SOUTHWEST FISHERIES CENTER

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IDENTIFICATION, CHEMISTRY, AND BEHAVIOR OF SEAL BOMBS USED TO CONTROL DOLPHINS IN THE YELLOWFIN TUNA PURSE-SEINE FISHERY IN THE EASTERN TROPICAL PACIFIC: POTENTIAL HAZARDS

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ADMINISTRATIVE REPORT LJ-90-08

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ABSTRACT

We examined seven types of seal bombs known to be in use in the fishery. Two U.S.-made, Class-C units contained a potassium perchlorate oxidizer in a mixture resembling an M-80 pyrotechnic. The others were foreign-made and contained potassium chlorate, an oxidizer that is more reactive and unstable than potassium perchlorate. All seven units probably have a TNT equivalency of 80% or greater and are injurious to dolphins to some degree when exploded underwater within 4 m, with moderately severe injury likely at 0.5 m or less.

INTRODUCTION

A very close association exists between adult yellowfin tuna and dolphin schools in the eastern tropical Pacific (ETP). Because of the association, purse-seine fishermen have found that the most efficient method of fishing for large yellowfin tuna in the ETP is to herd dolphin schools into their nets to catch the tuna that follow them (Perrin 1969). Herding tactics include rounding up the dolphins using speedboats, helicopter, net skiff, seiner, and the attendant noise and turbulance that they produce, to achieve and maintain control of the dolphins' swimming direction until the net is deployed around the school. The fishermen have tried and have continued to experiment with numerous devices to improve and strengthen their means of dolphin control. One of these devices is a small hand-thrown explosive, known as a "pest-control" or "seal-control device," or "seal bomb."

The seal bomb and its uses have evolved in the yellowfin tuna fishery. Probably as early as the introduction of the purse-seiner into the fishery in the 1950's, at least two kinds of seal bombs were already being used in sets on school fish (without dolphins) to try to keep the fish from avoiding or escaping the net (McNeely 1961). The first to be used, was the "old style 'cherry bomb' [a spherical, red-colored] firecracker-type explosive." This was replaced by "...larger, cylindrical-shaped explosives [M-80 in appearance, with the fuse placed on the side], with enough weight to make them sink" (McNeely 1961, p. 51; see our Fig. 1).

Seal-bomb use on dolphin schools, occurred at least as early as 1980 (Cassano et al. 1990). By then, the seal bomb had taken on a more familiar morphology, including larger size and end-fusing. The various types of seal bombs now known to be in use, are all about the same size (6.0 to 9.0 cm x 1.0 to 2.0 cm) and cylindrical shape (Fig. 2). All are weighted at one end and have a short waterproof fuse on the other. After being ignited and thrown, they sink to a depth of 1 to 4 meters before detonation. Apparently, they all are derived from the basic M-80 design, with only superficial differences such as weighting and waterproofing needed for their use in the water.

Seal bombs have become widely used in chase, encirclement, and release stages of dolphin sets in recent years. In 1989, the National Marine Fisheries Service's (NMFS) records of purse-seine sets showed seal-bomb use in dolphin sets to be 40% (Cassano et al. 1990). Nevertheless, apparently about 29% of the skippers in the U.S fleet do not use explosives at all, and 39% are reported to be using them only occasionally, i.e., in 15% or less of all of the dolphin sets that they make (Cassano et al. 1990).

The 1988 amendments to the Marine Mammal Protection Act of 1972 restrict the use of seal bombs in the yellowfin tuna fishery to Class-C pest control devices. In addition, they direct NMFS to determine that the use of Class-C seal bombs in purse-seine sets on dolphins does not increase injury to or mortality of the dolphins, otherwise further restrictive action is to be taken on seal-bomb use in the fishery.

The definition of "Class-C pest control devices" is central to these regulations. According to the Code of Federal Regulations (CFR) for the U.S. Department of Transportation (Office of the Federal register, National Archives and Records Admin., 1988), "Explosives, Class C, are defined as certain types of manufactured articles which contain Class A, or Class B explosives, or both, as components but in restricted quantities...Explosive pest control devices, class C explosives, consist of cardboard-pasteboard type tube not exceeding 4 inches [10.16 cm] in length and 3/4 inch [1.91 cm] in diameter...They may contain a mixture of potassium perchlorate, aluminum powder, sulfur, black powder, smokeless powder or similar pyrotechnic mixture. The component which produces the audible effect may not contain more than 40 grains [2.592 g] of explosive composition" (49 CFR, Ch.1, pp. 455 and 459).

Potassium perchlorate mixtures and black powder are Class A explosives (as is TNT), defined as those that will either detonate, or, "as in the case of black powder, present a maximum hazard in another way" (Meidl 1970, p. 62). Black powder is a Type-1 Class-A explosive because it deflagrates (burns rapidly) on contact with a spark or flame, but cannot be detonated. Thus, it is also known as a "low explosive" or low-velocity explosive as compared with "high explosives" (or high-velocity explosive which can be detonated (Ellern, 1968; du Pont 1969). Technically at least, potassium perchlorate compositions are Type-4 Class-A explosives because in a sufficient quantity (100 g) they will detonate, when unconfined, by contact with sparks or flame (Conkling 1985, p. 176). TNT is a Type-3 Class-A explosive because it can detonate, when unconfined, by a Number 8 blasting cap (Meidl 1970).

Recently, standard tests used to evaluate characteristics of high explosives have been conducted on materials containing potassium perchlorate, potassium chlorate, and other pyrotechnic mixtures (e.g., Petine and Taylor 1974; Nestle 1975; Swatosh and Cook 1975; McIntyre and McKown 1978; McKown and Westover 1979; McIntyre 1980). Results of such tests have led several researchers to apply percent-TNT-equivalent ratings of up to 80% to many pyrotechnic mixtures (Swatosh and Cook 1975; McKown and Westover 1979; McIntyre 1980).

Since early 1989, the Southwest Fisheries Center has studied several aspects of the problem in its investigation of the use of seal bombs, their effects, and biological implications. This report concerns a study of the seal bombs themselves, their physical description, chemical components, and behavioral characteristics and absolute strengths upon detonation.

METHODS AND MATERIALS

We examined seven types of seal bombs known to be in use in the purse-seine fishery (see Appendix 1 for manufacturer information). Each bomb type (hereinafter called units) was identified by size, color, and external markings. Small samples of units were measured for charge-weight on a Mettler PC 4400 or a Mettler TE 3600 balance with digital readouts. Chemical composition was determined by X-ray fluorescence using a scanning electron microscope model ISI-XS-30A with a fluorescent attachment connected to a Tracor Northern Microtrace analyzer.

In another part of the investigation into seal-bomb effects, open-water tests were conducted in which units at known depths were detonated on submerged stationary targets to determine damage from which to extrapolate impulse pressures at various depths and distances (Myrick et al. 1990). Observations of the underwater explosive behavior of some types of units in preliminary and in open-water tests, as well as damage to submerged targets, were used in evaluating relative strengths of the units by type.

Absolute strengths of units were estimated using TNT formulae for maximum peak shock-wave overpressure and impulse pressures given by Christian and Gaspin (1974) for underwater detonations using high velocity explosives. The pressure values yielded by these calculations were compared with those extrapolated from damage to caged live fish targets in the open-water tests (Myrick et al. 1990).

RESULTS

Description

Two types of legal Class-C units made by the same U.S. manufacturer were examined (Figs 2 A and B, 3 A and B, and Appendix 1). Both have bodies of yellow cardboard, 8.0 x 1.6 cm, with a green 8-second fuse. They have two chambers, a top chamber for explosive and a bottom chamber for silica used as a weight. Chambers are separated by a braided paper and plastic plug secured to the cylinder walls. One type of unit, produced in 1984, bears a green paper printed label with the California State Fire Marshall's seal of approval on it. The other, manufactured more recently, is all yellow with label and seal printed directly on the body.

Three types of units examined were made in Mexico by a single manufacturer (Figs 2 C and D, 3 C and D [only two types shown], and Appendix 1). All units are the same size, 9.0 x 2.0 cm, with an outer thin woven metallic-fabric fuse connected internally to a thick, woven fabric timing fuse that is deeply embedded in the explosive mixture. Internally, there is only one chamber containing explosive powder and calcium carbonate powder, used for weight, mixed together. Two of the three have red paper cardboard bodies with black printing, the other is white with dark blue printing. One red type and the white type have identical markings. On one side is an illustration of a purse seiner with a plume of water from an explosion next to it. On the opposite side is the manufacturer's "eh" logo in the shape of a triangle, next to which is printed "Peligro" in block capital letters. The markings of the second type of red unit differ from the first only in having the letters "AA" and the word "Petardo" at both ends.

Sixth, is a unit manufactured in Panama. It has a plain, undyed, brown paper cardboard body, 6.0 x 1.8 cm, with no markings or printing (Figs 2 E, 3 E). It has a common powder saftey fuse. The cylinder has three inner chambers: a small chamber next to the fuse end containing a granular, clay-like material, a middle chamber containing explosive powder, and a bottom chamber containing grayish silica and crushed seashells (probably beach sand) for weight. The partitions between chambers are feeble paper disks that permit leakage of materials between compartments. A flap from a cardboard package used to ship Panamanian units shows a purse seiner on one side and a tuna on the other with the word "Petardos" in capital block letters. The manufacturer is identified as Luces del Canajagua, the exclusive distributor is Gabriel Alvarado (see Appendix 1).

The other type is a Costa Rican unit (Figs 2 F, 3 F). It has a bright orange hard plastic body, 9.0 x 1.5 cm, with black printing and thin black borders on the ends, and a thick, black, waterproof timing fuse. This unit's plastic packaging alone may make it incompatible with the CFR definition of a legal Class-C pest control device, which requires that legal units "consist of a cardboard-pasteboard type tube..." On one side, at one end, a purse seiner is depicted, at the other end a tuna, and in the middle is a manufacturer's white circular logo with "Hermanos Calvo Solano" inside above and "Cartago CR." inside below. On the other side "Explosivo" appears in block capital letters, with smaller print below giving manufacturer information (Appendix 1). The unit has two chambers, one for explosive powder, the other containing a grayish silica sand. The chambers are separated by a flimsy paper disk that permits potentially dangerous inter-compartmental leakage.

Chemical Analysis and Apparent TNT Equivalence

A systematic chemical analysis, conducted on the seven types (Table 1) revealed that the oxidizer used in the two U.S. units was potassium perchlorate ($KClO_4$) and the oxidizer used in all units of foreign manufacture was potassium chlorate ($KClO_3$). Potassium chlorate is a highly sensitive explosive, with an ignition point well below 500 degrees C. Because of its instability, low ignition temperature, and rapid burning speed, it is much more hazardous than potassium perchlorate (Ellern 1968; Conkling 1985). It is also illegal (by omission) under the definition of Class-C pest control device (CFR, 49, Ch 1. p. 459). Mexican units contained from 60 to 66% oxidizer by weight of explosive. The Costa Rican units contained 64%, the U.S. yellow unit 65%, the Panamanian unit 69%, and there was 71% oxidizer in the U.S. green-labeled unit.

All units except the Panamanian units, contained small percentages of sulfur fuel, i.e., 11-15% in Mexican units, 4% in Costa Rican units, and 7-9% in U.S.-made units, with aluminum (Table 1). Panamanian units contained only aluminum fuel (plus traces of iron and sodium) mixed with its potassium chlorate oxidizer. Sulfur is a "fire-starter fuel," used to facilitate ignition because of its low ignition temperature of about 250 degrees C (Brauer 1974). Considering that the Mexican units had relatively more sulfur in addition to the high percentages of unstable potassium chlorate oxidizer, it would seem that these units would be the most powerful units, gram for gram, among those examined by us.

As to the aluminum components, U.S. units contained 22% (green label) to 26% (yellow unit) by charge weight. These are in close agreement with specifications from the distributor, who gives a single-composition formula for its product as: "64% potassium perchlorate, 26% pyro-aluminum powder, and 10% sulfur" (R. Robinson, California Seal Control Corp., San Pedro, CA, pers. comm. 1989). Assay of Mexican units for aluminum yielded 19% for the white type, 21% for the plain red, and 29% for the red "AA." The

Costa Rican unit had 32% aluminum by weight, and the Panamanian had 31%.

By comparing the compositions in Table 1, it is possible to divide the seven unit types into two groups based on presence or absence of sulfur:

1. 60-71% oxidizer with 19-30% aluminum and 4-15% sulfur (U.S., Mexican, and Costa Rican units), and

2. 69% oxidizer with 31% aluminum and no sulfur (Panamanian unit).

If we ignore the distinction between sulfur and aluminum, because both are fuels, then it is possible to lump all units into a single group characterized as containing 60 to 71% oxidizer and 29 to 40% fuel.

Mixtures of these proportions come under the category of "flash and sound mixtures," i.e., true explosives (Conkling 1985, p. 176). Except for a small amount of antimony sulfide (another fuel interchangeable with sulfur [Conkling 1985, p. 177; P. Stonebraker, Stoneco Inc., pers. comm. Nov. 1989], the general formula is similar to that of an M-80 explosive, which has a standard composition:

Potassium perchlorate	64.0 %
Aluminum	22.5 %
Sulfur	10.0 %
Antimony sulfide	3.5 %

(Conkling 1985; McIntyre 1980; P. Stonebraker, pers. comm. Nov. 1989). The ignition temperature of the M-80 mixture is 360 degrees C (Conkling 1985; McIntyre 1980) and its high explosive (TNT) equivalency is 80% (McIntyre 1980). This same TNT equivalency should apply to the U.S.-made units also, because the oxidizer is the same as in the M-80. However, because the foreign units contain potassium chlorate, a less stable oxidizer with a substantially lower ignition temperature, we would expect their explosion reaction to be more violent and to rate a higher TNT equivalency than that of the U.S. units.

If we characterize the Panamanian mixture as being different from the others because it lacks sulfur, we find that its oxidizer-fuel proportions are similar, except for the $KClO_3$ oxidizer, to an electric primer mixture described by McIntyre (1980) as containing 66.7% potassium perchlorate and 33.3% aluminum. The composition of the Panamanian unit, except for its $KClO_3$ instead of $KClO_4$, also resembles that of a commercial "sound pyrotechnic" called "Flash Thunder #4," which contains 72% potassium perchlorate and 28% aluminum (Shimizu 1981). McIntyre rates the electric primer mixture as having 50% high explosive equivalency, with an ignition temperature of 446 degrees C. By having a chlorate composition, the Panamanian unit should give a higher TNT rating and a lower ignition temperature than the perchlorate primer mixture rated by McIntyre (confirmed by P. Stonebraker, pers comm. Nov. 1989). No TNT rating has been given for Flash Thunder #4.

Charge-Weights and Relative Strengths

Given that all seven types of the units have mixtures similar to the M-80, the charge-weights determined for the units (Table 1) should allow direct determination of the relative unit-strengths. The difference in TNT equivalence of chlorate explosives (ClO_3) and perchlorate explosives (ClO_4) is not known to us, but chlorate mixtures produce stronger explosions gram for gram. For example, Shimizu (1981, p. 36) compared the surface-burning velocity of black powder (5-17 m-sec), $KClO_3$ with hemp coal (12-46 m-sec), and $KClO_4$ with hemp coal (10-19 m-sec). But McIntyre (1980) has not compared the TNT equivalence of similar mixtures with chlorate and perchlorate oxidizers. All foreign-made units had larger charges than the U.S.-made units, and thus the problem of whether the chlorate explosives should be given extra consideration in ranking relative strengths was not very important in this part of the study.

Since special consideration to the oxidizer was unnecessary, ranking the units based strictly on charge-weight was straight-forward. The weight of explosive material in samples from Mexico was 2.44 g for the white unit, 3.04 g for the plain red, and 4.02 g for the red "AA" unit. The samples from Costa Rica showed a range of 2.13 to 4.10 g and we chose the mean of the sample of 12 units, i.e., 3.82 g, as the working value. The Panamanian unit was represented by a mean value of 5.76 g from a sample weighed on a balance in one of our labs and a value of 4.33 g based on an analysis in which the methods were unknown to us. We used the mean of the first sample for comparison, although it was noted by each of us independently that charge weights of Panamanian units varied greatly. There were four mean values for the U.S. units: 1.40 and 1.90 for the green-labeled unit and 1.97 and 2.44 for the all-yellow unit. According to the distributor the standard unit contains 36 grains or 2.33 g of explosive, and we used the value given by the distributor because we assumed that it was based on a far larger number of units than we studied.

Behavior of Units Detonated

In preparation for open-water tests, U.S.-made and Panamanian units were detonated in water-filled, doubled, plastic trash bags placed inside of a 1/4-inch plywood packing crate about 0.7-m deep x 2.1-m long x 0.4-m wide, supported by the sides of the crate. One of the objectives of this preliminary exercise was to determine approximate explosive strengths of units before conducting formal tests. Detonation of U.S. units blew sides off the crate, crumpled 16-oz, air-filled aluminum cans and created a plume of water approximately 2.0-m high (Fig. 4C). Explosions of single Panamanian units blew sides off the crate and blew holes through the sides of the crate, shredded aluminum cans, and created a water plume approximately 12.0-m high (Figs 4 A and B).

In open-water tests, U.S., Mexican red "AA," Costa Rican, and Panamanian units were fired underwater on submerged air-filled and water-filled cans, gelatin-filled plastic bottles (used to try to simulate lungs), dolphin carcasses, cages of live fish, and various pressure-detecting objects (Myrick et al. 1990). U.S.-made units damaged air-filled cans (air cans) at 2.0 m. Mexican units damaged air cans at just less than 2.5 m. Panamanian units damaged air cans at about 2.5 m and severely damaged a dolphin carcass, the only type of unit tested that caused carcass damage, at 0.6 m (Table 2). Costa Rican units failed to explode in the tests, probably because of faulty electronic fusing.

After open-water tests, we extrapolated impulse pressures of seal-bomb explosions from percent of fish injury and mortality using scaled curves originally established by Yelverton et al. (1975) to determine fish mortality from known impulse pressures (Myrick et al. 1990). Shots of single U.S. green-label units gave impulse pressures of approximately 15-24 psi-msec at 0.5-0.7 m. Class-C units detonated in clusters of two probably generated 15 to 21 psi-msec at 1.5 m. Pressure for a Panamanian unit (5.76 g of M-80 potassium chlorate mixture) at 1.8 m was between 18 and 21 psi-msec. Pressure generated by a Mexican red "AA" unit (4.02 g of M-80 potassium chlorate mixture) at about 2.0 m was 15 psi-msec. This was the same pressure as that produced within a meter from source by the U.S. green-label units, apparently with ~ 2.0 g of M-80 potassium perchlorate mixture. However, the pressure from the Mexican red "AA" explosion was judged as weaker than that of an explosion of a 2-unit cluster of Class-C's (Myrick et al. 1990).

Relative Strengths Based on Combined Characteristics

The greater charge-weight and potassium chlorate-sulfur-aluminum mixture of at least the Mexican red "AA" unit (and presumably all Mexican units) produce a stronger shock-wave pressure over a greater distance than the lower weighted, U.S. units whose M-80 composition rates an 80% TNT strength. Presumably if tested, the chlorate oxidizer in an M-80 mixture would yield a TNT equivalency greater than 80%. Although the Costa Rican unit was not field-tested successfully, we rated its strength between the Mexican plain red and "AA" red units based on the weight and composition of its charge. We rated the 2-unit Class-C cluster stronger than the Mexican red "AA" unit because of the greater total charge-weight and higher pressure generated at distance. We rated the Panamanian unit strongest of all, because of its behavior, charge-weight, and chlorate oxidizer. Thus listed downward in order of increasing strength we finally have:

U.S.-made	2.33 g (standard)	80% TNT equivalent
Mexican		
white	2.44 g	>80% TNT equivalent
red	3.04 g	"
Costa Rican	3.82 g	"
Mexican		
red "AA"	4.02 g	"
U.S.-made		
2-unit clusters		
(total standard wt)	4.66 g	"
Panamanian	5.76 g	"

Calculations of Pmax and I for Seal-bomb Units

If the types of units we examined have a minimum 80% TNT-equivalency as we presume, then maximum peak overpressures (Pmax, the shock-wave pressure front) and impulse pressures (I, the integral of the pressure-time curve behind the pressure front) of the explosion shock wave may be calculated for charge-weights at distance using the TNT formulae described in Myrick et al. (1990) following Christian and Gaspin (1974). Table 3 gives Pmax and I values for seal-bomb charges of 0.5 to 5.0 g calculated on the basis of 80% of an equivalent charge-weight of TNT.

The criteria established by Yelverton et al. (1973, Table 10) to predict injury to submerged land mammals subjected to underwater explosions were based solely on impulse pressures:

Impulse Pressure Psi-msec	Criteria
40	No mortality. High incidence of moderately severe blast injuries.
20	High incidence of slight blast injuries.
10	Low incidence of trivial blast injuries.
5	Safe level. No injury.

According to the criteria, a submerged land mammal would be safe from injury at values of up to 5 psi-msec; it would risk trivial injury at values >5 to 10 psi-msec, slight injury between 10 and 20 psi-msec, and moderately severe injury between 20 and 40 psi-msec.

Considered on the basis of criteria using only impulse pressures (Table 3), a 0.5-g charge could cause trivial to slight injury at 0.3 m and a 1.0-g charge could cause slight to severe injury at 0.3 m and trivial to slight injury at 0.5 m. A charge of 2.0 g could cause slight to severe injury to mammals within 0.5 m and at least trivial injury out to about 2.5 m. The standard, 2.33-g Class-C unit could cause trivial injury as far away as almost 3.0 m. Charge weights within the range of the Costa Rican, Mexican red "AA," 2-unit clustered Class-C, and Panamanian devices could cause slight to severe injury within 1.0 m, trivial to slight injury out to at least 2.0 m, and trivial injury to 4.0 m.

Impulse-pressure levels are considered more important than Pmax levels in predicting injury and mortality from underwater explosions (Myrick et al. 1990). Nevertheless, given sufficiently high peak pressure, Pmax alone can cause injury and mortality and such risk would increase with increased Pmax irrespective of an increase in I. Christian and Gaspin (1974) established conservative minimum safe standoff limits of 50 psi maximum peak pressure in combination with 2.0 psi-msec impulse pressure for U. S. Navy swimmers. No injuries to mammals have ever been observed with Pmax of several hundred psi and I of 2 psi-msec, but the data are fragmentary (Christian and Gaspin 1974; Gaspin 1983).

Table 3 indicates that a 2.33-g Class-C unit should generate Pmax and I of 2,755 psi and 39 psi-msec, 712 psi and 13.1 psi-msec, 325 psi and 6.97 psi-msec, 206 psi and 4.8 psi-msec, and 149 psi and 3.7 psi-msec at 0.3, 1.0, 2.0, 3.0, and 4.0 m respectively. For a 1.0-g charge at the same distances Pmax and I would be expected to be 2,008 psi and 22.6 psi-msec, 519 psi and 7.6 psi-msec, 237 psi and 4.1 psi-msec, 150 psi and 2.8 psi-msec, and 108 psi and 2.2 psi-msec. The safe swimmer guidelines are well below the values calculated for pressures 4.0 m from an exploding 2.33-g standard Class-C unit and slightly below those calculated for a 1-g charge at 4.0 m (Table 3). This suggests that if the charge-weight of a standard unit were reduced by more than 50%, the pressure produced by its underwater detonation would nevertheless exceed Navy guidelines for safe limits within 4.0 m from the explosive. Theoretically, even a charge of only 0.5 g would generate a Pmax and I at between 2.0 and 3.0 m that would exceed the Navy safe swimmer guidelines (see Table 3).

Comparison of Extrapolated and Calculated Impulse Pressures

Comparisons of impulse pressures extrapolated from fish injury and mortality in open-water tests of various units (Myrick et al. 1990) with theoretical I values calculated using the TNT formula (from Table 3) show that our extrapolations are fairly close approximations of the calculated values (Table 4). The I, calculated for an underwater explosion of 80% of a 2-g TNT charge 0.5 m from source, was 22.3 psi-msec. It fell within the range of I (15-24 psi-msec) at 0.5 to 0.7 m for single Class-C green-labeled units (with a mean weight of about 1.9 g) extrapolated from fish damage (Myrick et al. 1990). Calculated I for 2-unit clusters of the green-labeled unit (with about 4 g total weight) at 1.5 m (12.8 psi-msec), and the Mexican "AA" and Panamanian units at greater distances were consistently somewhat less than the corresponding extrapolated values. Calculated I for the foreign-made units included values based on 100% as well as 80% TNT equivalency to anticipate an unknown effect of the greater explosive power of their chlorate mixtures (indicated by asterisks in Table 4). Calculations using 100% equivalency produced values in closer agreement with, but they were still slightly lower than, corresponding I extrapolations.

DISCUSSION AND CONCLUSIONS

Assumption that Seal Bombs have TNT Equivalency

The impulse-pressure extrapolations made by Myrick et al. (1990) depended on the assumption that the potassium chlorate and potassium perchlorate mixtures are TNT-like in their explosive behavior. One basis for the assumption was the result of a comparison between the sound wave form of a Class-C unit exploded underwater (recorded by Awbrey and Thomas 1987) and those of underwater explosions of five-pound charges of dynamite and black powder recorded by Hubbs and Rechnitzer (1952). The traces show that a Class-C unit is almost identical to dynamite (and other high explosives such as TNT) in having a very rapid rise time to maximum peak pressures (Pmax) and an almost equally rapid decay rate, but that black powder (a low-velocity explosive) generates a very slow and relatively slight pressure increase (Figs 5 A, B, and C).

Another basis for the assumption that the M-80 mixtures are TNT-like is that cavitation (shock-wave bubbles) and explosion plumes from 1- and 3-gram charges of $KClO_4$-Al 50:50 mixtures have been shown to be miniature replicas of those from 1.25-kg charges of TNT (Snay 1957, figs 13 and 14).

The assumption is based also on fish-injury and fish-mortality data generated by the open-water tests that enabled Myrick et al. (1990) to estimate impulse pressures using a model constructed by Yelverton et al. (1975) from test data in which high-velocity explosives were used. The successful use of the model in generating TNT-level impulse pressures from seal-bomb damage to fish probably justifies use of the model and the assumption.

In our view, the TNT-equivalency rating of the M-80 composition (by McIntyre 1980) and the compositional resemblance of all seven types of units to the M-80 described in our present study, supports the validity of the assumption also. It is our further opinion that those units with potassium perchlorate will rate a TNT equivalency higher than 80%.

Discrepancies Between Extrapolated and Calculated I

Although extrapolated and calculated impulse-pressure values in Table 4, are in fairly close agreement, the extrapolated values may be more reliable than the corresponding calculated values for at least three reasons. First, the true charge weights of the units used for estimates from fish were not known, nor was the actual explosive behavior of the clustered unit. Second, the standard TNT equation for I is modeled on a spherical charge that releases energy uniformly in all directions; seal-bombs are cylinders which release most of the energy through the side walls, not the ends. Finally, energy from the seal-bomb cylinder is channeled or focused through the point of rupture at the weakest part of the wall (Stonebraker, pers. comm. Nov. 1989). In such a case, the energy moving outward through the rupture would be concentrated, producing impulse pressures at distance in one direction that should be higher than those expected from the uniform release of energy from a spherical charge of the same weight.

Hazards to Dolphins

Based on an 80% TNT equivalency, the calculated impulse pressure generated by a spherical 2.3-g M-80 mixture, would be likely to cause slight to moderately severe blast injury to a submerged mammal within 0.5 m. It should present a risk of injury to a mammal at least out to about 3.0 m. At 4.0 m, the Pmax and I would still far exceed the Navy safe (human) swimmer guidelines established by Christian and Gaspin (1974). Because the standard 2.3-g U.S. unit may produce directional explosion pressures of more concentrated strength than the spherical model, we might expect these injury distances to be somewhat greater than those calculated.

Our study shows that all foreign and clustered U.S. units examined should produce a more powerful explosion than the single U.S. unit. If these conclusions are considered in concert with conclusions reached by Myrick et al. (1990) based on extrapolated impulse pressures, then all types of seal bombs now known to be in use in the purse-seine fishery probably are capable of inflicting slight to moderately severe injury when detonated at least within 0.5 m of a dolphin. Furthermore, we would expect some risk of trivial injury to a dolphin from any one of such seal bombs when detonated within 4.0 m. We base these estimates of injury-at-distance on impulse-pressure-injury criteria established by Yelverton et al. (1973) from tests of underwater explosions on submerged land mammals. However, risk of injury may be greater than that indicated by the impulse-pressure criteria when I is combined with high maximum peak overpressures of the shock-wave front.

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Table 1. Chemical composition of seal-bomb units used in the ETP yellowfin tuna purse-seine fishery. ("Class-C" indicates that units analyzed were within the legal maximum limit of 2.592 g of legal explosive material to be included as a Class-C explosive. Units containing potassium perchlorate [$KClO_4$] are legal under the Class-C definition; units with potassium chlorate [$KClO_3$] are illegal. Weights with * were determined in one of our labs, weight with ** was determined by outside source, weights without * were determined in the other of our labs.)

Type Unit	Total Net Weight (g) of Contents	Total Weight (g) N, $\bar{X}$ (and range) Explosive Mixture	Percent Composition By weight
U.S. Green (Class-C)		*N=5 $\bar{X}$=1.90 (1.7-2.2) N=3 $\bar{X}$=1.40	$KClO_4$ 71% S 7% Al 22%
U.S. Yellow (Class-C)	11.60	N=3 $\bar{X}$=1.97 *N=5 $\bar{X}$=2.44 (2.1-2.5)	$KClO_4$ 65% S 9% Al 26%
Mexican red "AA"	22.10	N=1 4.02	$KClO_3$ 60% S 11% Al 29%
Mexican red	21.90	N=1 3.04	$KClO_3$ 65% S 14% Al 21%
Mexican white	17.93	N=2 $\bar{X}$=2.44	$KClO_3$ 66% S 15% Al 19%
Panamanian	14.71	N=3 $\bar{X}$=5.76 **N=1 4.33	$KClO_3$ 69% Al 31% Fe (trace) Na (trace)
Costa Rican	17.46	N=3 $\bar{X}$=2.13 *N=12 $\bar{X}$=3.82 (3.0-4.1)	$KClO_3$ 64% S 4% Al 32% Fe (trace)

Table 2. Damage to targets and fish at distance by some types of seal-bomb units in open-water tests conducted 10 October 1989 (after Myrick et al. 1990), listed in charge-weight order (S= detonated single unit, SS= 2 single units detonated at different depths simultaneously).

Type Unit	Approximate charge-weight (g)	Target	Distance (m)	Damage
U.S. Green Label (S)	1.90	5 fish	0.0	5 injured
		3 fish	1.6	3 injured
		3 fish	0.0	3 injured
		5 fish	0.0	1 killed 4 injured
		air-filled can	2.0	dented
U.S. Green Label (SS)	1.90	5 fish	0.5	1 killed 4 injured
		5 fish	0.5	5 injured
		5 fish	0.5	1 killed 4 injured
		5 fish	0.7	1 killed 4 injured
		5 fish	0.0	5 injured
		5 fish	0.7	2 killed 3 injured
		air-filled can	<2.0	dented
Mexican red "AA" (S)	4.02	4 fish	2.0	4 injured
		air-filled can	<2.5	dented
Panamanian (S)	5.76	4 fish	1.8	4 killed
		dolphin carcass	0.6	damaged
		air-filled can	~2.5	dented

Table 3. Maximum peak overpressures (Pmax, in psi) and impulse pressures (I, in psi-msec) for underwater explosions of seal-bomb units with charge-weights of 0.5, 1.0, 2.0, 2.33, 2.5, 3.0, 4.0, and 5.0 g at 0.3, 0.5, 1.0, 1.5, 2.0, 3.0, and 4.0 m, calculated on the basis of 80% of an equivalent charge-weight of TNT.

	Weight of Explosive Charge (g)							
	0.5	1.0	2.0	2.33	2.5	3.0	4.0	5.0
0.3 m								
Pmax	1,547	2,008	2,599	2,755	2,832	3,028	3,384	3,685
I	14.3	22.6	35.4	38.9	40.8	45.8	55.1	63.5
0.5 m								
Pmax	874	1,136	1,479	1,557	1,601	1,712	1,913	2,083
I	9.2	14.3	22.3	24.6	25.8	28.9	34.8	40.1
1.0 m								
Pmax	399	519	671	712	732	782	874	952
I	4.9	7.6	11.9	13.1	13.7	15.4	18.5	21.4
1.5 m								
Pmax	253	328	425	450	463	495	553	602
I	3.4	5.3	8.6	9.1	9.5	10.6	12.8	14.8
2.0 m								
Pmax	183	237	307	325	334	357	399	435
I	2.6	4.1	6.3	7.0	7.3	8.2	9.9	11.4
3.0 m								
Pmax	115	150	194	206	211	226	252	275
I	1.8	2.8	4.4	4.8	5.0	5.7	6.8	7.9
4.0 m								
Pmax	83	108	140	149	153	163	183	199
I	1.4	2.2	3.4	3.7	3.9	4.4	5.2	6.0

Table 4. Comparison of extrapolated (e) and calculated (c) impulse pressures at distance from seal bombs exploded underwater. Calculated values with * and ** are based on 80 and 100% TNT charge-weight equivalents respectively, because units contain chlorate oxidizers that are assumed to be more powerful than the U.S. units which contain perchlorate oxidizers, with 80% TNT equivalency.

Unit	Weight of Charge (g)	Distance (m)	Impulse Pressure (psi-msec) e	c
U.S. Green				
Class-C single	~2.0	0.5-0.7	15-24	22.3
2-unit cluster	~4.0	1.5	15-21	12.8
Mexican "AA"	~4.0	2.0	15	*9.9-**11.4
Panamanian	~5.76	1.8	18-21	*13.8-**15.8

A

B

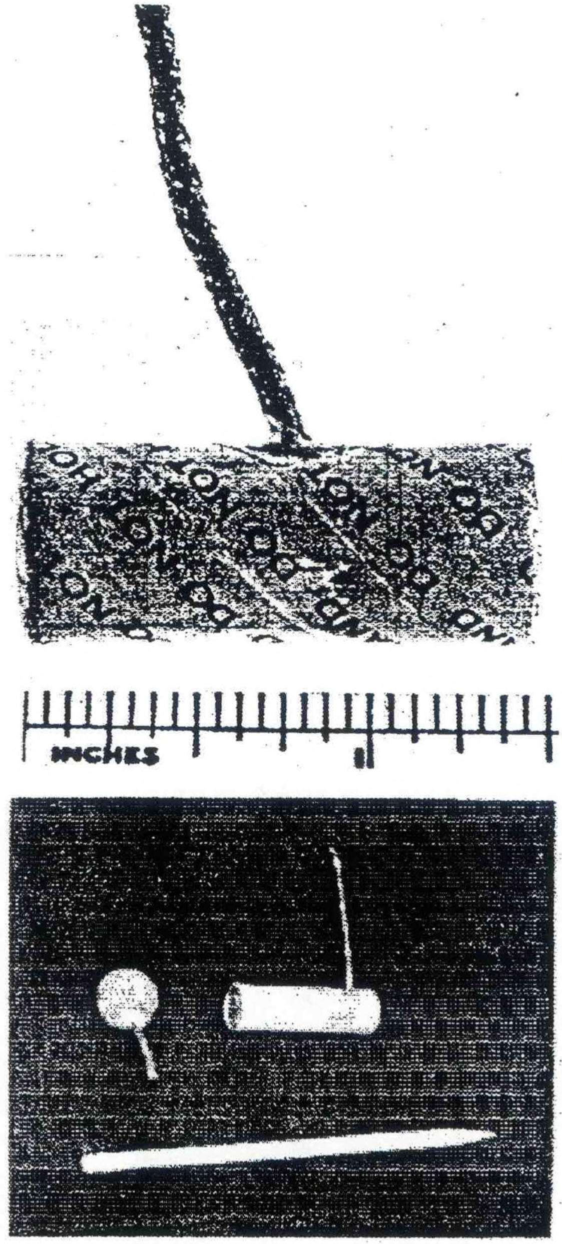


Figure 1 **A:** M-80 "salute" firecracker containing a 3g charge of potassium perchlorate mixture (after Hirsch and Ommaya 1952). **B:** Hand-thrown explosives used early in the yellowfin tuna purse-seine fishery. **Left:** "cherry bomb", **right:** M-80 type explosive (pencil at bottom for scale)(after McNeely 1961).

Figure 2

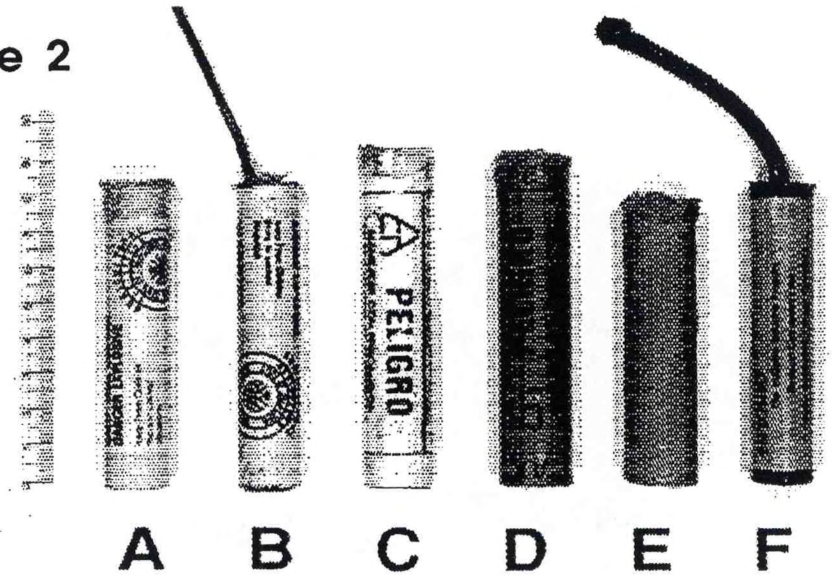
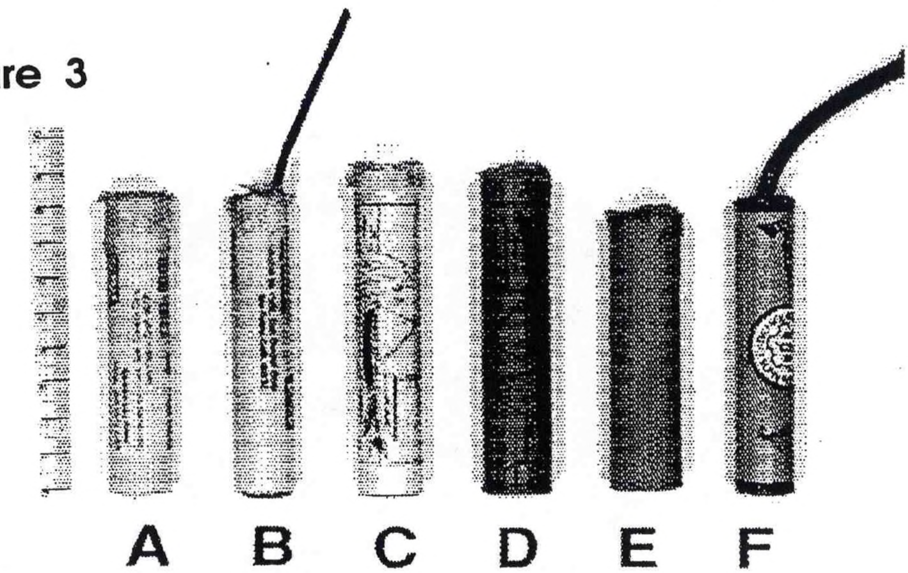


Figure 3



Both sides of six types of seal bombs. **A&B:** U.S. mfg. **C&D:** Mexican mfg. **E:** Panamanian **F:** Costa Rican.

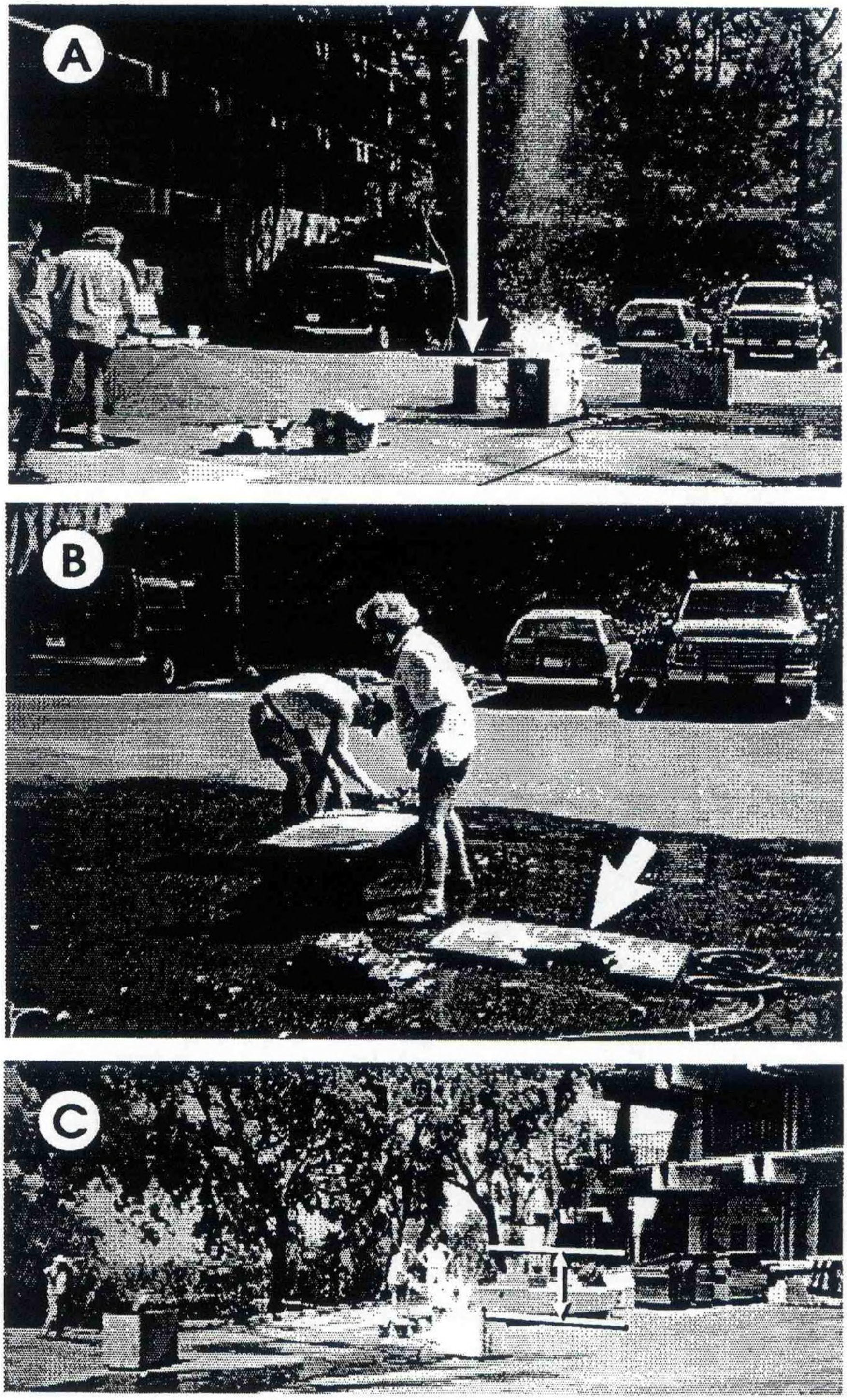


Figure 4 Preliminary tests of Panamanian unit (A&B) and U.S. made class-C unit (C). **A:** Explosion plume >12m high (large arrow). Note height of detonation wire (small arrow). **B:** Hole blown in side of packing crate support (arrow). **C:** Plume of class-C unit ~2m-high.

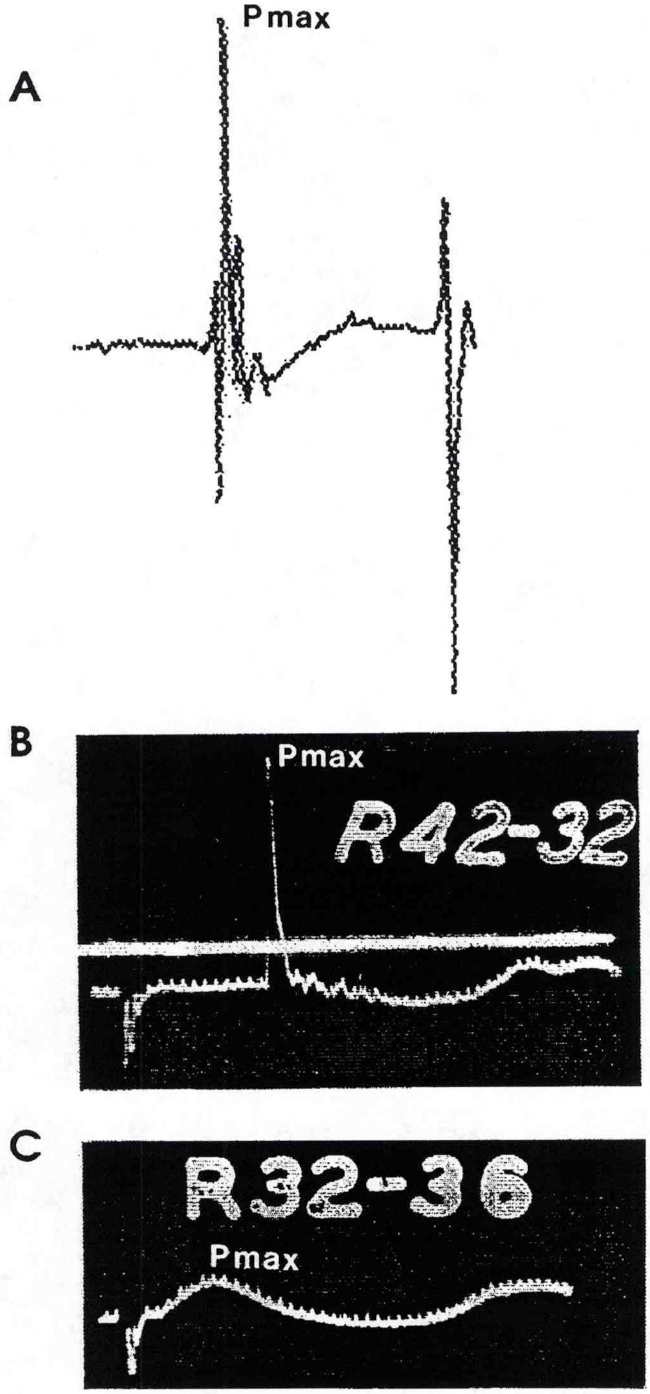


Figure 5 Soundwave forms of underwater explosions. **A:** Class-C seal bomb containing 2.3g of potassium perchlorate (from Awbrey and Thomas 1987). **B:** Five-pound charge of dynamite. **C:** Five-pound charge of black powder (B&C from Hubbs and Rechnitzer 1952).

Appendix 1. Information on seal-bomb manufacturers.

Unit	Manufacturer Information
U.S. Class-C	Stoneco Inc. P.O. Box 765, Trinidad, CO 81082.
Mexican	Explosivios y Herramientas, S.A. Avenida Yallarta 3089 Guadalajara, Jalisco, Mexico.
Costa Rican	Hermanos Calvo Solano Quircot, Cartago, C.R. Telephone No. 51-3293 License # 003MSP
Panamanian	Gabriel Alverado (distributor for Luces Del Canajaqua) APTDO 1128 Panama 9A Panama Telephone No. 64-4896 License # 3-3808