12

NSWC TR 88-114

EFFECTS OF UNDERWATER EXPLOSIONS ON FISH WITHOUT SWIMBLADDERS

BY J. F. GOERTNER, M. L. WILEY, G. A. YOUNG, AND W. W. MCDONALD

WEAPONS RESEARCH AND TECHNOLOGY DEPARTMENT

2 FEBRUARY 1994

Approved for public release; distribution is unlimited.

NSWC
Naval Surface Warfare Center
DAHLGREN DIVISION

NAVAL SURFACE WARFARE CENTER
DAHLGREN DIVISION • WHITE OAK DETACHMENT

Silver Spring, Maryland 20903-5640

NSWC TR 88-114

EFFECTS OF UNDERWATER EXPLOSIONS ON FISH WITHOUT SWIMBLADDERS

BY J. F. GOERTNER, M. L. WILEY, G. A. YOUNG, AND W. W. MCDONALD
WEAPONS RESEARCH AND TECHNOLOGY DEPARTMENT

1 FEBRUARY 1994

NAVAL SURFACE WARFARE CENTER
DAHLGREN DIVISION • WHITE OAK DETACHMENT
Silver Spring, Maryland 20903-5640

FOREWORD

The U.S. Navy has conducted a comprehensive program of research on the environmental effects of underwater explosion testing since 1970. The effects of underwater explosions on fish with swimbladders have been well documented, and current understanding of these effects is adequate to predict the extent of the hazardous region for a broad range of conditions. The mechanisms of possible injury to fish without swimbladders have received less attention because the available evidence indicates that these species are highly resistant to explosions. This report provides a first step toward defining and understanding the nature of the physiological response.

The test program was carried out by personnel of the Explosion Dynamics Branch of the Naval Surface Warfare Center under the direction of Dr. Joseph G. Connor. This report was prepared as part of the Ordnance Reclamation Project of the Naval Sea Systems Command (SEA 06R) under Program Element 63721N, Work Unit-Environmental Effects of Explosive Testing, and is one of a series published under this sponsorship.

Approved by:

Kurt F. Muell

KURT F. MUELLER, Head
Explosives and Warhead Division

ABSTRACT

Techniques were developed to study the effects of underwater explosions on fish without swimbladders. Detailed injury data were obtained from hogchokers (*Trinectes maculatus*) at distances from 30 to 80 inches from a 10-pound pentolite charge. The range for 50 percent probability of immediate-kill was 30 inches, which is about a factor of 100 less than for swimbladder fish of comparable size. The data demonstrate that these fish without swimbladders have an unusually high resistance to explosion effects. The degree to which these results carry over to other species without swimbladders is not known.

CONTENTS

CONTENTS (Cont.)

ILLUSTRATIONS

TABLES

SECTION 1

INTRODUCTION

Previous work on the effects of underwater explosions on fish has dealt mainly with species that have swimbladders. Early experiments showed that these were the most vulnerable to explosion effects.[1,2,3,4] A computational model was developed for predicting the probability of damage over a range of experimental conditions.[5,6] The model is based on the response of the swimbladder gas to the shock waves generated by an explosion. The bladder-gas oscillation results in damage to adjacent tissues and may also rupture the swimbladder.

Experiments by NSWC in 1973 and 1975 included hogchoker (*Trinectes maculatus*), a small sole (flatfish) that has no swimbladder. This species was apparently not harmed, even at 20 feet from a 105-pound pentolite charge (see Appendix A).* In order to define the damage ranges for fish of this type, we did a series of eleven tests in the Potomac River during September 1985 at Dahlgren, Virginia. The objective was to discover the mechanisms of injury and, in particular, the reason for the apparent invulnerability of this species to injury from explosions. As this was the first systematic effort to investigate injury to fishes of this type, the initial tests were exploratory and involved considerable trial-and-error. Procedures became more fully developed after the first seven shots. Data from the final four shots are considered to be the most complete and reliable, and were used to derive most of the results presented in this report.

---

* Extrapolation of the results of our present analysis indicates that probably about 37 percent of these fish were harmed, in that they would have exhibited abnormal swimming behavior after the test.

SECTION 2

EXPERIMENTAL AND ANALYTICAL METHODS

EXPERIMENTAL DESIGN AND CLASSIFICATION RESULTS

Fish, primarily hogchokers, were collected with an otter trawl in the Patuxent River and Chesapeake Bay, Maryland, and were transported by truck in a fish tank to the Naval Surface Warfare Center at Dahlgren, Virginia, where they were held in cages in a tidal creek. Aboard the testing barge, they were held in two steel tanks of approximately 350 gallons capacity with continuously flowing river water. These stock watering tanks were painted inside to limit exposure to the galvanized surface.

Eleven experiments were performed in the Potomac River beginning on 13 September and concluding on 25 September 1985. The experimental conditions are listed in Table 2-1. In each test, caged or otherwise restrained fish were placed at known horizontal ranges from the explosive charge and at the same depth as the explosive charge. Shock wave pressures were recorded to validate explosive performance.

The charges were cylinders of recast pentolite, i.e., remelted pentolite from unused charges. They were initiated by a J-2 electric detonator inserted into a half-inch deep hole drilled in the top of the charge. Specifications for the eleven nearly identical charges are summarized as follows:

Weight	10.16	±	0.26	pound
Diameter	5.98	±	0.08	inch
Height	5.96	±	0.15	inch
Density	1.68	±	0.04	gm/cc

where the error limits represent two standard deviations estimated in the usual manner.

The first test was conducted at a depth of ten feet. Hogchokers, summer flounder (*Paralichthys dentatus*), and spot (*Leiostomus xanthurus*) were held in polypropylene mesh cylindrical cages (about 30 inches long and 12 inches in diameter) at distances of 6, 10, 15, 22, and 30 feet from the explosive. Spot is a typical swimbladder fish and the summer flounder has no swimbladder* In addition, three hogchokers were suspended individually -- heads toward the charge -- in small bags made from the toe sections of nylon stockings. These were tied to the rigging at 19, 32, and 56 inches

---

* Analysis of the dissection results for spot (listed in Table 2-2) was considered beyond the scope of this report. The additional data needed for such analysis, e.g., the individual fish lengths, are available from the author's files and notebooks.

TABLE 2-1. TEST CONDITIONS

Shot	Date (1985)	Charge Weight (lb)	Charge Depth (ft)	Charge Diameter (inches)	Charge Height (inches)	Water Temperature at: 1-ft Depth (°C)	Water Temperature at: Charge Depth (°C)	Air Temp. (°C)
1	9/13	10.08	10	5.99	5.94	24.7	24.8	—
2	9/17	10.26	25	6.03	5.94	23.4	23.2	28
3	9/18	10.46	25	5.99	6.16	23.8	23.6	26
4	9/19	10.13	25	6.03	5.94	23.8	23.7	24
5	9/20	10.25	25	6.03	5.94	23.8	23.8	22
6	9/20	10.04	25	6.00	5.94	24.4	23.8	24
7	9/23	10.21	25	5.93	5.92	23.4	23.3	22
8	9/24	10.19	25	5.99	5.93	23.3	23.2	22
9	9/24	10.04	25	5.93	5.92	23.5	23.4	29
10	9/25	10.06	25	5.94	6.04	23.0	23.2	18
11	9/25	10.02	25	6.00	5.94	23.0	22.8	22

TABLE 2-2. EXPERIMENTAL RESULTS -- SHOT 1

DISTANCE FROM CHARGE (inches)	FISH RESTRAINT	NUMBER OF FISH	IMMEDIATE RESULT *	24-HR SURVIVAL (No. Survivors / No. Fish Held)
19	bag	1 hogchoker	not recovered	—
32	bag	1 hogchoker	no damage	—
56	bag	1 hogchoker	not recovered	—
72	Cage A	10 hogchoker	(3) no damage (cage damaged—7 fish lost)	---
	Cage B	10 hogchoker	(6) no damage (cage damaged—4 fish lost)	—
120	Cage A	4 flounder	(4) no damage	---
	Cage B	9 hogchoker	(9) no damage **	4/4
180	Cage A	11 hogchoker	(11) no damage **	6/6
	Cage B	10 hogchoker	(10) no damage **	5/5
264	Cage A	7 hogchoker	(7) no damage **	2/2
		10 spot	(8) level 3, (2) level 4	
	Cage B	10 hogchoker	(10) no damage **	5/5
		10 spot	(8) level 3, (2) level 4	
360	Cage A	10 hogchoker	(10) no damage **	6/6
		10 spot	(8) level 3, (2) level 4	
	Cage B	10 hogchoker	(10) no damage **	4/4
		10 spot	(5) level 3, (5) level 4	

---

* Numbers in brackets represent the number of specimens examined.

** Includes fish dissected after 24-hr survival.

from the center of the charge. The bags were attached to approximately 6-foot long recovery lines that were attached to the rigging away from the charge. The hogchokers averaged 116 mm total length; the flounder, 204 mm total length; and the spot, 154 mm fork length.

On this test, all of the spot were killed while none of the hogchokers or flounders sustained any apparent injury. Of the three hogchokers in bags close to the charge, two were not recovered, but the one placed at 32 inches was recovered alive with no apparent injuries. The cages six feet from the charge were damaged by the explosion, and some of the fish were lost. After this shot, the experiment was redesigned to study the explosion effects on hogchokers and flounders restrained in stockings at ranges of less than ten feet.

Table 2-2 lists the experimental conditions and data for Shot 1. Twenty-four hours after the test, all of the hogchokers that were recovered were still alive (with the exception of those hogchokers dissected immediately after the test). On this first test, we did not examine the post-shot swimming behavior, nor did we dissect the brain case. The damage levels for the spot, based on the scale developed for swimbladder fish by Hubbs, Schultz; and Wisner (1960),[7] are defined as follows:

Injury Level 0	No damage
Injury Level 1	Light hemorrhaging in tissues covering kidney
Injury Level 2	Light hemorrhaging throughout body cavity, some kidney damage
Injury Level 3	Severe hemorrhaging throughout body cavity, gross kidney damage, and swimbladder burst
Injury Level 4	Partial breakthrough of body wall, bleeding about anus
Injury Level 5	Ruptured body cavity, internal organs scrambled or lost

Tests 2 through 11 were conducted using the steel rig shown in Figures 2-1 and 2-2. The rig with charge and fish in place was supported from above (in horizontal position) by cables attached to the arm of a crane as it was swung overboard and lowered into the water. At firing depth, the rig was supported by cables attached to floats positioned so that the charge and fish were at a 25-foot depth. The rig was then towed a safe distance away from the barge for the shot. For these shots the test depth was increased to 25 feet in order to reduce damage to the rig and enable recovery of the rig and test specimens. After each shot the steel rig was welded and repaired for the next test.

On Shots 2 and 3 we varied standoff distances and evaluated different methods of attaching the fish restraining bags to the rig. The selected method required the use of a pair of marline (tarred cord) suspension lines stretched across the rig. Ten individually bagged fish (12 fish in Shots 10 and 11) were suspended from the upper line at measured distances from the charge (Figures 2-2 and 2-3). The lower line was used to restrain the fish from swinging and twisting. The fish were tied to the suspension lines with single strands of sewing thread -- approximately 2-pound breaking strength -- to allow the fish to break away from the suspension lines when the charge was detonated. The fish were recovered by means of strong nylon or linen lines which were tied at one end to the bag holding the fish and the other end to the steel rig on the opposite side from the charge. (See Figure 2-1.)

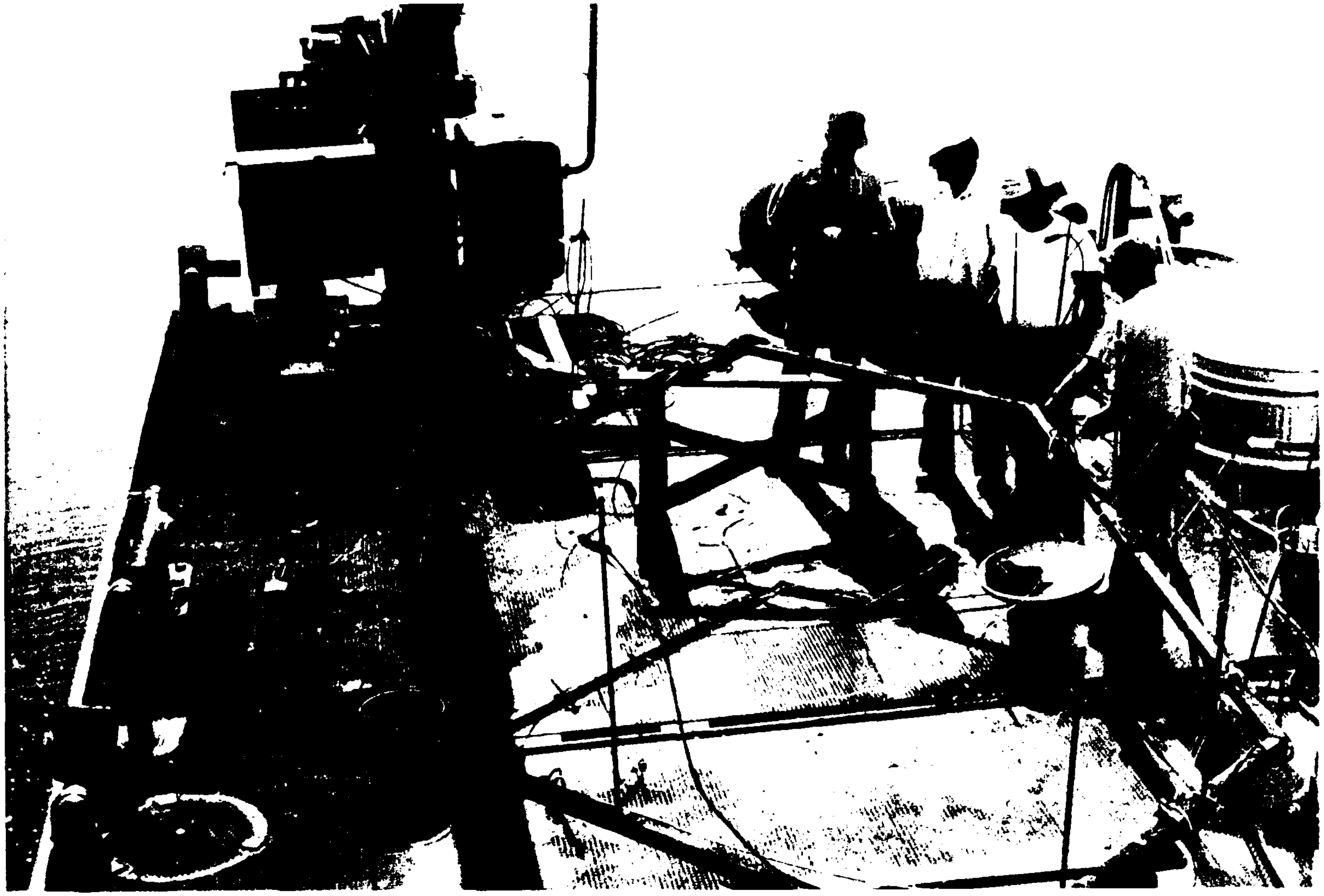

FIGURE 2-1 RIG WITH FISH AND RECOVERY LINES - SHOT 4

FIGURE 2-2 CHARGE AND FISH IN PLACE ON RIG, SHOT 10

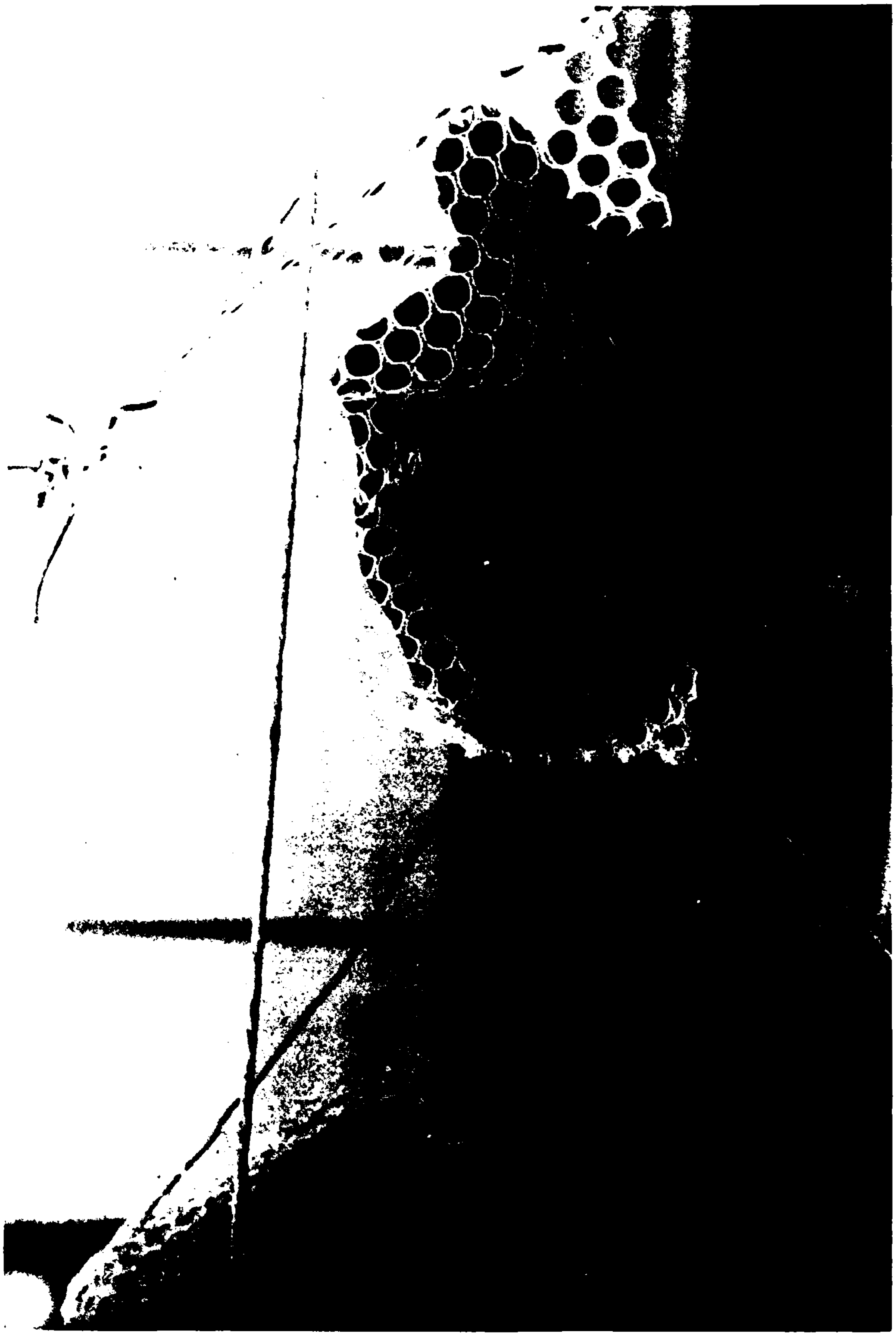

FIGURE 2-3 HOGCHOKER RESTRAINED IN BAG - SHOT 8

On Shots 2, 3, and 4, roughly half of the fish specimens were recovered after each shot. The primary cause for this low recovery-rate was probably air bubbles trapped inside the bags used to restrain the fish. On these shots, fish were inserted into the foot sections of nylon stockings which were then closed by tying a knot just above the fish. As the fish were lowered into the water, the air inside the wet stockings was trapped as a bubble. It seems likely that many of the bags were torn open by the radial oscillations of these air bubbles in response to the explosions. Data from Shots 2 and 3 were discarded. (On Shot 3 half of the fish had 1 cc of air injected into the abdominal cavity to simulate the presence of a swimbladder. Those results are discussed in Appendix B.)

On Shots 5, 6, and 7, the presence of entrapped air was still unrecognized. However, 29 out of the 30 fish specimens were recovered after those shots. The greater recovery rate on these shots was attributed to the facts that (a) the fish were located at greater distances from the charge, and (b) the bags holding the fish were made from two stockings -- one inside the other -- with the recovery line tied to knotted fabric at both the top and bottom of the bag.

The trapped air problem had not been entirely solved, but, with the greater ranges from the explosion and the doubly layered bags, fish were not being lost entirely. Although almost all of the specimens were recovered, many injuries were observed which did not appear to be directly attributable to the effects of the explosions.

The considerable number of severe local hemorrhages and tissue ruptures in the gills near the mouth were puzzling. Even more puzzling was the missing body parts -- parts of the tail and dorsal and anal fins -- in some cases the entire tail and a considerable part of the posterior body. It appeared as if they were torn off by a predator.

The situation was clarified after Shot 7. On Shots 4 through 7, the fish were held head-downward in the bags with the eye-side facing the charge. Depending on how close to the fish the knot closing the top of the stocking was tied, the tail of the fish was placed either inside or adjacent to a bubble of air trapped inside the wet bag as it entered the water. The oscillatory response of this air bubble, when excited by the shock wave from the explosion, could cause the observed external damage to posterior parts of the fish. (The bags were not torn open as on Shots 2 and 3.)

Also, it seemed likely that restraining the fish head downward was not a good procedure. This is not a natural position for the fish. Thus, it seemed possible that air was sometimes trapped inside the mouth of the fish when it entered the water. The restrained fish, held head-downward, was probably not able to eliminate this air. The trapped air, excited by the explosion shock wave, could account for the apparently anomalous instances of severe injuries to the gills. These considerations led to the fish orientation and method of restraint used for Shots 8 through 11.

On Shots 8 through 11, the fish were restrained in coarse nylon mesh bags which did not trap air as they were lowered into the water (see Figure 2-3). These bags were fashioned from 1/4-inch woven mesh nylon bags that are used to hold delicate garments when washed in the home laundry. For these shots, the fish were oriented horizontally with the eye-side facing the charge. This placed the gut upward and tilted the gill openings slightly upward. There were no instances of severe external damage to the fish and only two instances of injuries to the gills possibly caused by trapped gas.

Each time the rig was retrieved, the fish were immediately removed from the restraining bags and put into separate cages inside the large on-deck tanks of flowing river water. When all of the fish were removed from the rig, their condition was evaluated. Dead fish were placed on ice and were usually dissected within one or two hours. Fish that survived the explosion were held for 24 hours to determine delayed mortality. After 24 hours the swimming behavior of the live fish was again evaluated, and the fish were then placed on ice. These fish were anesthetized with an overdose of the anesthetic Tricaine Methanesulfonate (TMS) just before dissection.

Notes were kept during examination and dissection of the specimens. External damage was noted, the gills were examined, then the viscera, and finally, the heart. Beginning with Shot 6, the brain was examined for the presence of blood clots and hemorrhages.

In order to examine the brains of anesthetized fish, it was necessary to first remove the blood from the circulatory system, since the heart was still pumping. The procedure was as follows: (a) cuts were made in the gills when examination of the gills was completed; (b) the heart was cut open when examination of the heart was completed. This pumped the blood out of the circulatory system so that blood did not flow into the cranium as it was dissected. This procedure was begun starting with Fish No. 6 from Shot 8.

After the test program and dissections were completed, the following code was used to classify the severity of the observed hemorrhaging in the gills, viscera, heart, and brain:

Injury Level 0	No apparent injury
Injury Level 1	Slight hemorrhaging
Injury Level 2	Considerable hemorrhaging
Injury Level 3	Severe hemorrhaging
Injury Level 4	Massive hemorrhaging

A detailed description of the injury level criteria for the various organ systems is given in Table 2-3. The evaluations are summarized in Tables 2-4 and 2-5.

Control fish were handled in a manner similar to the handling of the experimental fish. Ten fish were placed in the same kind of bag, wetted, and hung in air for the same period as the test specimens. When the explosion rig went overboard, the controls were placed in a holding tank on deck. After the explosion and retrieval of the rig, the controls were removed from the holding tank to the deck until the experimental fish were removed from the rig and placed in cages in the holding tank. The controls were then removed from the bags and all were placed in a single cage and held for 24 hours in the same holding tank with the experimental fish that were still alive.

After 24 hours, the condition of the controls was evaluated. The controls were then saved -- either on ice or alive in the holding tank -- until the dissections of the test specimens were completed. Usually, the control fish were not dissected.

TABLE 2-3. INJURY LEVEL CRITERIA FOR HOGCHOKER ORGAN SYSTEMS

Level	Description
	Gills:
0	No Injury
1	Small blood clot on gills
2	Blood clots abundant on one or both sets of gills
3	Gills largely obscured by blood clots
4	(Not observed)
	Viscera:
0	No Injury
1	Small hemorrhage(s) on viscera (liver most frequently damaged)
2	Hemorrhages larger and more evident
3	Blood abundant within body cavity
4	(Not observed)
	Heart:
0	No Injury
1	Small blood clot within heart chamber or hemorrhage on surface of heart or tissues of heart chamber
2	More blood in heart chamber
3	Heart chamber full of blood
4	(Not observed)
	Brain:
0	No Injury
1	Blood clot(s) just visible in cranium, usually associated with inner ears (otoliths)
2	Blood clots larger and easily visible, usually associated with inner ears (otoliths)
3	Large blood clots in cranium
4	Cranium filled with blood

TABLE 2-4. OBSERVED INJURIES TO HOGCHOKERS -- SHOTS 4 THROUGH 7

Shot	Fish	Distance From Charge (inches)	Post Shot Swimming Response	24 Hour Swimming Response	Gills Injury Severity	Viscera Injury Severity	Heart Injury Severity	Brain Injury Severity
4	2	23.0	DEAD	DEAD	3	2	0	-
	3	20.5	DEAD	DEAD	3	-	0	-
	5	17.8	DEAD	DEAD	1	0	0	-
	7	18.2	DEAD	DEAD	1	0	3	-
	9	21.6	DEAD	DEAD	1	0	0	-
5	1	45.1	DEAD	DEAD	2	-	2	-
	2	37.4	Flutters	DEAD	-	-	-	2
	3	33.3	DEAD	DEAD	2	3	0	-
	4	30.5	DEAD	DEAD	1	1	3	-
	5	29.0	DEAD	DEAD	2	0	0	-
	7	29.6	DEAD	DEAD	3	1	0	-
	8	30.5	DEAD	DEAD	2	2	3	-
	9	35.4	DEAD	DEAD	2	0	3	-
	10	44.4	Swims Normally	Circles or Somersaults	0	0	-	2
6	1	58.3	Circles or Somersaults	Swims Abnormally	0	0	-	1
	2	48.0	No Evaluation (Alive)	DEAD	3	-	0	2
	3	43.0	No Evaluation (Alive)	Swims Abnormally	0	1	-	2
	4	39.5	DEAD	DEAD	1	-	0	-
	5	37.3	No Evaluation (Alive)	Motionless & Sinks	0	0	-	2
	6	37.3	Motionless & Sinks	DEAD	0	2	3	2
	7	38.3	DEAD	DEAD	1	0	0	2
	8	41.0	DEAD	DEAD	2	2	3	0
	9	45.8	No Evaluation (Alive)	Swims Normally	0	-	0	0
	10	58.3	No Evaluation (Alive)	No Evaluation (Alive)	1	0	0	0
7	2	47.3	DEAD	DEAD	3	0	2	2
	3	42.4	No Evaluation (Alive)	No Evaluation (Alive)	0	0	0	2
	4	38.8	DEAD	DEAD	3	0	2	2
	5	36.8	No Evaluation (Alive)	DEAD	2	2	0	2
	6	36.8	No Evaluation (Alive)	No Evaluation (Alive)	2	0	2	2
	7	38.6	No Evaluation (Alive)	No Evaluation (Alive)	2	-	0	2
	8	41.1	DEAD	DEAD	3	0	1	3
	9	46.4	No Evaluation (Alive)	DEAD	2	0	0	0

Notes:
"-" indicates that no evaluation was recorded.
"No Evaluation (Alive)" indicates that fish was alive but no swim response evaluation was recorded.

TABLE 2-5. OBSERVED INJURIES TO HOGCHOKERS -- SHOTS 8 THROUGH 11

Shot	Fish	Distance From Charge (inches)	Post Shot Swimming Response	24 Hour Swimming Response	Gills Injury Severity	Viscera Injury Severity	Heart Injury Severity	Brain Injury Severity
8	1	56.9	Motionless & Sinks	Swims Normally	0	0	0	3
	2	47.0	Swims Abnormally	DEAD	-	-	0	2
	3	42.0	Swims Abnormally	Motionless & Sinks	0	0	0	3
	4	38.3	Swims Abnormally	Motionless & Sinks	0	0	0	-
	5	36.4	Motionless & Sinks	Swims Abnormally	1	0	0	-
	6	36.5	Circles or Somersaults	Swims Normally	0	2	0	3
	7	37.9	Circles or Somersaults	Swims Normally	0	2	-	3
	8	40.8	Motionless & Sinks	DEAD	0	0	0	2
	9	46.0	Circles or Somersaults	DEAD	0	0	2	2
	10	57.5	Swims Abnormally	DEAD	0	0	2	2
9	1	46.7	Circles or Somersaults	Circles or Somersaults	0	0	0	2
	2	38.2	Motionless & Sinks	DEAD	0	0	-	3
	3	34.2	No Evaluation (Alive)	Motionless & Sinks	1	0	0	0
	4	31.2	DEAD	DEAD	2	1	0	2
	5	29.7	No Evaluation (Alive)	DEAD	3	0	2	2
	6	29.6	DEAD	DEAD	2	1	0	2
	7	30.6	DEAD	DEAD	3	3	3	0
	8	32.6	DEAD	DEAD	3	0	2	2
	9	36.6	Curls Up and Sinks	Motionless & Sinks	2	2	1	2
	10	45.2	Curls Up and Sinks	Circles or Somersaults	0	0	0	2
10	1	46.5	Motionless & Sinks	Circles or Somersaults	0	0	0	2
	2	42.1	Circles or Somersaults	DEAD	0	0	0	2
	3	38.6	Flutters	Swims Abnormally	0	2	0	2
	4	34.6	Motionless & Sinks	Flutters	0	0	0	2
	5	31.6	DEAD	DEAD	3	0	0	4
	6	30.2	No Evaluation (Alive)	Flutters	0	0	0	3
	7	30.2	Motionless & Sinks	DEAD	3	1	0	3
	8	31.0	Motionless & Sinks	DEAD	1	0	3	3
	9	32.8	Motionless & Sinks	DEAD	2	0	0	2
	10	36.9	Curls Up and Sinks	Curls Up and Sinks	0	1	0	2
	11	40.4	Circles or Somersaults	Swims Abnormally	1	2	0	2
	12	45.8	Circles or Somersaults	Swims Abnormally	0	1	0	2
11	1	79.9	Circles or Somersaults	Swims Abnormally	0	0	0	2
	2	72.6	Swims Normally	Swims Abnormally	0	0	0	2
	3	65.7	Circles or Somersaults	Circles or Somersaults	0	0	0	2
	4	58.4	Swims Normally	DEAD	0	0	0	-
	5	53.7	Circles or Somersaults	DEAD	0	0	2	2
	6	51.7	Curls Up and Sinks	DEAD	0	2	0	2
	7	50.3	Motionless & Sinks	Motionless & Sinks	0	0	0	2
	8	52.0	Swims Normally	Swims Normally	0	0	0	2
	9	55.5	Circles or Somersaults	Swims Abnormally	0	1	0	2
	10	62.3	Circles or Somersaults	DEAD	0	0	0	0
	11	68.3	Circles or Somersaults	DEAD	0	0	0	2
	12	78.0	Circles or Somersaults	DEAD	0	0	3	2

Notes:

"-" indicates that no evaluation was recorded.

"No Evaluation (Alive)" indicates that fish was alive but no swim response evaluation was recorded.

Prior to the beginning of the testing phase of the research program, a mistake was made in the preparation of the fish holding tanks that was later suspected to have affected the 24-hour responses of the control fish and some of the fish exposed to the explosions. It was originally planned to paint the inside of both of the galvanized steel holding tanks with epoxy to minimize the toxic effects of the zinc. As it turned out, however, one of the tanks was painted with latex paint and the other was sprayed with enamel. When the water flow rate through both tanks was halved while setting up for a test, it was noted that the hogchokers in the latex-painted tank started to die. Spot in the same tank were apparently not affected. The enamel-painted tank held only hogchokers, and these behaved normally. When the full water flow was resumed through both tanks, the surviving hogchokers in the latex-painted tank recovered and were swimming normally within about an hour. Apparently, either the latex paint or the scattered patches of uncovered zinc in the latex-painted tank were sufficiently toxic to kill the hogchokers when the flow rate of river water through the tanks was reduced.

STATISTICAL METHODS

The data analysis performed in this report involves three types of statistical analysis techniques: (a) the estimation of parametric distributions of response probability, (b) a goodness-of-fit test of the estimated distributions, and (c) a test of the independence of response attributes. Maximum likelihood theory was employed in all cases. The test of independence was necessarily nonstandard due to the fact that the fish, whose various responses to the explosions were to be compared, were actually subjected to different treatments, i .e., different shock wave pressures. The special theory and computer program required for the test of independence appear in Appendix C. The fitting (i.e., estimation) method and goodness-of-fit test employed are similar to those used in previous studies of fish response to underwater explosions.[5,6] A general account of the statistical estimation and goodness-of-fit theories can be found in a paper by McDonald (1989).[8]

In this report, we have represented the unknown response probabilities as functions of range using a log-logistic distribution function:

$$p = \frac{1}{1 + e^{-\lambda(\log_{10}R - \mu)}} \qquad (2\text{-}1)$$

where λ and μ are unknown parameters that are adjusted to fit the function to the binomial response observations. Equation (2-1) can also be regarded as the logistic distribution of the logarithm of the (critical) separation, R, between the fish and the explosive charge. λ and μ are parameters that determine the shape and location of the distribution in a manner analogous to the standard deviation and mean (or median) of the normal distribution. Here λ is related to the maximum slope of the S-shaped probability curve. (Because λ is found to be negative in this report, the "S" is actually backwards.) μ is the value of $\log_{10}R$ for which the probability equals 50 percent, i.e., the median of critical $\log_{10}R$ values.

SECTION 3

ANALYSIS OF HOGCHOKER SWIMMING RESPONSE AND MORTALITY DATA

SWIMMING RESPONSE CLASSIFICATIONS

In tabulating our notes on observations of fish swimming behavior following each test, we were able to describe the observations in terms of six levels of increasing impairment:

Level 1:	Swims abnormally
Level 2:	Circles and somersaults
Level 3:	Flutters
Level 4:	Curls up and sinks
Level 5:	Motionless and sinks
Level 6:	Dead

These categories were used to describe the swimming response observations in Tables 2- 4 and 2-5. For convenience, we classified observations of fish mortality as if they represented the ultimate category of swimming impairment.

In our analysis, we found it useful to simplify our treatment of the swimming response data and consolidate the swimming response impairment levels, listed above, within three broader categories defined in the following manner:

Category 1:	Does not swim normally (includes levels 1 through 6)
Category 2:	Does not swim (includes levels 3 through 6)
Category 3:	Dead (level 6)

Most of the analysis, here and in later sections of the report, is carried out in terms of these broader categories. However, for completeness, we also report for the immediate post-shot observations, our curve fits to the cumulative data pertaining to all six of the original swimming impairment classifications.

SWIMMING RESPONSE AND MORTALITY IMMEDIATELY AFTER TEST

The actual evaluations of immediate post-shot swimming response were made about 1/2-hour after the shot, and after the fish had been recovered from the test rig. Figure 3-1 shows our computed fits by the method of maximum likelihood for the probabilities of the three broader categories of swimming impairment immediately after the tests as functions of range. The lower plot shows the probability of a fish being dead (level 6). The estimated range for 50 percent immediate kill probability is 30 inches. (This percentile and the 50th percentiles pertaining to other levels of swimming impairment are listed in Table 3-1, column 4.) The center plot in Figure 3-1 shows the probability that a fish is not able to swim (level 3 response or greater). The estimated range for 50 percent probability of not being able to swim is 43 inches. The upper plot shows the probability that a fish is not able to swim normally (level 1 response or greater). The associated estimated range of 50 percent probability is 88 inches (obtained by extrapolation of the fit outside the range of the data). Figure 3-2 displays the three curves of Figure 3-1 together on the same plot.

Figure 3-3 shows the curve fits to the cumulative data pertaining to all six of the original swimming impairment classifications over the range spanned by the data. Figures 3-2 and 3-3 are included to permit the more flexible use of the estimated probability curves. For example, the probability of any single impairment level alone is just the difference between the cumulative curve beginning with that level and the cumulative curve of the immediately higher level. This is a consequence of the fact that the probability of the union of disjoint responses (e.g., p[levels 2 through 6]) is just the sum of the individual probabilities of the responses (i.e., p[level 2] + p[level 3] + ... + p[level 6]). Hence, the information for computing the probabilities of various and sundry combinations of the data are contained in the curves shown in Figures 3-2 and 3-3. As another example, the difference between the "does not swim normally" curve (level 1 or greater) and the "does not swim" curve (level 3 or greater) represents the probability that the fish swims, but abnormally. The probability for the occurrence of fish that are alive but cannot swim (p[level 3,4 , or 5]) is just the difference between the "does not swim" curve and the curve labeled as "dead."

Note that these fits and all other fits in this report, unless otherwise stated, are derived from Shots 8 through 11. In these tests, the fish were all located between 30 and 80 inches from the center of the charge. Any use of these fits outside of this range is an extrapolation of the data set. Figure 3-2 includes extrapolated regions on both sides of the range of the observed data. The intersection of the two lower curves at a horizontal range of about 2.1 feet is obviously incorrect. It is a result of the random nature of the fitted curves and, in this case, to the fact that the curves have been extrapolated. In cases where there is no other information, such extrapolations are often necessary.

Table 3-1 lists the values of the parameters λ and μ of the log-logistic distributions fitted to the swimming response and mortality data of Shots 8 through 11. Table 3-1 also includes the ranges corresponding to 50 percent probabilities (as calculated from μ) and details of the chi square goodness-of-fit tests. Data bins for the chi square tests were created by using the estimated probabilities and grouping contiguous points so that the estimated expected numbers of both injured and uninjured fish in each bin was at least equal to a constant value. This constant value ranged from 0.33 to 3.5 fish and was selected so that the chi square test statistic had at least one degree of freedom.

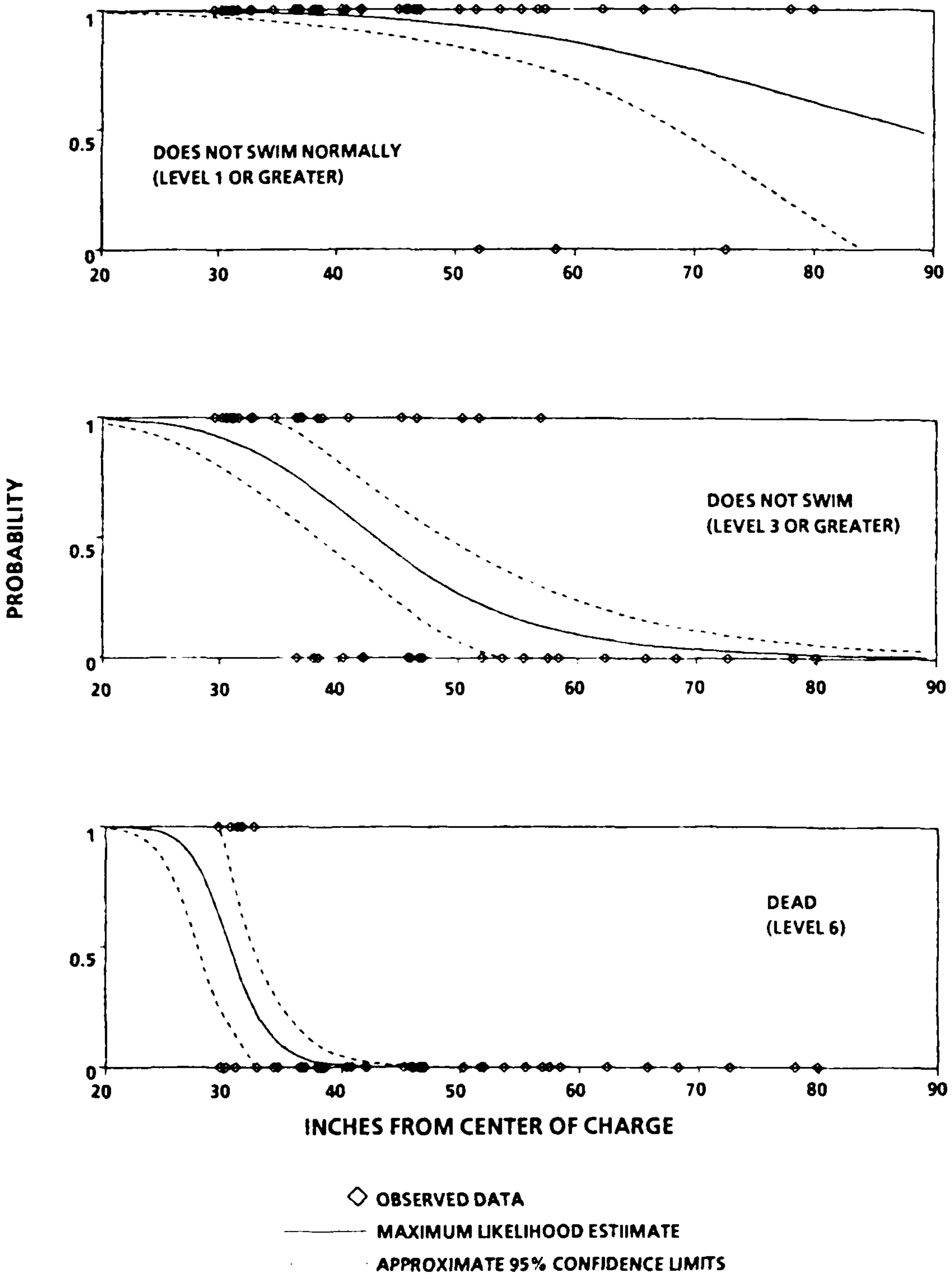

FIGURE 3-1. SWIMMING RESPONSE AND MORTALITY IMMEDIATELY AFTER TEST VS RANGE

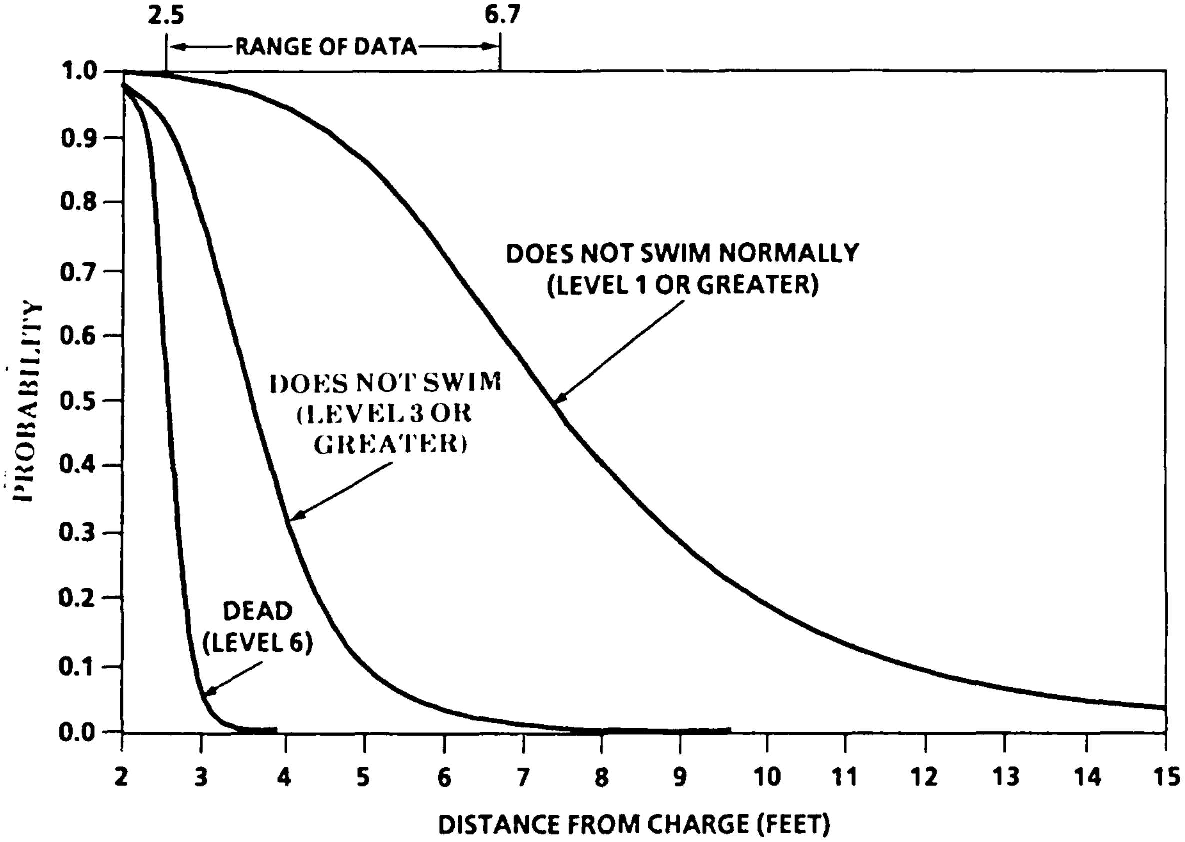

FIGURE 3-2. SWIMMING RESPONSE AND MORTALITY IMMEDIATELY AFTER TEST VS. RANGE

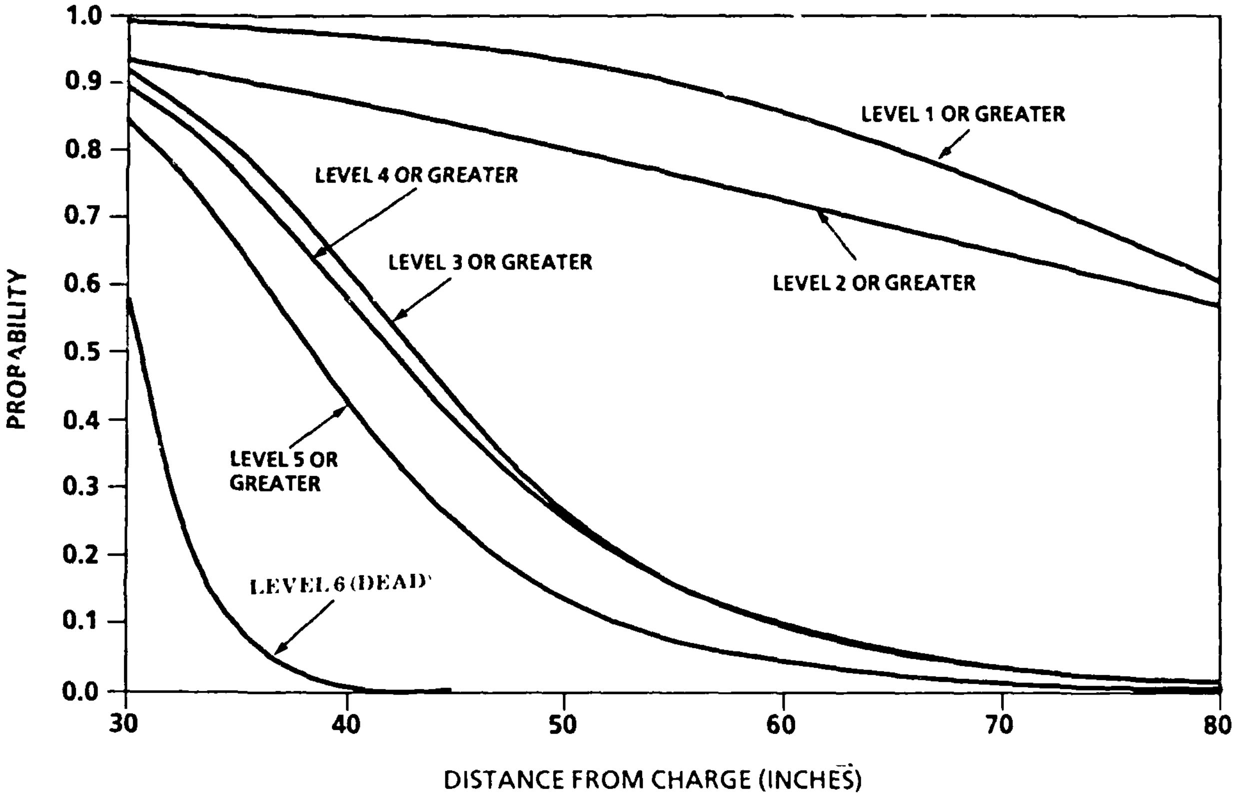

FIGURE 3-3. SWIMMING RESPONSE AND MORTALITY IMMEDIATELY AFTER TEST VS. RANGE

TABLE 3-1 MAXIMUM-LIKELIHOOD-FIT AND GOODNESS-OF-FIT TEST RESULTS FOR HOGCHOKER SWIMMING IMPAIRMENT AND MORTALITY DATA

(Independent variable = Range, R, in inches)

Swimming Impairment	Fit Coefficients			Chi Square Goodness-of-fit Test		
Description	λ	μ	P=50% Range (inches)	Degrees Freedom	Test Statistic	Chi Square 95th Percentile
Immediately After Test:						
Level 1 or greater (DOES NOT SWIM NORMALLY)	-10.79	1.946	88.3	1	0.0	3.8
Level 2 or greater	-5.498	1.959	91.0	1	0.5	3.8
Level 3 or greater (DOES NOT SWIM)	-15.46	1.634	43.1	2	0.2	6.0
Level 4 or greater	-14.59	1.624	42.1	2	1.9	6.0
Level 5 or greater	-15.97	1.584	38.4	2	2.9	6.0
Level 6 (DEAD)	-40.41	1.485	30.5	1	1.4	3.8
24 Hours After Test:						
Level 1 or greater (DOES NOT SWIM NORMALLY)	Uniform Probability = 0.897		---	1	0.0	3.8
Level 3 or greater (DOES NOT SWIM)	-4.306	1.770	58.9	1	0.0	3.8
Level 6 (DEAD)	Uniform Probability = 0.410		---	1	0.4	3.8

SWIMMING RESPONSE AND MORTALITY 24 HOURS AFTER TEST

Mortality of Controls

On 9 of the 11 tests, controls (i.e., hogchokers not subjected to the explosion but otherwise treated the same as the test specimens) were placed in the holding tanks alongside the test survivors. We recorded the mortality of these controls 24 hours after the tests. The results are listed in Table 3-2.

Of the 88 controls used in the test series and held for 24 hours after each shot, 19 percent (17 fish) died. In particular, of the 40 controls used in Shots 8 through 11, 18 percent (7 fish) were dead after 24 hours. Thus, in this series of tests roughly 20 percent of the controls were dead after 24 hours of captivity. It seems probable that this high mortality rate was due to poisoning of the fish in at least one or both of the holding tanks as a result of the mistake made in the painting of these tanks discussed in Section 2.

Mortality of Test Survivors

The high mortality of the controls due to the harsh environments in the holding tanks must be a significant consideration when evaluating the 24-hour mortality and 24-hour swimming response of the test survivors. Unfortunately, the harsh environment imposed on many of the test survivors makes conclusions based on *observations* 24 hours after the shots very tenuous.

Of the 39 test survivors on Shots 8 through 11, 41 percent (16 fish) were dead 24 hours after the test. This probably indicates that test survivors were less able than the controls to survive the harsh environments of the holding tanks. Whether the test survivors would have been able to survive for 24 hours in their natural habitat is a completely different matter.

In their natural habitat the test survivors would probably have been vulnerable to predation, since most (about 80%) could not swim normally. The fact that the observed mortality of these survivors is uniformly distributed with range from the explosion (see lower plot of Figure 3-4) indicates that this delayed mortality is not related to the immediate mortality or to the hemorrhaging in the gills observed in these tests.

Swimming Response 24 hours after Test

The upper two plots of Figure 3-4 show the probability fits to swimming response levels 1 and 3 as a function of range from the explosion. There do not appear to be any drastic changes in swimming behavior due to the 24-hour holding period, although we do see, upon comparison of Figures 3-4 and 3-1, a considerable broadening of the distributions over range, as an apparent result of a general loss of swimming ability over time. However, we will not attempt to draw any detailed conclusions due to the uncertainties introduced by the harsh environments in the holding tanks.

We do note, however, that out of the 39 survivors immediately after the tests, there were 3 normal swimmers (8%). Among the 23 survivors 24 hours after the tests

TABLE 3-2. 24-HOUR MORTALITY OF HOGCHOKER CONTROLS

Shot	Mortality (No. Dead/No. Controls)
1	0/10
2	---
3 *	5/10
4	---
5	2/10
6	2/10
7	1/8
8 **	4/10
9	0/6
10	3/12
11	0/12
Total for All Shots:	17/88 = 0.19
Total for Shots 8 thru 11:	7/40 = 0.18

Notes:

* For 10 Hogchokers with 1-cc air injected into gut, 24-hr mortality was 4/10

** Cage was sitting on end—crowding may have been cause of death.

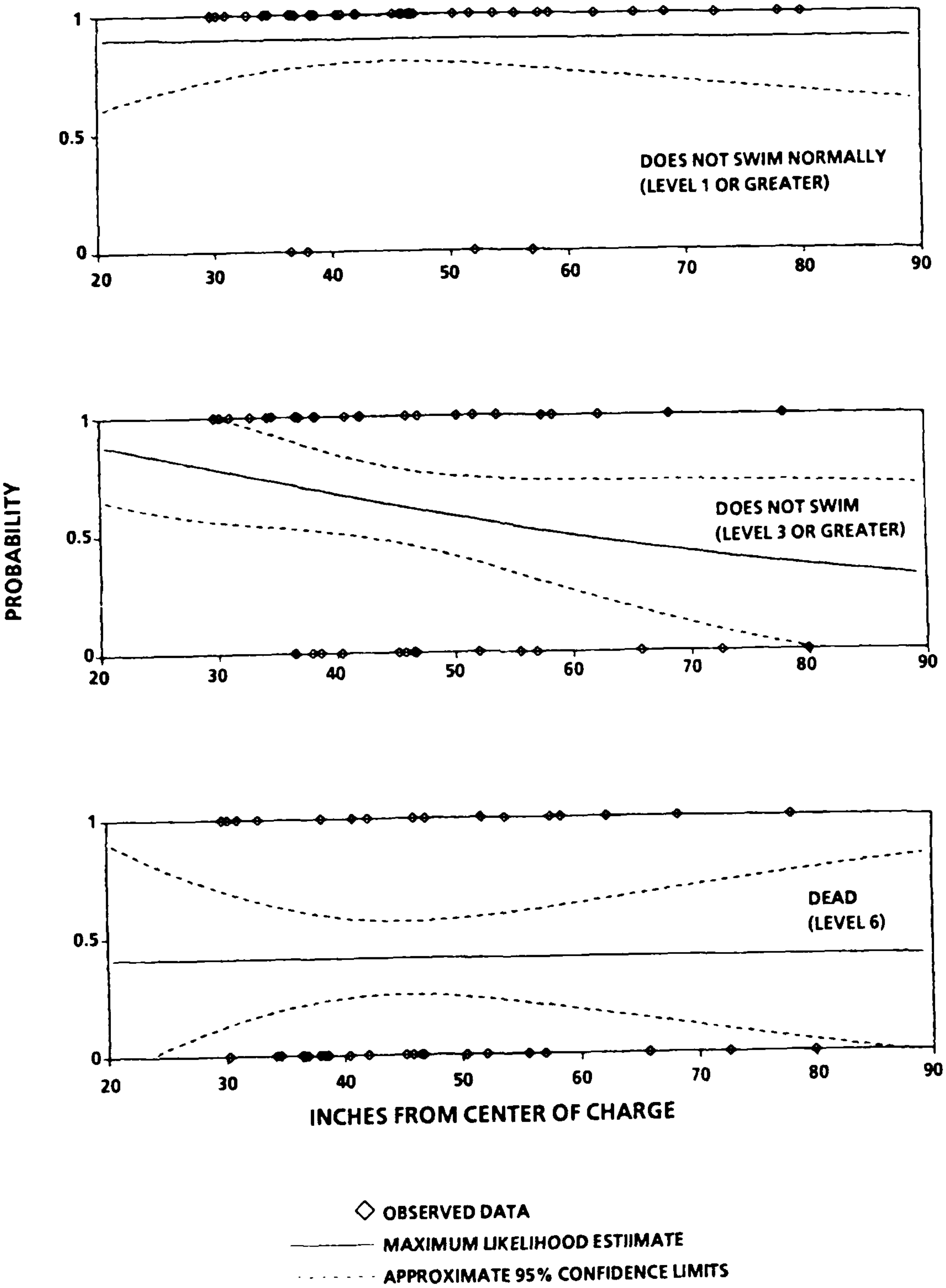

FIGURE 3-4. TEST SURVIVOR SWIMMING RESPONSE AND MORTALITY 24 HOURS AFTER TEST VS. RANGE

there were 4 normal swimmers (17%). Moreover, except for one fish among these normal swimmers 24 hours after the test, these were different fish, i.e., fish that were not swimming normally immediately after the test. Thus, a few individual fish did recover some swimming ability during the 24 hours after the tests.

SECTION 4

ANALYSIS OF HOGCHOKER DISSECTION DATA

Table 4-1 shows the estimated values of the log-logistic distribution parameters determined by maximum-likelihood fits to the cumulative data associated with levels of impairment to the gills, viscera, heart, and brain. Like Table 3-1, Table 4-1 also includes the estimated medians of the critical range distributions and characteristics of the goodness-of-fit tests. In all cases, the fits were not rejected by the chi square test. Here, also, data bins for the chi square test were based on the estimated expected numbers of injured and uninjured fish. This number ranged from 0.33 to 3.5 fish. In the cases of severe hemorrhaging in the viscera and massive hemorrhaging in the cranium, where the data was in the tails of the distributions, numbers as small as .33 fish per bin were necessary to produce tests with at least one degree of freedom. Although this strains the validity of the assumptions underlying the test somewhat,[8] the results are believed to be reasonable and correct. Plots of the various fits and discussions of the dissection observations are presented below. (Appendix D lists the complete data base--Shots 4 through 11--used as a starting point for the analysis presented in this report.)

HEMORRHAGING IN THE GILLS

Figure 4-1 shows the maximum-likelihood fits to the post-shot dissection observations of hemorrhaging in the gills. The three plots show the probabilities as functions of range estimated from the cumulative observations of levels 1, 2, and 3 hemorrhaging. For example, the upper plot of Figure 4-1 shows the probability of observing hemorrhaging of level 1 or greater as a function of range.

Comparison with Mortality Data

Note that all instances of observed hemorrhaging occurred at ranges of 40 inches or less. Note also that the curve for "severe hemorrhaging in the gills" is practically identical to the lower plot in Figure 3-1 for "immediate post-shot mortality." Figure 4-2 shows these two curves plotted together over the range of the test data. It would appear that there is a close correlation between our observations of hemorrhaging in the gills and immediate kill.

The plausibility of a causative relationship between gill hemorrhaging and fish mortality suggested by the probability curves of Figures 3-1 and 4-1 prompted a closer, more quantitative investigation of the question. A special statistical test of the hypothesis that the two responses were independent was devised. A rejection of the independence hypothesis would support the notion of a causative link; however, failure to reject would indicate that the data could simply result from statistical fluctuations of two independent responses rather than a cause and effect relationship.

TABLE 4-1. MAXIMUM-LIKELIHOOD FIT PARAMETERS AND GOODNESS-OF-FIT TEST RESULTS FOR HOGCHOKER DISSECTION DATA (Independent variable = Range, R, in inches)

		Fit Coefficients			Chi Square Goodness-of-fit Test		
Observation	Severity *	Lambda	Mean	P=50% Range (inches)	Degrees Freedom	Test Statistic	Chi Square 95th Percentile
Hemorrhaging in Gills	Slight	-35.17	1.550	35.5	2	.0	6.0
	Considerable	-42.61	1.519	33.0	1	.0	3.8
	Severe	-46.27	1.487	30.7	1	.0	3.8
Hemorrhaging in Viscera	Slight	-6.587	1.489	30.8	2	.0	6.0
	Considerable	-4.651	1.261	18.2	1	2.4	3.8
	Severe	-46.01	1.438	27.4	1	.1	3.8
Hemorrhaging around Heart	Slight	-1.748	.8880	7.7	2	1.0	6.0
	Considerable	-1.096	.3135	2.1	3	1.7	7.8
	Severe	-1.175	-.5510	.3	4	2.2	9.5
Hemorrhaging in Cranium	Considerable	Uniform Probability = 0.927		---	4	.0	9.5
	Severe	-8.301	1.451	28.2	1	.0	3.8
	Massive	-23.68	1.387	24.4	1	.1	3.8

---

* "or greater" (since these are cumulative probabilities)

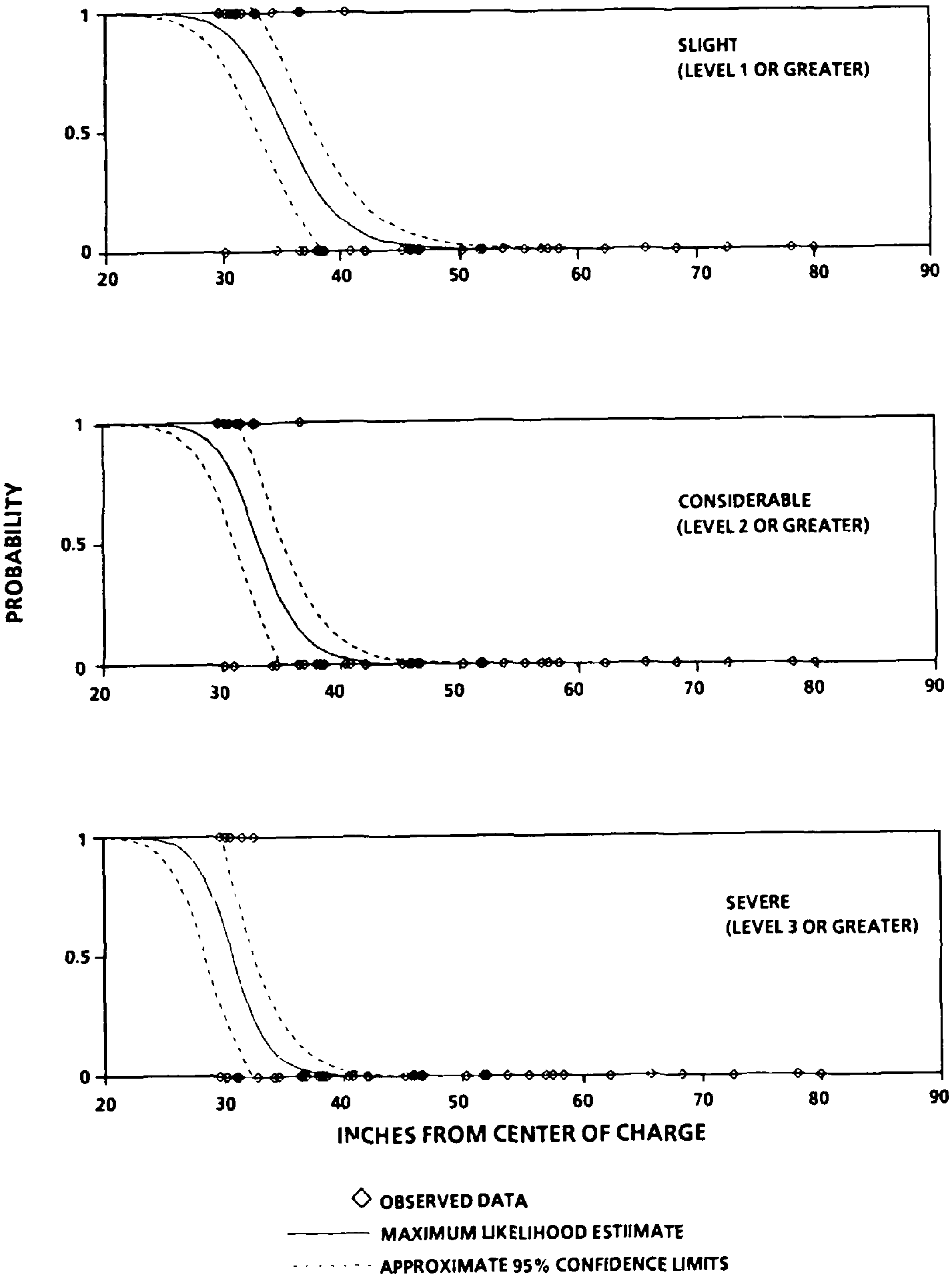

FIGURE 4-1. HEMORRHAGING IN THE GILLS VS. RANGE

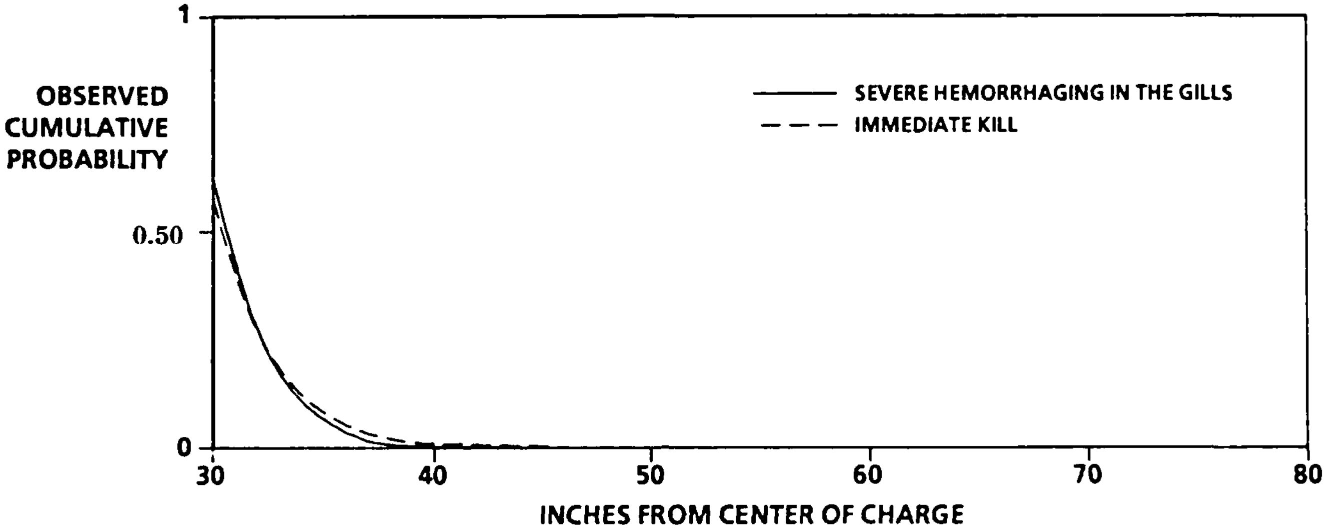

FIGURE 4-2. COMPARISON OF FITS FOR HEMORRHAGING IN THE GILLS AND IMMEDIATE KILL

The theory of the test and a computer program based on the theory are found in Appendix C. It should be noted, that the usual test of independence of attributes based on the standard 2 x 2 contingency table model (e.g., see Snedicor and Cochran, 1967, p215)[9] was not appropriate, because within each table the explosion conditions to which the fish were subjected varied.

Table 4-2 shows the results of statistical tests comparing the hogchoker mortality data with the three gill hemorrhaging responses described as slight (or greater), considerable (or greater), and severe (or greater). As stated above, these were also the categories used to estimate the probability curves appearing in Figure 4-1. The values of the test statistic, denoted here as χ^2, are compared with the 95th percentile of the χ^2 distribution with two degrees of freedom (5.99). Only the χ^2 value for the considerable (or greater) set of data was found to be significantly high. The slight (or greater) and the severe (or greater) data sets both produced χ^2 values that were not significantly high (below 5.99).

Table 4-3 gives a partial accounting of these test results. A more complete explanation requires the variance information used to calculate χ^2 as described in Appendix C, and this is not shown. Here we present contingency table categories and observed and estimated response frequencies (numerators denote the observed frequencies). Differences between observed and estimated frequencies, of course, suggest a departure between the model (based on independence) and the observations. The tables cannot be taken as ordinary contingency tables because, as stated previously, the fish considered in each table did not receive the same treatments, i.e., some received much higher shock wave pressures than others. The estimated frequencies were determined from the fitted probabilities given in Figures 3-1 and 4-1 under the assumption of response independence. For each level of hemorrhaging response the fish were divided into two groups for the purpose of calculating χ^2. The left column of tables involves fish from shots 8 and 9 (group 1) and the right column pertains to fish of shots 10 and 11 (group 2). Table 4-3 shows reasonable agreement between the observed and estimated frequencies. The frequencies associated with the considerable (or greater) level of hemorrhaging are not particularly different from those of the slight and severe (or greater) levels. However, the differences, in combination with the variance information, are apparently enough to push the χ^2 value above the critical rejection level for the considerable (or greater) level data.

We interpret these results in the following manner. First, it would be difficult to reconcile on the one hand dependency between the less severe level 2 hemorrhaging response and the mortality response, and, on the other hand, no dependency between the more severe level 3 hemorrhaging and mortality responses. It seems more likely that the level 2 and level 3 hemorrhaging responses are either both independent of the mortality response or both dependently related to the mortality response. The probability that the significant level 2 (or greater) result is incorrect (a type I error) is fixed by the design of the test to be about 5 percent. (In fact it is lower than 5 percent because the test is conservative. See Appendix C, Page C-4.) In fact, this may be as low as 3 percent because the test results would be the same at the 3 percent significance level. On the other hand, the probability that the level 3 (or greater) result favoring independence is incorrect (a type II error) is unknown. But, because of the small amount of data involved, it is likely, judging from past experience, that this probability is actually quite high, even as much as 30 or 40 percent. It seems reasonable, therefore, to conclude that these results suggest the presence of a cause and effect relationship between the considerable and severe levels of gill hemorrhaging and fish mortality, rather than independence. The

TABLE 4-2. TESTS OF INDEPENDENCE OF MORTALITY AND LEVELS OF GILL HEMORRHAGING IMMEDIATELY AFTER SHOT

GILL HEMORRHAGING LEVEL	SEVERITY LEVEL	CHI SQUARE TEST STATISTIC	CONCLUSION (at 5% Significance Level)
Slight or greater	1 or more	3.66	Not Significant
Considerable or greater	2 or more	7.14	Significant
Severe or greater	3 or more	4.39	Not Significant

Notes:
Chi square calculation based on theory and computer program of Appendix C.
Data grouping: Group 1 (Shots 8 and 9), Group 2 (Shots 10 and 11).
Chi square 95th Percentile (2 degrees of freedom) = 5.99

TABLE 4-3 RATIOS OF OBSERVED AND ESTIMATED FREQUENCIES ASSOCIATED WITH HOGCHOKER MORTALITY AND GILL HEMORRHAGING CATEGORIES

Group1

$$\begin{array}{cc} & \begin{array}{cc}\text{Dead} & \text{Alive}\end{array} \\ \begin{array}{c} H_1 \\ \text{Not } H_1 \end{array} & \begin{bmatrix} 2/1.33 & 1/1.40 \\ 2/1.39 & 14/14.88 \end{bmatrix} \end{array}$$

$$\begin{array}{cc} & \begin{array}{cc}\text{Dead} & \text{Alive}\end{array} \\ \begin{array}{c} H_2 \\ \text{Not } H_2 \end{array} & \begin{bmatrix} 4/2.00 & 2/2.86 \\ 0/0.71 & 13/13.42 \end{bmatrix} \end{array}$$

$$\begin{array}{cc} & \begin{array}{cc}\text{Dead} & \text{Alive}\end{array} \\ \begin{array}{c} H_3 \\ \text{Not } H_3 \end{array} & \begin{bmatrix} 4/2.32 & 4/4.93 \\ 0/0.40 & 11/11.35 \end{bmatrix} \end{array}$$

Group2

$$\begin{array}{cc} & \begin{array}{cc}\text{Dead} & \text{Alive}\end{array} \\ \begin{array}{c} H_1 \\ \text{Not } H_1 \end{array} & \begin{bmatrix} 1/1.02 & 1/1.28 \\ 0/1.26 & 22/20.44 \end{bmatrix} \end{array}$$

$$\begin{array}{cc} & \begin{array}{cc}\text{Dead} & \text{Alive}\end{array} \\ \begin{array}{c} H_2 \\ \text{Not } H_2 \end{array} & \begin{bmatrix} 1/1.66 & 2/2.52 \\ 0/0.62 & 21/19.20 \end{bmatrix} \end{array}$$

$$\begin{array}{cc} & \begin{array}{cc}\text{Dead} & \text{Alive}\end{array} \\ \begin{array}{c} H_3 \\ \text{Not } H_3 \end{array} & \begin{bmatrix} 1/1.95 & 4/3.80 \\ 0/0.33 & 19/17.91 \end{bmatrix} \end{array}$$

Table entries show: observed frequency / estimated frequency.

Data Grouping: Group 1 (Shots 8 and 9), Group 2 (Shots 10 and 11).

Symbol H denotes the hemorrhaging response; subscripts indicate injury levels as follows:
(1) slight or greater, (2) considerable or greater, and (3) severe or greater.

weakness of this statement is a consequence of the smallness of the data set. Since the probability of the type II error decreases with increasing sample size, it appears that a more conclusive statistical test would require more experimental data. The question of dependence between mortality and the slight hemorrhaging response appears to also require more data to be resolved.

There is support for the notion, therefore, that many of the fish that died simply bled to death. It seems likely that there are always small gas bubbles on the gill surfaces, and possible that the strong response of these bubbles to the explosion shockwave, and the consequent damage to gill tissues, provides the dominant mechanism for immediate kill.

HEMORRHAGING IN THE VISCERA

Figure 4-3 shows the fits to post-shot dissection observations of hemorrhaging in the viscera. These fits are based on our overall evaluation of the degree of hemorrhaging of the visceral organs (not including the heart). The three fits appear to comprise a reasonable set of observed data.

HEMORRHAGING AROUND THE HEART

Figure 4-4 shows the fits to post-shot dissection observations of hemorrhaging around the heart. Note that the fitted curves indicate only a weak dependence of the probability of hemorrhaging on distance from the charge. This may not actually be true since in all three plots this characteristic is largely the result of a single instance of level 3 hemorrhaging (weak individual?) at a range of 78 inches. Were this individual removed from these three fits, the upper two fits would be considerably different, and the lower fit would be drastically changed.

HEMORRHAGING IN THE CRANIUM

Figure 4-5 shows the fits to post-shot dissection observations of hemorrhaging in the cranium. The upper plot shows that considerable hemorrhaging (level 2 or greater) in the cranium is almost universal in the data from Shots 8 through 11 with a uniform probability of 0.927. However, for severe hemorrhaging (level 3 or greater), the probability falls off with distance (center plot). Massive hemorrhaging (level 4) was observed in only one fish (lower plot).

The brain damage appeared to be associated most closely with the inner ears. Each inner ear has three stony otoliths composed of calcium carbonate, the sagitta, lapillus and asteriscus, which function in the sense of balance and in hearing. The sagitta is relatively large, being 2 to 3 mm long in hogchokers of the size used. The inner ears are located within the cranium close to the brain. When damage was apparent in the brain, there were almost always hemorrhages in proximity to the otoliths. It appears that the violence of the motion near the charge affected the otoliths, which then transmitted the energy to the surrounding, less dense tissues, causing damage to them. It is likely that the otoliths, having much greater density than the surrounding soft tissues, do not accelerate at the same rate. A shearing action is thereby generated that results in damage to the surrounding soft tissues, which have about the same density as water. Damage to the inner ears could account for the peculiar swimming responses that were often observed. Since the inner ears (and otoliths) are in close proximity to the brain, it is also possible that some of the

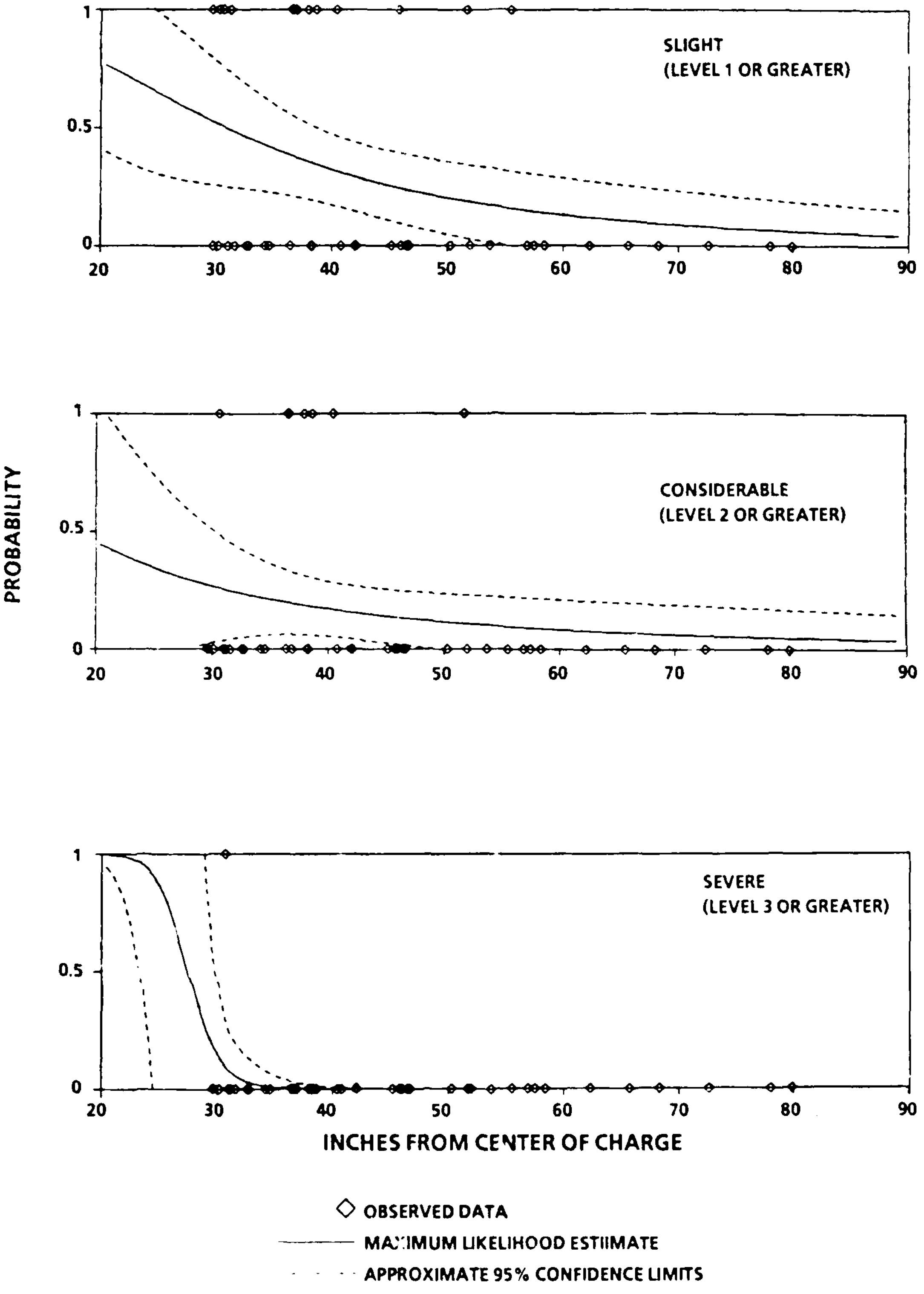

FIGURE 4-3. HEMORRHAGING IN THE VISCERA VS. RANGE

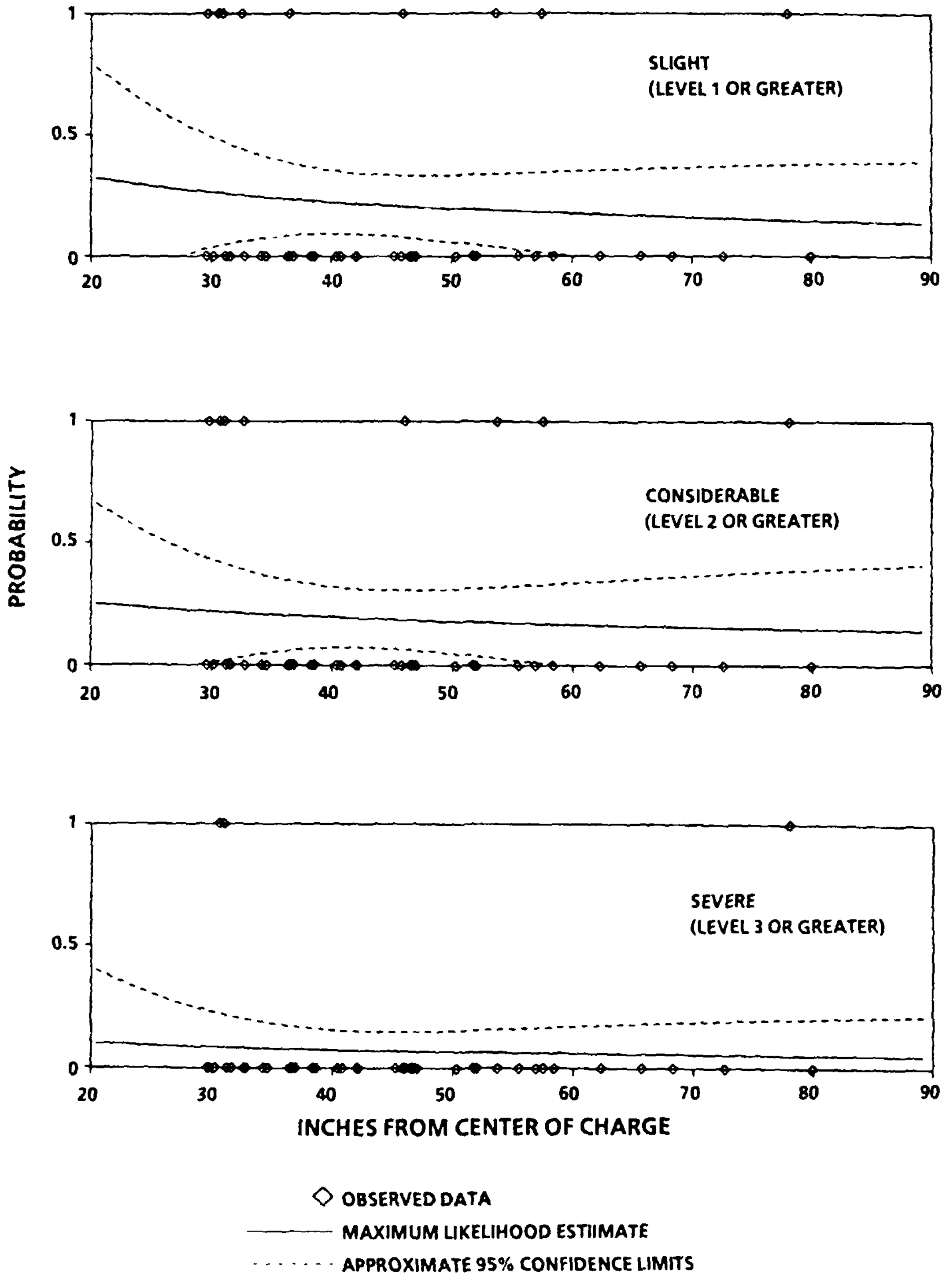

FIGURE 4-4. HEMORRHAGING AROUND THE HEART VS. RANGE

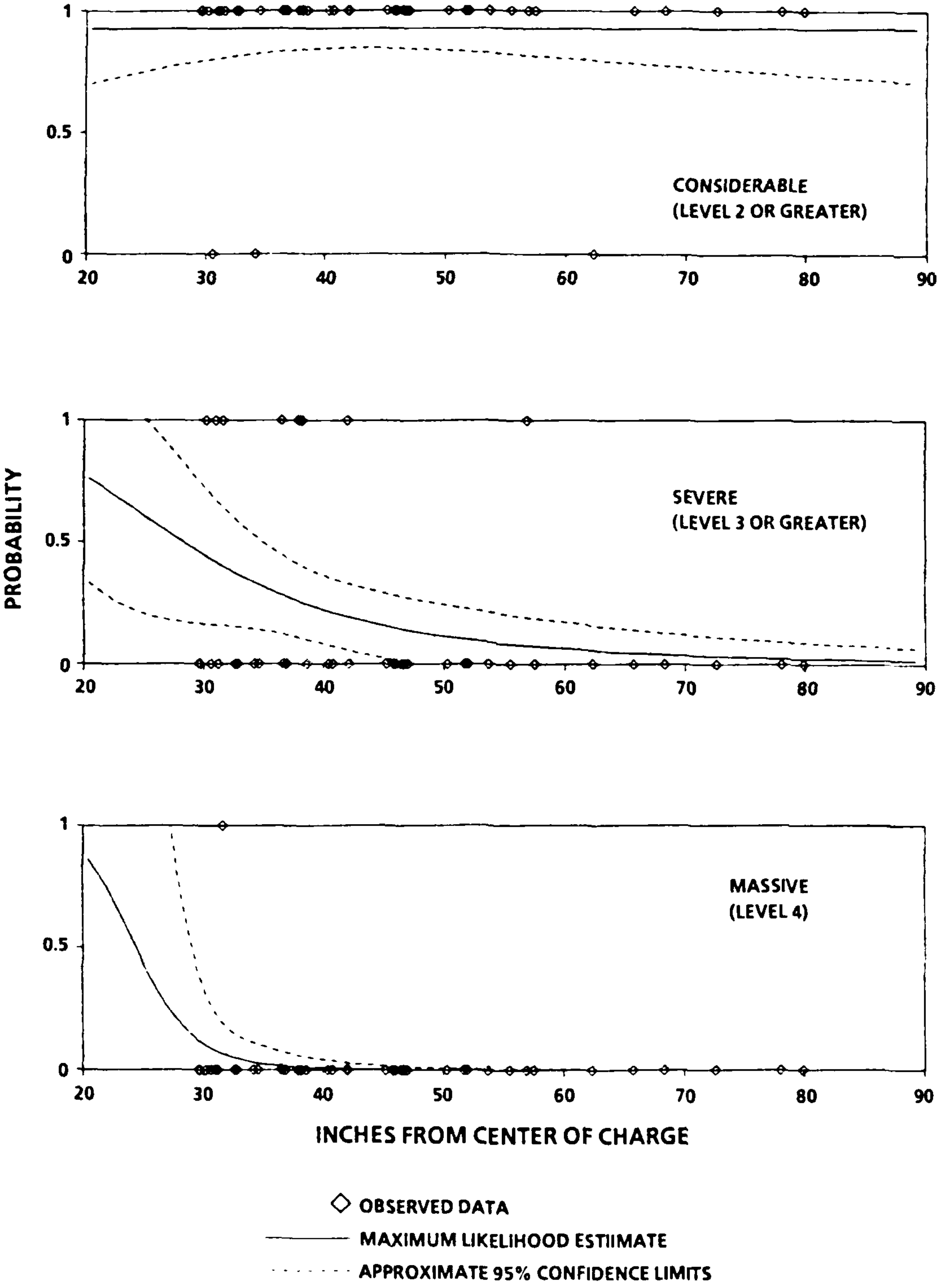

FIGURE 4-5. HEMORRHAGING IN THE CRANIUM VS. RANGE

delayed mortalities were due to damage to the central nervous system that was associated with the otoliths.

Comparisons with Swim Response Data

It is plausible to expect abnormal swimming behavior to be related to damage to the nervous system and, more specifically, to brain injury. Consequently, we looked for possible correlations between our swim response observations and observations of hemorrhaging in the cranium. A comparison of the upper plot of Figure 3-1 (level 1 or greater swimming impairment immediately after the shot) with the upper plot of Figure 4-5 (level 2 or greater brain hemorrhaging) shows that both swimming abnormalities and brain injuries occurred with high probabilities at all ranges. This is also true of the data displaying abnormal swimming response 24 hours later, as shown in the upper plot of Figure 3-4.

Table 4-4 shows the results of statistical tests of the hypotheses that the swimming abnormalities, observed both immediately following the shot and 24 hours later, were independent of brain hemorrhaging. The method and computer program described in Appendix C were used to perform these analyses. In neither case was the test statistic significant at the 5 percent significance level (or at even larger significance levels). The value of test statistic was larger for the data taken 24 hours after the shot (3.45) than for the immediate post shot observations (0.97). But, it is unlikely that this fact carries any additional significance.

The finding that our observations do not support a linkage between swimming abnormalities and brain hemorrhaging is probably due to the coarseness of, or lack of sophistication in, our observations of injury to the brain. Although we conducted more detailed autopsies on about half of the fish from the last two shots of the test series, numbers in these more detailed damage categories were insufficient for estimating probabilities. Therefore, damage probabilities were only estimated for observations of the general level of hemorrhaging in the cranium. It is this overall hemorrhaging in the brain case that does not correlate with our observations of abnormal swimming behavior.

TABLE 4-4. TESTS OF INDEPENDENCE OF LEVEL 1 (OR GREATER) SWIMMING IMPAIRMENT AND BRAIN HEMORRHAGING

Time after Shot	Chi Square Test Statistic	Conclusion (at 5% Significance Level)
Immediate	0.97	Not Significant
24 Hours	3.45	Not Significant

Notes:
Chi square calulation based on theory and computer program of Appendix C
Data grouping: Group 1 (Shots 8 and 9), Group 2 (Shots 10 and 11)
Chi Square 95th Percentile (2 degrees of freedom) = 5.99

SECTION 5

GENERALIZATION OF RESULTS

The observations of fish mortality and hemorrhaging described in this report were obtained from four replications of a single underwater explosion test geometry. We would like to extrapolate these observations, specifically, the maximum likelihood fits to the mortality, swim response, and hemorrhaging observations, to other explosion test geometries; but without further research we cannot do this with any degree of certainty.

In planning these tests, our working hypothesis was that the significant parameter for mortality and injury was $\Delta P_{max}/P_0$, the ratio of the highest overpressure to the ambient hydrostatic pressure. (On the present tests, ΔP_{max} is the initial peak pressure of the shock wave resulting from the detonation of the charge.) This working hypothesis was based on the assumption that tissue damage is related to tissue strains caused by the collapse of small gas bubbles as they respond to the shock wave pressure. At this time, we have no reason to abandon this hypothesis and, in fact, we propose that it be tested by further research. To this end, in this section we transform the independent variable in our maximum-likelihood fits to the mortality, swim response, and hemorrhaging from R, the range in inches from the center of the charge, to $\Delta P_{max}/P_0$.

EQUATION FOR ΔP_{max}

In order to transform the independent variable in our maximum likelihood fits from R to $\Delta P_{max}/P_0$, we need to know the shock wave overpressure, ΔP_{max} at each fish location. For Shots 8 through 11, fish were located from 30 to 80 inches directly off the side of our pentolite cylinders. To determine ΔP_{max} over this interval we use the hydrodynamic code computations of Sternberg and Hurwitz (1976).[10] Using our average charge weight (10.078 lbs) for Shots 8 through 11 and Sternberg and Hurwitz's charge density (1.65 gms/cc), we calculate a charge volume and get an equivalent spherical charge radius,

$$R_0 = 8.713 \text{ cm} = 3.430 \text{ inches.} \qquad (5\text{-}1)$$

Thus, in terms of R_0 the range of the fish locations for our experiments is

$$8.7 \leq R/R_0 \leq 23.3. \qquad (5\text{-}2)$$

Sternberg and Hurwitz's computations cover the range, $1 \leq R/R_0 \leq 40$. However their computations are for a centrally detonated spherical charge, not our test geometry which is a cylinder with a length-to-diameter (L/D) ratio = 1.0 which is detonated at one end. Sternberg (1987),[11] presents computational results for ΔP_{max} out to $R/R_0 = 15$ for pentolite cylinders detonated at one end. He gives results for ΔP_{max} directly off the side at $R/R_0 = 10$ and 15 (greatest range of this set of computations). At these ranges ΔP_{max} directly off the side is the same as for the centrally detonated sphere.* Very close to the charge, ΔP_{max} from these two charge configurations must be different, however, at greater ranges the ΔP_{max} should continue to be the same. Thus, for the range of fish locations in our experiments, we can use Sternberg and Hurwitz's computations for the centrally detonated sphere to determine ΔP_{max} at the fish locations on Shots 8 through 11.

For our purposes we put a curve of the form,

$$\Delta P_{max} = K\,(R/R_0)^{\alpha} \tag{5-3}$$

through their computed R/R_0 vs ΔP_{max} results, (10, 1.19 Kbar) and (20, 0.494 Kbar). We get $K = 22.076$ Kbar, $\alpha = -1.268$. Converting to range, R, in inches from our charge ($R_0 = 3.43''$) and pressure in pounds per square inch, we get

$$\Delta P_{max} = 1.5281\text{ E6 } R^{1.268} \tag{5-4}$$

where R is the range from the center of the charge in inches and ΔP_{max} is the peak pressure in psi.

EQUATION FOR $\Delta P_{max}/P_0$

To calculate $\Delta P_{max}/P_0$ we need P_0, the ambient hydrostatic pressure at the location of the fish. Since all the fish on Shots 8 through 11 were at the same 25-foot depth, P_0 is a constant given by

$$P_0 = \text{Patm} + \rho\, g\, h = \text{Patm}\,[1 + h/33.43] = 25.69 \text{ psi} \tag{5-5}$$

where,

Patm is the atmospheric pressure = 14.70 psi
ρ is the water density = 1.015 gms/cc
g is the acceleration of gravity = 32.15 ft/sec
h is the fish depth = 25 ft

Using Equations (5-4) and (5-5) we get

$$\Delta P_{max}/P_0 = 59482\, R^{1.268} \tag{5-6}$$

where, R is the range from the charge to the fish in inches.

TRANSFORMED MAXIMUM-LIKELIHOOD FITS

Rewriting Equation (2-1) for the log-logistic distribution function as

$$p = \frac{1}{1 + e^{-\ell}} \tag{5-7}$$

---

* The curve for ΔP_{max} for L/D = 1 in Sternberg, 1987,[11] Figure 9 is in error. In this figure, ΔP_{max} directly off the side should be the same as for the centrally detonated sphere (Sternberg, 1986).[12]

where,

$$\ell = \lambda[\log_{10}R-\mu] = \lambda'[\log_{10}(\Delta P_{max}/P_0) - \mu'] \qquad (5\text{-}8)$$

and using Equation (5-6) gives

$$\lambda' = -\lambda/1.268 \qquad (5\text{-}9)$$

$$\mu' = 4.774-1.268\mu \qquad (5\text{-}10)$$

for the needed transformation equations.

Table 5-1 lists the transformed fit coefficients λ' and μ' for each of the maximum-likelihood fits presented in Table 4-1. It also lists the value of the value of $\Delta P_{max}/P_0$ calculated from μ' corresponding to 50 percent probability. Substituting the transformed fit coefficients, λ' and μ', into Equations (5-7) and (5-8), one can easily calculate new curves as functions of the new variable, $\Delta P_{max}/P_0$, for any of our observations, i.e., curves to replace those shown in Figures 3-1 through 4-5. Figure 5-1 shows such curves for our swimming response and mortality observations. The swimming response curves of Figure 5-2 were obtained by taking the differences of the cumulative data curves in Figure 5-1 and, therefore, pertain to more specific categories of response, such as "swims, but abnormally" and "alive, but does not swim." The possibility of computing curves for such categories was discussed earlier in Section 3. Table 5-2 shows the values of transformed coefficients λ' and μ' for the curves fitted to the immediate post-shot cumulative data of all six swimming impairment levels. The corresponding $\log_{10}R$ related coefficients appeared previously in Table 3-1.

TABLE 5-1. MAXIMUM-LIKELIHOOD FIT COEFFICIENTS FOR INDEPENDENT VARIABLE, $\Delta P_{max}/P_o$

Observation	Severity	Fit Coefficients		P=50% Values	
		λ'	μ'	ΔPmax/Po	ΔPmax (psi)*
Swim Response Immediately after Test	Does Not Swim Normally	8.509E+0	2.306	203	5,200
	Does Not Swim	1.219E+1	2.702	504	12,900
	Dead	3.187E+1	2.891	778	20,000
Swim Response 24 hrs after Test	Does Not Swim Normally	Uniform Probability = 0.897		---	---
	Does Not Swim	3.396E+0	2.530	339	8,700
	Dead	Uniform Probability = 0.410		---	---
Hemorrhaging in Gills	Slight	2.774E+1	2.809	644	16,500
	Considerable	3.360E+1	2.848	705	18,100
	Severe	3.649E+1	2.888	774	19,900
Hemorrhaging in Viscera	Slight	5.195E+0	2.886	769	19,800
	Considerable	3.668E+0	3.175	1,496	38,400
	Severe	3.629E+1	2.951	893	22,900
Hemorrhaging around Heart	Slight	1.379E+0	3.648	4,446	114,000
	Considerable	8.644E-1	4.376	23,795	611,000
	Severe	9.267E-1	5.473	296,940	7,630,000
Hemorrhaging in Cranium	Considerable	Uniform Probability = 0.927		---	---
	Severe	6.547E+0	2.934	859	22,100
	Massive	1.868E+1	3.015	1,036	26,600

---

*Calculated for a fish at 25-ft depth, i.e., Po = 25.69 psi .

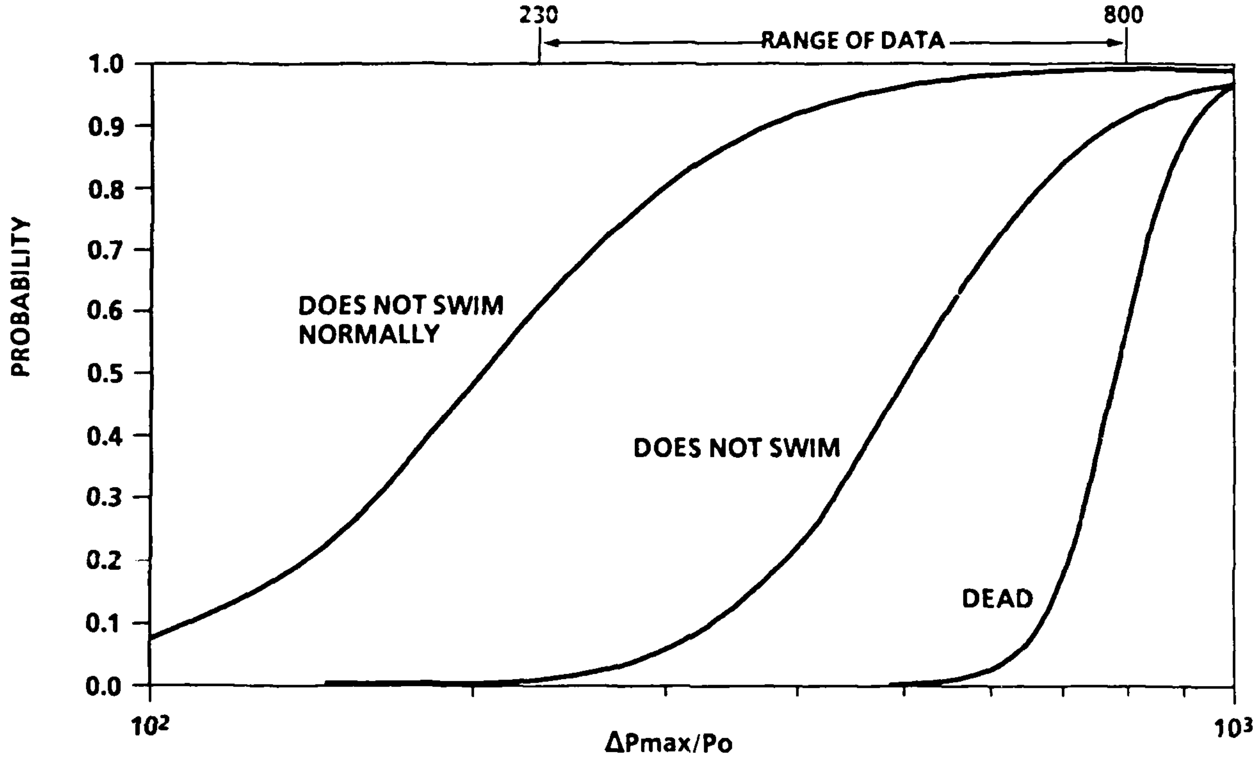

FIGURE 5-1. SWIMMING RESPONSE AND MORTALITY IMMEDIATELY AFTER TEST VS. $\Delta P_{MAX}/P_0$

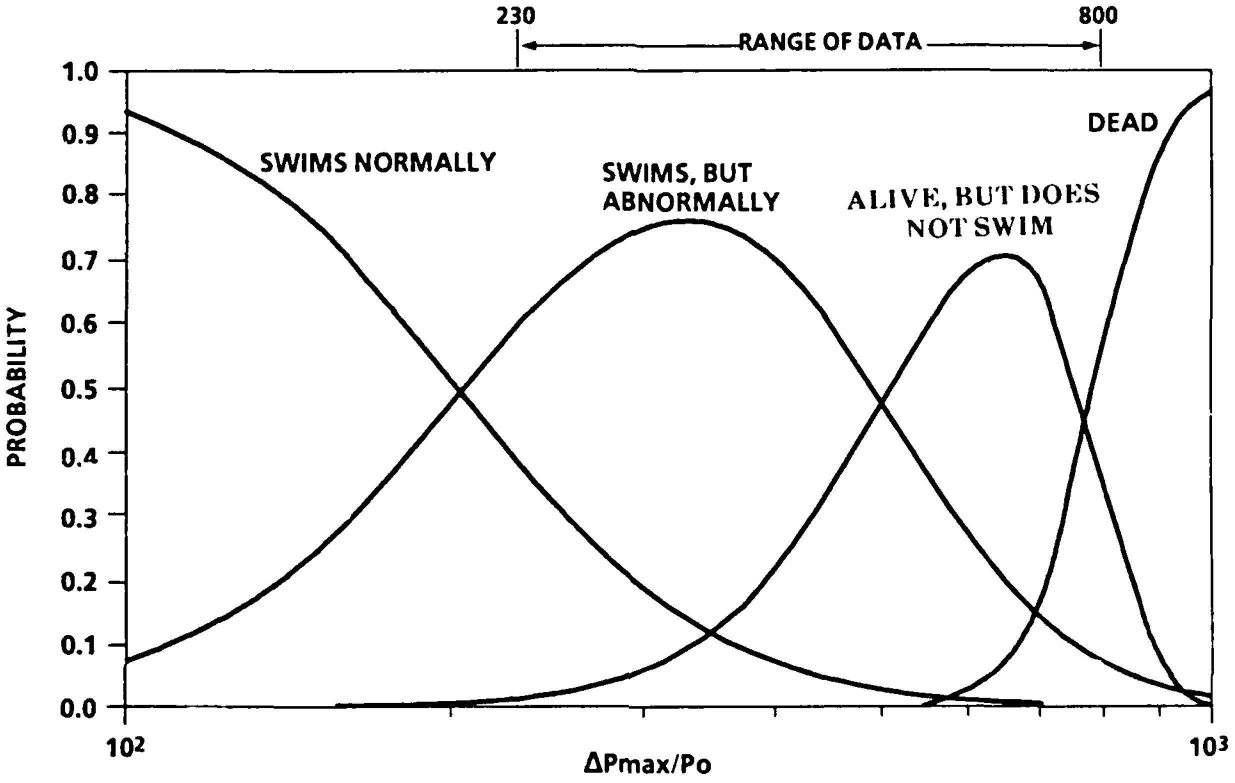

FIGURE 5-2. PROBABILITY OF EACH OBSERVED SWIMMING RESPONSE IMMEDIATELY AFTER TEST VS. ΔPmax/Po

TABLE 5-2. MAXIMUM-LIKELIHOOD FIT COEFFICIENTS FOR INDEPENDENT VARIABLE, $\Delta P_{max}/P_0$ (IMPAIRMENT OF SWIMMING BEHAVIOR IMMEDIATELY AFTER TEST)

Swimming Impairment	Fit Coefficients		P=50% Values	
Description	λ'	μ'	ΔPmax/Po	ΔPmax (psi)*
Level 1 or greater (DOES NOT SWIM NORMALLY)	8.509	2.306	203	5,200
Level 2 or greater	4.336	2.290	195	5,010
Level 3 or greater (DOES NOT SWIM)	12.19	2.702	504	12,900
Level 4 or greater	11.51	2.715	519	13,300
Level 5 or greater	12.59	2.765	582	15,000
Level 6 (DEAD)	31.87	2.891	778	20,000

---

* Calculated for a fish at 25-ft depth, i.e., Po = 25.69 psi.

SECTION 6

ANALYSIS OF FLOUNDER MORTALITY AND DISSECTION DATA

This analysis is based on limited test data obtained from six summer flounder *(Paralichtys dentatus):*

Shot 1:	4 fish held in a single cage
Shot 7:	2 fish held head-downward in separate bags.

None of this data is precisely comparable to the hogchoker data obtained from Shots 8 through 11. Nevertheless, we will use it to estimate rough bounds for the immediate mortality, immediate swim-response and hemorrhaging in the *gills*.

Since the first test was done at a different depth, we will use the injury parameter, $\Delta P_{max}/P_o$, to do this analysis.

4 FISH ON SHOT 1

The charge was at a 10-foot depth and the fish were at an 11-foot depth resting on the bottom of a polypropylene mesh cage at a horizontal range of 10 feet from the charge. Using Equations (5-4) and (5-5), gives $\Delta P_{max}/P_o = 180$.

All four of these fish were recovered alive and had no apparent external injuries. Nor, were any injuries discovered upon dissection. On this first test, however, we did not examine the post-shot swimming behavior nor did we dissect the brain case. W e summarize the results -- for immediately after the test -- as follows:

- All four fish were alive
- There was no hemorrhaging in the gills.

2 FISH ON SHOT 7

Both the charge and the fish were at a 25-foot depth. The fish were suspended, head-downward, eye-side facing the charge, in double-thickness bags made from nylon stockings, at ranges of 57.8 inches and 58.6 inches from the charge. One fish was recovered dead; the other was alive (but died within 10 minutes). Upon dissection, both fish appeared to have sustained considerable hemorrhaging resulting from trapped air bubbles (due to the method of suspension), which could have been the cause of death. Thus, these fish probably received much greater injury than if they had been suspended by the method used for the hogchokers on Shots 8 through 11.

ROUGH ESTIMATES OF INJURY PARAMETERS FOR FLOUNDER

The summer flounder and hogchoker are closely related fish belonging to the same order (Pleuronectiformes), the so-called "flatfishes." We would expect their susceptibility to explosion injury to be rather similar. The results from the six flounder we tested do not conflict with this assumption. However, in handling the fish prior to testing, the flounder were more difficult to keep alive. They appeared to be more sensitive to environmental insults, such as overcrowding or temperature/salinity changes, and also to rough handling. Therefore, while we have no hard evidence to the contrary, we are reluctant to assume that the flounder is as resistant to explosion injury as the hogchoker.

Our approach will be as follows. It seems unlikely that the flounder is more resistant to explosion injury than the hogchoker. Therefore, we will take the hogchoker results, as an estimated lower bound for explosion injury to flounder. For an estimated upper bound we will use a plausible transformation of the hogchoker results that will maximize the susceptibility to injury but still be consistent with the test results from the six summer flounder.

Estimated Upper Bound Injury Parameters

On Shot 7, two summer flounder were at approximately the same distance from the charge. Immediately after the shot, one was dead; the other was alive. The average range, R, was 58 inches, roughly twice the 50 percent mortality range, R = 30 inches, for hogchokers. Since the injuries sustained by these fish were partly due to the method of suspension used to position the fish, this range constitutes a conservative estimate for the 50 percent mortality range for the flounder. We will generalize this result in making our estimates for the upper-bound probabilities of the immediate mortality, immediate swim-response and hemorrhaging in the gills by assuming that the maximum-likelihood fit parameters for each of these injuries can be obtained from the corresponding hogchoker fit by using the transformation,

$$R'' = 2R \tag{6-1}$$

where, R and R" are the range from the charge for hogchoker and flounder, respectively. Thus, from Equations (5-7) and (5-8), for each fit,

$$\lambda\,[\log_{10} R - \mu] = \lambda''\,[\log_{10} R'' - \mu''] \tag{6-2}$$

where the double-primed quantities refer to the upper-bound probabilities for flounder. Using Equation (6-1) to eliminate R" gives

$$\lambda\,[\log_{10} R - \mu] = \lambda''\,[\log_{10} R - (\mu'' - \log_{10} 2)] \tag{6-3}$$

which must be true for all values of R. Thus,

$$\lambda'' = \lambda \tag{6-4}$$

$$\mu'' = \mu + \log_{10} 2 = \mu + 0.301 \tag{6-5}$$

for the upper-bound parameters for flounder in terms of the range, R . The corresponding flounder upper-bound parameters, λ''' and μ''', in terms of $\Delta P_{max}/P_o$ are then given by equations (5-9) and (5-10), i.e.,

$$\lambda''' = -\lambda''/1.268 = -\lambda/1.268 \quad (6\text{-}6)$$

$$\mu''' = 4.774 - 1.268\,\mu'' = 4.392 - 1.268\,\mu. \quad (6\text{-}7)$$

Alternatively, by substituting Equations (5-9) and (5-10) into (6-6) and (6-7), respectively, we get

$$\lambda''' = \lambda' \quad (6\text{-}8)$$

$$\mu''' = \mu' - 0.382 \quad (6\text{-}9)$$

which give λ''' and μ''' in terms of λ' and μ', the corresponding hogchoker parameters which have been referenced to $\Delta P_{max}/P_0$.

Table 6-1 lists the estimated fit coefficients, λ''' and μ''', for the upper-bound of injuries to flounder. These have been calculated from the coefficients listed in Table 5-1 using Equations (6-8) and (6-9). The last two columns in Table 6-1 give the corresponding computed probabilities for injuries at the flounder locations on Shot 7 and Shot 1. As required, these upper-bound estimates predict a negligible probability of death and of gill hemorrhaging for the flounder location on Shot 1. They also predict a significant amount of immediate post-shot swimming impairment for flounder at this location. Unfortunately, we did not examine for swimming impairment on Shot 1.

We believe the fit coefficients listed in Table 6-1 represent conservative estimates for the upper-bounds of the injury probabilities to summer flounder, and that the true probabilities lie somewhere between these estimates and lower-bound estimates calculated using the fit coefficients listed in Table 5-1.

Finally, we believe it reasonable to assume that these estimated bounds on the injury probabilities for summer flounder may also apply to the entire "flatfish" order. But, we would be hesitant to extend the assumption to all non-swimbladder fish.

TABLE 6-1. UPPER-BOUND INJURY ESTIMATES FOR FLOUNDER
(Injury Parameter = $\Delta P_{max}/P_o$)

		Fit Coefficients			Parameter Values at Flounder Locations:	
					Shot 7	Shot 1
				Range:	58.3 inches	120.6 inches
				Depth:	25 feet	11 feet
				ΔPmax/Po:	343	180
Observation	Severity	λ'''	μ'''		Calculated Probability	
Swim Response Immediately after Test	Does Not Swim Normally	8.509E+0	1.924		.995	.943
	Does Not Swim	1.219E+1	2.320		.932	.312
	Dead	3.187E+1	2.509		.698	.0003
Hemorrhaging in Gills	Slight	2.774E+1	2.427		.953	.0086
	Considerable	3.360E+1	2.466		.911	.0008
	Severe	3.649E+1	2.506		.741	.0001

SECTION 7

DISCUSSION

AIR BUBBLES

The general observation that the presence of air or gas cavities is of overriding importance in causing underwater explosion injuries to fish and animals is reinforced by the results from these tests. Inevitably, the degree and type of injuries depend on the size and location of the bubble(s). Both external air bubbles and air injected into the gut resulted in severe injuries to the hogchokers. In swimbladder fish, the role of the swimbladder gas cavity is well established.[5,6] Similar results have also been documented in tests with mammals (e.g., Fletcher, Yelverton, and Richmond, 1976).[13] We would expect the presence of air or gas cavities to also be a critical component of the underwater explosion injury process for other untested forms of marine life, such as sea turtles. (Appendix E presents a discussion by one of us on the general problem of injuries to marine life caused by underwater explosions.)

The fact that hogchokers do not have significant gas cavities (larger than approximately 0.1 mm in diameter) is probably the reason for their relative invulnerability to underwater explosions. We suspect that they do, however, have microbubbles of gas smaller than 0.1 mm in diameter distributed throughout their tissues, and that these are the mechanism for the injuries, such as gill hemorrhaging and abnormal swimming behavior, that have been observed on these tests. Gas bubbles of this size would be excited into violent radial oscillation by the shock wave from the explosion. This excitation amounts to a step change in the outside pressure since the oscillation period of these bubbles is large relative to the rise time of the shock, but small relative to its decay time. Under these conditions the amplitude of the bubble oscillation is described as a function of $\Delta P_{max}/P_0$, the ratio of the shock wave peak pressure to the ambient hydrostatic pressure. This was the rationale for hypothesizing the generalized damage parameter, $\Delta P_{max}/P_0$, used to extrapolate the data from these tests to other explosion geometries.

BRAIN HEMORRHAGING

Besides air bubble collapse the only other damage mechanism possibly observed in these tests was differential motion of the otoliths, which may have caused hemorrhaging observed within the cranium. There was considerable variability in this observation. Hemorrhaging due to this mechanism would scale by the damage variable, $\Delta P_{max}/K_0$, where $K_0 = \rho o C_0^2$, which is the bulk modulus of the fishes' tissue; and, ρo is the tissue density, and C_0 is the sound speed in the tissue. (For practical purposes it is sufficient to take these parameter values from the ambient water.) Since K_0 is essentially a constant, the shock wave peak pressure, ΔP_{max}, can be used as the damage parameter for extrapolation of injuries due to this mechanism.

It is important to note that both damage parameters, $\Delta P_{max}/P_0$ and $\Delta P_{max}/K_0$, refer to the pressure behind a shock front, i.e., rise time $\approx 10^{-12}$ sec. In both cases, a slow rise to the same ΔP_{max} will not excite the same damage mechanism.

BRAIN DAMAGE AND MORTALITY

Many species of lower vertebrates (fishes, amphibians, reptiles) are noted for an apparent reluctance to die, even after severe injuries. If kept moist and cool, the isolated heart may continue to beat for hours, stimulated to contract by an intrinsic pacemaker. The part of the brain that is responsible for controlling respiratory movements in fishes is diffuse rather than confined to a delimited area.[14] Extensive damage to the cerebellum and medulla oblongata, the parts of the brain adjacent to the inner ears, is probably necessary to cause immediate cessation of respiratory movements. These two features of the hogchoker physiology may explain why many of the fish continued to live for many hours after the brain had been damaged by an explosion.

EFFECT OF THE BOTTOM

For fish near or resting on the bottom, the presence and nature of the bottom, whether rock, hard shell, sand, or soft mud, might also affect the injury response of the fish in unforeseen ways. Further, we should expect modification of the peak pressure due to the presence of a bottom to influence the injury response. Thus, the results of this study should probably be applied to this problem in terms of the variable, $\Delta P_{max}/P_0$. (See Section 5, "GENERALIZATION OF RESULTS.")

ANGLE OF ATTACK

For Shots 8 through 11, the hogchokers were positioned along a support line eye-side to the charge. (See Figure 2-2.) Taking the forward direction as 0 degree, the attack angles varied between about 40 and 140 degrees. In our analysis, we did not take this variation into account; and, we do not believe it is necessary to do so. However, flounders, hogchokers, and related species normally rest with blind side against the bottom. Thus, for a nonbottom explosion, the direction to the explosion would be off the eye-side and would often be within the range covered by these experiments.

ESTIMATED MAXIMUM RANGE FOR SIGNIFICANT INJURIES

For these hogchoker tests 90 percent of the immediate kill occurred within a radius of 35 inches from the charge. It is obvious, however, that fish at considerably greater ranges received significant injuries and it is of interest to estimate the extent of these injuries. To do this we must make some assumptions. Our basic assumption is that our observation "fish does not swim normally" coincides with the region of "significant injuries." A second assumption is that we can extrapolate our fit to the observations of "does not swim normally" beyond the maximum range of the test data, i.e., beyond 80 inches from the charge. Making these two assumptions, we estimate (using Equations (5-7) and (5-8)) that for these hogchoker tests 90 percent of the significant injuries occurred within a radius of 141 inches from the charge.

APPLICATION OF RESULTS TO OTHER NON-SWIMBLADDER FISH

Many kinds of benthic fish have no swimbladder. There are also many non-swimbladder fish that do not live on the bottom, e.g., many of the tunas and their relatives as well as sharks and some rays.

As this test series was relatively limited in scope, application of the results to other species is speculative. For example, the summer flounder proved to be more sensitive to handling than the hogchokers and many did not survive during the pre-test holding. The limited data on flounders indicate that doubling the immediate kill range determined for hogchokers is not unreasonable. In the previous section, this assumption was generalized in order to estimate outer-bound ranges for mortality and injuries to flounder.

It is likely that many other non-swimbladder fish (possibly, all non-swimbladder fish) are more resistant than the swimbladder fish to injury by explosions. However, without further testing (or understanding of the damage mechanism) it is risky to extrapolate our results to non-swimbladder fish other than the flatfishes (order pleuronectiformes)

KILL RANGES - SWIMBLADDER VS. NON-SWIMBLADDER FISH

Figure 7-1 shows the estimated inner limit and outer limit contours of 10 percent immediate kill probability for flounder, calculated using a 10-pound pentolite charge exploded at 10-foot depth. The inner limit contour is the measured hogchoker result. The curves were calculated from the parameters listed for immediate kill in Tables 5-1 and 6-1 using Equations (5-4), (5-5), (5-7) and (5-8).

Figure 7-2 shows these same contours replotted along with a similar 10 percent kill probability contour calculated for 1-pound swimbladder fish (O'Keeffe (1984), Figure 2)[15] Note that these swimbladder fish are killed out to a horizontal range of 315 feet, which is more than an order of magnitude greater than our upper limit estimate for flounder. Figure 7-3 is a more generalized comparison. It compares the maximum horizontal extent for kill probability contours ranging from 10 to 90 percent calculated for flounder with those calculated for swimbladder fish of various sizes (O'Keeffe (1984), Figures 1, 2, and 3)[15] Note that in all cases, the maximum horizontal extent of the swimbladder fish kill probability contour is more than an order of magnitude greater than the corresponding maximum estimate (outer limit) for flounder.

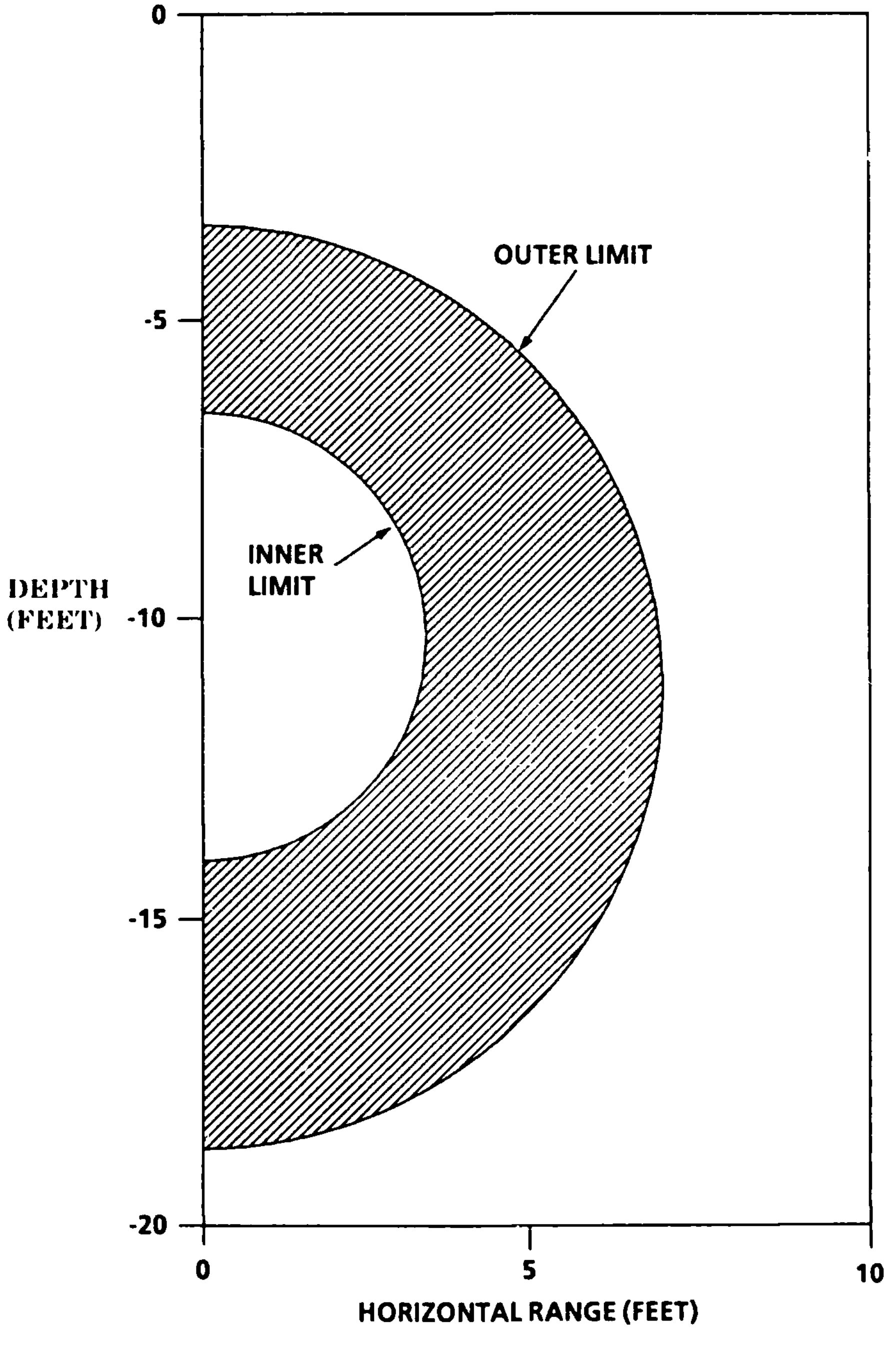

FIGURE 7-1. INNER AND OUTER LIMITS OF 10 PERCENT KILL PROBABILITY CONTOUR FOR FLOUNDER

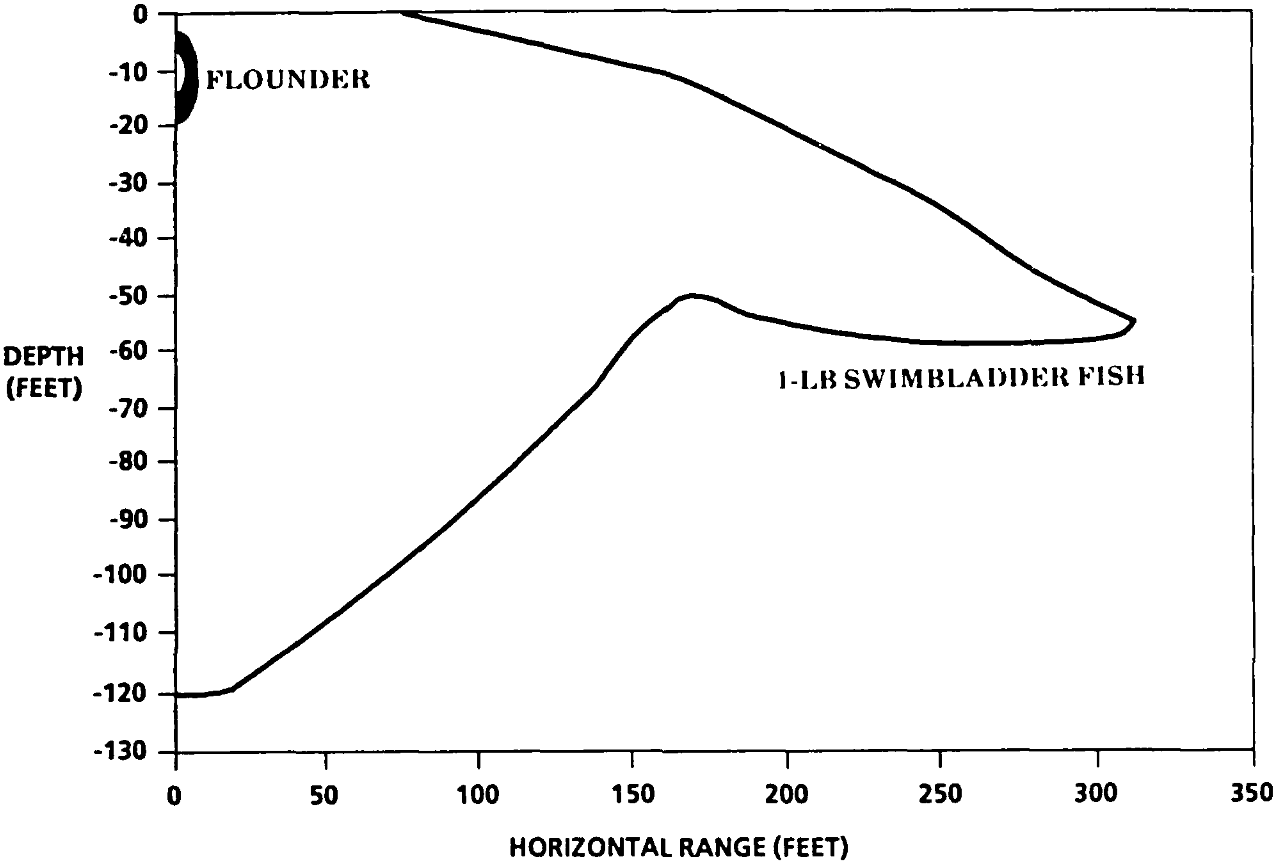

FIGURE 7-2. COMPARISON OF 10 PERCENT KILL PROBABILITY CONTOURS FOR FLOUNDER AND 1-POUND SWIMBLADDER FISH--10-POUND PENTOLITE, 10-FOOT DOB

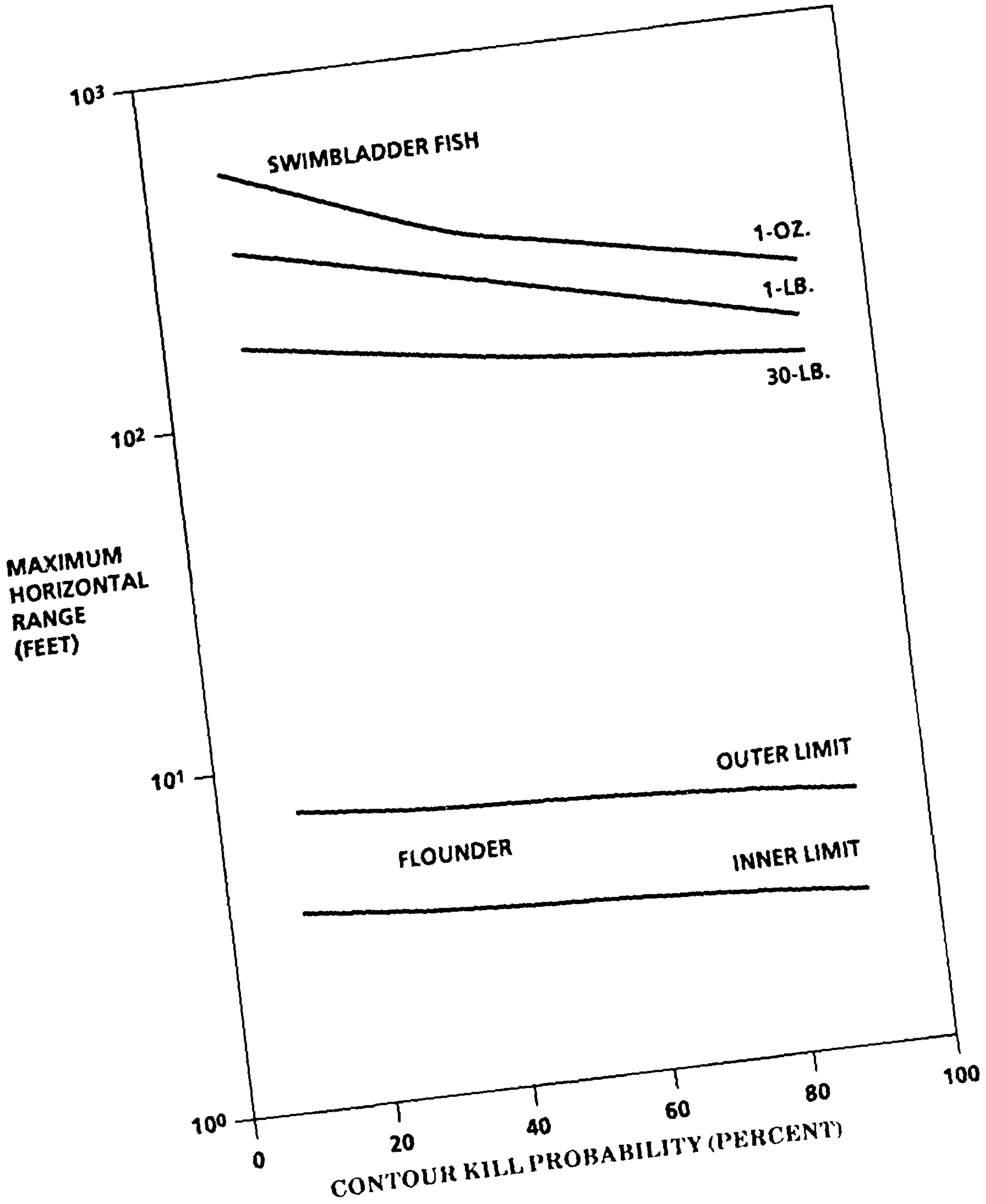

FIGURE 7-3. MAXIMUM HORIZONTAL EXTENT FOR CONTOURS OF CONSTANT KILL PROBABILITY FOR FLOUNDER AND SWIMBLADDER FISH--10-POUND PENTOLITE, 10-FOOT DOB

SECTION 8

CONCLUSIONS

1. Immediate death (both hogchokers and flounder) appeared to be caused by loss of blood resulting from hemorrhaging in the gills. (A more conclusive statement regarding the cause of immediate death would require a larger test sample.) Due to difficulties in keeping these fish alive in holding tanks, no useful data on delayed mortality was obtained.

2. The observed impairment of swimming (hogchokers only) -- which occurred at greater ranges (lower shock wave pressures) than the gill hemorrhaging - did not appear to be directly related to the observed hemorrhaging in the cranium. The cause of this observed abnormal swimming was not determined. It was possibly due to undetected injuries to the brain and/or nervous system.

3. The results presented in this report support the point of view that if precautions are taken to avoid injury to swimbladder fish in test programs, there is little likelihood that fish without bladders will be injured. These precautions usually consist of acoustic surveillance of the area within the 10 percent kill probability range for the smallest swimbladder fish (the most vulnerable) and the avoidance of testing if schools or significant numbers of fish are present.

SECTION 9

RECOMMENDATIONS FOR FUTURE WORK

ADDITIONAL SPECIES OF FISH

As the single species of non-swimbladder fish studied may not be typical, other species of non-swimbladder fish should also be studied.

ADDITIONAL EXPLOSION GEOMETRIES

Practically all of the experimental data was obtained from four replications of a single explosion geometry. The suggested generalization to other explosion geometries should be verified experimentally. For this we will need experimental data from both larger and smaller explosions, and also from tests with fish at greater depths.

IMPROVED STORAGE OF TEST SPECIMENS, SURVIVORS, AND CONTROLS

The high rate of mortality among the controls precluded obtaining useful data on mortality and swim response 24 hours after the tests. To obtain such data, it is essential that techniques for keeping fish alive in a healthy environment be in place before the start of the test series. In particular, attention must be paid to chemical contamination from holding tanks, pumps, and hoses.

REFERENCES

1. Wiley, M. L. and Wilson, J. S., *Environmental Effects of Explosive Testing*, Ref. No. 74-9, Chesapeake Biological Laboratory, Univ. of Md., Nat. Res. Inst, 1974.

2. Gaspin J. B., *Experimental Investigations of the Effects of Underwater Explosions on Swimbladder Fish, I: 1973 Chesapeake Bay Tests*, NSWC/WOL TR 75-58, Naval Surface Weapons Center, Silver Spring, MD, 1975.

3. Wiley, M. L. and Peters, G. B., *Detailed Studies of the Effects of Underwater Explosions on Fish with Observations on Common Invertebrates*, Ref. No. 75-147, Chesapeake Biological Laboratory, Univ. of Md,. Center for Environmental and Estuarine Studies, 1975.

4. Gaspin, J. B., Wiley, M. L., and Peters, G. B., *Experimental Investigations of the Effects of Underwater Explosions on Swimbladder Fish, II: 1975 Chesapeake Bay Tests*, NSWC/WOL/TR 76-61, Naval Surface Weapons Center, Silver Spring, MD, 1976.

5. Goertner, J. F., *Dynamical Model for Explosion Injury to Fish*, NSWC/WOL TR 76-155, Naval Surface Weapons Center, Silver Spring, MD, 1978.

6. Wiley, M.L., Gaspin, J. B. and Goertner, J. F., "Effects of Underwater Explosions on Fish with a Dynamical Model to Predict Fishkill," *Ocean Science and Engineering*, Vol. 6, No. 2, pp. 1981, 223-284.

7. Hubbs, C. L., Schultz, E. P. and Wisner R., Unpublished preliminary report on *Investigation of Effects on Caged Fishes from Underwater Nitro-Carbo-Nitrate Explosions*, U. of Cal. Scripps Institute of Oceanography, 1960.

8. McDonald, W. M., "A Statistical Approach to the Prediction of Dynamic Structural Failure," ASME paper No. 89-OCN-1 4, *Proceedings of the Energy-Sources Technology Conference and Exhibitions*, Houston, TX, 22-25 January 1989.

9. Snedicor, G. W. and Cochran, W. G., *Statistical Methods*, Iowa State University Press, Ames, IA, 1967.

10. Sternberg, H. M. and Hurwitz H., " Calculated Spherical Shock Waves Produced by Condensed Explosives in Air and Water, Table 3," *Proceedings Sixth Symposium (International) on Detonation*, U.S. Government Printing Office, Washington, DC, 1976, p. 537.

REFERENCES (continued)

11. Sternberg, H. M., "Underwater Detonation of Pentolite Cylinders," *Physics of Fluids*, Vol. 30 (3), 1987.

12. Sternberg, H. M., Private Communication, 1986.

13. Fletcher, E. R., Yelverton, J. T., and Richmond, D. R, *The Thoraco-Abdominal System's Response to Underwater Blast*, Report No. LF-55, Lovelace Foundation for Medical Education and Research, Albuquerque, NM, 1976.

14. Shelton G., "The Regulation of Breathing," In W.S. Hoar and D.J. Randall (editors), *Fish Physiology*, Vol. IV, *The Nervous System, Circulation, and Respiration*, Academic Press, NY, 1970, pp. 293-359.

15. O'Keeffe D. J., *Guidelines for Predicting the Effects of Underwater Explosions on Swimbladder Fish*, NSWC TR 82-326, Naval Surface Warfare Center, Silver Spring, MD, 1984.

NOMENCLATURE

Chi Square	Random variable computed from deviations to fit
Degrees of Freedom	Value of the parameter of the chi square distribution associated with tests of goodness-of-fit and independence of attributes
DOB	Depth of burst, i.e., distance from water surface to center of charge
NSWC	Naval Surface Warfare Center
P=50% Range	Range from charge at which probability of occurrence is 50%
P=95% Limit	Magnitude of Chi Square which would be exceeded by random fluctuations 5% of the time
P_0	Ambient hydrostatic pressure (at fish)
ΔP_{max}	Highest overpressure relative to ambient hydrostatic pressure (at fish)
R	Fish distance from charge (measured from center of charge to gill plate on eyed side)
R"	Conservative-estimate range from charge to flounders based on hogchoker data for fish at range, R, along with assumption that flounders at range, R" = 2R, receive the same injuries as hogchokers at range R . The charge and the fish are assumed to be at the same ambient hydrostatic pressure.
R_0	Radius of an equivalent spherical charge (obtained using specified explosive density and the mass of the actual charge)
24-hr Mortality	Fraction of fish dead 24 hours after test
λ, μ	Log-logistic probability distribution parameters for hogchokers (also, flounder lower bound) in terms of range from the charge in inches (10-lb Pentolite, 25-ft DOB)

NOMENCLATURE (continued)

λ', μ'	Log-logistic probability distribution parameters for hogchokers (also, flounder lower bound) in terms of injury parameter, $\Delta P_{max}/P_0$
λ'', μ''	Log-logistic probability distribution parameters for flounder upper bound in terms of range from the charge in inches (10-lb Pentolite, 25-ft DOB)
λ''', μ'''	Log-logistic probability distribution parameters for flounder upper bound in terms of injury parameter, $\Delta P_{max}/P_0$

APPENDIX A

HOGCHOKER DATA FROM PRIOR TEST PROGRAMS

Hogchokers were used as non-swimbladder controls in the 1973 and 1975 Chesapeake Bay tests. The other species tested included spot and white perch. In 1973, four-hundred thirty-seven hogchokers were placed in cages at ranges of 42 to 780 feet; in 1975, one hundred thirty-eight hogchokers were in cages at ranges of 20 to 300 feet.

Since these two sets of test data showed a slight injury to only five of the hogchokers and no injury to the others, even at positions where the spot and white perch received heavy damage, the hogchoker results were not discussed in detail and some of the data were not published.

Table A-1 summarizes the hogchoker data from these two prior test programs. The injuries were evaluated using the damage levels for swimbladder fish developed by Hubbs, Schultz, and Wisner (1960).[A-1] (These damage levels are also listed in the discussion of Shot 1 in Part 2 of this report.) In view of subsequent experience, it seems likely that the five Level 1 injuries to hogchokers recorded on Shots 518 and 519 were artifacts caused by dissection and not injuries from the explosions.

During the 1975 program, 18 hogchokers were placed in a cage on Test 782 at a distance of 300 feet from a 70.4-pound charge. Ten of these had 0.88 ml of air injected into the body cavity and eight were normal specimens. Two of the hogchokers with injected air suffered Level 1 damage (light hemorrhaging) and the rest were not injured.

TABLE A-1. HOGCHOKER DATA FROM 1973 AND 1975 CHESAPEAKE BAY TESTS

(On Shots 521, 532, 524, and 525, a few fish were held for observation of delayed mortality.)

Date	Shot	Charge Weight (lb)	Charge Depth (ft)	Peak Pressure (psi)	Horizontal Distance from Charge (ft)	Cage Depth (ft)	Dissection Results		Delayed Mortality	
							No Damage (No. of Fish)	Level 1 Damage (No. of Fish)	(No. Survivors / No. Fish Held)	Time After Shot
1973 Test Results										
7/16	517	1	5	311	42	5	10			
				321	42	20	10			
				-	118	5	10			
				104	118	20	10			
				64	190	5	10			
7/17	518	8	20	363	82	5	9	1		
				415	82	5	10			
				107	250	5	9	1		
				75	380	10	10	1		
				71	380	20	9	1		
7/18	519	8	40	-	82	5	10			
				267	82	20	10			
				86	250	5	9	1		
				69	380	10	10			
				55	380	20	10			
7/20	521	31	30	360	125	10	10		9/10	24 hrs
				121	370	5	5			
				116	370	18	11			
				-	580	10	5			
				64	678	10	3		3/5	72 hrs
7/23	522	31	30	388	125	10	9			
				125	370	5	5			
				105	370	18	9			
				60	580	10	5			
				69 (?)	700	10	5			
7/24	523	31	15	343	125	10	5			
				99	370	5	5			
				129	370	18	5			
				-	580	10	5			
				40 (?)	700	10	10		10/10	48 hrs
7/27	524	68	40	382	170	10	5			
				118	500	10	5		5/5	68 hrs
				111	500	18	5		5/5	68 hrs
				83	500	40	5			
				61	780	10	5			

Note: "-" indicates that pressure was not recorded.

TABLE A-1. (Continued)

							Dissection Results		Delayed Mortality	
Date	Shot	Charge Weight (lb)	Charge Depth (ft)	Peak Pressure (psi)	Horizontal Distance from Charge (ft)	Cage Depth (ft)	No Damage (No. of Fish)	Level 1 Damage (No. of Fish)	(No. Survivors / No. Fish Held)	Time After Shot
7/30	525	68	70	346	170	10	5			
				104	500	10	5		5/5	20 hrs
				113	500	18	5			
				91	500	40	5			
				62	780	10	5			
8/2	529	1	20	119	110	40	5			
				68	190	5	5			
				62	190	30	5			
				37	262	5	5			
				43	262	30	5			
8/2	530	1	40	123	110	40	5			
				69	190	5	5			
				71	190	30	5			
				42	262	5	5			
				43	262	30	5			
8/3	531	8	40	111	250	10	5			
				75	315	10	5			
				68	380	10	5			
				46	540	10	5			
				29	760	10	5			
8/7	532	200	25*	1679	50	25	2			
				484	110	5	2			
1975 Test Results										
7/10	798	75	27*		20	27	5			
					30	27	5			
					50	27	5			
					100	27	5			
					150	27	5			
					200	27	5			
7/11	799	105	25*		20	25	10			
					30	25	10			
					50	25	10			
					100	25	10			
					150	25	10			
					200	25	10			
					30	5	10			
					50	5	10			
					100	5	10			
5/19	782	70.4	30	170	300	45	8			
						45**	8	2		

---

* Charge resting on bottom.

** These ten hogchokers had 0.88 ml of air injected into the body cavity.

REFERENCE

A-1. Hubbs, C. L., Schultz, E. P., and Wisner, R., Unpublished preliminary report on *Investigation of Effects on Caged Fishes from Underwater Nitro-Carbo-Nitrate Explosions*, U. of Cal. Scripps Institute of Oceanography, 1960.

APPENDIX B

INJURY TO HOGCHOKERS WITH AIR INJECTED INTO ABDOMINAL CAVITY

In Shot 3, nineteen fish were suspended in nylon bags at an average distance of 8.6 inches from the explosive (range 7 to 10.5 inches). Nine fish had 1 cc of air injected into the abdominal cavity with a needle and syringe to simulate the presence of a swimbladder. Of the 11 fish recovered, 7 had not been injected, 3 had been injected, and the other fish had lost its label. All recovered fish were dead and showed obvious damage. All had parts and pieces blown away (especially in the tail region), which was probably caused by the pulsation of air bubbles within the nylon bags or within the mouth. Many fish had small puncture wounds that appeared to result from small pieces of shrapnel. The air-injected fish all had pulverized viscera that would be classified as Level 4 or 5 damage in swimbladder fish. The fish with the label missing was probably one that had been injected with air, since it also had pulverized viscera resembling the type of damage to the fish known to be air-injected. Several of the non-injected fish had gill or heart damage, but, except for one fish, no instances of apparent visceral damage were noted.

In summary, we note that the presence of 1 cc of air injected into the abdominal cavity resulted in complete destruction (pulverization) of the visceral organs, while the viscera of the hogchokers which had not been injected appeared to be undamaged. Although of little quantitative value, this result is a dramatic illustration of the potential of a gas cavity to cause underwater explosion injuries to fish and animals.

APPENDIX C: THEORY AND COMPUTER PROGRAM FOR TESTING INDEPENDENCE OF ATTRIBUTES

In this appendix we develop the theory and computer program used in the text to examine the association between two dichotomous responses, such as mortality (dead or alive) and gill bleeding (hemorrhaging or not hemorrhaging). The intent was to develop a means for determining if the responses observed significantly departed from those that would be expected if the response mechanisms were independent. The usual theory for testing the independence of attributes in 2 x 2 contingency tables does not apply to the data of interest here because all individuals did not receive the same treatment. This was a consequence of the fact that the separations between the fish and the explosive charges varied. Another complication imposed by the data was that there were few or no replications of trials. These features of the data are accounted for in the following theory, which is easily extended to additional classes or outcomes.

We will identify the two response variables by the letters A and B, and denote the two response levels of each variable as A_1, A_2, B_1 and B_2, where A_2 and B_2 are the events complementary to A_1 and B_1. The pairs A_iB_j, i=1,2, j=1,2, denote the four possible unique outcomes of a trial or test of a single individual. It will be convenient to refer to these outcomes by a single index k as follows:

	A_1	A_2
B_1	k=1	k=2
B_2	k=3	k=4

In the mortality (A), gill bleeding (B) example, k=1 would denote dead and hemorrhaging; k=2, alive and hemorrhaging and so forth.

It will be of interest to consider certain groupings of the trials, and we will employ a subscript g to denote the specific group membership. Let δ_{krg} be a binary indicator of the kth outcome in the rth trial of the gth group. That is, we set $\delta_{krg}=1$ if the kth outcome occurs, and $\delta_{krg}=0$ otherwise. Since only one of the outcomes can occur, we have $\sum \delta_{krg}=1$, where the summation is over k. We will allow the test conditions in the rth trial of the gth group to be arbitrary. Hence, as is the case for the data of interest, the trials may be conducted at different ranges. If we denote the probability of the kth outcome in the rth trial of the gth group as p_{krg}, the following relationships hold:

$$\sum_k p_{krg} = 1 \qquad \text{(C-1)}$$

$$E(\delta_{krg}) = p_{krg} \qquad \text{(C-2)}$$

$$\mathrm{Var}(\delta_{krg}) = p_{krg}(1-p_{krg}) \tag{C-3}$$

$$\mathrm{Cov}(\delta_{krg},\delta_{k'r'g'}) = \begin{cases} -p_{krg}\, p_{k'rg} & ,\ r = r',\ g = g' \\ 0 & ,\ \text{otherwise.} \end{cases} \tag{C-4}$$

We wish to devise a test statistic that is χ^2 distributed under the null hypothesis that outcomes are statistically independent. Because we are allowing few or no replications of a particular trial, we can not use the Pearson test statistic that is derived by invoking the usual (Lindberg-Levy) central limit theorm (see C.R. Rao, 1973, p127).[C-1] Instead we must use the Liapunov central limit theorem which requires a different formulation.

Consider the random variables

$$Y_{kg} = [\, n_{kg} - \mu_{kg}] \Big/ \sigma_{kg}, \quad k=1,\ldots,4, \tag{C-5}$$

where $n_{kg} \equiv \sum_{r=1}^{r_g} \delta_{krg}$ is the number of kth outcomes occurring in the gth group,

$$\mu_{kg} = E(n_{kg}) = \sum_{r=1}^{r_g} p_{krg}\ , \tag{C-6}$$

and
$$\sigma_{kg} = \sqrt{\mathrm{Var}(\, n_{kg})} = \left(\sum_{r=1}^{r_g} p_{krg}(\, 1 - p_{krg}) \right)^{1/2} . \tag{C-7}$$

Here, r_g is the total number of test conditions in the gth group. From Equations (C-2), (C-3), and (C-4) we find

$$E(Y_{kg}) = 0, \tag{C-8}$$

$$\mathrm{Var}(Y_{kg}) = 1, \tag{C-9}$$

and
$$\mathrm{Cov}(\, Y_{kg},Y_{k'g'}) = E(Y_{kg}\, Y_{k'g'}) = E\left(\frac{(n_{kg} - \mu_{kg})}{\sigma_{kg}} \quad \frac{(n_{k'g'} - \mu_{k'g'})}{\sigma_{k'g'}} \right)$$

$$= \frac{1}{\sigma_{kg}\sigma_{k'g'}} \Big(E(\, n_{kg}\, n_{k'g'}) - \mu_{kg}\, \mu_{k'g'}\Big) = \begin{cases} \dfrac{-1}{\sigma_{kg}\sigma_{k'g'}} \displaystyle\sum_{r=1}^{r_g} p_{krg} p_{k'rg} & ,\ g = g' \\ 0 & ,\ \text{otherwise.} \end{cases} \tag{C-10}$$

For the gth group, then, the variance-covariance matrix V_g for the outcome variables $Y_{1g}, Y_{2g}, Y_{3g}, Y_{4g}$, has the following form

$$V_g = \begin{bmatrix} 1 & \frac{-1}{\sigma_{1g}\sigma_{2g}} \sum_{r=1}^{r_g} p_{1rg}p_{2rg} & \cdots & \frac{-1}{\sigma_{1g}\sigma_{4g}} \sum_{r=1}^{r_g} p_{1rg}p_{4rg} \\ \frac{-1}{\sigma_{2g}\sigma_{1g}} \sum_{r=1}^{r_g} p_{2rg}p_{1rg} & 1 & \cdots & \frac{-1}{\sigma_{2g}\sigma_{4g}} \sum_{r=1}^{r_g} p_{2rg}p_{4rg} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{-1}{\sigma_{4g}\sigma_{1g}} \sum_{r=1}^{r_g} p_{4rg}p_{1rg} & \frac{-1}{\sigma_{4g}\sigma_{2g}} \sum_{r=1}^{r_g} p_{4rg}p_{2rg} & \cdots & 1 \end{bmatrix} \tag{C-11}$$

V_g is of rank 3 since there is a row vector $\lambda' = (\sigma_{1g}, \sigma_{2g}, \sigma_{3g}, \sigma_{4g})$ such that $\lambda' V_g = 0$. This is easily seen by direct multiplication and the use of Equation (C-1).

It has been shown (McDonald, 1989)$^{C\text{-}2}$ that the distribution of random variables of the form Y_{kg} tends to a normal distribution as $r_g \to \infty$, by virtue of the Liapunov central limit theorem. Then it follows from the multivariate central limit theorem (see C.R. Rao, 1973, p128)$^{C\text{-}1}$ that the distribution of the vector $(Y_{1g}, Y_{2g}, Y_{3g}, Y_{4g})'$ tends to a multivariate singular normal distribution with mean 0 and variance-covariance matrix V_g^{∞}, which denotes the limiting form of V_g. Furthermore, it follows that the distribution of the reduced vector $\underline{Y}_g^* = (Y_{1g}, Y_{2g}, Y_{3g})'$ is approximately (nonsingular) multivariate normal with mean 0 and variance-covariance matrix V_g^* of full rank obtained by deleting the last row and column of V_g.

Suppose we have a total of γ groups, and we define the complete reduced response vector as $\underline{Y}^* = (\underline{Y}_1^*, \underline{Y}_2^*, \ldots, \underline{Y}_\gamma^*)$; then $\underline{Y}^*$ is approximately multivariate normal with mean 0 and variance-covariance matrix

$$V^* = \text{Block Diag}\,(V_1^*, V_2^*, \ldots, V_\gamma^*) \tag{C-12}$$

of rank 3γ. Consequently, we find (see Searle, 1971, p.57)$^{C\text{-}3}$ that the quadratic form

$$\begin{aligned} X^2 &= \underline{Y}^{*\prime} V^{*-1} \underline{Y}^* \\ &= \sum_{g=1}^{\gamma} \underline{Y}_g^{*\prime} V_g^{*-1} \underline{Y}_g^* \end{aligned} \tag{C-13}$$

is approximately χ^2 distributed with 3γ degrees of freedom. This statistic shall be the basis of the test for independence.

To conduct a test of the independence hypothesis we must calculate the outcome probabilities under the assumption of independence and from these calculate X^2. If we let $P(A_1|r,g)$ denote the probability of response A_1 for the rth trial of the gth group, and let $P(B_1|r,g)$ denote the probability for response B_1, we can express the outcome probabilities under the assumption of independence as

$$\begin{aligned} p_{1rg} &= P(A_1|r,g)\,P(B_1|r,g) \\ p_{2rg} &= P(A_1|r,g)\,(1-P(B_1|r,g)) \\ p_{3rg} &= (1-P(A_1|r,g))\,P(B_1|r,g) \\ p_{4rg} &= (1-P(A_1|r,g))\,(1-P(B_1|r,g)). \end{aligned} \tag{C-14}$$

This, of course, makes use of the fact that responses A_2 and B_2 are the complementary events. Maximum likelihood estimates of the outcome probabilities, under the independence hypothesis, can thus be obtained from the maximum likelihood estimates of the marginal response probabilities as presented in the text (Tables 3-3 and 4-1).

The theory of the ordinary χ^2 test (see e.g., Kendall and Stuart, 1973, chapter 30)[C-4] shows that if the expected numbers of outcomes per group are large enough and the test hypothesis true, the X^2 statistic is approximately distributed according to a χ^2 distribution with between 3γ-ν and 3γ degrees of freedom, where ν is the number of parameters estimated from the data (such as λ and μ of Equation (1) in the text). In general terms, it is expected that much of the theory and practice used in the ordinary χ^2 test should be valid for the present test. The conservative test of the independence hypothesis is carried out by comparing the value of X^2 with a selected percentile (such as the 5th) of the $\chi^2(3\gamma\text{-}\nu)$ distribution, the corresponding percentile of the $\chi^2(3\gamma)$ distribution always being larger. The hypothesis of independence is rejected if X^2 exceeds this percentile. The manner in which the data should be grouped is somewhat arbitrary. In the present application at least two groups must be used since four parameters are estimated. The maximum number of groups should not be so large that the expected number μ_{kg} of each of the four outcomes becomes too small. In the present study we used two groups with the fish of Shots 8 and 9 in group 1 and those of Shots 10 and 11 in group 2. This grouping scheme resulted in reasonable expectations per group and seemed preferable to a grouping based on the fish's range from the explosion.

COMPUTER PROGRAM

FOR

TESTING INDEPENDENCE OF ATTRIBUTES

```
      PROGRAM CTA
C  CTA CALCULATES A CHI SQUARE TEST STATISTIC BASED ON THE THEORY
C  PRESENTED IN APPENDIX E OF NSWC TR 88-114
      REAL LAMDA1, MU1, LAMDA2, MU2
      INTEGER R(2)
      DIMENSION NSHOT(100),NFISH(100),LEVELS(100,7),RANGE(100),
     1 PP(100,2),LA(100),P(4,50,2),EY(4,2),NUM(4,2),YS(3,2),VS(3,3,2),
     2 VSI(3,3,2),SIGY(4,2)
C
C READ IN FISH RESPONSE DATA AND RANGES
      OPEN(1,FILE='DATA',STATUS='OLD')
      N=0
   10 N=N+1
      READ(1,20,END=50)
     1 NSHOT(N),NFISH(N),(LEVELS(N,L),L=1,7),RANGE(N),AFISH
   20 FORMAT(9I5,F5.1,A10)
      NN=N
      GO TO 10
   50 CLOSE(1)
C
C READ PARAMETER MLES AND RESPONSE DATA; CALCULATE PROBABILITIES
C
      WRITE(*,*) 'ENTER LAMBDA, MU, 1ST ATTRIBUTE INDEX, & LEVEL'
      READ (*,*) LAMDA1, MU1, ICAT1, LEV1
      IF(LAMDA1.GE.0.) THEN
        WRITE(*,*) 'ENTER CONSTANT PROBABILITY VALUE'
        READ(*,*) PROB1
      ENDIF
      DO 100 N=1,NN
        IF(LAMDA1.GE.0.) THEN
          PP(N,1)=PROB1
        ELSE
          PP(N,1)=1./(1.+EXP(-LAMDA1*(LOG10(RANGE(N))-MU1)))
        ENDIF
  100 CONTINUE
C
      WRITE(*,*) 'ENTER LAMBDA, MU, 2ND ATTRIBUTE INDEX, & LEVEL'
      READ (*,*) LAMDA2, MU2, ICAT2, LEV2
      IF(LAMDA2.GE.0.) THEN
        WRITE(*,*) 'ENTER CONSTANT PROBABILITY VALUE'
        READ(*,*) PROB2
      ENDIF
      DO 110 N=1,NN
        IF(LAMDA2.GE.0.) THEN
          PP(N,2)=PROB2
        ELSE
          PP(N,2)=1./(1.+EXP(-LAMDA2*(LOG10(RANGE(N))-MU2)))
        ENDIF
  110 CONTINUE
C
C CALCULATE OUTCOME NUMBERS AND PROBABILITIES FOR GROUPS
      R(1)=0
      R(2)=0
```

```
      DO 120 K=1,4
      DO 120 IG=1,2
      NUM(K,IG)=0.
  120 CONTINUE
      DO 130 N=1,NN
      IF(LEVELS(N,ICAT1).EQ.-1 .OR. LEVELS(N,ICAT2).EQ.-1) GO TO 130
      IF(NSHOT(N).EQ.8 .OR. NSHOT(N).EQ.9) THEN
        IG=1
      ELSEIF(NSHOT(N).EQ.10 .OR. NSHOT(N).EQ.11) THEN
        IG=2
      ENDIF
      IF(LEVELS(N,ICAT1).GE.LEV1) THEN
        IF(LEVELS(N,ICAT2).GE.LEV2) THEN
          K=1
        ELSE
          K=3
        ENDIF
      ELSE
        IF(LEVELS(N,ICAT2).GE.LEV2) THEN
          K=2
        ELSE
          K=4
        ENDIF
      ENDIF
      NUM(K,IG)=NUM(K,IG)+1
      R(IG)=R(IG)+1
      IR=R(IG)
      P(1,IR,IG)=PP(N,1)*PP(N,2)
      P(2,IR,IG)=(1.-PP(N,1))*PP(N,2)
      P(3,IR,IG)=PP(N,1)*(1.-PP(N,2))
      P(4,IR,IG)=(1.-PP(N,1))*(1.-PP(N,2))
  130 CONTINUE
C
C CALCULATE GROUP MEANS AND STANDARD DEVIATIONS
      DO 150 IG=1,2
      DO 150 K=1,4
      EY(K,IG)=0.
      VARY=0.
      IRF=R(IG)
      DO 140 IR=1,IRF
        EY(K,IG)=EY(K,IG)+P(K,IR,IG)
        VARY=VARY+P(K,IR,IG)*(1.-P(K,IR,IG))
  140 CONTINUE
      SIGY(K,IG)=SQRT(VARY)
  150 CONTINUE
      WRITE(*,*) '      OBS RESPONSES, EST MEANS AND STD DEVIATIONS'
      WRITE(*,*) 'OUTCOME      GROUP 1                      GROUP2'
      WRITE(*,'(I5,I10,2F10.5,I10,2F10.5)')
     1 (K,(NUM(K,IG),EY(K,IG),SIGY(K,IG),IG=1,2),K=1,4)
C
C CALCULATE REDUCED RESPONSE VECTOR
      DO 160 K=1,3
      DO 160 IG=1,2
```

```
      YS(K,IG)=(NUM(K,IG)-EY(K,IG))/SIGY(K,IG)
  160 CONTINUE
C
C CALCULATE REDUCED VARIANCE-COVARIANCE MATRICES
      DO 180 IG=1,2
      DO 180 KR=1,3
      DO 180 KC=1,KR
        IF(KC.EQ.KR) THEN
          VS(KR,KC,IG)=1.
          GO TO 180
        ENDIF
        SUM=0.
        IRF=R(IG)
        DO 170 IR=1,IRF
          SUM=SUM+P(KR,IR,IG)*P(KC,IR,IG)
  170   CONTINUE
        VS(KR,KC,IG)=-SUM/SIGY(KR,IG)/SIGY(KC,IG)
        VS(KC,KR,IG)=VS(KR,KC,IG)
  180 CONTINUE
C
C INVERT REDUCED VARIANCE COVARIANCE MATRICES
      DO 200 IG=1,2
      CALL INVERT(VSI(1,1,IG),VS(1,1,IG))
  200 CONTINUE
C
C CALCULATE TEST STATISTIC AND PRINT
      X2=0.
      DO 220 IG=1,2
      DO 220 KR=1,3
      DO 220 KC=1,3
        X2=X2+YS(KR,IG)*VSI(KR,KC,IG)*YS(KC,IG)
  220 CONTINUE
      WRITE(*,*) 'TEST STATISTIC (2 DOF) = ', X2
      STOP
      END
C
C
C
      SUBROUTINE INVERT(AI,A)
      DIMENSION AI(3,3),A(3,3)
      DET=A(1,1)*A(2,2)*A(3,3)+A(2,1)*A(3,2)*A(1,3)+A(3,1)*A(2,3)*A(1,2)
     1 -A(1,3)*A(2,2)*A(3,1)-A(2,3)*A(3,2)*A(1,1)-A(3,3)*A(2,1)*A(1,2)
      AI(1,1)= (A(2,2)*A(3,3)-A(2,3)*A(3,2))/DET
      AI(2,1)=-(A(1,2)*A(3,3)-A(1,3)*A(3,2))/DET
      AI(1,2)= AI(2,1)
      AI(2,2)= (A(1,1)*A(3,3)-A(1,3)*A(3,1))/DET
      AI(3,1)= (A(1,2)*A(2,3)-A(1,3)*A(2,2))/DET
      AI(1,3)= AI(3,1)
      AI(3,2)=-(A(1,1)*A(2,3)-A(1,3)*A(2,1))/DET
      AI(2,3)= AI(3,2)
      AI(3,3)= (A(1,1)*A(2,2)-A(1,2)*A(2,1))/DET
      RETURN
      END
```

REFERENCES

C-1. Rao, C. R., Linear Statistical Inference and Its Applications, 2nd Edition, John Wiley & Sons, Inc., NY, 1973.

C-2. McDonald, W. W., "A Statistical Approach to the Prediction of Dynamic Structural Failure," ASME paper No. 89-OCN-14, Proceedings of the Energy Sources Technology Conference and Exhibitions, Houston, TX, 22-25 Jan 1989.

C-3. Searle, S. R., Linear Models, John Wiley & Sons, Inc., NY, 1971.

C-4. Kendall, M. G., and Stuart, A., The Advanced Theory of Statistics, 3rd Edition, Vol. 2, Charles Griffin and Co. Ltd. London, 1973, Chap 30.

APPENDIX D

HOGCHOKER DATA BASE

Table D-1 lists the data base summarizing measured data; observations of mortality, injuries and swimming behavior; and dissection notes recorded for Tests 4 through 11. Table D-2 provides more detailed explanations of the column headings of Table D-1. Tables D-3 through D-9 provide the meanings of the comment abbreviations used in Table D-1

The hogchoker data base (Table D-1) was compiled using the data base program, D-Base 2, on a 64K CPM personal computer. The hogchoker data base was the starting point for almost all of the quantitative results presented in this report, e.g., Tables 4-1 and 5-1 and also the input data to the maximum-likelihood fits.

TABLE D-1. HOGCHOKER DATA BASE

						Dissection				
Shot/ Fish	Range (in.)	Post-Shot Swimming Response	24-hour Swimming Response	Sex	Length (mm)	Month: Day	Hour: Minute	Pre-Shot Condition	External Injuries	Miscellaneous Comments
4 2	23.0	DEAD	DEAD	M	103	9:19	13:13	NoComment	PrtTFnGn1 SmSknHms1	DamLevl:1
4 3	20.5	DEAD	DEAD	xx2	93	9:19	13:03	NoComment	BigScrape ScrpdGIPl	DamLevl:2 GilsWyte1
4 5	17.8	DEAD	DEAD	xx2	95	9:19	12:40	NoComment	SmSkinHms SplitSkin	DamLevl:1 GilsPale
4 7	18.2	DEAD	DEAD	F	92	9:19	12:55	NoComment	PrtTylGon BrzOvrVis SmPunct:2	DamLevl:1 GilsPale OneEyeFsh
4 9	21.6	DEAD	DEAD	F	122	9:19	12:45	NoComment	MstTFnGon OnlyExtDm	DamLevl.1 GilsPale
5 1	45.1	DEAD	DEAD	F	141	9:20	14:18	NoComment	PrtTFnGon PcsDFnGon	NoComment
5 2	37.4	Swm:Fltrs	DEAD	xx2	115	9:23	13:41	NoComment	NoEval:6	NoComment
5 3	33.3	DEAD	DEAD	M	83	9:20	14:43	NoComment	PrtJawGon PnctNrAFn SlDamDFn	NoComment
5 4	30.5	DEAD	DEAD	F	140	9:20	11:55	NoComment	SmPnctWnd	NoComment
5 5	29.0	DEAD	DEAD	M	121	9:20	11:45	NoComment	SevBruise	NoComment
5 7	29.6	DEAD	DEAD	M	108	9:20	14:05	NoComment	TylDnuded Contusion	NoComment
5 8	30.5	DEAD	DEAD	xx2	130	9:20	12:20	NoComment	SmPunct:1 HlfTFnGon	NoComment

TABLE D-1. (Continued)

Shot/ Fish	Gill Injuries	Visceral Injuries	Heart Beating?	Heart Injuries	Brain Injuries	Blood in Orbit?	Otolith Hemorrhaging?
4 2	Severe Hemrgd:Bo	Considrbl IntestHem	Yes	OK:6	NoEval:7	NoEval:7	NoEval:7
4 3	Severe Hemrgd:Bo BldVsDam1	NoCom:1 GallBlBkn	NoComment	OK:7 NoBldNHrt	NoEval:7	NoEval:7	NoEval:7
4 5	Slight Hemrgd:Es	OK:4	Yes	OK:4	NoEval:7	NoEval:7	NoEval:7
4 7	Slight Hemrgd:Bs	OK:4	Yes	Severe BldNHrtSk	NoEval:7	NoEval:7	NoEval:7
4 9	Slight Hemrgd:Es	OK:4	YesSlytly	OK:4	NoEval:7	NoEval:7	NoEval:7
5 1	Considrbl Hemrgd:Es HemCovrEs	NoComment	Yes	Considrbl BldNHrtSk MicroExam	NoEval:7	NoEval:7	NoEval:7
5 2	NoEval:4	NoEval:4	NoEval:7	NoEval:7	Considrbl BldNBcase	NoEval:7	NoEval:8
5 3	Considrbl Hemrgd:Bo	Severe BldNGut:1	Yes	OK:6	NoEval:7	NoEval:7	NoEval:7
5 4	Slight PctDamEs2 HemCovrEs	Slight LvHmPelFn	Yes	Severe BldNHrtSk BldNSak:2	NoEval:7	NoEval:7	NoEval:7
5 5	Considrbl Hemrgd:XX PctDamXX1	OK:4	Yes	OK:4	NoEval:7	NoEval:7	NoEval:7
5 7	Severe Hemrgd.Bo HemCovrEs	Slight LvHmsOnBs	NoComment	OK NoClots	NoEval:7	NoEval:7	NoEval:7
5 8	Considrbl Hemrgd:Bo	Considrbl LvHmPelFn	Yes	Severe BldNHrtSk BldClot:4	NoEval:7	NoEval:7	NoEval:7

TABLE D 1. (Continued)

Shot/ Fish	Range (in.)	Post-Shot Swimming Response	24-hour Swimming Response	Sex	Length (mm)	Dissection Month: Day	Dissection Hour: Minute	Pre-Shot Condition	External Injuries	Miscellaneous Comments
5 9	35.4	DEAD	DEAD	F	109	9:20	12:03	NoComment	SmPnctDFn	NoComment
5 10	44.4	Swm:Norml	Swm:Circl	F	109	9:23	13:43	NoComment	NoEval:6	NoComment
6 1	58.3	Swm:Circl	Swm:Abnor	F	119	9:23	13:50	BactInf:3	None	NoComment
6 2	48.0	NoComment	DEAD	F	143	9:20	15:11	NoComment	MstTFnGon PtDrFnGon	NoComment
6 3	43.0	NoComment	Swm:Abnor	xx2	85	9:23	14:19	NoComment	SmHmAtAFn	NoComment
6 4	39.5	DEAD	DEAD	xx2	110	9:20	14:55	BactInf:2	BrusdHead	GilDamNly
6 5	37.3	NoComment	Swm:NoMoo	xx2	94	9:23	14:26	NoComment	HemNrTail ThrdTFnGn PtDFnGon1	GilsPink
6 6	37.3	Swm:NoMoo	DEAD	F	105	9:20	15:45	NoComment	BldySpot1 HlfTFnGon	NoComment
6 7	38.3	DEAD	DEAD	F	119	9:20	15:01	NoComment	BldySpot2 FinWnds1 PnctWnds1	NoComment
6 8	41.0	DEAD	DEAD	M	97	9:20	15:23	NoComment	PrtTFnGn2 OnlyExtDm	HtNGlsCOD
6 9	45.8	NoComment	Swm:Norml	F	112	9:23	14:43	NoComment	PrtTFnGn3	FishAlive MovinGils
6 10	58.3	NoComment	NoComment	xx2	86	9:23	14:50	NoComment	Abrasions	NoComment

TABLE D-1. (Continued)

Shot/ Fish	Gill Injuries	Visceral Injuries	Heart Beating?	Heart Injuries	Brain Injuries	Blood in Orbit?	Otolith Hemorrhaging?
5 9	Considrbl Hemrgd:XX CantSeSrc	OK:5	YesSporat	Severe BldNHrtSk BldClot:3	NoEval:7	NoEval:7	NoEval:7
5 10	OK	OK	NoEval:7	NoEval:7	Considrbl BldNBcase	NoEval:7	NoEval:8
6 1	OK	OK	NoComment	NoEval:7	Slight BldNBcase	NoEval:7	NoEval:8
6 2	Severe Hemrgd:Bo	NoComment	Yes	OK NoClots	Considrbl BldNBcase BldVsDm:1	NoEval:7	NoEval:8
6 3	OK:3	Slight LvHmPelFn BoneyRegn	NoComment	NoEval:7	Considrbl BldNBcase	NoEval:7	NoEval:8
6 4	Slight Hemrgd:Bo HemCovrEs	NoComment	Yes	OK NoClots	NoEval:7	NoEval:7	NoEval:7
6 5	OK	OK	NoComment	NoEval:7	Considrbl BldNBcase	NoEval:7	NoEval:8
6 6	OK:2	Considrbl LvHmPelFn	NoComment	Severe BldNHrtSk HrtDamgd	Considrbl BldNBcase BldVesBkn	NoEval:7	NoEval:8
6 7	Slight HmNJnt:Bs	OK	Yes	OK NoClots	Considrbl BldNBcase CausODeth	NoEval:7	NoEval:8
6 8	Considrbl Hemrgd:Bo	Considrbl BldInGut	NoComment	Severe BldNHrtSk FrothyBub	OK SeemsNorm NoBigClot	NoEval:7	NoEval:8
6 9	OK	NoComment	NoComment	OK	OK	NoEval:7	NoEval:8
6 10	Slight Hemrgd:Es	OK	NoComment	OK	OK	NoEval:7	NoEval:8

TABLE D 1. (Continued)

Shot/ Fish	Range (in.)	Post-Shot Swimming Response	24-hour Swimming Response	Sex	Length (mm)	Dissection Month: Day	Dissection Hour: Minute	Pre-Shot Condition	External Injuries	Miscellaneous Comments
7 2	47.3	DEAD	DEAD	F	116	9:23	16:22	NoComment	HlfTFnGon HlfAFnGon	NoComment
7 3	42.4	NoComment	NoComment	F	110	9:24	15:32	NoComment	TailGone	GilsPale3
7 4	38.8	DEAD	DEAD	xx2	120	9:23	16:32	NoComment	PtBdyGon1	NoComment
7 5	36.8	NoComment	DEAD	xx2	111	9:24	15:40	NoComment	HlfTFnGon ThrdAFnGn	NoComment
7 6	36.8	NoComment	NoComment	F	100	9:24	15:55	NoComment	PtBdyGon2	NoComment
7 7	38.6	NoComment	NoComment	M	115	9:24	16:04	NoComment	TailGone BdyMasrtd	GilsPale DedAwile1
7 8	41.1	DEAD	DEAD	F	123	9:23	16:44	NoComment	HlfTFnGon	NoComment
7 9	46.4	NoComment	DEAD	F	130	9:24	16:14	NoComment	MstTFnGon	NoComment
8 1	56.9	Swm:NoMoo	Swm:Norml	F	136	9:25	15:01	NoComment	None	FishAlive
8 2	47.0	Swm:Abnor	DEAD	F	107	9:25	15:13	NoComment	None	DeadAwile
8 3	42.0	Swm:Abnor	Swm:NoMoo	M	134	9:25	15:18	NoComment	None	NoComment
8 4	38.3	Swm:Abnor	Swm:NoMoo	xx2	139	9:25	15:30	NoComment	None	NoComment
8 5	36.4	Swm:NoMoo	Swm:Abnor	F	133	9:25	15:44	NoComment	None	NoComment

TABLE D-1 (Continued)

Shot/ Fish	Gill Injuries	Visceral Injuries	Heart Beating?	Heart Injuries	Brain Injuries	Blood in Orbit?	Otolith Hemorrhaging?
7 2	Severe Hemrgd:Bo	OK	Yes	Considrbl BldNHrtSk	Considrbl BldNBcase BldClot:1	NoEval:7	NoEval:8
7 3	OK	OK	NoComment	OK	Considrbl BldNBcase Old:frSht	NoEval:7	NoEval:8
7 4	Severe PctDamEs1	OK	NoComment	Considrbl BldNHrtSk	Considrbl BldNBcase AirBubbs	NoEval:7	NoEval:8
7 5	Considrbl Hemrgd:Bo HemCovrEs	Considrbl LvHmPelFn	NoComment	OK	Considrbl BldNBcase	NoEval:7	NoEval:8
7 6	Considrbl Hemrgd:Es HemCovrBs	OK	Yes	Considrbl BldNHrtSk	Considrbl BldNBcase	NoEval:7	NoEval:8
7 7	Considrbl HemrgdEs1	NoEval:6	Yes	OK NoClots	Considrbl BldNBcase Hemrage:G	NoEval:7	NoEval:8
7 8	Severe Hemrgd:Bo	OK	Yes	Slight BldNHrtSk BldClts:T	Severe BldNBcase	NoEval:7	NoEval:8
7 9	Considrbl Hemrgd:Bo HemCovrBs	OK	NoComment	OK NoClots	OK	NoEval:7	NoEval:8
8 1	OK	OK	Yes	OK	Severe BldNBcase	NoEval:7	NoEval:8
8 2	NoEval:4	NoEval:4	No	OK	Considrbl BldNBcase	NoEval:7	NoEval:8
8 3	OK	OK	Yes	OK	Severe BldNBcase BldVsDm:2	NoEval:7	NoEval:8
8 4	OK	OK	Yes	OK	NoEval:5	NoEval:7	NoEval:8
8 5	Slight Hemrgd:Es	OK	Yes	OK	NoEval:5	NoEval:7	NoEval:8

TABLE D-1. (Continued)

						Dissection				
Shot/ Fish	Range (in.)	Post-Shot Swimming Response	24-hour Swimming Response	Sex	Length (mm)	Month: Day	Hour: Minute	Pre-Shot Condition	External Injuries	Miscellaneous Comments
8 6	36.5	Swm:Circl	Swm:Norml	M	143	9:25	15:54	NoComment	None	NoComment
8 7	37.9	Swm:Circl	Swm:Norml	M	117	9:25	16:08	NoComment	None	NoComment
8 8	40.8	Swm:NoMoo	DEAD	F	140	9:25	16:17	BactInf:1	None	GilsPink1
8 9	46.0	Swm:Circl	DEAD	F	131	9:25	16:23	NoComment	None	NoComment
8 10	57.5	Swm:Abnor	DEAD	F	127	9:25	16:35	NoComment	None	DeadAwile Stiff GilsWhite
9 1	46.7	Swm:Circl	Swm:Circl	F	143	9:25	16:43	NoComment	None	FishAlive Anesthtzd
9 2	38.2	Swm:NoMoo	DEAD	F	127	9:25	16:54	BactInf:1	None	DeadAwile GilsPale
9 3	34.2	NoComment	Swm:NoMoo	F	135	9:25	17:02	NoComment	None	FishAlive Anesthtzd
9 4	31.2	DEAD	DEAD	xx2	132	9:24	14:19	NoComment	None	NoComment
9 5	29.7	NoComment	DEAD	F	123	9:25	17:12	NoComment	None	DeadAwile GilsPale
9 6	29.6	DEAD	DEAD	F	128	9:24	14:36	NoComment	None	NoComment
9 7	30.6	DEAD	DEAD	F	125	9:24	14:49	NoComment	None	NoComment
9 8	32.6	DEAD	DEAD	F	117	9:24	15:17	NoComment	None	NoComment

TABLE D-1. (Continued)

Shot/ Fish	Gill Injuries	Visceral Injuries	Heart Beating?	Heart Injuries	Brain Injuries	Blood in Orbit?	Otolith Hemorrhaging?
8 6	OK	Considrbl LvHmPelFn OthrVisOK	Yes	OK	Severe BldNBcase BledFish	NoEval:7	NoEval:8
8 7	OK	Considrbl LvHmPelFn	NoEval:6	NoEval:6	Severe BldNBcase	NoEval:7	NoEval:8
8 8	OK	OK	NoComment	OK NoClots	Considrbl BldNBcase LsThnFsh7	Yes:1	NoEval:8
8 9	OK	OK	NoComment	Considrbl BldNHrtSk Hemrage:F	Considrbl BldNBcase	No:NoCom	NoEval:8
8 10	OK	OK	NoComment	Considrbl BldNHrtSk Hemrage:E	Considrbl BldNBcase BrnMushy1	Yes	NoEval:8
9 1	OK	OK	Yes	OK	Considrbl BldNBcase BledFish	No	NoEval:8
9 2	OK	OK	NoComment	NoEval:3	Severe BldNBcase BrnMushy2	Yes	NoEval:8
9 3	Slight Hemrgd:XX	OK	Yes	OK NoClots	OK	No:NoCom	NoEval:8
9 4	Considrbl Hemrgd:Es	Slight LvHmPelFn	Yes	OK	Considrbl BldNBcase	NoEval:7	NoEval:8
9 5	Severe Hemrgd:Bo	OK	No	Considrbl BldNHrtSk ProbDam:1	Considrbl BldNBcase	No:NoCom	NoEval:8
9 6	Considrbl Hemrgd:Bo	Slight LvHmPelFn	Yes	OK	Considrbl BldNBcase	NoEval:7	NoEval:8
9 7	Severe Hemrgd:Bo HmNJnt:Es	Severe BldNGut:2 LvHms	Yes	Severe BldNHrtSk Damaged:1	OK SeemsNorm TinyClots	NoEval:7	NoEval:8
9 8	Severe Hemrgd:Bo PctDamEs3	OK	Yes	Considrbl BldNHrtSk	Considrbl BldNBcase	NoEval:7	NoEval:8

TABLE D-1. (Continued)

Shot/ Fish	Range (in.)	Post-Shot Swimming Response	24-hour Swimming Response	Sex	Length (mm)	Dissection Month: Day	Dissection Hour: Minute	Pre-Shot Condition	External Injuries	Miscellaneous Comments
9 9	36.6	Swm:Curls	Swm:NoMoo	F	129	9:25	17:23	NoComment	None	FishAlive Anesthtzd GilsPale
9 10	45.2	Swm:Curls	Swm:Circl	xx2	165	9:25	17:36	NoComment	None	FishAlive Anesthtzd
10 1	46.5	Swm:NoMoo	Swm:Circl	F	112	9:26	11:39	NoComment	None	NoComment
10 2	42.1	Swm:Circl	DEAD	F	111	9:26	11:51	NoComment	None	DeadAwile GilsPink
10 3	38.6	Swm:Fltrs	Swm:Abnor	M	107	9:26	11:58	NoComment	None	NoComment
10 4	34.6	Swm:NoMoo	Swm:Fltrs	F	118	9:26	12:07	NoComment	None	NoComment
10 5	31.6	DEAD	DEAD	F	115	9:26	12:16	NoComment	None	Stiff OnIce25hr
10 6	30.2	NoComment	Swm:Fltrs	F	105	9:26	12:30	NoComment	None	NoComment
10 7	30.2	Swm:NoMoo	DEAD	M	104	9:26	13:04	NoComment	Dscolratn	GlsDcmpsd GilsMushy
10 8	31.0	Swm:NoMoo	DEAD	F	114	9:26	13:14	NoComment	None	DeadAwile GilsWhite Note2
10 9	32.8	Swm:NoMoo	DEAD	F	117	9:26	13:21	NoComment	SplitAnFn	DeadAwile GilsPale
10 10	36.9	Swm:Curls	Swm:Curls	F	113	9:26	13:30	NoComment	None	NoComment
10 11	40.4	Swm:Circl	Swm:Abnor	xx1	112	9:26	13:43	NoComment	None	Note1

TABLE D-1. (Continued)

Shot/ Fish	Gill Injuries	Visceral Injuries	Heart Beating?	Heart Injuries	Brain Injuries	Blood in Orbit?	Otolith Hemorrhaging?
9 9	Considrbl HemCovrBs	Considrbl LvHmPelFn	Yes	Slight BldNHrtSk MinorHem1	Considrbl BldNBcase	No:NoCom	NoEval:8
9 10	OK SmHemTung	OK	Yes	OK	Considrbl BldNBcase	No:NoCom	NoEval:8
10 1	OK	OK	Yes	OK	Considrbl BldNBcase	No:NoCom	NoEval:8
10 2	OK	OK	No	OK	Considrbl BldNBcase	No:NoCom	NoEval:8
10 3	OK	Considrbl LvHmPelFn	Yes	OK	Considrbl BldNBcase BldNFluid	No:NoCom	NoEval:8
10 4	OK	OK	Yes	OK	Considrbl BldNBcase	No:NoCom	NoEval:8
10 5	Severe Hemrgd:Bo	OK	YesSlowly	OK	Massive BldNBcase	No:NoCom	NoEval:8
10 6	OK	OK	Yes	OK	Severe BldNBcase	Yes	NoEval:8
10 7	Severe DamgdBo:1 HemCovrBs	Slight LvHmPelFn	No	OK	Severe BldNBcase	Yes	xxHemrgOt
10 8	Slight HemCovrXX	OK Dcompsd:1	No	Severe BldNHrtSk BldClts:6	Severe BldNBcase	No:NoCom	NoComment
10 9	Considrbl Hemrgd:Bs PctDamBs1	OK	No	OK	Considrbl BldNBcase	No:NoCom	xxHemrgOt
10 10	OK	Slight LvHmPelFn	Yes	OK	Considrbl BldNBcase NoClots:1	Yes	BoHemrgOt
10 11	Slight HemCovrXX	Considrbl LvHmPelFn	Yes	OK	Considrbl BldNBcase	No	BoHemrgOt

TABLE D-1. (Continued)

Shot/ Fish	Range (in.)	Post-Shot Swimming Response	24-hour Swimming Response	Sex	Length (mm)	Dissection Month: Day	Dissection Hour: Minute	Pre-Shot Condition	External Injuries	Miscellaneous Comments
10 12	45.8	Swm:Circl	Swm:Abnor	F	129	9:26	14:05	NoComment	None	NoComment
11 1	79.9	Swm:Circl	Swm:Abnor	M	115	9:26	14:55	BactInf:1	None	NoComment
11 2	72.6	Swm:Norml	Swm:Abnor	F	126	9:26	15:08	NoComment	None	NoComment
11 3	65.7	Swm:Circl	Swm:Circl	F	124	9:26	15:15	NoComment	None	NoComment
11 4	58.4	Swm:Norml	DEAD	M	99	9:26	15:25	NoComment	None	DeadAwile GilsPale1 Stinks:1
11 5	53.7	Swm:Circl	DEAD	F	122	9:26	15:34	NoComment	None	DeadAwile GilsPale Limber
11 6	51.7	Swm:Curls	DEAD	F	113	9:26	15:39	TailInjry	None	DeadAwile Stiff
11 7	50.3	Swm:NoMoo	Swm:NoMoo	F	152	9:26	15:47	NoComment	SlDCdlPed PrtTFnGn1	NoComment
11 8	52.0	Swm:Norml	Swm:Norml	F	120	9:26	16:00	NoComment	None	NoComment
11 9	55.5	Swm:Circl	Swm:Abnor	M	124	9:26	16:06	NoComment	None	NoComment
11 10	62.3	Swm:Circl	DEAD	M	91	9:26	16:20	BactInf:2	None	DeadAwile GilsPale Limber
11 11	68.3	Swm:Circl	DEAD	F	121	9:26	16:24	NoComment	None	DeadAwile GilsPale
11 12	78.0	Swm:Circl	DEAD	F	120	9:26	16:34	NoComment	None	DeadAwile Stiff GilsPink

TABLE D-1 (Continued)

Shot/ Fish	Gill Injuries	Visceral Injuries	Heart Beating?	Heart Injuries	Brain Injuries	Blood in Orbit?	Otolith Hemorrhaging?
10 12	OK	Slight LvHmPelFn	Yes	OK	Considrbl BldNBcase	No:NoCom	BsHemrgOt
11 1	OK	OK	Yes	OK	Considrbl BldNBcase	No:NoCom	BsHemrgOt
11 2	OK	OK	Yes	OK	Considrbl BldNBcase NoClots:1	No:NoCom	BsHemrgOt
11 3	OK	OK	Yes	OK	Considrbl BldNBcase	No:NoCom	BoHemrgOt
11 4	OK	OK	No	OK NoVisiDam	NoEval:1	No:NoCom	BsHemrgOt
11 5	OK	OK	No	Considrbl BldNSak:1 ProbDam:1	Considrbl BldNBcase BldClts:2	No:NoCom	BoHemrgOt
11 6	OK	Considrbl LvHmHrtSk	No	OK	Considrbl BldNBcase NoClots:1	No:NoCom	BoHemrgOt
11 7	OK	OK	Yes	OK	Considrbl BldNBcase BldClts:2	No:NoCom	NoEval:2
11 8	OK	OK	Yes	OK	Considrbl BldNBcase BldClts:4	No:NoCom	BoHemrgOt
11 9	OK	Slight LvHmPelFn	Yes	OK	Considrbl BldNBcase	Yes	NoEval:2
11 10	OK	OK	No	OK	OK NoClots	No:NoCom	NoClots
11 11	OK	OK	No	OK	Considrbl BldNBcase BldClts:2	No:NoCom	NoClots:2
11 12	OK HemCovrBs	OK LvDarkRed NoDamage	No	Severe BldNHrtSk BldClts:6	Considrbl BldNBcase BldClot:6	No:NoCom	BsHemrgOt

TABLE D-2. DESCRIPTION OF TABLE D-1 COLUMN HEADINGS

Column Heading	Description
Shot/Fish	Shot number/ Fish specimen number
Range	Fish distance from charge (inches), measured from center of charge to gill plate on eyed side
Post-Shot Swimming Response	Post-shot swimming behavior evaluation 20-to-30 minutes after the shot
24-hour Swimming Response	Swimming behavior evalution 24 hours after the shot
Sex	Sex of fish specimen determined upon dissection
Length	Total length of fish (millimeters)
Dissection — Month: Day	Date of fish specimen dissection (Month: Day)
Dissection — Hour: Minute	Time of fish specimen dissection (Hour: Minute)
Pre-Shot Condition	Pre-shot condition of fish
External Injuries	Descriptions of external injuries caused by explosion
Miscellaneous Comments	Miscellaneous comments & notes recorded at time of dissection
Gill Injuries	Overall evaluation of degree of hemorrhaging in gills; description of injuries
Visceral Injuries	Overall evaluation of degree of hemorrhaging of the visceral organs (not including the heart); description of injuries
Heart Beating?	Was heart still pumping at time of dissection (Yes/No)?
Heart Injuries	Overall evaluation of degree of hemorrhaging inside the pericardium (heart sack); description of injuries
Brain Injuries	Overall evaluation of degree of hemorrhaging inside the braincase; description of hemorrhaging and miscellaneous comments pertinent to brain
Blood in the Orbit?	Is there blood in the orbit of the blind-side eye (the eye which migrated from the blind side of the fish) (Yes/No)?
Otolith Hemorrhaging?	Evaluation of hemorrhaging adjacent to the otoliths (hemorrhaging adjacent to the otoliths was not distinguished from other hemorrhaging inside the braincase until the last few dissections)

TABLE D-3. LIST OF COMMENTS USED FOR SWIMMING RESPONSE, SEX AND PRE SHOT CONDITION

Comment Code	Full Comment
BactInf:1	Bad case of bacterial infection
BactInf:2	Bacterial infection on tail
BactInf:3	Fish has severe body reddening (bacterial infection?)
DEAD	Fish is dead
F	Female
M	Male
NoComment	No Comment Recorded
Swm:Abnor	Swims, but abnormally
Swm:Circl	Swims in tight circles or does somersalts
Swm:Curls	Does not swim - curls to blind side & sinks
Swm:Fltrs	Does not swim - sort of flutters
Swm:NoMoo	Does not swim - fish remains motionless & sinks
Swm:Norml	Swims normally
TailInjry	Part of tail gone (worn off)
xx1	Can't see sex organs
xx2	Sex not recorded

TABLE D-4. LIST OF COMMENTS USED FOR EXTERNAL INJURIES

Comment Code	Full Comment
Abrasions	Large abrasion (approx. 2 cm long) above lateral line, end of tail fin is abraded
BdyMasrtd	Posterior 20% of body is mascerated
BigScrape	Big scrape & contusion starts just behind eyes and extends to back on eyed side
BldySpot1	Bloody spot behind head on blind side
BldySpot2	Bloody hemorrhage on head on blind side
BrusdHead	Bruised area on head behind eyes
BrzOvrVis	Bruise over visera
Contusion	Contusion over gut cavity on eyed side
Dscolratn	Discoloration on head & body on eyed side
FinWnds1	1/2 of ventral lobe of tail fin gone, last 1/2 cm of anal fin gone
HemNrTail	Hemorrhage near tail on eyed side
HlfAFnGon	Half of anal fin is gone
HlfTFnGon	Half of tail fin is gone
MstTFnGon	Most of tail fin is gone
NoEval:6	No Evaluation -- no comments recorded
None	No significant external damage
OnlyExtDm	(This is the only external damage)
PcsDFnGon	Small pieces gone from dorsal fin near tail
PnctNrAFn	Puncture (hole) on edge of body near anal fin (half-way back on fin) on blind side
PnctWnds1	Puncture wounds on dorsal & anal fins
PrtJawGon	Part of lower jaw is gone
PrtTFnGn1	Small portion of tail fin gone
PrtTFnGn2	Small piece of ventral lobe of tail fin is gone
PrtTFnGn3	Tip of tail fin gone
PrtTFnGon	Part of tail fin is gone
PrtTylGon	15-to-20 mm of tail blown away
PtBdyGon1	Tail & posterior 1.5 cm of body gone
PtBdyGon2	Posterior one-fourth of body gone
PtDFnGon1	1-cm piece of dorsal fin is gone
PtDrFnGon	Part of dorsal fin near tail is gone
ScrpdGlPl	Scrape (like something hit fish) on gill plate at end of gill slit on eyed side
SevBruise	Severe bruise across body on eyed side just ahead of caudle peduncle
SlDCdlPed	Slight damage to caudal peduncle
SlDamDFn	Posterior end of dorsal fin is slightly damaged
SmHmAtAFn	Small hemorrhage next to anal fin
SmPnctDFn	Small laceration or puncture thru base of dorsal fin just above caudle peduncle
SmPnctWnd	Small puncture wound on gill plate on eyed side (right over heart chamber)
SmPunct:1	Small puncture just under lateral line below gill opening on blind side
SmPunct:2	Small puncture in eyed side (does not go into body cavity -- external only)
SmSkinHms	Small skin hemorrhages (not like those from handling) on eyed side
SmSknHms1	Small hemorrhages near anal fin on eyed side
SplitAnFn	Split in middle of anal fin
SplitSkin	Split skin on abdominal cavity on eyed side
TailGone	Tail is gone
ThrdAFnGn	One-third of anal fin is gone
ThrdTFnGn	One-third of tail fin is gone
TylDnuded	End of tail denuded, only filaments left

TABLE D-5. LIST OF MISCELLANEOUS COMMENTS AND NOTES RECORDED AT TIME OF DISSECTION

Comment Code	Full Comment
Anesthtzd	Fish anesthetized before dissecting
DamLevl:1	Damage level 1 (Hubbs, Shultz & Wisner) *
DamLevl:2	Damage level 2 (Hubbs, Shultz & Wisner) *
DeadAwile	Fish apparently dead when iced
DedAwile1	Looks like fish as been dead some time (this fish was alive when put on ice)
FishAlive	Fish Alive
GilDamNly	"Some damage to gills" is only apparent damage
GilsMushy	Gills mushy
GilsPale	Gills pale
GilsPale1	Gills look pale & mushy
GilsPale3	Gills are pale, like fish has lost a lot of blood
GilsPink	Gills still pink
GilsPink1	Gills pink, but don't look fresh
GilsWhite	Gills white
GilsWyte1	Gill filaments are white
GlsDcmpsd	Gills decomposed
HtNGlsCOD	Death due to damage to heart & gills
Limber	Fish still limber
MovinGils	Moving Gills
NoComment	No Comment Recorded
Note1	Tried to dissect orbit of right eye -- not successful -- no bony socket
Note2	Mesh pattern from holding-cage imprinted on eyed-side
OnIce25hr	Fish on ice 25 hrs (since 9/25, 11:25)
OneEyeFsh	This fish has only one eye (natural variation -- fish not damaged)
Stiff	Fish is stiff
Stinks:1	Fish a bit stinky

---

* Attempt to equate observed damage to gills, heart and viscera to damage classification for swimbladder fish published by Hubbs, Shultz & Wisner, Univ. of Cal. (Scripps), 1960

FIGURE D-6. LIST OF COMMENTS USED FOR GILL INJURIES

Comment Code	Full Comment
BldVsDam1	First gill arch on blind side has spot where blood vessels are blown out
CantSeSrc	Can't see source of blood
Considrbl	Considerable hemorrhaging -- blood clots abundant on one or both sets of gills
DamgdBo:1	A lot of blood inside gills -- gills were damaged, but can not tell where
HemCovrBs	Hemorrhage on inside of gill cover on blind side
HemCovrEs	Hemorrhage on inside of gill cover on eyed side
HemCovrXX	Blood clot on inner surface of gill cover extends down into base of baciostical apparatus
Hemrgd:Bo	Hemorrhaged on both sides
Hemrgd:Bs	Hemorrhaged on blind side
Hemrgd:Es	Hemorrhaged on eyed side
Hemrgd:XX	Blood in gills -- side not specified
HemrgdEs1	Hemorrhaged on eyed side, blind side OK
HmNJnt:Bs	Hemorrhaging in joint of gill cover where it joins to head on blind side
HmNJnt:Es	Blood clot near juncture of gills & lower jaw structure on eyed side
NoEval:4	No Evaluation -- fish dead too long
NoEval:6	No Evaluation -- no comments recorded
OK	O.K. -- no apparent damage
OK:2	Assumed OK -- no recorded pertinent comment other than "Gills Pale"
OK:3	Assumed OK -- no pertinent recorded comments other than "no other visible damage" and "heart not examined"
PctDamBs1	Damage to gill cover on blind side -- looks like puncture wound (from air-bubble collapse in mouth?)
PctDamEs1	Gill filaments sheared-off on first gill arch on eyed side (looks like something blew-thru from mouth -- bubble-collapse damage?)
PctDamEs2	Bloody spot on gills on eyed side (caused by puncture)
PctDamEs3	Hole in bronchiostegal membranes on eyed side -- air-bubble collapse damage? -- wound could not have been inflicted externally
PctDamXX1	Epithelium disconnected -- damaged gill filaments -- looks like something went thru gill and did damage, but no hole to outside
Severe	Severe hemorrhaging -- gills largely obscured by blood clots
Slight	Slight hemorrhaging -- small blood clot on gills
SmHemTung	Small hemorrhage on tongue

TABLE D-7. LIST OF COMMENTS USED FOR VISCERAL INJURIES

Comment Code	Full Comment
BldInGut	Blood in body cavity
BldNGut:1	Lots of blood in abdominal cavity
BldNGut:2	A lot of blood in gut cavity -- blood vessel adjacent to ovary apparently ruptured
BoneyRegn	Boney region adjacent to head
Considrbl	Considerable hemorrhaging -- hemorrhages larger and more evident
Dcompsd:1	Mushy -- starting to decompose
GallBlBkn	Gall bladder broken
IntestHem	Hemorrhage on intestine
LvDarkRed	Liver is dark red
LvHmHrtSk	Large hemorrhage on liver on front face where it touches heart chamber
LvHmPelFn	Hemorrhaging on forward lobe of liver where it comes in contact with base of pelvic fin
LvHms	Hemorrhages in liver
LvHmsOnBs	Many small hemorrhages on blind side of liver
NoCom:1	No comment except "Gall bladder broken"
NoComment	No Comment Recorded
NoDamage	No apparent hemorrhages or damage
NoEval:4	No Evaluation -- fish dead too long
NoEval:6	No Evaluation -- comments not recorded
OK	O.K. -- no apparent damage
OK:4	OK, based on recorded statement "no apparent damage to internal organs"
OK:5	Assumed OK -- no pertinent comments recorded
OthrVisOK	Other visceral organs look OK
Severe	Severe hemorrhaging -- blood abundant within body cavity
SlightHem	Slight hemorrhaging -- small hemorrhage(s) on viscera, liver usually damaged

TABLE D-8. LIST OF COMMENTS USED FOR HEART INJURIES

Comment Code	Full Comment
BldClot:3	Damage to heart -- heart covered by blood clot -- contracting sporatically -- seems like membrane between auricle and ventricle is torn
BldClot:4	Hole into heart chamber (not near external puncture) -- big clot in heart chamber -- can't see exact site of damage in heart
BldClts:6	Entire pericardial chamber filled with blood clots -- heart damaged
BldClts:T	Appears to be some blood clots in heart chamber
BldNHrtSk	Blood inside the pericardium, hemorrhaging around the heart
BldNSak:1	Clotted blood present inside pericardium -- don't know origin
BldNSak:2	Apparent damage to heart -- pericardium full of blood -- may be related to puncture wound on gill plate
Considrbl	Considerable hemorrhaging -- more blood in heart chamber
Damaged:1	Damage to heart -- blood spurted out upon cutting open pericardium
FrothyBub	Frothy bubbles in pericardium -- lots of big clots around heart -- clots seem to have froth in them -- very strange
Hemrage:E	Surface of heart appears bruised -- congealed blood in heart-muscle tissue
Hemrage:F	A lot of blood clots inside pericardium -- hemorrhages in tissues around the heart
HrtDamgd	Heart Damaged
MicroExam	Examination with microscope showed nothing additional
MinorHem1	Minor hemorrhaging in pericardial tissues
NoBldNHrt	No blood in the heart, all pumped out thru the gills
NoClots	No blood clots
NoEval:3	No Evaluation -- heart accidently cut & leaked blood
NoEval:6	No Evaluation -- comments not recorded
NoEval:7	No Evaluation -- not examined
NoVisiDam	No Visible Damage
OK	O.K. -- no apparent damage
OK:4	OK, based on recorded statement "no apparent damage to internal organs"
OK:6	Assumed OK -- no pertinent recorded comments other than "heart beating"
OK:7	Assumed OK -- no pertinent recorded comments other than "No blood in heart, all pumped out thru gills"
ProbDam:1	There probably was heart damage -- hard to evaluate due to deteriation of specimen
Severe	Severe hemorrhaging -- heart chamber full of blood
Slight	Slight hemorrhaging -- small clot within heart chamber or hemorrhage on surface of heart or tissues of heart chamber

TABLE D-9. LIST OF COMMENTS USED FOR BRAIN INJURIES

Comment Code	Full Comment
AirBubbs	Air bubbles in braincase
BldClot:1	Large clot ventral to brain
BldClot:6	Blood clot ventral to brain -- brain damage does not appear to be severe
BldClts:2	Blood clots scattered thruout entire brain
BldClts:4	Minor hemorrgages around other parts of brain (besides otoliths)
BldNBcase	Blood in the braincase
BldNFluid	Diffuse blood in fluid around brain -- Blood clots on surface of brain
BldVesBkn	Blood vessel in brain broken
BldVsDm:1	Appears to have been some damage to circulatory system around the brain
BldVsDm:2	A lot of damage to circulatory system around the brain
BledFish	After inspection, cut gills and heart, respectively, in order to remove blood from fish
BoHemrgOt	Blood around both otoliths
BrnMushy1	Appear to be some hemorrhages in the braincase -- brain deteriorated, kind of mushy
BrnMushy2	A lot of hemorrhaging (probably real) -- hard to evaluate due to deterioration
BsHemrgOt	Blood around otolith on blind-side
CausODeth	Cause of Death
Considrbl	Considerable hemorrhaging -- blood clots larger and easily visible, usually associated with inner ears (otoliths)
Hemrage:G	Diffuse blood in braincase (not clotted) -- appears to have been some damage to circulatory system around the brain
LsThnFsh7	Less blood in braincase than Fish #7
Massive	Massive hemorrhaging -- cranium filled with blood
No	No -- No blood in orbit of eye which has migrated from blind side
No:NoCom	No (assumed)--no comment recorded -- dissection and examination of orbit of blind-side eye was done, however, as part of the braincase inspection
NoBigClot	Some blood in the braincase, no big clot
NoClots	No blood clots
NoClots:1	No blood in braincase except for that in ear(s) and/or eye-orbit
NoClots:2	Apparently not much bleeding around otoliths
NoComment	No Comment Recorded
NoEval:1	Brain decomposed -- no further evaluation (beyond hemorrhaging in ears)
NoEval:2	Could not evaluate because dissection-cut made in wrong place
NoEval:5	No Evaluation -- need to bleed fish before cutting braincase when heart is still pumping strongly
NoEval:7	No Evaluation -- not examined
NoEval:8	No Evaluation -- blood around otoliths not distinguished from other blood in braincase
OK	O.K. -- no apparent damage
Old:frSht	Looks like old blood clots, i.e., from bleeding which occurred immediately after the shot
SeemsNorm	Seems Normal
Severe	Severe hemorrhaging -- large blood clots in cranium
Slight	Slight hemorrhaging -- blood clot(s) just visible in cranium, usually associated with inner ears (otoliths)
TinyClots	One or two tiny clots in the braincase -- no apparent damage to brain
Yes	Yes -- Blood in orbit of eye which has migrated from blind side
Yes:1	Large well-coagulated clot in orbit behind eye which has migrated from blind side
xxHemrgOt	Blood around otolith -- side not specified

APPENDIX E

THOUGHTS ON PHYSIOLOGICAL EFFECTS OF EXPLOSIONS ON MARINE LIFE

The general subject of the physiological effects of underwater explosions on marine life has received limited scientific attention. However, investigators in related fields of research have acquired data that might prove useful for the possible refinement of existing injury and safety models, which are based mainly on the response of air or gas cavities in fish and marine mammals to the shock waves produced by the explosions. These cavities include the lungs of mammals, the swimbladders of fish, small bubbles or air pockets in the intestines, and possible microbubbles in tissues or body fluids.

The lack of injury to hogchokers, except when close to an explosive charge, is probably due to the absence of obvious air cavities. However, it is possible that microbubbles exist in the tissues of these fish and other species, just as in human tissue. These bubbles are too small to be detected visually. In humans, they have radii of a few micrometers (Lewin and Bjorno, 1981).[E-1]

The response of such microbubbles in humans has become of concern in the field of medicine because of the use of microsecond pulses of ultrasound as a diagnostic technique (Flynn and Church, 1988).[E-2] Investigators have defined a "transient cavity," i.e., one that expands to a critical maximum radius and then collapses violently. The gas temperature and pressure reach extremely high values and a shock wave is generated in the surrounding medium during collapse and rebound. These effects cause localized tissue damage. Ayme-Bellegarda (1990)[E-3] and Holland and Apfel (1990)[E-4] point out that a bubble in the presence of a boundary can be more damaging because of the formation of a jet in the collapsing bubble. The jet is directed toward the boundary.

Another medical technique of interest is the use of a focussed shock wave for the breakup of kidney stones (extracorporeal shock wave lithotripsy). Fowlkes and Crum (1988)[E-5] point out that a single pulse, such as that used for this purpose, can cause cavitation in human tissue.

A different mechanism of possible damage to tissue is heating caused by the passage of an acoustic or shock wave (Sehgal and Greenleaf, 1982).[E-6] In the field of medicine, focussed ultrasound may be used to create local hyperthermia to inhibit the growth of cancer. In other applications, such as the diagnostic use of ultrasound, heating is relatively small. However, the process of heating is complex because of the presence of bone (Wu and Din, 1990).[E-7] In general, however, it seems doubtful that the heating of tissue would be of concern for marine life in the vicinity of underwater explosions.

The response of bubbles, and other air cavities , to acoustic waves has been studied extensively. Free bubbles in water have a resonant frequency that is inversely proportional to the bubble radius. However, air pockets or bubbles in tissue exhibit a more complex reaction to acoustic waves and pressure pulses.

For example, it is known that the operation of active sonar is strongly affected by acoustic scattering by the swimbladders of fish. The bladders resonate when ensonified at the proper frequency. Initially, swimbladders were modeled as spherical air bubbles, as in the fish-injury model for these species (Goertner, 1978).[E-8] Acoustic scattering can now be modeled with sophisticated models that include the effects of the viscosity and heat conduction of fish flesh on the resonant frequency of swimbladders (e.g., Love, 1978).[E-9]

A related field is the development of echo sounders for the detection of fish, both for scientific and commercial applications (Cushing, 1973).[E-10] Fish with swimbladders are relatively easy to detect, but fish without swimbladders can also be detected because bones and scales have a higher reflection coefficient than flesh, which has a density and acoustic velocity that differs only slightly from the values in sea water. The differences in density and acoustic velocity would help to explain localized types of injury from shock waves, e.g., the movement of otoliths in the case of hogchokers.

The response of a swimbladder or other air cavity to the shock wave from an underwater explosion is not the same as the response to an acoustic wave. The shock wave (and rarefaction wave that usually follows) have a finite amplitude and a brief duration. However, these finite amplitude effects also appear in some of the ultrasonic medical techniques and in shock wave lithotripsy. Application of the extensive theoretical efforts in the biomedical field, and in other fields described above, would: (1) aid in the understanding of why different marine species respond differently to the same explosions; (2) clarify the different mechanisms of injury; and (3) provide data on the physical properties of fish and mammal tissue that can be used to refine the existing models.

REFERENCES

E-1. Lewin, P. A. and L. Bjorno, "Acoustic Pressure Amplitude Thresholds for Rectified Diffusion in Gaseous Microbubbles in Biological Tissue," *J. Acoust. Soc. Am.*, Vol 69, 1981, pp 846-852.

E-2. Flynn, H.G. and C. C. Church, "Transient Pulsations of Small Gas Bubbles in Water," *J. Acoust. Soc. Am.*, Vol 84, 1988, pp 985-998.

E-3. Ayme-Bellegarda, E. J., "Collapse and Rebound of a Gas-Filled Spherical Bubble Immersed in a Diagnostic Ultrasonic Field," *J. Acoust. Soc. Am.*, Vol 88, 1990, pp 1054-1060.

E-4. Holland, C. K. and R. E. Apfel, "Thresholds for Transient Cavitation Produced by Pulsed Ultrasound in a Controlled Nuclei Environment," *J. Acoust. Soc. Am.*, Vol 88, 1990, pp 2059-2069.

E-5. Fowlkes, J.B. and L. A. Crum, "Cavitation Threshold Measurements for Microsecond Length Pulses of Ultrasound," *J. Acoust. Soc. Am.*, Vol 83, 1988, pp 2190-2201.

E-6. Sehgal, C. M. and J. F. Greenleaf, "Ultrasonic Absorption and Dispersion in Biological Media: A Postulated Model," J. *Acoust. Soc. Am.*, Vol 72, 1982, pp 1711-1718.

E-7. Wu, J. and G. Du, "Temperature Elevation in Tissues Generated by finite-Amplitude Tone Bursts of Ultrasound," *J. Acoust. Soc. Am.*, Vol 88, 1990, pp 1562-1577.

E-8. Goertner, J. F., *Dynamical Model for Explosion Injury to Fish*, NSWC/W0L TR 76-155, Naval Surface Weapons Center, Silver Spring, MD, 1978.

E-9. Love, R. H., "Resonant Acoustic Scattering by Swimbladder-Bearing Fish," *J. Acoust. Soc. Am.*, Vol 64, 1978, pp 571-580.

E-10. Cushing, D., *The Detection of Fish*, Pergamon Press, Oxford, 1973.

DISTRIBUTION

DOD ACTIVITIES (CONUS)	Copies
ATTN: CODE 1123B	1
CODE 1141SB (D. COSTA)	1
CHIEF OF NAVAL RESEARCH	
800 N. QUINCY STREET, BCT 1	
ARLINGTON, VA 22217-5000	
ATTN: SEA-06KR12 (R. CASSEL)	3
SEA-60E (P. HAGAN)	1
COMMANDER	
NAVAL SEA SYSTEMS COMMAND	
WASHINGTON, DC 20362-5105	
ATTN: TECHNICAL LIBRARY	2
CODE 3831 (L. CARLTON)	1
COMMANDER	
NAVAL UNDERSEA WARFARE CENTER DIVISION	
NEWPORT, RI 02841-5047	
ATTN: TECHNICAL LIBRARY	1
CODE 17	1
CODE 175 (J.W. SYKES)	1
CODE 1750.2 (W. CONLEY)	1
CODE 1750.2 (P. MANNY)	1
COMMANDER	
CARDEROCK DIVISION	
NAVAL SURFACE WARFARE CENTER	
BETHESDA, MD 20084-5000	
ATTN: TECHNICAL LIBRARY	1
CODE 69.1 (M. RILEY)	1
CODE 69.2 (J. CRAIG)	1
CODE 69.2 (R. KREZEL)	1
DIRECTOR	
UNDERWATER EXPLOSIONS RESEARCH OFFICE	
CARDEROCK DIVISION	
NAVAL SURFACE WARFARE CENTER	
PORTSMOUTH, VA 23709	
ATTN: LIBRARY	1
COMMANDING OFFICER	
NAVAL RESEARCH LABORATORY	
WASHINGTON, DC 20375	
SUPERINTENDENT	1
NAVAL POSTGRADUATE SCHOOL	
MONTEREY, CA 93940	

DISTRIBUTION (Cont.)

Copies

ATTN: TECHNICAL LIBRARY 1
CODE 3120 (R. BUHL) 1
CODE N3210 (J. LO TURCO) 1
CODE 3310 (H. LOFTON) 1
COMMANDING OFFICER
COASTAL SYSTEMS STATION
DAHLGREN DIVISION
NAVAL SURFACE WARFARE CENTER
PANAMA CITY, FL 32407-5000

ATTN: TECHNICAL LIBRARY 1
COMMANDER
NAVAL AIR WARFARE CENTER
WEAPONS DIVISION
CHINA LAKE, CA 93555-6001

ATTN: TECHNICAL LIBRARY 1
COMMANDER
INDIAN HEAD DIVISION
NAVAL SURFACE WARFARE CENTER
101 STRAUSS AVE
INDIAN HEAD, MD 20640-5000

ATTN: CHARLES HANEY 1
COMMANDING OFFICER
NAVAL AIR WARFARE CENTER
AIRCRAFT DIVISION DETACHMENT KEY WEST
KEY WEST, FL 33040-0005

ATTN: CODE 203 (WILLIAM SLOGER) 1
COMMANDING OFFICER
SOUTHERN DIVISION
NAVAL FACILITIES ENGINEERING COMMAND
P. O. BOX 10068
CHARLESTON, SC 29411-0068

ATTN: CODE 4830 (S. HERTING) 1
COMMANDER
NAVAL SURFACE WARFARE CENTER
PORT HUENEME DIVISION
PORT HUENEME, CA 93043-5007

ATTN: CDR WYNN CALLAND 1
ASSISTANT SECRETARY OF THE NAVY
(INSTALLATIONS AND ENVIRONMENT)
NAVY DEPARTMENT
WASHINGTON, DC 20360-1000

DISTRIBUTION (Cont.)

	Copies
ATTN: CODE N44EP1K (K. DEPAUL)	1
CODE N44EP1 (T. PEELING)	1
CHIEF OF NAVAL OPERATIONS DEPARTMENT OF THE NAVY WASHINGTON, DC 20350-2000	
ATTN: CODE 521 (C. HUI)	1
CODE 522 (P. SELIGMAN)	1
COMMANDER NAVAL OCEAN SYSTEMS CENTER SAN DIEGO, CA 92152-5000	
CENTER FOR NAVAL ANALYSES 4401 FORD AVENUE ALEXANDRIA, VA 22302-0268	1
ATTN: TECHNICAL LIBRARY DIRECTOR DEFENSE NUCLEAR AGENCY WASHINGTON, DC 20305	1
ATTN: LIBRARY DIRECTOR DEFENSE ADVANCED RESEARCH PROJECTS AGENCY 1400 WILSON BLVD. ARLINGTON, VA 22209	1
ATTN: SECURITY OFFICE DEFENSE TECHNICAL INFORMATION CENTER CAMERON STATION ALEXANDRIA, VA 22304-6145	12
ATTN: CODE STECS-LI (P. TENNANT) LIVE FIRE VULNERABILITY DIRECTORATE US ARMY COMBAT SYSTEMS TEST ACTRIVITY ABERDEEN PROVING GROUND, MD 21005-5059	1

DISTRIBUTION (Cont.)

Copies

NON-DOD ACTIVITIES

ATTN: GIFT AND EXCHANGE DIVISION 4
LIBRARY OF CONGRESS
WASHINGTON, DC 20540

ATTN: C. ORAVETZ 1
T. HENWOOD 1
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
NATIONAL MARINE FISHERIES SERVICE
SOUTHEAST REGIONAL OFFICE
9450 KOGER BOULEVARD
ST. PETERSBURG, FL 33702

ATTN: A. MYRICK 1
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
NATIONAL MARINE FISHERIES SERVICE
SOUTHWEST FISHERIES CENTER
P. O. BOX 271
LA JOLLA, CA 92038-0271

ATTN: G. GITSCHLAG 1
E. KLIMA 1
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
NATIONAL MARINE FISHERIES SERVICE
SOUTHEAST FISHERIES CENTER
GALVESTON LABORATORY
4700 AVENUE U
GALVESTON,TX 77551

ATTN: CODE 243 (C. LEVENSON) 1
NAVAL OCEANOGRAPHIC AND ATMOSPHERIC
RESEARCH LABORATORY
BLDG. 1005
NSTL STATION,MS 39529

ATTN: LIBRARY 1
VIRGINIA INSTITUTE OF MARINE SCIENCE
GLOUCESTER POINT, VA 23062

ATTN: LIBRARY 1
CENTER FOR ENVIRONMENTAL AND ESTUARINE STUDIES
CHESAPEAKE BIOLOGICAL LABORATORY
BOX 38
SOLOMONS, MD 20688-0038

DISTRIBUTION (Cont.)

	Copies
INTERNAL DISTRIBUTION:	
E231	2
E232	3
E342 (GIDEP)	1
G05 (J. GOELLER)	1
G08 (R. KAVETSKY)	1
G83 (L. LIPTON)	1
G90 (W. WASSMANN)	1
GH4 (M. WALCHAK)	1
GH4 (L. MONTGOMERY)	1
R10	1
R102 (D. PHILLIPS)	1
R11	1
R12	1
R13	1
R14	1
R16	1
R14 (R. BARASH)	1
R14 (J. CONNOR)	1
R14 (T. FARLEY)	1
R14 (J. GASPIN	1
R14 (J. F. GOERTNER)	10
R14 (F. HAINS)	1
R14 (G. HARRIS)	1
R14 (R. MERSIOWSKY)	1
R14 (W. MCDONALD)	5
R14 (M. WILEY)	5
R14 (G. YOUNG)	10
R44 (W. SZYMCZAK)	1

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
1 February 1994

3. REPORT TYPE AND DATES COVERED

4. TITLE AND SUBTITLE
Effects of Underwater Explosions on Fish without Swimbladders

5. FUNDING NUMBERS
PE - 63721N
PR - S0400
TA - S0400

6. AUTHOR(S)
J. F. Goertner, M. L. Wiley, G. A. Young and W. W. McDonald

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Naval SurfaceWarfare Center
Dahlgren Division, White Oak Detachment
10901 New Hampshire Avenue
Silver Spring, MD 20903-5640

8. PERFORMING ORGANIZATION REPORT NUMBER
NSWC TR 88-114

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

Techniques were developed to study the effects of underwater explosions on fish without swimbladders. Detailed injury data were obtained from hogchokers (*Trinectes maculatus*) at distances from 30 to 80 inches from a 10-pound pentolite charge. The range for 50 percent probability of immediate-kill was 30 inches, which is about a factor of 100 less than for swimbladder fish of comparable size. The data demonstrate that these fish without swimbladders have an unusually high resistance to explosion effects. The degree to which these results carry over to other species without swimbladders is not known

14. SUBJECT TERMS
Underwater Explosions

15. NUMBER OF PAGES
114

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT
UNCLASSIFIED

18. SECURITY CLASSIFICATION OF THIS PAGE
UNCLASSIFIED

19. SECURITY CLASSIFICATION OF ABSTRACT
UNCLASSIFIED

20. LIMITATION OF ABSTRACT
SAR

GENERAL INSTRUCTIONS FOR COMPLETING SF 298

The Report Documentation Page (RDP) is used in announcing and cataloging reports. It is important that this information be consistent with the rest of the report, particularly the cover and its title page. Instructions for filling in each block of the form follow. It is important to ***stay within the lines*** to meet ***optical scanning requirements***.

Block 1. Agency Use Only *(Leave blank)*.

Block 2. Report Date. Full publication date including day, month, and year, if available (e.g. 1 Jan 88). Must cite at least the year.

Block 3. Type of Report and Dates Covered. State whether report is interim, final, etc. If applicable, enter inclusive report dates (e.g. 10 Jun 87 - 30 Jun 88).

Block 4. Title and Subtitle. A title is taken from the part of the report that provides the most meaningful and complete information. When a report is prepared in more than one volume, repeat the primary title, add volume number, and include subtitle for the specific volume. On classified documents enter the title classification in parentheses.

Block 5. Funding Numbers. To include contract and grant numbers; may include program element number(s), project number(s), task number(s), and work unit number(s). Use the following labels:

C - Contract
G - Grant
PE - Program Element
PR - Project
TA - Task
WU - Work Unit Accession No.

BLOCK 6. Author(s). Name(s) of person(s) responsible for writing the report, performing the research, or credited with the content of the report. If editor or compiler, this should follow the name(s).

Block 7. Performing Organization Name(s) and Address(es). Self-explanatory.

Block 8. Performing Organization Report Number. Enter the unique alphanumeric report number(s) assigned by the organization performing the report.

Block 9. Sponsoring/Monitoring Agency Name(s) and Address(es). Self-explanatory.

Block 10. Sponsoring/Monitoring Agency Report Number. *(If Known)*

Block 11. Supplementary Notes. Enter information not included elsewhere such as: Prepared in cooperation with...; Trans. of...; To be published in.... When a report is revised, include a statement whether the new report supersedes or supplements the older report.

Block 12a. Distribution/Availability Statement. Denotes public availability or limitations. Cite any availability to the public. Enter additional limitations or special markings in all capitals (e.g. NOFORN, REL, ITAR).

DOD - See DoDD 5230.24, "Distribution Statements on Technical Documents."
DOE - See authorities.
NASA - See Handbook NHB 2200.2
NTIS - Leave blank.

Block 12b. Distribution Code.

DOD - Leave blank.
DOE - Enter DOE distribution categories from the Standard Distribution for Unclassified Scientific and Technical Reports.
NASA - Leave blank.
NTIS - Leave blank.

Block 13. Abstract. Include a brief ***(Maximum 200 words)*** factual summary of the most significant information contained in the report.

Block 14. Subject Terms. Keywords or phrases identifying major subjects in the report.

Block 15. Number of Pages. Enter the total number of pages.

Block 16. Price Code. Enter appropriate price code ***(NTIS only)***

Blocks 17.-19. Security Classifications. Self-explanatory. Enter U.S. Security Classification in accordance with U.S. Security Regulations (i.e., UNCLASSIFIED). If form contains classified information, stamp classification on the top and bottom of the page.

Block 20. Limitation of Abstract. This block must be completed to assign a limitation to the abstract. Enter either UL (unlimited) or SAR (same as report). An entry in this block is necessary if the abstract is to be limited. If blank, the abstract is assumed to be unlimited.