REPORT ON EXPERIMENTS DESIGNED TO DETERMINE EFFECTS OF UNDERWATER EXPLOSIONS ON FISH LIFE[1]

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[1] Contributions from the Scripps Institution of Oceanography, New Series, No. 576. Submitted for publication March, 1952. In the conduct of the research and in the preparation of the article we have at times been carried out beyond our depth. We, therefore, very sincerely record thanks to those who have given us a helping hand. Encouragement, advice, and assistance have been furnished by many persons, including Frances N. Clark, Edward C. Greenhood, John E. Fitch, and others, of the California Department of Fish and Game; William W. Rand, of the Union Oil Company; Capt. Tom Crawford and crew, of that company's exploring ship, the SUBMAREX; R. A. Peterson, E. Pat Shultz, and Robert Day, of the United Geophysical Company; Louis N. Waterfall, consultant; Alfred B. Focke, of the United States Navy Electronics Laboratory; Carl H. Eckart, Russell W. Raitt, John D. Isaacs, Roger R. Revelle, Francis P. Shepard, Donald B. Sayner, Theodore R. Folsom, Conrad Limbaugh, and many others at the Scripps Institution of Oceanography.

INTRODUCTION

In the exploitation of major natural resources conflicts of values and interests often arise. Such a conflict arose when the oil industry, in its effort to meet the increasing demand for its product and to prepare for future needs, undertook seismographic exploration for untapped oil deposits in the rock layers beneath the coastal waters of Southern California. Such exploration requires a point source of intense low-frequency sound and the most practicable generating source is an explosion. Particularly effective and practicable, as explorations in the Gulf of Mexico have demonstrated, is the standard 60 percent gelatine dynamite, which produces a sharp shock wave with an abrupt front of great pressure intensity (Figure 8). Such a wave gives excellent results from the seismographic viewpoint. Unfortunately, however, this type of wave is very injurious to fishes that have an air-bladder, and most of the important food and game species possess this structure. Heavy mortalities of valued fishes resulted from the seismographic studies in the waters of Southern California (Aplin, 1947; Fitch and Young, 1948) and from tests made in Chesapeake Bay (Coker and Hollis, 1950). As a result of the fish killings in California the permits for submarine oil exploration were revoked in 1949, and were not renewed until September, 1951. The renewals were granted after the experiments recounted below had indicated it as probable that black powder would yield usable seismographic data without killing fish in disastrous numbers.

Research to determine the effects of underwater explosions on marine life has been limited. The effects of detonating explosives have received attention by Knight (1907), Gowanloch and McDougall (1944-1946), Aplin (1947), Indrambarya (1949), Gowanloch (1950), and Coker and Hollis (1950), as also in two reports (Anonymous, 1947 and 1948) on the cooperative researches in Chesapeake Bay. We have found no published data on the biological effects of underwater discharges of such relatively slow-burning explosives as black powder.

OBSERVATIONS ON THE EFFECTS OF LARGE CHARGES IN A RESTRICTED REGION

The first set of definite observations made by us to determine effects of underwater explosions on fishes was a by-product of geological experiments conducted by the Scripps Institution of Oceanography in cooperation with the United States Navy. Navy personnel did the firing. The primary object was to determine whether turbidity currents could be induced in submarine canyons by explosions set off at or near the head of the canyon. The tests were conducted in Scripps Submarine Canyon Shepard, 1949, 1951a, b), immediately north of Scripps Institution, near La Jolla, California (Figure 1). The first trials were run on April 6 and 7, 1950, when ten 50-pound dynamite charges were set off, two near the sandy main head of the canyon at a depth of about 60 feet, two near the middle of this arm at a depth of about 250 feet, and six in the rocky main canyon, near its confluence with Sumner Branch, at depths of about 325 to 350 feet. Large fish kills resulted, but the collection was somewhat incomplete and selective (listed in first column of Table 1). Of the total recorded **kill** of 1,431 fish, 1,032 were blacksmith and 245 were rockfish of various species (for scientific names see list on page 366).

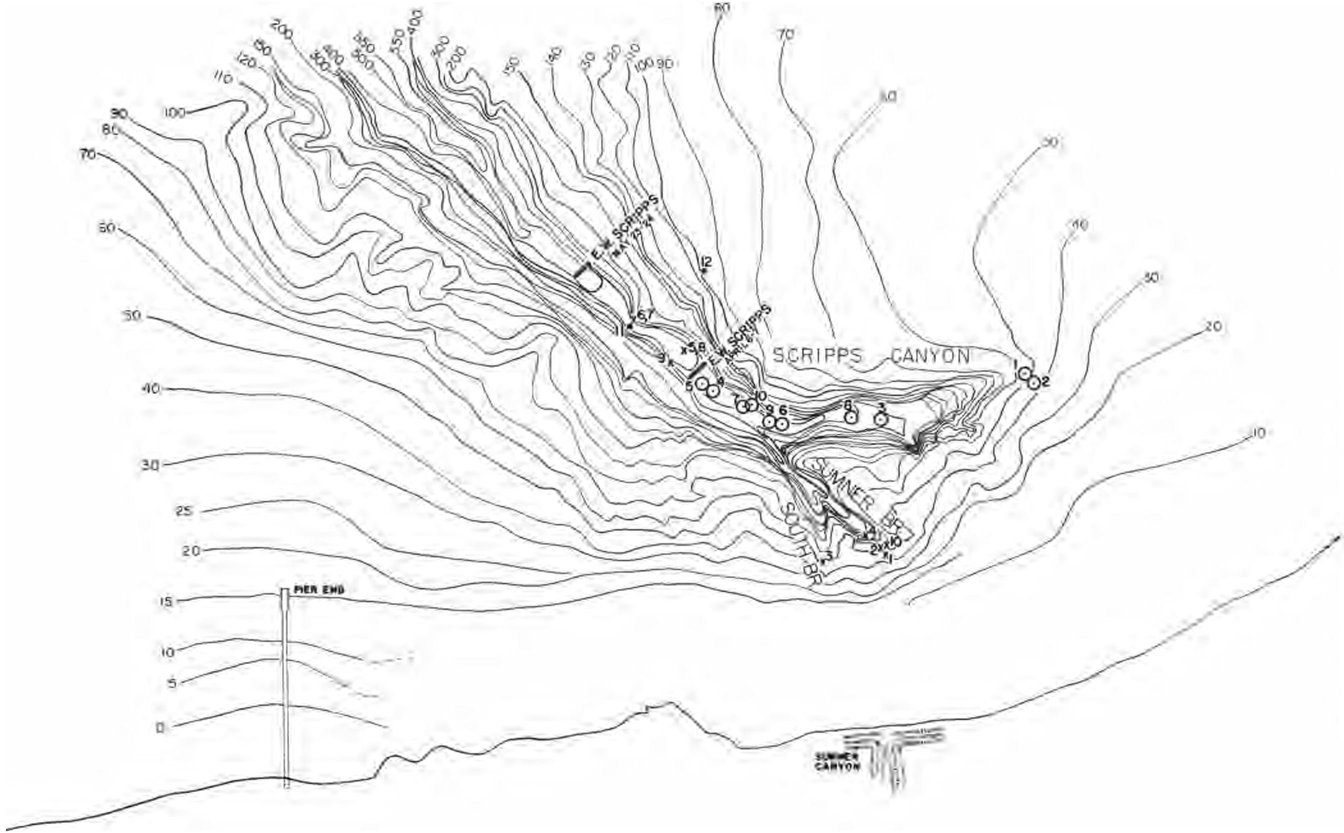

FIGURE 1. Map of Scripps Submarine Canyon, showing location of dynamite explosions of April 6-7 (circles) and May 23-24 (crosses), 1950. See Table 1. The pier us 1,000 teet long. *Traced trom map* provided *by Dr. Francis* P. *Shepard.*

TABLE 1

Record of Fish Collected Dead or Dying at Surface After Dynamite Explosions in Scripps Submarine Canyon, California

For scientific names see p. 366. This plus sign (+) indicates that additional specimens were destroyed but not recovered.

Date (1950)	Apr. 6-7	May 23							May 24			Totals May 23	Totals May 24
Blast No. (Figure 1)		1	2	3	4	5	6-7	8	9	10-11	12-13	1-8	9-13
Depth (blast on bottom)	60-350	50	79	55	90	405	430	405	325±	60±	450± (&100)	50-405	60-450
Time of blast (about)	1007-1619	0925	1030	1100	1310	1350	1440 1455	1555	1000	1030	1130	0925-1555	1000-1130
Weight of charge, pounds	50 or 100	50 or 100	50 or 100	50 or 100	100	50	50+50	100	100	50+50	50(+4)	50-100	50-100(+4)
Pacific sardine	--	--	--	1	--			2			--	3	--
Panama bristlemouth	1	--	--	--	--	--	-	--			--	--	--
Kelp bass	27	53	1	4	3	--	--		--		--	61	--
Sand bass	--	7	--	--	--	--	--	--	--		--	7	--
Grunion	29++	2	--	20	--	72	--	--	10		62+	94	77+
Jacksmelt	54+	21	8	12	29	7	--	3	--		7+	80	7+
Kelp topsmelt	--	1	--	--	--	9	1	15	-		5+	26	5+
Jack mackerel	--	--	--	1		--	--	--			--	1	--
Sargo	--	4	3	--	--	--		--			--	7	--
Ocean whitefish	3	--	--	--	--	--	--	--			--	--	--
Pink seaperch	16			--		1	--	6			8+	7	8+*
Buttermouth seaperch	--	--		1		--	--	--			--	1	--
Sharpnose seaperch	3	--	--	--			--	1			--	1	1
Rubberlip seaperch	3	1	--	--	--			1			--	2	--
Pile perch	1	3	--	--	--			1			--	4	--
Blacksmith	1,032	1,978	334	289	39			47			2	2,687	6
Garibaldi	1	--	--	--	--	--	--	--			--		--
California sheepshead	3+	63	3	1	2	--		1			--	70	--
Opaleye	3	--	--	--	--		--	--			--	--	--
Bocaccio	4	--	--	12		--	--	--			1	12	1
Bass rockfish	30	--	2	13		--	--	1			--	16	--

Vermilion rockfish	15+							2			5*	2	5*
Kelp rockfish	25	1	4	7	4							16	
Widow rockfish	1					1						1	
Spotted rockfish	83		3	1	1			192	1			197	1
Halfband rockfish	9					2		3				5	
Speckled rockfish	46				1			2			4*	3	4*
Rosy rockfish	7					2	1					3	
Greenspotted rockfish	7					3		3			1*	6	1*
Pink rockfish	10					15	6	2			1*	23	1*
Starry rockfish	3					3	2	1			2*	6	2*
Spanishflag								1				1	
Striped rockfish	1										1*		1*
Brown rockfish					1							1	
Whitebelly rockfish	2								1				1
Calico rockfish	1												
Treefish	1												
Rockfish (species?, very yg.)							2					2	
Crested goby			1	7								8	
Zebra goby	1												
Northern midshipman	2							1				1	
Spotted cusk-eel	7					2		1				3	
Totals	1,431+	2,134	359	369	80	117	12	286	13	9	99+	3,357	121+

* Fish so marked, plus 50 to 100 additional pink seaperch that were not recovered, were presumably destroyed by the unscheduled blast northwest of the main explosions.

The local fish population presumably recovered between the operations of April 6-7 and May 23-24. The similarity between the lists of fishes destroyed on the two occasions (Table 1) is striking.

During the second operation, on May 23 and 24, an effort was made to tally all fish killed. Six 50- or 100-pound charges were set off, four on May 23 and two, close together, on May 24, near the sandy heads of South Branch and Sumner Branch, in depths of 50 to 90 feet ; and six were discharged in the rocky main canyon, at depths of about 325 to 450 feet, four on May 23 and two on May 24; in addition, one unscheduled 4-pound charge was exploded on May 24, above the northwestern wall of the main canyon. The two sets of explosions were discharged to either side of the area blasted on April 6 and 7. In view of the large radius of kill observed, however, it is assumed that the canyon was affected not only near each set of shots but also through much of the intervening area. Due to the extreme narrowness and straight alignment of the rock-walled canyon, it may be assumed that the effects of the explosions were intensified up and down the trench.

The very extensive kill on the first day (May 23) was probably almost complete for the regions affected. Approximately duplicated shots of the second day yielded only 121 fish. Of these, 89, or 74 percent, were silversides (Atherinidae), free-swimming fish whose numbers were presumably unaffected by the explosions of the previous day. Of the 32 remaining fish, 22 (marked with an asterisk in Table 1) were almost certainly killed above the northwestern canyon wall or on the canyon edge, for they appeared well north of the others and later, presumably as the result of the unscheduled 4-pound shot set off in that region near the surface. Eliminating these two sets of specimens, only 10 fish were taken as a result of the four shots of the second day, where 3,357 were picked up following the eight shots on the first day. It seems possible that most of the fish population was destroyed through perhaps 1,000 or 1,500 feet of the upper part of the submarine canyon. The destructiveness of large dynamite charges may be very extensive.

In the four successive shallow-water shots of May 23 there was a marked decrease in the kill, particularly in the series (1, 2, and 4) at the head of Sumner Branch (Table 1 and Figure 1) . Had the fish merely moved down into the main Scripps Canyon, more would likely have been killed by the subsequent charges (6-8) in deeper water. The rather high mortality from blast 8, contrasting with the lesser kill of blast 5, discharged about two hours earlier at the same location, may have resulted from a down-canyon movement of the fish between the two shots.

It is obvious that the bottom fish did not move into the canyon overnight, between the days in May when the explosions were set off, either from possible refuges in the steep-walled tributaries or from more distant habitats. There is reason to believe, however, that the population was again restored within a few months. In extensive diving operations with self-contained units Conrad Limbaugh and other students found during 1951 that fish again abounded in the canyon, in the general region where the fish life had been largely eliminated on May 23-24, 1950. Here at depths of 35 to 185 feet Limbaugh observed 31 species of fish (for scientific names see list p. 366). The blacksmith, again the most abundant fish, was observed in particularly large concentrations at the heads of canyons and at the junctions of the tributaries. Various species of rockfish were seen in considerable numbers along the rim of the canyon below 100 feet and at the canyon junctions. At depths of 50 to 100 feet, along the rim, kelp bass and ocean-whitefish were observed at times in large schools. Several seaperches (Embiotocinae) were occasionally found in large numbers at depths of 35 to 60 feet. At times large schools of señoritas were seen at depths less than 50 feet. In general, in 1951, fish were apparently more numerous in and over the canyon than in any comparable near-by area. The fish life of the canyon, which is often favored by local anglers, had seemingly become restored.

1951 EXPERIMENTS

In 1951 experiments were conducted for the specific purpose of determining whether methods applicable to seismographic exploration for oil might be found that would cause no considerable fish mortality. These trials were conducted by the Union Oil Company of California on the exploring ship Submarex, under a permit granted by the California Department (then Division) of Fish and Game on March 2, 1951 (later amended). The operations were restricted in several ways and the permit specified that the experiments would be a joint enterprise of the oil company and the Scripps Institution of Oceanography of the University of California. A preliminary report was prepared in May, 1951, for the use of the State Fish and Game Commission and of other parties particularly concerned. It serves as the main basis for this presentation.

At the outset of these experiments the object was to determine whether small charges of dynamite jetted into the bottom (Figure 2) might be exploded without causing serious harm to the fish life in the overlying water. It was determined, however, that fish confined in experimental cages and others, free-swimming, were seriously affected. After repeated trials failed to indicate that small jetted charges of either dynamite or Hercomite would be inoccuous, experiments were undertaken with explosives (Hercules FFG and FFFG black powders) having lower peak intensities and lower frequencies.

The black powder charges were first jetted into the bottom, but when it appeared that the bubble pulse produced by such powder when jetted as deep as 40 feet might interfere with the geophysical analysis, the project was expanded (by extension of the permit) to include trials with the charge lying on the bottom and with the charge hung a few feet below the surface.

The experiments were observed by Edward Greenhood, representing the Department of Fish and Game, as well as by the Scripps representative (Rechnitzer) and the Union Oil Company's geologist (William W. Rand). On several occasions other officials of the Scripps Institution and of the California State Fisheries Laboratory observed the trials and on one day Messrs. DeWitt, Harrison, and Woods, representing the Ocean Fish Protective Association, were aboard. The stipulations of the permit (as amended) were rigidly adhered to and every facility was provided for the conduct of the experiments and for the observation and recording of the results. A boat with crew (Figure 4) was made available to the observers. The boat stood by in readiness for each shot, in order to pick up any marine life that might be killed or injured by the blast. All information regarding the methods involved in carrying out the experiments


2
3
4
5

and all information gathered from them were made available to the observers.

The work was started off Silver Strand, which separates San Diego Bay from the ocean. Explosions 6, 9-13, and 16, as seriated in Tables 2-4, were set off here. The next test (25) was made just north of La Jolla. The work was then transferred to the vicinity of the Orange—Los Angeles county line, after sedimentary overburden of adequate depth for the jetted tests could not be located off San Diego County.

In each set of experiments an effort was made to keep as nearly uniform as possible all varying factors other than size and position of the charge.

Materials and Methods

Fishes

Seven species of fish, marked by an asterisk in the list on page 366 were used in the experimental cages. Some individuals of each kind were killed in cages by the dynamite charges. Four of these species and seven others were killed by dynamite while free-swimming. These are marked by a dagger (†). In the two Hercomite trials anchovies and one queenfish were killed. In the black powder experiments only the anchovy was killed in cages and one Pacific mackerel was the only fish killed while free-swimming.

The number of species used in the experiments was limited because few kinds were readily available. Anchovies were frequently the only kind obtainable ; jack mackerel, kingfish, sardine, queenfish, pompano, and grunion made up a very small percentage of any single purchase. In the San Diego area fish were taken when available, either from holding receivers or directly from the fishing boat. In the San Pedro area fish were purchased daily from local bait dealers at approximately 7.30 a.m., within eight hours after capture. The specimens were taken directly from their holding tanks. Therefore, the fish, after transfer to the holding tank on the research vessel, had been handled only twice by dipnets and were taken from the ocean as recently as was practicable. None were held over from the operations of the previous day. The kingfish were mostly taken by hook and line. They were seemingly sound when placed in the cages. In general, the fish were in excellent condition and were considered to be suitable experimental material.

The fish were held in a 4' X 4' X 4' wooden commercial-type bait tank, through which at all times an adequate flow of fresh sea water was maintained by an air-free pump. The tank was placed on board where the fish when dip-netted out of the tank could be transferred rapidly in a bucket to the live cages (Figure 5). All fish kept well throughout the experiments. Fatalities due to handling were negligible. It was found by experiment that internal injuries, such as those produced by a blast, could be simulated only by extraordinarily rough treatment.

FIGURE 2. Jetting a charge into the ocean **floor. Photograph by William W. *Rand, April, 1951.***

FIGURE 3. Loading position of the nine-cage unit. Photograph by William W. *Rand, April, 1951.*

FIGURE 4. Motor launch scouting for possible free kill. *Photograph by William W. Rand, April, 1951.*

FIGURE 5. Loading fish into a bottom cage. Photograph *by William W. Rand, April, 1951.*

Cages

In order to avoid possible absorption of shock-wave energy by such air-containing material as twine netting and wooden frames, all cages were constructed of 1-inch mesh galvanized hardware cloth laid over a welded frame of 1-inch steel rod (Figure 6). They were similar to those used in previous investigations (Aplin, 1947; Anonymous, 1948). The dimensions of each were 18" X 36" X 36". A door 18" X 18" was placed on one 18" X 36" side. Usually only two cages were used in each experiment, one near the surface and one on the bottom. In some experiments, nine cages were secured five feet apart, both vertically and horizontally, by an agle-iron frame (Figure 7). The nine-cage unit was held in an upright position by four buoys. To this unit an extra buoyed surface cage was attached.

Control cages, one at the surface and one on the bottom, were placed in a few experiments 100 to 200 feet from the shot. None of the fish in the controls showed any damage attributable to the blast.

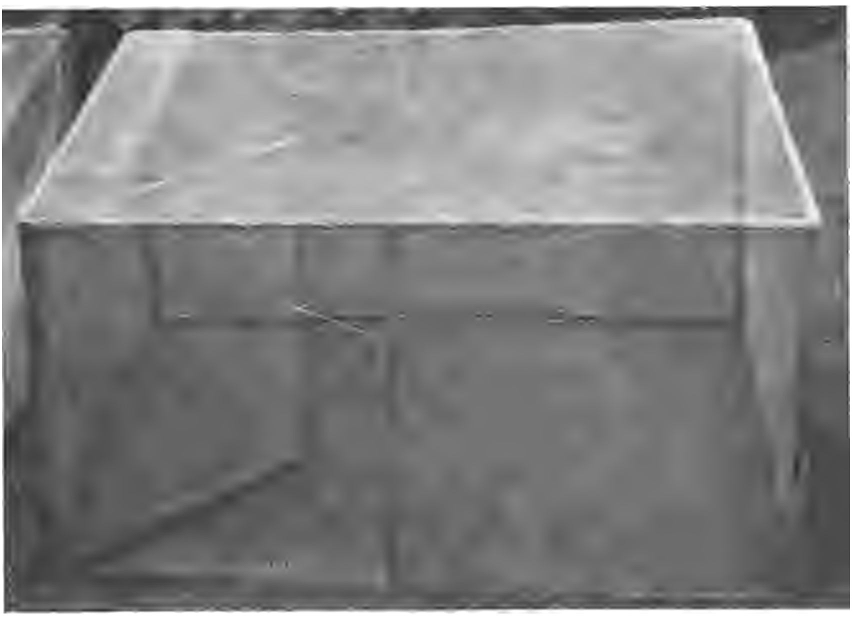

FIGURE 6. All-metal holding cage (18" x 36" x 36"). *Photograph by William W. Rand, April, 1951.*

Handling of Cages

The cages were submerged on edge to a depth of 18 or more inches alongside a launch that was tied to the research vessel (Figure 5). The launch permitted the operating crew to work at water level. The fish were gently poured from the bucket into the live cage. When the door was secured the cage was completely submerged. Once in the water, the cage righted itself, due to the bridling, so that the fish were limited in vertical movement to 18 inches. The cages were then placed in position for the firing of the charge. Loading time for each cage was about one minute.

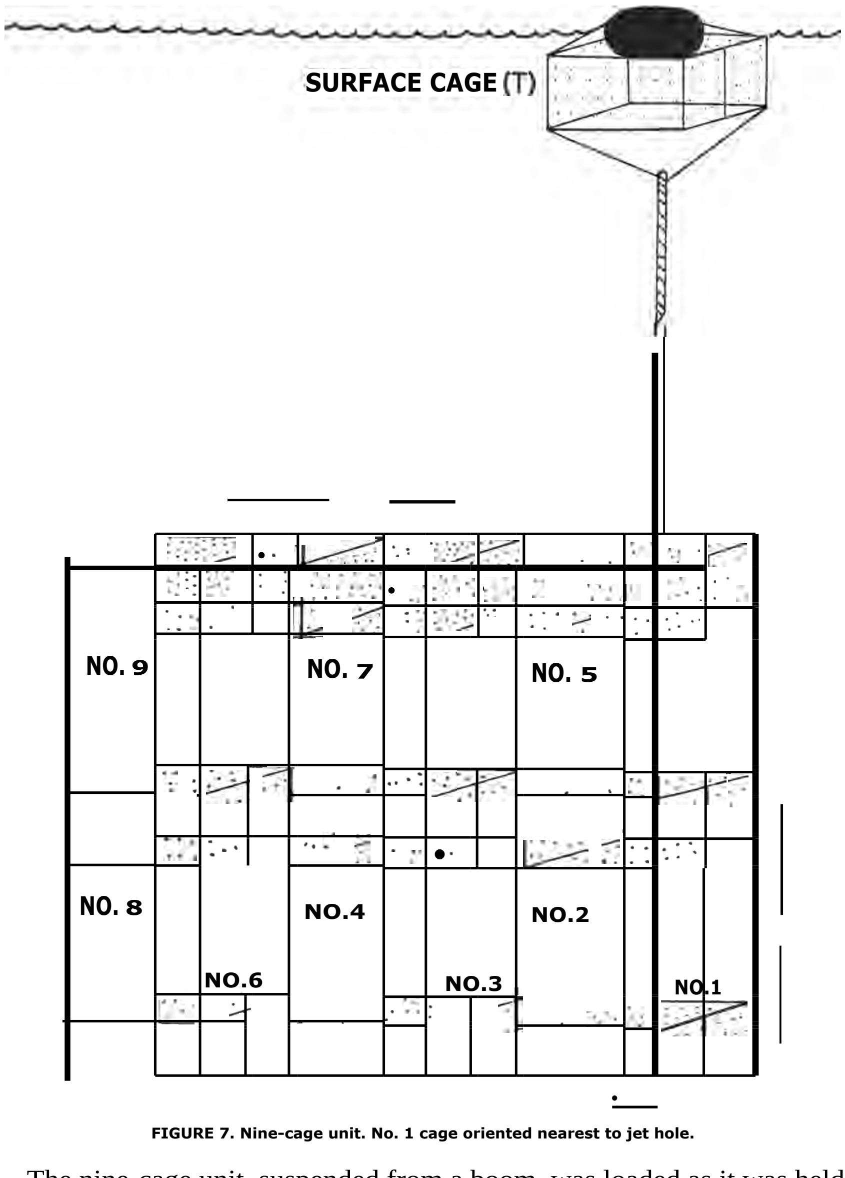

FIGURE 7. Nine-cage unit. No. 1 cage oriented nearest to jet hole.

The nine-cage unit, suspended from a boom, was loaded as it was held at 90 degrees from its final position, so that the door of each cage was up (Figure 3). When a row of three cages had been loaded, as described above, the unit was lowered so that the next row could be similarly filled. On completion of the loading, which required about 15 minutes, the cage was turned to its original position with a 36" X 36" side up.

A recording instrument was attached to the top of one of the cages, which was placed as nearly vertically over the shot as was feasible. The specific cage from the bottom is indicated in Tables 2-4. The recording device measured the peak intensity of the shock wave (Figures 8-9, which is recorded in p.s.i. (pounds per square inch). It is assumed, in general, that the fish in a particular cage were subjected, approximately, to the pressure indicated by the instrument attached to that cage, but in some experiments (as in Exp. 19), the fish were probably subject to less pressure because they were in the shadow zone (p. 362). It would have been better to have placed the instrument in the center of the cage, as was done in the Chesapeake Bay experiments (Anonymous, 1947, 1948).

When the charges were jetted, a crew member standing on the research vessel placed the nearest bottom cage (No. 1) as close to the jet hole as he could. He set the cages free when they were aligned with the shot wire leading to the jetted charge. Precise placement of the No. 1 cage proved difficult, particularly in deep water. The actual distance between charge and cage ("Hydrophone Dist." in Tables 2-4) was computed whenever the hydrophone was attached to a cage. The lower cage normally rested on the bottom and was equipped with a grapple to restrict its movement during the experiment. The paired cages were secured together by a line. The upper cage, supported by a steel buoy, floated just beneath the surface.

In those experiments (1, 40-44, 46, 50; Tables 2, 4), in which the explosive was floated either two or four feet beneath the surface, the upper cage floated just beneath the surface, but was held off to the side of the explosion rather than approximately over the blast. This was accomplished by a line 20 feet long, which was kept taut by another line running to the research vessel. The lower cage was suspended in mid-water either 40 feet below the charge or 40 feet below the surface cage.

In four experiments (51, 52, 60, 61) the bottom cage was separated either 5 or 10 feet from the charge by a metal rod and the recording instrument was attached to this cage.

Within about 10 or 15 minutes, after all the equipment was set in place, the ship was moved approximately 100 feet from the site of the blast. Immediately after the firing the launch was run to the site of the shot, in order to make prompt observations of caged fish and of whatever free marine life might surface.

As soon as it was evident that no free-swimming fish were damaged or that all that were going to surface had already done so, the cages were pulled aboard the launch and the fish were removed for dissection, analysis, and preservation. Controls indicated that it was unnecessary to leave fish in cages for any prolonged period, as dissection reveals the damage. It is believed that the damage is produced almost momentarily by the blast. All fish subjected to experiments involving black powder were dissected immediately on board the research vessel and were then preserved.

Handling of Charges

A standard factory-prepared charge of five pounds of 60 percent strength dynamite was used. Smaller charges were prepared from sections of a five-pound stick. Larger charges were formed by binding five-pound units together.

Initially a quantity of Hercules FFG or FFFG powder was weighed out on a spring balance and placed in a piece of automobile radiator hose. Subsequent charges of approximately the same weight were prepared by filling sections of hose of equal length with powder. Charges exceeding 20 pounds, with the exception of the 40-pound charge in Experiment 45, were packed in two types of containers, which gave different results. The 45-pound charges were placed either in five-gallon shark-liver cans (each holding approximately 45 pounds, as determined by R. A. Peterson, of United Geophysical Company), or in two sheet-metal tubes, which were bound together to make a charge of about 40 pounds. Each tube was approximately five inches in diameter and twenty-five inches long. One detonator was placed in each tube and one in each five-gallon tin. The charge sizes as recorded in the table were obtained from William W. Rand.

Pressure Measurements

The pressures, recorded in pounds per square inch (Tables 2-4), were calculated by and obtained from E. Pat Shultz and Robert Day of the United Geophysical Company. The measurements were made with an underwater piezoelectric (tourmaline) gauge of type B (as illustrated by Cole, 1948, Fig. 5.11). Shultz reports (in letter) that "much of our technique followed the methods of Cole, and we used the well-known " Q-Step " system of calibration described by him on page 192, together with gauge constants supplied by the makers (Cambridge Thermionic Corp.) and independently checked by us with measurements of explosives (TNT) of standardized strength."

Permanent records were obtained by photographing the screen of a cathode-ray oscilloscope. Sample records for dynamite and black powder explosions illustrate a fundamental difference (Figures 8-9). The dynamite explosion record shows the sharp, violent nature and abrupt front of the pressure peak, as contrasted with the slow development of peak pressure of small amplitude from a black powder explosion.

During these trials it was found by Shultz that, when plotted on a log-log scale, the peak pressure near the bottom from jetted five-pound dynamite charges bore a linear relationship (Figure 10) to the distance from the explosion (the "Hydrophone Dist.") and the pressure decreased inversely as the 2.6 power of the distance, rather than the approximately 1.15 power usually reported for sea water.

Miscellaneous Data

Locality of each operation was obtained from the captain of the research vessel. Water depths were read directly from a Bludworth fathometer which signals in both fathoms and feet. Bottom samples were obtained from the jetting apparatus; in some experiments, also by diving. Rechnitzer and Limbaugh occasionally dove with self-contained diving apparatus in an attempt to determine effects that were not visible at the surface.

Criteria for Damage

• To stay on the safe side from the standpoint of the conservation and utilization of the fishery resources, rigid criteria were adopted for estimating the damage done to fish. Any apparent injury not definitely

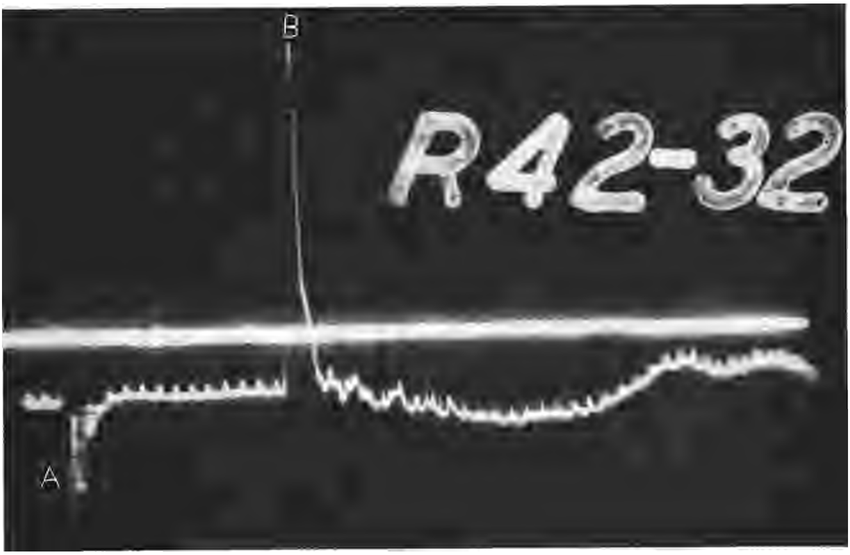

FIGURE 8. Oscillogram of 5-lb. dynamite explosion No. 19. (A) Charge fired. (B) Peak pressure, 83 p.s.i. The distance from (A) to the base of peak (B) measures the time required for the shock to travel from the explosion to the hydrophone. The distances between the small peaks represent milliseconds. *Photograph by E. Pat Shultz and Robert Day, April, 1951.*

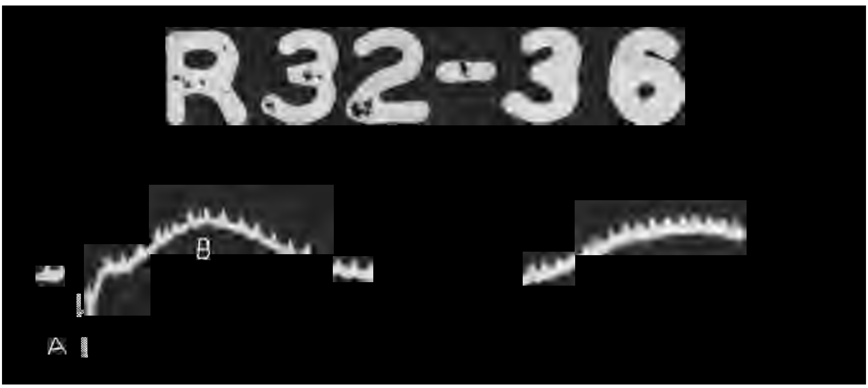

FIGURE 9. Oscillogram of 5-lb. black-powder explosion No. 65. Peak pressure (B), 6.8 p.s.i. *Photograph by E. Pat Shultz and Robert Day, April, 1951.*

attributable to handling or to other causes than that of the explosion was interpreted as an indication of probable death due to the blast. It is thought highly probable that most fish seriously injured by a blast would succumb later, through weakness, disease, or predation. Under favorable conditions, however, some and perhaps many of the affected fish, particularly those that are only temporarily stunned, probably recover and survive without permanent harm. The criteria, therefore, may have been too rigid. Further research is indicated.

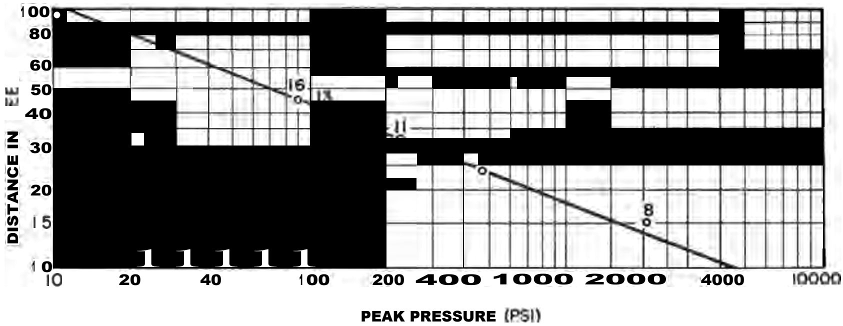

FIGURE 10. The decay with distance of the pressure from 5-lb. dynamite charges (decreasing inversely as the 2.6 power of the distance). Redrawn from graph prepared by E. Pat Shultz.

Internal damage, as determined by dissection, involved : (1) any hemorrhaging obviously not due to dissection, regardless of whether or not the cause of the bleeding was determined ; (2) any break in the viscera or peritoneum ; (3) a burst air-bladder ; (4) a ruptured kidney ; (5) gonad damage, or milt or eggs free in the abdominal cavity. Usually but not always any one of these symptoms was accompanied by several others, but in some tests only one was apparent.

Controls indicated that hemorrhaging in the muzzle and eyes of anchovies was due to confinement in the cages.

Results

Sharply contrasting results were obtained with dynamite (Table 2) and black powder (Table 4). Some comparative data were secured with Hercomite (Table 3).

The largest dynamite charges used in these experiments (10 pounds) do not compare with those that were often employed in the earlier seismographic studies nor with those utilized in the submarine-canyon studies reported above. Fish kills, nevertheless, resulted.

Ten-pound Charges of 60 Percent Dynamite

Whether exploded just below the surface (Exp. 1) or jetted 50 to 55 feet into the bottom sediment (Exps. 2-3), the 10-pound charges proved fatal to fish. The surface explosion, as would be expected from previous operations, killed fish (8 sauries). It was set off without the use of caged fish, to determine whether fish were present where they were not being killed by black powder. Both jetted blasts killed caged fish. One explosion destroyed caged fish from surface to bottom. The other blast, with somewhat lower indicated peak intensity, killed fish in the surface cage but not in the bottom container ; in addition it destroyed two free-swimming fish.

Five-pound Jetted Dynamite Charges

The 19 experiments (Nos. 4-22) performed with a five-pound jetted charge of 60 percent dynamite also indicated fatal results. This charge was used most frequently for three reasons : (1) it was thought to be desirable from a seismographic viewpoint ; (2) this size of charge was most conveniently handled in the jetting operation ; and (3) it was desired to have an experimental standard.

TABLE 2

Data on Effects of Underwater Explosions With 60 Percent Dynamite

The experiments are here numbered in sequence from more lethal to less lethal results, without reference to the sequence in which the trials were run. Controls are marked "Contr." in place of the pounds of the charge. Under "Location," "down" means below surface, "Bott." indicates that the charge lay on the bottom, and "J." stands for jetted. Under "Hydrophone Loc." (location), "Surf." and "Bott." respectively indicate attachment to surface cage or to bottom cage. The "Nos." in this column and under "Cage Loc." (location) refer to the cage numbers in the multiple-cage trials (Figure 7). "Hydrophone Dist." (distance) from charge was computed from the seismographic record. Full vernacular names and the scientific names are given on p. 366. Under "Free Fish Killed" the total kill of uncaged fish is estimated, including fish seen to be eaten by gulls and those seen swimming with greatly disturbed equilibrium.

Exp.	Lbs.	Location	Hydrophone		Peak p.s.i.	Water depth, feet	Cage loc.	Fish species	Fish in cages		Free fish killed
			Loc.	Dist., feet					Unharmed	Killed	
1	10	4' down	--	--	--	100	None	Saury	--	--	8
2	10	J. 50'	Surf.	82	82	29	Surf.	Sardine	0	1	0
								Anchovy	0	8	0
								Jack mackerel	0	2	0
								Pompano	0	1	0
							Bott.	Sardine	2	0	0
								Anchovy	6	0	0
								Jack mackerel	2	0	0
							--	Kingfish	--	--	2
3	10	J. 55'	No. 5	52	148	30	Surf.	Anchovy	0	18	0
							No. 1	Anchovy	7	0	0
							No. 2	Anchovy	0	10	0
							No. 3	Anchovy	10	4	0
							No. 4	Anchovy	8	5	0
							N. 5	Anchovy	0	16	0
							No. 6	Anchovy	7	7	0
							No. 7	Anchovy	0	13	0
							No. 8	Anchovy	0	16	0
							No. 9	Anchovy	0	6	0
3	Contr.						Surf.	Anchovy	10	0	0
							Bott.	Anchovy	11	0	0

4	5	J. 5'				27	None	Queenfish Kingfish			4 3
5	5	J. 7'	Bott.	61	163	22	None	Jacksmelt White seaperch			8 2
6	5	J. 15'	Bott.		403	56	Surf. Bott.	Anchovy Anchovy Jacksmelt	0 0	6 3 --	0 0 200
7	5	J. 15'	Surf.	49	176	30	Surf. Bott.	Anchovy Anchovy Jacksmelt	0 0	9 12 --	0 0 20
8	5	J. 15-18'	No. 2	22	1,343	30	Surf. Nos. 1-9	Anchovy Anchovy Jacksmelt White seaperch	0 0	3 51	0 0 80 1
8	Contr.						Surf. Bott.	White seaperch White seaperch	14 6	0 0	0
9	5	J. 25'	Bott.	24	468	56	Surf. Bott.	Anchovy Anchovy Jacksmelt Grunion	0 0	6 2	0 0 200 2
10	5	J. 30'	Bott.	29	501	56	Surf. Bott.	Anchovy Anchovy	4 4	0 0	0 0
11	5	J. 32'	Bott.	32	225	56	Surf. Bott.	Anchovy Anchovy Pacific mackerel Kingfish	0 0	3 3	0 0 1 4
12	5	J. 35'	Bott.	43	89	82	Surf. Bott.	Anchovy Anchovy	0 6	6 0	0 0
12	Contr.						Surf.	Anchovy	11	0	0

- These fish, in five of the earlier experiments, were not dissected and might have had internal injuries which later would have been regarded as indicative of probable death.

TABLE 2—Continued

Data on Effects of Underwater Explosions With 60 Percent Dynamite

Exp.	Lbs.	Location	Hydrophone		Peak p.s.i.	Water depth, feet	Cage loc.	Fish species	Fish in cages		Free fish killed
			Loc.	Dist., feet					Unharmed	Killed	
13	5	J. 35-40'	Bott.	42	111	56	Surf.	Queenfish	1	0	0
								Kingfish	1	0	1
							Bott.	Kingfish	2	0	--
14	5	J. 40'	Bott.	50	110	78	Surf.	Anchovy	10	0	0
								Jack mackerel	3	0	0
								Kingfish	3	2	0
							Bott.	Anchovy	6	0	0
								Jack mackerel	2	0	0
								Kingfish	5	0	0
15	5	J. 40'	No. 5	44	106	30	Surf.	Anchovy	10	0	0
							Nos. 1-9	Anchovy	57	0	0
15	Contr.						Surf.	Anchovy	30	0	0
							Bott.	Anchovy	7	0	0
16	5	J. 40'	Bott.	45	90	82	Surf.	Anchovy	6	0	0
							Bott.	Anchovy	4[1]	0	0
17	5	J. 40'	Surf.		43	26	Surf.	Anchovy	5	3	0
								Jack mackerel	1	2	0
								Kingfish	0	2	1
							Bott.	Anchovy	7	0	0
								Kingfish	0	1	--
								Shiner seaperch	--	--	1
17	Contr.						Surf.	Sardine	2	0	0
								Anchovy	4	0	0
								Jack mackerel	1	0	0
							Bott.	Anchovy	5	0	0
								Jack mackerel	3	0	0
18	5	J. 45'				30	Surf.	Anchovy	0	10	0
							Bott.	Anchovy	0	6	0
								Kingfish			1

19	5	J. 45'	Bott.	65	83	92	Surf.	Anchovy	4	2	0
							Bott.	Anchovy	6	0	0
20	5	J. 50'	Bott.		106	30	Surf.	Sardine	2	0	0
								Anchovy	3	0	0
								Jack mackerel	4	0	0
							Bott.	Sardine	[illegible]	0	0
								Anchovy	1	0	0
								Jack mackerel	1	0	0
20	Contr.						Surf.	Sardine	2	0	0
								Anchovy	4	0	0
								Jack mackerel	1	0	0
							Bott.	Anchovy	5	0	0
								Jack mackerel	3	0	0
21	5	J.50'	No. 5	67	76	30	Nos. 1-9	Anchovy	83	0	0
							1-2,4-9	Jack mackerel	11	0	0
22	5	J.65'	No. 5			30	Surf.	Anchovy	0	9	0
							Bott.	Anchovy	0	5	0
23	2½	J. 15'	Surf.		125	30	Surf.	Anchovy	0	7	0
							Bott.	Anchovy	5	2	0
24	2½	J. 15'	Surf.	75	50	30	Surf.	Anchovy	4	0	0
							Bott.	Anchovy	7	3	0
25	2½	J. 35-40'	Bott.		162	56	Surf.	Anchovy	0	8	0
							Bott.	Anchovy	7	2	0
								Jack mackerel	--	--	340
								Pacific mackerel			1
								Slim midshipman			1
								Pipefish			1
26	[illegible]	J. 10'	Surf.	34	186	28	Surf.	Anchovy	0	6	0
							Bott.	Anchovy	0	7	0
							--	Jacksmelt			5
27	1½	J. 10'				30	None	Jacksmelt			1
								White seaperch			1

I These fish, in five of the earlier experiments, were not dissected and might have had internal injuries, which later would have been regarded as indicative of probable death.

TABLE 2—Continued

Data on Effects of Underwater Explosions With 60 Percent Dynamite

Exp.	Lbs.	Location	H[illegible]		Peak [illegible]	Water depth, feet	Cage [illegible]	Fish species	Fish in cages		Free fish killed
			Loc.	Dist., feet					Unharmed	Killed	
28	[illegible]	J. 15'	No. 5	20	296	30	Nos. 1-3, 5-9	Anchovy	7	38	0
							No. 4	Anchovy	0	6	0
								Grunion	0	1	0
29	[illegible]	J. 15'	Surf.	43	117	30	Surf.	Anchovy	0	5	0
								Grunion	0	2	0
30	[illegible]	J. 15'	B[illegible].	52	30	30	None				0
31	[illegible]	J. 15'	B[illegible].	54	24	30	Surf.	Anchovy	6		
32	[illegible]	J.25'	Surf.	60	73	29	Surf.	Anchovy	0	4	0
								Grunion	0	2	0
							B[illegible].	Anchovy	0	5	0
33	[illegible]	J. 30'	B[illegible].	26	128	29	Surf.	Anchovy	2	7	0
								Grunion	0	1	0
							B[illegible].	Anchovy	3	4	0
34	[illegible]	J. 30'	Surf.	65	54	29	Surf.	Anchovy	6	0	0
								Grunion	2	0	0
							B[illegible].	Anchovy	8	0	0
35	[illegible]	J. 30'	Surf.	68	50	29	Surf.	Anchovy	4	2	0
								Grunion	0	2	0
							B[illegible].	Anchovy	5	0	0
36	[illegible]	J. 30'	Surf.	65	45	29	Surf.	Anchovy	6	0	0
								Grunion	1	0	0
							B[illegible].	Anchovy	10	0	0

TABLE 3

Data on Effects of Underwater Explosions With Hercomite

For abbreviations see sublegend to Table 2

Exp.	Lbs.	Location	Hydrophone		Peak p.s.i.	Water depth, feet	Cage loc.	Fish species	Fish in cages		Free fish killed
			Loc.	Dist., feet					Unharmed	Killed	
37	4	J. 20'	Bott.	17	193	30	Surf.	Anchovy	0	9	0
							Bott.	Anchovy	0	5	0
								Queenfish	0	1	0
38	4	J. 30'	Bott.	29	138	30	Surf.	Anchovy	0	12	0
							Bott.	Anchovy	0	9	0
38	Contr.						Surf.	Anchovy	4	0	0
							Bott.	Anchovy	4	0	0
39	Contr.					30	Surf.	Anchovy	5	0	0
							Bott.	Anchovy	6	0	0

TABLE 4

Data on Effects of Underwater Explosions With FFG and FFFG Black Powder

For abbreviations see sublegend to Table 2

Exp.	Lbs.	Location	Hydrophone		Peak p.s.i.	Water depth, feet	Cage loc.	Fish species	Fish in cages		Free fish killed
			Loc.	Dist., feet					Unharmed	Killed	
40	45	4' down	Bott.	43	160	100	Surf.	Anchovy	10	0	0
							Bott.	Anchovy	5	0	0
								Pompano	1	0	0
							--	Pacific mackerel	--	--	1
41	45	4' down	Bott.	39	124	100	Surf.	Anchovy	11	0	0
							Bott.	Anchovy	9	0	0
42	45	4' down	Bott.	23	--	100	Surf.	Anchovy	9	0	0
43	40	4' down	Bott.	61	--	100	Surf.	Anchovy	1	6	0
							Bott.	Anchovy	8	0	0
44	40	4' down	Bott.	56	--	100	Surf.	Anchovy	1	8	0
							Bott.	Anchovy	7	0	0
45	40	J. 10'	Bott.	37	41	30	Surf.	Anchovy	12	0	0
							Bott.	Anchovy	12	0	0
46	20	4' down	Surf.	21	20	100	None	--	-	--	
47	20	J. 10'	--	--	--	30	Surf.	Anchovy	4	0	0
								Queenfish	1	0	0
							Bott.	Anchovy	8	0	0
48	20	J. 10'	Bott.	17	48	30	Surf.	Anchovy	8	0	0
							Bott.	Anchovy	6	0	0
49	20	J. 10'	Bott.	14	58	30	Surf.	Anchovy	10	0	0
							Bott.	Anchovy	8	0	0
50	10	2' down	Bott.	23	--	100	Surf.	Anchovy	10	0	0
								Grunion	1	0	0
51	10	Bott.	Bott.	14		30	Surf.	Anchovy	5	2	0
							Bott.	Anchovy	1	4	0
52	10	Bott.	Bott.	21	--	30	Surf.	Anchovy	6	0	0
							Bott.	Anchovy	7	0	0
53	10	J. 5'	--	--	--	30	Surf.	Anchovy	6	0	0
							Bott.	Anchovy	7	0	0
54	10	J. 5'	--	--		30	Surf.	Anchovy	6	0	0
							Bott.	Anchovy	2	0	0
55	10	J. 10'	Bott.	20	10.8	30	Surf.	Anchovy	7	0	0
								Jack mackerel	2	0	0
							Bott.	Anchovy	7	0	0

56	10	J. 10'	Bott.	13	10	30	Surf.	Anchovy	4
								Kingfish	2
							Bott.	Anchovy	5
								Jack mackerel	1
								Kingfish	2
57	9	J. 20'	Bott.	73	4.0	92	Surf.	Anchovy	8
							Bott.	Anchovy	5
58	9	J. 20'	Bott.	27	11	92	Surf.	Anchovy	8
							Bott.	Anchovy	10
59	9	J. 20'				92	Surf.	Anchovy	12
							Bott.	Anchovy	8
60	5	Bott.	Bott.	11	38	30	Surf.	Anchovy	4
							Bott.	Anchovy	6
61	5	Bott.	Bott.	10	32	30	Surf.	Anchovy	9
							Bott.	Anchovy	9
62	5	J. 5'	Bott.	13	6.7	30	Surf.	Anchovy	11
								Grunion	1
								Kingfish	1
							Bott.	Anchovy	11
								Grunion	1
								Kingfish	2
63	5	J. 5'	Bott.	92	1.7	30	Surf.	Anchovy	10
								Pompano	1
								Kingfish	1
							Bott.	Anchovy	7
								Kingfish	1
64	5	J. 10'	Surf.	38	1.5	30	Surf.	Anchovy	7
								Pompano	1
								Jack mackerel	1
							Bott.	Anchovy	7
								Pompano	1
								Jack mackerel	1
65	5	J. 10'	Bott.	19	6.8	30	Surf.	Anchovy	4
								Pompano	4
								Jack mackerel	1
							Bott.	Anchovy	6
								Jack mackerel	3
								Queenfish	1
66	5	J. 10'				30	Surf.	Anchovy	4
								Queenfish	2
							Bott.	Anchovy	7
67	4	J. 20'	Bott.	25	7.8	92	Surf.	Anchovy	8
							Bott.	Anchovy	4

Some of the variation in the indicated kill is attributable to the fact that the test fish in some of the early trials, listed in Table 2 as Exps. 10, 13, 15, 16, and 20, were not dissected immediately and hence might have shown, on closer scrutiny, signs of injury (p. 347) that we construe as probably fatal. The peak intensity of shock recorded for these experiments is well above the apparent lethal threshold of 40 to 70 p.s.i. indicated by other experiments (as Exp. 17), and measured as indicated on p. 345.

Five-pound charges damaged fish at distances of about 65 feet (measured by hydrophone data in Exp. 19 and estimated from the jetted depth in Exp. 22) . A pressure of 83 p.s.i., however, was recorded in Exp. 19 at the bottom cage where fish were apparently unharmed. It is probable that the fish were in the shadow zone (p. 362) of the focused compression wave.

The dampening effect of the bottom sediments on the shock wave was usually not great enough to eliminate the lethal effects of five-pound dynamite explosions, even though most of the trials were run where there is a very deep sedimentary overburden of clay-sand mixture, which is thought to be more effective than sand in decreasing the transmitted energy. The hard-rock surface here is presumably too deep to produce an effective reflection of the downward component.

With increase in depth of jetting there was, with some irregularities, a decrease in the observed kill. Large kills of free-swimming fish were recorded only for shots jetted less than 30 feet. At intermediate depths of jetting the kill was commonly greater in the surface than in the bottom cage. When the five-pound charge was jetted deeper than 35 feet (10 experiments, Nos. 13-22), there was usually little or no kill in either surface or bottom cage, or in the surrounding water. In two trials (No. 18, charge jetted to 45 feet, and No. 33, charge jetted to the greatest depth attained in any of the experiments, 65 feet), however, there was complete destruction of the fish in both cages. Clearly, the effects of dynamite explosions are difficult to interpret and unsafe to predict.

Two and One-half Pound Jetted Dynamite Charges

Caged fish were damaged in all three experiments (23-25) using 2½ pounds of 60 percent dynamite. Experiment 25 resulted in the killing of more free fish than any other during the entire test period. Forty-four jack mackerel, one Pacific mackerel, one midshipman, and one kelp pipefish were recovered. Approximately 300 additional jack mackerel were injured but did not surface completely. They were sufficiently incapacitated to make us believe that they probably would not have recovered before being preyed upon by predators, such as sea lions, several of which, in fact, soon entered the experimental area and probably fed on the injured fish. By diving, an attempt was made to estimate the total number of fish killed or damaged, but turbidity rendered the observations incomplete. Although it was estimated that the charge was jetted 35-40 feet into the sand bottom, the recorded peak pressure of 162 p.s.i. at the surface and the heavy kill suggest that the charge may have been inadvertently pulled to a shallower depth, or that the location of the charge very close to the underlying hard rock may have nearly doubled the intensity of the shock in the water. In the two other experiments no free-swimming fish were killed and the destruction of caged fish was about two-thirds and one-fifth, respectively.

One and One-quarter Pound Jetted Dynamite Charges

The lethal effects on fish of underwater explosions of jetted dynamite were by no means eliminated by a reduction of the charge to only 1¼ pounds. Free-swimming fish were killed by the two explosions at the jetted depth of 10 feet (Exps. 26-27), but none were destroyed in the nine trials (Exps. 28-36) in which the charge was jetted 15 to 30 feet. Of the nine experiments in which cages were used, there was a partial to complete kill of the caged fish in six trials. In Exp. 26, with the charge jetted to 10 feet, all 13 of the caged fish plus 5 free-swimming jacksmelt were killed. In Exp. 28, with the charge jetted to 15 feet, 45 out of 52 experimental fish were destroyed. In another trial (Exp. 29), with the same depth of jetting, all fish were killed ; in yet another (Exp. 31), all survived. In Exp. 32, with the charge at 25 feet, there was a complete kill. In the three runs with the explosion at 30 feet the results were varied. In the whole series there was a heavy to complete kill when the peak p.s.i. was recorded as greater than 70, and little or no kill when the peak was below 60 pounds.

Four-pound Jetted Hercomite Charges

When it became apparent that even very small jetted charges of dynamite often kill fish, two trials were run with Hercomite powder (Table 3), in water 30 feet deep. Four-pound charges were jetted 20 and 30 feet, respectively. .Peak pressures of 193 and 138 p.s.i. were recorded at the bottom cages, respectively 17 and 29 feet from the blast (measured instrumentally). These determinations indicate that the cages were directly over the blasts. All 36 fish in the surface as well as the bottom cages were killed in the two experiments. In two controls, the 19 fish used were unharmed. Though only the two experiments were run it seems probable that Hercomite resembles dynamite in its lethal effects on fishes.

Black Powder Charges

Strikingly different results were attained as soon as black powder (FFG and FFFG) was tried and rather consistent evidence accumulated

TABLE 5

Fish Killed During Oil Exploration Under Permit From California Department of Fish and Game *

September 4, 1951, to March 21, 1952

Pt. Conception to San Mateo Point

Number of fish killed per shot	Number of open shots	Number of jetted shots	Total shots
0	2,332	508	2,840
1	1	2	3
9	1	0	1
20	1	0	1
200	0	2	2
Total number of shots	2,335	512	2,847
Total fish killed	30	402	432
Average kill per shot	0.013	0.79	0.15

A maximum of 45 pounds of Hercules FFFG black powder was used on all work during the month of September, 1951; revision of permit effective October 1, 1951, allowed a maximum of 90 pounds of powder on both open and jetted shots. In general the practice has been to use 40 pounds of powder on jetted shots and the maximum of 90 pounds on open shots.

as the experiments were continued (Table 4). Very few fish were killed either inside or outside the cages, even when the weight of the charges was increased to 45 pounds and some of the charges were fired on the bottom and others were exploded just below the surface—in positions where dynamite is often very destructive. In the subsequently resumed seismographic surveys, according to reports by the state observers, extremely few fish have been killed, even by charges up to 90 pounds (Table 5).

In 17 experiments (Nos. 45, 47-49, 53-59, 62-67), in which from 4 to 40 pounds of black powder were exploded after having been jetted into the bottom sediments 5 to 20 feet, not a single fish death, on the basis of stringent criteria (p. 345), was recorded either inside or outside the cages.

In the two trials (60 and 61) in which five pounds of black powder was exploded on the bottom none of the fish was killed in cages held only five feet away, or in the overlying surface cages, or in the surrounding water. In two similar experiments (51 and 52), in which the cage was held only 10 feet away from a 10-pound black powder explosion on the bottom, none of the fish were killed in one trial, but half in the two cages were destroyed in the other. No free-swimming fish were killed in these experiments.

Ten-pound and twenty-pound charges of black powder when exploded just below the surface (Exps. 50 and 46) killed no fish anywhere. Subsurface explosions of 40 and 45 pounds (Exps. 41-44) varied in effect, depending apparently on either the type of container or the number of detonators employed. In two trials most of the fish in the surface cages were destroyed by 40-pound charges of black powder formed by binding together two sheet-metal containers five inches in diameter and 25 inches long, discharged by two detonators. Charges of similar weight in a shark-liver can with a single detonator caused no kill to caged fish only 20 feet from the explosion. That fish at somewhat greater distances are probably not killed by even such large charges of black powder is indicated by the fact that only one free-swimming fish, a mackerel, was destroyed in these four rigid tests. This was the only fish that was killed outside a cage in any of the 28 black powder experiments.

The resistance of fish to black powder explosions was dramatically exhibited in Exp. 54, in which 10 pounds of black powder exploded so close that the cage was badly damaged and partly covered with debris and the door was blown in (Figure 11). Though covered with mud, the two fish that failed to escape showed no signs of damage.

Effects of a jetted black powder shot are evident very soon—in about four or five seconds when the shot is in water about 30 feet deep. The large volume of suddenly generated gas carries mud and fine sand to the surface, forming a mushroom-shaped boil (Figure 12) that rapidly spreads over the surface. The resulting slick (Figure 13) usually has a diameter of 50 to 100 feet, depending on the size and depth of the charge. The amount of sand and mud that is brought to the surface seems to be relatively limited, for it forms only a superficial layer of murky water, below which clearer water can be observed. Jetted dynamite produces much less

FIGURE 11. Bottom cage damaged by 10-lb. black powder explosion No. 54. Remaining fish showed no damage. ***Photograph by William W. Rand, April, 1951.***

FIGURE 12. Gas boil produced by a black powder explosion. ***Photograph by William W. Rand, April, 1951.***

FIGURE 13. Slick following a black powder explosion boil. ***Photograph by William W. Rand, April, 1951.***

gas and often no boil. The arrival of the shock wave from a dynamite explosion can be noted at a calm surface by the region of cavitation, which momentarily forms a small hump or dome.

In respect to both sound and shock the effects of black powder shots are relatively slight, as compared with explosions of dynamite or Hercomite. Frequently the jetted shots are barely audible and in the launch are often missed entirely. Black powder shots near the surface produce spouts 50 to 150 feet high, according to the size of the charge, but generate much less noise than do similar dynamite or Hercomite explosions.

The black powder explosions did not seem to have any conspicuous influence on the availability of game fish to sportsmen, as such fish were taken in the immediate vicinity soon after the shots were fired. They were apparently neither driven away nor deterred from feeding.

Explanation of Results

To explain the varied effects on fish life of underwater explosions it is desirable to examine and analyze individual components of the explosion complex, although, in general, the pattern of waves and other associated physical phenomena are quite complicated and, so far as we can learn, their interaction and the resultant forces are not completely understood. The most significant parameters are thought to be the amplitude (peak pressure), the type of compression wave, and rarefaction.

Underwater explosions produce two types of positive pressure waves, the initial compression or shock wave and the following bubble-pulse wave (Cole, 1948). The primary disturbance to the water during an explosion is caused by the arrival of the compression wave from the reacting explosive. Once initiated, the disturbance is propagated through the water as a pulse of compression with a leading front, which is steep (a shock front) or gentle, depending on the explosive used (Figures 8-9) . The top of the pressure curve represents the peak pressure. In a uniform medium the peak pressure undergoes an exponential decay that is a function of the type of charge, its weight, and the distance from the charge. The peak pressure at a given distance is greater for larger weights, but increases only in proportion to the one-third power of the charge. The peak pressure from a given charge decreases with increasing distances. The rate of decay of energy varies with conditions. In open water the peak pressure from dynamite explosions is usually indicated as varying inversely as the 1.15 power of distance (not the 3.0 power assumed by Fitch and Young, 1948, p. 55). When the explosive is jetted into the bottom, the rate of energy decay is much greater. Data obtained during the experiments indicate that the approximate pressure near the bottom from jetted five-pound dynamite charges varies inversely as the 2.6 power of the distance (p. 345; Figure 10).

In either dynamite or black powder explosions the bubble pulse, shown at the right side in Figures 8 and 9, is relatively of long duration and low maximum pressure, without an abrupt front. In dynamite discharges, the bubble pulse has a maximum pressure far below that of the shock pulse. No indications were obtained that the bubble pulse from any of the explosions observed was of major significance in the destruction of fish.

The differential effects of dynamite and black powder explosions are attributable directly or indirectly to the abrupt shock wave produced by dynamite blasts. Dynamite detonates with a large and rapid evolution of energy, attaining its maximum intensity almost instantaneously. Once started, the disturbance is propagated through the water as a pulse of compression with a very steep shock front (Figure 8) . Hercomite, to judge from its effects on fish in two experiments, resembles dynamite in its action, Black powder, in contrast, burns more slowly and does not produce a shock wave with an abrupt front (Figure 9). Nor, with comparable charges, is the peak intensity nearly so high. The lethal threshold peak pressures from dynamite explosions varied in our tests from 40 to 70 p.s.i. (as measured by the research engineers of the United Geophysical Company), whereas peak pressures from black powder explosions as high as 124 to 160 p.s.i. (similarly measured) did not kill fishes in the experimental cages (Tables 2, 4) . One obvious reason why fish are resistant to black powder explosions, even of high intensity, is their relative immunity to less than almost instantaneous pressure changes. In other experiments fish subjected by us rather slowly to hydrostatic pressures as great as 1,000 p.s.i. showed no apparent physical damage, even after a relatively sudden release of the pressure. Positive pressure in the range of 15 to 500 p.s.i. (one to 33 atmospheres), even though maintained for a 12-hour period, produced, so far as could be observed, little immediate effect and no lasting discomfort or pathology. Regnard (1884) found that freshwater fish whose air-bladder had previously been emptied of air showed no effect when a pressure of 100 atmospheres of pressure was applied to them.

The reason why a large decrease in the weight of a dynamite charge results in unexpectedly little reduction in the kill is that the peak pressure does not bear a linear relation to the weight of the charge, but, rather, varies as the one-third power of charge size. A five-pound charge, for example, yields about one-third the peak pressure that a 125-pound charge does. The usefulness of a charge for seismographic work does not decrease in direct proportion to its reduced weight, but, similarly, the fish-killing powers do not decrease in that ratio.

It seems probable that the peak pressure from the black power explosions does not increase at as high a rate as does the pressure from dynamite blasts. E. Pat Shultz reports (in letter) that "With black powder increasing the charge size probably does not increase the peak pressure very much, but rather merely increases the duration of the pressure pulse. This is because the propagation rate of the burning is less than that of sound, and hence the full effect does not arrive at a distant point all at one time, as in a shock wave."

It was noted early in the experiments with dynamite that while fish in the surface cage were physically damaged by the blast, those in the bottom cage, nearest the explosion, often suffered no harm or less damage (Exps. 2, 3, 12, 14, 17, 19, 23, 25, 35) . It was noted further that the free fish that were killed were mostly surface rather than bottom inhabitants. These observations can be explained in part only on the assumption that many bottom dwellers do not possess air-bladders and are therefore more resistant to explosions. Such bottom fishes as the kingfish, and others with large air-bladders, were found to be in the immediate area during some of the tests, but few were killed.

The greater mortality at the surface is probably caused by the intensity there of the rarefaction wave. It is assumed that, when reflected from the surface of a less dense medium, as from the water-air interface, a compression wave, if of sufficient amplitude, assumes the opposite sign through change of phase and is thus transformed, with some loss of energy, into a negative-pressure pulse, called a rarefaction wave (Cole, 1948). The suddenly applied negative pressure (considering atmospheric pressure as the base of reference) is probably particularly deleterious, even though, as Cole (1948) indicates, negative pressures as great as one atmosphere are not likely to be realized in natural waters, because of the dissipation of energy through cavitation.

In a system involving much less rapid changes, a negative pressure of 25 inches of mercury applied for a period of 15 seconds has been held to kill a number of freshwater species having air-bladders (Hogan, 1940) Preliminary experiments by us indicate that marine fishes with an air-bladder are quickly killed by negative pressures of between 20 and 30 inches of mercury, whereas those without an air-bladder survive such treatment.

That suddenly applied negative pressures kill fish appears to be indicated by the outward explosion of the air-bladders. In a report published by the Chesapeake Biological Laboratory it is stated that "post mortem observation showed that the edges of holes in the swim bladder were turned outward and that blood from broken vessels in the wall of the bladder had been blown into the abdominal cavity" (Anonymous, 1948). Similar observations were independently made during the experiments just concluded. Dynamite-destroyed kingfish had the visceral cavity filled with gas, which had obviously been released, under some pressure, from the ruptured air-bladder, thereby rendering the fish buoyant.

Negative pressure may cause injury or death in part through the formation of bubbles in the body fluids. We assume, in particular, that negative pressure may liberate dissolved gases suddenly enough and in sufficient quantity to rupture the walls of unprotected blood vessels.

The deadliness of the rarefaction wave is doubtless greatest near the surface. The negative-pressure wave is propagated downward through the water, but becomes sharply attenuated with distance and tends to be cancelled by the increase in hydrostatic pressure and, at certain times and locations, by the simultaneous arrival of compression waves reflected from the bottom.

The difference in deadliness to fishes of dynamite and black powder explosions is presumably due in part to much higher negative pressures induced by dynamite. Cole (1948: 261) wrote that "in nearly all cases a negative absolute pressure is predicted for explosive waves of short duration." The wave from black powder blasts is of relatively long duration and low amplitude (Figures 8-9) .

Large variations in fatalities in different cages may have been caused by the focusing of the path of the blast energy. The energy that is transmitted upward through the jet hole spreads out through the broad conical crater formed during the jetting (the craters were observed by diving). It is assumed that much of the energy emerging from the crater and from the surrounding bottom deposits is propagated through the water in a cone of similar form, leaving a shadow zone close to the bottom around the crater. The nine-cage unit was adopted in part to determine whether differential damage might be detected as a consequence of the directed energy. In Exp. 3, for example, there appears to have been such a focusing of the energy, for the kill was differential, with no deaths in the bottom cage nearest the crater but complete mortality in the directly overlying cages (compare data in Table 2 with the cage diagram, Figure 7). The compression pulse, measured at the surface, was 148 p.s.i., well beyond the lethal threshold recorded in the experiments (40-70 p.s.i.). That the margin of the cone of high pressure may be sharp is suggested by certain experiments, for example Exp. 19, in which fish were unharmed in the bottom cage although a gauge attached to the top of this cage registered a peak pressure of 83 p.s.i., also within the usual fatal dose.

Great variation was observed in the damage to fish caused by the underwater explosions. The variable factors appear to include, among others, the type and amplitude of the pressure pulse, the kind of bottom, and the structure and size of the fish. It is obvious that no simple explanation could be offered for all of the varied results, even though knowledge of the physical phenomena associated with fish and with explosives were much more complete than it is. The knowledge at hand, however, allows us to reach some plausible inferences.

As the pathological conditions of hemorrhaging, burst air-bladders, and general disruption of the viscera are shown by dissection and as the sequence of events of an underwater explosion are rapid compression soon followed by rarefaction, it appears reasonable to suspect that compression suddenly applied and rarefaction are the factors that lethally damage fish, particularly those near the surface.

CONCLUSIONS AND SUMMARY

This investigation arose from a conflict between different interests involved in the exploitation of the marine resources of California. Seismographic exploration for submarine oil had been suspended, through the revocation of licenses, because the explosions had destroyed large numbers of fish. The purpose of the study was to determine if the explosives might not be handled in such a way, as through a reduction in the size of charge or through altered methods, that most of the danger of killing fish would be eliminated.

Large charges of such violent explosives as dynamite—say from 50 to 200 pounds—were known to be very destructive to fish life. Considerable areas can be more or less depopulated by repeated blasts, as indicated by operations observed in a submarine canyon. Repopulation, however, took place within a few months.

Charges even as small as ten, five, two and one-half, or one and one-quarter pounds often killed fish, even when the explosive had been buried many feet in the bottom sediments. The amount of loss varied and was difficult to assess completely. Hercomite appeared to resemble dynamite in its effect on fishes.

The lethal effects of small charges of dynamite is in agreement with expectation, since the peak pressure varies as the one-third power of the weight of the charge. For example, a one-pound charge produces one-half the pressure that an eight-pound charge does. The effect of even large explosions becomes dissipated with distance, quite rapidly when the charge is jetted. For five-pound jetted dynamite charges used in these trials the peak pressure near the bottom varied as the 2.6 power of the distance.

The effect of underwater explosions of such substances as dynamite if often intensified at the surface, where the positive compression wave is reflected as a rarefaction wave. Fishes are very susceptible to negative pressures (that is, to pressures less than the atmospheric pressure). Black powder is much less effective than dynamite in producing such negative pressures.

Black powder explosions proved to be relatively inoccuous in a series of experiments, even with charges as high as 20 to 45 pounds, whether the charge was buried in the sediments, resting on the bottom, or suspended near the surface. These results were rather unexpected, though consistent with other observations. The resistance of fish to even larger black powder explosions is obviously due to the relatively slow burning quality of this powder. Oscillograms showed that the energy from black powder explosions is not propagated on the very abrupt front that emanates from a dynamite blast. Resistance to very large and relatively rapid changes in positive pressure is a known attribute of fishes, but they cannot tolerate the armost instantaneous changes induced by high explosives. The rigidly construed lethal-threshold peak pressures from dynamite explosions, as measured by the research engineers, varied from 40 to 70 p.s.i. in our tests,[2] whereas peak pressures from black powder explosions as high as 124 to 160 p.s.i. did not kill fishes in the experimental cages. Indications were obtained that black powder discharges do not even drive fish away or prevent them from feeding.

The experiments strongly indicated that it would be safe to utilize even large charges (to at least 45 pounds) of black powder, as a source of energy for submarine seismographic surveys. Unknown and untested factors, including the size of the fish and of its air-bladder, led us to make some reservations in judgment—reservations that could best be tested during actual operations, by observing the effects of such explosions on free-swimming fishes of varied sorts and sizes. Such checking has been maintained and the reports of recent surveys support the view that the use of black powder in charges as large as 90 pounds will not cause excessive loss of fish.

It would therefore appear that the State is not confronted with a problem of oil [illegible] fish. The evidence leads to the conclusion that exploration for oil can be continued without the undue destruction of fish life. A major conflict of interests in the exploitation of our marine resources seems to have been resolved.

O[illegible] C[illegible] B[illegible] (A[illegible], 1947, 1948) Indicate[illegible] TNT[illegible]. O[illegible]. C[illegible].

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FISH SPECIES MENTIONED

Only the vernacular names are used in the text. The species used in the 1951 experiments are marked by an asterisk (*), by a dagger (†), or by both, as explained on page 341. Some of these species and all those unmarked below, except the señorita, were killed in Scripps Submarine Canyon in 1950, as detailed in Table 1.

*Pacific sardine, *Sardinops caerulea* (Girard)
*Ocean northern anchovy, *Engraulis mordan mordax* Girard
Panama bristlemouth, *Vinciguerria lucetia* (Garman)
†Pacific saury, *Cololabis saira* (Brevoort)
Kelp bass, *Paralabrax clathratus* (Girard)
Sand bass, *Paralabraz nebulifer* (Girard)
*tGrunion, *Leuresthes tenuis* (Ayres)
†Jacksmelt, *Atherinopsis californiensis* Girard
Kelp topsmelt, *Atherinops affinis cedroscensis* Hubbs
*flack mackerel, *Trachurus symmetricus* (Ayres)
*California pompano, *Palometa simillima* (Ayres)
tPacific mackerel, *Pneumatophorus japonicus diego* (Ayres)
Sargo, *Anisotremus davidsoni* (Steindachner)
*†Kingfish (tomcod croaker), *Genyonemus lineatus* (Ayres)
*†Queenfish, *Seriphus politus* Ayres
Ocean whitefish, *Caulolatilus princeps anomalus* (Cooper)
Shiner seaperch, *Cymatogaster aggregata* (Gibbons)
Pink seaperch, *Zalembius rosaceus* (Jordan and Gilbert)
Buttermouth seaperch, *Embiotoca* sp.
tWhite seaperch, *Phanerodon furcatus* Girard
Sharpnose seaperch, *Phanerodon atripes* (Jordan and Gilbert)
Rubberlip seaperch, *Rhacochilus tonotes* Agassiz
Pile perch, *Damalichthys vacca* Girard
Blacksmith, *Chromis punctipinnis* (Cooper)
Garibaldi, *Hypsypops rubicunda (Girard)*
California sheepshead, *Pimelometopon pulchrum* (Ayres)
Opaleye, *Girella nigricans* (Ayres)
Sefforita, *Owyjulis californica* (Gunther)
Bocaccio, *Sebastodes paucispinis* (Ayres)
Bass rockfish, *Sebastodes serranoides* Eigenmann and Eigenmann
Vermilion rockfish, *Sebastodes rosaceus* (Girard) (=*S. miniatus*)
Kelp rockfish, *Sebastodes atrovirens* (Jordan and Gilbert)
Widow rockfish, *Sebastodes ovalis* Ayres
Spotted rockfish, *Sebastodes hopkinsi* Cramer
Halfband rockfish, *Sebastodes semicinctus* Gilbert
Speckled rockfish, *Sebastodes umbrosus* (Jordan and Gilbert)
Rosy rockfish, *Sebastodes* sp. (=*S. rosaceus* of recent authors)
Greenspotted rockfish, *Sebastodes chlorostictus* (Jordan and Gilbert)
Pink rockfish, *Sebastodes eos* Eigenmann and Eigenmann
Starry rockfish, *Sebastodes constellatus* (Jordan and Gilbert)
Spanishflag, *Sebastodes rubrivinctus* (Jordan and Gilbert)
Striped rockfish, *Sebastodes elongatus* (Ayres)
Brown rockfish, *Sebastodes auriculatus* (Girard)
Whitebelly rockfish, *Sebastodes vexillaris* (Jordan and Gilbert)
Calico rockfish, *Sebastodes dalli* (Eigenmann and Beeson)
Treefish, *Sebastodes serriceps* (Jordan and Gilbert)
Rockfish (species?) ; very young, *Sebastodes* sp.
†Kelp pipefish, *Syngnathus californiensis* Storer
Crested goby, *Coryphopterus nicholsti* (Bean)
Zebra goby, *Lythrypnus zebra* (Gilbert)
Northern midshipman, *Porichthys not atus* Girard
tSlim midshipman, *Porichthys myriaster* Hubbs and Schultz
Spotted cusk-eel, *Otophidium taylori* (Girard)

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64157 6-52 3M