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THE RELATIONSHIP BETWEEN FISH SIZE AND THEIR RESPONSE TO UNDERWATER BLAST

John T. Yelverton, et al

Lovelace Foundation for Medical Education and Research

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Lovelace Foundation for Medical Education and Research
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Albuquerque, New Mexico 87115

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Fish were exposed to underwater blasts in an artificial pond, 220 x 150 ft, that was 30 ft deep. The underwater-blast impulse levels required for 50-percent mortality, 1-percent mortality, and no-injuries were determined for eight species of fish. There was good correlation between the LD_{50} impulse and the body weight of the fish. These ranged from 1.7 psi·msec

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20. ABSTRACT (Continued)

for 0.02-g guppy fry to 49.5 psi·msec for 744-g carp. No difference was detectable in the underwater blast response of fish that had ducted swimbladders and those that had nonducted swimbladders. Application of the results of this study to predicting the response of fish to underwater explosions was discussed.

PREFACE

This report presents the results of a study conducted to determine the response of fish to underwater explosions. The information should be applicable to government agencies and private industry groups required to prepare Environmental Impact Statements in connection with detonating high explosives in a water environment. The data can be used to predict ranges from underwater explosions at which fish will be killed and to predict ranges where there would be no effect.

The fish used in this study were supplied by the Bureau of Sport Fisheries and Wildlife, Division of Fish Hatcheries, U. S. Department of the Interior, Fish and Wildlife Service. The cooperation of R. E. Elkin, Jr., Regional Director, is acknowledged.

This research was conducted according to the principles enunciated in the Guide for Laboratory Animal Facilities and Care prepared by the National Academy of Sciences-National Research Council.

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INTRODUCTION

The primary objective of this study was to determine the tolerance of different species of fish to underwater blasts. Secondary objectives were: (1) to compare the underwater shock response of fish having ducted swimbladders with fish having nonducted swimbladders, (2) to determine the effect of a nearby reflecting surface on fish, and (3) to gather information on the survival time and recovery rate of blast-injured fish.

The swimbladders of fish, since they contain a gas, determine the fish's vulnerability to underwater shock. The swimbladder is a hydrostatic organ that aids in regulating the fish's buoyancy. Fish may be divided into three groups in connection with their swimbladders. Physostomes are those fish that have a small diameter duct connecting their swimbladder to their gastrointestinal tract. Physoclists are those fish that have swimbladders without a duct. Some fish have no swimbladders at all and are practically invulnerable to underwater shock.

The underwater-shock facility at this laboratory provided an ideal site to study the underwater-blast effects on fish. Repeated tests could be run with a minimum of time and effort under strictly controlled conditions.

Furthermore, previous experience at this laboratory, References 1 and 2, has shown that the response of mammals and birds to underwater blasts was related to the impulse in the underwater shock. This information enabled the fish experiments to be designed in the most efficient manner.

METHODS

Underwater Test Facility

The test facility was an artificial body of fresh water, 220 x 150 [illegible] at its surface. It was 30 ft deep over its 30- x 100-ft center portion, Figure 1. The entire pond was lined with black polyvinyl plastic 20 mils thick. A 6-inch-deep layer of sand was located beneath the plastic in the 30-ft-deep portion of the bottom. The sides of the pond had a 2-to-1 slope. The long axis of the pond was east to west. Two sets of rigging spanned the pond in a north-south direction. The main rigging, located 80 ft from the west end, consisted of a grid 14 x 24 ft which could be raised and lowered by an electric winch on the south bank. The other rigging was approximately 30 ft from the east end of the pond. Its center grid was 5 x 10 ft which could be raised and lowered by a hand winch on the south bank. The test pond contained approximately [illegible].2 million gallons of

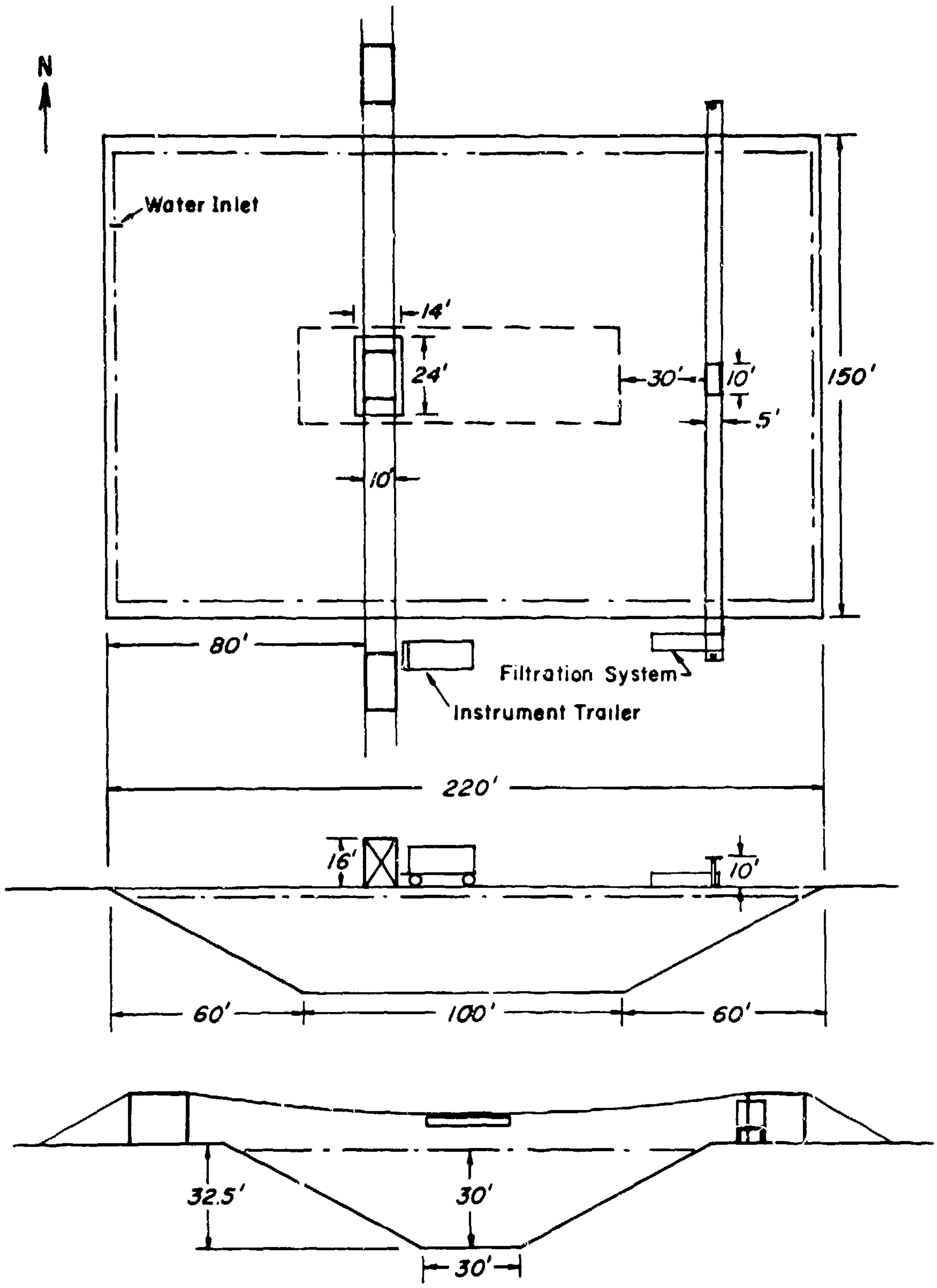

Figure 1. Underwater Test Faci'ity.

tap water. Water temperatures during this study ranged between 9 and 23°C.

The ambient air pressure at the pond was 12.0 psia.

Pressure-Time Measurements

There were four channels of pressure-time measuring instrumentation. The methods and equipment used for measuring and recording the underwater-blast wave basically are those described in References 1 and 2. The pressure-time gages were a recent modification of the Naval Surface Weapons Center's (formerly Naval Ordnance Laboratory) gage, Type B. Sensing elements of the gages consisted of four 1/4-inch-diameter tourmaline discs mounted in a Tygon® tube filled with silicone oil (Dow-Corning No. 200 dielectric oil). Signals from the gages were passed through a cathode-follower K amplifier unit and recorded on a dual-beam oscilloscope (Tektronix Model 555 with Type D preamplifier plug-in units). To ensure accurate time measurements, timing marks were placed on the oscilloscope with a time-marker generator.

High-Explosive Charges

Bare spheres of Pentolite, weighing 1-lb, were used throughout this study. The charges were fired by electric blasting caps (Dupont E99) inserted to the center of the charge through a 3/16-inch detonator well.

Types of Fish

Eight different species of fish were used in this study. There were five species of fish with ducted swimbladders (physostomes) and three species of fish with non-ducted swimbladders (physoclists). The physostomes were top minnow (Gambusia affinis), goldfish (Carrasius auratus), carp (Cyprinus carpio), rainbow trout (Salmo gairdneri), and channel catfish (Ictalurus punctatus). Guppy (Lebistes reticulatus), bluegill (Lepomis macrochirus), and large mouth black bass (Micropterus salmoides) were the physoclists. Since large and small ones were available within five of the species, there were a total of 13 body weight groups. The average body weight of the groups ranged from 0.02 g for the guppy fry to 744 g for the large carp.

Fish Cages

Except for the guppies and top minnows, all fish were held in place during the blast by cages. The cages were roughly cylindrical in shape with a frame of 1/16- to 1/8-inch-diameter steel rods covered with nylon or plastic fish net. The mesh size was from 1/4 to 7/8 inch. The largest mesh size that would keep the fish from escaping was used to reduce to a minimum the amount of material that could possibly shield the fish from the underwater shock, Figure 2. Cages varied in size and were made tight fitting for the individual species so that they could be held at an exact depth.

Most of the fish were exposed one per cage with their long axes perpendicular to the radial line from the charge. The small bluegills and the small goldfish were tested 5 or 10 per cage. The majority of the tests were run with cages slung beneath the main rigging and the charges were to the east. The very small fish, including the guppy, guppy fry, and top minnow, were released from a dip net 0.25 ft beneath the surface 1 sec before detonation and retrieved within 1 to 2 sec afterward with a dip net. Groups of 10 to 40 fish were tested at one time in this manner.

The larger fish were maintained in two ponds that were 15 x 30 ft and from 2 to 6 ft deep. Smaller fish were maintained in 50-gallon aquaria. Immediately after each test, fish were transported in aerated tanks to 4- x 4-ft observation tanks located in a trailer adjacent to the test pond. With the exception of the overnight deaths, all

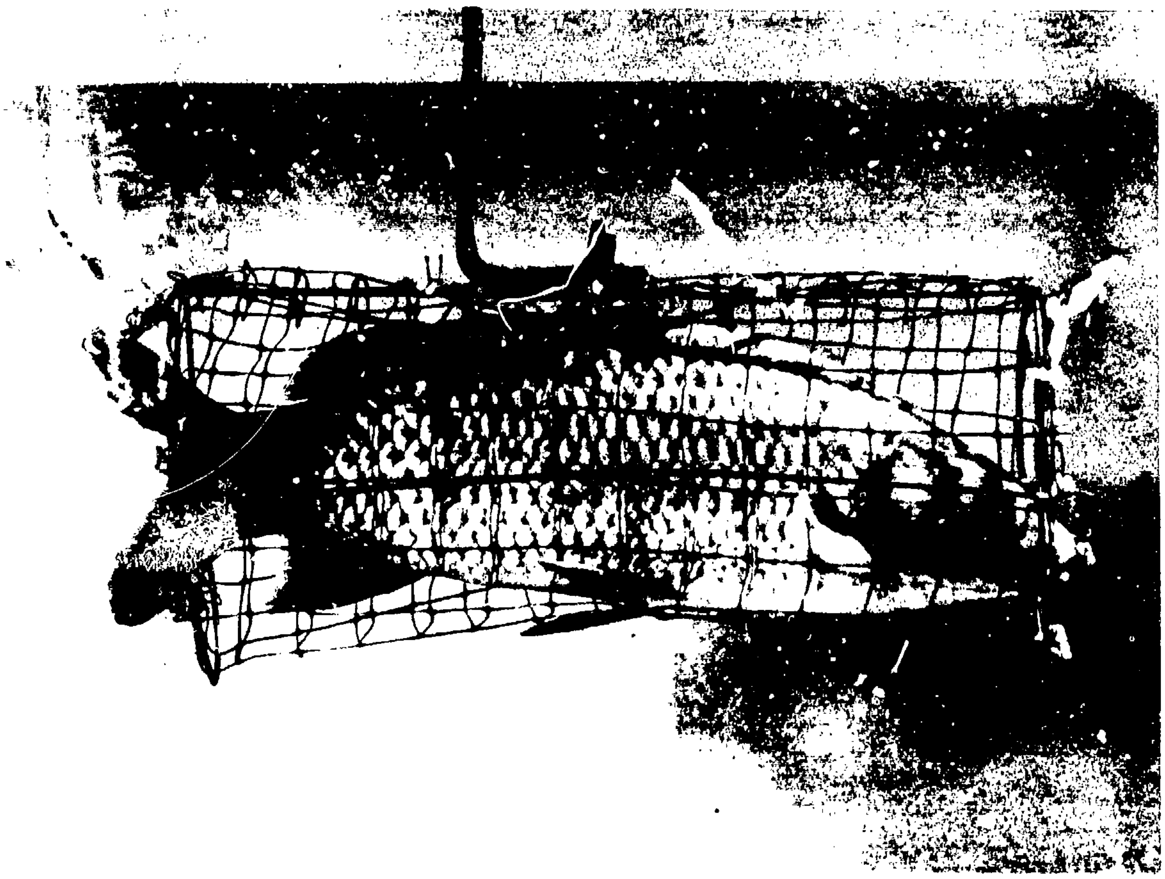

Figure 2. Carp in Cage.

fatalities were autopsied within 30 min after the test. Groups of fish that survived blasts in the lethal range were observed for 2 weeks.

Geometry of Exposure

Fish Depth Constant - Slant Range Varied

Most of the tests were conducted with the fish at 1-ft depths and the charges detonated at 10-ft depths. Groups of fish were placed at various distances from the charge within and beyond the lethal zone out to a no-injury range. The following fish were tested at 1-ft depths: small goldfish, catfish, bluegill, and carp; large goldfish, catfish, bluegill, and carp; and trout and bass.

Small carp were also tested at 0.17- and 10-ft depths, charges at 10-ft, and the slant range varied. Top minnows and guppies, including the guppy fry, were located at 0.25-ft depths.

To avoid excessive ranges in obtaining smaller impulses, the depth of fish and/or charge were reduced. This was necessary to avoid subjecting the fish to shock reflections from along the west bank of the pond. For determining the no-effect level for small carp, small goldfish, and large goldfish, the depths of fish were decreased and the charge was placed at 5 ft. The ranges, depths, and numbers of fish are listed in tables in the appendix of this report.

Fish Depth Varied - Slant Range Constant

By keeping the depth of charge and slant range constant and by varying the depth of the fish, it was possible to vary the impulse levels and keep the peak pressure constant. For instance, the small bluegills were tested at a constant slant range of 91 ft, with a constant peak pressure of 128 psi, and impulses ranging from 10 psi·msec to 5 psi·msec. The fish were placed at depths from 2.5 to 1 ft with the charges at depths of 10 ft. To get impulse levels less than 5 psi·msec, the depth of burst was decreased to 5 ft, Table A-12.

Fish Against a Reflecting Surface

Groups of catfish and small carp were tested against a reflecting surface normal to the direct shock wave, Table A-15. A 4- x 5-ft steel plate, 5/8-inch thick, was slung from a raft. The fish cages were at 1-ft depths and against the steel plate. This was to simulate conditions where fish are located on or near the bottom. The charges were fired at 10-ft depths and the slant ranges were varied.

Probit Analysis

Probit analysis of the data provided mortality curves relating percent mortality in probit units to the logarithm of impulse. A computer calculated the mortality curves where there were a number of data points, i.e., large and small bluegill, top minnow, small goldfish, small catfish, small carp, and trout. In other instances, the probit equation curve was calculated from a single datum point. The probit equation is $y = a+b \cdot \log(x)$, where y is the percent mortality in probit units, a and b are the intercept and slope constants, and log(x) is the logarithm of the impulse. The one datum point for large catfish was 47-percent mortality at an impulse of 36 psi·msec. By substituting these values in the probit equation and taking the slope constant of the small catfish, the intercept constant is calculated yielding the probit equation for large catfish. From the equation, the LD_1, LD_{50}, and LD_{99} values were calculated.

RESULTS

Survival Times

The fish that were lethally injured by the blast and returned to the observation tanks showed no consistent pattern as to whether or not they rose to the surface or sank to the bottom. This was true for each species. It was only those fish that were exposed to underwater blast in the lethal ranges that appeared hurt from external signs. These were decreased movement, disorientation, and erratic gill movement. The endpoint for death was cessation of gill movement. In many instances, gill movement would stop and then start again within a few minutes.

The mortality-time pattern over a 24-hr period for five species of fish appears in Figure 3. Of the 72 carp dying from underwater blast, about half were dead within 1/2 hr and 85 percent within 1 hr. Ninety percent of the deaths occurred within 4 hr and there were only five fish that expired between 6 and 24 hr. The survival times of trout appeared to be longer than those of the other species.

Of the 14 carp and catfish observed for a 2-wk period, only one death occurred on Day 5 (7%). These fish were subjected to LD_{50} blast levels. There were no deaths among the large numbers of small bluegill, guppy, and top minnow during the 2-wk period. The small carp and catfish that were autopsied at the end of the 2-wk period showed definite signs of having had swimbladders ruptured. Evidently, fish can survive with ruptured swimbladders.

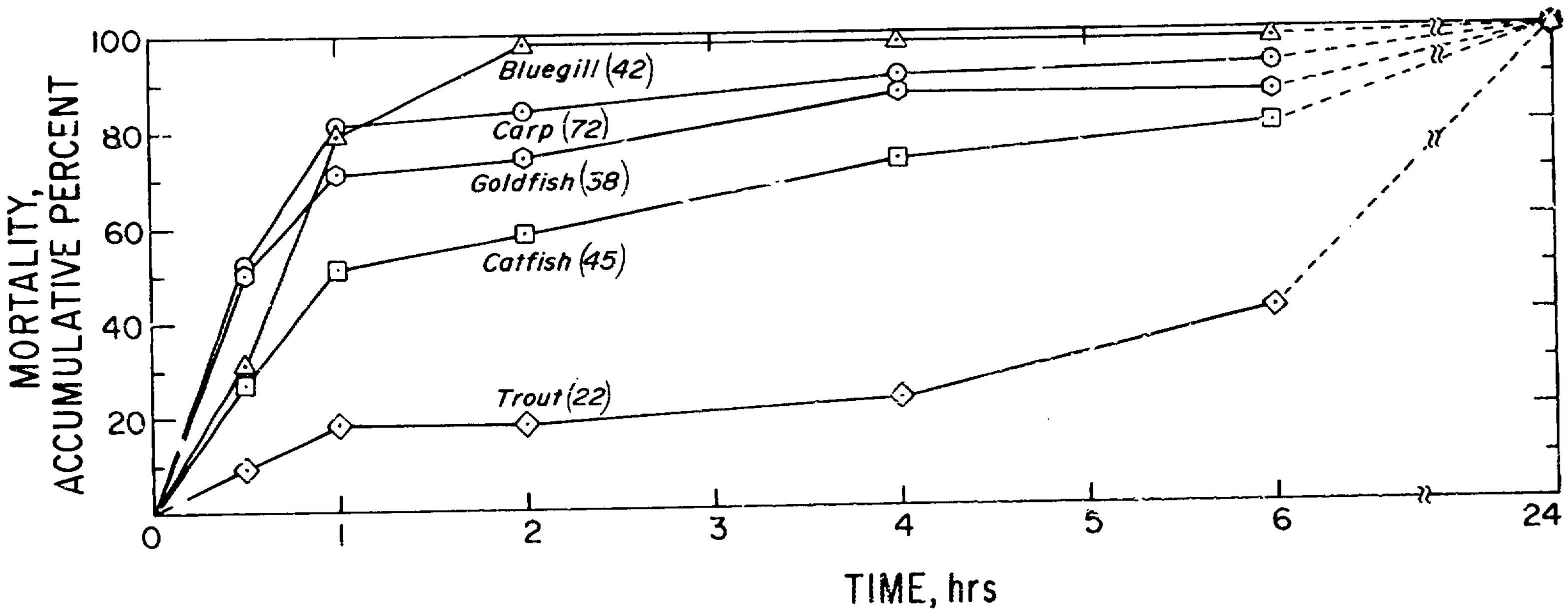

Figure 3. Mortality-Time Distribution for Fish.

Nature of Injuries

The internal organs were examined mostly to record swimbladder ruptures and kidney damage. The internal organs most commonly damaged were the swimbladders, kidneys, and livers. In most instances, there was hemorrhaging associated with the disruption of these organs, Figure 4. In no instances were the abdominal walls ruptured by the underwater shocks. Fish that received underwater blasts below lethal levels and internally sustained only minor hemorrhages to their swimbladders and kidneys appeared to swim about normally.

Mortality in Relation to Impulse

Table 1 summarizes the results of the probit analysis and lists the impulse required for 1-, 50-, and 99-percent mortality along with probit equations. A typical probit-mortality curve, for small carp tested at 1-ft depths, is illustrated in Figure 5.

A regression line, relating the LD_{50} impulse to the mean body weight of each group, appears in Figure 6.

According to Figure 6, there was little or no difference between the impulse required for 50-percent mortality for fish having ducted swimbladders and fish having non-ducted swimbladders. Also, the larger the fish (body weight),

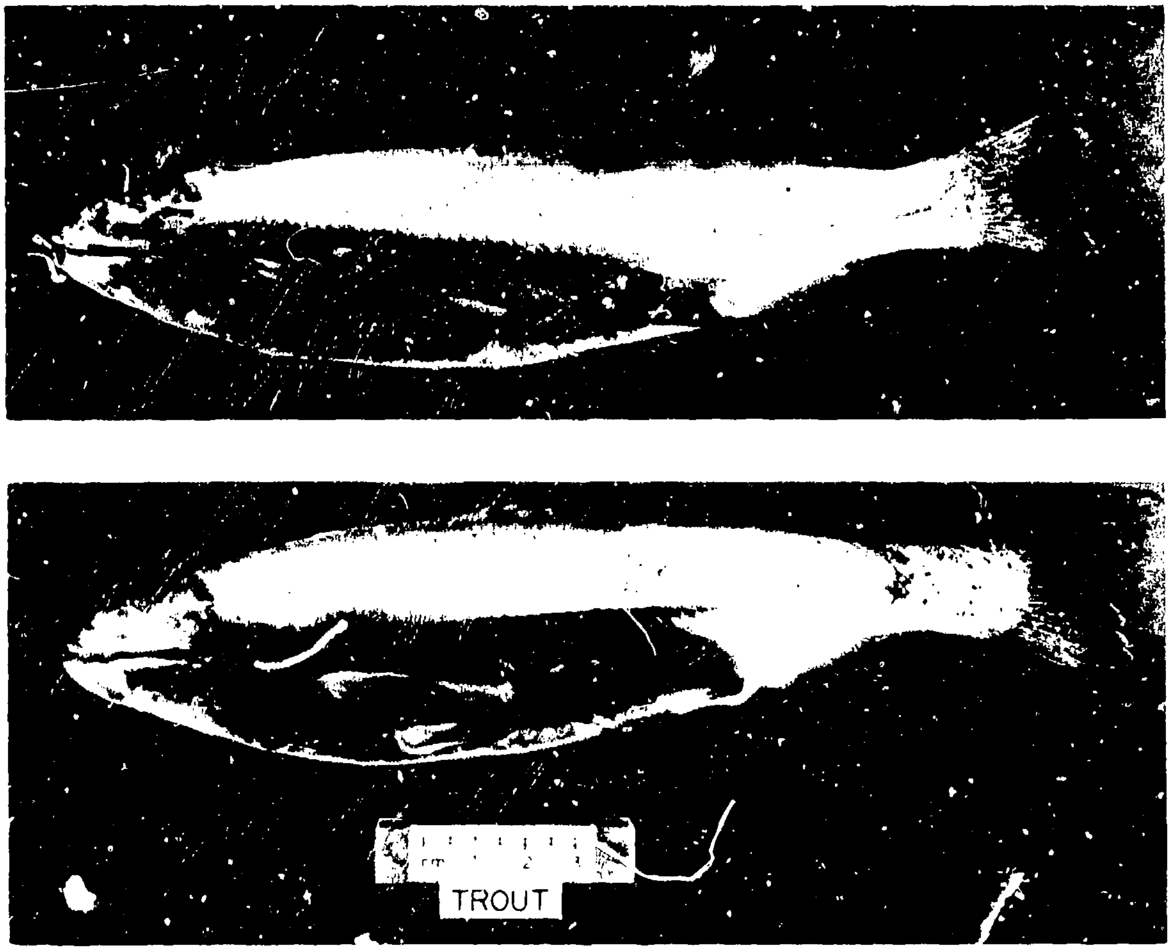

Figure 4. Sagittal Sections of Trout. Upper: control. Lower: experimental, showing ruptured swim-bladder and surrounding hemorrhage.

TABLE 1

RESULTS OF PROBIT ANALYSIS

Species	Depth of Fish, ft	Number of Fish	Mean Body Weight, g	Impulse, psi·msec LD$_1$	Impulse, psi·msec LD$_{50}$	Impulse, psi·msec LD$_{99}$	Probit Equation
Physostomes							
Top Minnow (Gambusia affinis)	0.25	229	0.47	1.3 (0.9-1.6)	3.4 (3.0-3.8)	8.9 (7.1-12.5)	y = 2.089+5.516 logx
Small Goldfish (Carrasius auratus)	1	50	1.4	3.0 (1.2-4.1)	6.2 (5.0-7.3)	12.5 (9.6-28.2)	y = -0.976+7.557 logx
Small Channel Catfish (Ictalurus punctatus)	1	60	105	17.6 (4.4-23.2)	33.3 (27.4-43.1)	63.0 (46.6-295)	y = -7.781+8.395 logx
Small Carp (Cyprinus carpio)	0.17	60	149	19.0 (6.9-22.5)	27.4 (24.2-31.7)	39.5 (33.2-115)	y = -16.119+14.686 logx
	1	60	117	16.7 (10.2-19.2)	23.5 (21.2-25.5)	33.1 (29.0-51.4)	y = -16.440+15.644 logx
	10	35	113	14.9 (4.6-18.6)	26.2 (23.8-31.9)	46.2 (35.5-192)[a]	y = -8.395+9.445 logx
Rainbow Trout (Salmo gairdneri)	1	65	143	12.3 (2.6-15.4)	20.7 (17.8-36.7)	35.0 (27.0-208)[b]	y = -8.436+10.207 logx
Large Goldfish (Carrasius auratus)	1	6	245	13.0 –	26.5 –	53.8 –	y = -5.756+7.557 logx
Large Channel Catfish (Ictalurus punctatus)	1	15	338	19.5 –	36.8 –	69.7 –	y = -8.148+8.395 logx
Large Carp (Cyprinus carpio)	1	12	744	35.1 –	49.5 –	69.7 –	y = -21.511+15.644 logx
Physoclists							
Guppy Fry (Lebistes reticulatus)	0.25	75	0.02	0.7 –	1.7 –	4.6 –	y = 3.687+5.516 logx
Guppy Adult (Lebistes reticulatus)	0.25	26	0.13	1.0 –	2.7 –	7.2 –	y = 2.603+5.516 logx
Small Bluegill (Lepomis macrochirus)	1, 1.7, 2.5[c]	40	1.4	4.3 (2.8-5.1)	6.7 (5.9-7.5)	10.4 (8.9-14.8)	y = -5.063+12.174 logx
Large Bluegill (Lepomis macrochirus)	1	40	88	17.7 (14.1-19.0)	20.7 (19.6-21.9)	24.3 (22.7-30.2)	y = -40.078+34.231 logx
Large Mouth Black Bass (Micropterus salmoides)	1	4	146	18.8 –	26.5 –	37.3 –	y = -17.266+15.644 logx

1-lb charges detonated at 10-ft depths

[a] 90-percent confidence limits

[b] 85-percent confidence limits

All others were 95-percent confidence limits

[c] Slant range held constant

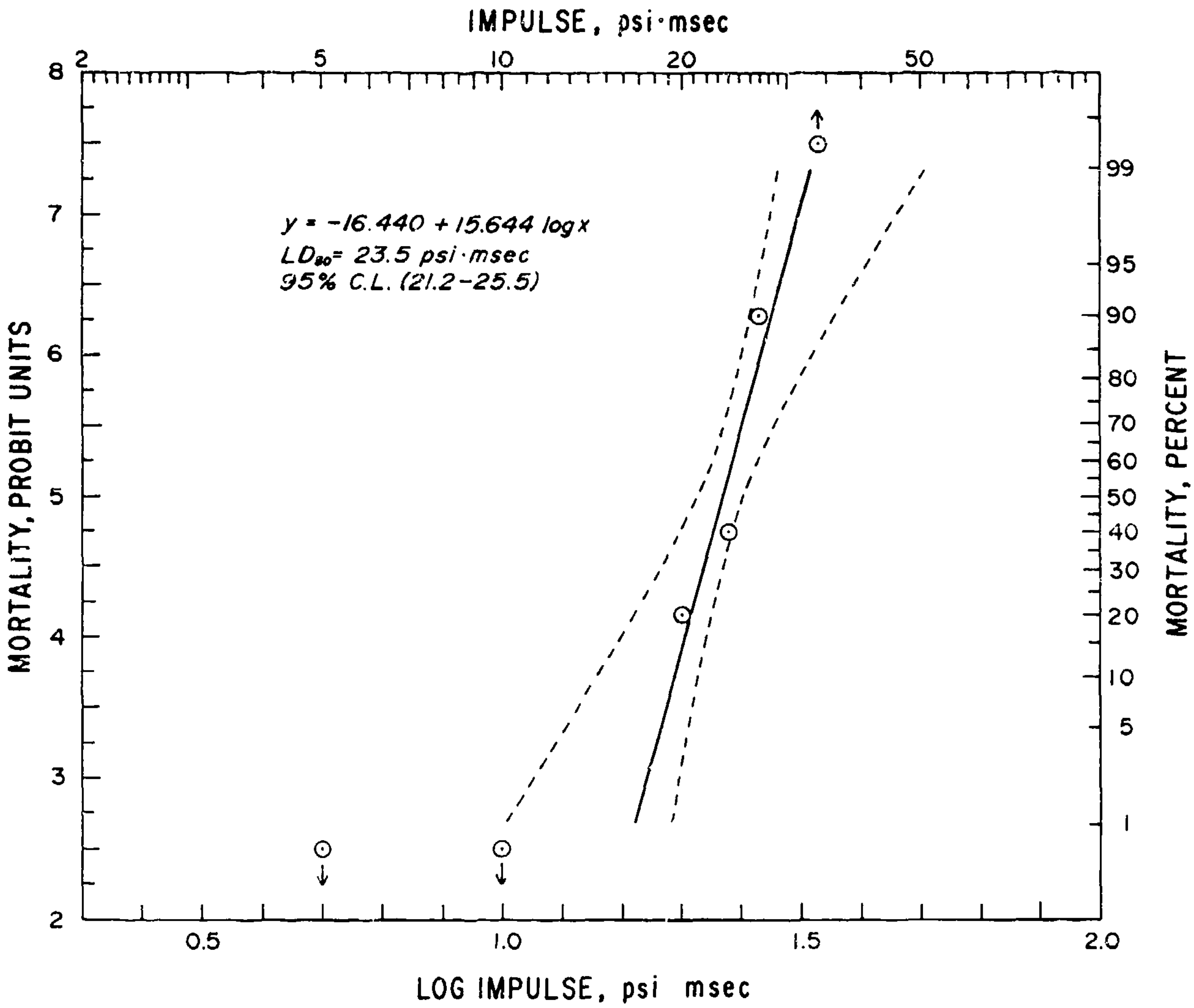

Figure 5. Probit Mortality Curve for Carp Tested at 1-Ft Depths. There were 10 carp per point: arrows indicate 0 or 100% mortality.

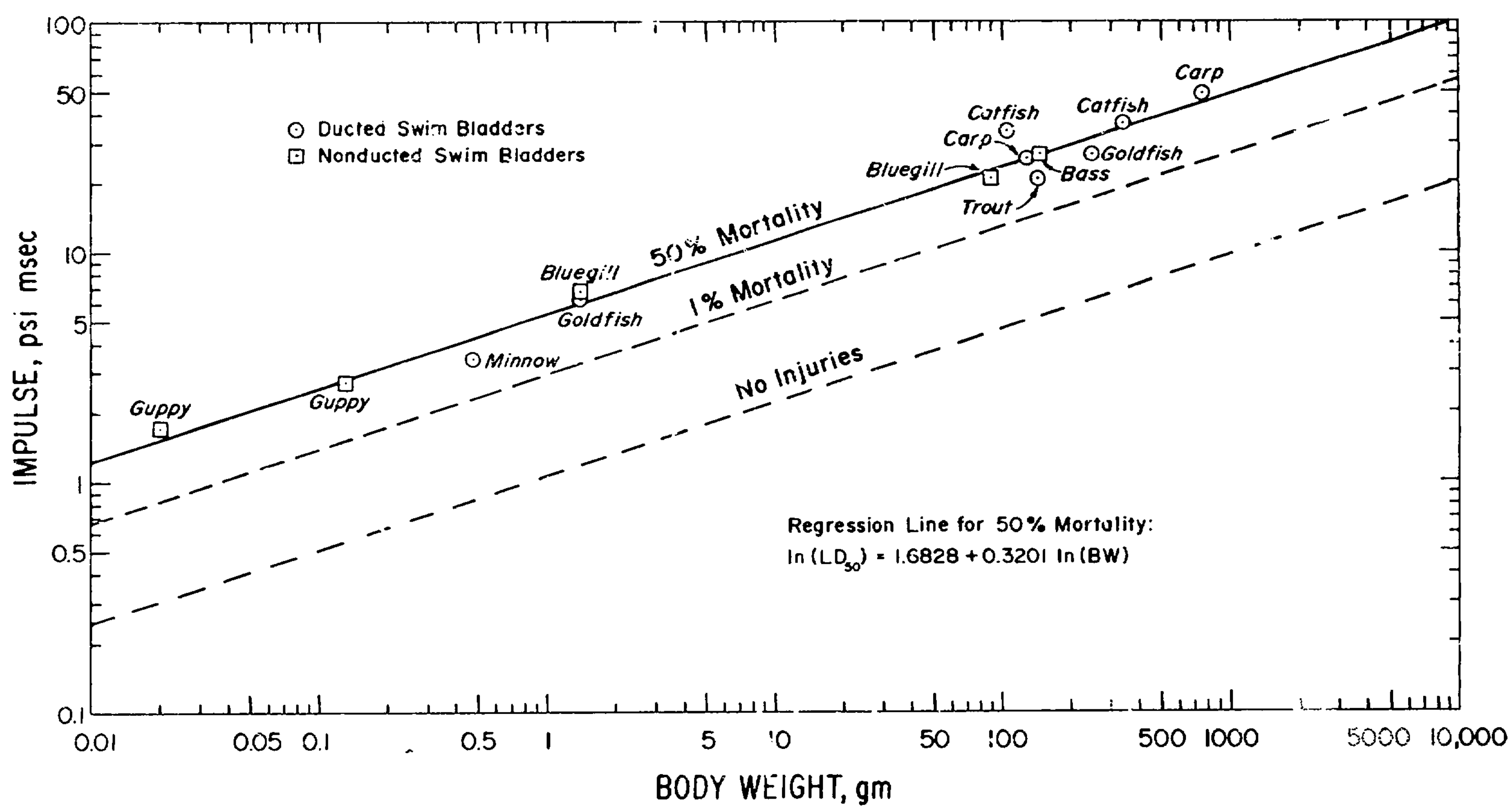

Figure 6. Response of Fish to Underwater Blast as a Function of Impulse and Body Weight. Impulse for 1% mortality was approximately 0.55 of the 50% mortality. Impulse for no-injuries was approximately 0.20 of the 50% mortality.

the higher the impulse required for 50-percent mortality. This was true both within a species and between species.

The 1-percent mortality curve was 0.55 of the LD_{50} values and represents an average of those in Table 1. The no-injuries curve in the figure represents approximately 0.20 of the respective LD_{50} values and represents an averaging of the information in Appendix A. Strictly speaking, this curve represents the highest impulse for no-injuries.

Fish were tested at several depths to confirm the assumption that the impulse was the damage parameter, and that the impulse could be applied to predict the tolerance of fish that normally are located very near the surface where the duration of an underwater-blast wave would be extremely short. As can be seen in Table 1, the impulse for 50-percent lethality for carp tested at 0.17 ft (27.4 psi·msec), 1 ft (23.5 psi·msec), and 10 ft (26.2 psi·msec) was not significantly different. In contrast, the corresponding peak pressures associated with these LD_{50} impulses varied markedly--810 psi at 0.17 ft, 335 psi at 1 ft, and 176 psi for carp tested at the 10-ft depths.

That the peak pressure was not the damage parameter was also demonstrated in those tests wherein the fish (small bluegill) were placed at increasing depths but at a constant slant range from the explosive charge. In those instances, the peak pressure remained constant and the impulse and ortality increased with the depth of the fish, Table A-12.

Fish Against a Reflecting Surface

The impulse required for 50-percent mortality among small catfish and small carp tested against the steel plate was 35.9 and 23.1 psi·msec, respectively (Table A-15). These values were measured by underwater-blast gages, 1 ft deep while against the steel plate and include the incident and reflected waves. According to the records, the peak pressure was double that which would occur at the equivalent range and depth in the absence of the plate. The impulse was increased by about 20 percent. The LD_{50} for catfish and carp, located against the steel plate, was not significantly different than it was for catfish (33.3 psi·msec) and carp (23.5 psi·msec) tested at 1-ft depths in the absence of the plate.

DISCUSSION

The results of this study provided information on the underwater-blast response of fish ranging in weight from 0.02 to near 800 g. It can not be stated, at this time, how far the results can be extrapolated in order to predict the blast tolerance of larger fish. Data on the blast response of larger fish would be desirable.

Obviously, before one can predict the ranges from a given charge weight and burst depth at which fish of a given size would be killed, a knowledge of the indigenous fish population would be required. Once the impulse values of interest are selected, they have to be converted to slant ranges. Curves giving the ranges at which given impulses will occur appear in Figure 7. The curve takes into account the weight of charge, depth of burst, and depth of fish. To enter the graph, first calculate the quantity of the depth of charge x depth of fish/charge weight$^{2/3}$. Second, calculate the impulse/charge weight$^{1/3}$. Third, read off the scaled slant range on the Y axis where the impulse value of interest intersects the curve. Multiply the scaled range by the cube root of the charge weight to get the slant range.

An example of a problem that can be envisioned is as follows: How far away from a river estuary must 2,000-lb charges be detonated so that 200-g fish would not be harmed? The depth of burst is 80 ft and the water depth is 500 ft. The fish of interest in the river always reside within 20 ft of the surface. According to Figure 6, 200 g fish would

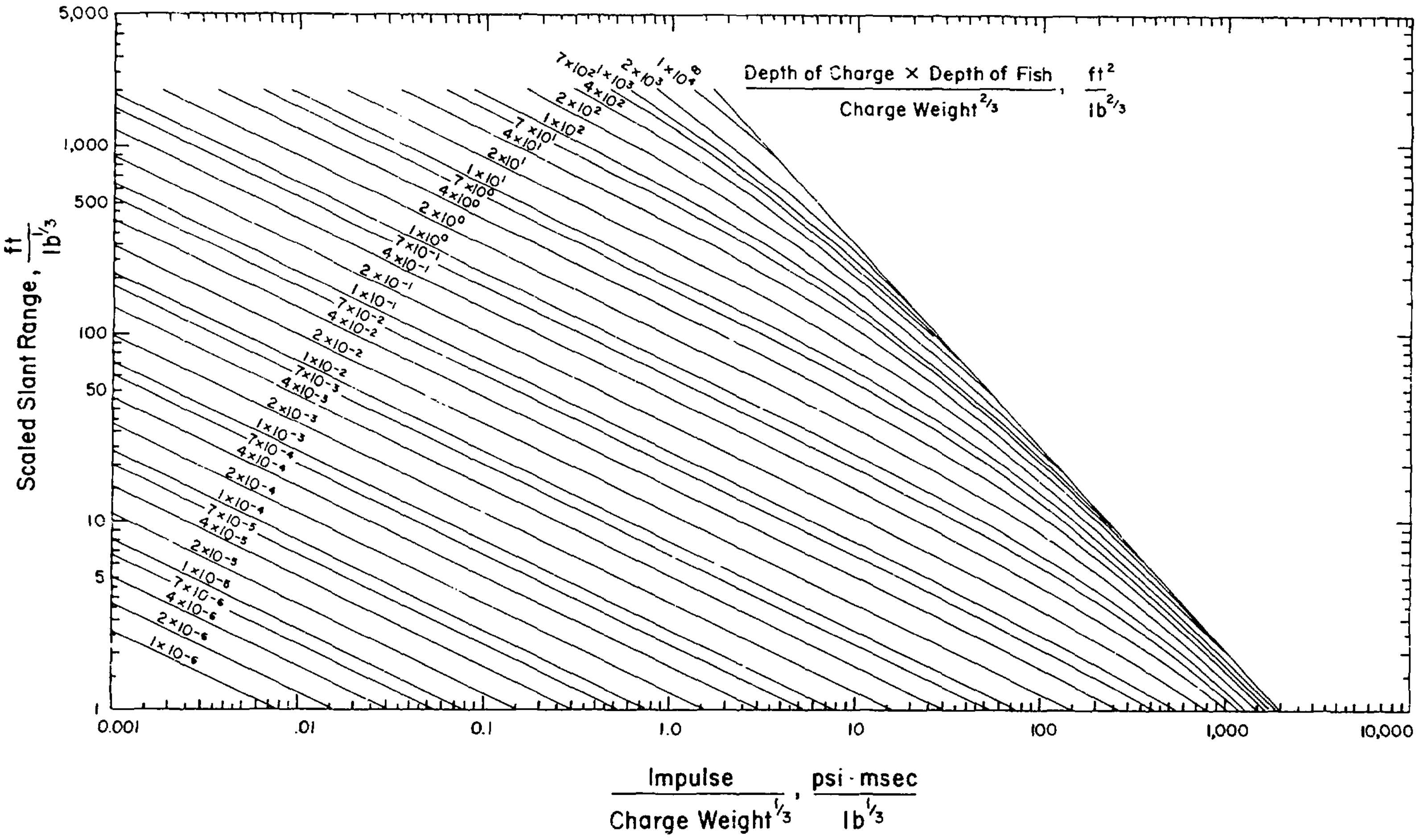

Figure 7. Curves for Use in Calculating Ranges for Various Impulses. Taken from reference 2.

not be injured at an impulse of 6 psi·msec. It would then be necessary to determine the range from the charge where 6 psi·msec occurs at a 20-ft depth--it would be the worst case--and fish closer to the surface would receive smaller impulses, of less than 6 psi·msec.

First, solve the quantity:

Depth of Charge x Depth of Fish/Charge Weight$^{2/3}$:

$$80 \times 20/2{,}000^{2/3} = 10$$

Second, solve:

Impulse/Charge Weight$^{1/3}$:

$$6/2{,}000^{1/3} = 0.5$$

Third, read the scaled slant range of 280 on the Y axis where 0.5 on the X axis intercepts the curve for 10:

Scaled slant range = Slant range/charge weight$^{1/3}$:

$$280 \times 12.6 = 3{,}500 \text{ ft}$$

For fish that dwell near the bottom or next to banks, the impulse in the reflected wave should be added to that in the incident wave. Theoretically, the incident shock wave impulse would double upon normal reflection. This would vary with the nature of the reflecting surface (bottom) angle of incidence, and the like.

To be most precise, the information contained in this report should only be used to predict fish response under conditions analogous to those of this experiment; that is, for underwater-blast waves having steep fronts with exponential decay typical of those recorded in free water and near the surface. There is uncertainty in predicting fish response at long ranges from very large explosions because of the difficulty in forecasting the impulse. At long ranges, the wave shape can be altered by such things as water temperature gradients. Also, the bottom reflection can be multiplied by focusing, associated with the characteristics of the bottom terrain. When focusing occurs, the impulse in the bottom reflection would be more than twice that in the incident wave.

Another damage model, recently set forth in References 3 and 4, proposes that the negative pressure drop or cavitation of the water may correlate with fish damage. This damage model is being checked experimentally at that laboratory along with an analytical model describing the oscillations of bubbles in the water when struck by an underwater shock. The latter should form the basis of a damage model that takes into account the swimbladder itself. Swimbladder volumes were measured in the present study, but since the fish response correlated with body weight and time was limited, no further analysis was undertaken.

Reference 5 reports guidelines for evaluating the effects of underwater explosions on fish. These include mechanisms of injury, how fish location varies seasonally and with time of day, and what steps can be taken in avoiding fish kill.

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APPENDIX

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TABLE A-1

TOP MINNOW TESTED AT 0.25-FT DEPTHS

Slant Range, ft	Peak Pressure, psi	Impulse, psi·msec	Cut-Off Time, msec	Mortality
41	308	7	0.026	20/20
49	253	5	0.021	31/40
69	174	2.5	0.015	10/34
86	136	1.6	0.012	1/40
107	107	1.0	0.010	0/45
124	91	0.7	0.008	0/50

TABLE A-2

SMALL GOLDFISH TESTED AT 1.0-FT DEPTHS

Slant Range, ft	Peak Pressure, psi	Impulse, psi·msec	Cut-Off Time, msec	Mortality
20	678	62	0.206	5/5
26	508	43	0.160	5/5
42	300	20	0.100	5/5
62	195	10	0.068	10/10
73	163	8	0.057	7/10
91	128	5	0.046	4/15
91[a]	128	1.4	0.012	0/10[b]
91[c]	128	0.7	0.006	0/10[d]

[a] Depth of fish, 0.5 ft; depth of charge, 5 ft

[b] Few minimal injuries.

[c] Depth of fish, 0.25 ft; depth of charge, 5 ft

[d] No injuries.

TABLE A-3

SMALL CATFISH TESTED AT 1-FT DEPTHS

Slant Range, ft	Peak Pressure, psi	Impulse, psi·msec	Cut-Off Time, msec	Mortality
26	508	43	0.160	9/10
30	434	34	0.138	3/10
35	366	27	0.119	4/10
42	300	20	0.110	0/10
62	195	10	0.068	0/10[a]
91	128	5	0.046	0/10[b]

[a] Few minimal injuries

[b] No injuries

TABLE A-4

SMALL CARP TESTED AT 0.17-FT DEPTHS

Slant Range, ft	Peak Pressure, psi	Impulse, psi·msec	Cut-Off Time, msec	Mortality
11	1309	61	0.031	10/10
13	1089	45	0.027	10/10
16	867	30	0.022	7/10
18	762	25	0.019	3/10
21	643	18	0.017	0/10
28	468	11	0.012	0/10

TABLE A-5

SMALL CARP TESTED AT 1-FT DEPTHS

Slant Range, ft	Peak Pressure, psi	Impulse, psi·msec	Cut-Off Time, msec	Mortality
30	434	34	0.138	10/10
35	366	27	0.119	9/10
38	335	24	0.110	4/10
42	300	20	0.100	2/10
62	195	10	0.068	0/10[a]
91	128	5	0.046	0/10[b]
91[c]	128	2.7	0.023	0/5
91[d]	128	1.4	0.012	0/5

[a] Few minimal injuries
[b] No injuries
[c] Depth of fish, 1 ft; depth of charge, 5 ft
[d] Depth of fish, 0.5 ft; depth of charge, 5 ft

TABLE A-6

SMALL CARP TESTED AT 10-FT DEPTHS

Slant Range, ft	Peak Pressure, psi	Impulse, psi·msec	Cut-Off Time, msec	Mortality
61	199	30	0.673	4/5
66	182	27	0.624	4/10
73	163	24	0.566	5/10
84	140	20	0.494	1/10

TABLE A-7

TROUT TESTED AT 1-FT DEPTHS

Slant Range, ft	Peak Pressure, psi	Impulse, psi·msec	Cut-Off Time, msec	Mortality
37	345	25	0.113	9/10
40	316	22	0.105	2/10
44	285	19	0.095	11/20
49	253	15	0.086	0/10
56	218	12	0.075	0/10
91	128	5	0.046	0/5[a]

[a] No injuries

TABLE A-8

LARGE GOLDFISH

Depth of Charge, ft	Depth of Fish, ft	Slant Range, ft	Peak Pressure, psi	Impulse, psi·msec	Cut-Off Time, msec	Mortality
10	1.0	32	404	31	0.130	1/1
10	1.0	34	378	28	0.123	1/1
10	1.0	37	345	25	0.113	0/1
10	1.0	40	316	22	0.105	0/1
10	1.0	50	248	15	0.084	0/1
10	1.0	63	192	10	0.067	0/1
5	2.0	91	128	5	0.046	0/1[a]
5	1.0	91	128	2.7	0.023	0/1
5	0.5	91	128	1.4	0.012	0/1[b]
5	0.25	91	128	0.7	0.006	0/1

[a] Minimal injury

[b] No injury

TABLE A-9

LARGE CATFISH TESTED AT 1-FT DEPTHS

Slant Range, ft	Peak Pressure, psi	Impulse, psi·msec	Cut-Off Time, msec	Mortality
29	451	36	0.144	7/15

TABLE A-10

LARGE CARP TESTED AT 1-FT DEPTHS

Slant Range, ft	Peak Pressure, psi	Impulse, psi·msec	Cut-Off Time, msec	Mortality
21	643	58	0.196	1/1
22	611	54	0.188	1/1
23	582	51	0.180	1/1
24	555	48	0.172	0/1
26	508	43	0.160	0/1
28	468	38	0.149	0/1
30	434	34	0.139	0/1
32	404	31	0.130	0/1
34	378	28	0.123	0/1
37	345	25	0.113	0/1
50	248	15	0.084	0/1[a]
63	192	10	0.067	0/1[b]

[a] Minimal injury
[b] No injury

TABLE A-11

GUPPY TESTED AT 0.25-FT DEPTHS

Slant Range, ft	Peak Pressure, psi	Impulse, psi·msec	Cut-Off Time, msec	Mortality
Adults:				
69	174	2.5	0.015	11/26
Fry:				
69	174	2.5	0.015	30/37
124	91	0.7	0.008	0/18
144	77	0.6	0.007	0/20[a]

[a] Few minimal injuries

TABLE A-12

SMALL BLUEGILL TESTED AT
CONSTANT SLANT RANGE OF 91 FT

Depth of Charge, ft	Depth of Fish, ft	Peak Pressure, psi	Impulse, psi·msec	Cut-Off Time, msec	Mortality
10	2.5	128	10	0.115	10/10
10	1.7	128	8	0.078	12/15
10	1.0	128	5	0.046	1/15
5	1.0	128	2.7	0.023	0/10
5	0.5	128	1.4	0.012	0/10[a]
5	0.25	128	0.7	0.006	0/10[b]

[a] Minimal injuries
[b] No injuries

TABLE A-13

LARGE BLUEGILL TESTED AT 1-FT DEPTHS

Slant Range, ft	Peak Pressure, psi	Impulse, psi·msec	Cut-Off Time, msec	Mortality
37	345	25	0.113	10/10
40	316	22	0.105	8/10
44	285	19	0.095	1/10
48	259	16	0.087	0/10
91	128	5	0.046	0/5[a]
91[b]	128	2.7	0.023	0/5[c]

[a] Minimal injuries

[b] Depth of charge, 5 ft

[c] No injuries

TABLE A-14

LARGE MOUTH BASS TESTED AT 1-FT DEPTHS

Slant Range, ft	Peak Pressure, psi	Impulse, psi·msec	Cut-Off Time, msec	Mortality
32	404	31	0.130	1/1
34	378	28	0.123	1/1
37	345	25	0.113	0/1
40	316	22	0.105	0/1

TABLE A-15

SMALL CATFISH AND CARP
TESTED AGAINST REFLECTING PLATE

Slant Range, ft	Peak Pressure, psi	Impulse, psi·msec	Cut-Off Time, msec	Mortality
<u>Catfish</u>:				
31	814[a]	38	0.126	7/10
33	780	37	0.118	5/10
35	742	34	0.109	3/10
38	620	30	0.108	3/10
91	274	7	0.061	0/10
$y = -8.348+8.582 \log x$				
LD_{50} = 35.9 psi·msec				
<u>Carp</u>:				
42	534	24	0.093	3/5
56	372	15	0.069	0/5
$y = -16.339+15.644 \log x$				
LD_{50} = 23.1 psi·msec				

[a] Includes incident and reflected waves