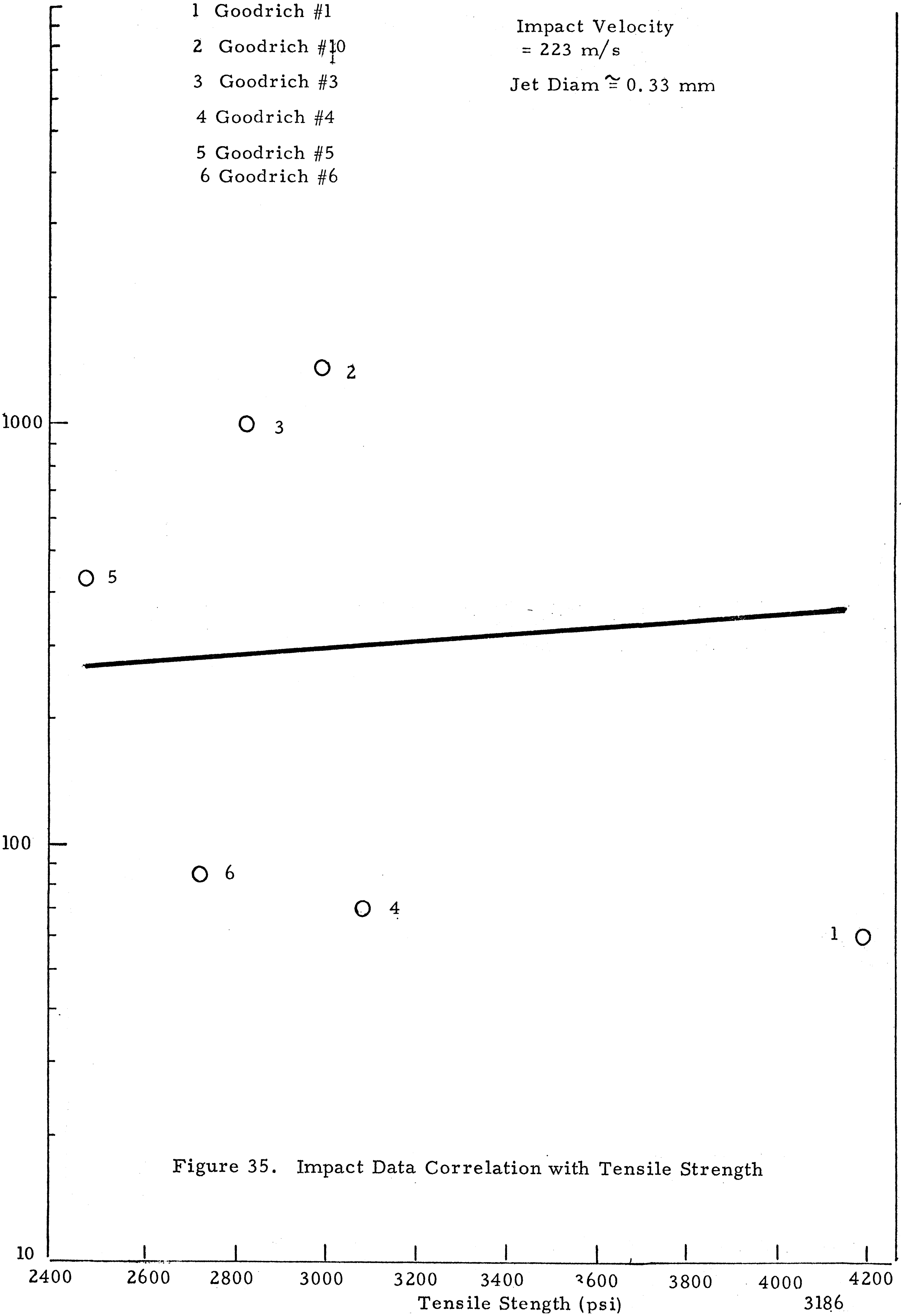


Figure 35. Impact Data Correlation with Tensile Strength

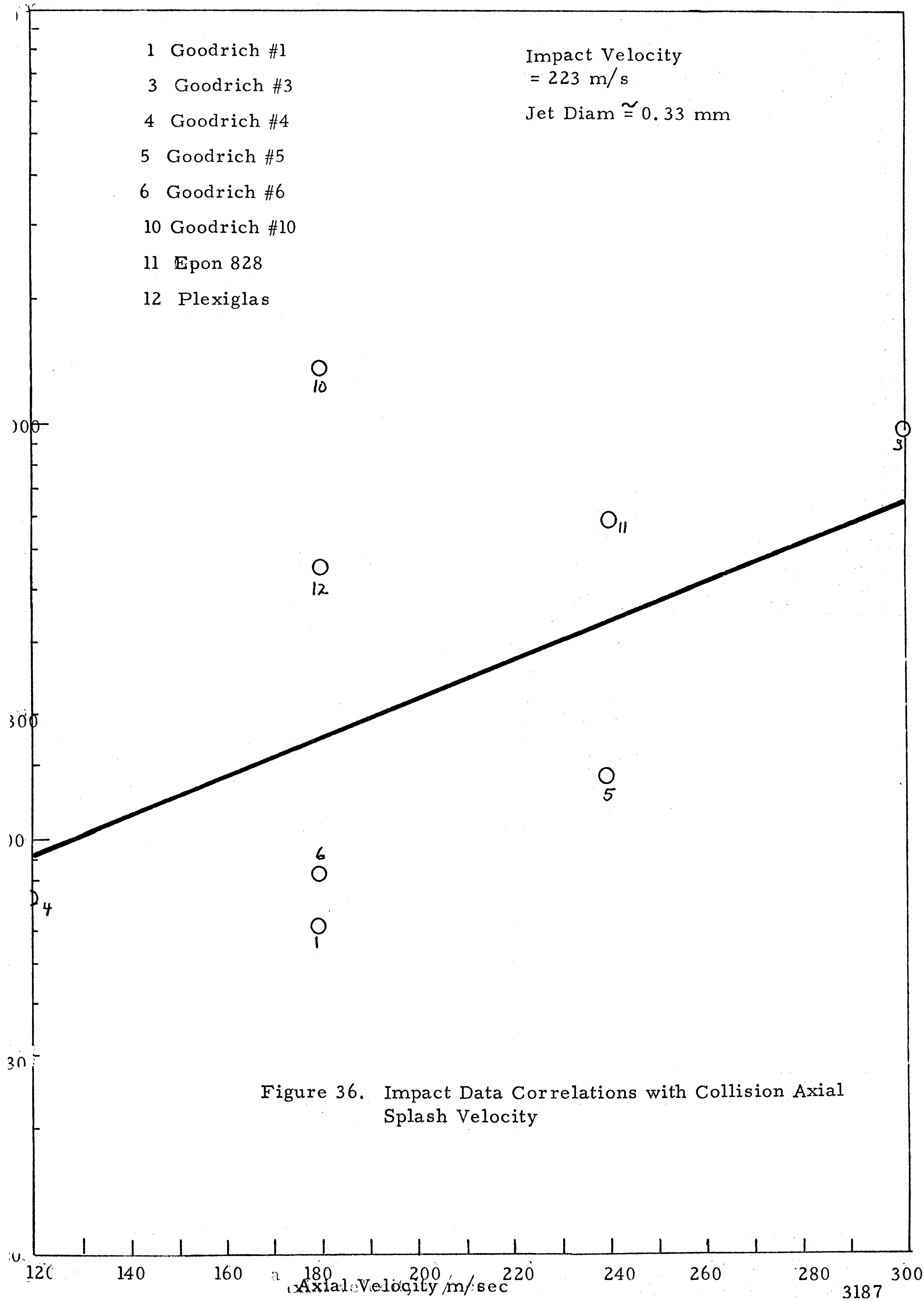


Figure 36. Impact Data Correlations with Collision Axial Splash Velocity

c

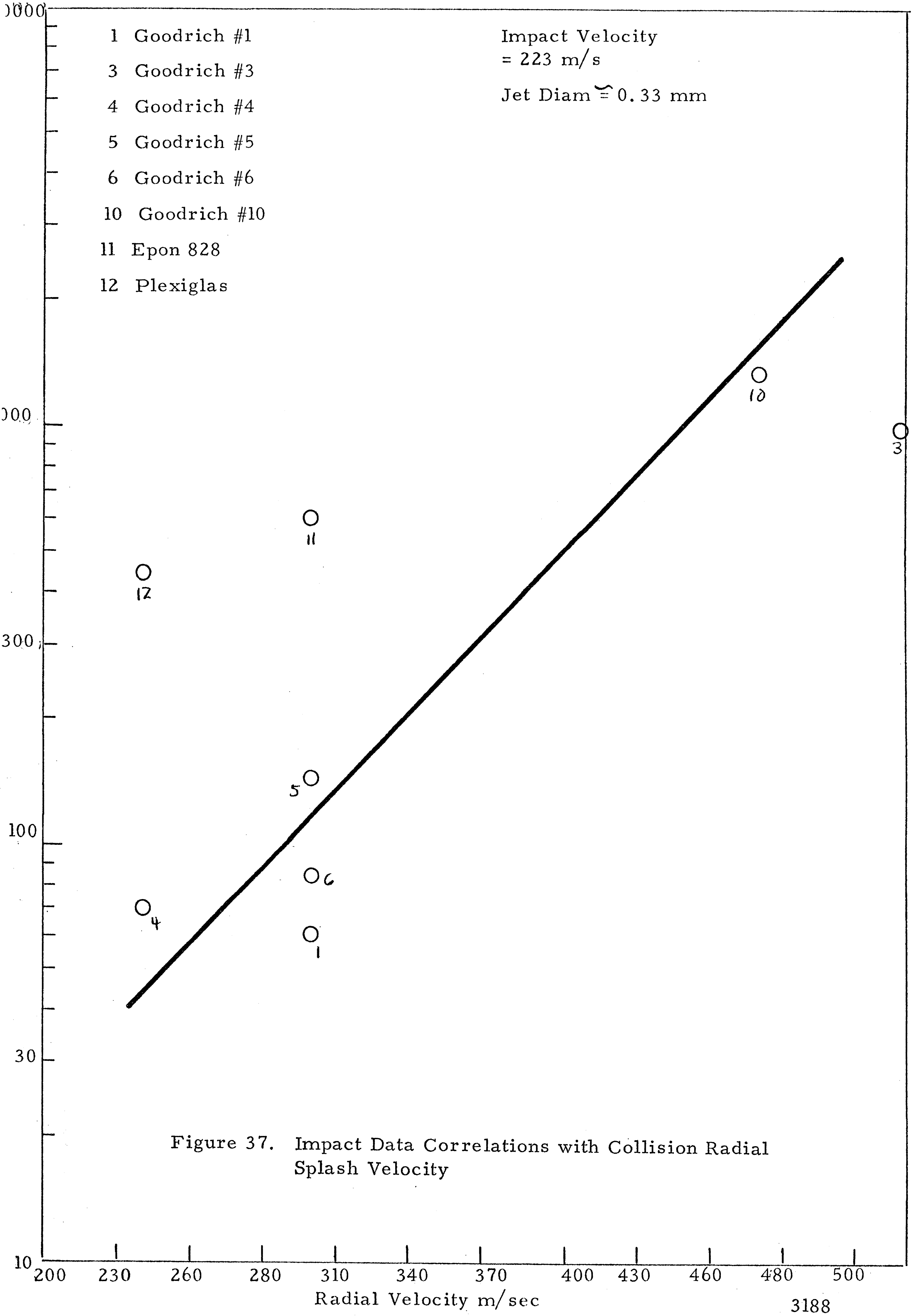


Figure 37. Impact Data Correlations with Collision Radial Splash Velocity

3188

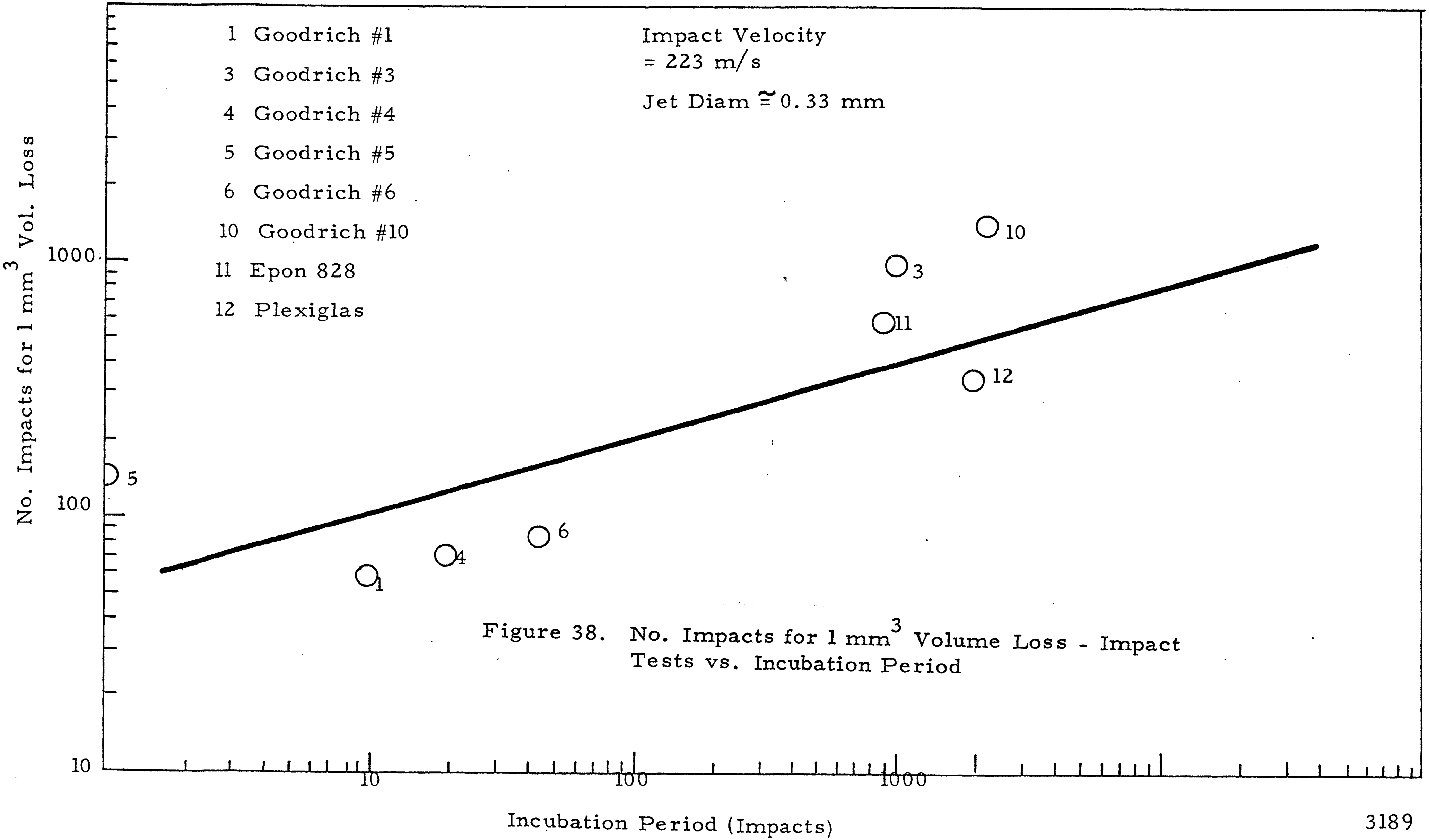


Figure 38. No. Impacts for 1 mm^3 Volume Loss - Impact Tests vs. Incubation Period

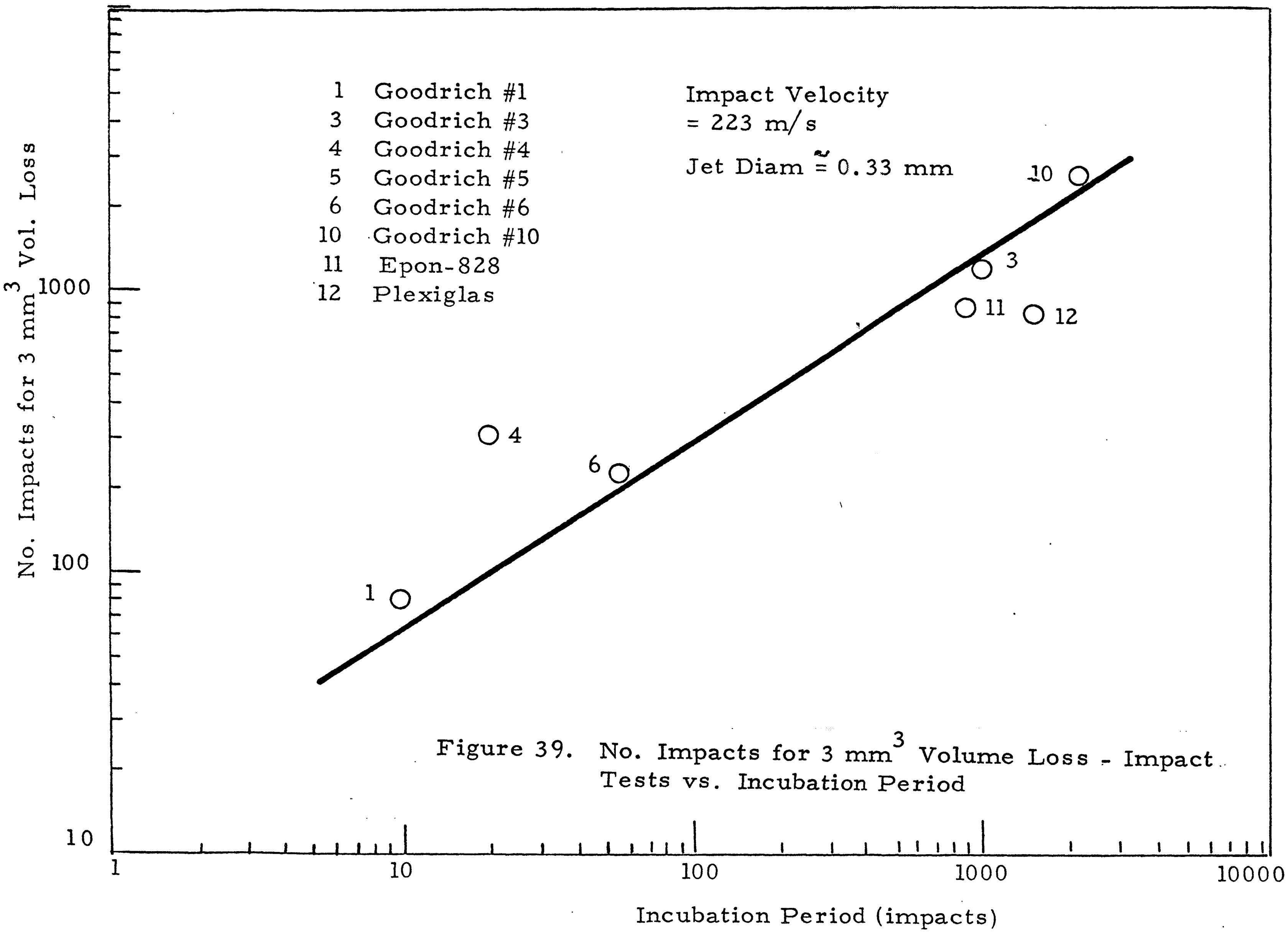


Figure 39. No. Impacts for 3 mm^3 Volume Loss - Impact Tests vs. Incubation Period

3190

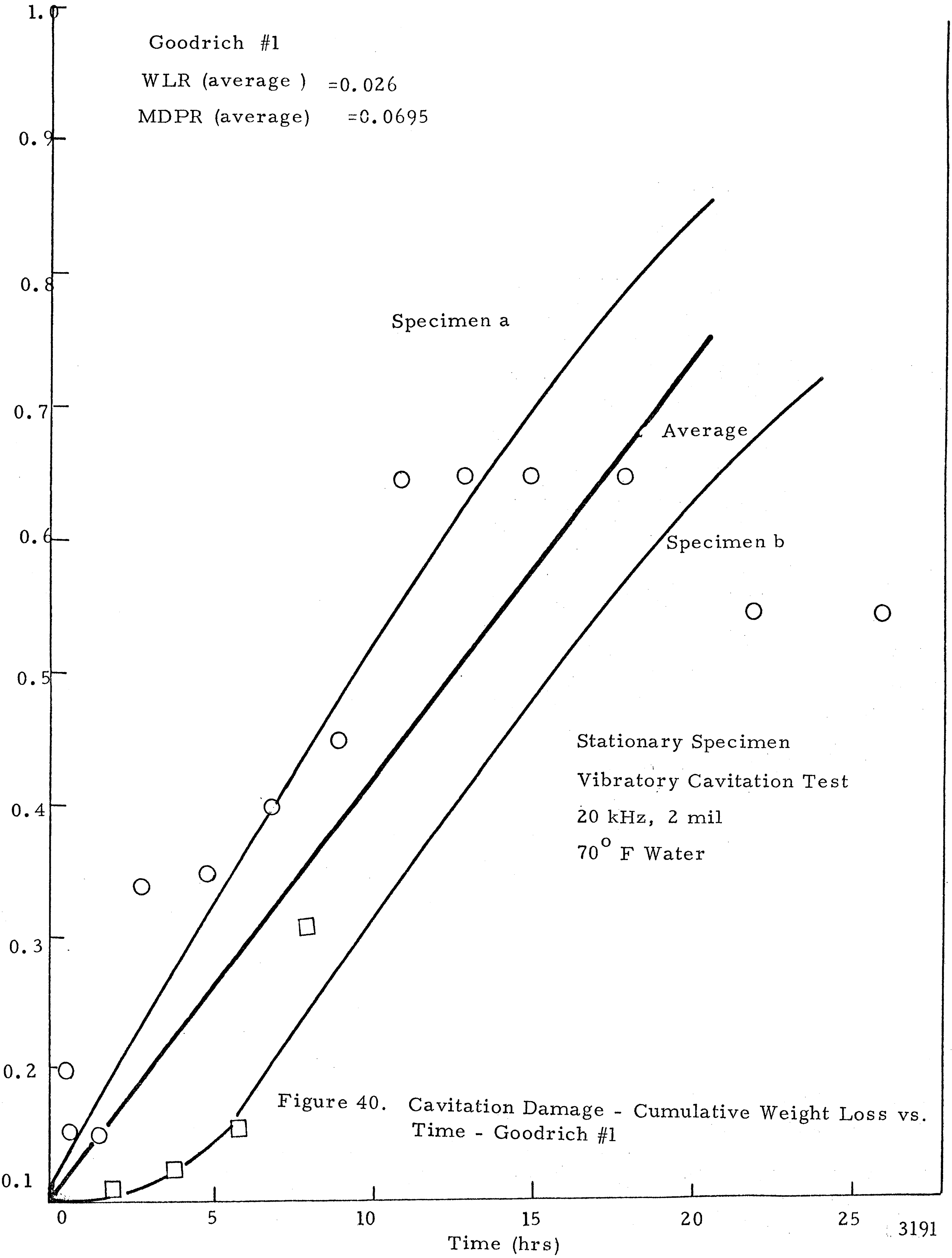


Figure 40. Cavitation Damage - Cumulative Weight Loss vs. Time - Goodrich #1

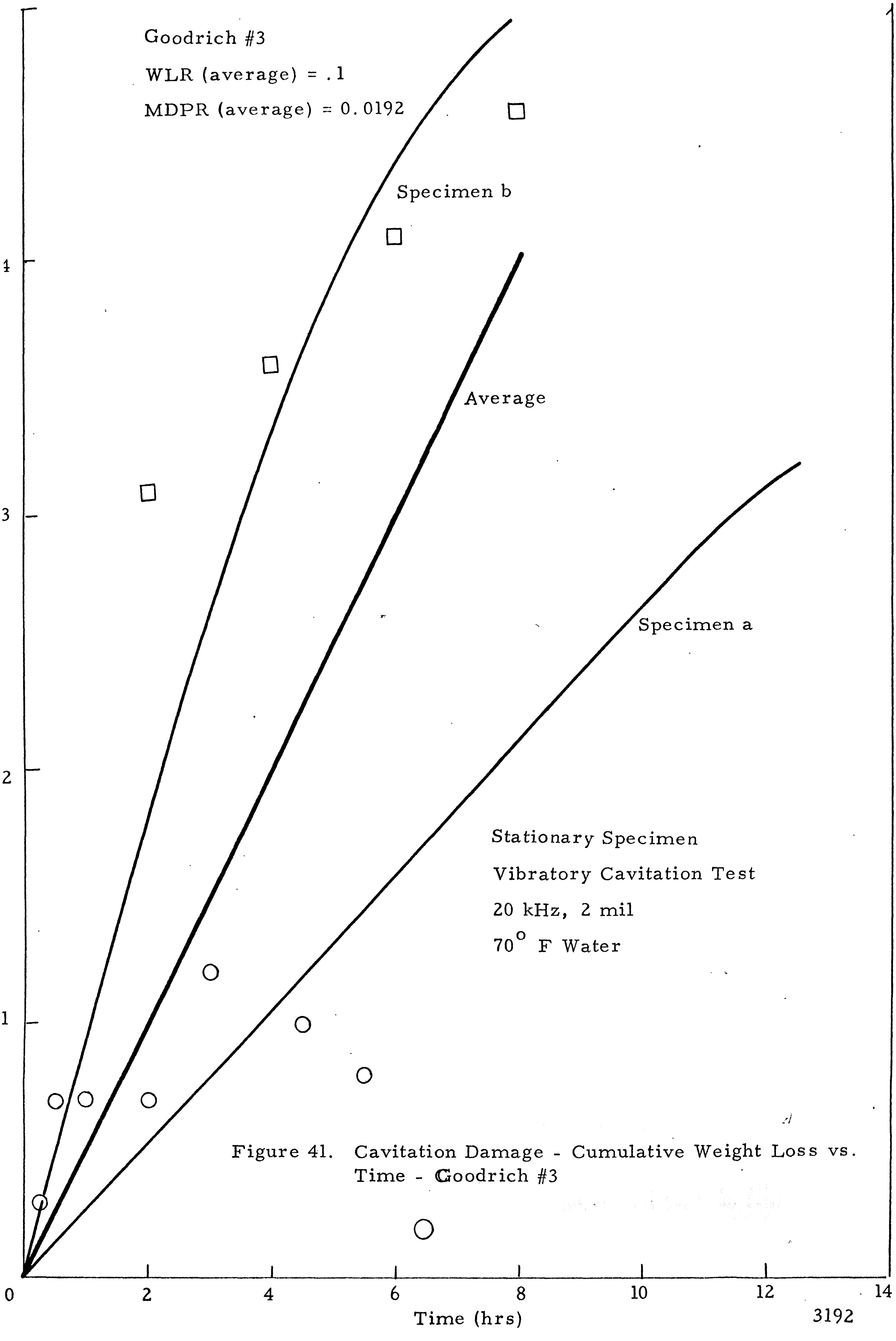


Figure 41. Cavitation Damage - Cumulative Weight Loss vs. Time - Goodrich #3

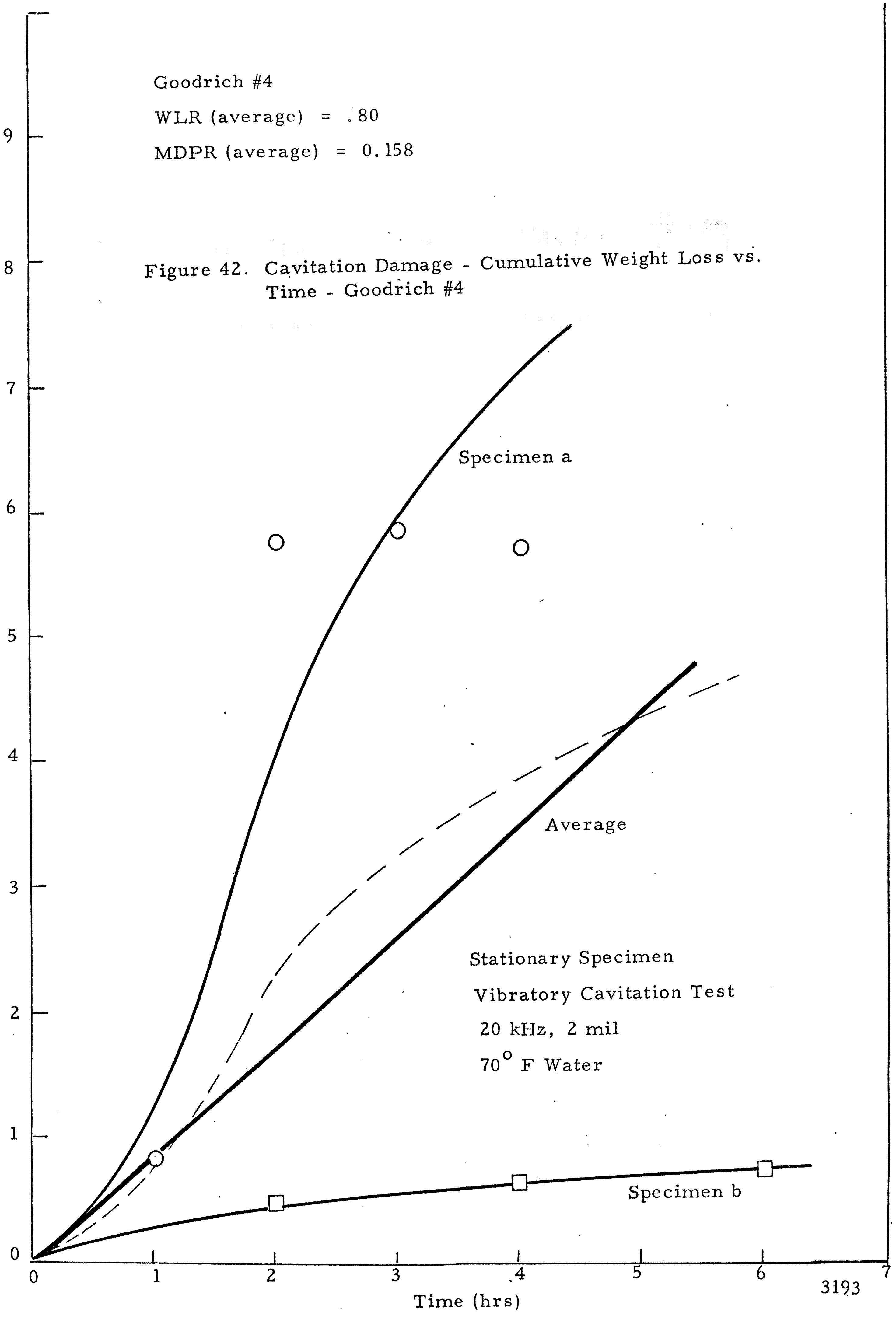


Figure 42. Cavitation Damage - Cumulative Weight Loss vs. Time - Goodrich #4

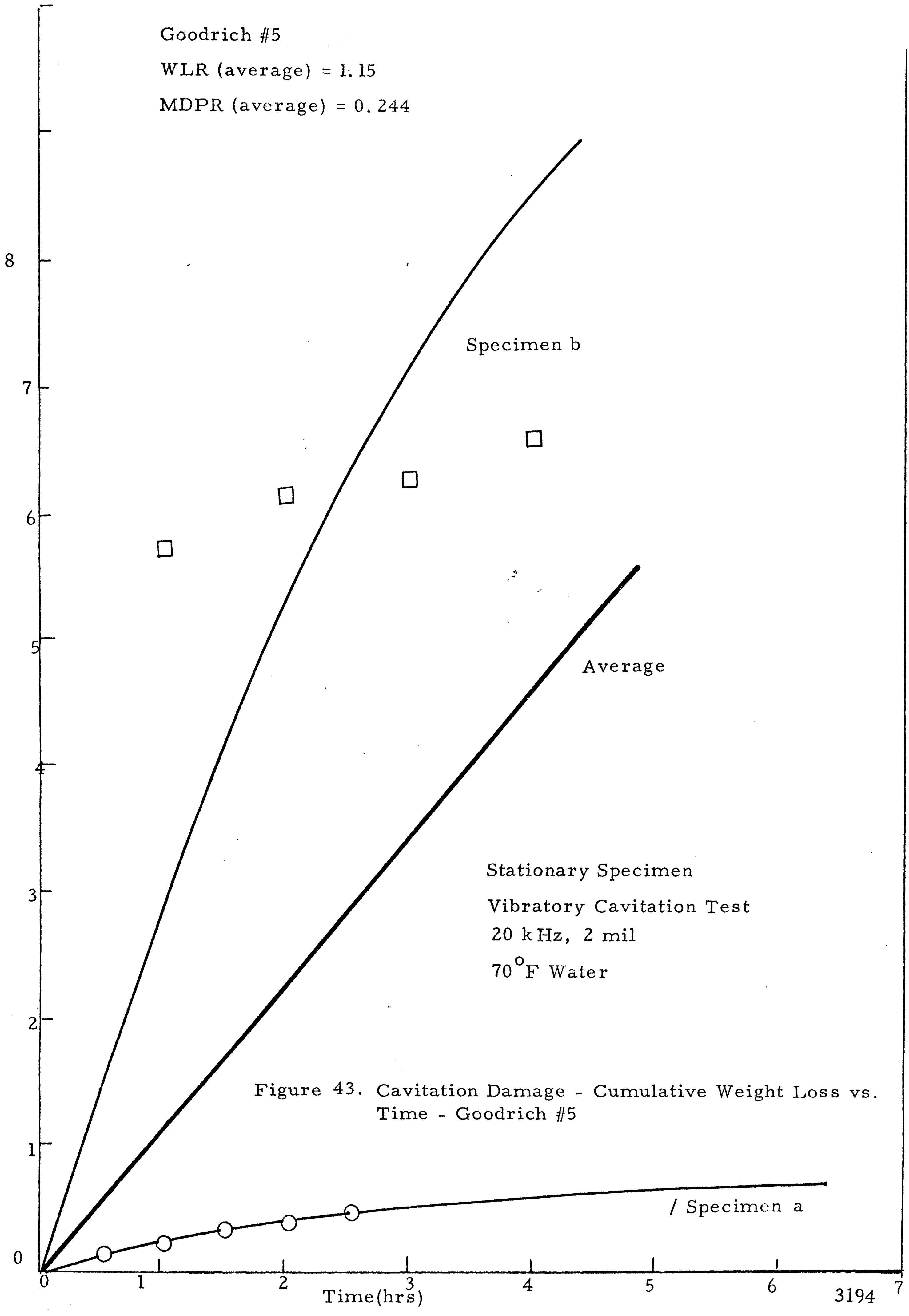


Figure 43. Cavitation Damage - Cumulative Weight Loss vs. Time - Goodrich #5

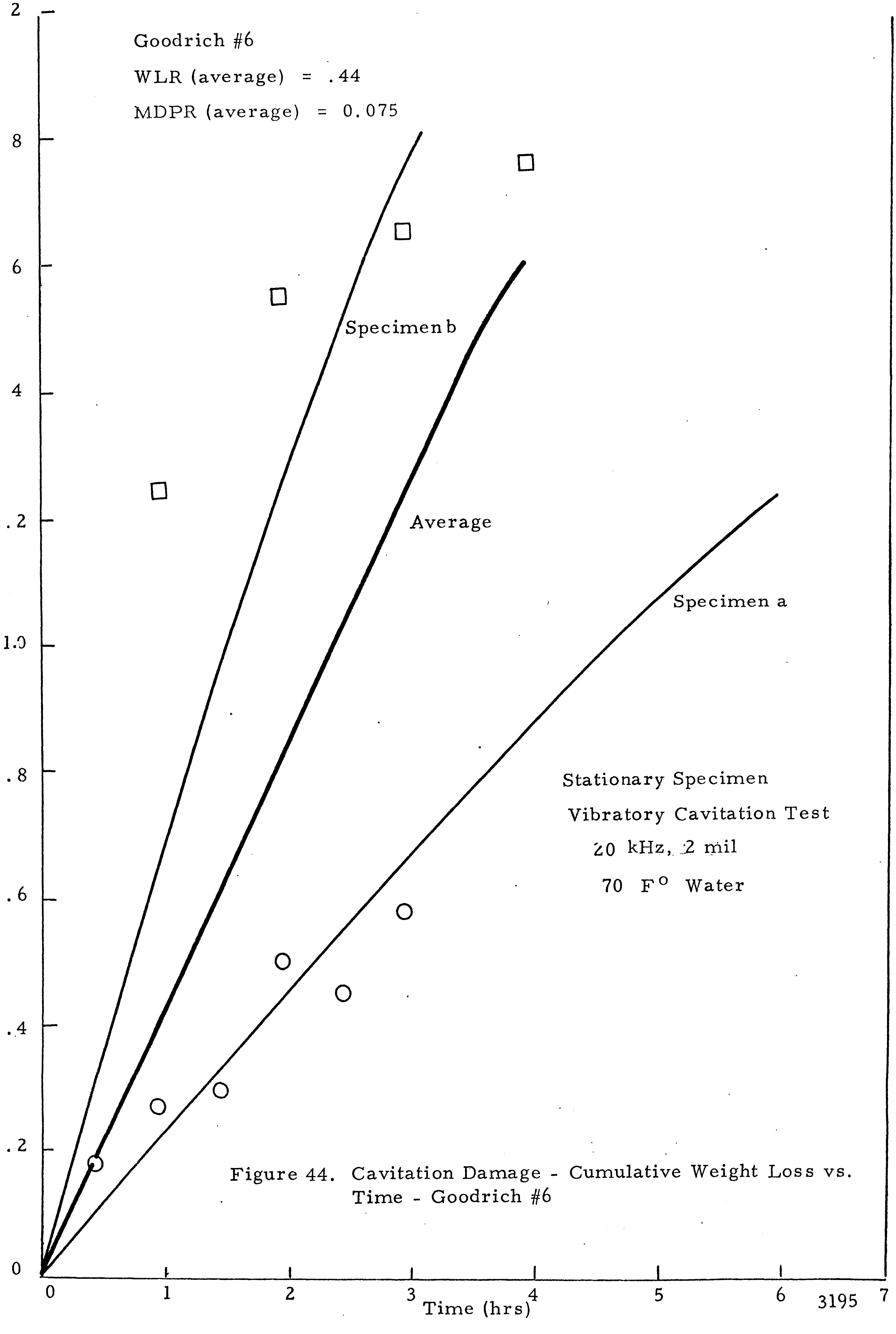


Figure 44. Cavitation Damage - Cumulative Weight Loss vs. Time - Goodrich #6

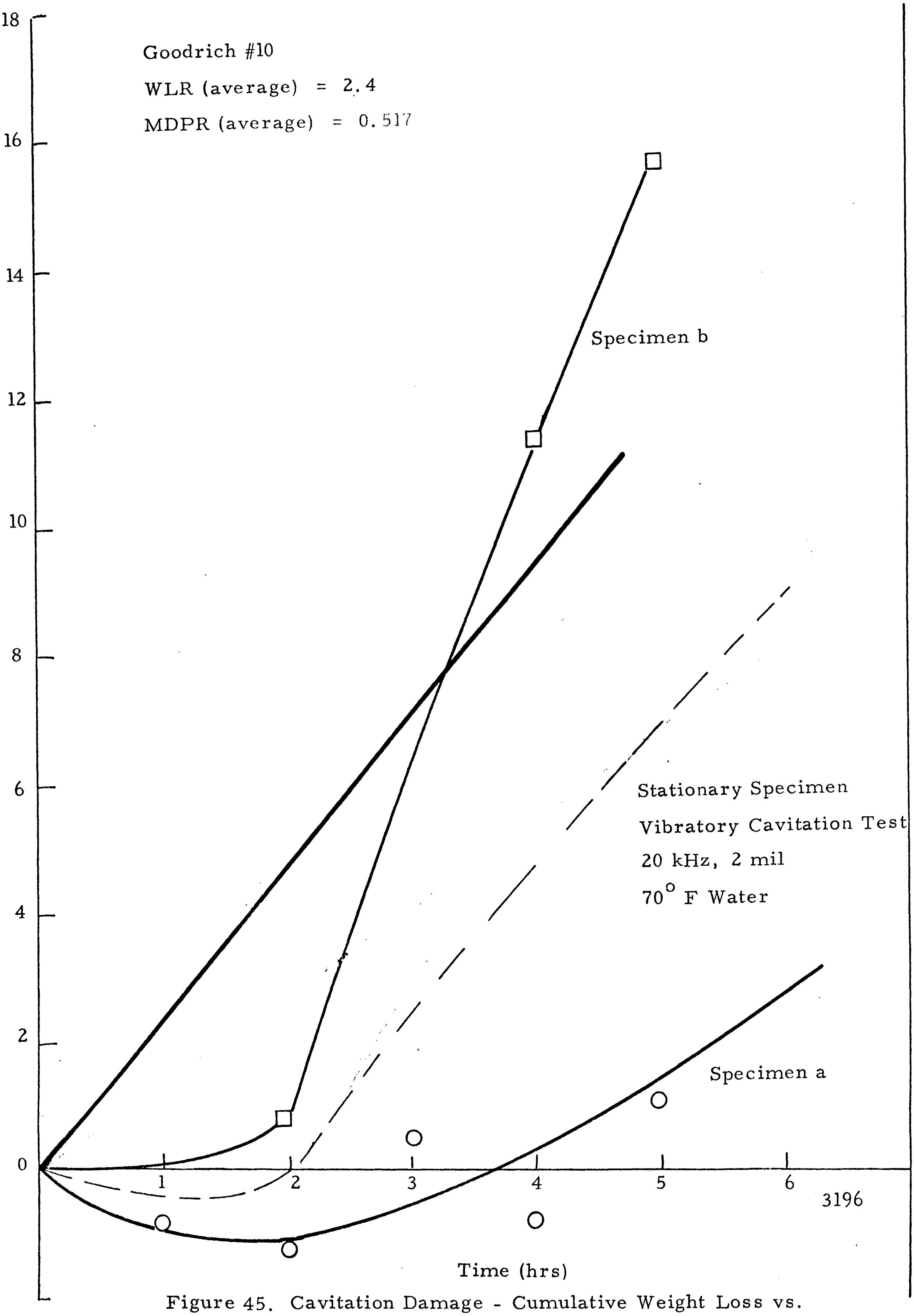


Figure 45. Cavitation Damage - Cumulative Weight Loss vs. Time - Goodrich #10

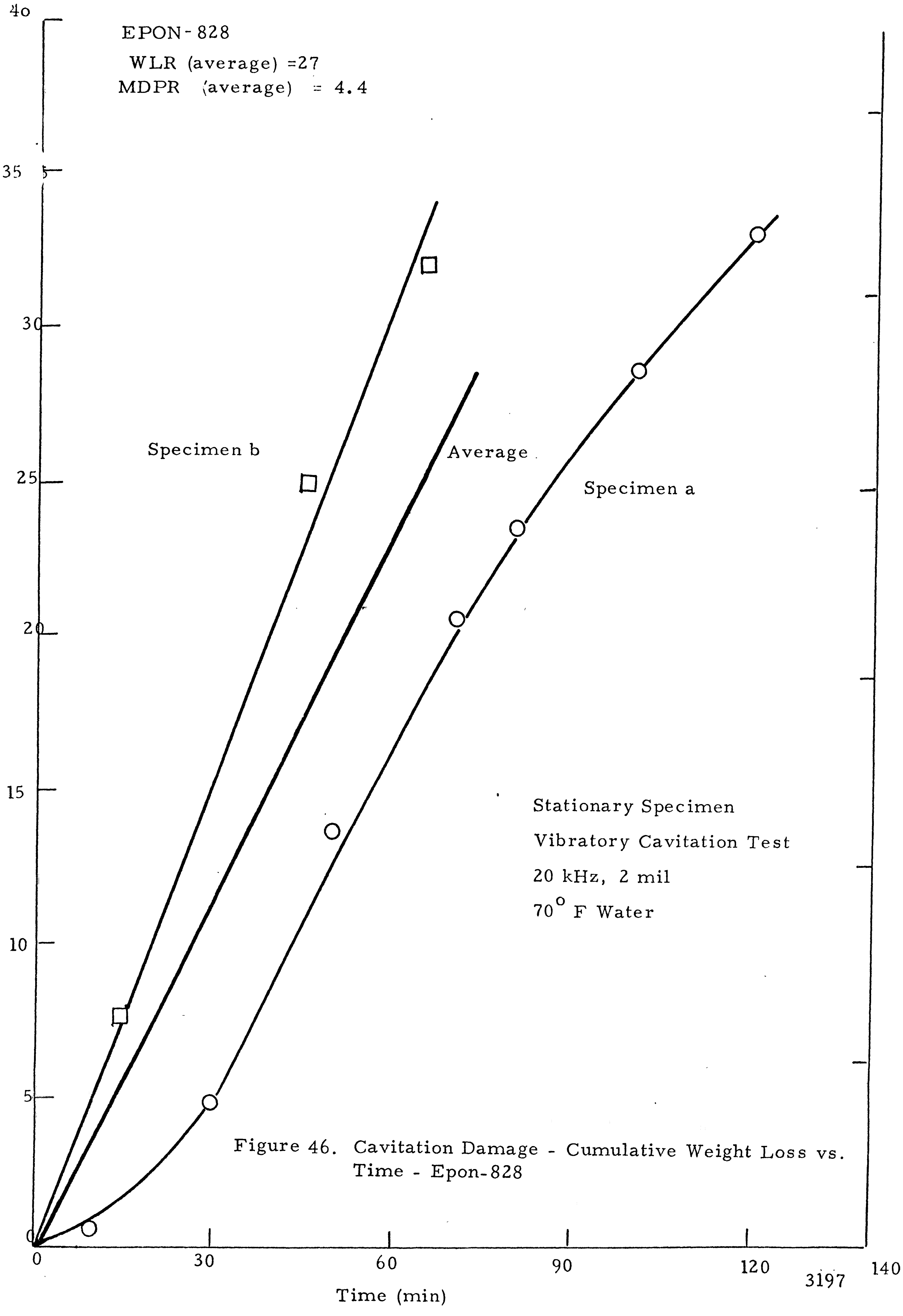


Figure 46. Cavitation Damage - Cumulative Weight Loss vs. Time - Epon-828

3197

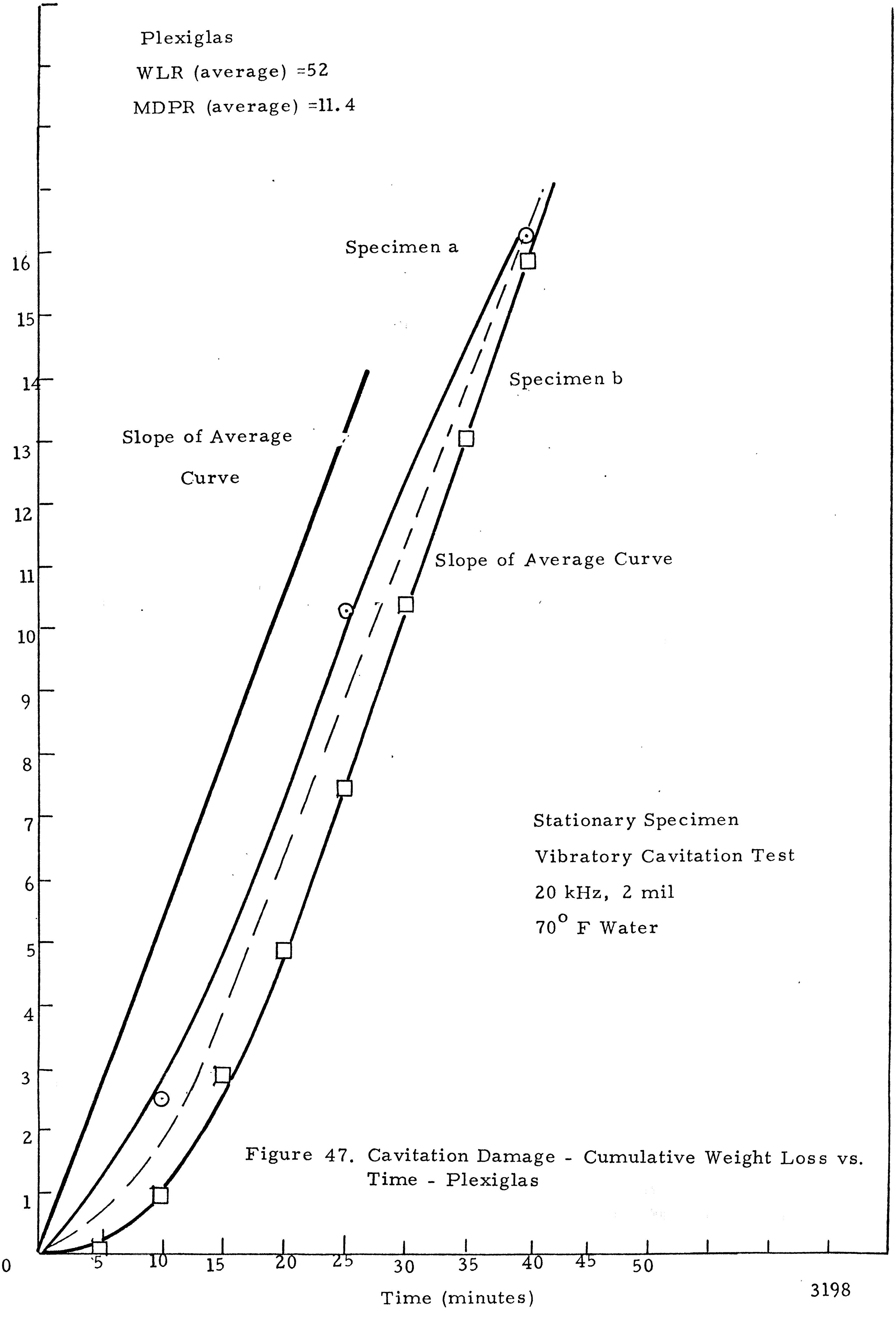


Figure 47. Cavitation Damage - Cumulative Weight Loss vs. Time - Plexiglas

3198

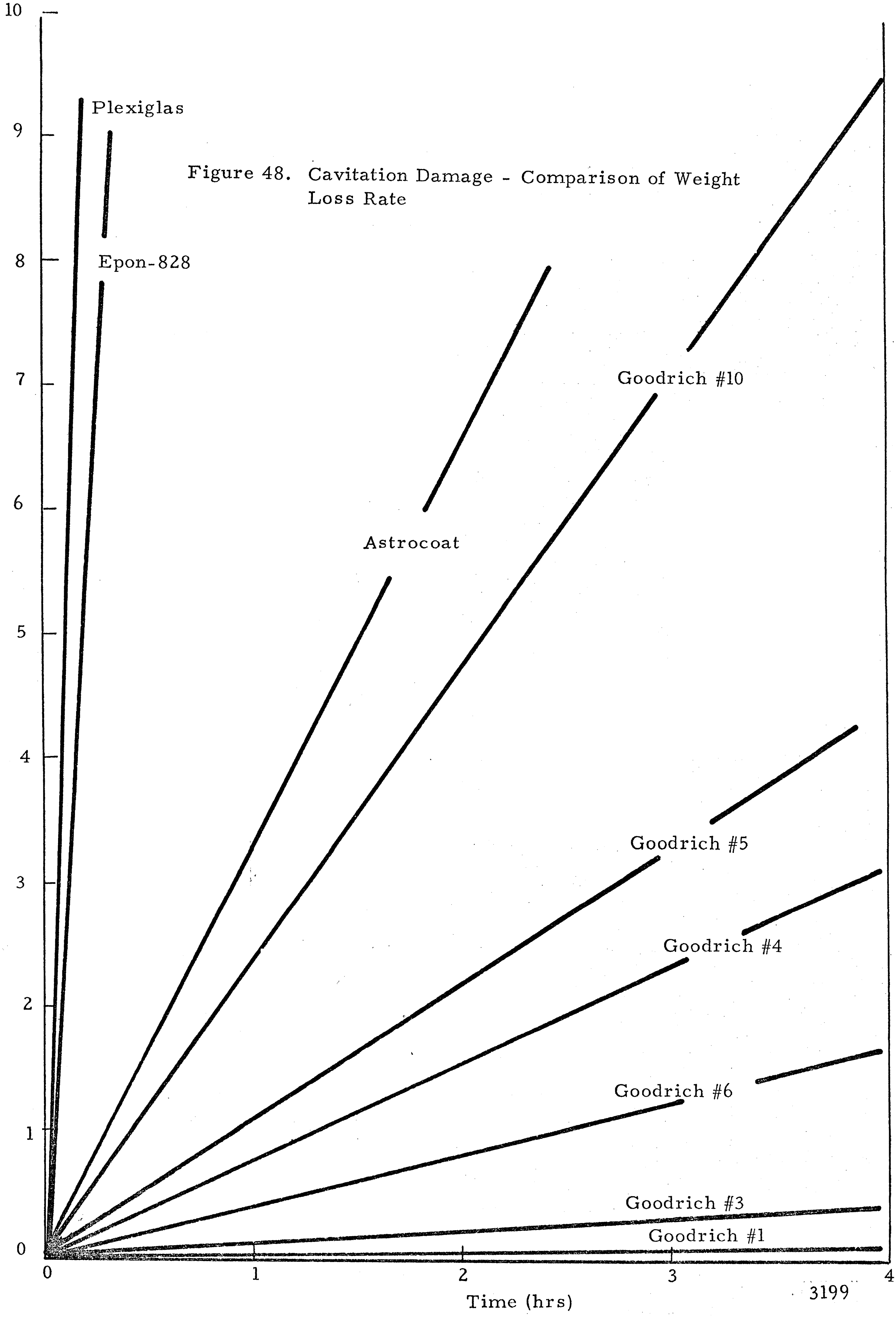


Figure 48. Cavitation Damage - Comparison of Weight Loss Rate

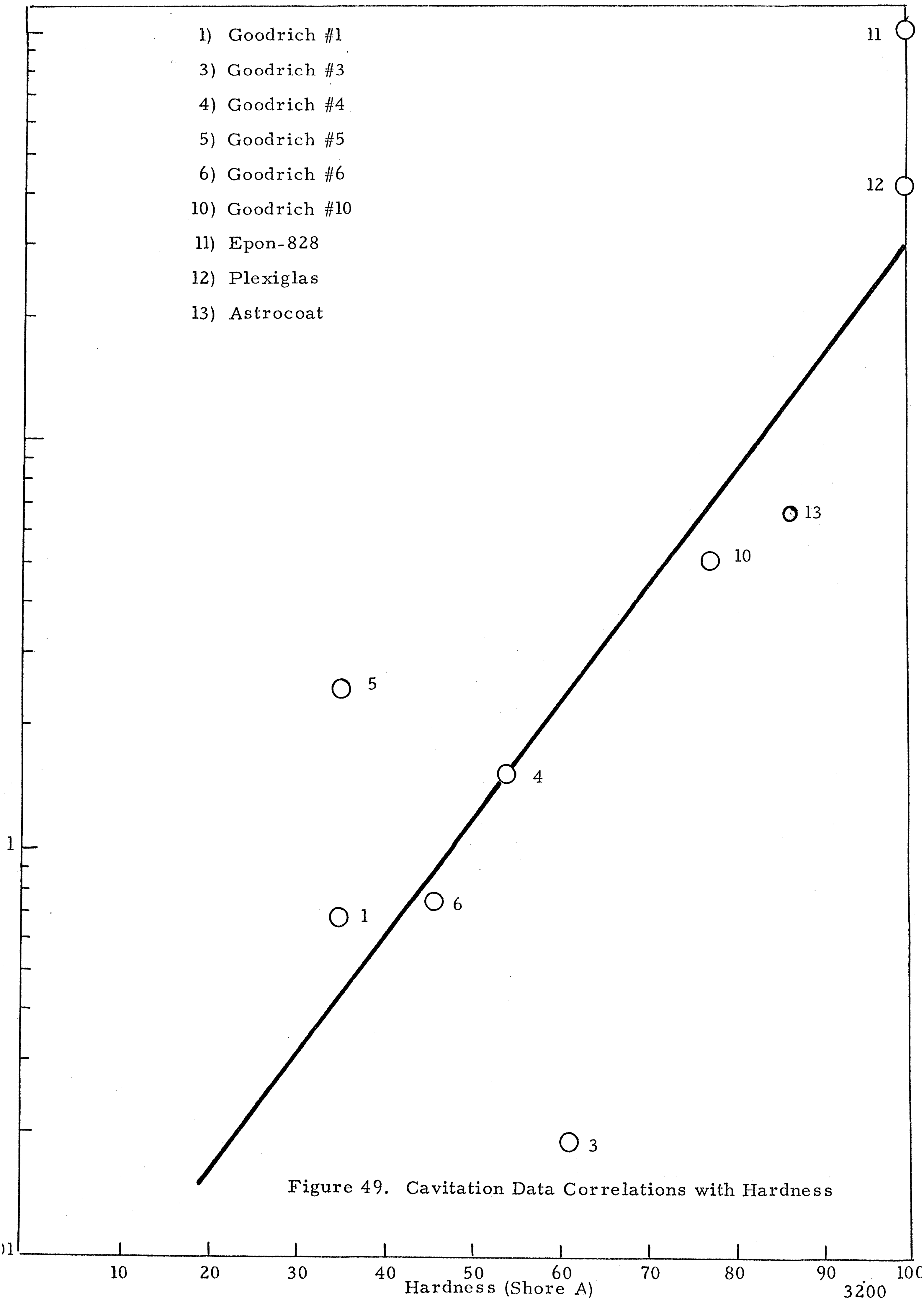


Figure 49. Cavitation Data Correlations with Hardness

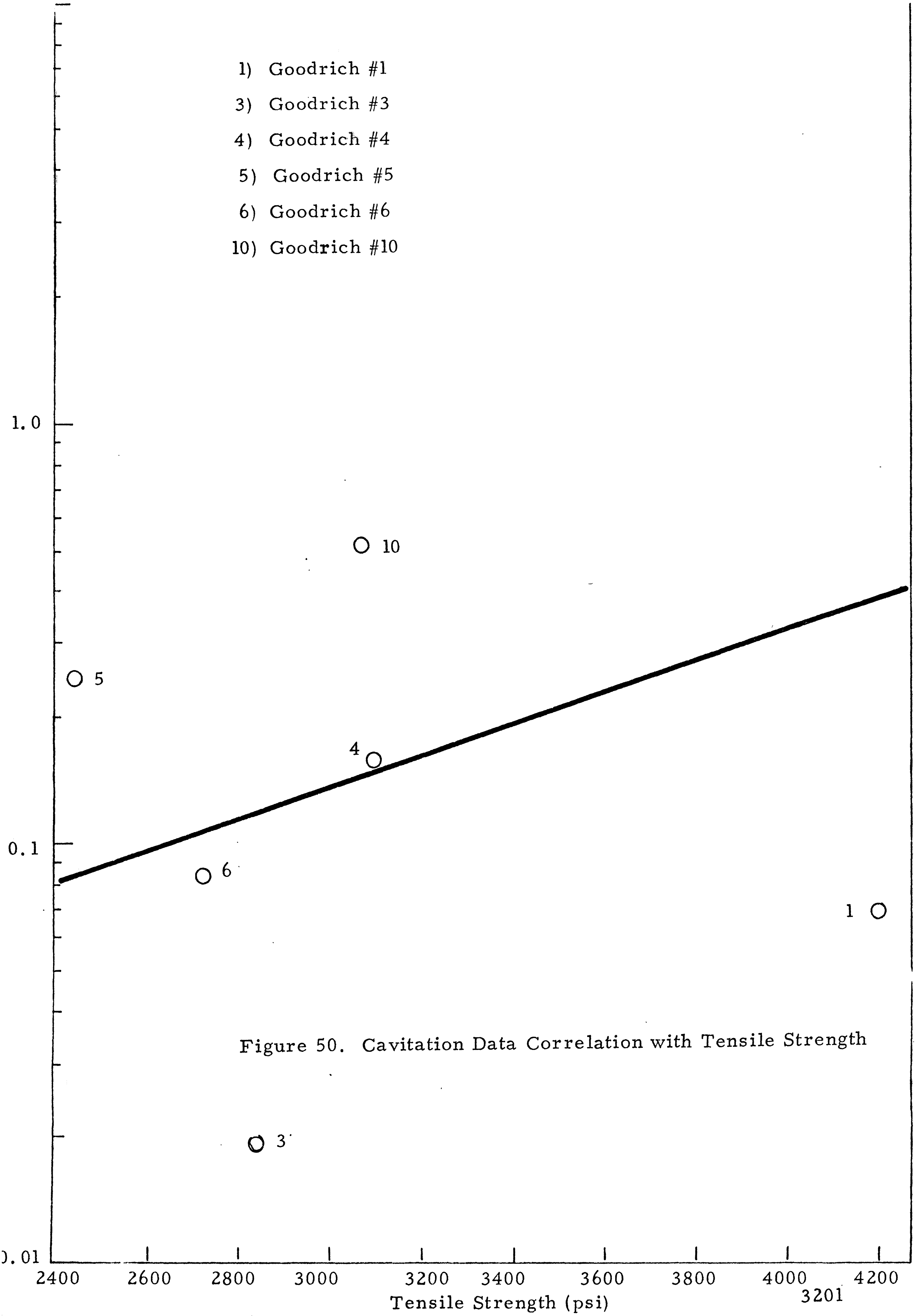


Figure 50. Cavitation Data Correlation with Tensile Strength

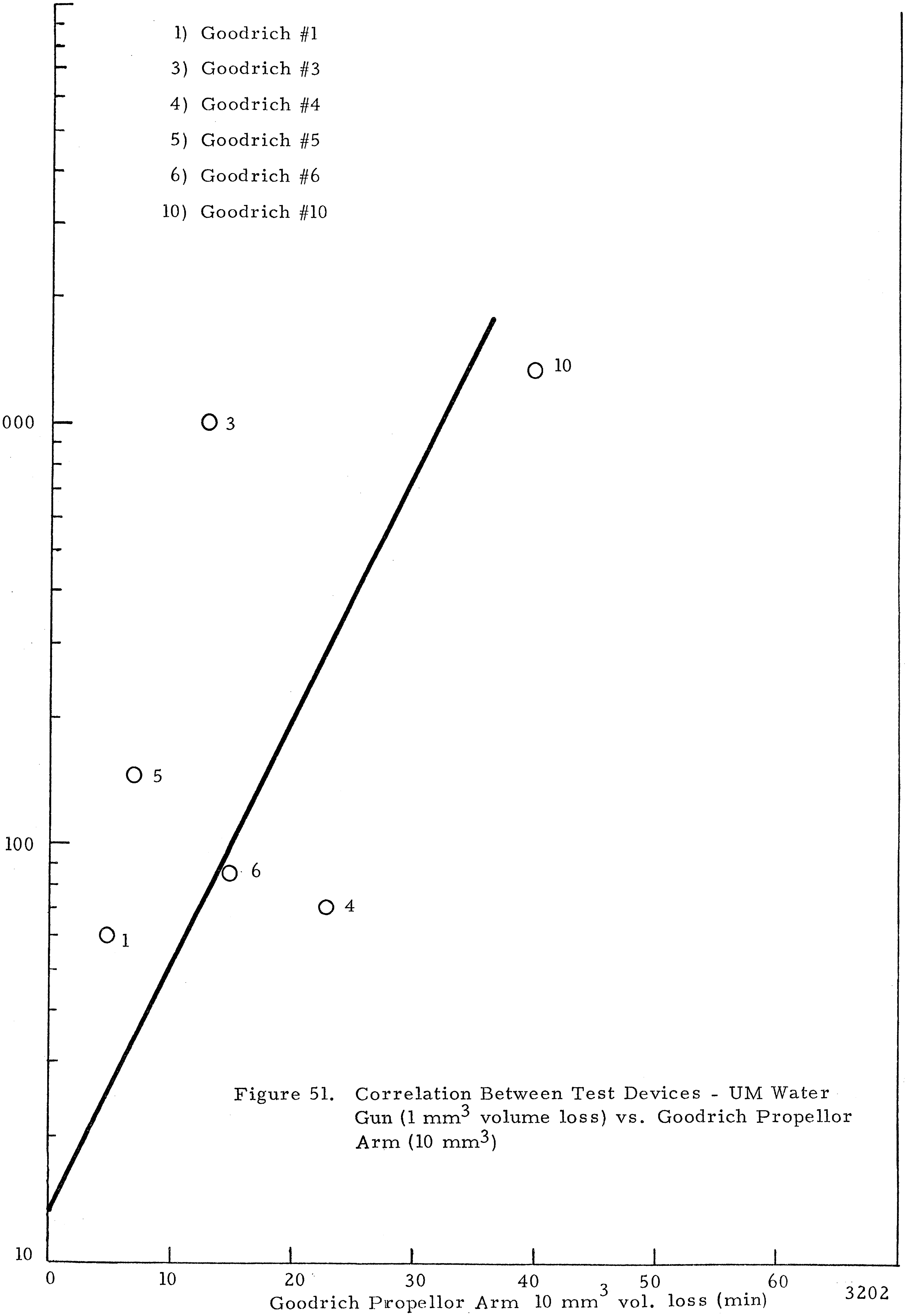


Figure 51. Correlation Between Test Devices - UM Water Gun (1 mm^3 volume loss) vs. Goodrich Propellor Arm (10 mm^3)

3202

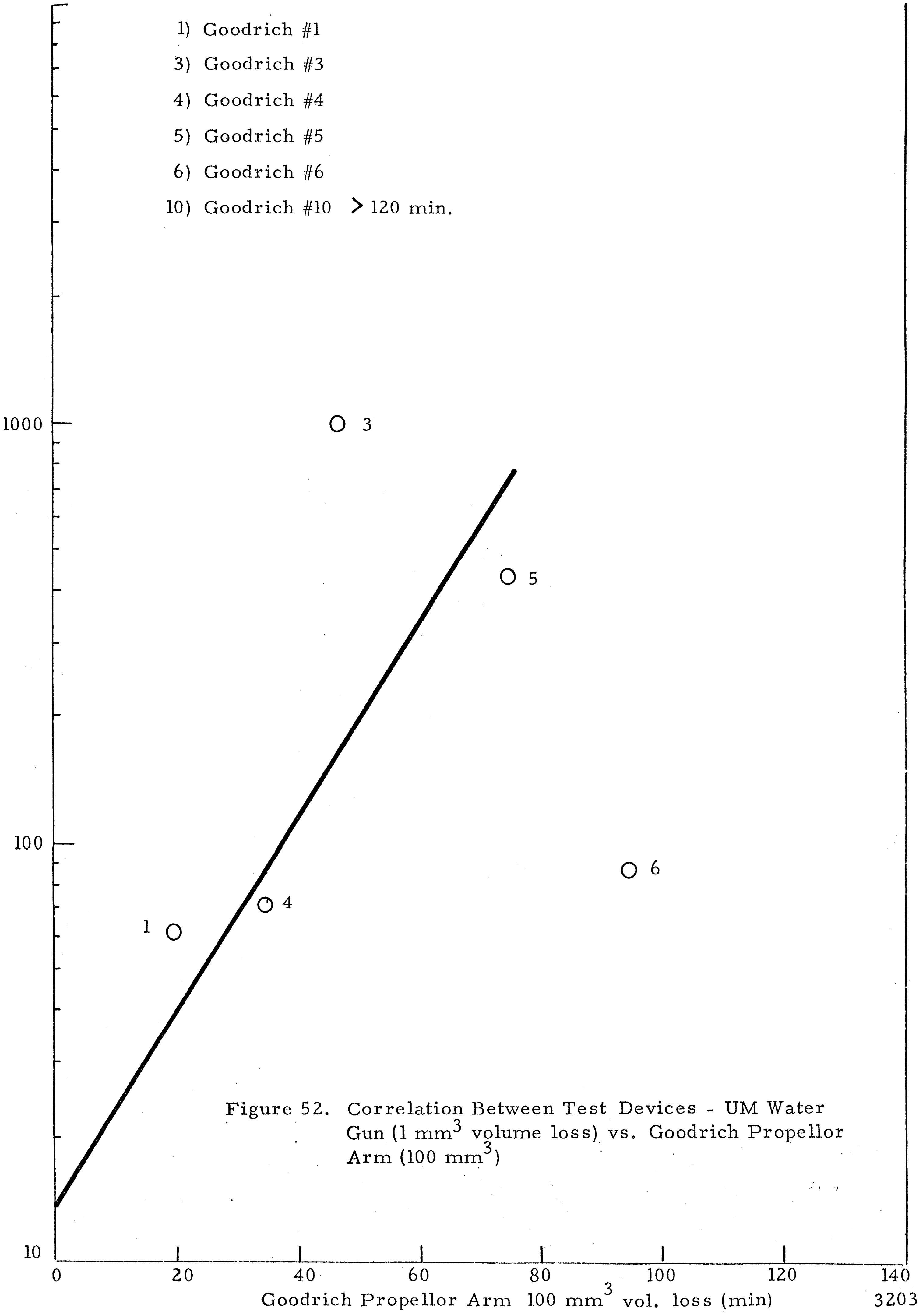


Figure 52. Correlation Between Test Devices - UM Water Gun (1 mm^3 volume loss) vs. Goodrich Propellor Arm (100 mm^3)

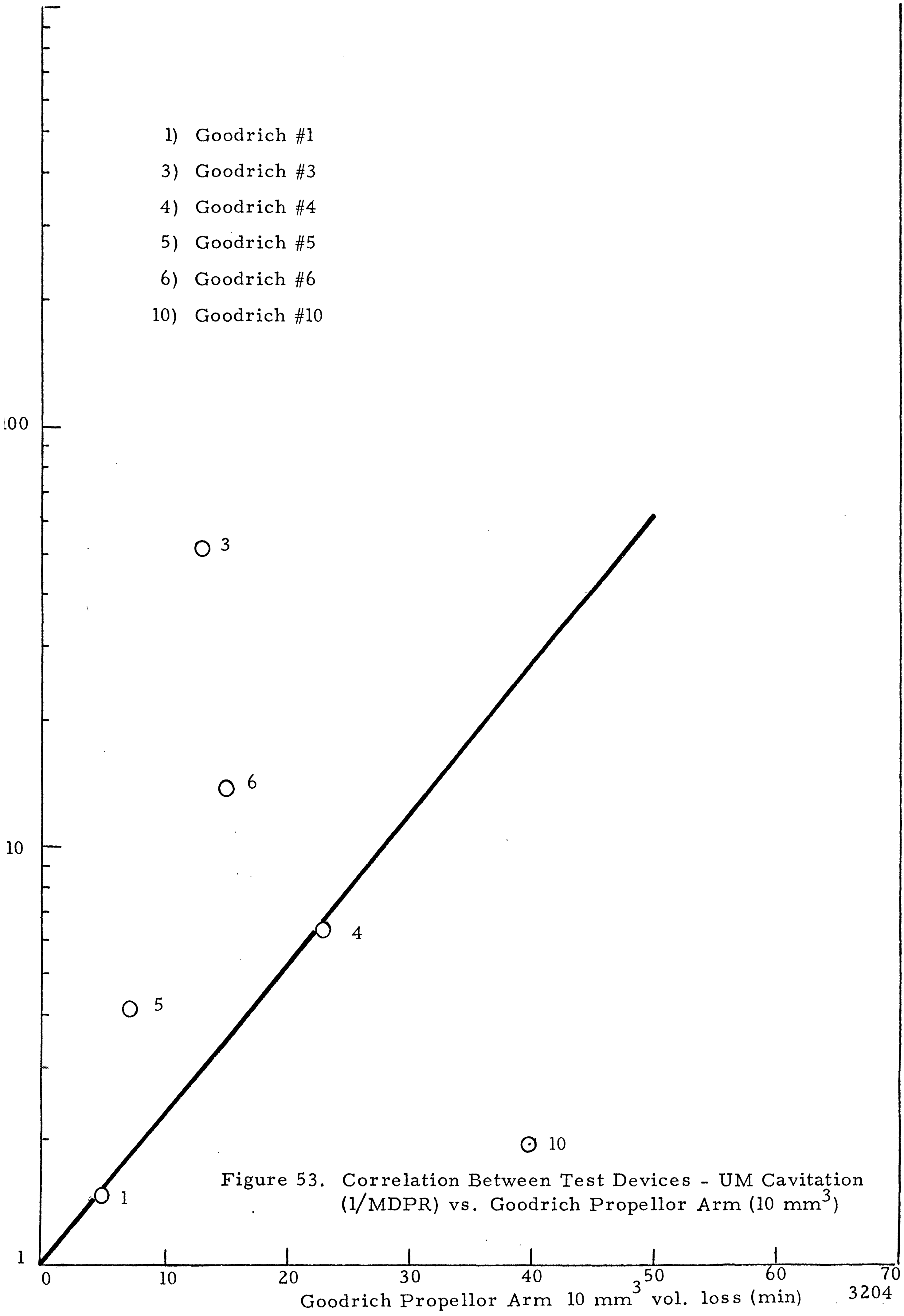


Figure 53. Correlation Between Test Devices - UM Cavitation (1/MDPR) vs. Goodrich Propellor Arm (10 mm^3)

3204

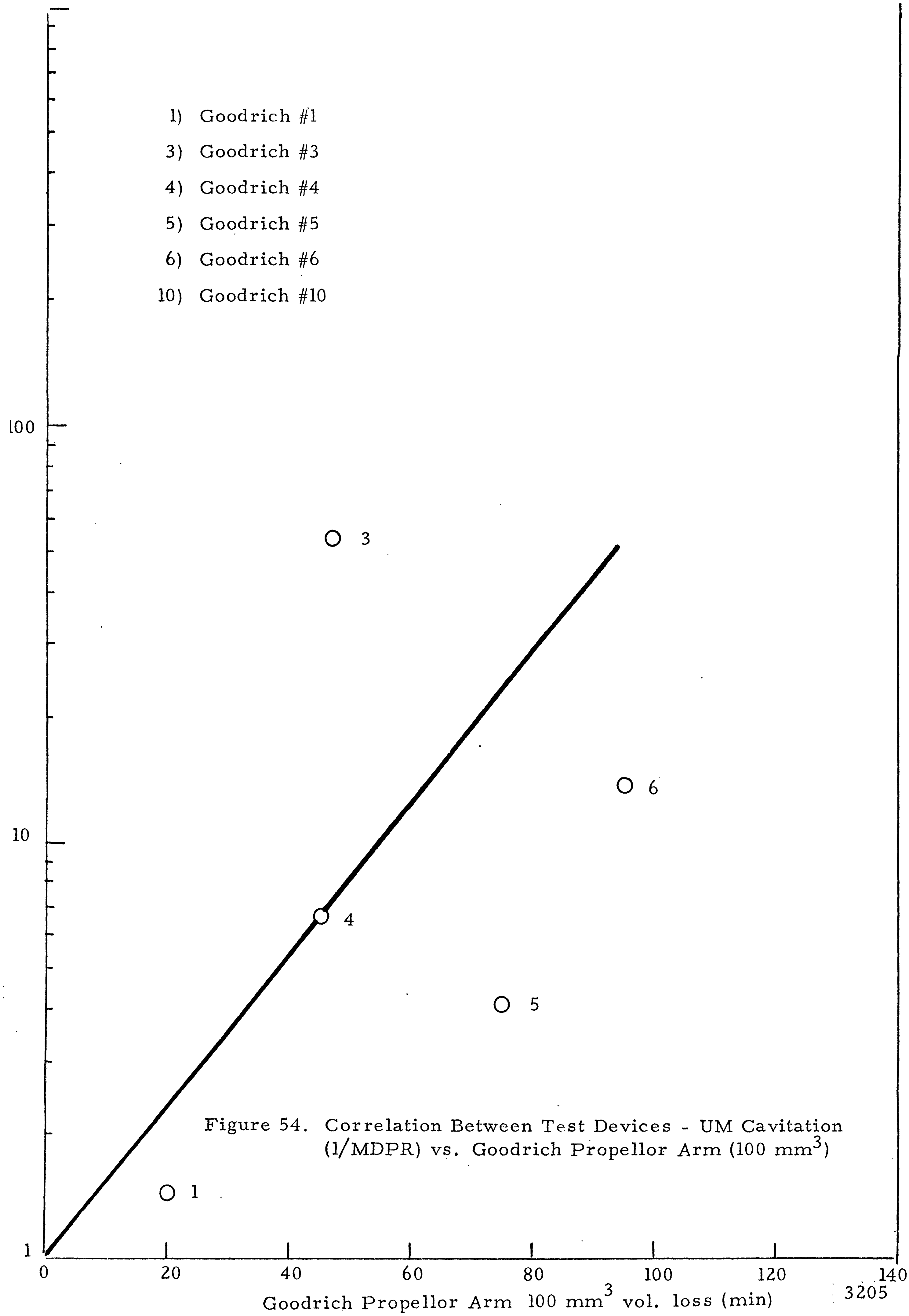
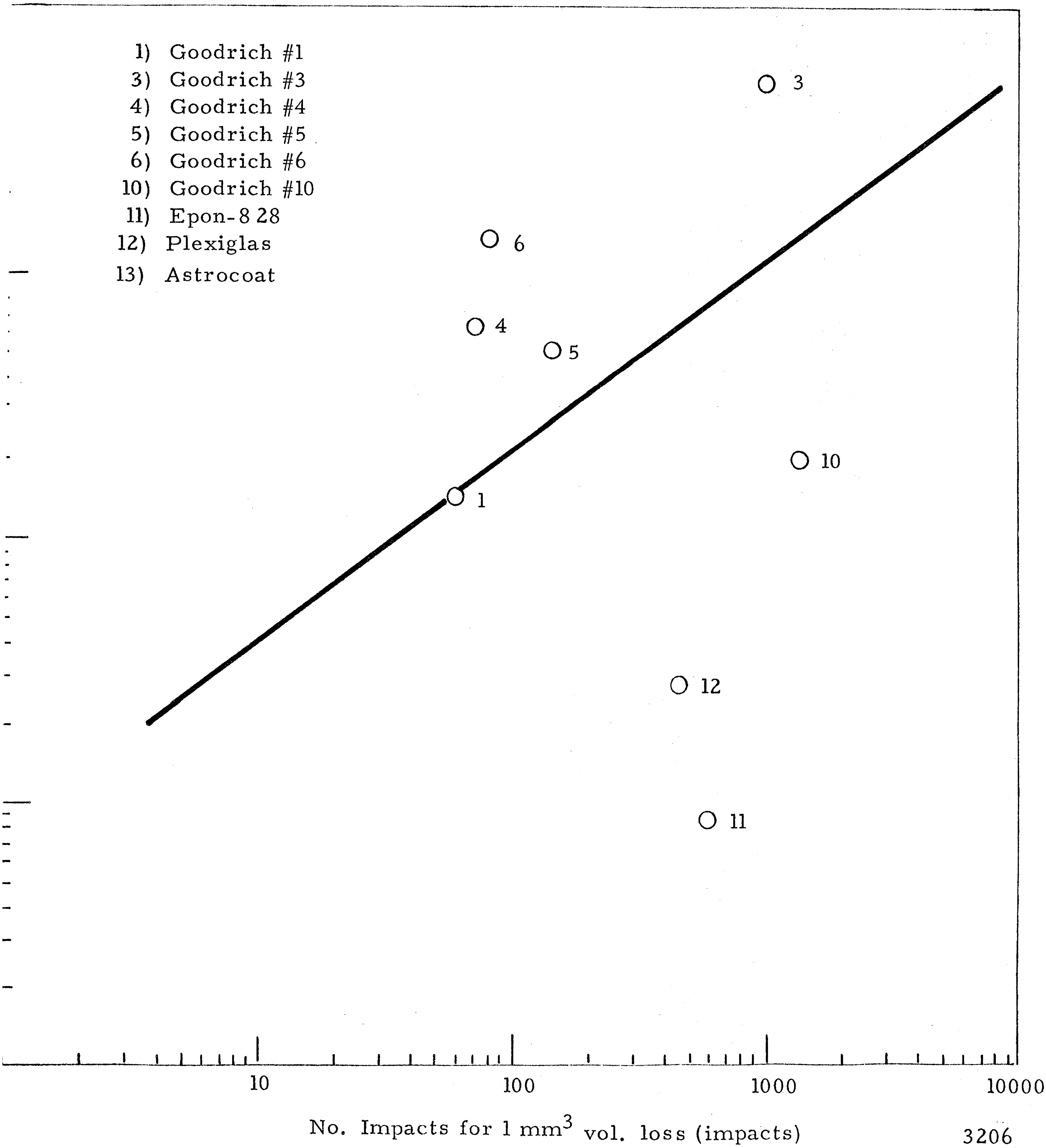


Figure 54. Correlation Between Test Devices - UM Cavitation (1/MDPR) vs. Goodrich Propellor Arm (100 mm^3)

3205

Figure 55. Correlation Between UM Cavitation and UM Water Gun



3206

Table 1
Materials Damage and Mechanical Properties

Material	Hardness Shore A	Tensile Strength psi	Elongation %	Density gm/cm^3	Gun WLR mg/imp	Cavit WLR mg/hr.	Impact to 3mm^3 Vol Loss	Impacts to 1 mm^3 Vol. Loss	Incubation Period-Gun Impacts	MDPR Cavitation mils/hr.
Goodrich #1	36	4190	740	0.975	0.039	0.026	81	61	10	0.0695
Goodrich #3	62	2830	710	1.359	0.059	0.15	1200	1000	1000	0.0192
Goodrich #4	55	3090	580	1.321	0.081	0.80	300	71	20	0.158
Goodrich #5	37	2440	1000	1.229	0.05	1.10	630	143	0	0.244
Goodrich #6	45-48	2730	1080	1.574	0.029	0.44	218	86	55	0.075
Goodrich #10	75-80	3000	900	1.215	0.012	2.4	2490	1370	2200	0.517
Epon-828 Laminate	99.5	--	--	1.60	0.125	52.00	860	600	890	11.4
Plexiglas	99.5	--	--	1.19	0.29	27.00	810	460	1500	4.4
Astrocoat	89	--	--	1.10	0.004	3.20	13,500	12,900	12,666	0.75

Table 2

Liquid Impact Collision Parameters

Specimen	Max. V_{ax} m/s	Max. $V_{rad.}$ m/s	Max. Radial Vel. of Splash-Back Plume m/s (Impact Vel. = 223 m/s)	Max. Plume Ht. (40 μs) mm Left	Right	Avg.
Goodrich #1	180 (0-1.7 μs)	299 (0-1.7 μs)	28	1.8	2.2	2.0
Goodrich #3	299 (0-1.7 μs)	539 (0-1.7 μs)	108	3.3	3.7	3.5
Goodrich #4	120 (0-1.7 μs)	240 (0-1.7 μs)	110	3.8	5.4	4.6
Goodrich #5	240 (0-1.7 μs)	299 (0-1.7 μs)	37	2.8	2.7	2.7
Goodrich #6	180 (0-1.7 μs)	299 (0-1.7 μs)	63	4.1	4.5	4.3
Goodrich #10	180 (0-1.7 μs)	1170	80	4.6	4.5	4.6
Epon-828	240 (0-1.7 μs)	299 (0-1.7 μs)	170	2.0	2.2	2.1
Plexiglas	180 (0-1.7 μs)	240 (0-1.7 μs)	180	1.8	2.3	2.1

Table 3-A

Comparison of Various Test Facilities

Material	Goodrich Propeller Arm: Time for 100 mm^3 Vol. Loss Min.	Goodrich Propeller Arm: Time for 10 mm^3 Vol. Loss Min.	U-M Water Gun: Impacts for 1 mm^3 Vol. Loss	U-M Cavitation: $\left(\frac{1}{MDPR}\right)_{max}$ hr/mil.
Goodrich #1	20	5	61	1.44
Goodrich #3	47	13	1000	52.0
Goodrich #4	45	23	71	6.32
Goodrich #5	75	7	143	4.10
Goodrich #6	95	15	86	13.33
Goodrich #10	> 120	40	1370	1.93
Epon-828			600	0.088
Plexiglas			460	0.227
Astrocoat			12,900	1.34

Table 3-B

Erosion Resistance Normalized to Goodrich #1

Material	Goodrich Propeller Arm		U-M Water Gun	U-M Cavitation
Goodrich #1	1.000	1.000	1.000	1.000
Goodrich #3	2.37	2.6	16.4	36.1
Goodrich #4	2.25	4.6	1.17	4.38
Goodrich #5	3.25	1.4	2.36	2.85
Goodrich #6	4.75	3.0	1.41	9.25
Goodrich #10		8.0	22.4	1.34
Epon-828			9.85	0.061
Plexiglas			7.58	0.1572
Astrocoat			211.4	0.77

Table 3-C

Relative Rankings for Erosion Resistance*

Material	Goodrich Propellor Arm			U-M Water Gun		U-M Cavitation	
	$10\ mm^3$	$100\ mm^3$	60 min.	Impacts to 1 mm^3		Mils/hr.	
Goodrich #1	1	1	1	1	1**	5	8**
Goodrich #5	2	4	4	4	4	2	5
Goodrich #3	3	3	3	5	7	6	9
Goodrich #6	4	5	5	3	3	4	7
Goodrich #4	5	2	2	2	2	3	6
Goodrich #10	6	6	6	6	8	1	4
Epon-828					6		1
Plexiglas					5		2
Astrocoat					9		3

*Highest Value = Greatest resistance

**This column includes Epon-828, Plexiglas, and Astrocoat in the rankings

APPENDIX

MATERIAL DAMAGE SHEET

Material EPON 828 EPOXY GLASS LAMINATE	
Number C-3	

RUNNING CONDITIONS

Horn Ti	Temperature 70°F
% Power 28%	Pressure 1 atm
Approx. Date 12-15-69 to 12-17-69	Torque 85 in lb
Prerun	
Surface Preparation	

BASIS FOR CALCULATIONS

Density 1.64 g/cm³	Area 0.235 in²
MDP Factor 0.158 mil/mg	

Comments: Rain erosion – close proximity test with 304 SS tip (incorrect power setting for 2 mil double amplitude)

DATA

Time Interval	Cumulative Time	Weight Loss	Cumulative Weight Loss	MDP	Cumulative MDP
5 min	5 min	1.00 mg	1.00 mg	.158 mil	.158 mil
5	10	0.61	1.61	.096	.254
5	15	0.67	2.28	.106	.360
5	20	0.98	3.26	.155	.515
10 min	10 min	0.75 mg	0.75 mg	.119 mil	.119 mil
20	30	4.12	4.87	.652	.771
20	50	8.89	13.76	1.405	2.176
20	70	6.84	20.60	1.081	3.257
10	80	3.11	23.71	.491	
20	100	5.04	28.75	.796	
20	120	4.50	33.25	.712	

JET GUN DATA SHEET

Sample No. GOOD RICH

Material #1

Density

Spring

Meniscus Withdraw: ·1.2

Angles of Attack 90°

Mass Loss Rate

Volume Loss Rate

DATE	JET SPEED	NO. OF SHOT	WEIGHT	LOSS	ACC. LOSS
10, 14. 70	1090 ft ~~320~~ ft/sec	0	40.91987	0	0
	— " —	20	40.91955	0.32	0.32
	— " —	70	40.91835	1.20	1.52
	— " —	90	40.91612	2.23	3.75
	— " —	90	40.92010		
	— " —	220	40.91576	4.34	8.09
	— " —	320	40.91515	0.61	8.70
	— " —	420	40.91435	0.80	9.50
	— " —	520	40.91146	2.89	12.39

JET GUN DATA SHEET

Sample No. GOOD RICH

Material #3

Density

Spring

Maximum Withdrawl

Angles of Attack

Mass Loss Rate

Volume Loss Rate

DATE	JET SPEED	NO. OF SHOT	WEIGHT	LOSS	ACC. LOSS
0-14	~~320 ft/s~~ 1090 ft/s	0	4[redacted]934	0	0
	— " —	900	40.62865	0.69	0.69
	— " —	1000	40.62822	0.43	1.12
	— " —	1075	40.62706	1.16	2.28
	— " —	1175	40.62626	0.80	3.28
	— " —	1375	40.58437	41.89	45.17
	— " —	1875	40.57722	7.15	52.32
	— " —	3375	40.55251	24.71	77.03
	— " —	7875	40.48862	63.89	140.92
	— " —	8000	40.47338	15.24	156.16
	— " —	9000	40.41951	53.87	210.03

JET GUN DATA SHEET

Sample No

Material Goodrich #4

Density

Spring

Meniscus Withdrawl

Angles of Attack

Mass Loss Rate

Volume Loss Rate

DATE	JET SPEED	NO. OF SHOT	WEIGHT	LOSS	ACC. LOSS
10-14	320 m/sec	0	40.85965	0	0
		40	40.85881	0.84	0.84
		90	40.85831	0.50	1.34
		150	40.85735	0.96	2.30
		250	40.85619	1.16	3.46
		400	40.85509	1.10	4.56
		550	40.84591	9.18	13.75
		700	40.84471	1.20	14.95
		900	40.84295	1.76	16.71

JET GUN DATA SHEET

Sample No Goodrich #5

Material

Density

Spring

Meniscus Withdrawal

Angles of Attack

Mass Loss Rate

Volume Loss Rate

DATE	JET SPEED	NO. OF SHOT	WEIGHT	LOSS	ACC. LOSS
	0	84	41.23055	0.10	1.06
		94	41.23045	0.10	1.16.

JET GUN DATA SHEET

Sample No. Good Rich
Material #5
Density
Spring
Meniscus Withdrawl
Angles of Attack
Mass Loss Rate
Volume Loss Rate

DATE	JET SPEED	NO. OF SHOT	WEIGHT	LOSS	ACC. LOSS
6-15-70	320 m/sec	0	41.23085	0	0
		2	41.23070	0.15	0.15
		4	41.23068	0.02	0.17
6-15-70		4	41.23100		
		10	41.23077	0.23	0.40
		14	41.23065	0.12	0.52
6-16-70		14	41.23100		
		24	41.23075	0.25	0.75
		24	41.23080	[illegible]	[illegible]
		44	41.23069	0.11	0.86
		44	41.23075		
		74	41.23065	0.10	0.96

JET GUN DATA SHEET

Sample No Goodreich

Material # 6.

Density

Spring

Meteors Withdrawl

Angles of Attack

Mass Loss Rate

Volume Loss Rate

DATE	JET SPEED	NO. OF SHOT	WEIGHT	LOSS	ACC. LOSS
10-21	320 m/sec	~~100~~ 0	39.96626	0	0
		100	39.96466	1.60	1.60
		200	39.96178	2.88	4.48
		300	39.95756	4.22	8.70
		400	39.95740	0.16	8.86
		800	39.95316	4.24	13.10
		1100	3995216	1.00	14.10

JET GUN DATA SHEET

Sample No. GOOD RiCH #10

Material

Density

Spring

Moments Withdraw?

Angles of Attack

Mass Loss Rate

Volume Loss Rate

DATE	JET SPEED	NO. OF SHOT	WEIGHT	LOSS	ACC. LOSS
0-21	320 m/se	0	40.10549 ~~39.96696~~	0	0
		1500	40.10054	4.85	4.85
		2250	40.09816	1.38	6.23
		3750	40.09770	0.46	6.69
		4750	40.09517	2.53	9.22
		5150	40.09075	4.42	13.64
		5650	40.08900	1.75	15.39

MATERIAL DAMAGE SHEET NAVY 2

erial PLEXIGLAS

ber I-2, #2

RUNNING C ITIONS

n T1	mperature 275°
ower 27.5	Pressure 28.50"
rox. Date May 9, 1960	Torque

rum 15'

face Preparation ~ NONE

BASIS FOR CALCULATIONS

sity ?	Area

Factor

ments RAIN EROSION

DATA

e nterval	Cumulative Time	Wt. Loss	Cumulative Wt. Loss	MDP	Cumulative MDP
5	5	.13	.13		
5	10	.81	.94		
5	15	1.94	2.88		
5	20	1.97	4.85		
5	25	2.58	7.43		
5	30	2.91	10.34		
5	35	2.70	13.04		
5	40	2.84	15.88		

MATERIAL DAMAGE SHEET

Material	Natural Rubber — 0.033" thick
Number	XA-5435-1a B.F. Goodrich

RUNNING CONDITIONS

Horn Ti	Temperature 70°F
% Power 36%	Pressure atmospheric
Approx. Date 1-12-70 to 1-19-70	Torque 85 in-lb
Prerun	
Surface Preparation	

BASIS FOR CALCULATIONS

Density	Area
MDP Factor	

Comments: Rain erosion — close proximity test with 304SS tip

DATA

Time Interval	Cumulative Time	Weight Loss	Cumulative Weight Loss	MDP	Cumulative MDP
5 min	5 min	0.10 mg	0.10 mg		
10	15	0.10	0.20		
30	45	-0.05	0.15		
1 hr	1 hr 45 min	0.00	0.15		
1 hr 15 min	3 hr	0.19	0.34		
2 hr	5 hr	0.01	0.35		
2	7	0.05	0.40		
2	9	0.05	0.45		
2	11	0.20	0.65		
2	13	0.00	0.65		
2	15	0.00	0.65		
3	18	0.00	0.65		
4	22	-0.10	0.55		
4	26	0.00	0.55		

MATERIAL DAMAGE SHEET

...ial Goodrich

...er 1 b

RUNNING CONDITIONS

Ti	...mperature
...er 40	Pressure
...x. Date	Torque

...m

...ce Preparation

BASIS FOR CALCULATIONS

...ty	Area

...actor

...nts

DATA

...erval	Cumulative Time	Wt. Loss	Cumulative Wt. Loss	MDP	Cumulative MDP
2 hr	2	.11	.11		
2	4	.02	.13		
2	6	.03	.16		
2	8	.15	.31		

MATERIAL DAMAGE SHEET

Material	Neoprene, 0.033" thick
Number	XA-5435-3a B.F. Goodrich

RUNNING CONDITIONS

Horn Ti	Temperature 70°F
% Power 36%	Pressure atmospheric
Approx. Date 1-19-70 to 1-20-70	Torque 85 in.lb
Prerun	
Surface Preparation	

BASIS FOR CALCULATIONS

Density	Area
MDP Factor	

Comments: Rain erosion – close proximity test with 304 SS tip

DATA					
Time Interval	Cumulative Time	Weight Loss	Cumulative Weight Loss	MDP	Cumulative MDP
5 min	5 min	0.04 mg	0.04 mg		
10	15	-0.01	0.03		
15	30	0.04	0.07		
30	60	0.00	0.07		
1 hr	2 hr	0.00	0.07		
1	3	0.05	0.12		
1½	4½	-0.02	0.10		
1	5½	-0.02	0.08		
1	6½	-0.06	0.02		

MATERIAL DAMAGE SHEET

...al

...r Good RICH 3 b

RUNNING CONDITIONS

	...mperature
...er	Pressure
...t. Date	Torque

...n

...ce Preparation

BASIS FOR CALCULATIONS

...ty	Area

...ector

...nts

DATA

...erval	Cumulative Time	Wt. Loss	Cumulative Wt. Loss	MDP	Cumulative MDP
2 hr	2	.31	.31		
2 hr	4	.05	.36		
2 hr	6	.15	.41		
2 hr	8	.05	.46		

MATERIAL TEST DATA SHEET

Material: Neoprene 0.035 in. thick

Number: XA-5435-4a B.F. Goodrich

TESTING CONDITIONS

Horn: Ti	Temperature: 70°F
% Power: 36%	Pressure: atmospheric
Approx. Date	Torque: 85 in. lb
Precon	
Surface Preparation	

BASIS FOR CALCULATIONS

Density	Area
MDP Factor	

Comments.

DATA

Time Interval	Cumulative Time	Weight Loss	Cumulative Weight Loss	MDP	Cumulative MDP
1 hr	1 hr	0.85 mg	0.85 mg		
1	2	4.95	5.80		
1	3	0.05	5.85		
1	4	-0.10	5.75		

MATERIAL DAMAGE SHEET

ial

er *GOODRICH 4b.*

RUNNING CONDITIONS

	..mperature
er	Pressure
x. Date	Torque

m

ce Preparation

BASIS FOR CALCULATIONS

ty	Area

actor

ents

DATA

terval	Cumulative Time	Wt. Loss	Cumulative Wt. Loss	MDP	Cumulative MDP
2	2	.47	.47		
2	4	.20	.67		
2	6	.05	.72		
2	8	.05	.77		

[illegible] SHEET

[illegible] Neoprene 0.035 in thick

[illegible] XA-5435-5a B.F. Goodrich

[illegible] CONDITIONS

Horn Ti	Temperature 70°F
% Power 36%	Pressure atmospheric
Approx. Date	Torque 85 in-lb
Prerun	
Surface Preparation	

BASIS FOR CALCULATIONS

Density	Area
MDP Factor	

Comments:

DATA

Time Interval	Cumulative Time	Weight Loss	Cumulative Weight Loss	MDP	Cumulative MDP
1 hr	1 hr	0.22 mg	0.22 mg		
1	2	0.04	0.26		
1	3	0.02	0.28		
1	4	0.14	0.42		
1	5	0.05	0.47		

MATERIAL DAMAGE SHEET

ial

er GOODRICH 5b

RUNNING CONDITIONS

	...mperature
er	Pressure
x. Date	Torque

m

ce Preparation

BASIS FOR CALCULATIONS

ty	Area

actor

nts

DATA

erval	Cumulative Time	Wt. Loss	Cumulative Wt. Loss	MDP	Cumulative MDP
2	2	5.75	5.75		
2	4	.40	6.15		
2	6	.12	6.27		
2	8	.31	6.58		

MATERIAL DAMAGE SHEET

Material	Neoprene – 0.030" thick
Number	XA - 5435 - 6a B.F. Goodrich

RUNNING CONDITIONS

Horn "Ti"	Temperature 70°F
% Power 36%	Pressure atmospheric
Approx. Date 1-20-70 to 1-21-70	Torque 85 in-lb
Prerun	
Surface Preparation	

BASIS FOR CALCULATIONS

Density	Area
MDP Factor	

Comments: Rain erosion – close proximity test with 304 SS tip

DATA

Time Interval	Cumulative Time	Weight Loss	Cumulative Weight Loss	MDP	Cumulative MDP
1hr	1hr	0.18 mg	0.18 mg		
1	2	0.09	0.27		
1	3	0.03	0.30		
1	4	0.20	0.50		
1	5	-0.05	0.45		
1	6	0.13	0.58		

MATERIAL DAMAGE SHEET

al

r B.F. GoodRICH -6b.

RUNNING CONDITIONS

	...mperature
er	Pressure
:. Date	Torque

n

ce Preparation

BASIS FOR CALCULATIONS

ty	Area

ector

nts

DATA

erval	Cumulative Time	Wt. Loss	Cumulative Wt. Loss	MDP	Cumulative MDP
2	2	1.25	1.25		
2	4	0.30	1.55		
2	6	0.10	1.65		
2	8	0.10	1.75		

MATERIAL DAMAGE SHEET

Material Estane - 0.030" thick

Number XA-5435-10a BF Goodrich

RUNNING CONDITIONS

Horn Ti	Temperature 70°F
% Power 36%	Pressure atmospheric
Approx Date	Torque 85 in-lb
Fretum	
Surface Preparation	

BASIS FOR CALCULATIONS

Density	Area
MDP Factor	

Comments.

DATA

Time Interval	Cumulative Time	Weight Loss	Cumulative Weight Loss	MDP	Cumulative MDP
1 hr	1 hr	-0.81 mg	-0.81 mg		
1	2	-0.40	-1.21		
1	3	1.78	0.57		
1	4	-0.96	-0.39		
1	5	1.48	1.09		

MATERIAL DAMAGE SHEET

...ial

...r *B.F. Goodrich 10 b*

RUNNING CONDITIONS

	...mperature
...er	Pressure
...x. Date	Torque

...n

...ce Preparation

BASIS FOR CALCULATIONS

...ty	Area

...actor

...nts

DATA

...erval	Cumulative Time	Wt. Loss	Cumulative Wt. Loss	MDP	Cumulative MDP
2	2	.90	.90		
2	4	10.53	11.43		
1	5	05.22	15.75		