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Cavitation and Multiphase Flow Laboratory

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Liquid Impingement and Cavitation Damage of Candidate Rain Erosion Materials at Various Impact Velocities and Angles

by

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ABSTRACT

Six aircraft rain erosion candidate materials, supplied by Naval Air Development Center (NADC) have been tested in the University of Michigan water gun facility for impact erosion resistance at Mach Numbers referred to in air at STP ranging from 1.5 to 0.6 and at angles of impact ranging from perpendicular (90°) to 30°. A 7th material was tested at Mach 0.9, 90°. The results are compared with previous results obtained for Epon-828 and Plexiglas. All of the materials were also tested in a stationary specimen vibratory cavitation facility. It is concluded that V sin θ is not a suitable correlating parameter for these materials since an incremental change in V produces generally a different damage increment than the corresponding increment in sin θ. The "damage exponent" was ~ 5, as observed in other tests for perpendicular impact for one material, but appears to depend on both angle and material. The relative ranking of materials produced by the cavitation test and the impact test for the maximum velocity at 90° is fairly similar.

TABLE OF CONTENTS

LIST OF FIGURES

Figure		Page

Figure		Page

I. INTRODUCTION

As a final portion of our present contract with NADC, we have tested 7 materials for rain erosion resistance using our repeating water gun device over a range of velocities between approximately Mach 1.5 and 0.6 (referred to air at STP) and impact angles between 90° (perpendicular impact) and 30°. In addititition cavitation tests using our vibratory facility (with stationary specimen) were to be made upon the same materials. These tests have all been completed and the full results are included in this report. The effect of impact angle and velocity are evaluated for the materials and a comparison is made between cavitation and impact erosion rates.

II. EXPERIMENTAL EQUIPMENT

A. Impact Facility

For the liquid impact tests, a repeating water gun previously described in detail [1, e.g.] was utilized. This device produces liquid jets with velocities up to about 600 m/s (~ Mach 1.5), 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. Generally, the initial stage of the impact is with a "precursor jet" of diameter somewhat smaller (about 1/2 mm) than that of the main jet diameter which is about 1.5 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. For these tests, considerable investigation of suitable rig parameter settings, using our high-speed motion picture apparatus, was made to assure that the required impact velocities could be achieved without significant change in jet shape. The typical jet shape utilized is as shown in Fig. 1. The angle of impact is adjusted as required between

30° and 90°, and the distance to point of impact is maintained constant.

B. Cavitation Facility

All the materials were also tested in cold water ($70^{\circ}F$) in our vibratory stationary specimen set-up, previously described. The specimen is held 20 mils from the tip of the vibrating horn;[1] horn double amplitude is 2 mils and frequency 20 kHz.

III. EXPERIMENTAL RESULTS

A. Experimental Conditions and Materials

The six materials initially supplied by NADC were each to be tested at 4 Mach numbers (1.5, 1.2, 0.9, and 0.6 referred to air at STP) and at 3 angles of impact (90°, 60°, and 30°). An additional material was eventually furnished to be tested only at 0.9 Mach and 90° impact angle. For comparison purposes, 2 additional materials were also tested, Epon-828 and Plexiglas, at various conditions. The materials and test conditions are listed completely and specified in Table 1. Epon-828 and Plexiglas were called Navy #1 and #2 respectively, the initial 6 materials supplied for this particular program were called Navy #3 - #8, and the final material Navy #9. All of the above materials were also tested in the vibratory stationary specimen cavitation facility.

All materials were tested for impact resistance in the water gun facility at the maximum velocity and 90°. These tests were continued to a maximum of 10,000 impacts, or until a first maximum weight loss rate had been reached and passed. In most cases the same tests were made at the other angles, but if no damage were achieved in a given test, the same material was not further tested under less damaging conditions, i.e., at reduced velocity and/or more oblique angle. Tests at the lower Mach numbers were continued to a maximum of 20,000 impacts. In those cases where no damage was achieved at a relatively high Mach number, the tests were not carried out at lower Mach number or less damaging angle. Table 1 shows the complete matrix of tests performed. It lists for each material maximum weight loss per impact, "incubation period", and impacts to 5 mm^3 volume loss, which is taken as the most meaningful measure of a real incubation period and figure of merit. Maximum volume loss rate (MDPR) is listed for the cavitation tests. In addition the hardness and density* of each material is listed. "Incubation period" is estimated by extrapolation of that portion of the curve, where a rapid increase in damage occurs, to zero. It is believed that impacts to a finite but small volume loss is more meaningful, and this latter parameter is used in this report.

B. Experimental Results

Figure 2 - 34 are the basic plots of weight loss vs. number of impacts for the various conditions and materials. From these, incubation period (as described above), impacts to 5 mm^3 volume loss, and maximum weight and volume loss rates are calculated. Fig. 35-a and -b are plots of impacts to 5 mm^3 volume loss vs. angle of impact, with impact velocity in Mach units (at STP) as curve parameter.

Figure 36 is a similar curve for maximum volume loss rate. Fig. 37 shows the effect of velocity variation at constant angle upon impacts to 5 mm^3 volume loss (as contrasted to Fig. 35 and 36 which show the effect of angle variation at constant velocity). Fig. 38 combines the two velocity parameters into V sin θ as abscissa (which has commonly been utilized in the past). This last figure (Fig. 38) indicates that V sin θ is not a sufficient correlating parameter for these tests for

*Measured approximately in our laboratory by stripping off a small piece of coating and weighing.

those cases where sufficient data is available for an evaluation. For example, the curves of Navy 6 at 1.5 M and 1.2 M (the only cases for which the effect of M and 0 can be examined separately) are widely separated. The effects of variation of 0 or V alone are shown in Fig. 35 - 37.

Figure 37 indicates the damage exponent for the relation

$$\text{Number Impacts/Vol.} \propto 1/V^n$$

It is shown that $n \cong 5$ for Navy 6 (material for which most data is available) at $\theta = 90^\circ$, but increases to 6.6 at 60°. Not enough data are available to determine a value at 30°. More sparse data for Navy 4 at 90° indicates $n \cong 20$ for this material over the velocity range available. No other assessments of n can be made from the present tests. However, we believe that it is a function of both velocity range and material, and have so indicated in the past.

Fig. 39 and 40 show impacts to 5 mm^3 volume loss and maximum volume loss rate vs. hardness for all materials (with the exception of Navy #9 which was only tested at reduced velocity) against hardness. The plots indicate a general trend at best which could not be used for engineering predictions.

Fig. 41 - 49 are the basic cavitation damage curves showing weight loss against time. The cavitation data is much less reproducible for materials of this type due to the difficult of preventing moisture penetration into the substrate which affects seriously the weight loss measurements. Since weight losses are so small and erratic, no meaningful estimate of incubation period is possible. Figure 50 correlates maximum MDPR from these tests against hardness. Again there is only a fairly general trend with hardness, and only limited capability for engineering prediction.

Figure 51 plots the reciprocal of maximum cavitation volume loss rate (MDPR) against impacts to 5 mm^3 volume loss for the various materials showing that a reasonable correlation exists between liquid impact and cavitation resistance for these materials.

Figure 52-55 are photos of damaged specimens from the impact tests at maximum velocity 90^o angles, and also from the cavitation tests. Figure 56-59 show typical damage patterns resulting from oblique impact (30^o and 60^o).

Table 2-A summarizes the damage results at maximum velocity along with the results from the cavitation test. Table 2-B shows the same data normalized to the least resistant material which then has a value of unity, the more resistent materials having the higher values. Table 2-C lists the relative rankings of the materials in maximum velocity impact at 90^o (according to impacts to 5 mm^3 volume loss and maximum MDPR for the cavitation test).

IV. CONCLUSIONS

The following major conclusions result from this work.

1. Six aircraft rain erosion materials supplied by NADC have been tested using our water gun device at impact velocities ranging from 1.5 to 0.6 Mach and impact angles from 90^o to 30^o a room temperature. All of these materials suffered some weight loss at the maximum condition of Mach 1.5 at 90^o, but Navy #5 (Midland Magna Ceramic) was the best. Several of the materials suffered no damage at Mach 1.2 at any angle, but Navy#6(Chycar AFG) was damaged at all conditions. Thus the effects of angle and velocity could be evaluated. A 7th material, Navy #9, was tested as requested only at Mach 0.9, 90^o, and suffered considerable damage at that condition. Complete damage results are shown in Table 1, and comparison under Mach 1.5 at 90^o for the Navy materials tested under this condition is made between impact and cavitation tests in Table 2. Some results for Epon-828 and Plexiglas (Navy #1 and #2) are also included for comparison. These latter two were tested at Mach 1.82 only.

2. All materials have also been tested in our stationary specimen vibratory cavitation facility. These results are compared with the impact results for maximum velocity and 90^{o} in Table 2. For this family of materials the relative erosion resistance rankings according to impact and cavitation tests is quite similar, particularly for impacts to 5 mm^3 volume loss.

3. For this particular group of materials and impact test device, damage rate cannot be correlated against V sin θ alone as has often been hypothesized. A proportionate increase in V produced generally a different damage increment than a similar increase in sin θ.

4. The damage exponent appears to depend on both material and angle for these tests. A value of about 5 (as often expected) was found for the only material where comprehensive data was available (Navy 6) at 90^{o} impact, but n = 6.6 was found for 60^{o} and the same. No other evaluation of the effect of angle was possible. Very sparse data for Navy 4 (only other comparison possible) indicated $n \cong 20$ at 90^{o}. A computerized study of the impact phenomenon is proceeding in this laboratory at present which will hopefully help to clarify this situation (2).

V. REFERENCES

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 Int'l Conf., Rain Erosion and Assoc. Phenomena, Farnborough, England, 1970; also available as Report UMICH 02643-5-I, May 1970.

2. Y. C. Huang, Ph.D. Thesis, 1970 (in preparation).

Table 2 - Comparison of Materials, and Water C[illegible] with Cavitation Tests, at 90° Impact, Mach 1.5

A. Actual Data

Material	MDPR (Cavit. -mils/hr.)	Impacts to 5 mm^3 Vol. Loss	Max. WLR (mg/Impact)
Navy 1	11.4	7*	1.95
Navy 2	4.4	2.4*	4.96
Navy 3	0.34	33	0.366
Navy 4	0.75	10	1.833
Navy 5	0.63	812	0.90
Navy 6	0.84	14	5.25
Navy 7	4.91	12	2.55
Navy 8	5.16	127	0.058
Navy 9	41.5	300	0.044**

*Mach = 1.82

**Mach = 0.9 ; not compared in rankings because of low test Mach.

B. Normalized Data

Material	MDPR (Cavit.)	Impacts to 5 mm^3 Vol. Loss	Max. WLR (mg/impact)
Navy 1	33.60	0.212	5.32
Navy 2	12.90	0.073	13.6
Navy 3	1.00	1.00	1.00
Navy 4	2.50	0.302	5.00
Navy 5	1.85	24.6	2.46
Navy 6	2.47	0.422	14.40
Navy 7	14.40	0.362	6.95
Navy 8	15.20	3.84	0.158
Navy 9	122.	9.02	0.120

C. Material Rankings

(Most resistant material = Highest ranking)

Navy 1	2	2	4
Navy 2	5	1	2
Navy 3	9	6	7
Navy 4	6	3	5
Navy 5	8	8	6
Navy 6	7	5	1
Navy 7	4	4	3
Navy 8	3	7	8
Navy 9	1	--	--

3022

1. Typical Jet Shape

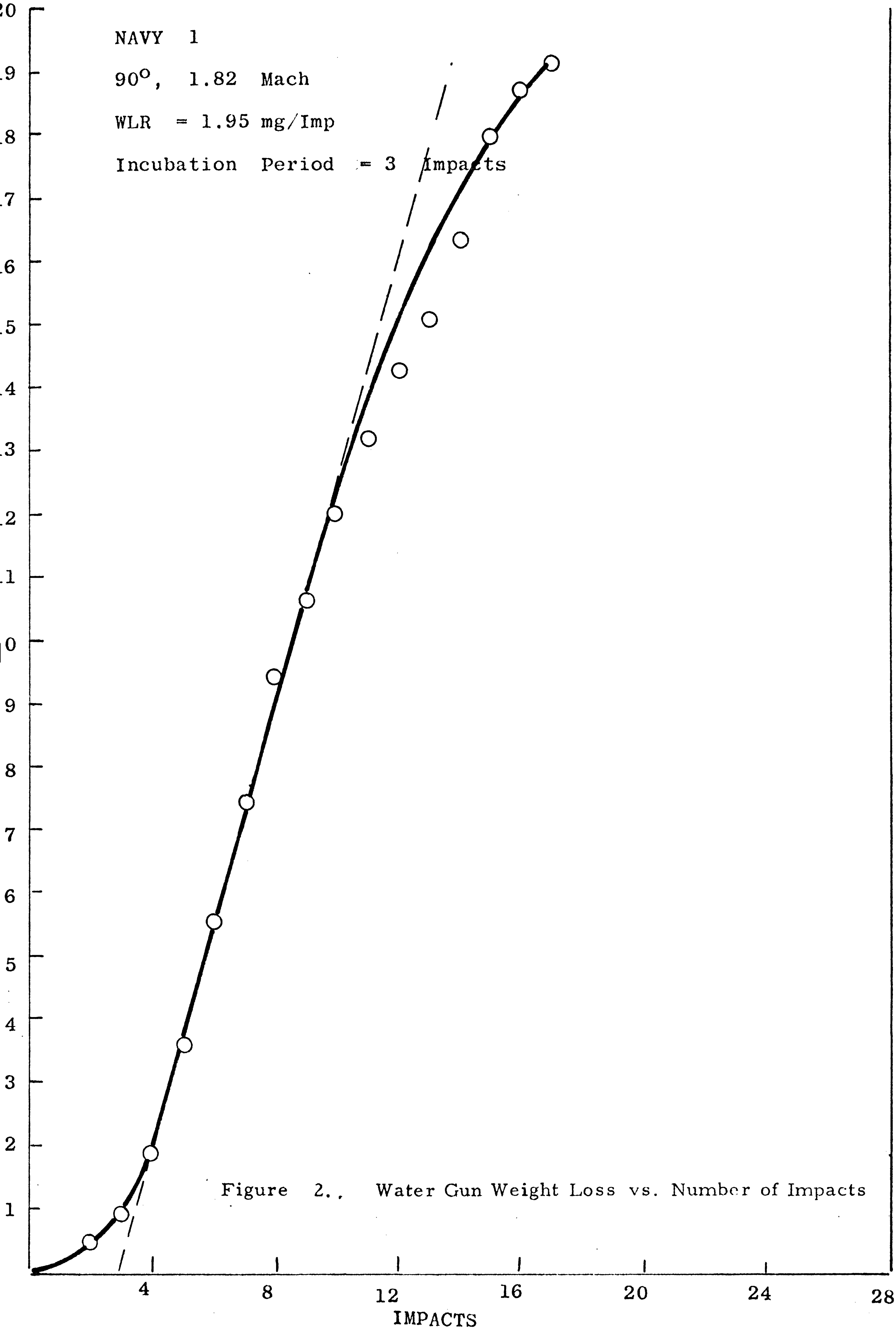

Figure 2.. Water Gun Weight Loss vs. Number of Impacts

3207

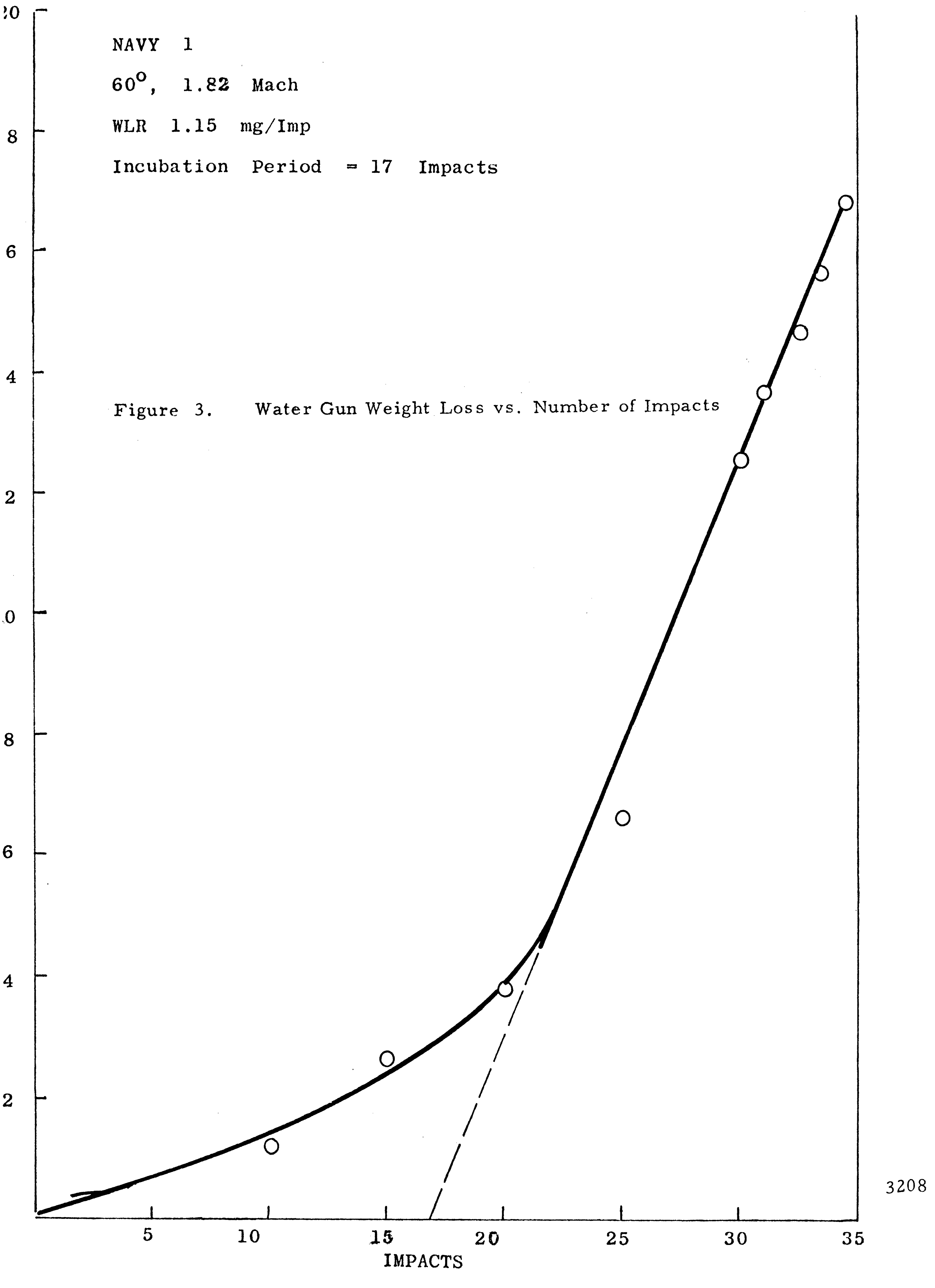

Figure 3. Water Gun Weight Loss vs. Number of Impacts

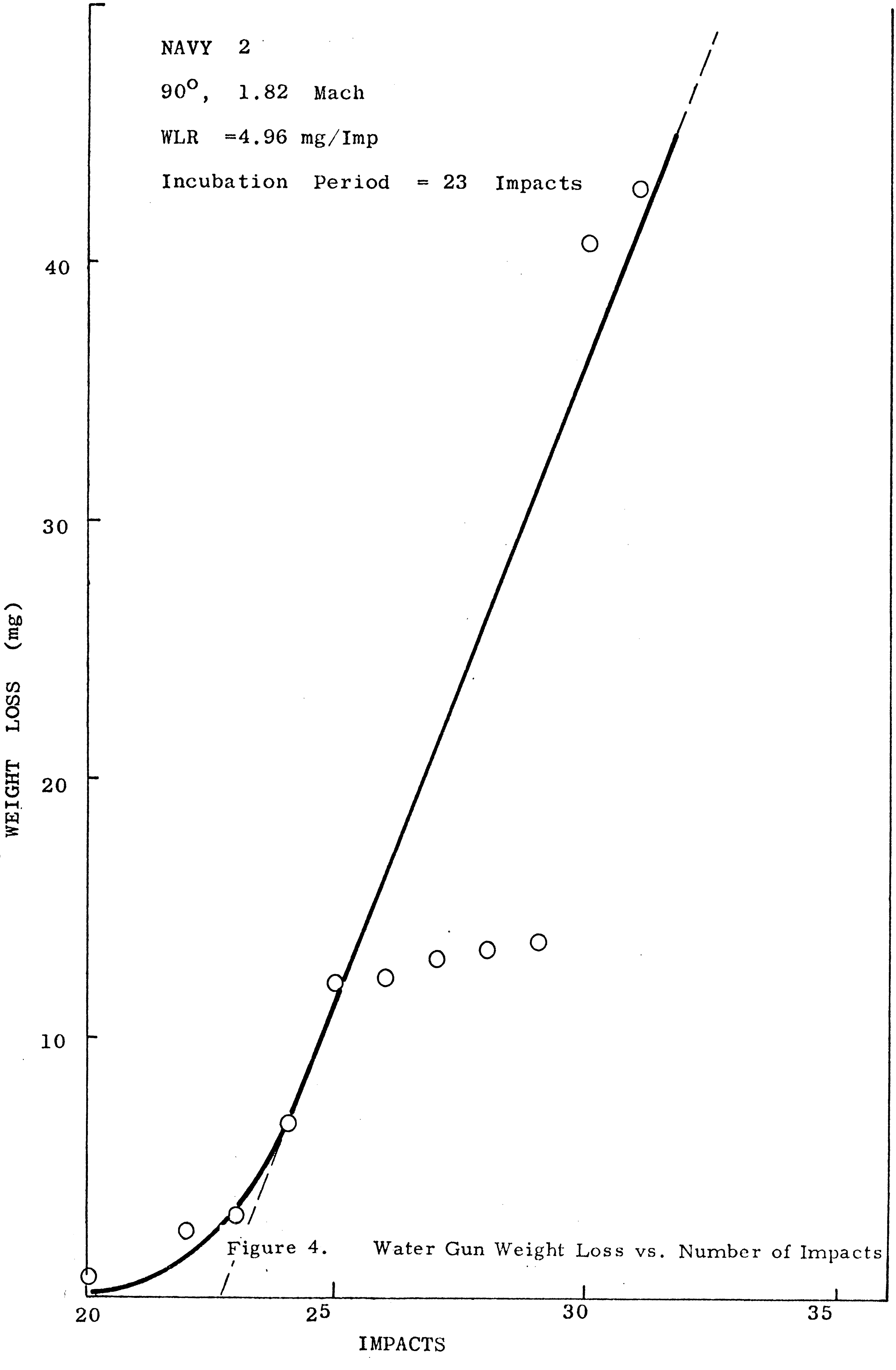

Figure 4. Water Gun Weight Loss vs. Number of Impacts

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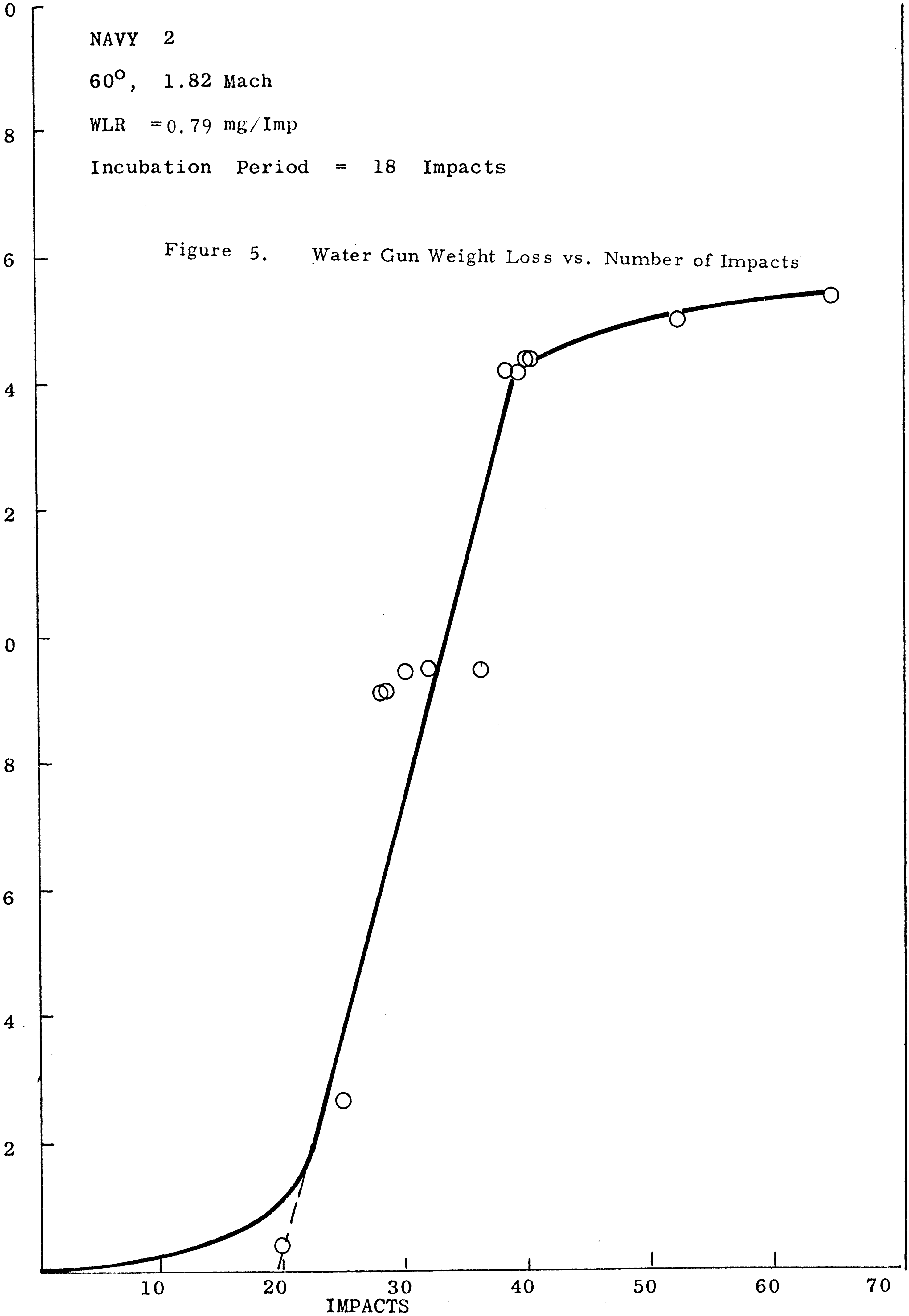

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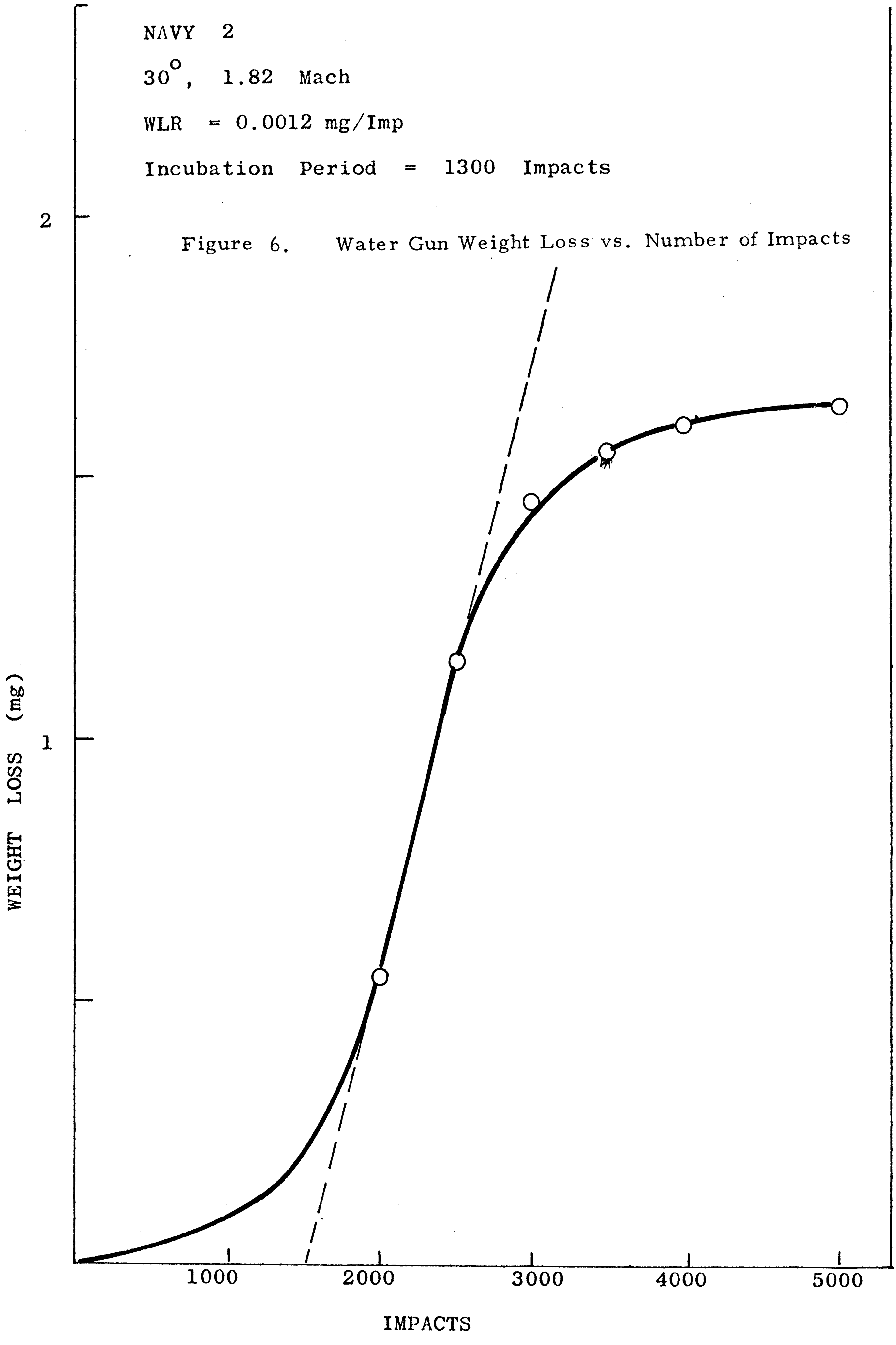

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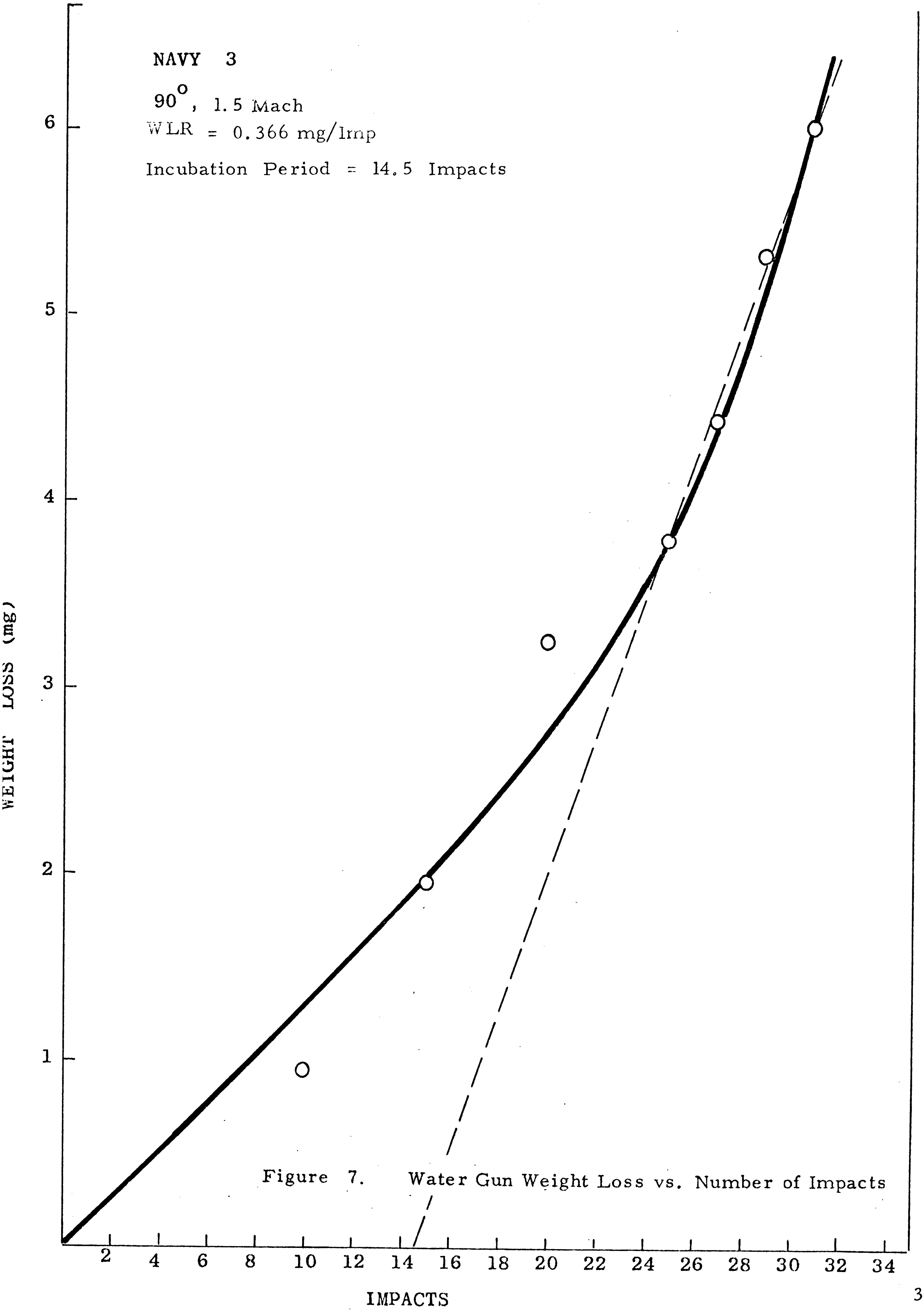

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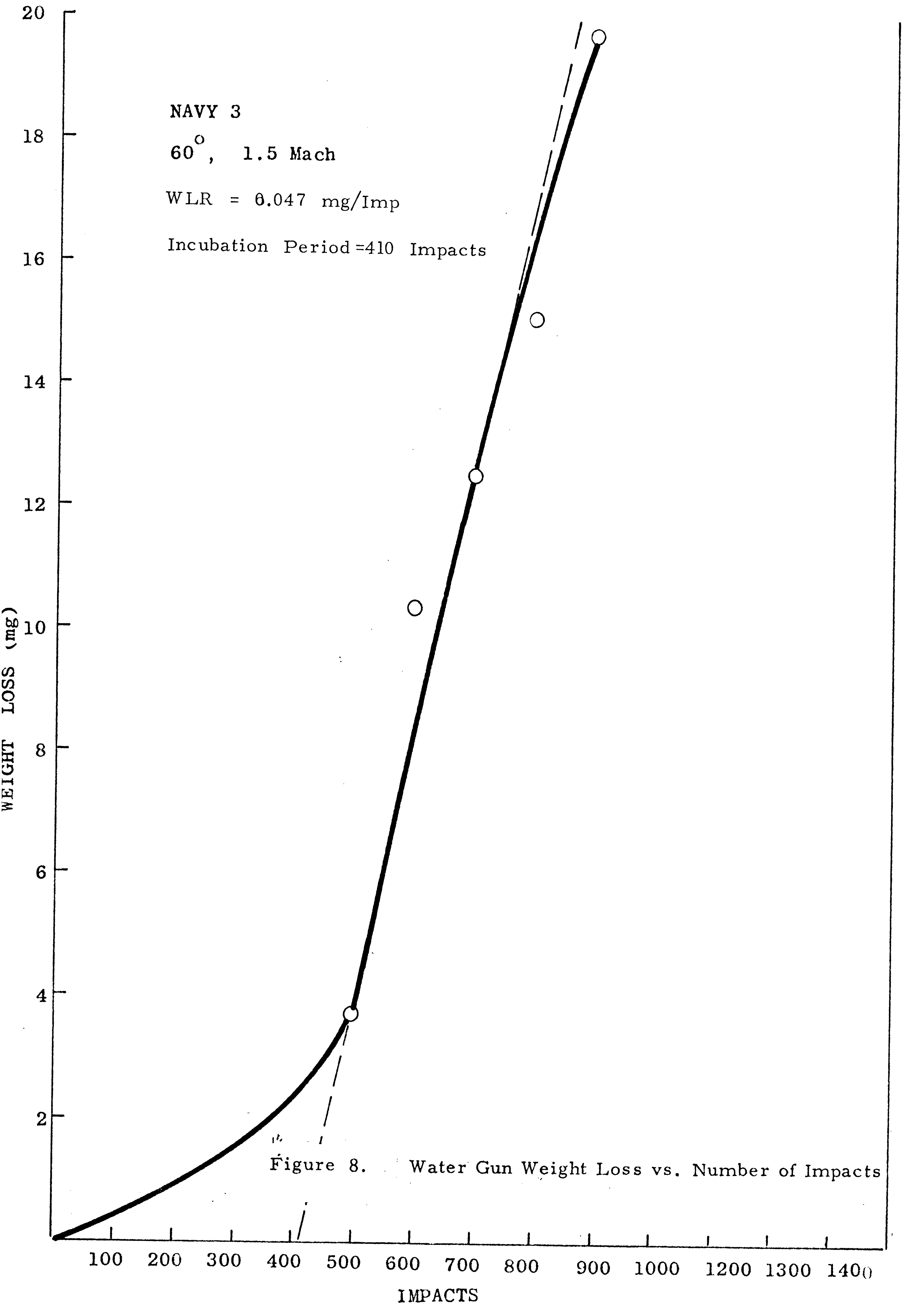

Figure 8. Water Gun Weight Loss vs. Number of Impacts

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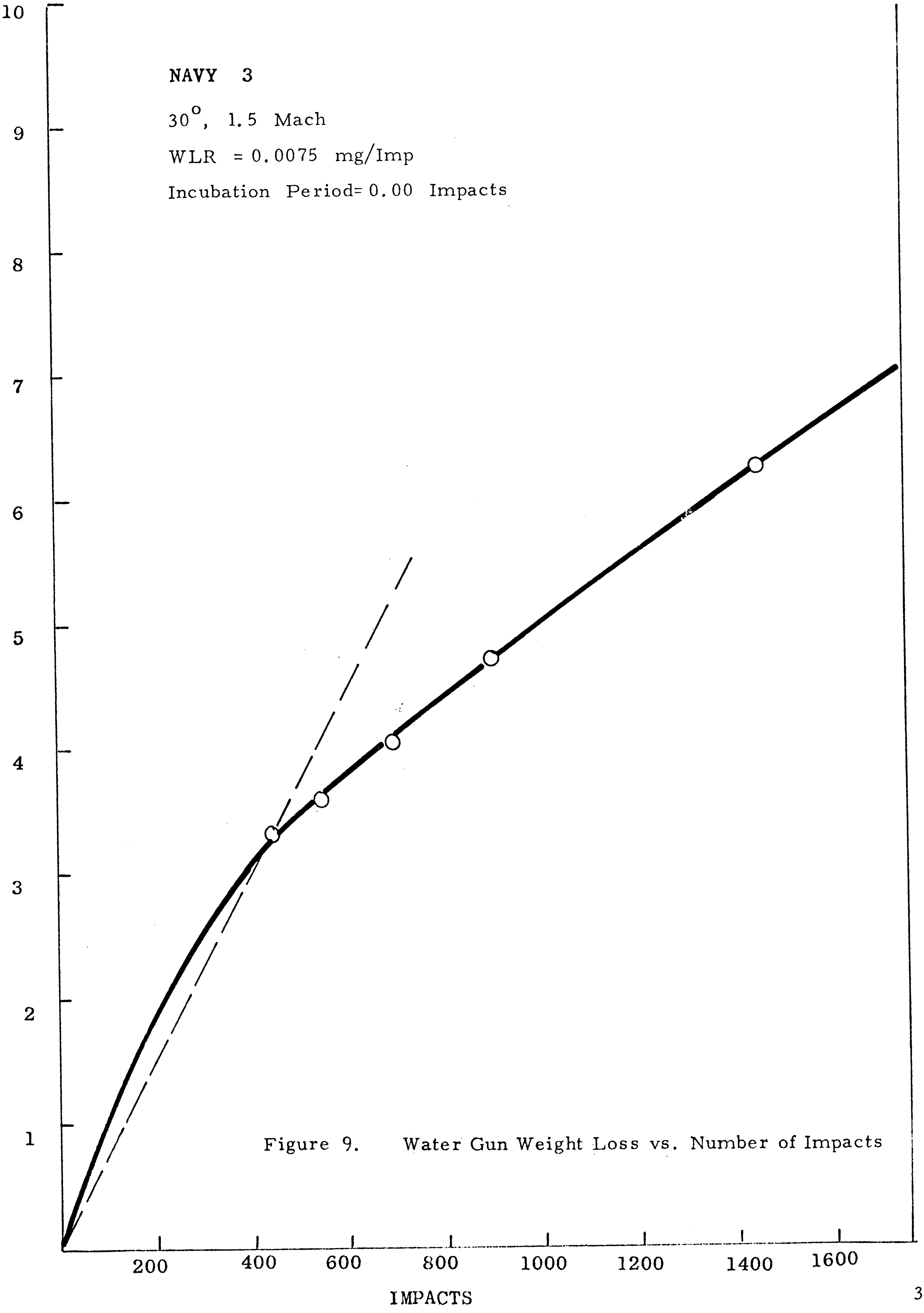

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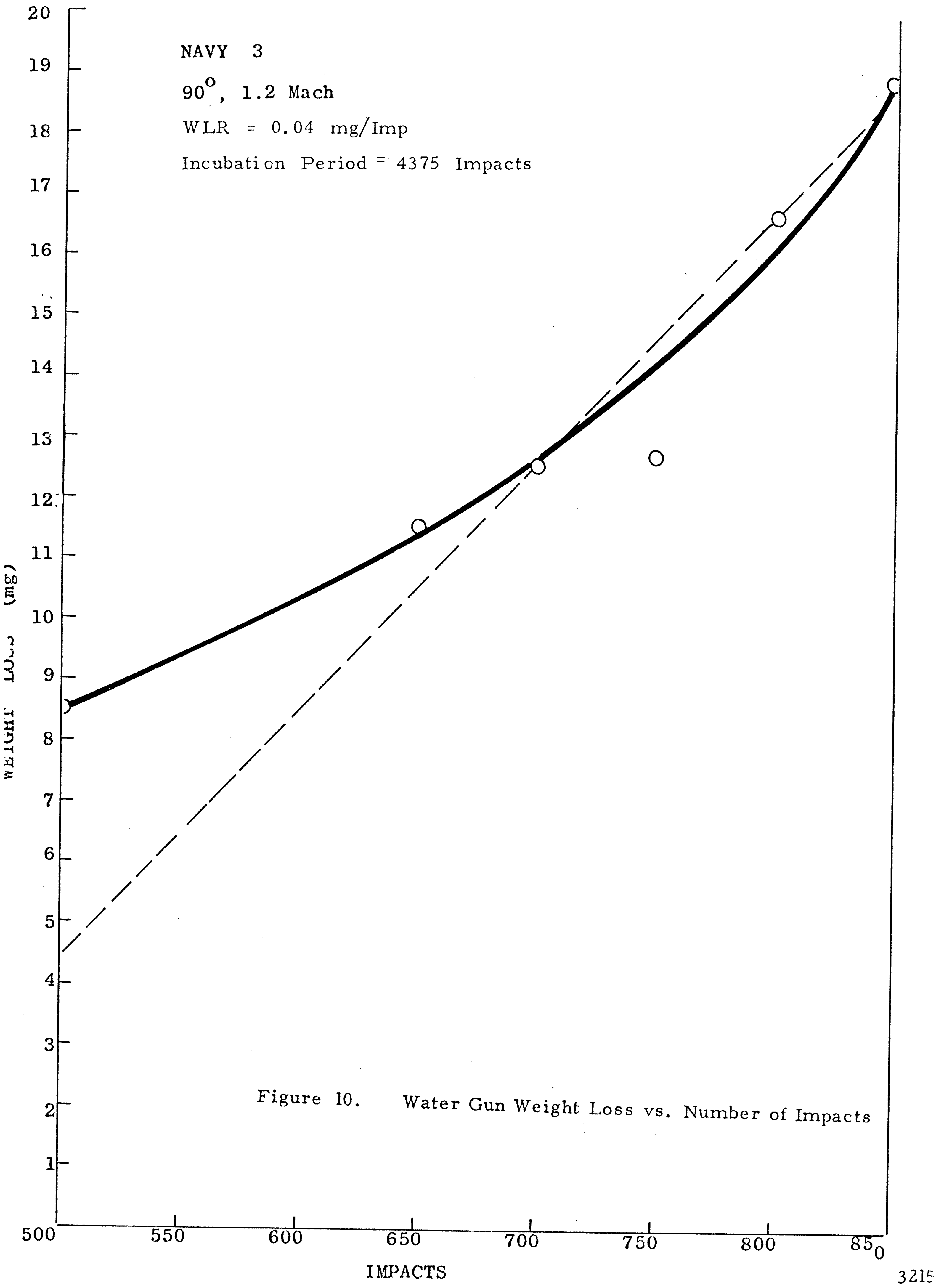

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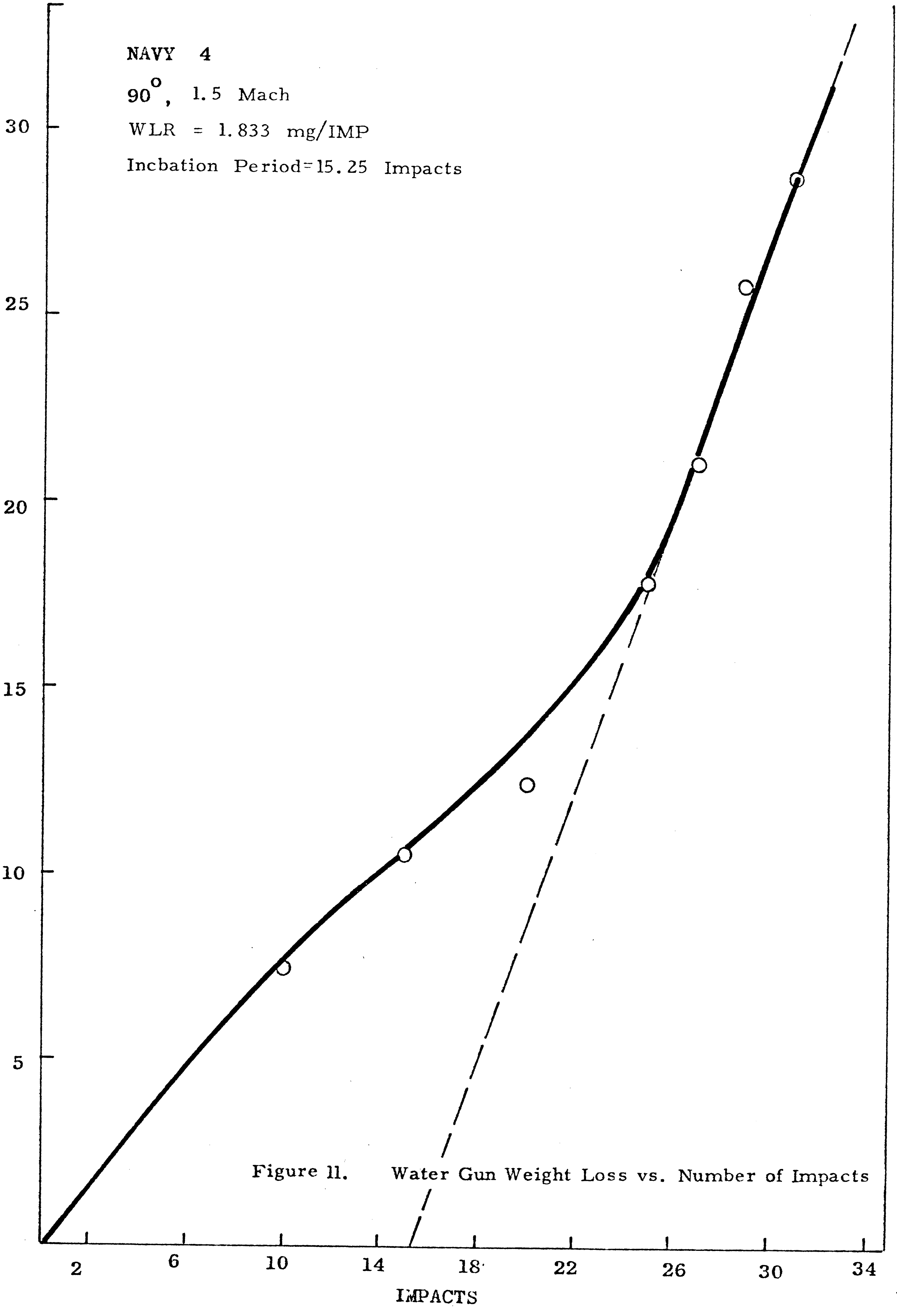

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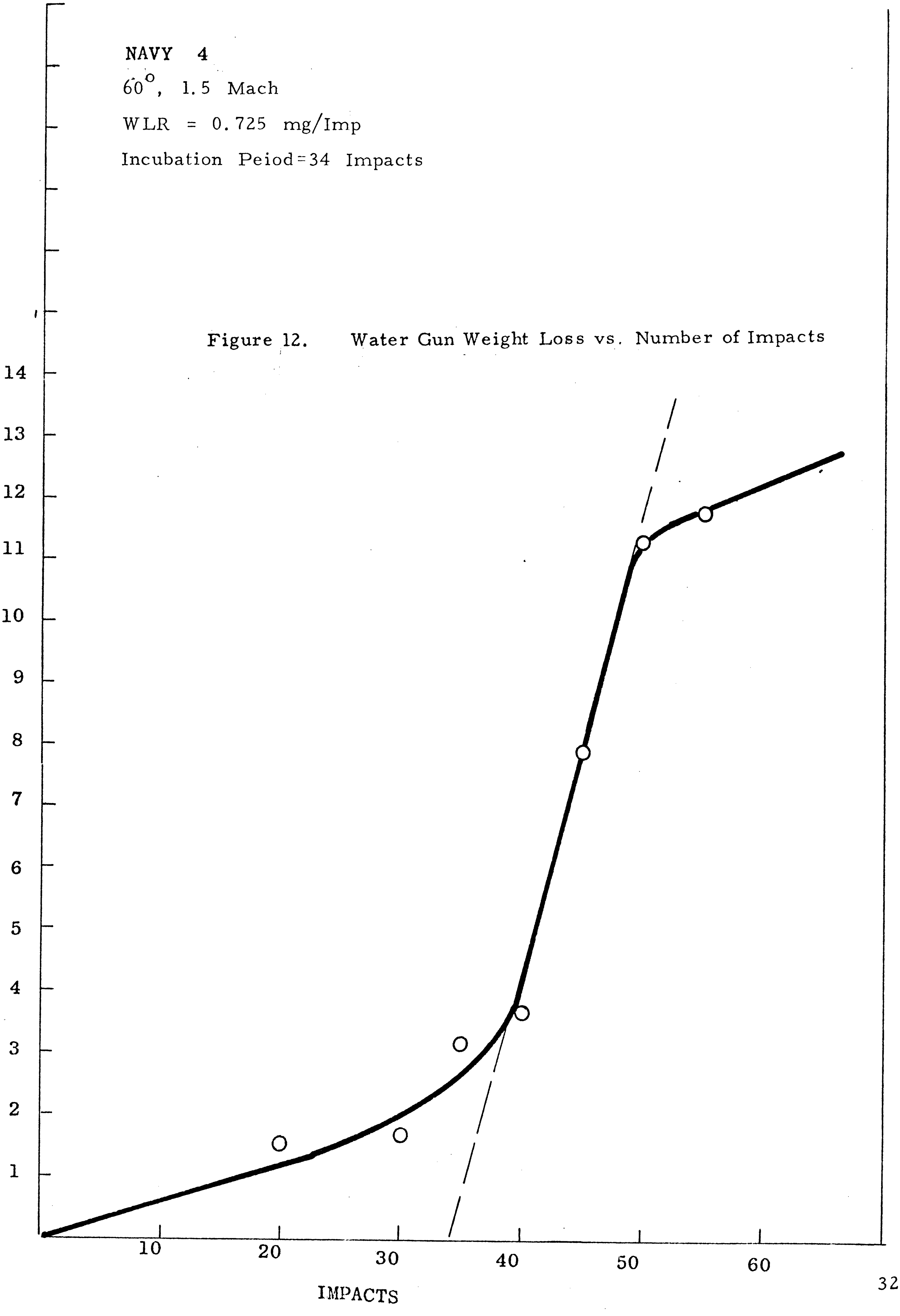

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3217

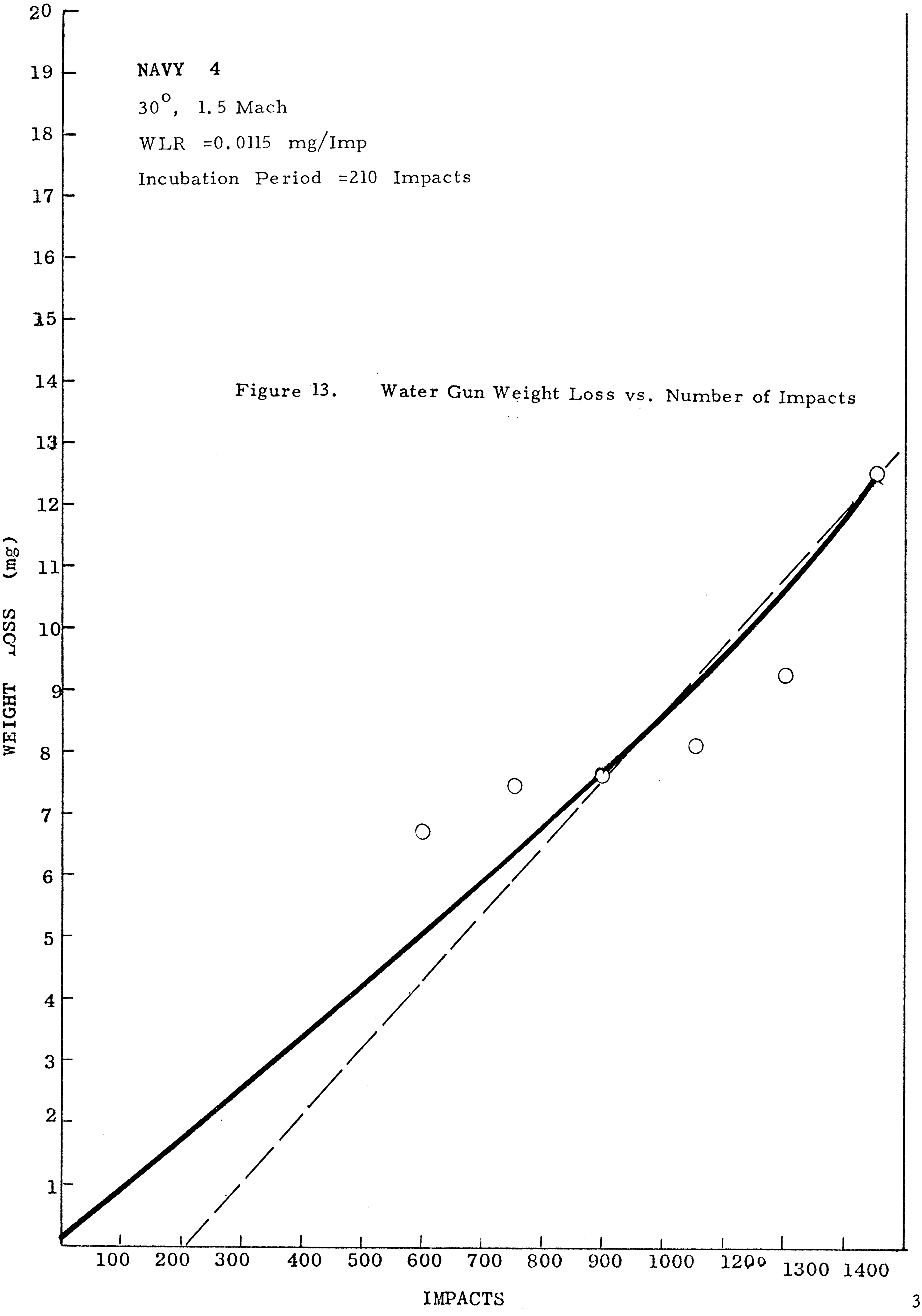
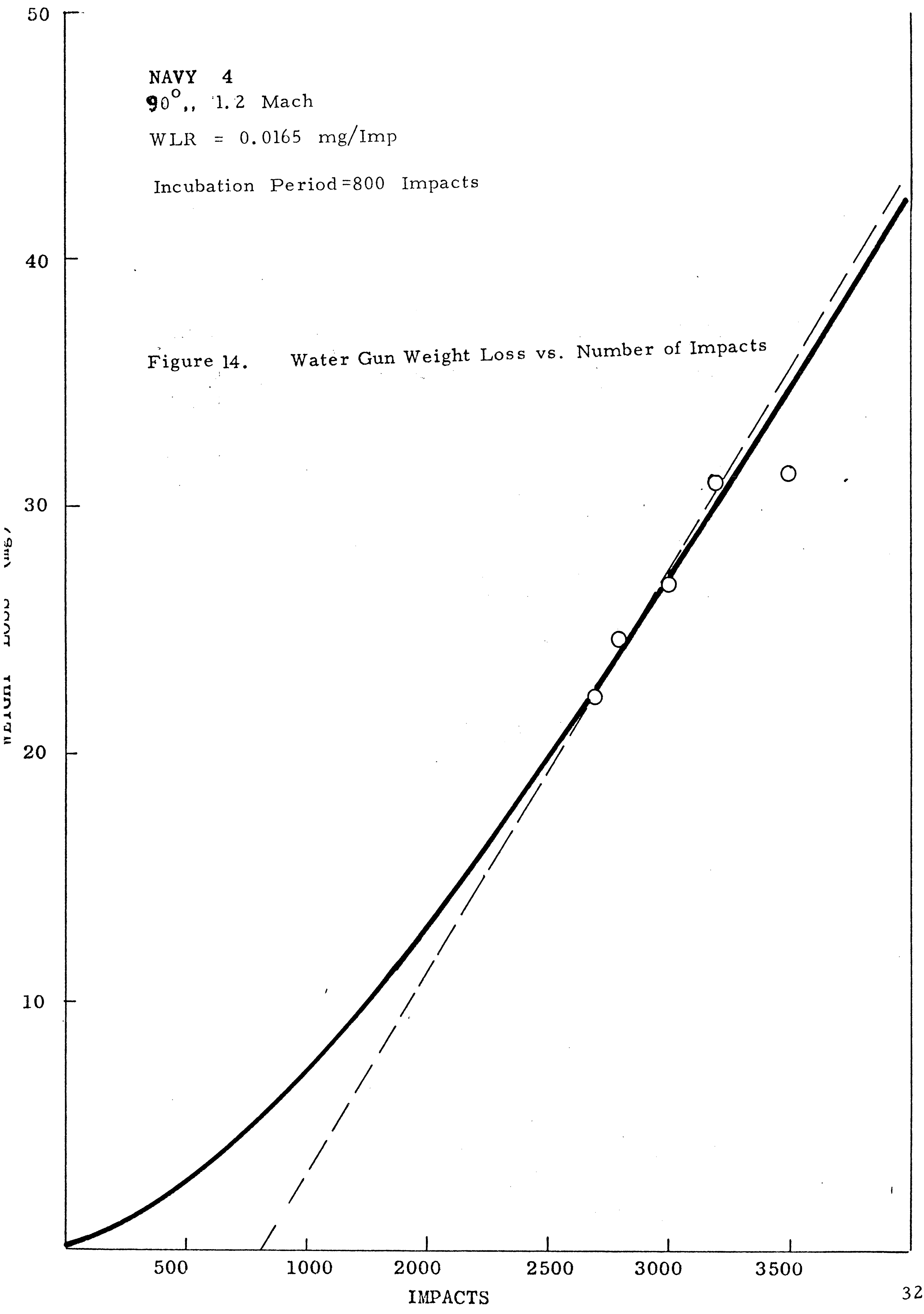


Figure 13. Water Gun Weight Loss vs. Number of Impacts

3218



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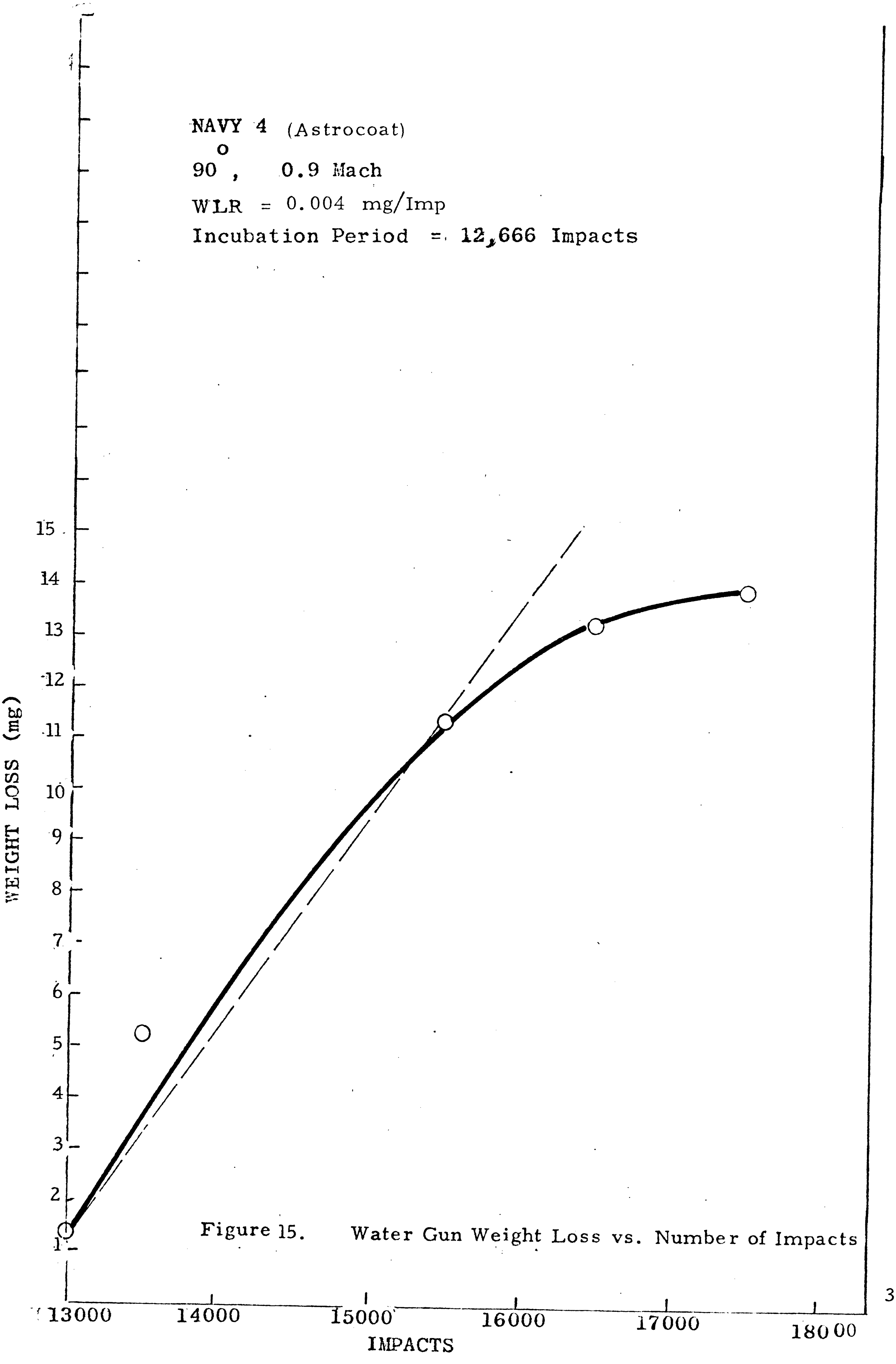

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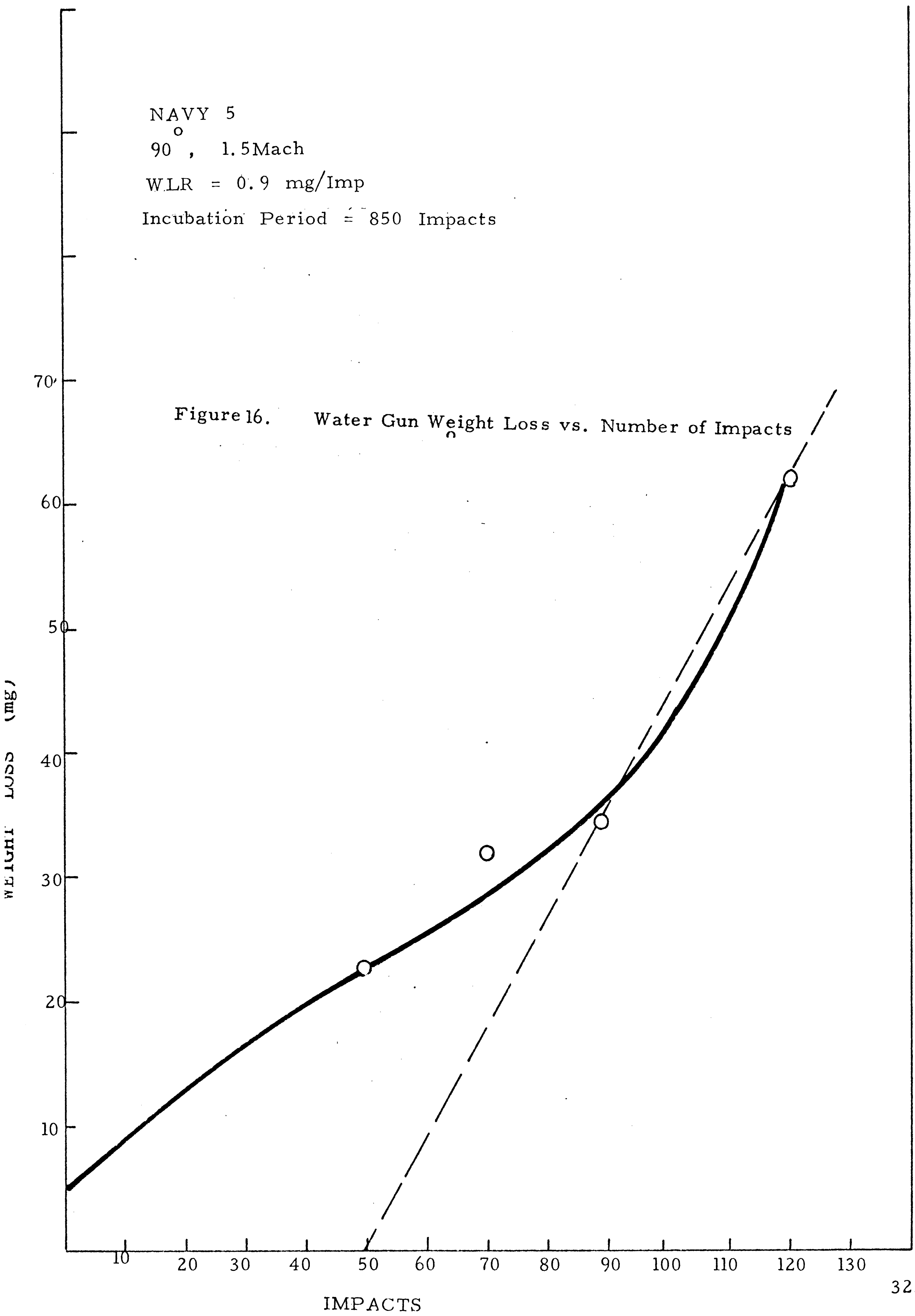

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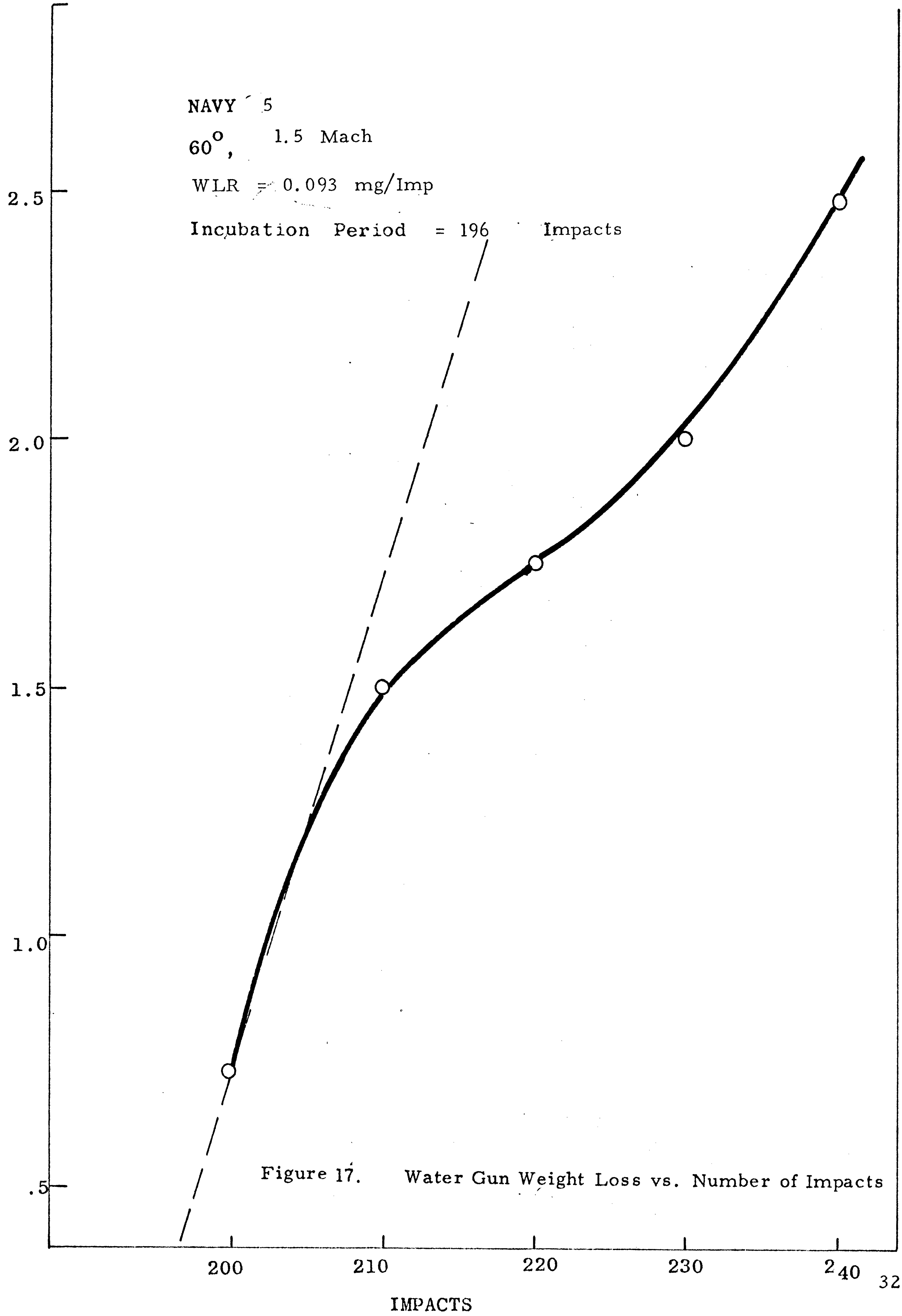

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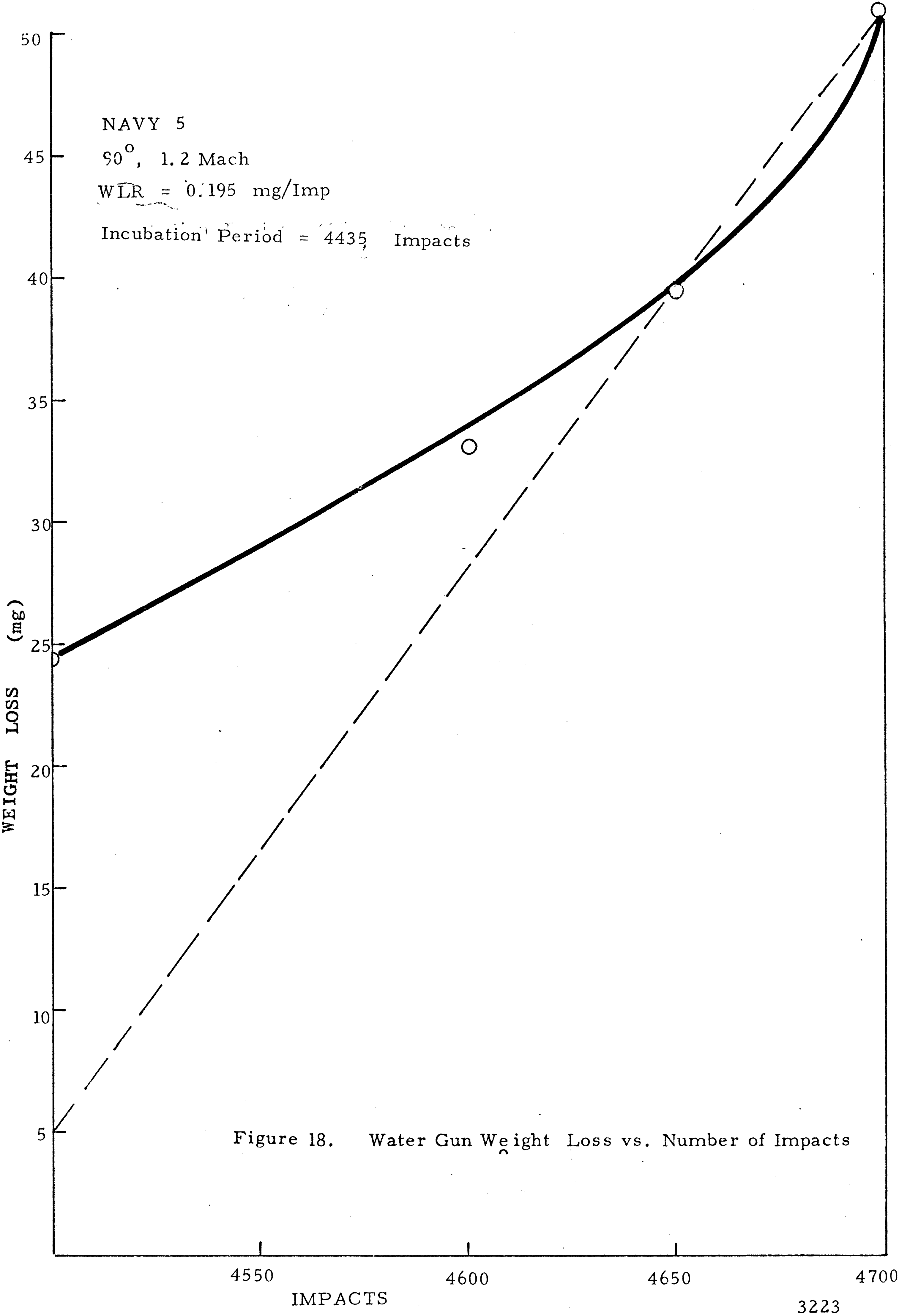
3222



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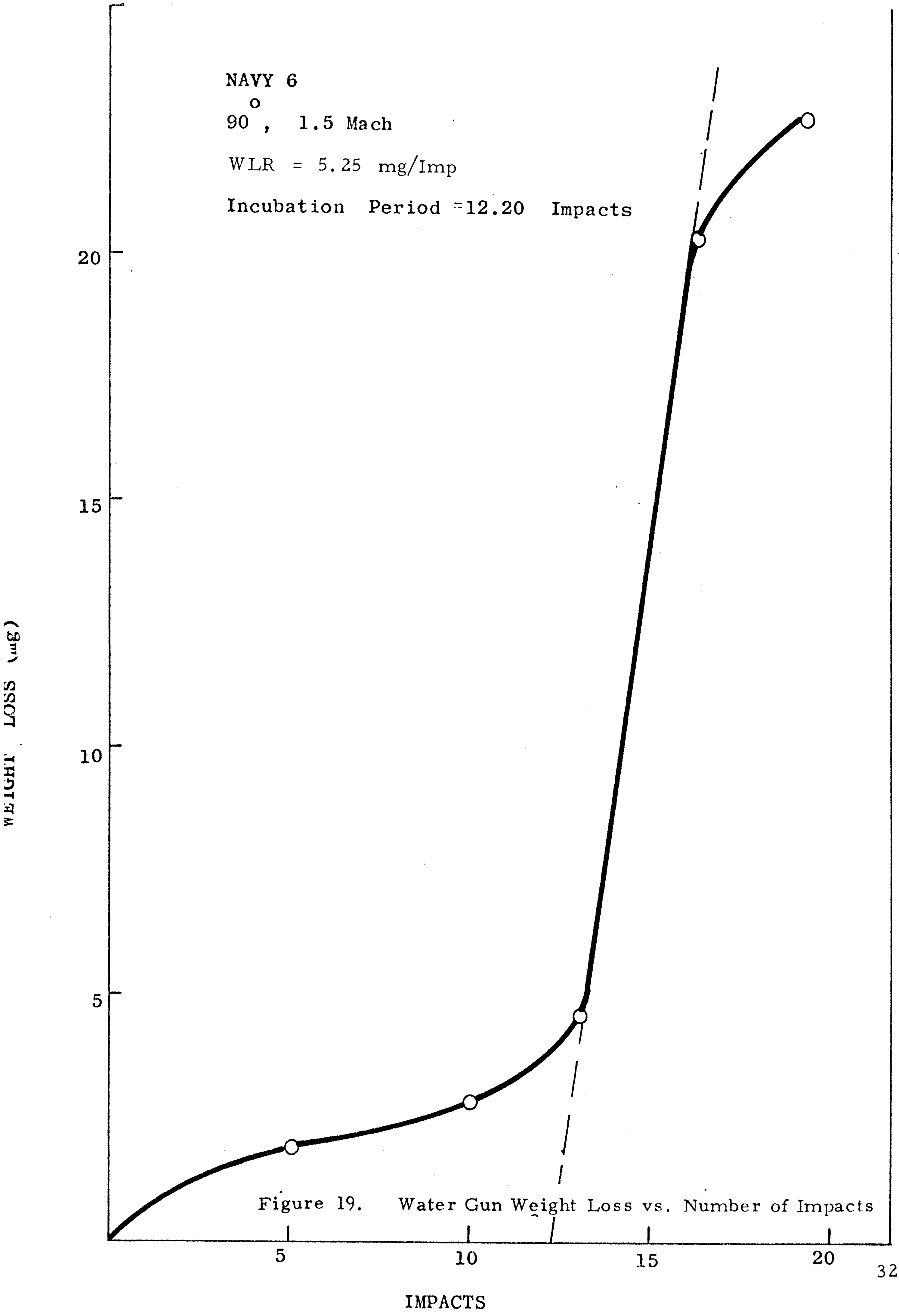

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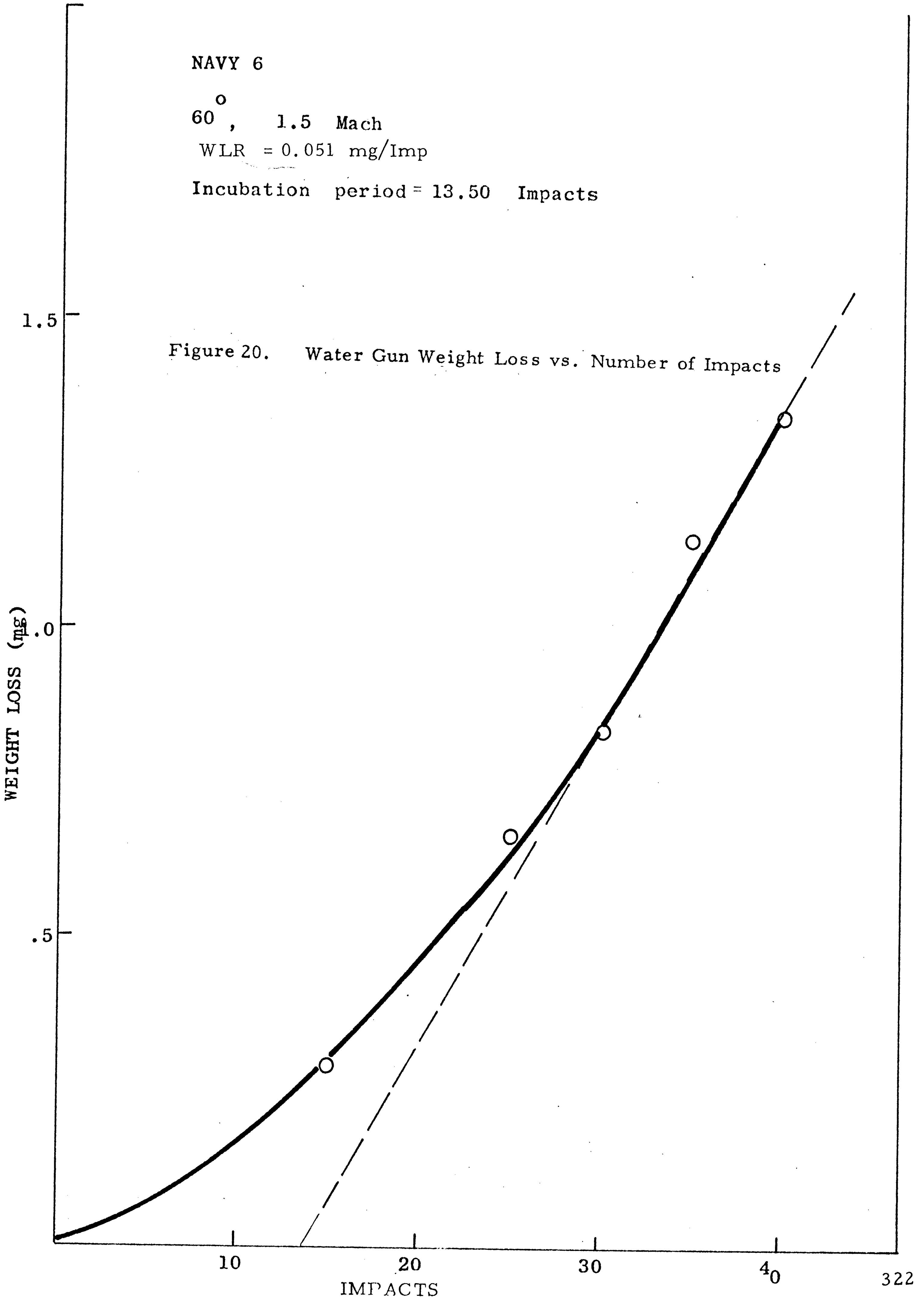

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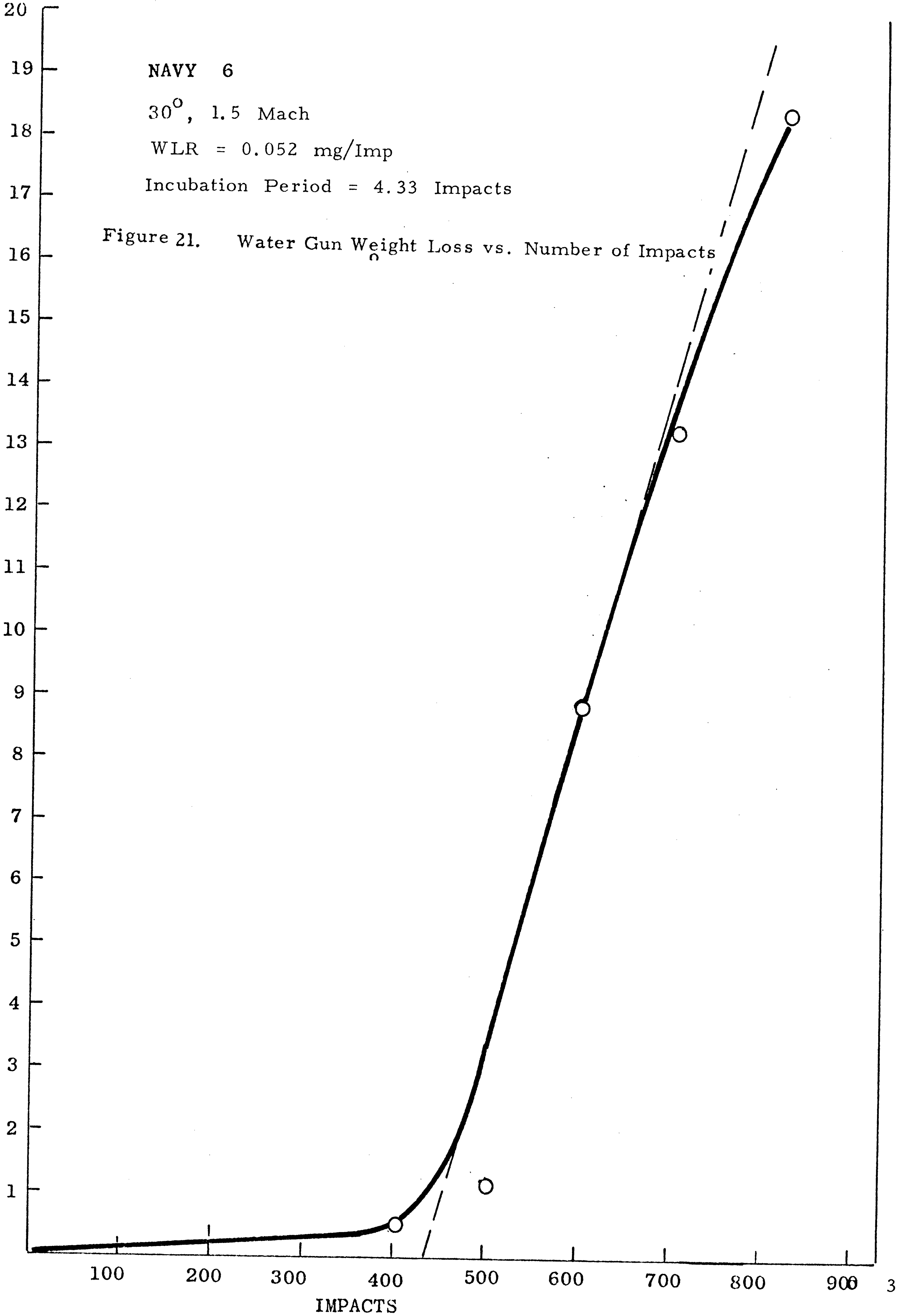

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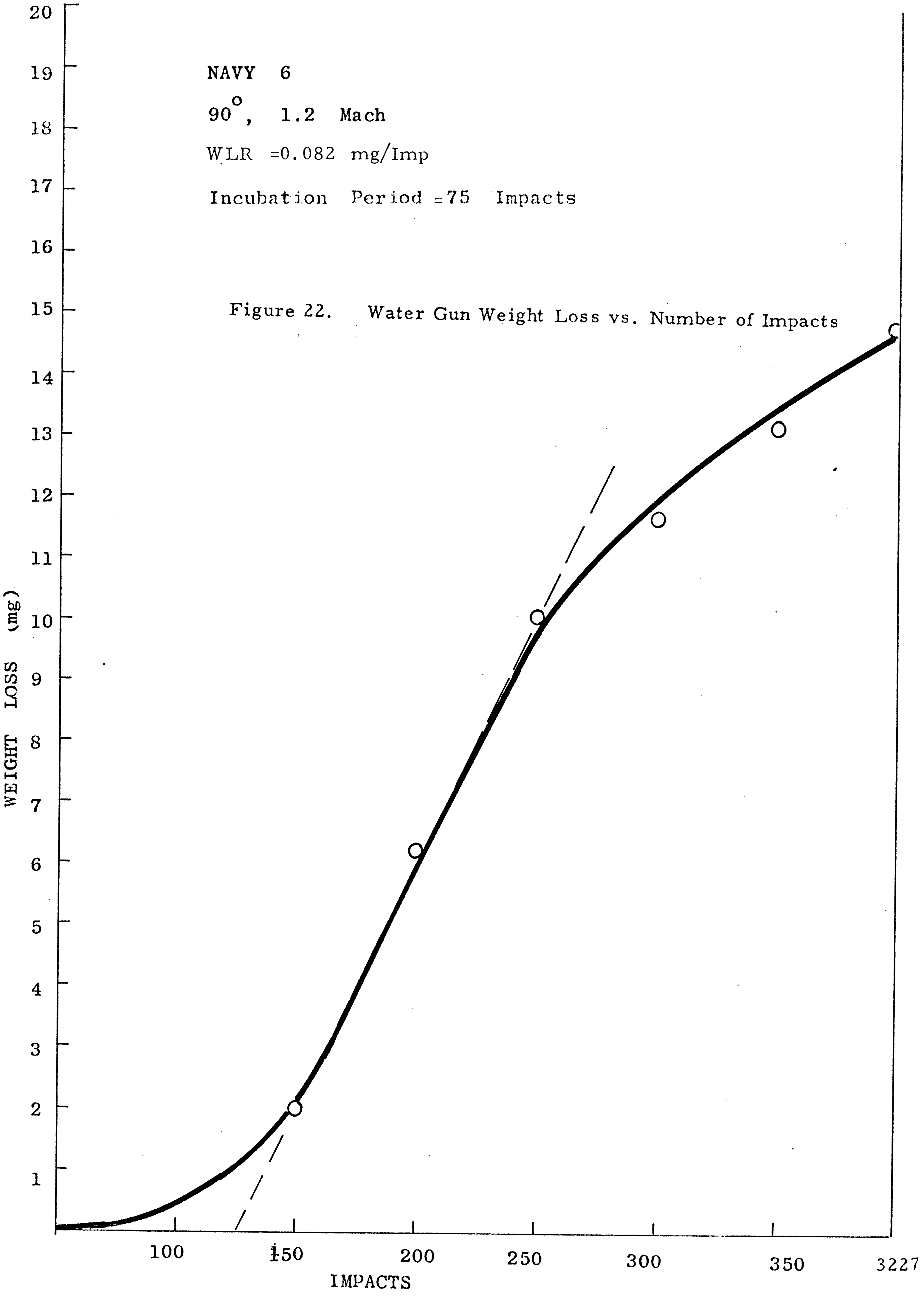
3226



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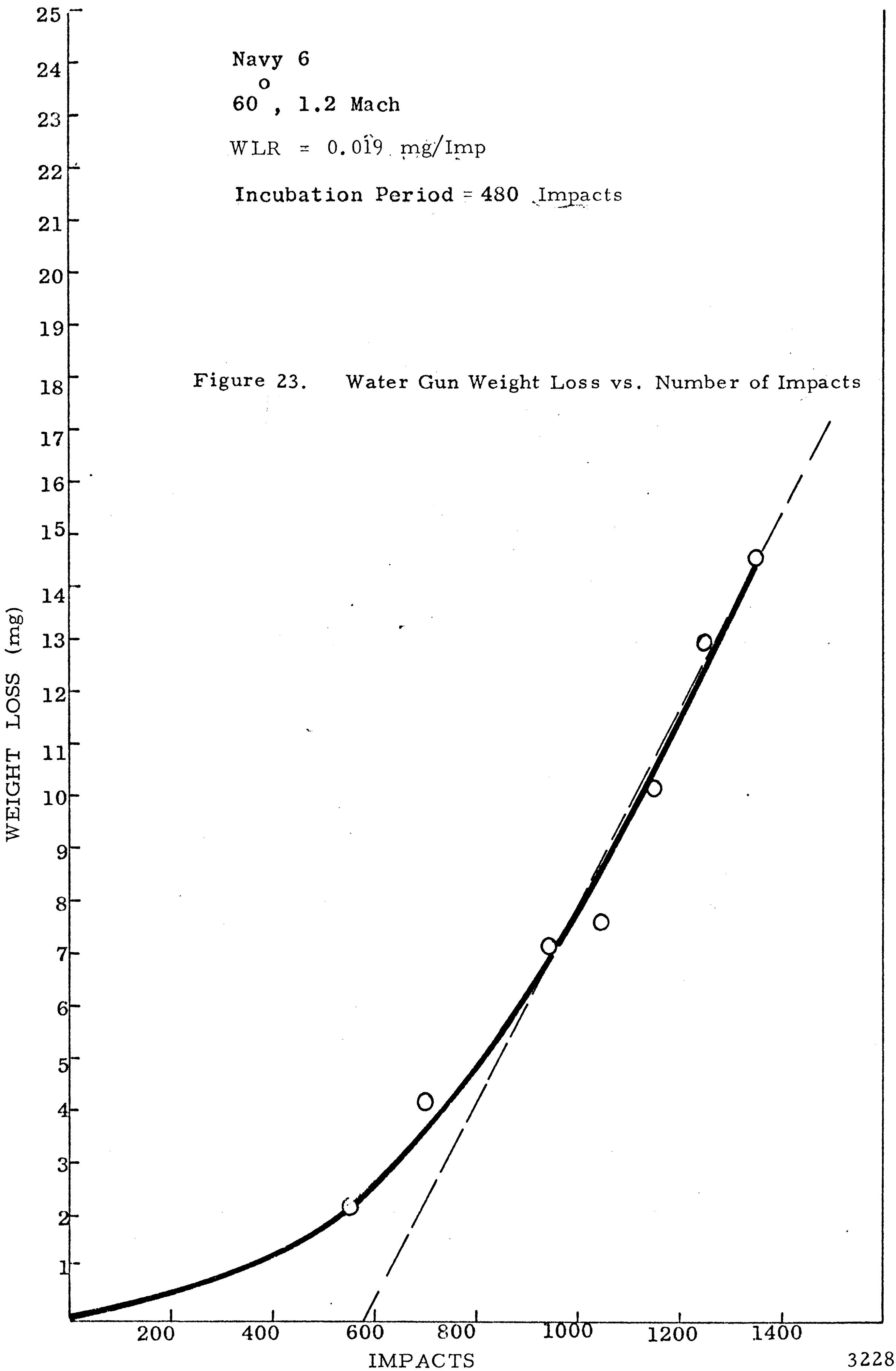

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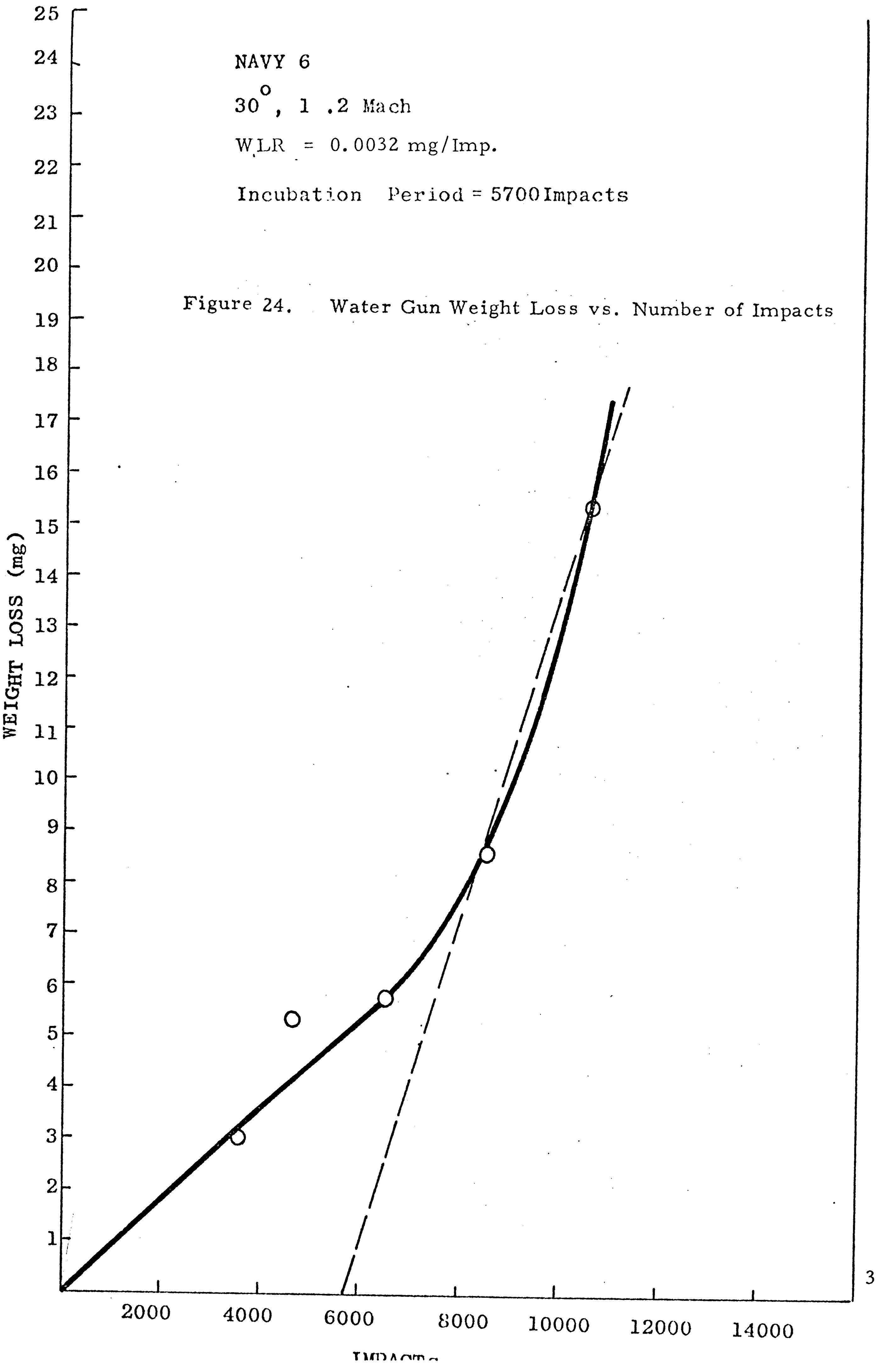

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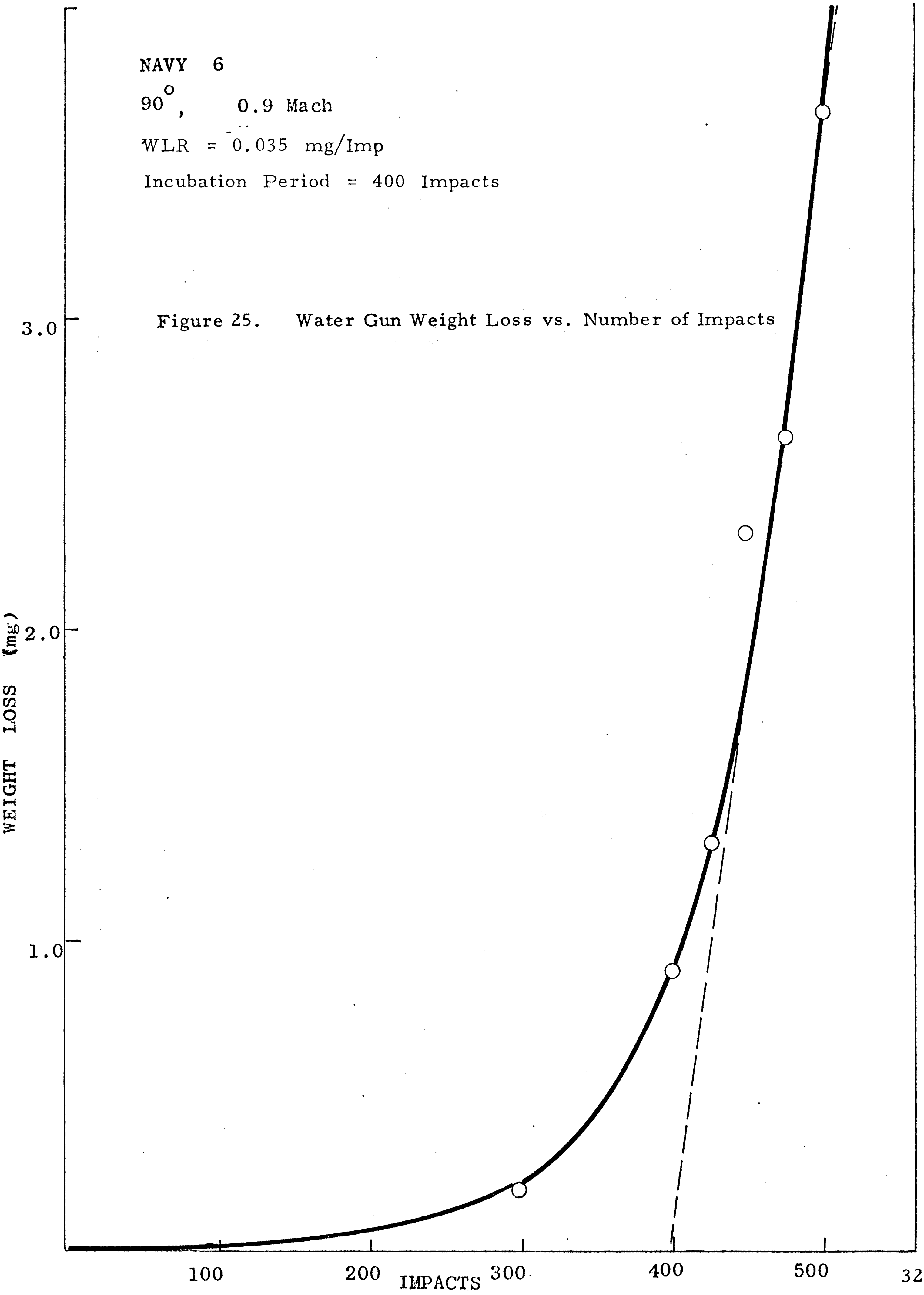

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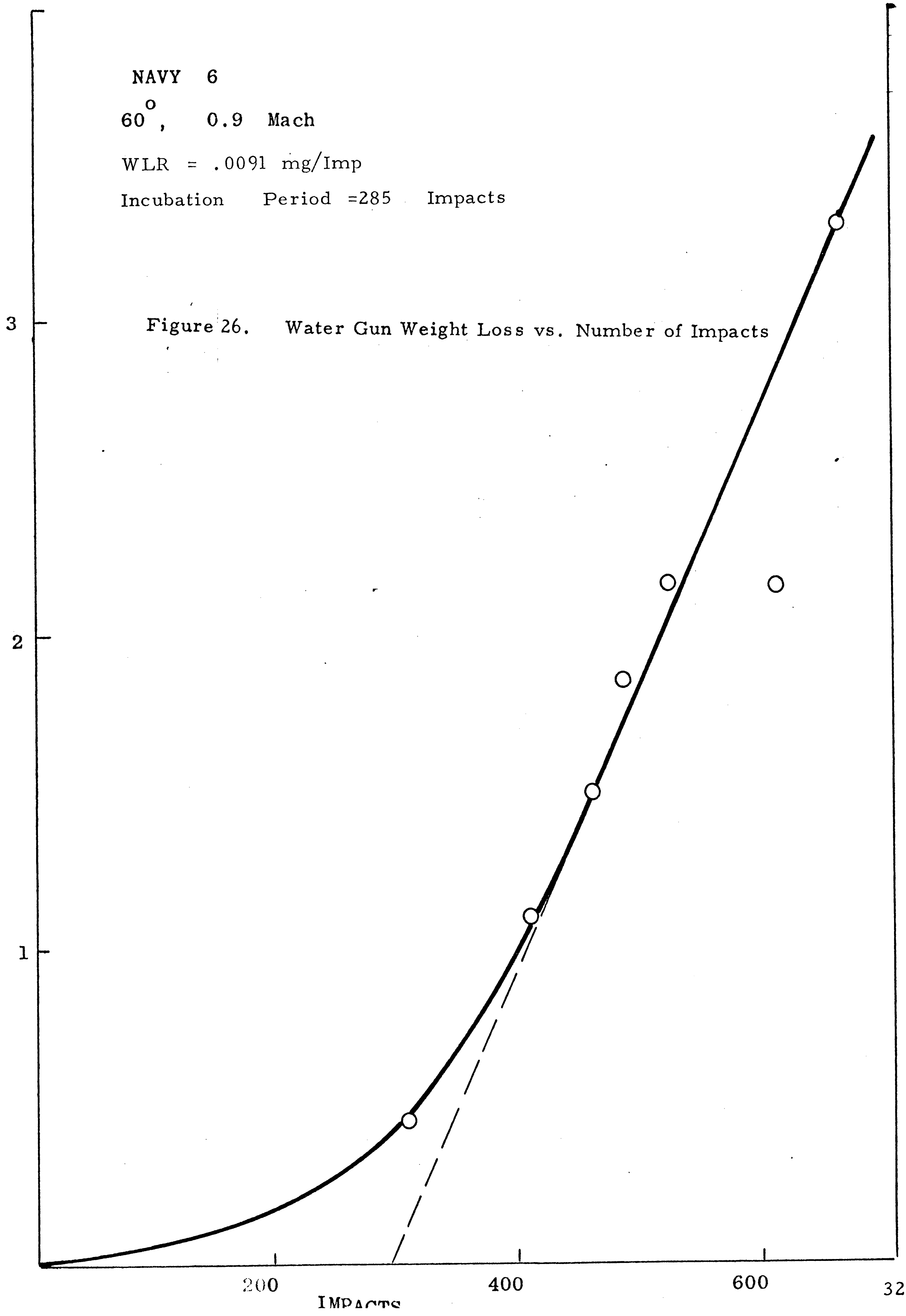

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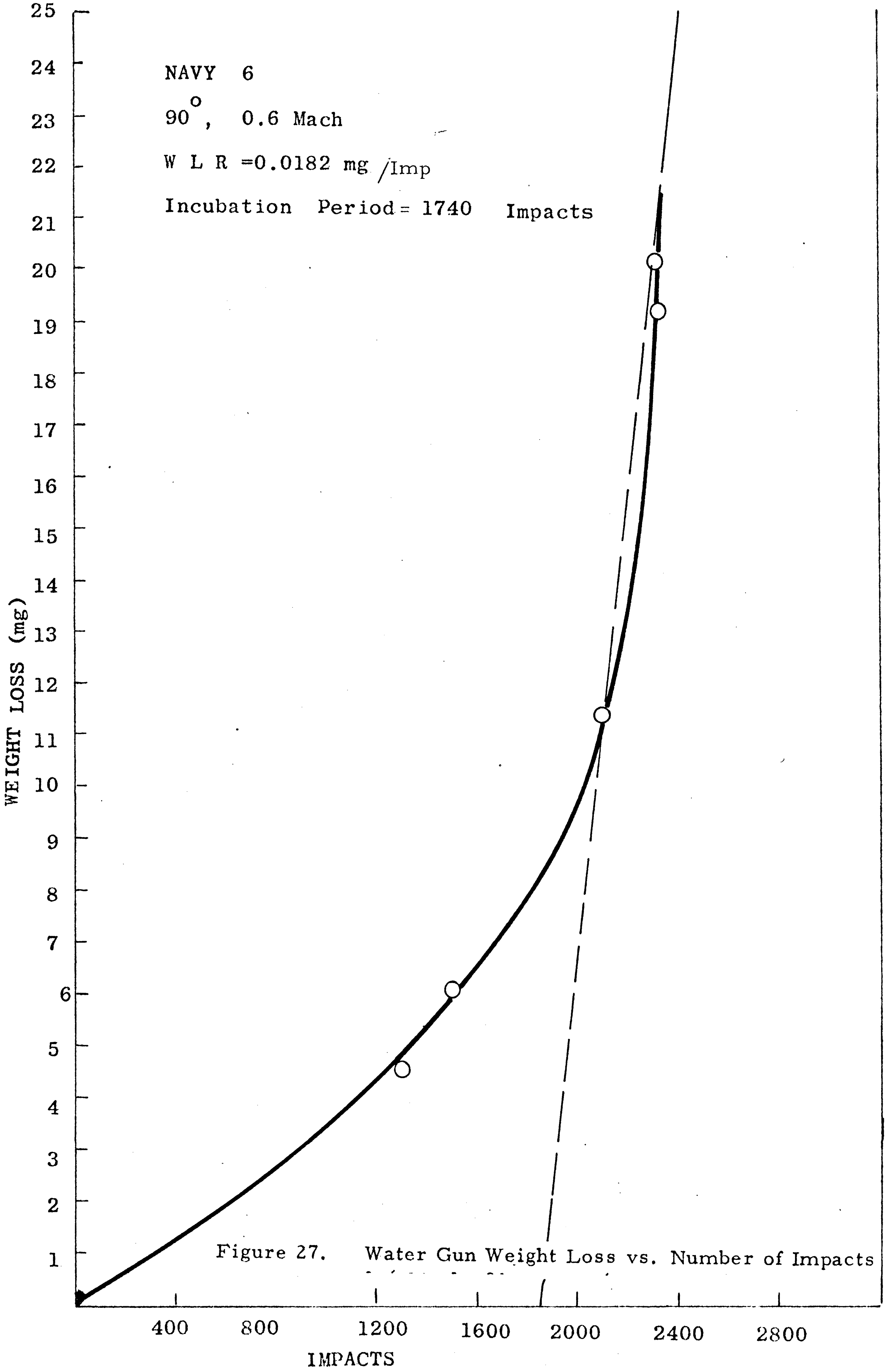

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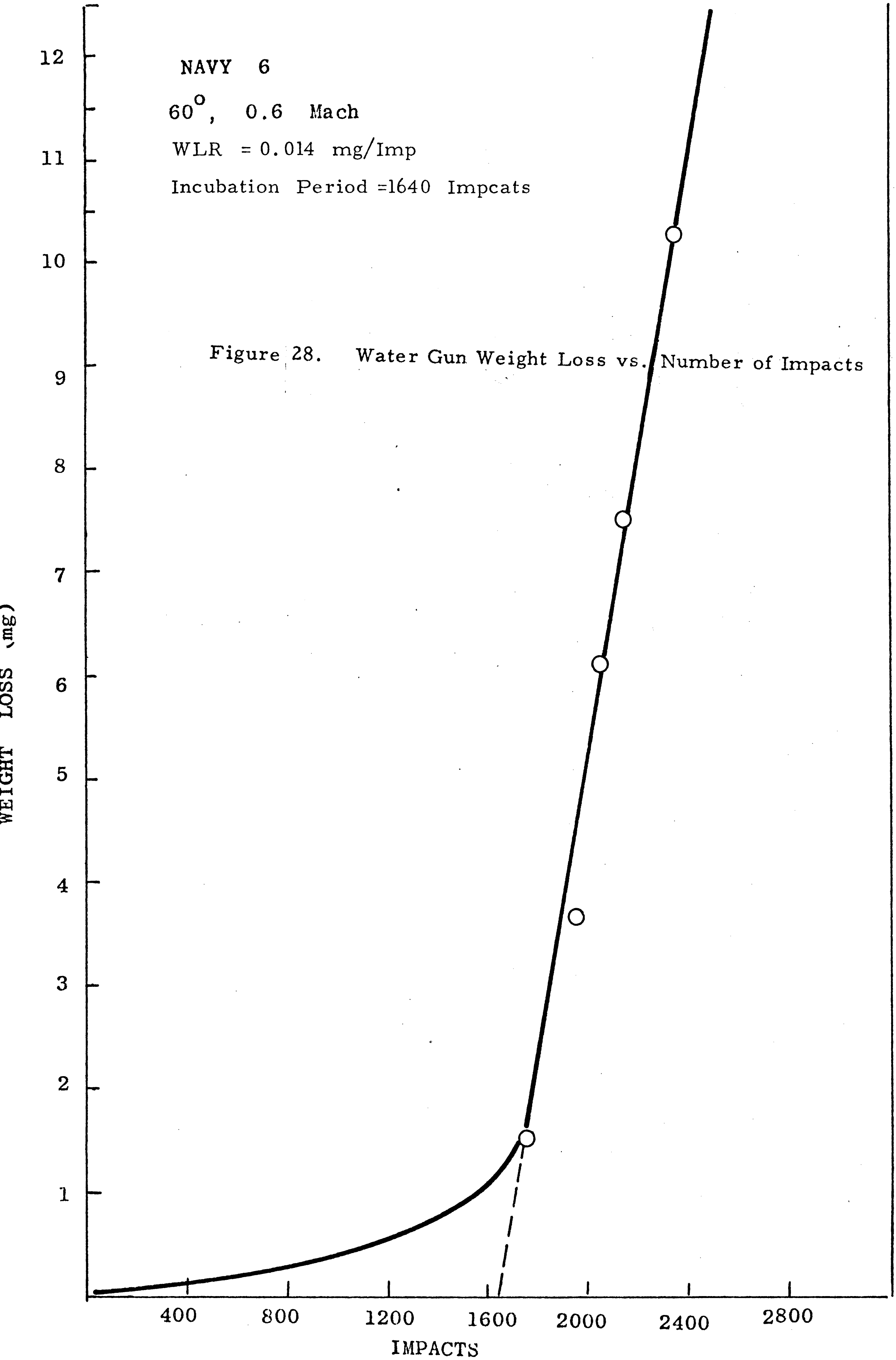

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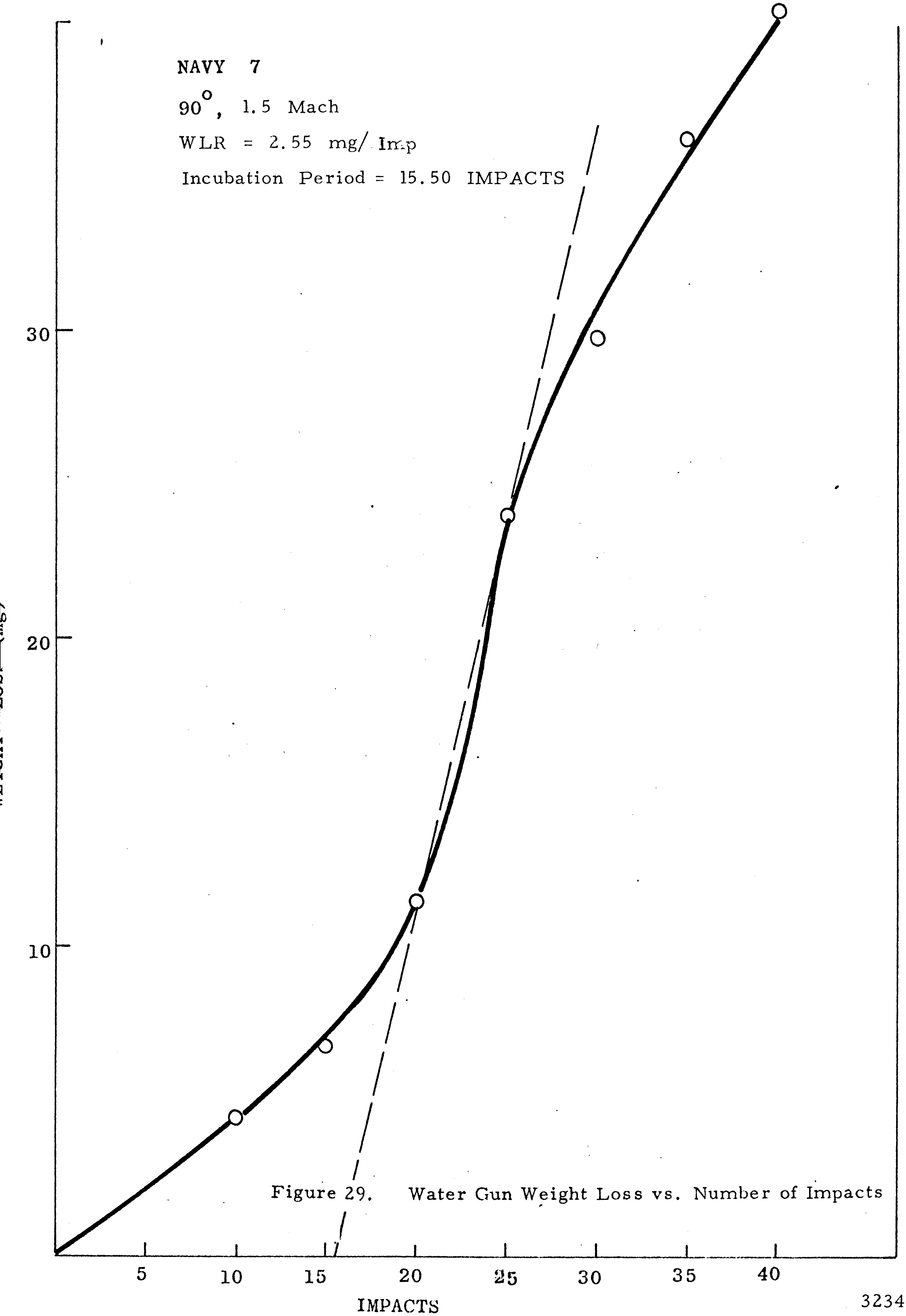

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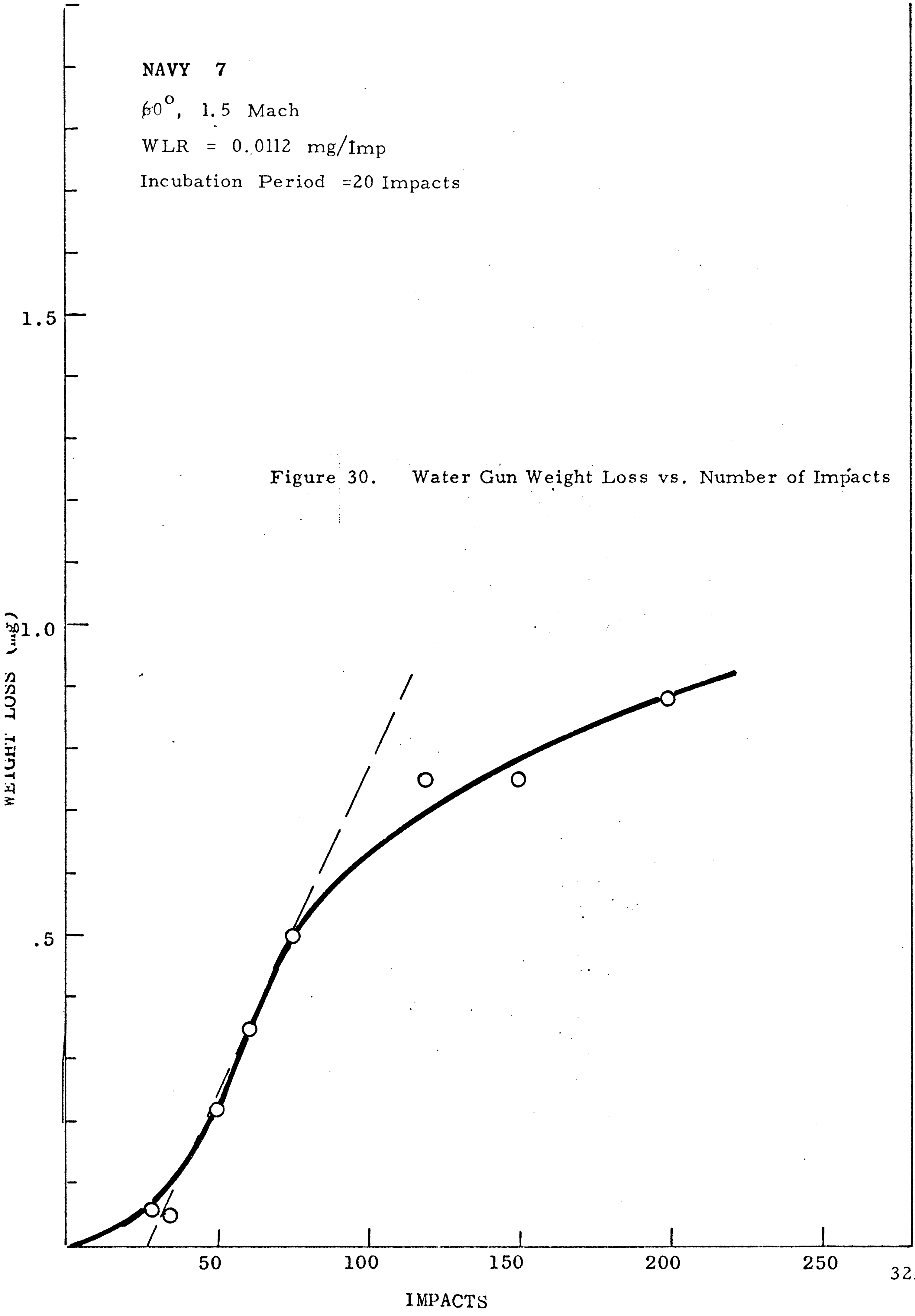

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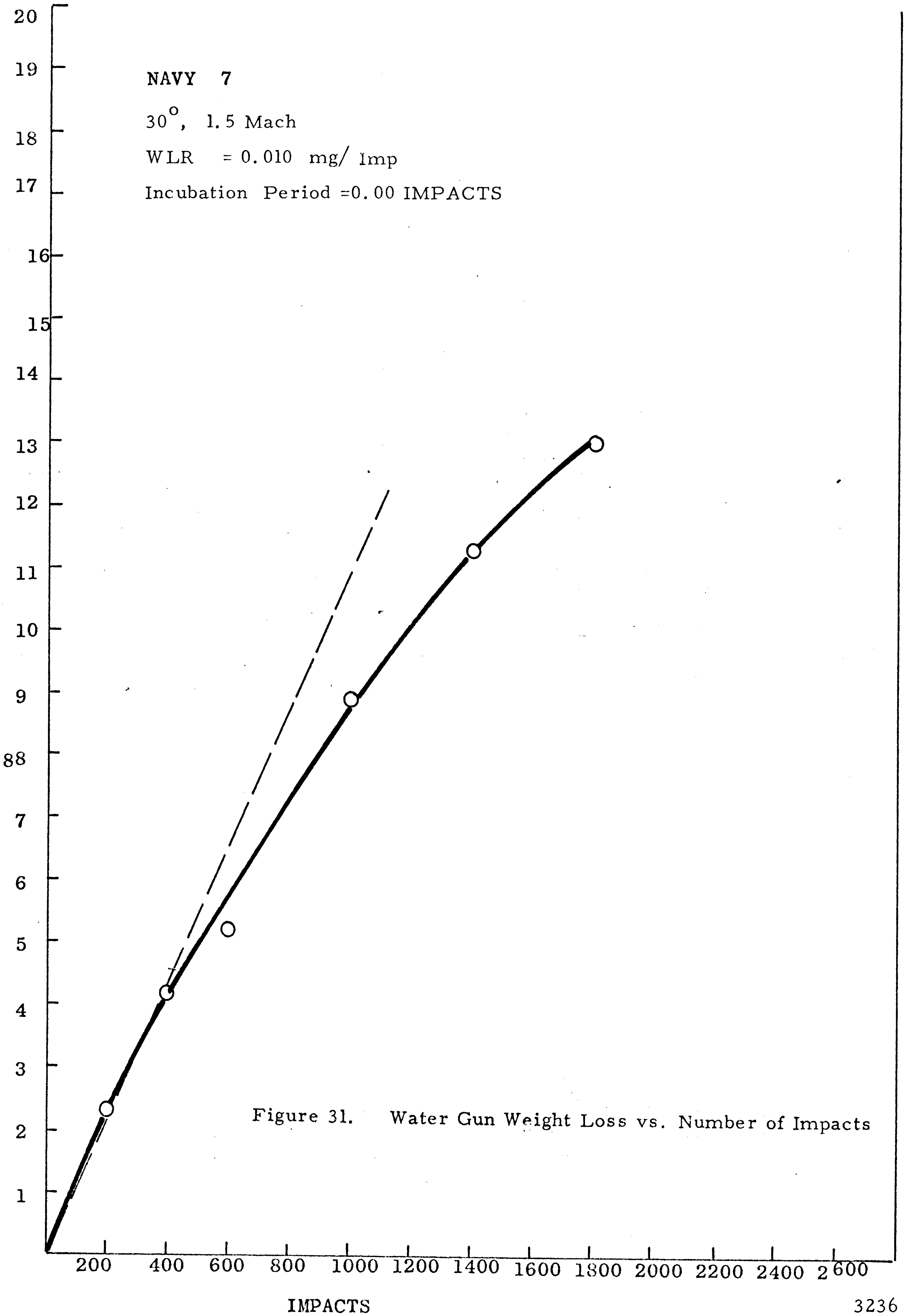
3235



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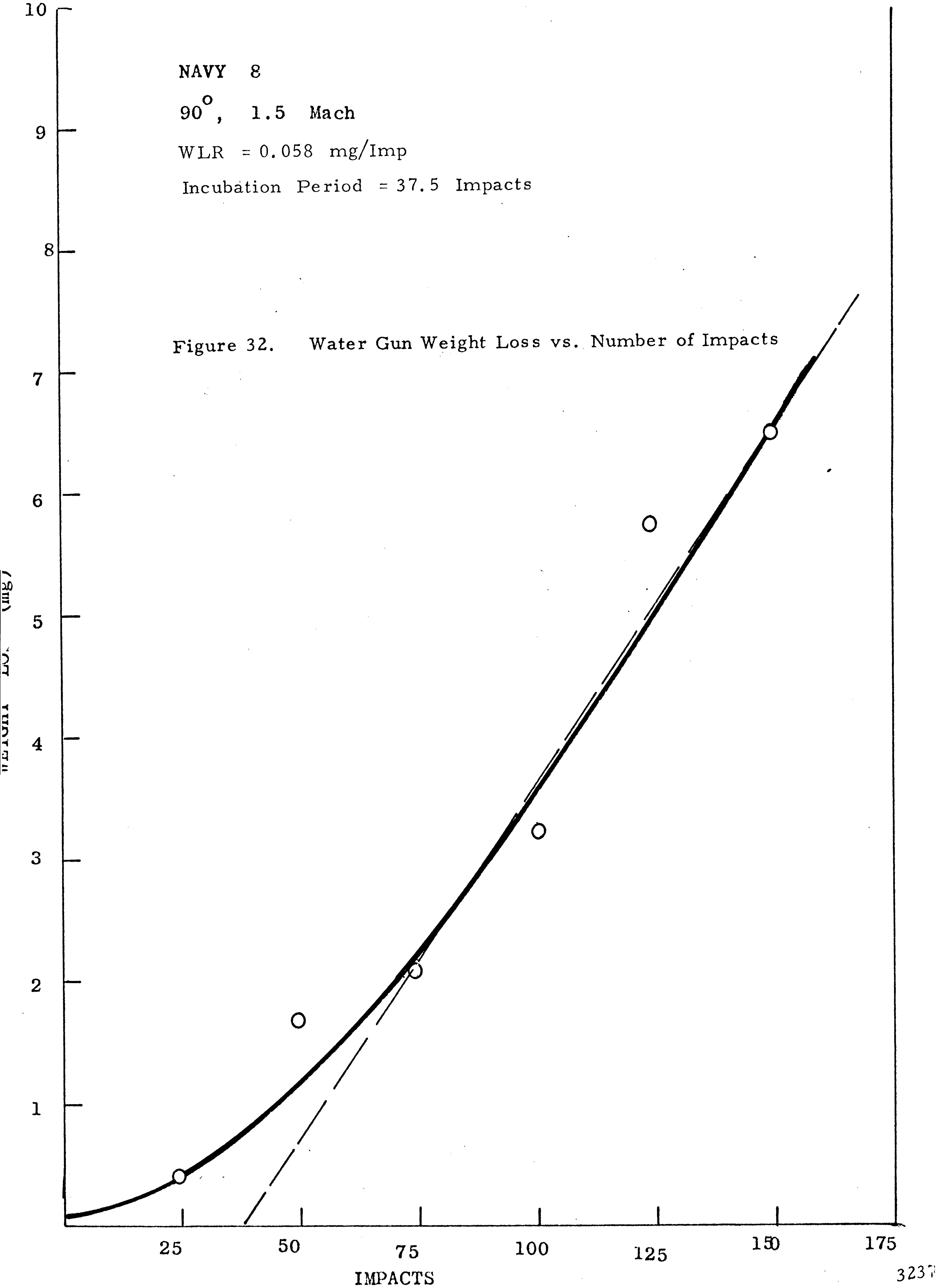

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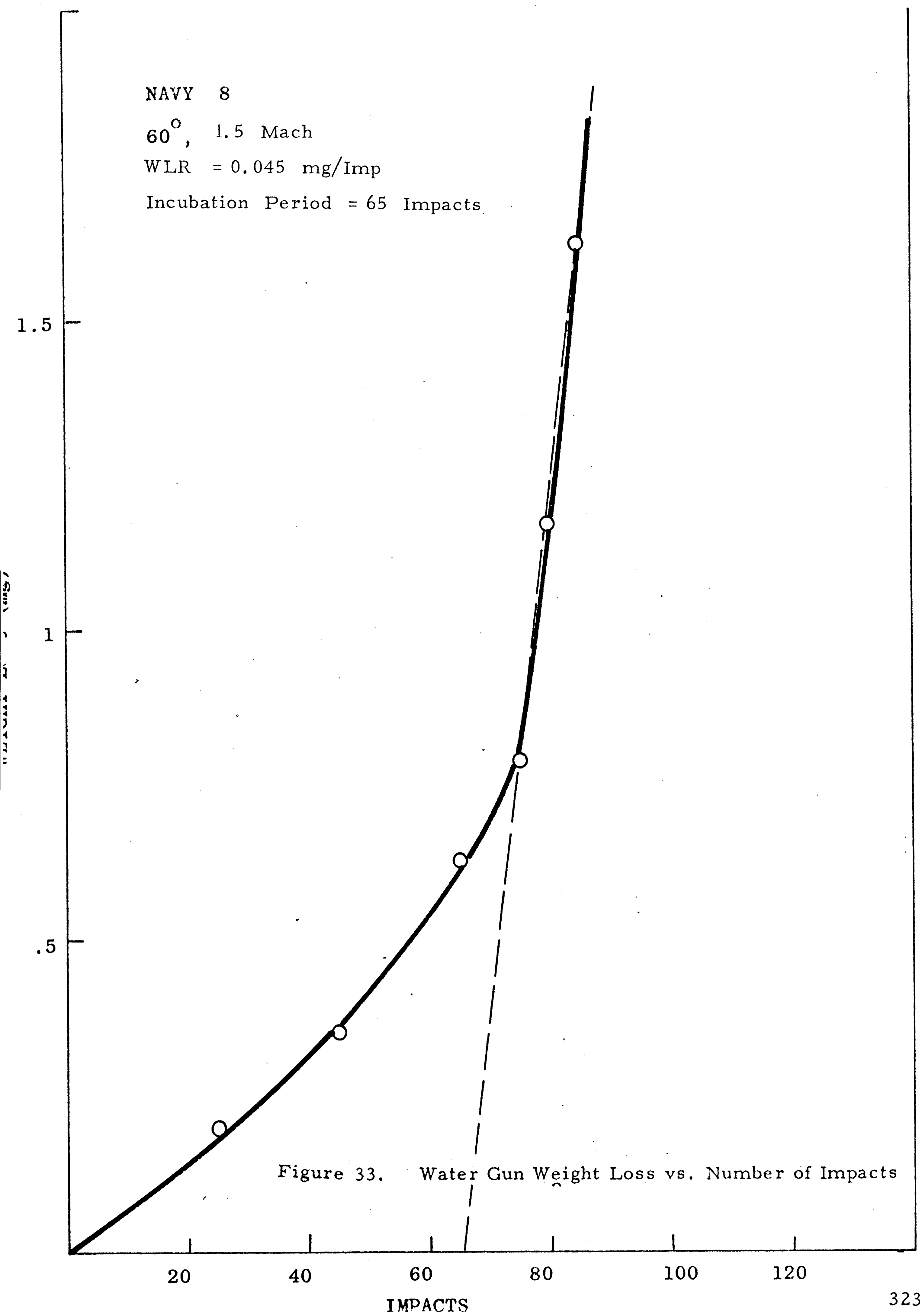

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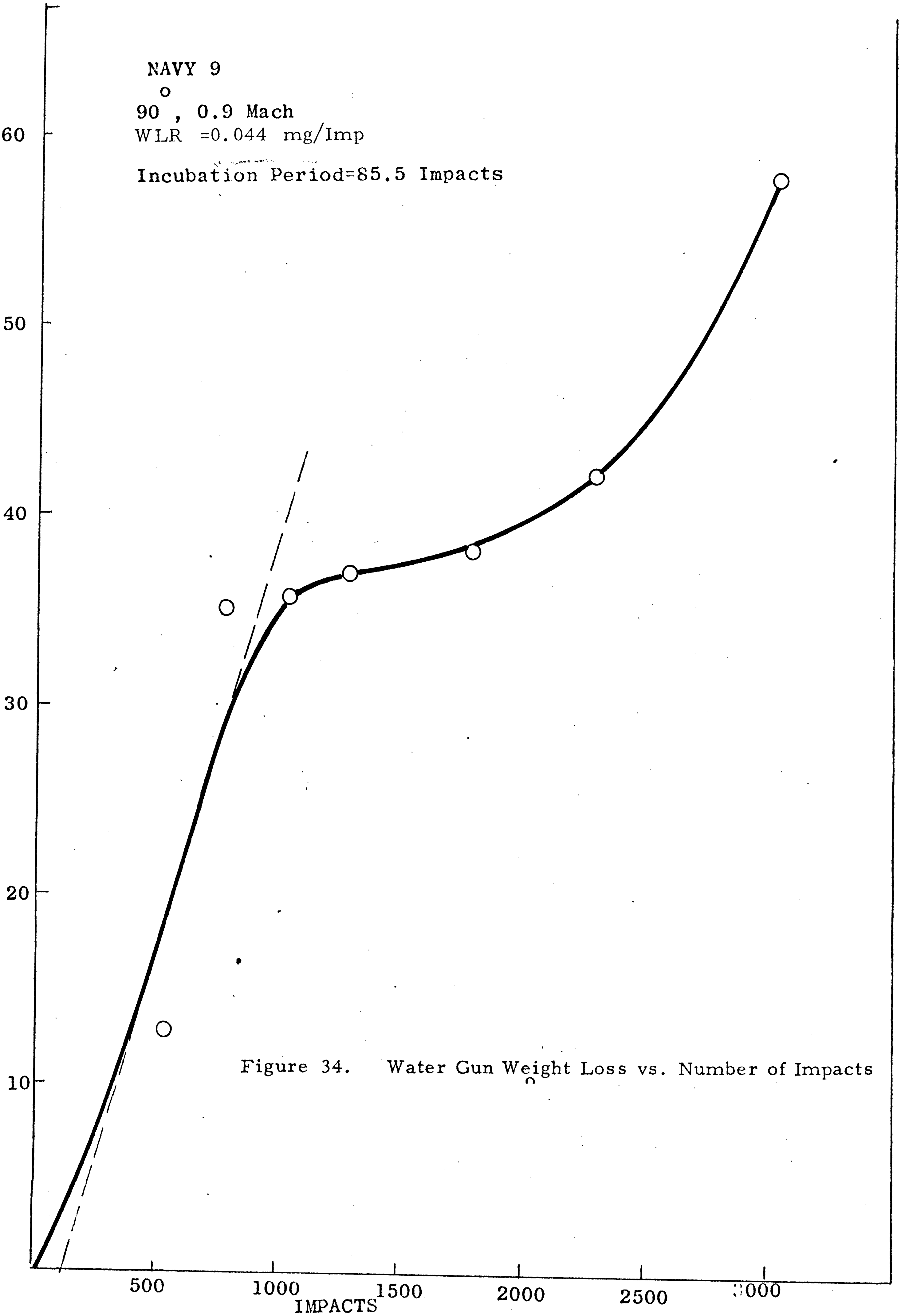


Figure 34. Water Gun Weight Loss vs. Number of Impacts

Figure 35a. Water Gun Impacts to 5 mm^3 Volume Loss as Function of Velocity and Angle for Navy 6, Curves of Constant Mach Number

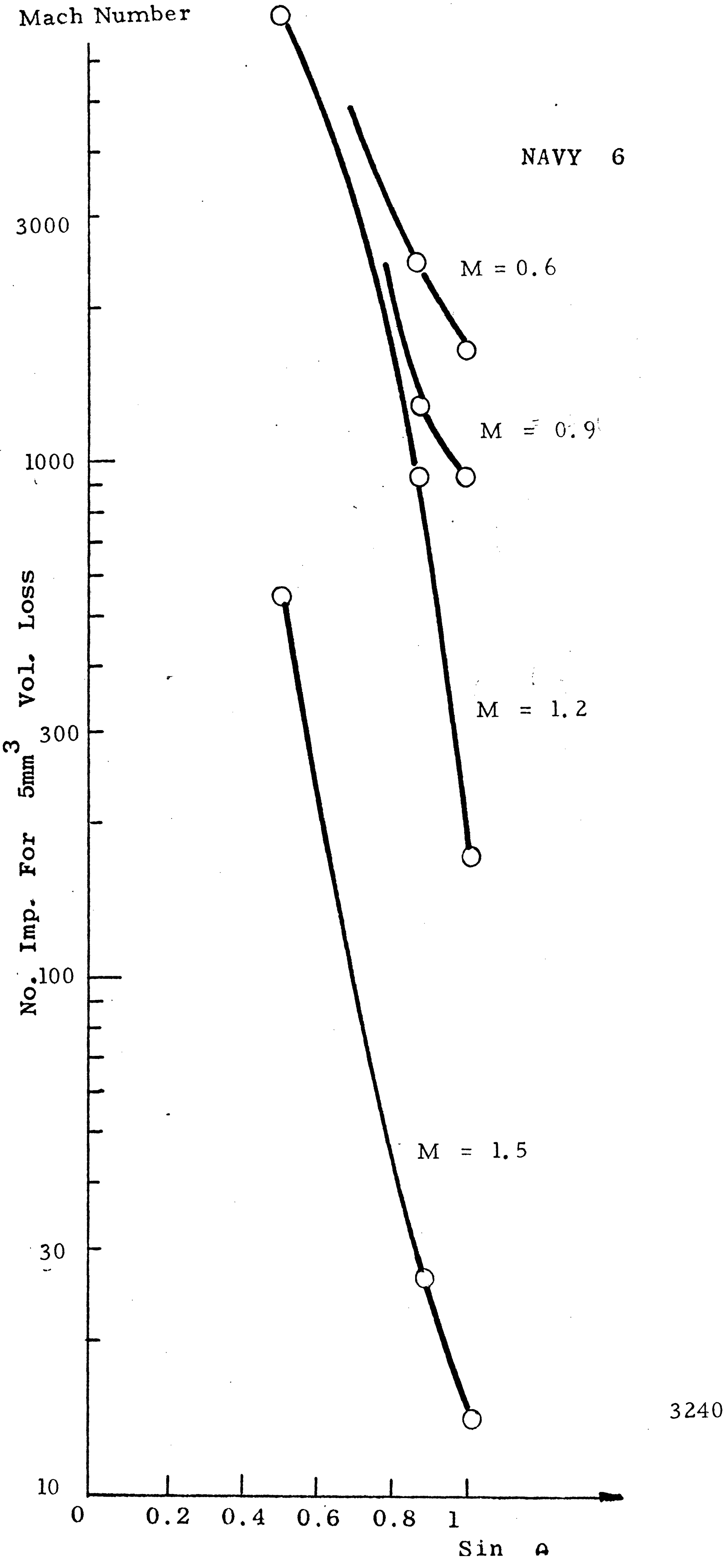


Figure 35b. Water Gun Impacts to 5 mm^3 Volume Loss as Function of Velocity and Angle for Navy Materials Excluding 6, Curves of Constant Mach Number

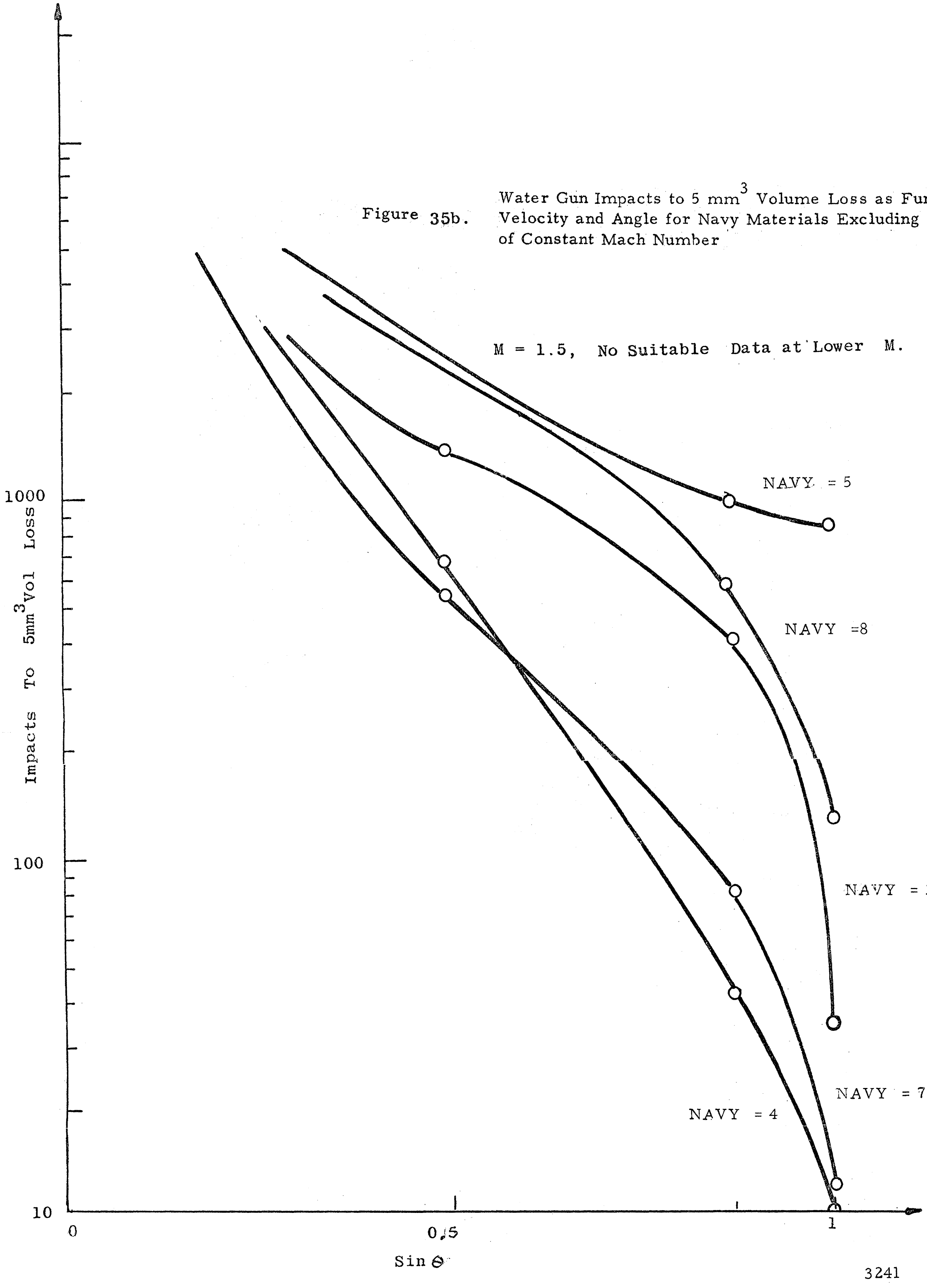
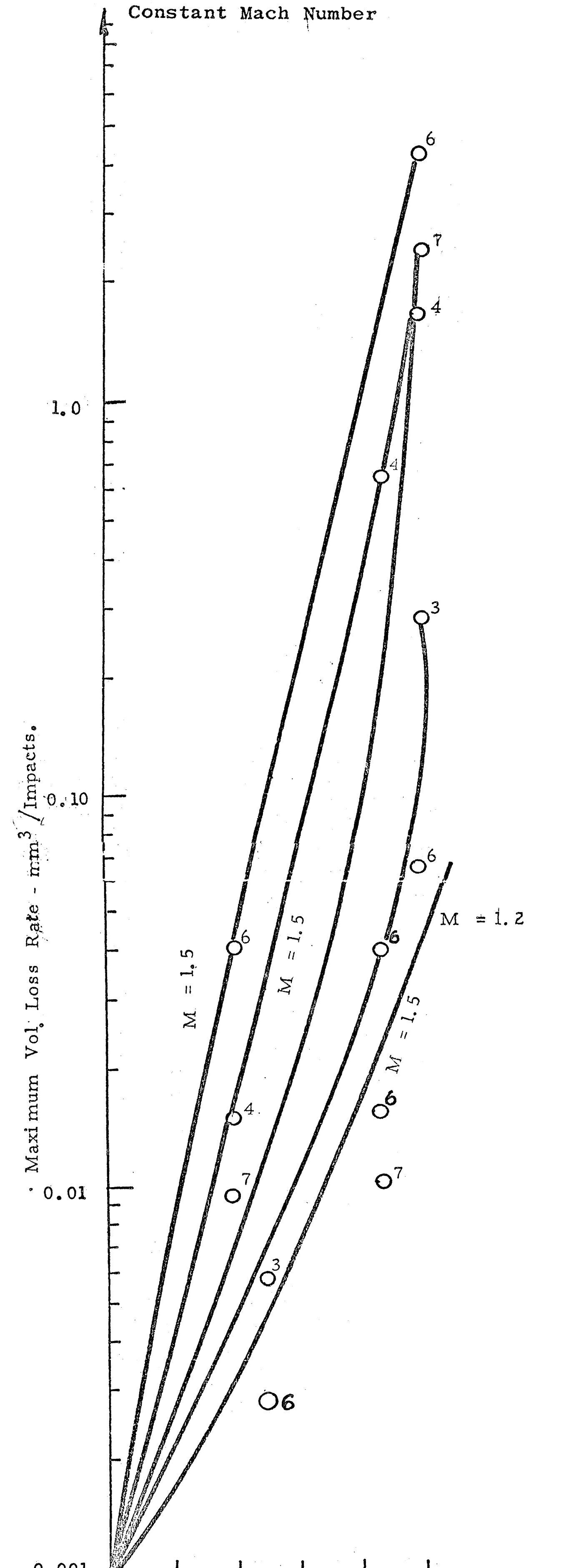


Figure 36. Velocity and Angle for All Material Curces of Constant Mach Number



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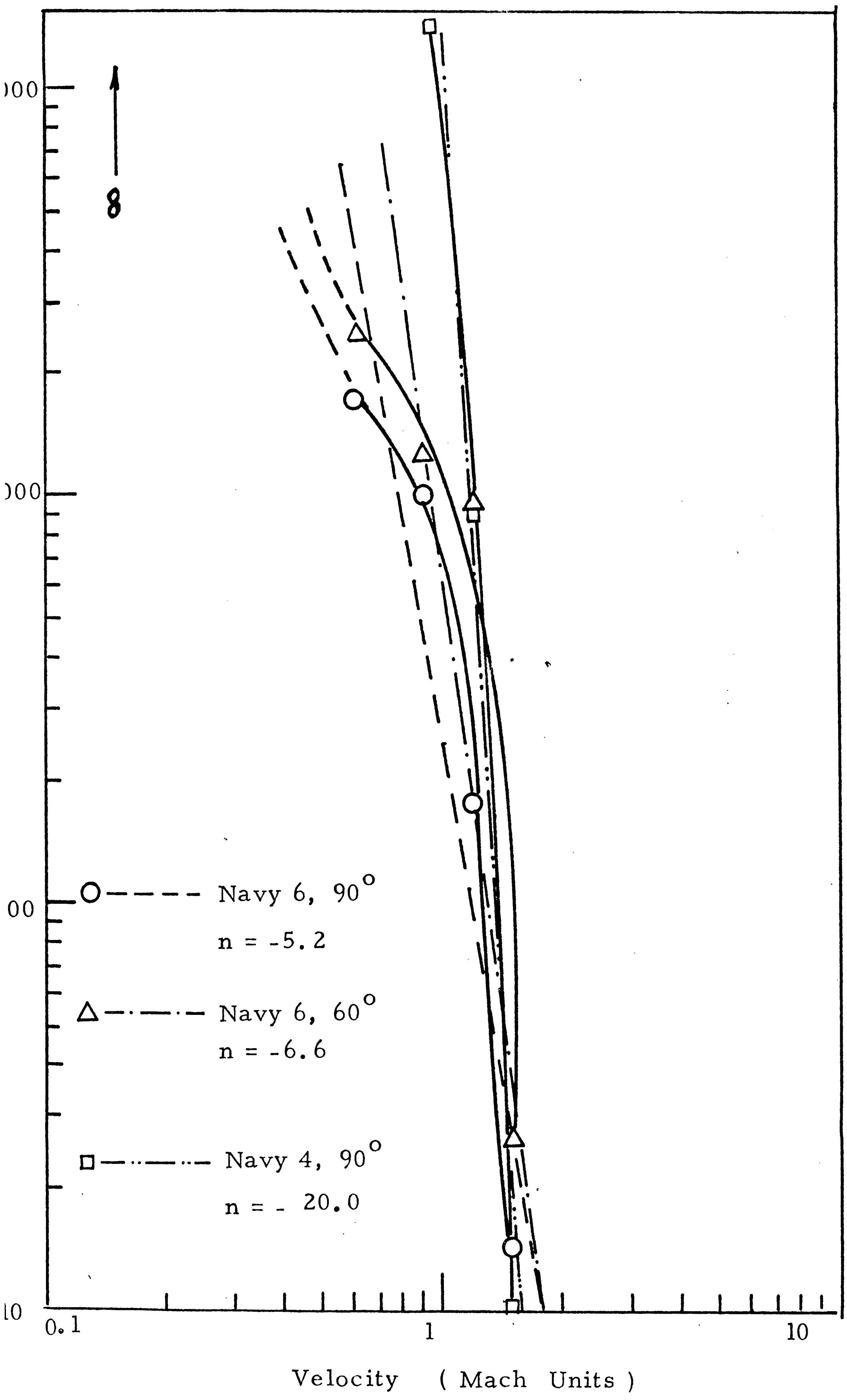


3243

Figure 37. Water Gun Impacts to 5mm^3 Volume Loss as Function of Velocity and angle for Navy 6 and 4, Curves of Constant angle of Impacts.

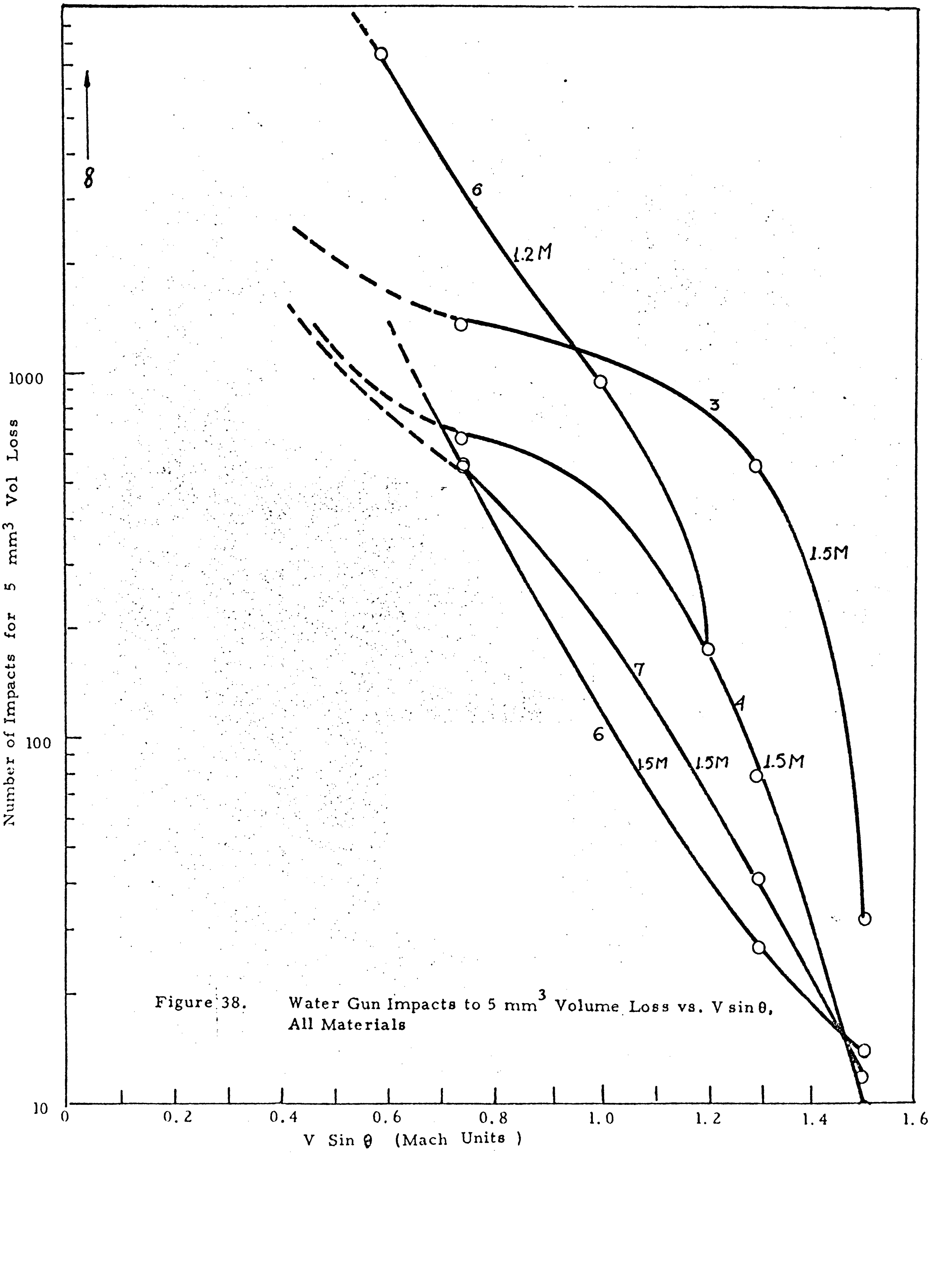
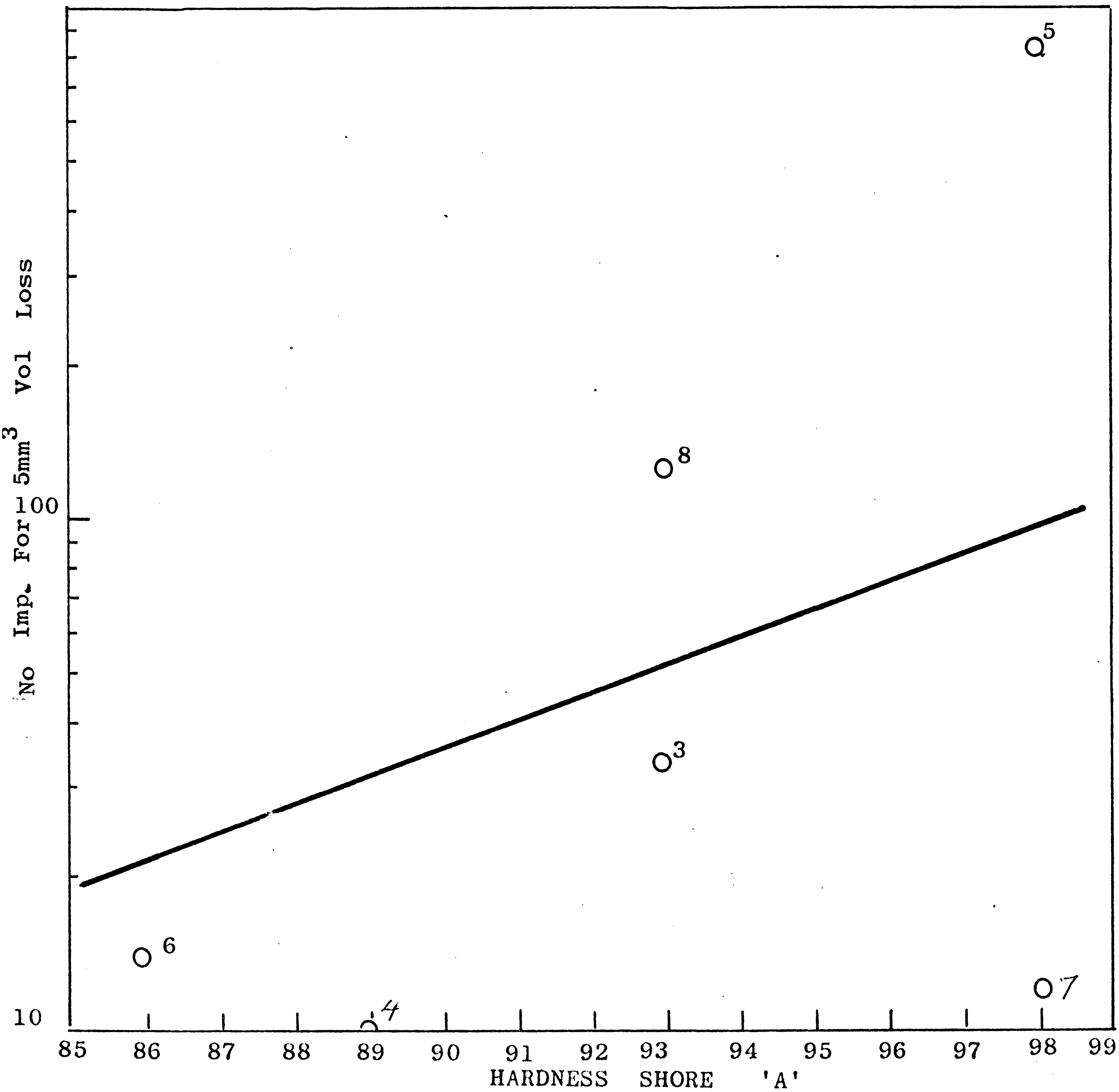


Figure 38. Water Gun Impacts to 5 mm^3 Volume Loss vs. V sin θ, All Materials

3244

Figure 39. Number of Impacts for 5 mm^3 Volume Loss vs. Shore-A Hardness



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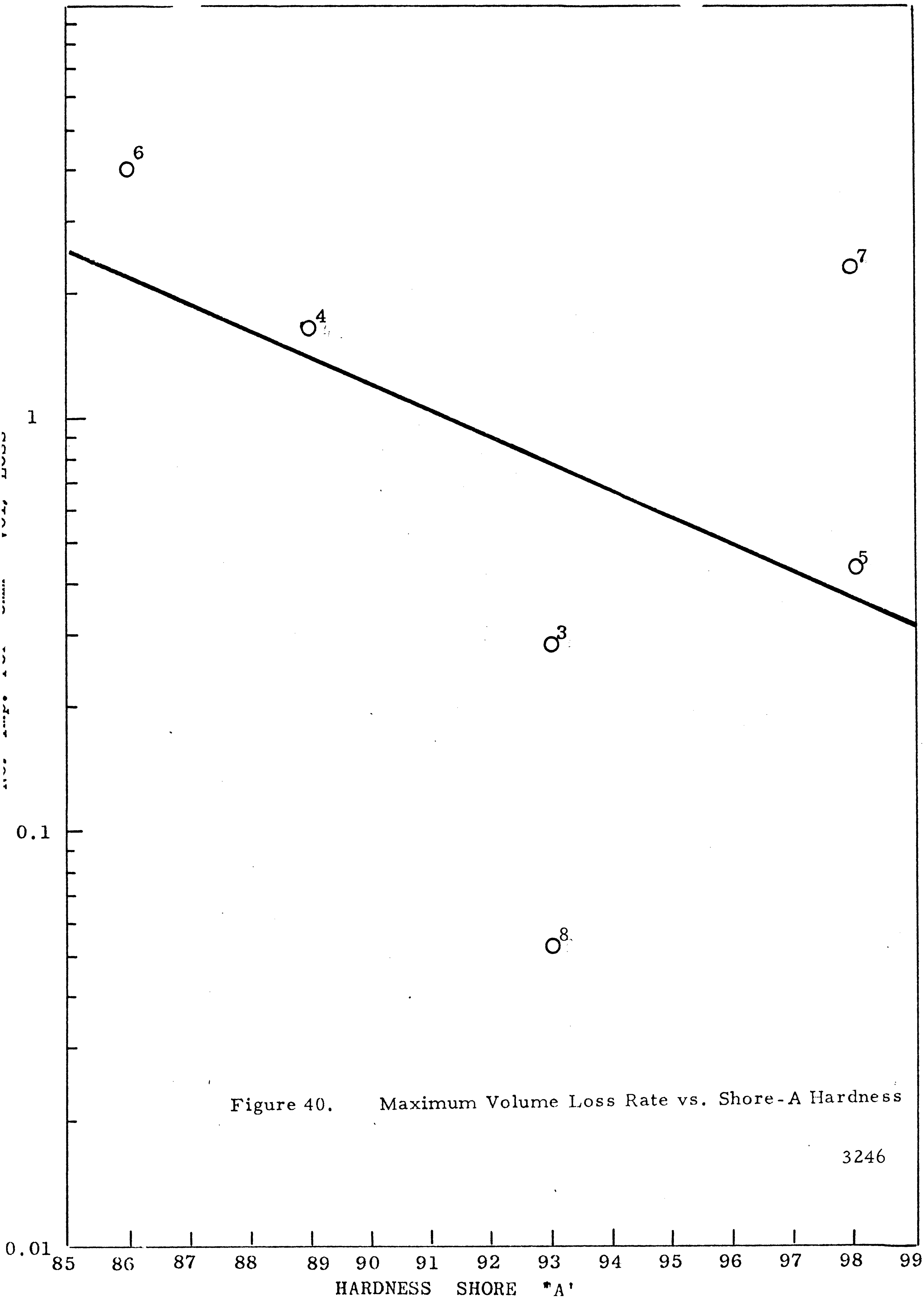


Figure 40. Maximum Volume Loss Rate vs. Shore-A Hardness

3246

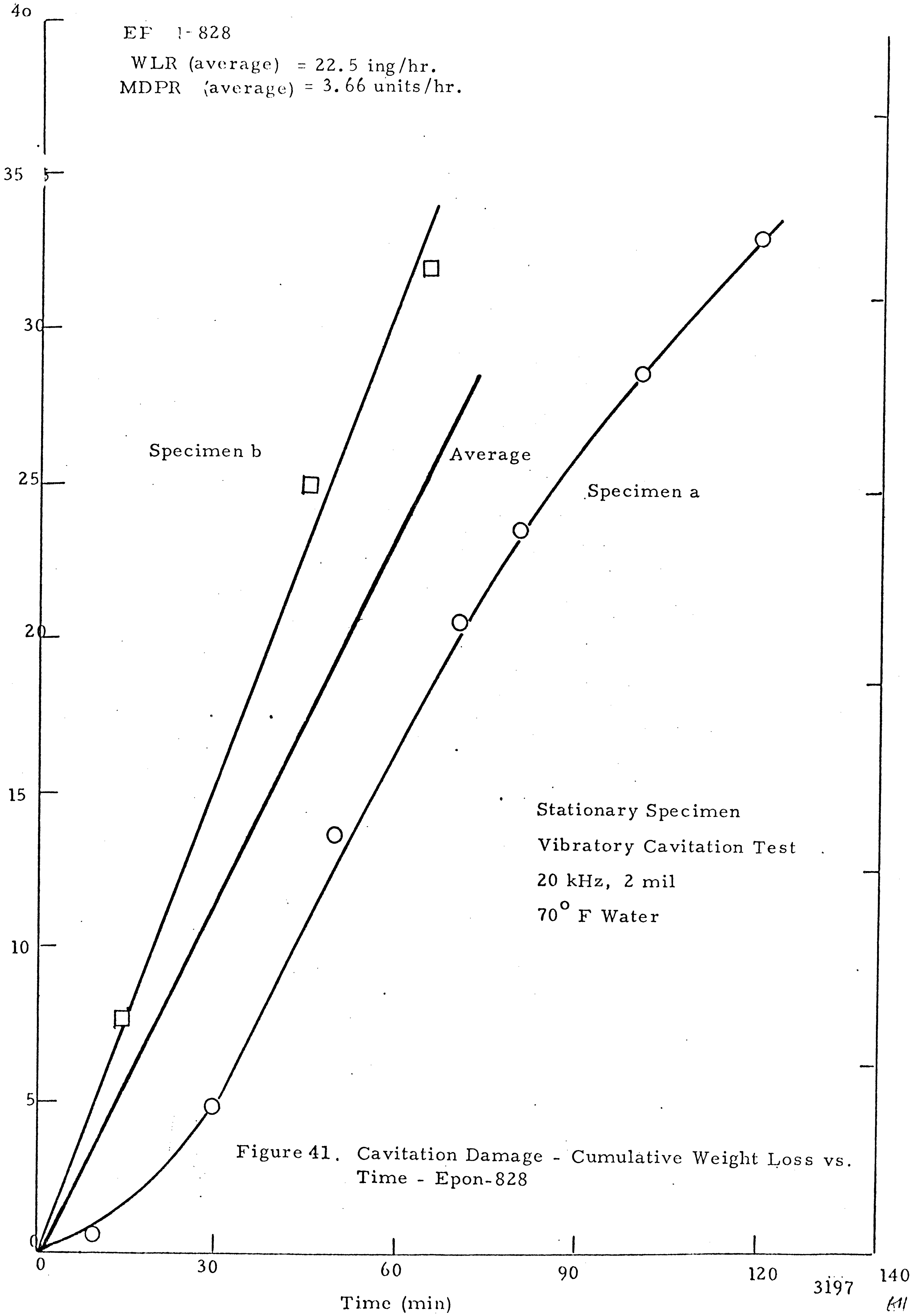


Figure 41. Cavitation Damage - Cumulative Weight Loss vs. Time - Epon-828

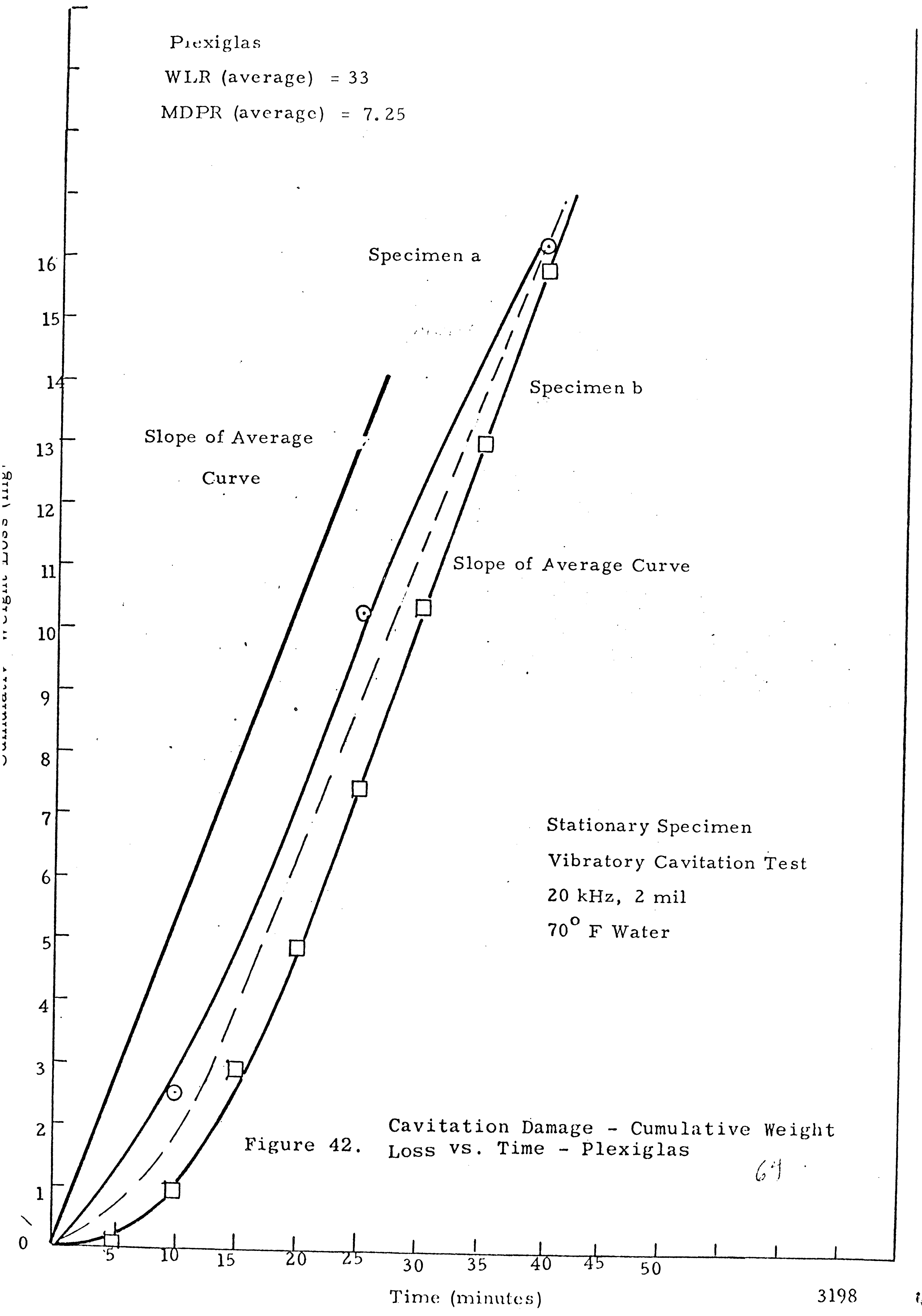


Figure 42. Cavitation Damage - Cumulative Weight Loss vs. Time - Plexiglas

64

3198

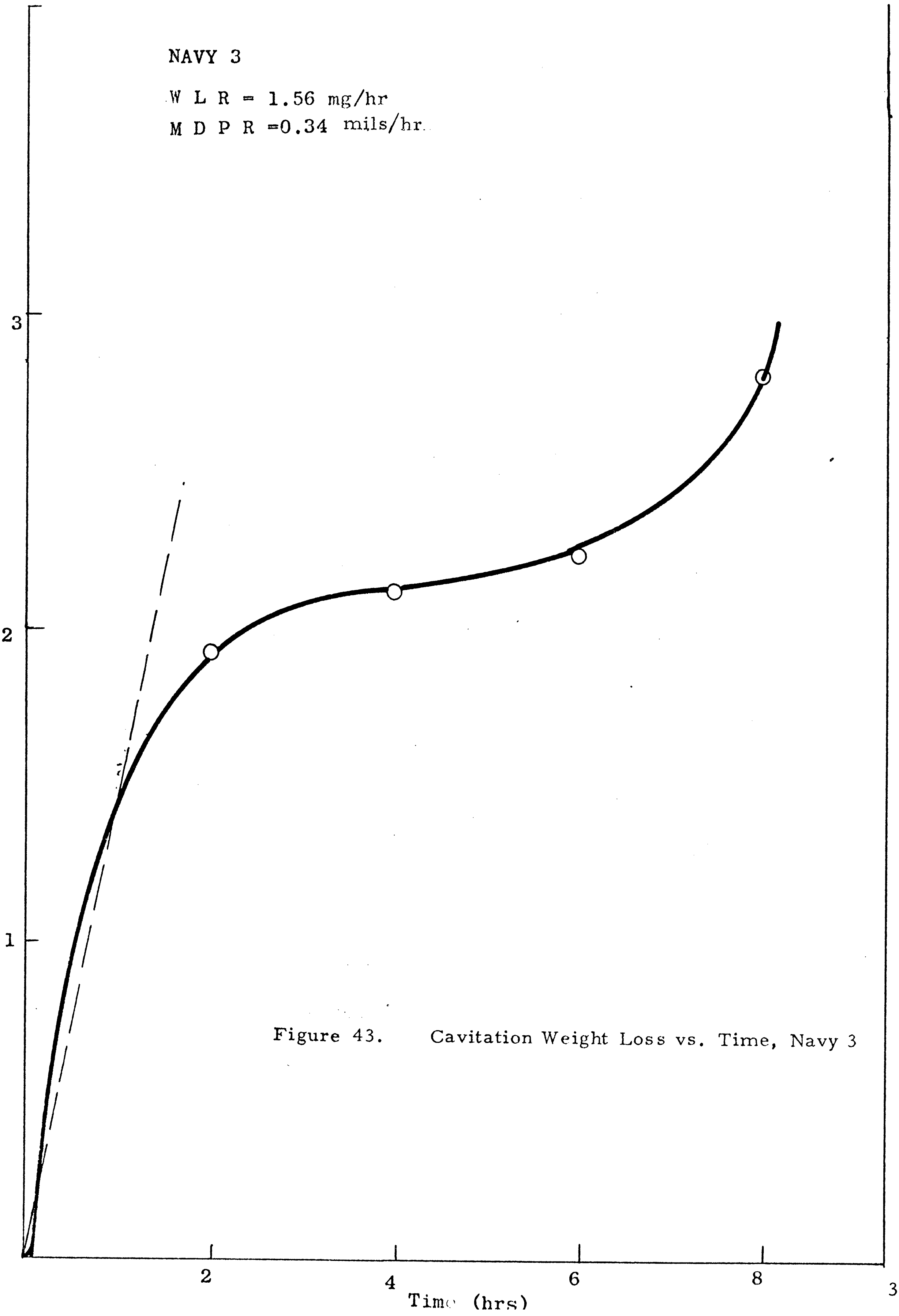


Figure 43. Cavitation Weight Loss vs. Time, Navy 3

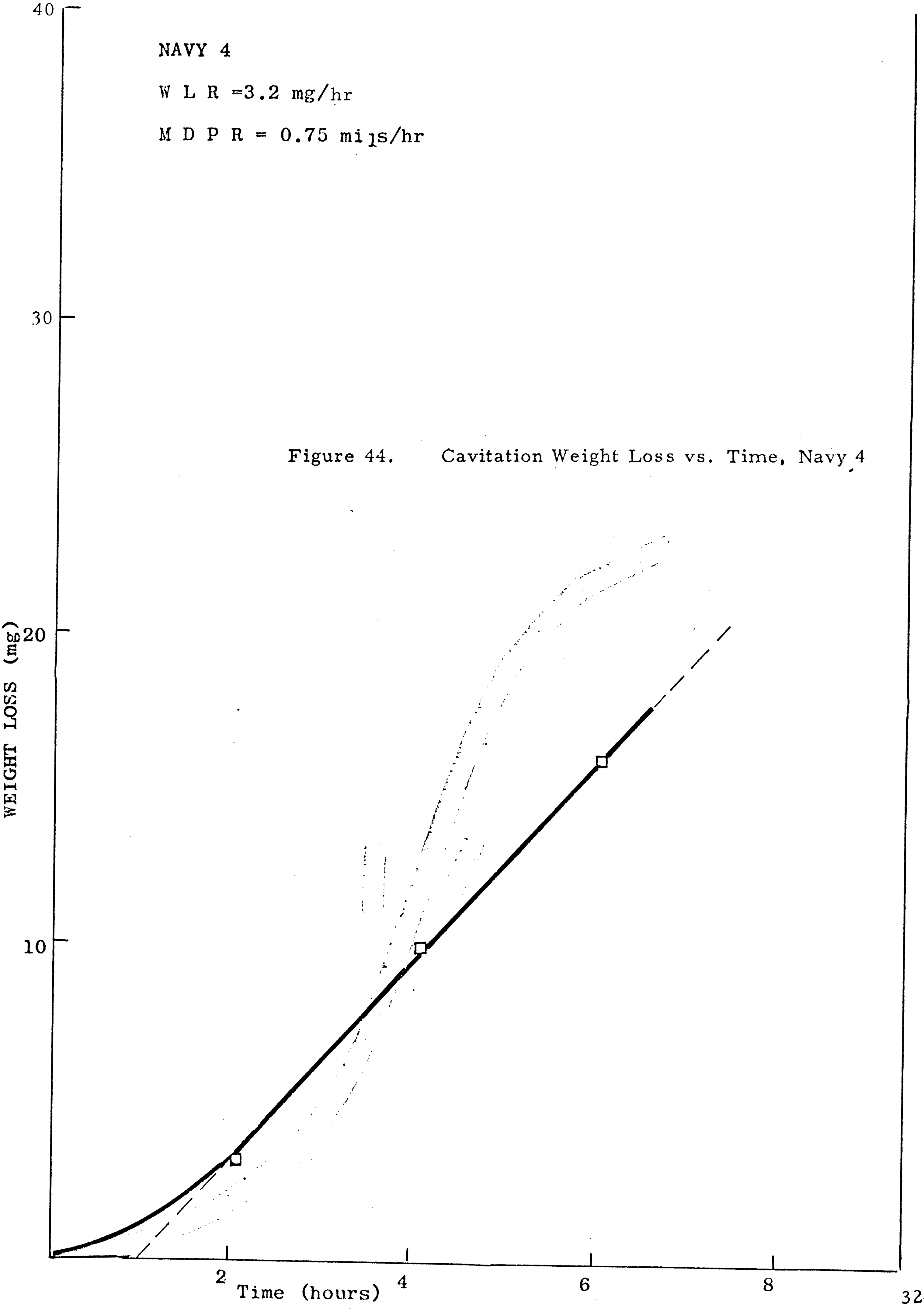


Figure 44. Cavitation Weight Loss vs. Time, Navy 4

3248

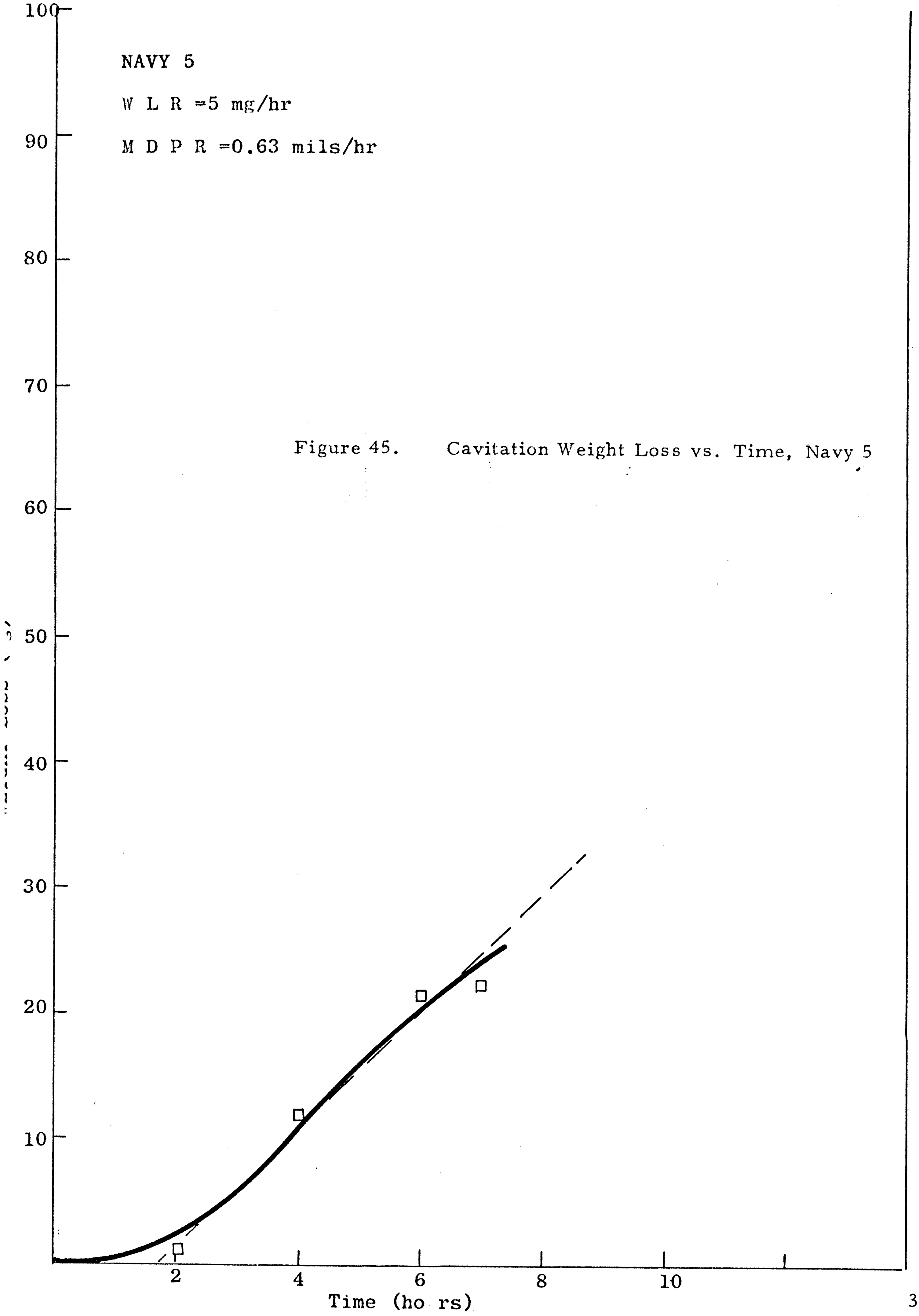


Figure 45. Cavitation Weight Loss vs. Time, Navy 5

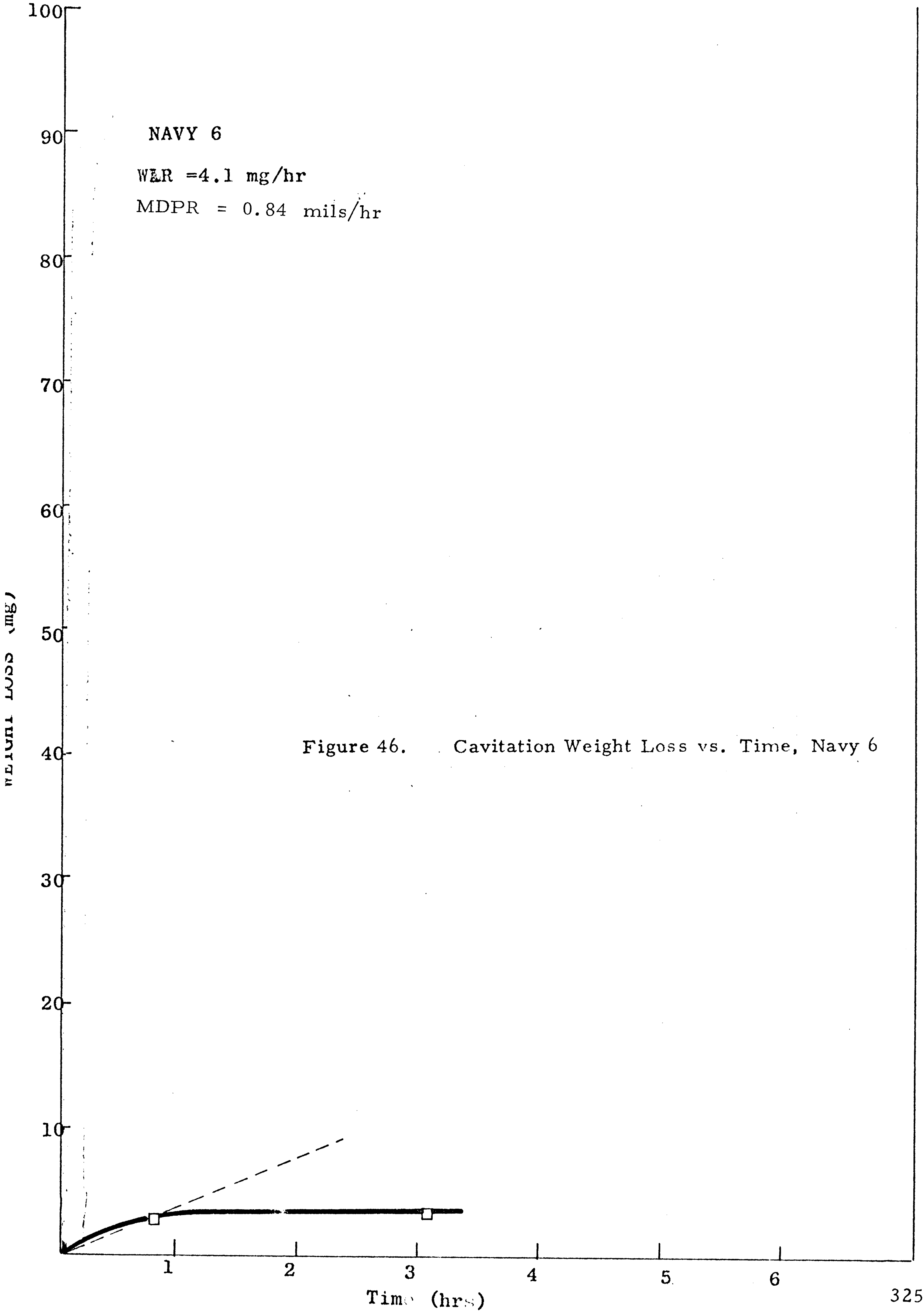


Figure 46. Cavitation Weight Loss vs. Time, Navy 6

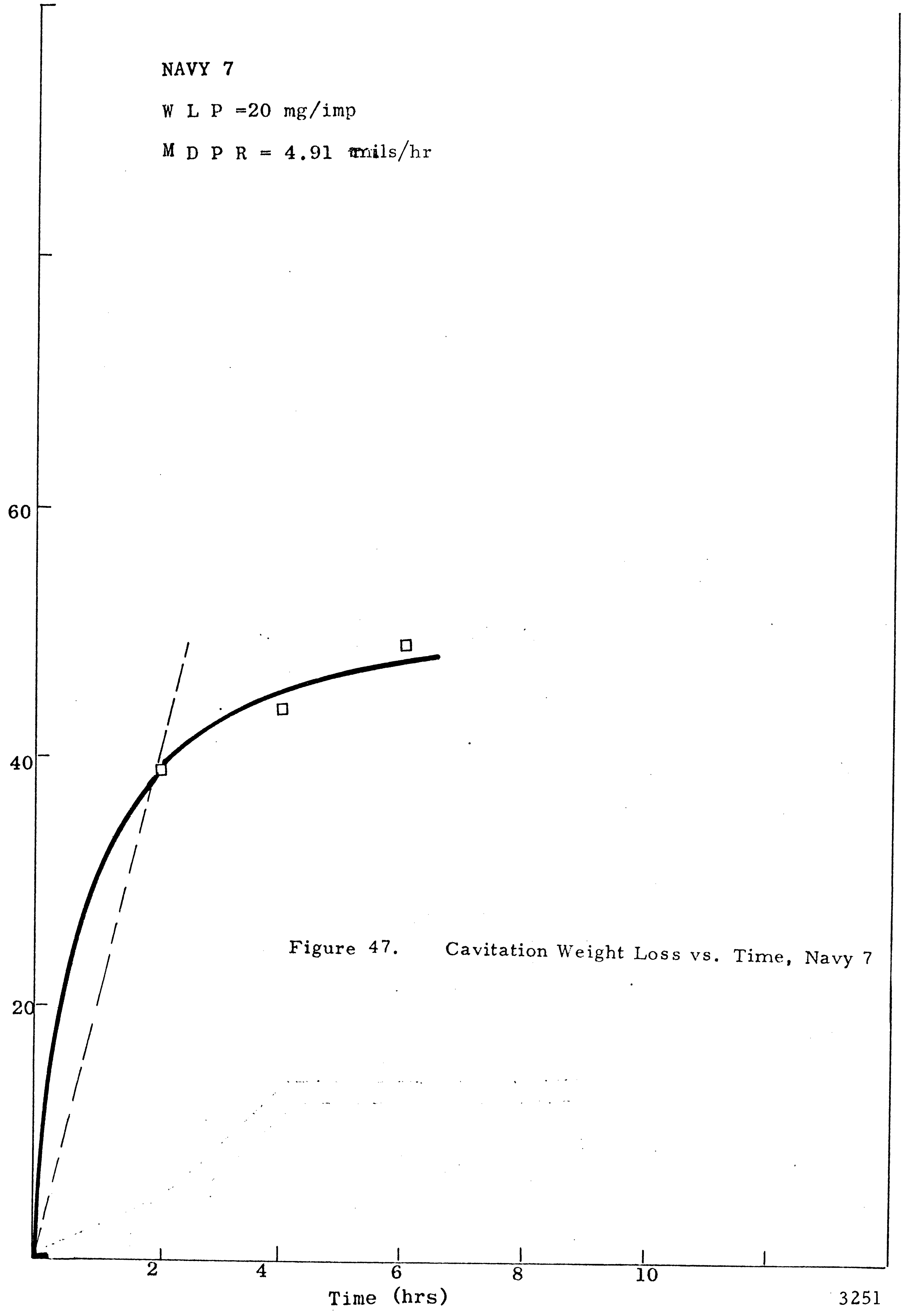


Figure 47. Cavitation Weight Loss vs. Time, Navy 7

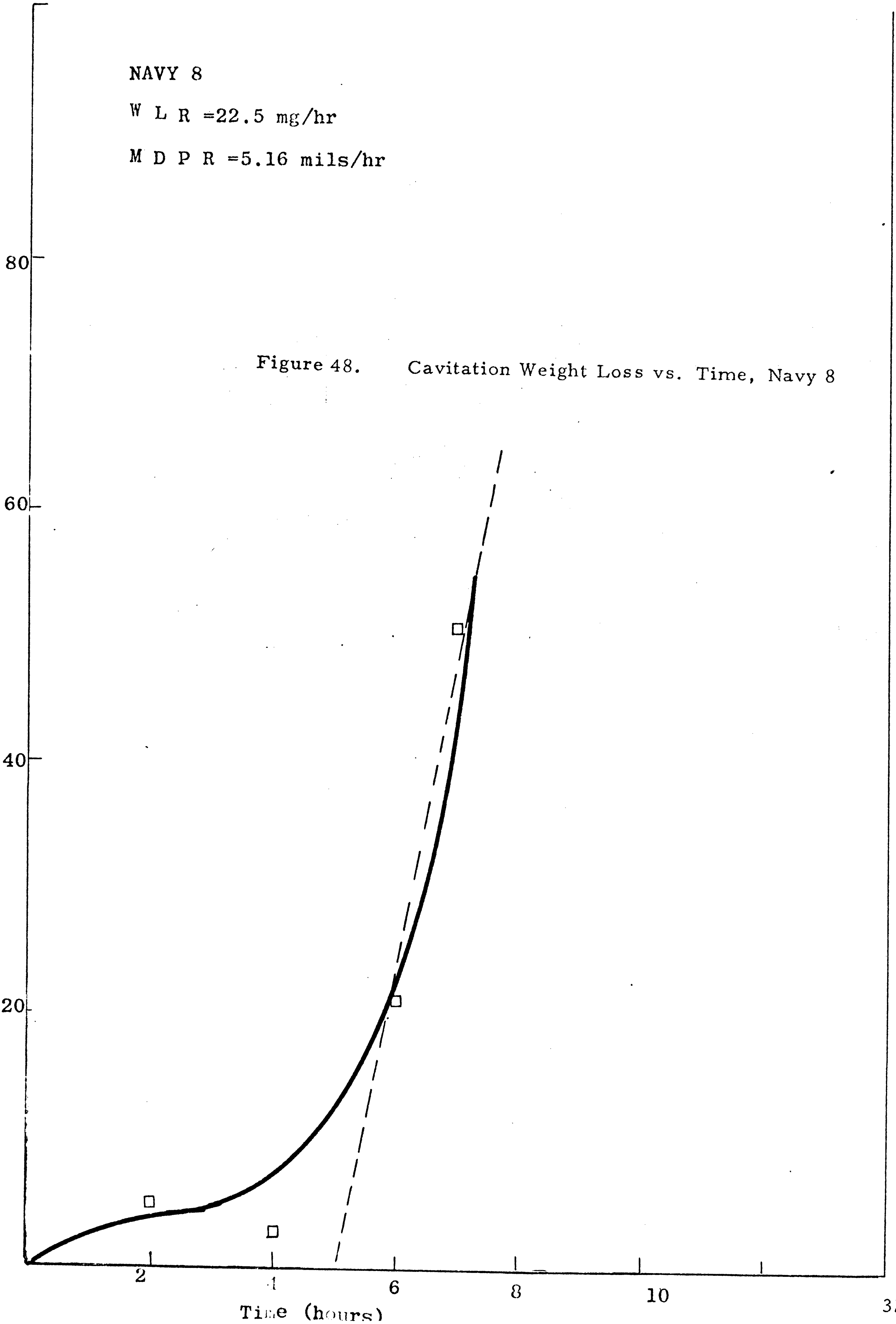


Figure 48. Cavitation Weight Loss vs. Time, Navy 8

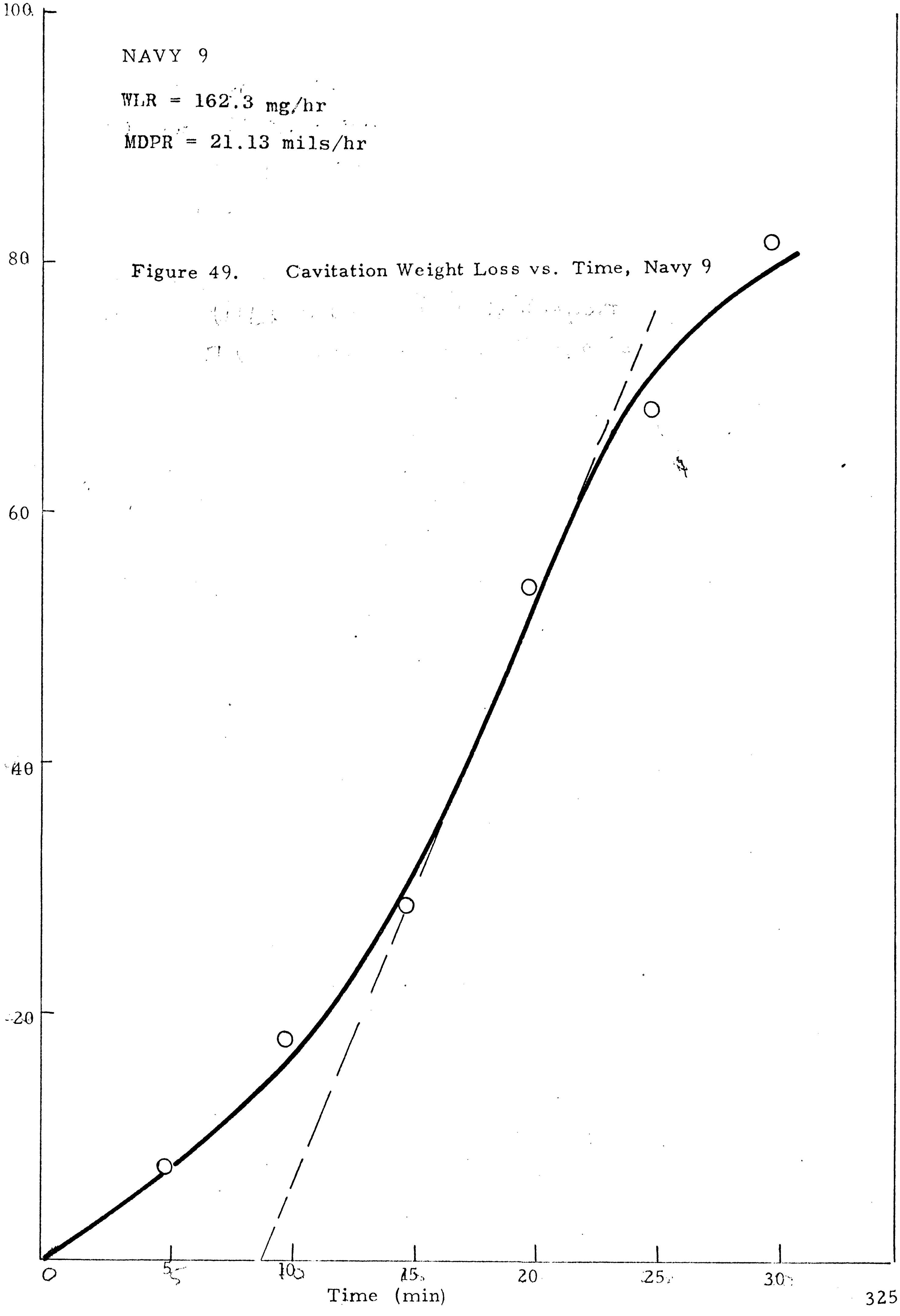


Figure 49. Cavitation Weight Loss vs. Time, Navy 9

3253

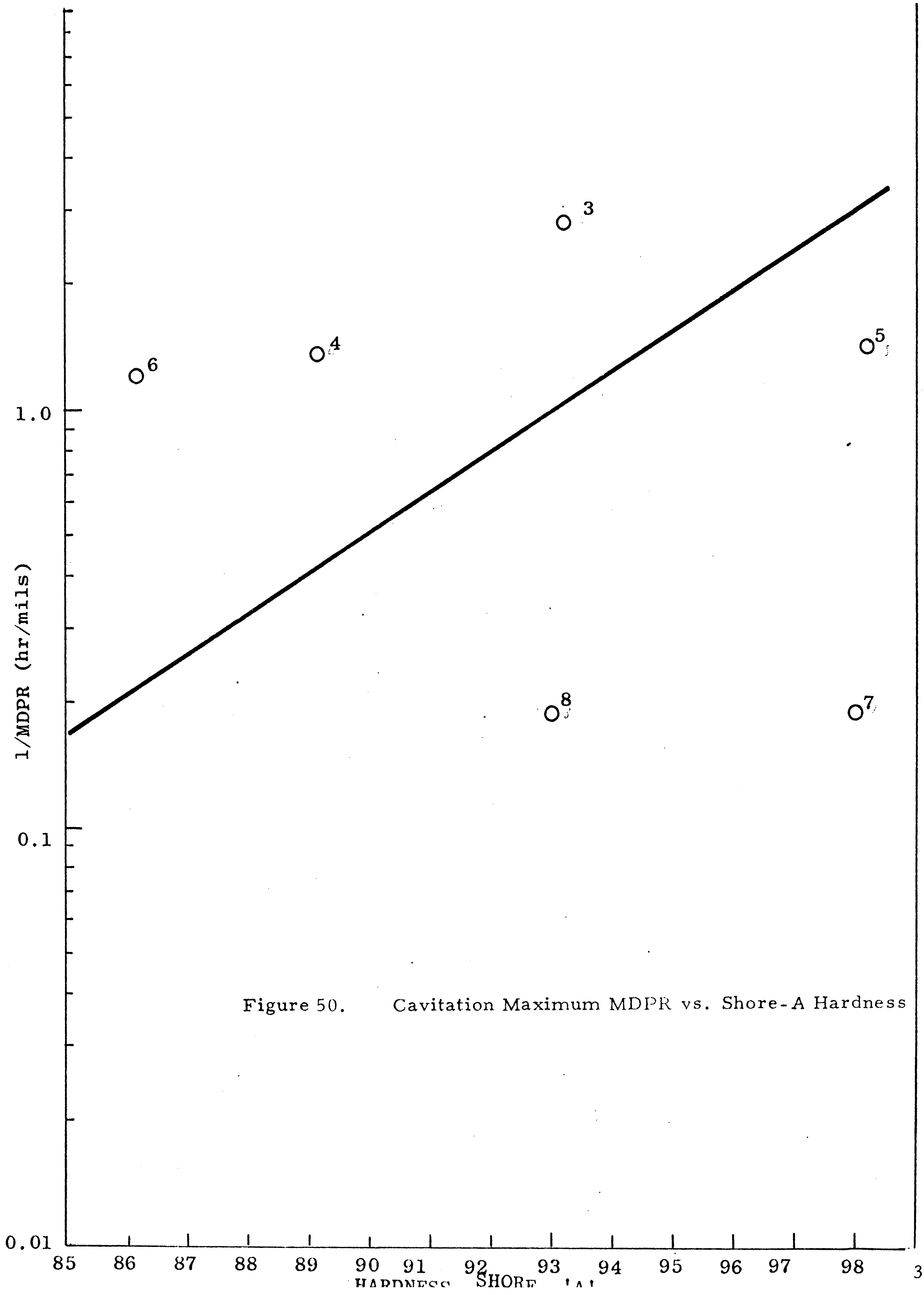
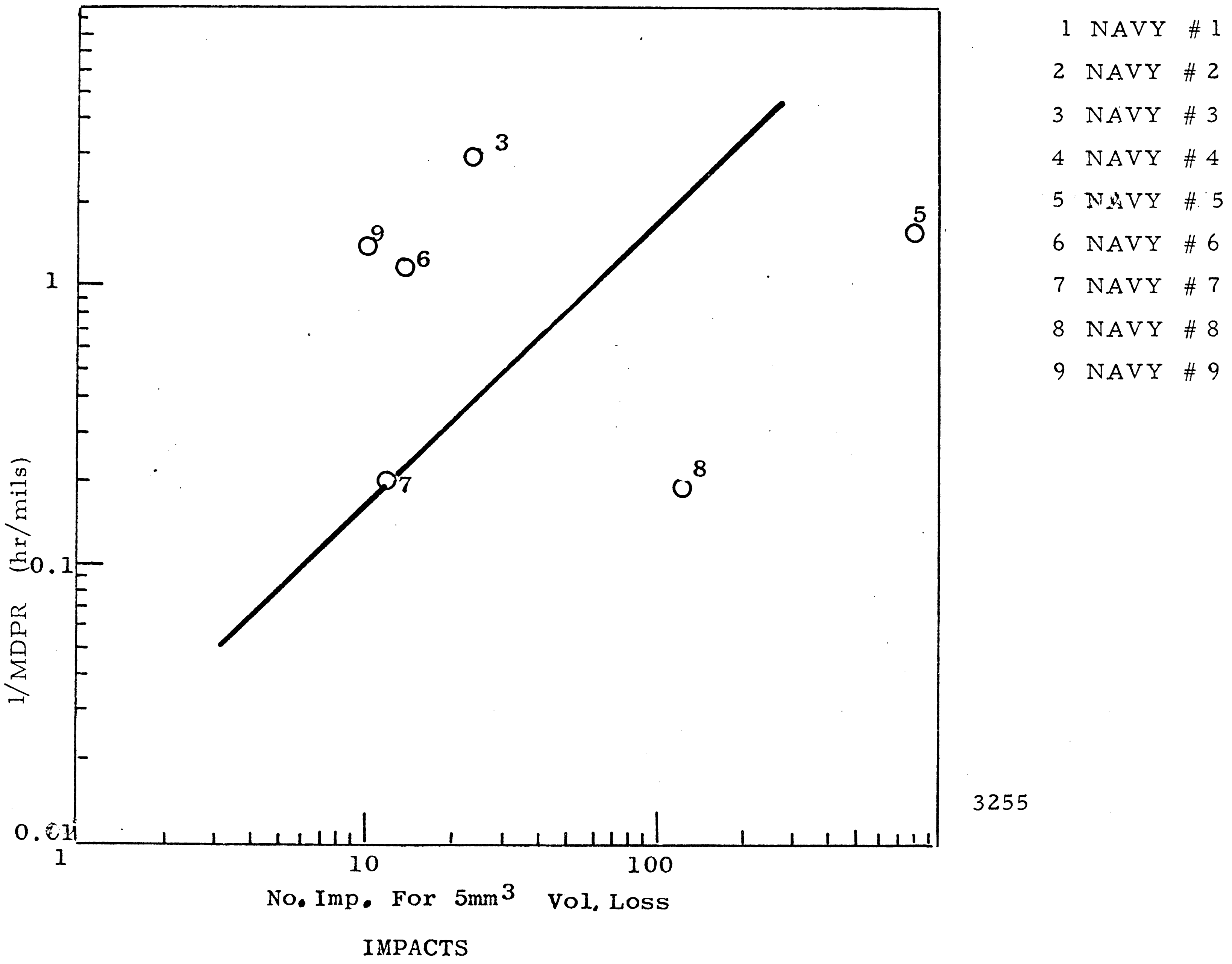
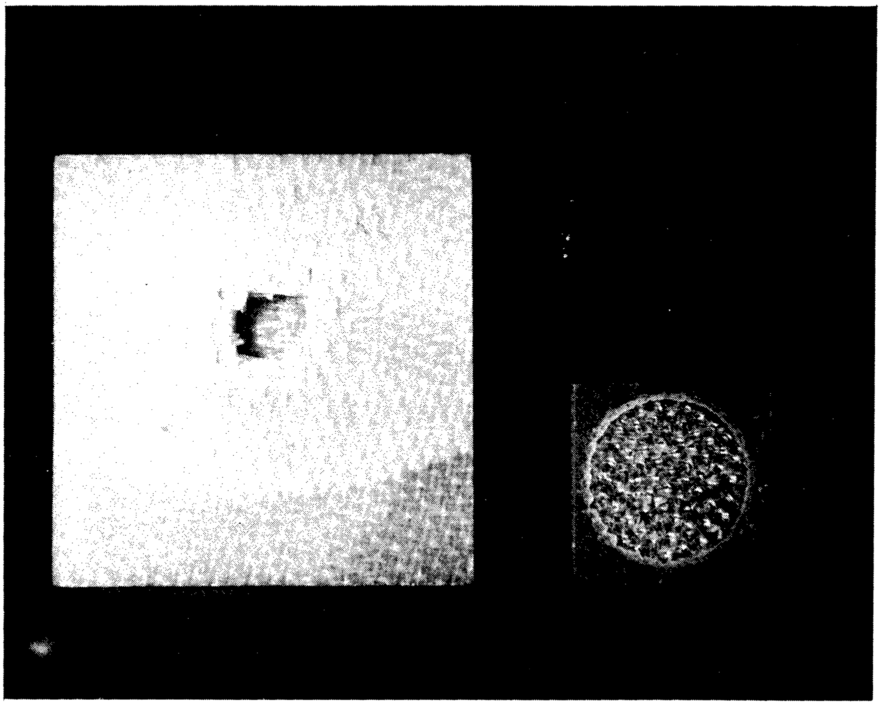


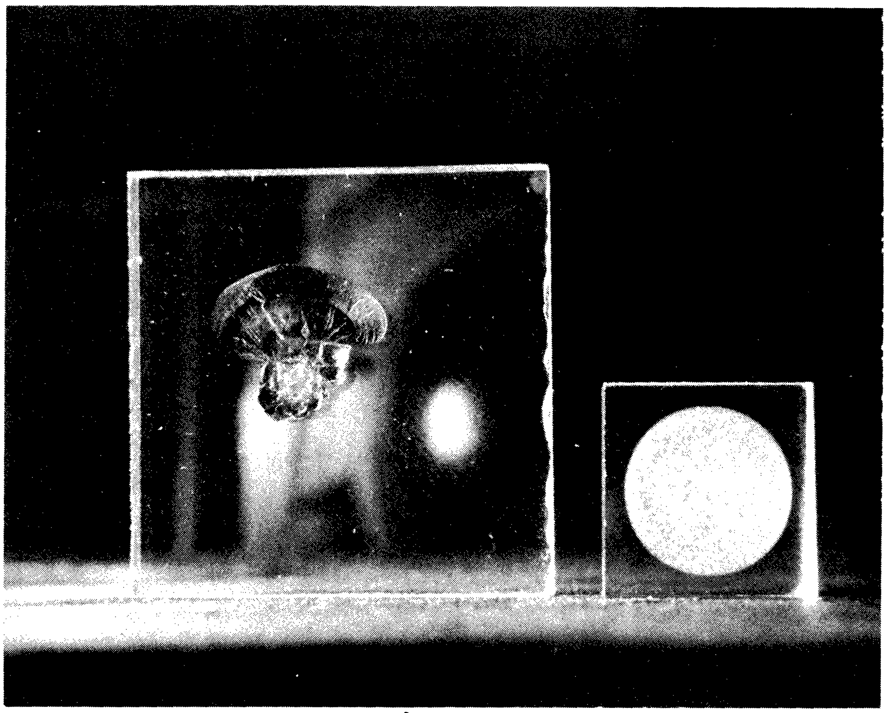
Figure 50. Cavitation Maximum MDPR vs. Shore-A Hardness

Figure 51. Comparison Between Cavitation and Impacts vs. Erosion Resistance





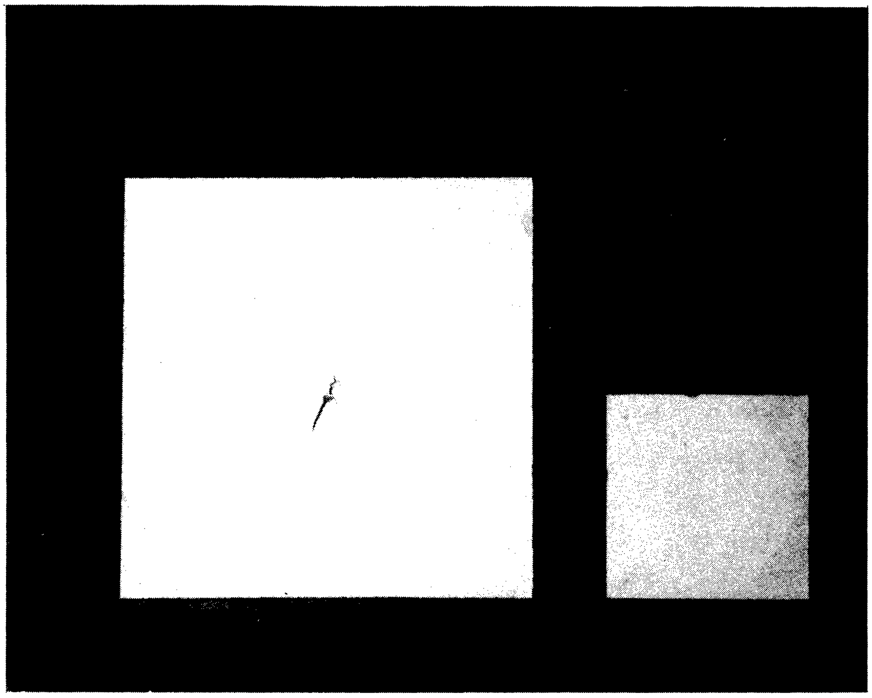
(a)

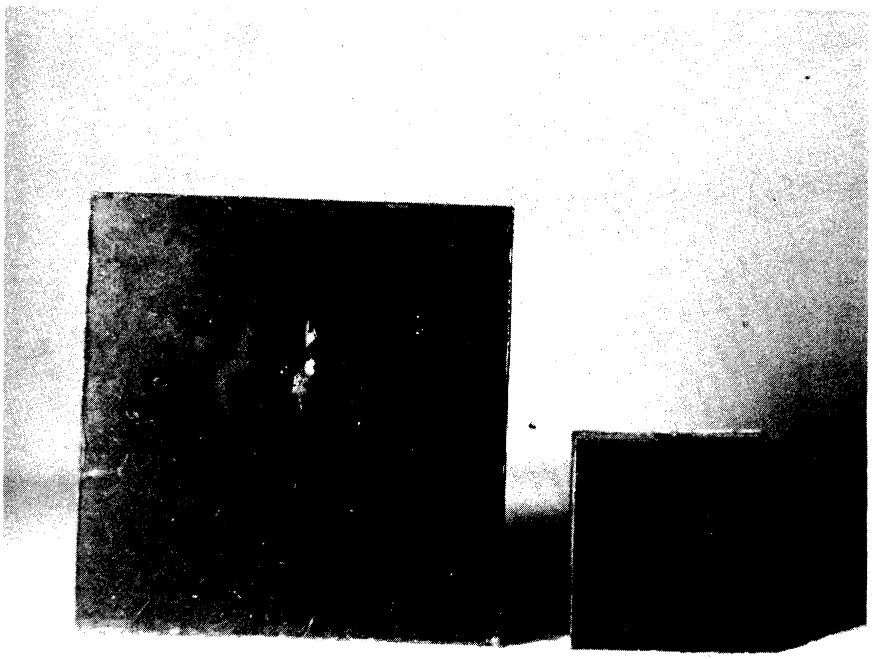


(b)

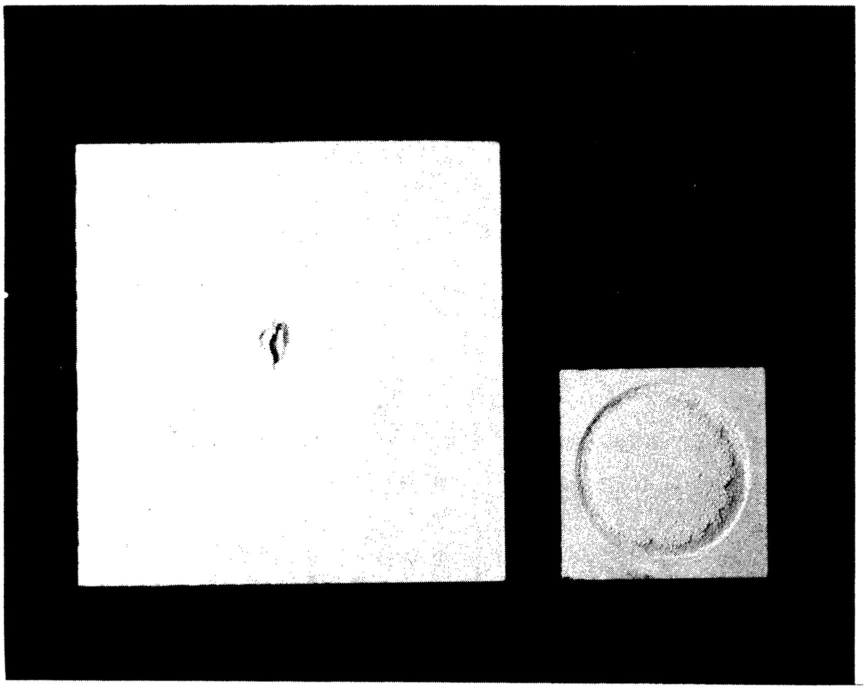
3184

52. Damage and Specimens Perpendicular Impact and Cavitation
Navy 1 and 2 (1.8 Mach, 90°)

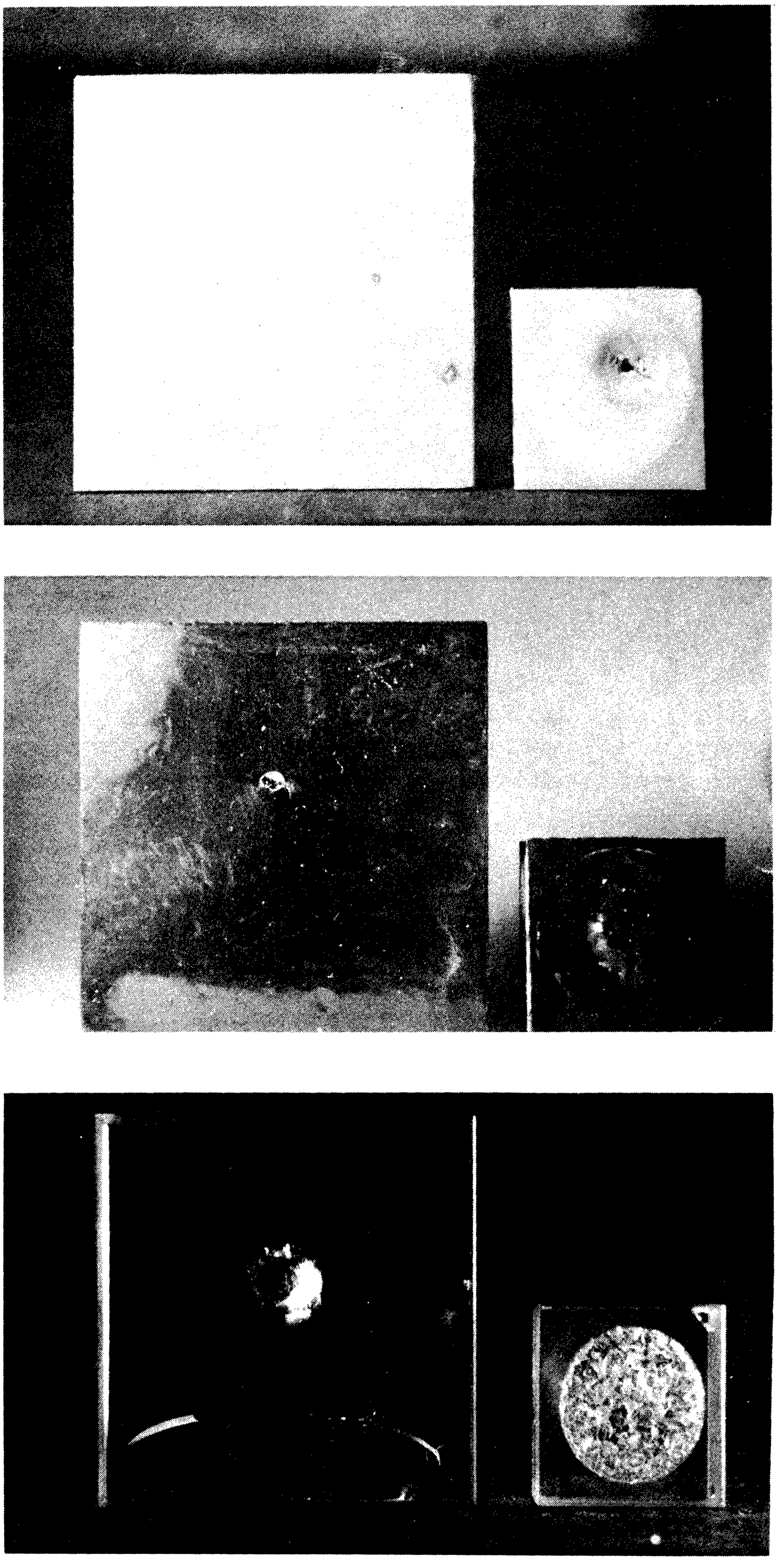




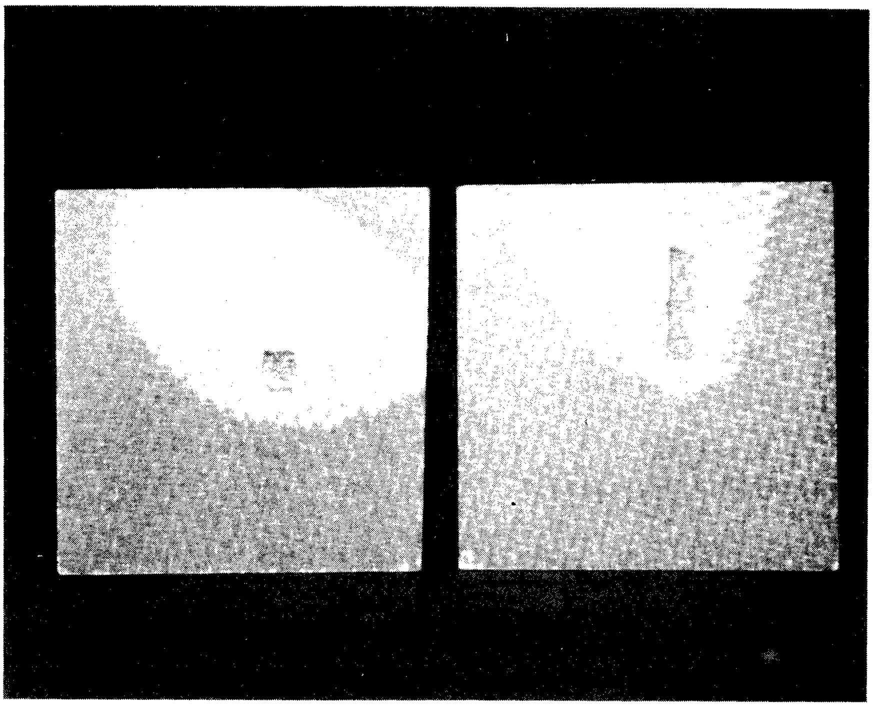
53. Damage and Specimens Perpendicular Impact and Cavitation Navy 3 and 4 (1.5 Mach, 90°)

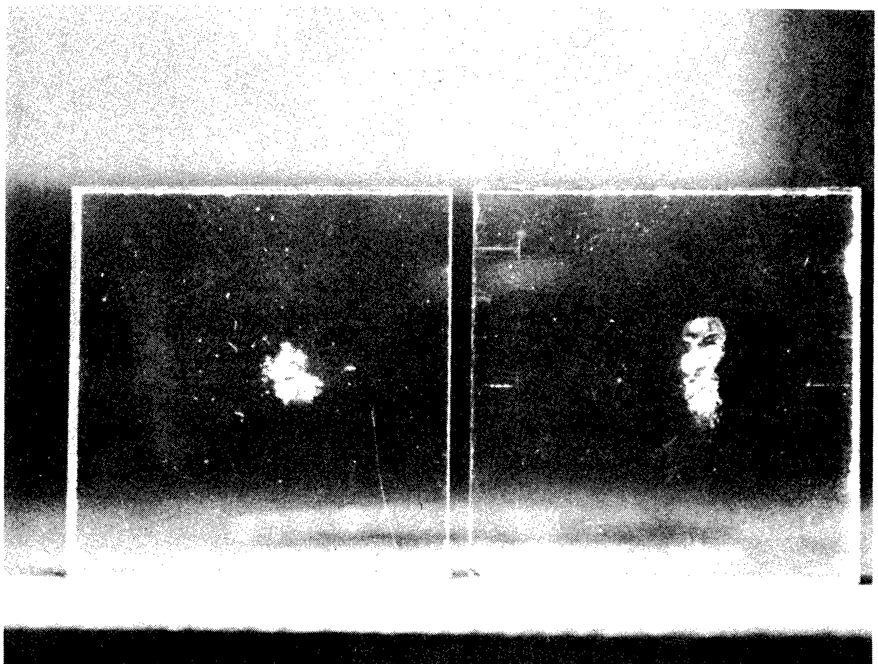


54. Damage and Specimens Perpendicular Impact and Cavitation Navy 5 and 6 (1.5 Mach, 90°)

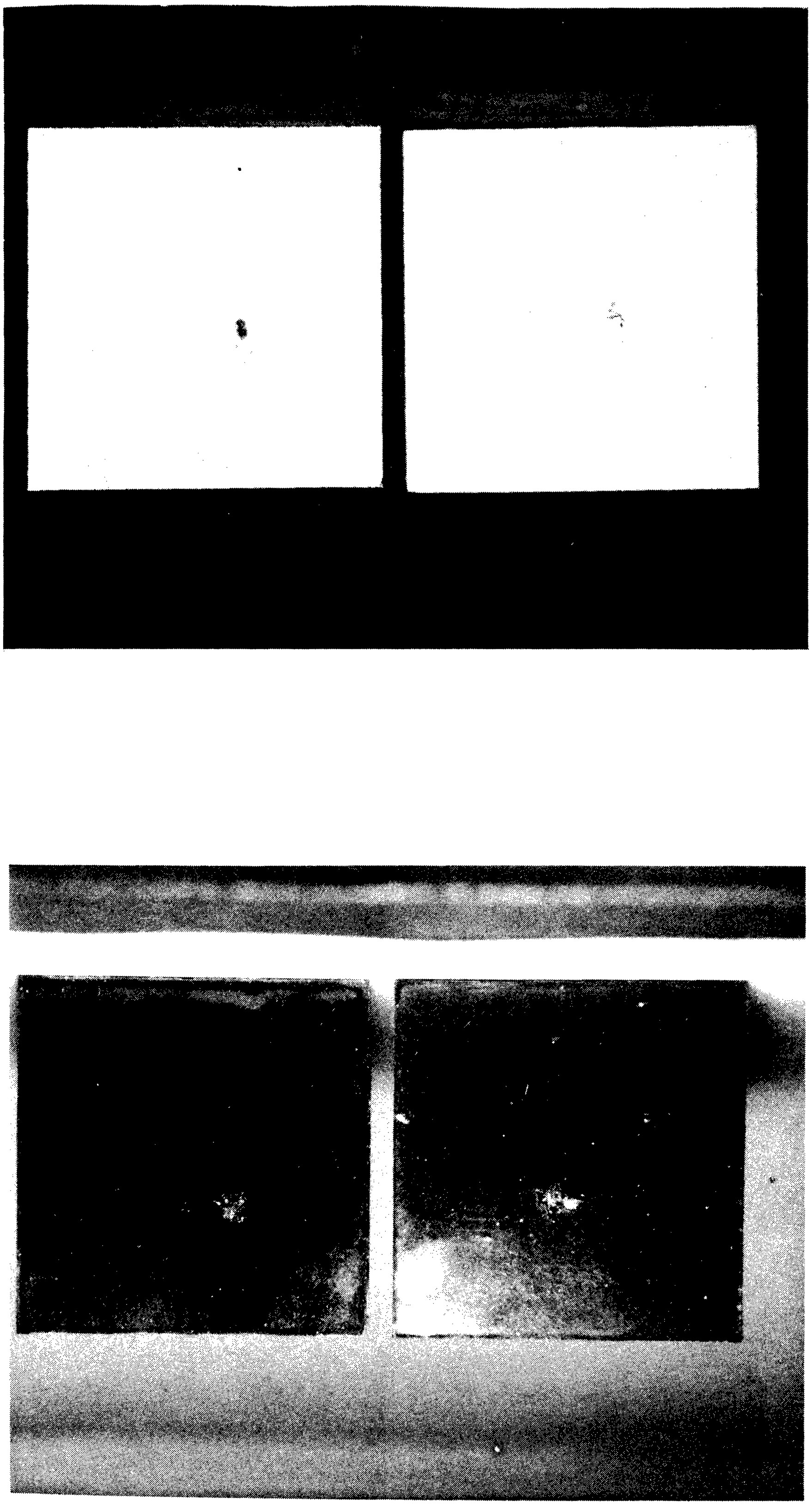


55. Damage and Specimens Perpendicular Impact and Cavitation Navy 7, 8, and 9 (1.5 Mach, 90°)

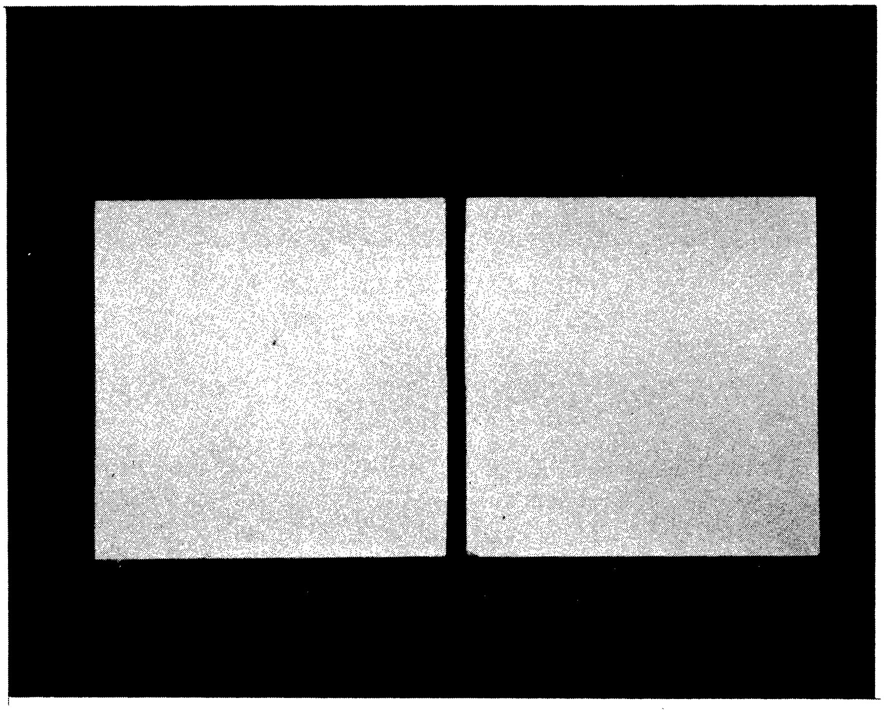


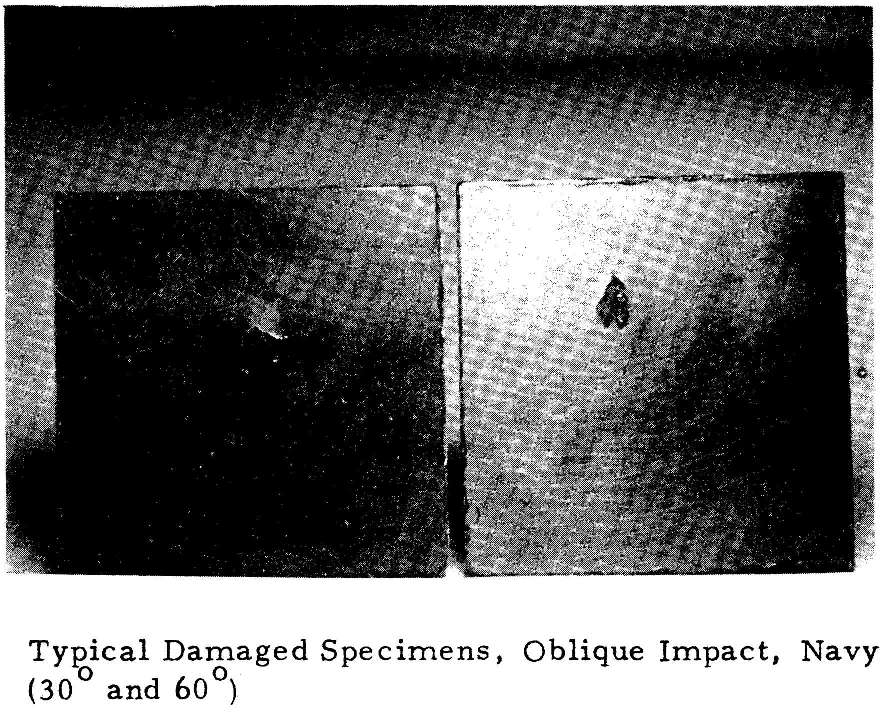


56. Typical Damaged Specimens, Oblique Impact, Navy 1 and 2 (30^{o} and 60^{o})

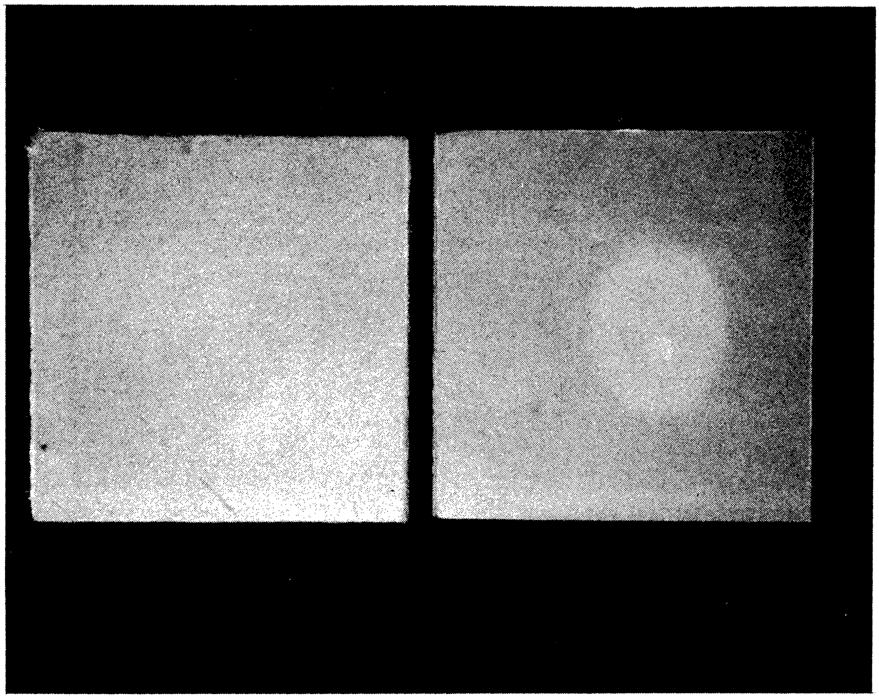


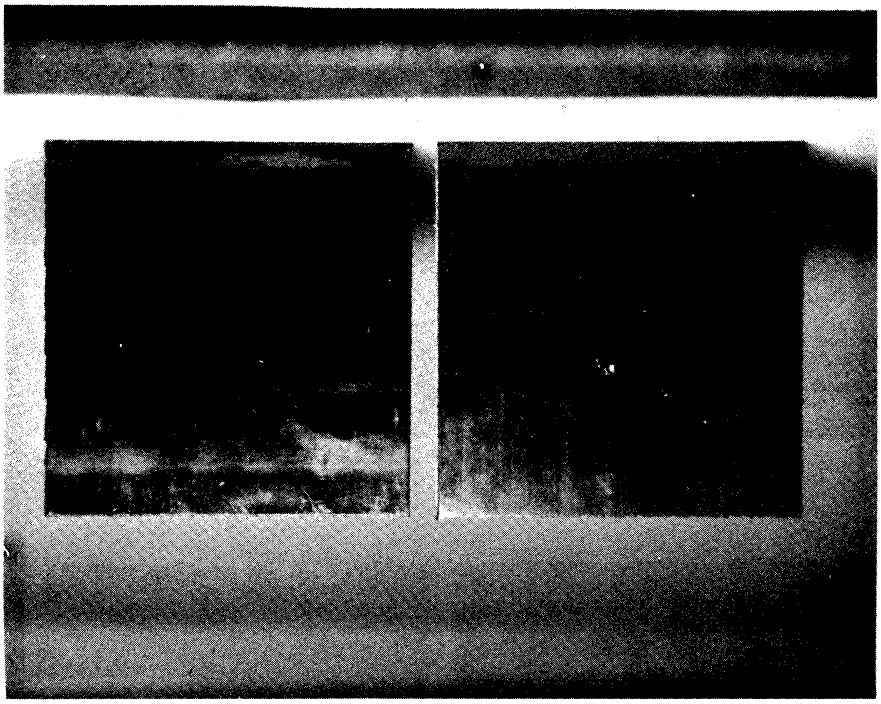
57. Typical Damaged Specimens, Oblique Impact, Navy 3 and 4 (30^o and 60^o)





58. Typical Damaged Specimens, Oblique Impact, Navy 5 and 6 (30° and 60°)





59. Typical Damaged Specimens, Oblique Impact, Navy 7 and 8 (30^{o} and 60^{o})

APPENDIX

[illegible]

ベンド #1

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

Angle of Attack

[illegible]

[illegible]

DATE	[illegible]	NO. OF SHOT	WEIGHT	LOSS	ACC. LOSS
	320 m/sec	0	10.13083	0	0
		1750	10.12745	3.38	3.38
		1000	10.12061	6.84	10.22
		1250	10.08549	45.12	55.34
		1500	10.04602	38.97	94.31
		1750	10.02900	17.52	111.83
		2100	9.98924	39.76	151.59

JET GUN DATA SHEET

Sample No. NV 7 #2

Material EPON 828 EPOXY LAMINATE

Density 1.64 gm/cm³

Spring 13/16

Meniscus Withdrawl -4.5

Angles of Attack 90°

Mass Loss Rate 1.95 mg/IMP

Volume Loss Rate

DATE	JET SPEED	NO. OF SHOT	WEIGHT	LOSS	ACC. LOSS
12/20		0	10.39405	—	—
		2	10.39355	50	50
		3	10.39320	35	85
		4	10.39215	105	190
		5	10.39050	165	355
		6	10.38850	200	555
		7	10.38662	188	743
12/21		7	10.38600	—	—
		8	10.38400	200	943
		9	10.38277	123	1066
		10	10.38140	137	1203
		11	10.38030	110	1313
		12	10.37915	115	1428
12/22		12	10.37898	—	—
		13	10.37818	80	1508
		14	10.37689	129	1637
		15	10.37530	159	1796
		16	10.37459	71	1867
12/30		16	10.37325	—	—
		17	10.37275	50	1917
		18	10.37190	85	2002

OPERATOR GILBERT HWANG

JET GUN DATA SHEET

Sample No. NV 1 #1

Material EPON 828 EPOXY LAMINATE

Density

Spring 13/16

Meniscus Withdrawl -45

Angles of Attack 90°

Mass Loss Rate

Volume Loss Rate

DATE	JET SPEED	NO. OF SHOT	WEIGHT	LOSS	ACC. LOSS
12/20		0	10.25919	—	—
		2	10.25820	99	99
		3	10.25730	90	189
		4	10.25615	115	304
		5	10.25438	177	481
		6	10.25280	158	639
		7	10.25080	200	839
12/21		7	10.25035	—	—
		8	10.24844	191	1030
		9	10.24677	167	1197
		10	10.24521	156	1353
		11	10.24386	135	1488
		12	10.24276	110	1598
12/22		12	10.24265	—	—
		13	10.24185	80	1678
		14	10.24066	119	1797
		15	10.23953	113	2010
		16	10.23870	83	2093
12/30		16	10.23751	—	—
		17	10.23729	22	2115
		18	10.23675	104	2219
			OPERATOR	GILBERT HOWARDS	

NAVY 1 #3

EPON 828 EPOXY

13/16

−4.5

Angle of attack 60° ↑

Mass Loss Rate 1.15 mg/imp

Volume Loss Rate

DATE	JET SPEED	NO. OF SHOT	WEIGHT	LOSS	AGG LOSS
6/6	577	0	10.61073		
		10	10.60951	122	122
		15	10.60807	144	266
6/7		15	10.60825		
		20	10.60712	113	379
		25	10.60414	298	677
		28	10.60037	377	1054
		29	10.59955	82	1136
6/13	603	29	10.60119		
		30	10.59994	115	1251
		31	10.59900	94	1355
6/14		31	10.59910		
		32	10.59800	110	1465
		33	10.59700	100	1565
		34	10.59585	115	1680

OPERATOR GILBERT HWANG

JET GUN DATA SHEET

Sample No. NAVY 1 #4

Material EPON 828 EPOXY

Density

Spring 13/16

Meniscus Withdrawl -.45

Angles of Attack 60°

Mass Loss Rate

Volume Loss Rate

DATE	JET SPEED	NO. OF SHOT	WEIGHT	LOSS	ACC. LOSS
6/6	377	0	10.11221		
		10	10.10965	256	256
		15	10.10730	235	491
6/7		15	10.10696		
		20	10.10433	263	764
		25	10.09973	460	1224
		28	10.09690	283	1517
		29	10.09600	90	1607
6/13	603	29	10.09741		
		30	10.09640	101	1708
		31	10.09545	95	1803

OPERATOR GIL HWANG

NAVY #2
PLEXIGLAS

DATE	JET SPEED	NO. OF SHOT	WEIGHT	LOSS	[illegible]
	320 M/S	0	6.41331	0	0
		750	6.41076	2.54	2.54
		1000	6.40829	1.47	4.01
		1150	6.32711	81.18	85.19
		1500	6.32242	4.69	89.88
		1750	6.32242	0	89.88
		2100	6.31914	3.28	93.16

JET GUN DATA SHEET

Sample No. NV 2 #1

Material PLEXIGLAS 2 UVA

Density 1.19 gm/cm³

Spring 13/16

Meniscus Withdrawl -45

Angles of Attack 90°

Mass Loss Rate 496 mg/IMP

Volume Loss Rate

DATE	JET SPEED	NO. OF SHOT	WEIGHT	LOSS	ACC. LOSS
12/26		0	7.13755	—	—
		5	7.13741	14	14
		10	7.13728	13	27
		15	7.13695	33	60
		20	7.13675	20	80
		22	7.13500	175	255
		23	7.13448	52	307
		24	7.13087	361	668
12/29		24	7.13035	—	—
		25	7.12500	535	1203
		26	7.12474	26	1229
		27	7.12402	72	1301
		28	7.12370	32	1333
12/30		28	7.12370	—	—
		29	7.12330	40	1373
		30	7.09638	2692	4075
		31	7.09429	209	4284
			OPERATOR	GILBERT	HWANG

JET GUN DATA SHEET

Sample No. NV 2 #2

Material PLEXIGLAS 2 UVA

Density

Spring 13/16

Meniscus Withdrawl -45

Angles of Attack 90°

Mass Loss Rate 2.04 mg/IMP

Volume Loss Rate

DATE	JET SPEED	NO. OF SHOT	WEIGHT	LOSS	ACC. LOSS
12/26		0	6.34106	—	—
		5	6.34080	26	26
		10	6.34080	0	26
		15	6.34055	25	51
		20	6.34005	50	101
		22	6.33987	18	119
		23	6.33955	22	141
		24	6.33843	112	253
12/29		24	6.33790	—	—
		25	6.33724	66	329
		26	6.33520	204	533
		27	6.32862	658	1291
		28	6.32726	136	1427
12/30		28	6.32725	—	—
		29	6.32666	59	1486
		30	6.32560	106	1592
		31	6.32197	363	1965
			OPERATOR	GILBERT	HWANG

JET GUN DATA SHEET

Sample No. NAVY 2 #3

Material ~~EPON 828 EPOXY~~ PLEXIGLAS 2 UVA

Dencity 1.19 gm/cm³

Spring 13/16

Meniscus Withdrawl -45

Angles of Attack 60°

Mass Loss Rate 1.13 mg/IMP, 0.084 mg/IMP

Volume Loss Rate

DATE	JET SPEED	NO. OF SHOT	WEIGHT	LOSS	ACC. LOSS
6/07	577	0	6.47865		
		20	6.47826	39	39
		25	6.47595	231	270
		28	6.46951	644	914
		29	6.46945	006	920
6/13	603	29	6.47151		
		30	6.47125	26	946
		32	6.47125	0	946
6/14		32	6.47118		
		34	6.47115	3	949
		36	6.46635	480	1429
		37	6.46635	0	1429
6/20	552	37	6.46885		
		40	6.46875	10	1439
		45	6.46870	5	1444
		55	6.46820	50	1494
		65	6.46780	40	1534
		75	6.46682	98	1633

OPERATOR GILBERT HWANG

JET GUN DATA SHEET

Sample No. NAVY 3 #1

Material

Density

Spring

Meniscus Withdrawal

Angles of Attack

Mass Loss Rate

Volume Loss Rate

DATE	JET SPEED	NO. OF SHOT	WEIGHT	LOSS	ACC. LOSS
6/20	553	0	4.68503	—	—
		10	4.68478	25	25
6/21		10	4.68625	—	—
		20	4.68613	12	37
		25	4.68610	3	40

JET GUN DATA SHEET

Sample No. NAVY 3 #2

Material

Density

Spring

Meniscus Withdrawl

Angles of Attack

Mass Loss Rate

Volume Loss Rate

DATE	JET SPEED	NO. OF SHOT	WEIGHT	LOSS	ACC. LOSS
6/20	553	0 10	4.65720 4.65745	— 0	— 0
6/21		10 20	4.65905 4.65886	— 19	— 19
		75	4.65850	36	55

MATERIAL DAMAGE SHEET

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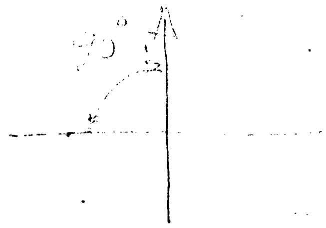

DATA

Impact ...erval	Cumulative Impact Time	Wt. Loss	Cumulative Wt. Loss	MDP	Cumulative MDP
[illegible]	1	0.95	0.95		
[illegible]	10	0.99	1.94		
5	20	1.31	3.25		
5	25	0.55	3.80		
2	27	0.65	4.45		
2	29	0.90	5.35		
[illegible]	31	0.69	[illegible]		

NAVY 1

90°

DATE	[illegible]	[illegible]	WEIGHT	[illegible]	[illegible]
	0.9M				
917		0	4.77415	0	
— " —		13,000	4.77277	1.38	1.38
— " —		13,500	4.76892	3.85	5.23
— " —		15,500	4.76284	6.08	11.31
— " —		16.500	4.76095	1.89	13.20
— " —		17.500	4.76022	0.75	13.95

MATERIAL DAMAGE SHEET

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RUNNING CONDITIONS

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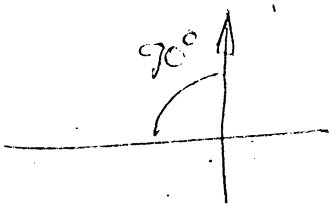

DATA

impacts erval	Cumulative ~~Time~~ impacts	Wt. Loss	Cumulative Wt. Loss	MDP	Cumulative MDP
10	10	7.50	7.50		
15	15	3.02	10.52		
5	20	1.84	12.36		
5	25	5.42	17.78		
2	27	3.25	21.03		
2	29	4.15	25.18		
2	31	2.85	28 63		

MATERIAL DAMAGE SHEET

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RUNNING CONDITIONS

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[illegible]er	Pressure
[illegible]x. Date	Torque

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BASIS FOR CALCULATIONS

[illegible]ty	Area

[illegible]actor

[illegible]nts

DATA

Impacts [illegible]erval	Cumulative ~~Time~~ Impacts	Wt. Loss mg.	Cumulative Wt. Loss	MDP	Cumulative MDP
2000	2000	-6.60	-6.60		
200	2200	30.55	23.95		
100	2300	0.70	24.65		
200	2500	2.20	26.85		
[illegible]	2700	4.25	31.10		
[illegible]	3000	0.45	31.55		

MATERIAL DAMAGE SHEET

al NAVY 5

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RUNNING CONDITIONS

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. Date	Torque

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BASIS FOR CALCULATIONS

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1.2M angel 90°

DATA

impacts erval	Cumulative ~~Time~~ impacts	Wt. Loss	Cumulative Wt. Loss	MDP	Cumulative MDP
500	4500	24.19	24.19		
100	4600	9.15	33.34		
150	4650	6.14	39.48		
50	4700	11.66	51.14		
25	PENETRATE				

MATERIAL DAMAGE SHEET

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RUNNING CONDITIONS

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BASIS FOR CALCULATIONS

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DATA

...erval	Cumulative Time	Wt. Loss	Cumulative Wt. Loss	MDP	Cumulative MDP
[illegible]	[illegible]	[illegible]	1.02		
[illegible]	[illegible]	[illegible]	[illegible]		
5	35	[illegible]	[illegible]		
5	40	0.45	[illegible]		
[illegible]	45	[illegible]	[illegible]		
[illegible]	[illegible]	[illegible]	11.5[illegible]		
[illegible]	[illegible]	[illegible]	11.[illegible]		
[illegible]	75	1.65	13.43		

MATERIAL DAMAGE SHEET

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RUNNING CONDITIONS

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er	Pressure
s. Date	Torque

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BASIS FOR CALCULATIONS

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DATA

erval	Cumulative Time	Wt. Loss	Cumulative Wt. Loss	MDP	Cumulative MDP
[illegible]	[illegible]	6.45	6.46		
[illegible]	[illegible]	2.71	[illegible]		
[illegible]	900	[illegible]	4.61		
[illegible]	[illegible]	2.16	[illegible]		
[illegible]	[illegible]	1.11	[illegible]		
[illegible]	[illegible]	[illegible]	11.51		
[illegible]	1600	[illegible]	11.47		

JET GUN DATA SHEET

Sample No N[illegible]

Material

Density

Spring

Meniscus Withdrawl

Angles of Attack 90°

Mass Loss Rate 0.9 mg/IMP

Volume Loss Rate

DATE	JET SPEED	NO. OF SHOT	WEIGHT	LOSS	ACC. LOSS
	H.1	0	5.66[illegible]	0	—
		[illegible]	5.65[illegible]	4.99	4.99
		900	5.6[illegible]945	17.61	22.[illegible]
		870	5.63[illegible]	9.45	32.[illegible]
		890	5.6[illegible]	3.45	35.[illegible]
		[illegible]	5.62072	[illegible]	41.[illegible]
		920	5.5[illegible]	21.21	[illegible]
			Nikki		

Sample No. NAVY 5 #14

[illegible]

[illegible]

[illegible] 13/16

[illegible] -4.5

Angle of Attack 60°

Mass Loss Rate .093 mg/IMP

Volume Loss Rate

DATE	JET SPEED	NO. OF SHOT	WEIGHT	LOSS	ACC. LOSS
7/5	522	0	5.24884	—	—
		200	5.24808	73	73
		210	5.24~~832~~ 4732	76	149
		220	5.24707	25	174
		230	5.24670	27	201
		240	5.24623	47	248
		TESTING LAYER COMPLETELY PENETRATED.			

GILBERT HWANG

[illegible] NAVY 6 #2

[illegible]

[illegible]

[illegible] 13/16

[illegible] -4.5

Angle of Attack 90°

Mass Loss Rate 5.75 mg/IMP

Volume Loss Rate

DATE	JET SPEED	NO. OF SHOT	WEIGHT	LOSS	SUM LOSS
		0	5.52875	—	—
		5	5.52670	205	205
		10	5.52570	100	305
		13	5.52400	170	475
		16	5.50825	1575	2050
		19	5.50580	245	2295

OPERATED BY NIKKI

PLOTTED BY GILBERT HWANG

NAVY 6 #4

13/16

-45

60°

Mass Loss Rate .051

Volume Loss Rate

DATE	JET SPEED	NO. OF SHOT	WEIGHT	LOSS	ACC. LOSS
7/5	522	0	5.05081	—	—
		15	5.05052	29	29
		25	5.05015	37	66
		30	5.04998	17	83
		35	5.04967	31	114
		40	5.04947	20	134

OPERATOR: GILBERT HUANG

MATERIAL DAMAGE SHEET

ial NAVY C

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RUNNING CONDITIONS

	...mperature
er	Pressure
s. Date	Torque

n

ce Preparation — —

BASIS FOR CALCULATIONS

ty	Area

actor

nts SPEED OF JET 12M. angel 90°

DATA

shots erval	Cumulative Time shots	Wt. Loss	Cumulative Wt. Loss	MDP	Cumulative MDP
100	100	1.98	1.98		
50	150	4.24	6.22		
50	200	3.89	10.13		
50	250	1.44	11.57		
50	300	1.55	13.12		
	~~PENETRATE~~				
50	350	1.73	14.65		

MATERIAL DAMAGE SHEET

NAVY 6

—

— RUNNING CONDITIONS

—	..mperature
—	Pressure
Date —	Torque

—

: Preparation —

BASIS FOR CALCULATIONS

/ —	Area

—

:tor

:s SPEED OF JET 1.2M. angel 90°

DATA

:hots rval	Cumulative ~~Time~~ Shots	Wt. Loss	Cumulative Wt. Loss	MDP	Cumulative MDP
00	100	1.98	1.98		
50	150	4.24	6.22		
50	200	3.89	10.13		
50	250	1.44	11.57		
50	300	1.55	13.12		
	[illegible]				
50	350	1.73	14.85		

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

Angle of [illegible]

[illegible] Loss Rate

[illegible] Loss [illegible]

DATE	[illegible]	NO. OF SPOT	WEIGHT	LOSS	[illegible] LOSS
[illegible]	[illegible]	[illegible]	[illegible]		
		[illegible]	[illegible]	[illegible]	

NAVY 6

600

	0.6				
9/15	6	0	5.01462	0	
		1740	5.01310	1.52	1.52
		1940	5.01090	2.20	3.72
		2010	5.00840	2.50	6.22
		2140	5.00704	1.36	7.58
		2340	5.00438	2.66	10.24
		2790	4.99800	6.38 ~~2.57~~	16.62 ~~12.80~~

MATERIAL DAMAGE SHEET

ial NAVY 3B

er

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	.00193	.00193		
2	4	.00019	.00212		
2	6	.00011	.00223		
2	8	.00057	.00280		

NAVY 6

13/16

60°

$0.91 \times 10^{-?}$ mg/...

9/5		0	5.02700	—	—
		300	5.02655	45	45
9/6		300	5.02686	—	—
		400	5.02610	76	111
		450	5.02570	40	151
9/7		450	5.02620	—	—
		475	5.02685	35	186
		525	5.02665	30	216
		600	5.02668	−3	213
		650	5.02550	118	331

NAVY 6

90°

	0.6				
9/16		0	5.02439	0	
		1300	5.01989	4.50	4.50
		1550	5.01831	1.58	6.08
		2050	5.01307	5.24	11.32
		2350	5.00427	8.80	20.12
		3100	5.00187	2.40	22.52

[illegible]

[illegible] A[illegible]

[illegible]

[illegible]

[illegible]

Angles of Attack

Mean Loss Rate

Volume Loss Rate

DATE	[illegible] SPEED	NO. OF SHOT	WEIGHT	LOSS	[illegible] LOSS
7/20	1[illegible]	[illegible]	5.6[illegible]	0	0
	36—	[illegible]00	5.6[illegible]	[illegible]	[illegible]
		[illegible]00	5.6[illegible]517	1.67	1.1[illegible]
		[illegible]	5.6[illegible]113	1.[illegible]	[illegible]
		1000	5.6[illegible]	2.[illegible]	[illegible]
		1[illegible]00	5.6[illegible]	2.[illegible]	11.[illegible]
7/21		1[illegible]00	5.6[illegible]1[illegible]		
		1[illegible]	5.[illegible]	1.71	1[illegible]

JET GUN DATA SHEET

Sample No. NAVY 7 #4

Material

Density

Spring 13/16

Meniscus Withdrawal -4.3

Angles of Attack 60°

Mass Loss Rate .0112 mg/imp

Volume Loss Rate

DATE	JET SPEED	NO. OF SHOT	WEIGHT	LOSS	ACC. LOSS
7/11		0 25	5.11700 5.11695	— 5	5
		35 50	5.11695 5.11678	0 17	5 22
		60	5.11665	13	35
7/12		60 75	5.11713 11698	— 15	50
		100 120	5.11683	25	75
		150 200	5.11683 5.11670	13	88
		OPERATED	BY	GILBERT	HWANG

NAVY 7

Angle of Attack 60°

Mean Loss Rate

Volume Loss Rate

DATE	SPEED	NO. OF SHOT	WEIGHT	LOSS	AVG. LOSS
[illegible]-5	12M	0	5.06887	0	[illegible]
		20,000	5.06734	1.53	1.53
		STOP			

JET GUN DATA SHEET

Sample No. NAVY 8 #4

Material

Density

Spring 13/16

Meniscus Withdrawal -45

Angles of Attack 60°

Mass Loss Rate .045 mg/MP

Volume Loss Rate

DATE	JET SPEED	NO. OF SHOT	WEIGHT	LOSS	ACC. LOSS
7/11		0	4.94325	—	0
		25	4.94305	20	20
		45	4.94280	15	35
		65	4.94200	—	
7/12		65	4.94252	28	63
		75	4.94236	16	79
		80	4.94198	38	117
		85	4.94153	45	162
		OPERATOR	GILBERT HWANG		

[illegible] DATA SHEET

[illegible] No. [illegible]

[illegible]

[illegible]

[illegible]

[illegible]

Angle of Attack

Mass Loss Rate

Volume Loss Rate

DATE	JET SPEED	NO. OF SHOT	WEIGHT	LOSS	ACC. LOSS
[illegible]	[illegible]	0	[illegible]	—	
		[illegible]	[illegible]	—	[illegible]
		[illegible]	[illegible]	—	
		1600	[illegible]	[illegible]	[illegible]
		Stop [illegible]		[illegible]	

[illegible]: NAVY 3 12M 60°

[illegible]

[illegible]

Measuring Method

Angle of Attack: 60°

Mass Loss Rate

Volume Loss Rate

DATE	JET SPEED	NO. OF IMPT	WEIGHT	LOSS	CUM. LOSS
		10.000	1.94734	0	0

MATERIAL DAMAGE SHEET

...ial NAVY B

...r

RUNNING CONDITIONS

	...mperature
...er	Pressure
...s. Date	Torque

...n

...ce Preparation

BASIS FOR CALCULATIONS

...ty	Area

...actor

...nts ~~Jet speed~~
SPEED OF JET
1.2 MACH
angel 90°

DATA

impacts ...erval	Cumulative Time	Wt. Loss	Cumulative Wt. Loss	MDP	Cumulative MDP
500	4500	8.43	8.43		
150	4650	3.10	11.53		
50	4700	1.01	12.54		
50	4750	0.20	12.74		
50	4800	3.94	16.68		
50	4850	2.24	18.92		