NSWC TR 82–188

PREDICTION OF UNDERWATER EXPLOSION SAFE RANGES FOR SEA MAMMALS

BY JOHN F. GOERTNER

RESEARCH AND TECHNOLOGY DEPARTMENT

16 AUGUST 1982

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NAVAL SURFACE WEAPONS CENTER

Dahlgren, Virginia 22448 • Silver Spring, Maryland 20910

FOREWORD

The Navy is required to assess the environmental consequences of all its activities and to take appropriate measures to avoid or mitigate adverse effects. In the case of underwater explosion testing, the effect on marine life of most concern is the possible killing of fish. Marine mammals are rarely encountered at test sites, but the effects on these animals are given special attention because of legislation such as the Endangered Species Act and the Marine Mammal Protection Act. Although a low level of fish-kill can be tolerated in most cases, harmful effects on marine mammals are not acceptable.

This study was conducted to determine the ranges within which sea mammals could be injured. Its purpose is to provide guidance to personnel engaged in underwater explosion testing, but the method is also useful for planning underwater blasting for channel clearance or construction.

This work was funded by the Naval Sea Systems Command (SEA-62R) under Program Element 63721N, Work Unit: Environmental Effects of Explosive Testing. This report is one of a series published under this sponsorship during a period of about ten years.

The assistance of George A. Young in reviewing this report is gratefully acknowledged.

APPROVED BY:

J. F. PROCTOR
Energetic Materials Division

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ILLUSTRATIONS

TABLES

1. INTRODUCTION AND SUMMARY

The problem is to determine the region of injury to sea mammals such as whales, porpoises and manatees for explosion tests and blasting operations. Our starting point is the body of experimental data which has been obtained by the Lovelace Foundation from underwater explosion tests using dogs, sheep and monkeys.[1,2] The solution consists of scaling these results using plausible physical models to large sea mammals and to different charge sizes and explosion geometries.

The method has been used at this Center in the planning and in the environmental assessments for Navy underwater explosion tests. It has been implemented by a computer program (MAMDAM) which outputs the predicted contour (locations) corresponding to slight injury for a given weight mammal. This is a level of injury from which the animals would recover on their own.

The purpose of this report is to describe both this computer program (Section 2) and typical results (Section 3). This information can be used to avoid injuries to animals by postponing explosive operations if the animals are within the zone of possible injury.

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1. Richmond, Donald R., Yelverton, John T., and Fletcher, E. Royce, "Far-Field Underwater-Blast Injuries Produced by Small Charges," Lovelace Foundation, DNA 3081T, 1973.
2. Yelverton, John T., et al, "Safe Distances from Underwater Explosions for Mammals and Birds," Lovelace Foundation, DNA 3114T, 1973.

2. METHOD OF SOLUTION

The Lovelace Foundation studies[1,2] indicate that hemorrhaging in and around the lungs is the primary source of injury to submerged mammals. These studies also indicate that another significant source of injury to submerged mammals is excitation of radial oscillations in the small gas bubbles which are normally present in the small and large intestines. These are two distinct mechanisms for injury. We will scale them separately for each location in the explosion pressure field and then use the more severe of these two mechanisms to define our injury region.

Lung Hemorrhaging. The severity of lung hemorrhaging appears to be related to the amplitude of the excitation of the lung cavity by the explosion. For our purposes this motion can be approximated by the radial oscillation response of an equal volume spherical air bubble in water subjected to the same pressure wave.

We will assume that the explosion loading is impulsive. We will get around the difficulty that this is not true for long duration positive pressures by using a modification of the concept of partial positive impulse used by Bowen et al to describe air-blast mammal mortality test results.[3]

For this purpose we compute the small amplitude oscillation period $\overline{T}$ for the substitute air bubble,

$$\overline{T} = 2\pi A_0 \sqrt{\rho/3\gamma p_0} \qquad (2.1a)$$

where A_0 is the at-rest bubble radius, ρ is the water density (= 1.940 slugs/ft^3), γ is the adiabatic exponent for air (= 1.40), and p_0 is the hydrostatic pressure.[4]

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[3] Bowen, I. G., et al., "Biophysical Mechanisms and Scaling Procedures Applicable in Assessing Responses of the Thorax Energized by Air-Blast Overpressures or by Non-Penetrating Missiles," Lovelace Foundation, DASA 1857, 1966.

[4] Kennard, E. H., "Radial Motion of Water Surrounding a Sphere of Gas in Relation to Pressures Waves," 1943, published in Vol. II of Underwater Explosion Research, Office of Naval Research, 1950.

Inserting the values for the water density and adiabatic exponent, equation 2.1a becomes

$$\bar{T} = 29.7 \frac{A_o}{\sqrt{p_o}} \text{ milliseconds} \qquad (2.1b)$$

where A_o is in inches and p_o is in pounds per square inch.

The at-rest bubble radius A_o is calculated from the estimated lung volume V_o at hydrostatic pressure p_o using

$$A_o = [V_o/(4/3)\pi]^{1/3} \qquad (2.2)$$

V_o in turn is estimated from the estimated lung volume V_1 at atmospheric pressure assuming isothermal compression to hydrostatic pressure p_o, i.e.,

$$V_o = V_1 \times (p_1/p_o) \qquad (2.3)$$

where p_1 is the atmospheric pressure (generally taken equal to 14.7 psi). V_1 in turn is estimated from the body mass of the sea mammal under the assumption that like large land mammals - dogs, sheep and monkeys of the experimental data set - the lung volume in liters is approximately 3% of the body mass in kilograms. Thus,

$$V_1 = 1.83 \text{ M} \qquad (2.4)$$

where V_1 is the lung volume in cubic inches and M is the body mass in kilograms.

Next we compute the positive pressure duration, TPOS, from the difference in travel times for the direct and surface-reflected pressure waves, using a constant velocity of sound.

In order to compute the impulse, I, to be used for calculating the lung cavity response, we define a parameter, τ, which we take as the lesser of the times, TPOS and 0.2 $\overline{T}$. We use the parameter, τ, as the integration limit for computing the impulse, I, to be used in this analysis. Thus,

$$I \equiv \int_{0}^{\tau} p(t)\, dt \tag{2.5}$$

where

$$p(t) = \begin{cases} \mathrm{PMAX} \cdot \mathrm{EXP}(t/\theta) & (t \leq 1.8\theta) \quad (2.6a) \\ \mathrm{PMAX} \cdot \mathrm{EXP}(-1.8) \cdot \mathrm{EXP}\left(-\dfrac{t - 1.8\theta}{4.3\theta}\right) & (t > 1.8\theta) \quad (2.6b) \end{cases}$$

and PMAX and θ are the peak pressure and decay constant for the incident explosion pressure wave. Through the introduction of the parameter, τ, we are attempting to define an effective (or partial) impulse for the excitation due to long duration pressures.

The peak pressure PMAX in psi and the decay constant θ in milliseconds can be calculated from the similitude relations for pentolite developed at this Center.

$$\mathrm{PMAX} = 2.46 \times 10^{4} \, (R/W^{1/3})^{-1.19} \tag{2.7}$$

$$\theta = 0.052 \, W^{1/3} \, (R/W^{1/3})^{0.26} \tag{2.8}$$

where W is the explosive mass in pounds and R is the slant range from the charge in feet. For these environmental studies we have not accounted for differences in explosive output among detonating explosives.

Assuming that the lung hemorrhaging is related to the amplitude of the induced oscillation, described for example by AMAX/AMIN, where AMAX and AMIN are the maximum and minimum radii of the oscillations, we are led to a damage parameter for scaling lung injuries in the form of the product,

$$I/(A_o \rho^{1/2} p_o^{1/2}) \qquad (2.9)$$

where ρ is the water density, since under impulsive loading, AMAX/AMIN can be computed as a function of this dimensionless product[5].

For a diving mammal the equivalent lung radius A_o at ambient pressure is related to A_1 the radius at atmospheric pressure by

$$A_o = A_1 (p_1/p_o)^{1/3} \qquad (2.10)$$

where p_1 is the atmospheric pressure. Substituting (2.10) into (2.9) our damage parameter becomes

$$I/(A_1 p_1^{1/3} \rho^{1/2} p_o^{1/6}) \qquad (2.11)$$

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5. Goertner, John F., Fish Killing Potential of a Cylindrical Charge Exploded Above the Water Surface, NSWC/WOL TR 77-90, 1978. See Section 3.4 and Equation 3.4.5.

Since the lung volume is assumed proportional to the body mass of the mammal, for the equivalent lung radius A_1 we have

$$A_1 \propto M^{1/3} \tag{2.12}$$

where M is the body mass of the mammal. Substituting (2.12) into (2.11) and dropping the constant water density ρ, the damage parameter for scaling lung injuries becomes

$$I/(M^{1/3}\ p_1{}^{1/3}\ p_o{}^{1/6}) \tag{2.13}$$

Note that this scaling parameter is no longer dimensionless. (Using the equations developed in this section, I found it convenient to express the impulse I in psi-milliseconds, the body mass M in kilograms, the atmospheric pressure p_1 in psi, and the hydrostatic pressure p_o in psi.)

The critical values used for the damage parameters in this study are those values at which the animals sustained only slight injuries. These values were taken from the Lovelace Foundation sheep-dog-monkey data.[2] For lung related injuries slight injury occurred at an impulse of 20 psi-milliseconds for a 40 kilogram animal. Atmospheric pressure p_1 was about 12 psi and the hydrostatic pressure p_o was about 12.9 psi (corresponding to 2-foot immersion depth).*

Intestinal Injuries. Since we do not know the sizes of air bubbles in the intestines we will make the conservative assumption that their oscillation periods are short relative to the duration of the incident pressure wave. This leads to a

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* For most of these tests the animals were held vertically in the water with their lungs 1, 2, or 10 feet below the surface. For the tests at 2 and 10 feet, sheep were supplied air thru a face mask tied to their heads. The average atmospheric pressure at the Lovelace Foundation is about 12 psi.

damage parameter for injuries due to the excitation of these bubbles of the form

$$\mathrm{PMAX}/p_0 \tag{2.14}$$

where PMAX is the maximum or peak incident overpressure. From the Lovelace Foundation sheep-dog-monkey data we estimate slight injuries to occur by this mechanism at about 600 psi at an ambient pressure of about 12.9 psi.

What we do now is compute two injury regions - one by the lung injury mechanism, the other by the intestinal injury mechanism. We then take the outer boundary of these two regions as the contour for incurring slight injury to the mammal.

Contouring Parameters. We accomplish our task by computing two contouring parameters - one for lung injuries, the other for intestinal injuries. These contouring parameters have the mathematical form of an injury probability as a function of the appropriate damage parameter, i.e.,

$$P = 1/\left\{1 + \mathrm{EXP}[-\lambda(\mu-\bar{\mu})]\right\} \tag{2.15}$$

where P is the contouring parameter, λ is a constant assigned some arbitrary value based on the computation mesh size, $\mu = \mathrm{LOG}_{10}$ [DAMAGE PARAMETER], and $\bar{\mu}$ is the value of μ computed from the damage parameter value corresponding to the desired contour. Note that regardless of the value assigned to λ, P-values greater than 0.5 lie inside the contour corresponding to $\bar{\mu}$ and P-values less than 0.5 lie outside. Thus if at each mesh point of the region surrounding the explosion we compute both the contouring parameter for lung injury and the contouring parameter for intestinal injury, we can obtain the contouring parameter for injury by either of the two mechanisms by simply selecting at each mesh point the greater of the two computed values. The corresponding contour for injury by either of the two mechanisms is then obtained by interpolating for a value of 0.5 over the entire grid.

3. SAMPLE PROBLEMS

3-1. WHALES - KEY WEST

These computations were done as part of a Preliminary Environmental Assessment for an ongoing program of routine shock testing of Naval targets, including ships, with large conventional explosive charges placed under water. The current site is in the Atlantic Ocean about 19 nautical miles SSE of Key West, Florida. The average water depth is 900 feet. The explosive is HBX-1, a standard Navy explosive, placed in steel cases. There are three typical explosion test geometries: a 1,200 pound charge at a depth of 125 feet, a 10,000 pound charge at a depth of 200 feet, and a 40,000 pound charge at a depth of 200 feet.

The results are shown in Figures 3.1.1, 3.1.2, and 3.1.3 for the three explosion configurations employed at the test site and for 20-foot and 55-foot whales. For these computations it was assumed that the body mass versus length for whales is given by[6]

$$M = 6.23\ L^3 \tag{3.1.1}$$

where M is the body mass in kilograms and L is the length in meters. For 20-foot and 55-foot whales this gives:

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[6] Ommanney, F.D., Lost Leviathan, Dodd, Mead and Co., New York, 1971.

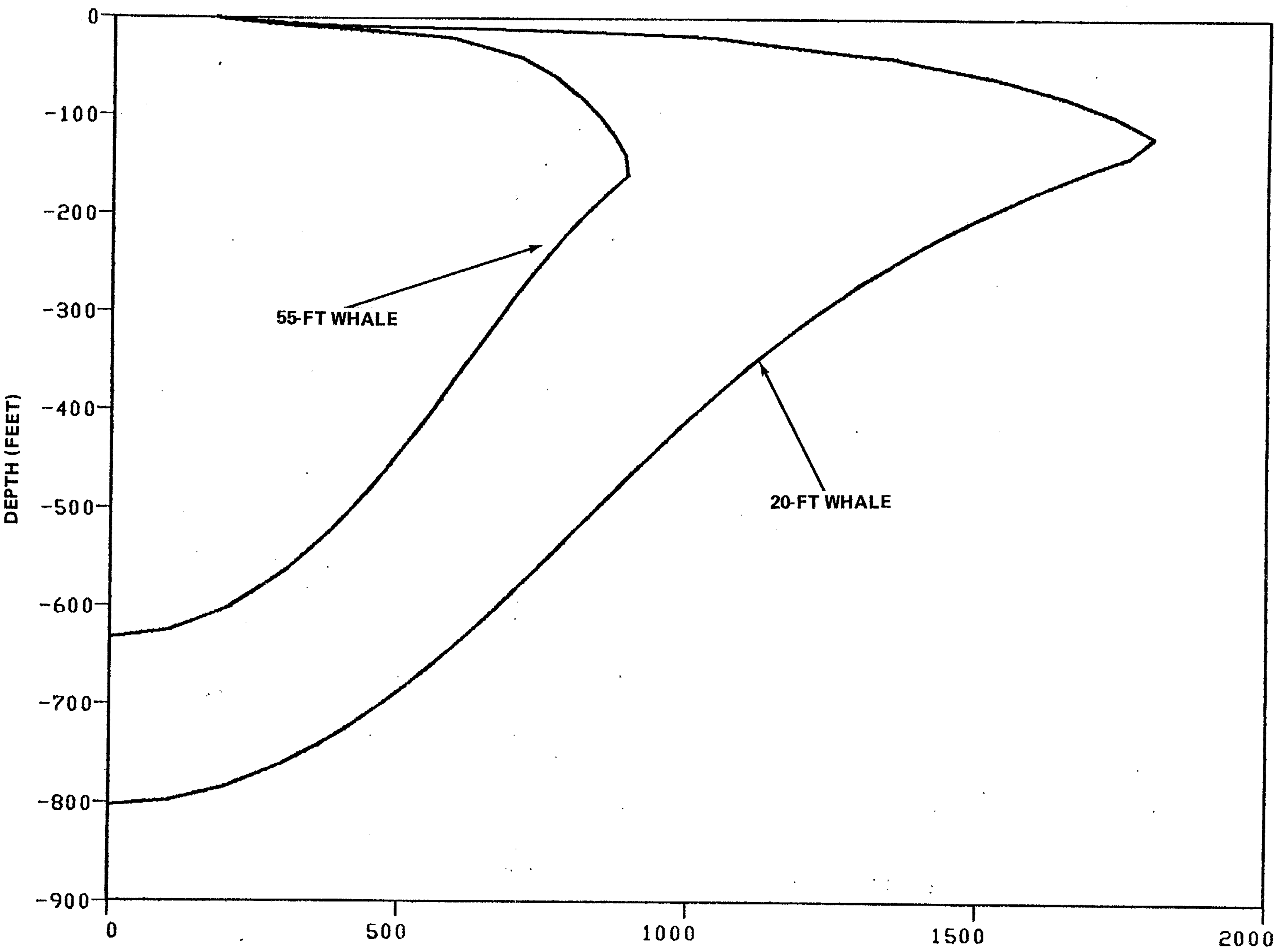

FIGURE 3.1.1. CONTOURS FOR SLIGHT INJURY TO WHALES: 1200-LB CHARGE AT 125-FT DEPTH

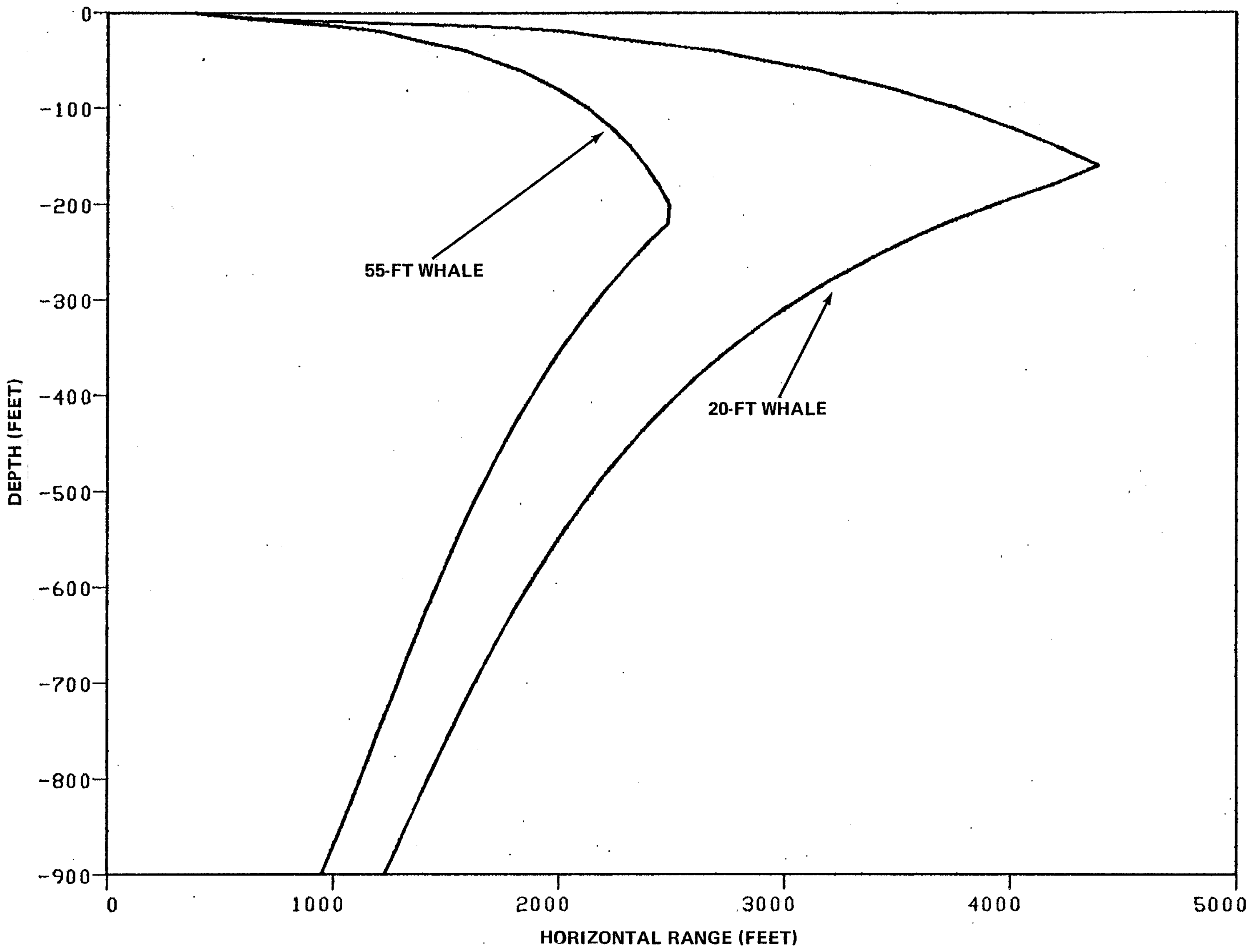

FIGURE 3.1.2 CONTOURS FOR SLIGHT INJURY TO WHALES: 10,000-LB CHARGE AT 200-FT DEPTH

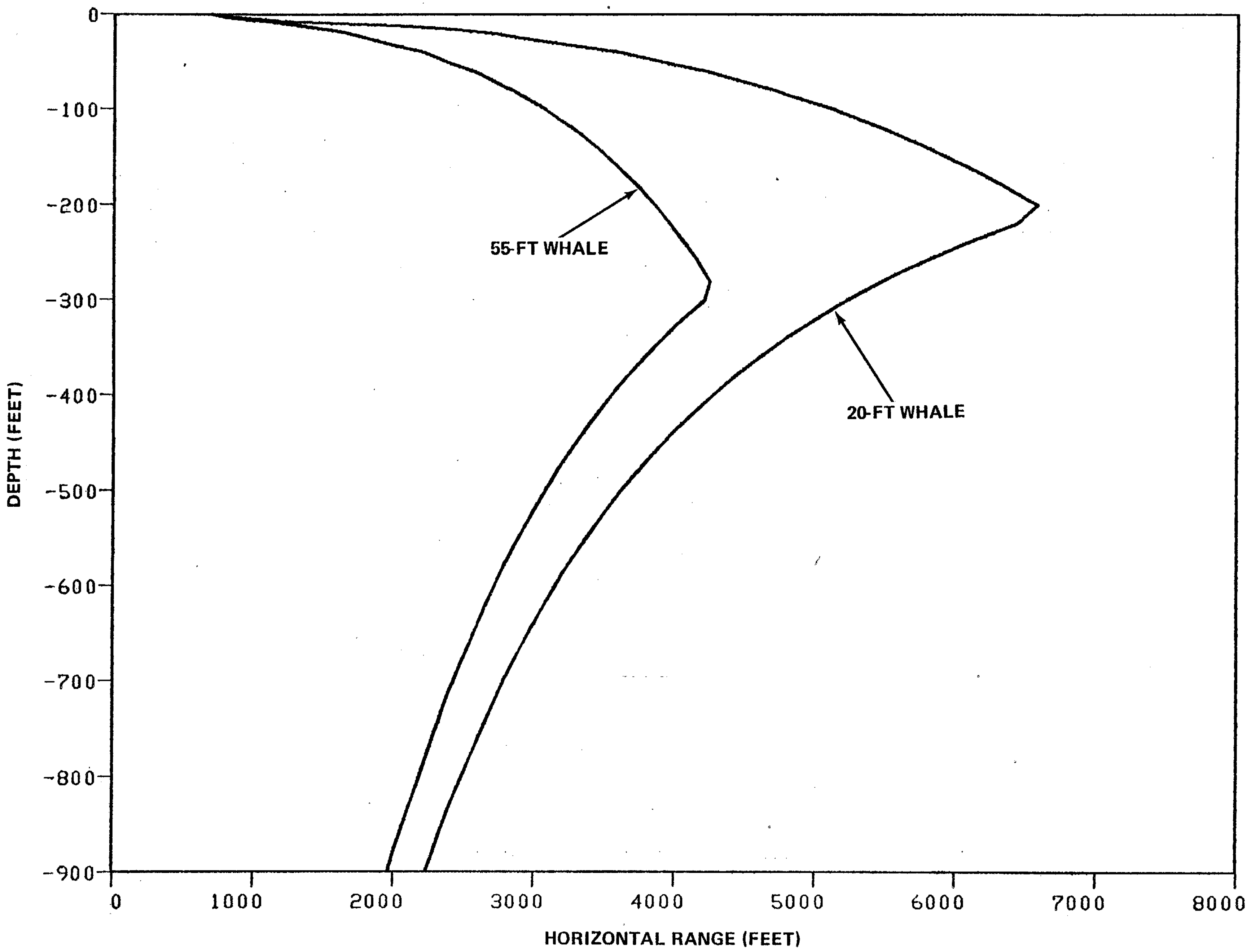

FIGURE 3.1.3. CONTOURS FOR SLIGHT INJURY TO WHALES: 40,000-LB CHARGE AT 200-FT DEPTH

Length		Body Mass	
(Feet)	(Meters)	(Kilograms)	(English Tons)
20	6.1	1.41×10^3	1.6
55	16.8	29.4×10^3	32

Note that the extent of the predicted regions for incurring injuries are larger for the smaller whales.

3-2. WHALES - NORTH ATLANTIC

These computations were done as part of a Preliminary Environmental Assessment for explosion tests employing 10,000 pound HBX-1 charges fired under water in the North Atlantic. The water depth was about 15,000 feet. The charge depths were 400 meters (1312 feet) and 1300 meters (4265 feet).

The results for 20-foot and 55-foot whales are shown in Figures 3.2.1, 3.2.2 and 3.2.3 for the two charge depths. For explosive charges fired at such great depths, two separate injury regions will often occur - a deep roughly spherical region enclosing the charge, and a shallow disk directly over the charge near the water surface. Two such regions occur with the 4,265-foot depth explosion. Figure 3.2.2 shows the shallow disk regions for the two whale sizes. Figure 3.2.3 shows the deeper spherical regions surrounding the charge.

The rough overall dimensions from these 10,000-pound explosion computations are summarized in Table 3.2.1. In Table 3.2.1 the small (insignificant) shallow disk region for the 55-foot whale (shown in Figure 3.2.2) has been omitted.

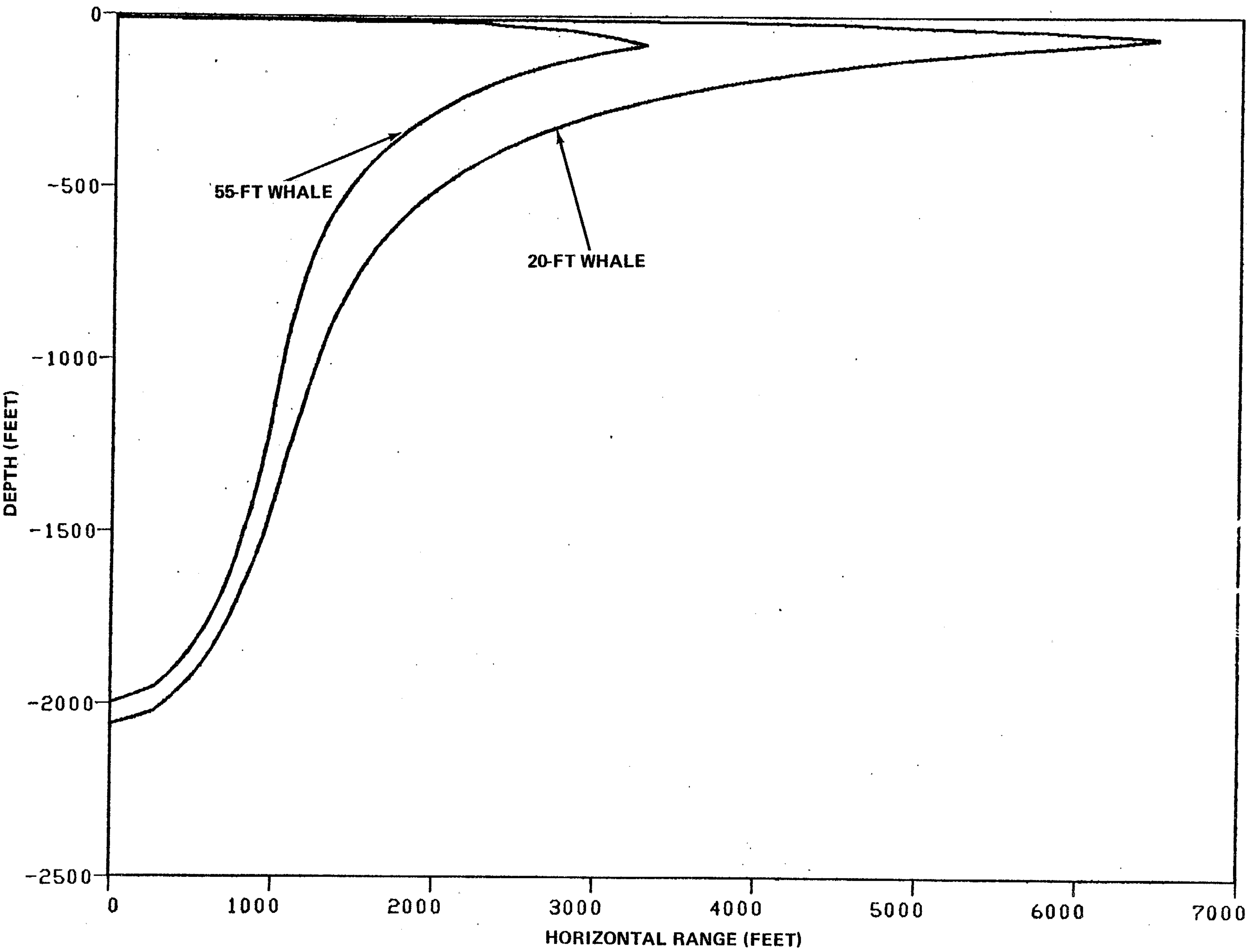

FIGURE 3.2.1. CONTOURS FOR SLIGHT INJURY TO WHALES: 10,000-LB CHARGE AT 1,312 FEET

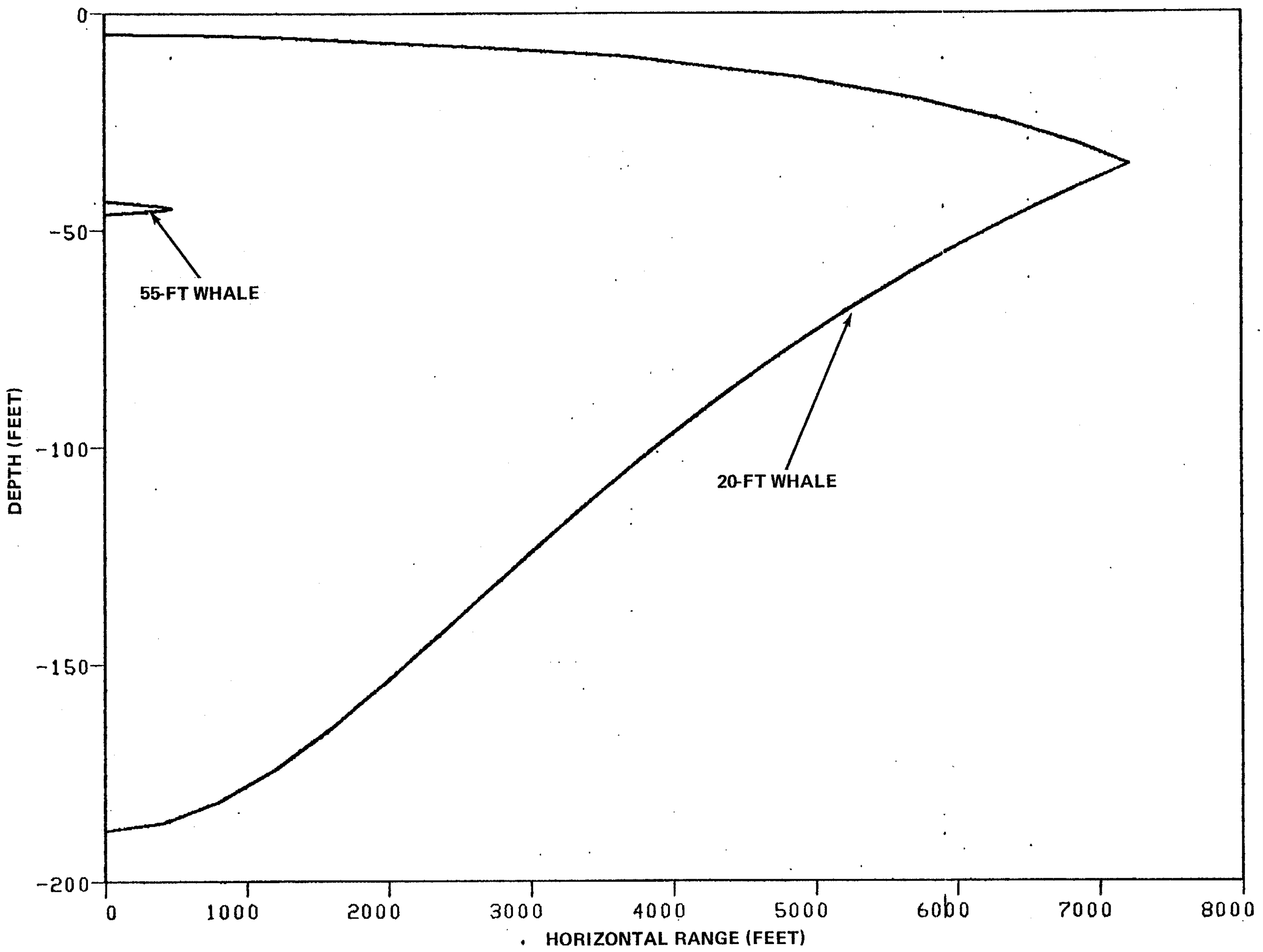

FIGURE 3.2.2. CONTOURS FOR SLIGHT INJURY TO WHALES: 10,000-LB CHARGE AT 4,265 FEET: SURFACE DISK

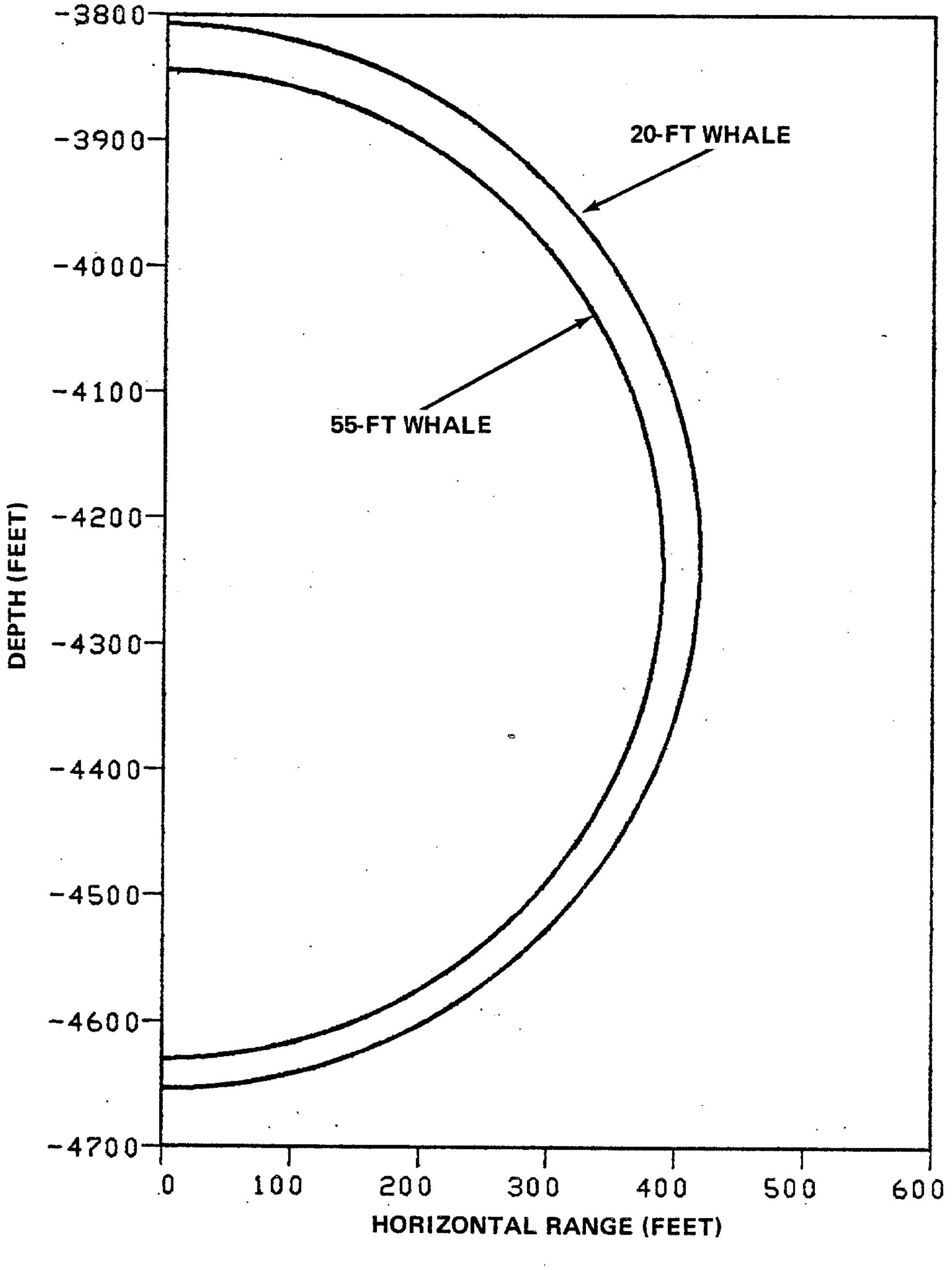

FIGURE 3.2.3. CONTOURS FOR SLIGHT INJURY TO WHALES: 10,000-LB CHARGE AT 4,265 FEET: DEEP SPHERE

TABLE 3.2.1.- HORIZONTAL EXTENT OF REGIONS OF SLIGHT INJURY TO WHALES BY 10,000-POUND EXPLOSIONS

Depth of Explosion (feet)	Length of Whale (feet)	Maximum Horizontal Radius	
		Near Water Surface (feet)	At Explosion Depth (feet)
1,312	20	6500	1060
1,312	55	3300	930
4,265	20	7200	420
4,265	55	None	390

3-3. PORPOISES

These computations are new for this report and were done for the Navy shock testing conditions at the Key West, Florida test site (see Section 3-1). The computations were done for the two sizes of Atlantic Bottlenose Dolphin (Tursiops Truncatus) - 8-foot long adults and 3.3-foot long newborn calves. For the body mass we assumed that the body mass versus length is given by

$$M = 12\ L^3 \tag{3.3.1}$$

where M is in kilograms and L is in meters.

For a 3.3-foot long and an 8-foot long Bottlenose Dolphin this gives:

	Length		Body Mass	
	(feet)	(meters)	(kilograms)	(pounds)
Calf	3.3	1.01	12.2	27
Adult	8.0	2.44	174	384

The computed results - locations (contours) where slight injuries to the porpoise are predicted - are shown in Figures 3.3.1, 3.3.2 and 3.3.3.

These computations can also be used for other similar size dolphins or porpoises, such as the variety of Bottlenose Dolphin found in the Western Atlantic which are a bit larger, and the Common Dolphin (Delphinus delphi) which are a bit smaller. Note that this section and Figures 3.3.1 through 3.3.3 have been labelled "porpoises" rather than "dolphins" in order to avoid confusion with the dolphin fish which is not related to these deep diving mammals.

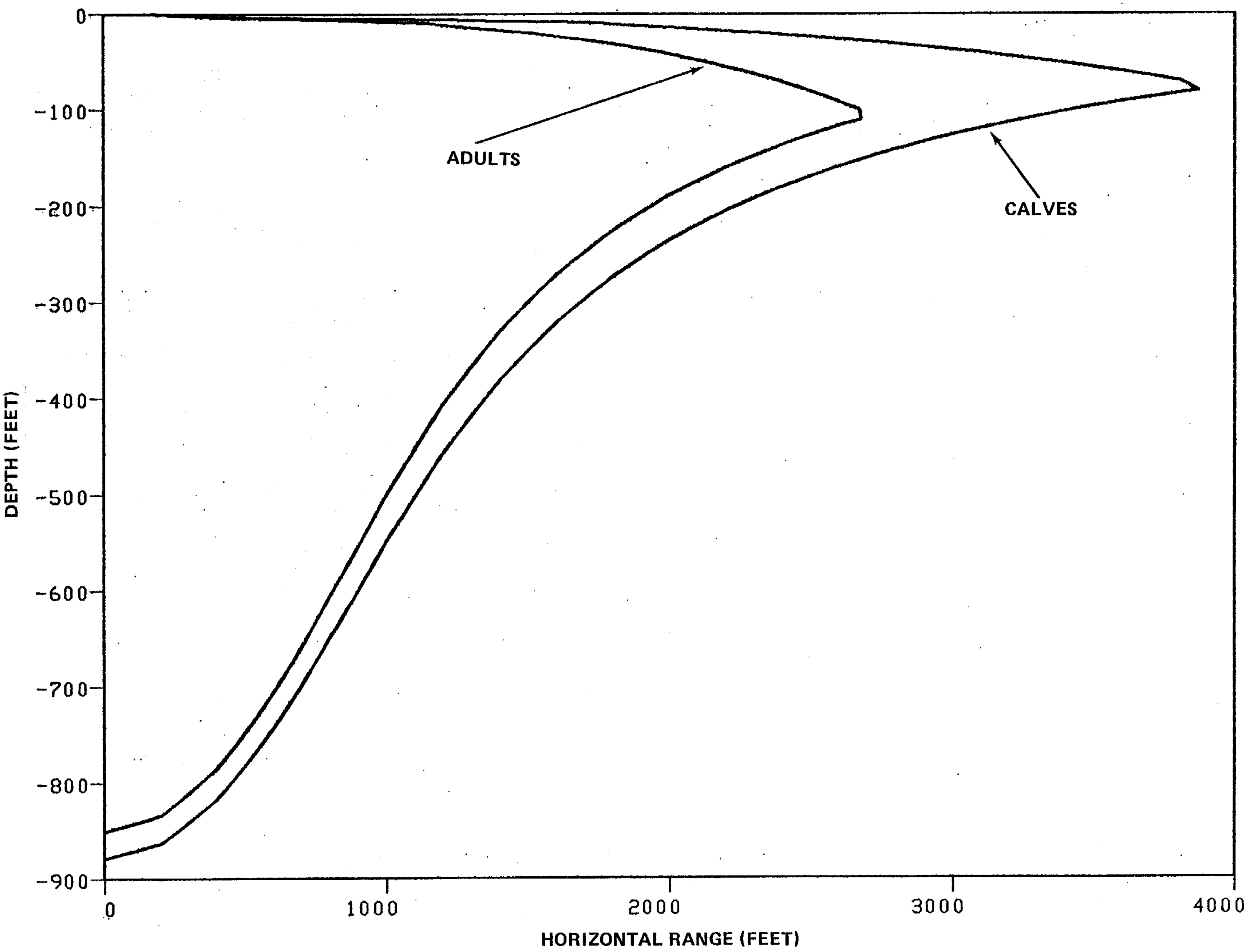

FIGURE 3.3.1. CONTOURS FOR SLIGHT INJURY TO PORPOISES : 1200-LB CHARGE AT 125 FEET

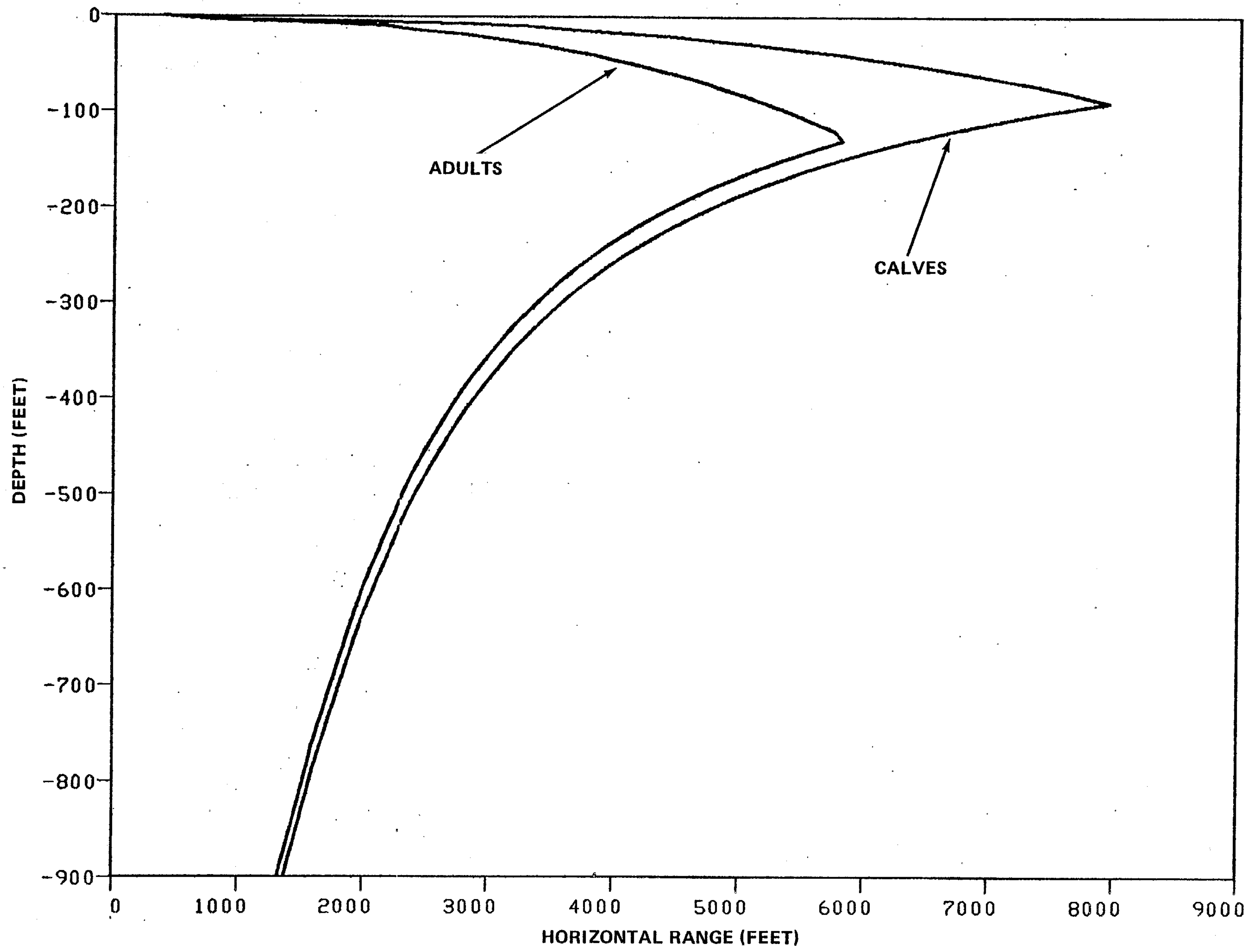

FIGURE 3.3.2. CONTOURS FOR SLIGHT INJURY TO PORPOISES: 10,000-LB CHARGE AT 200 FEET

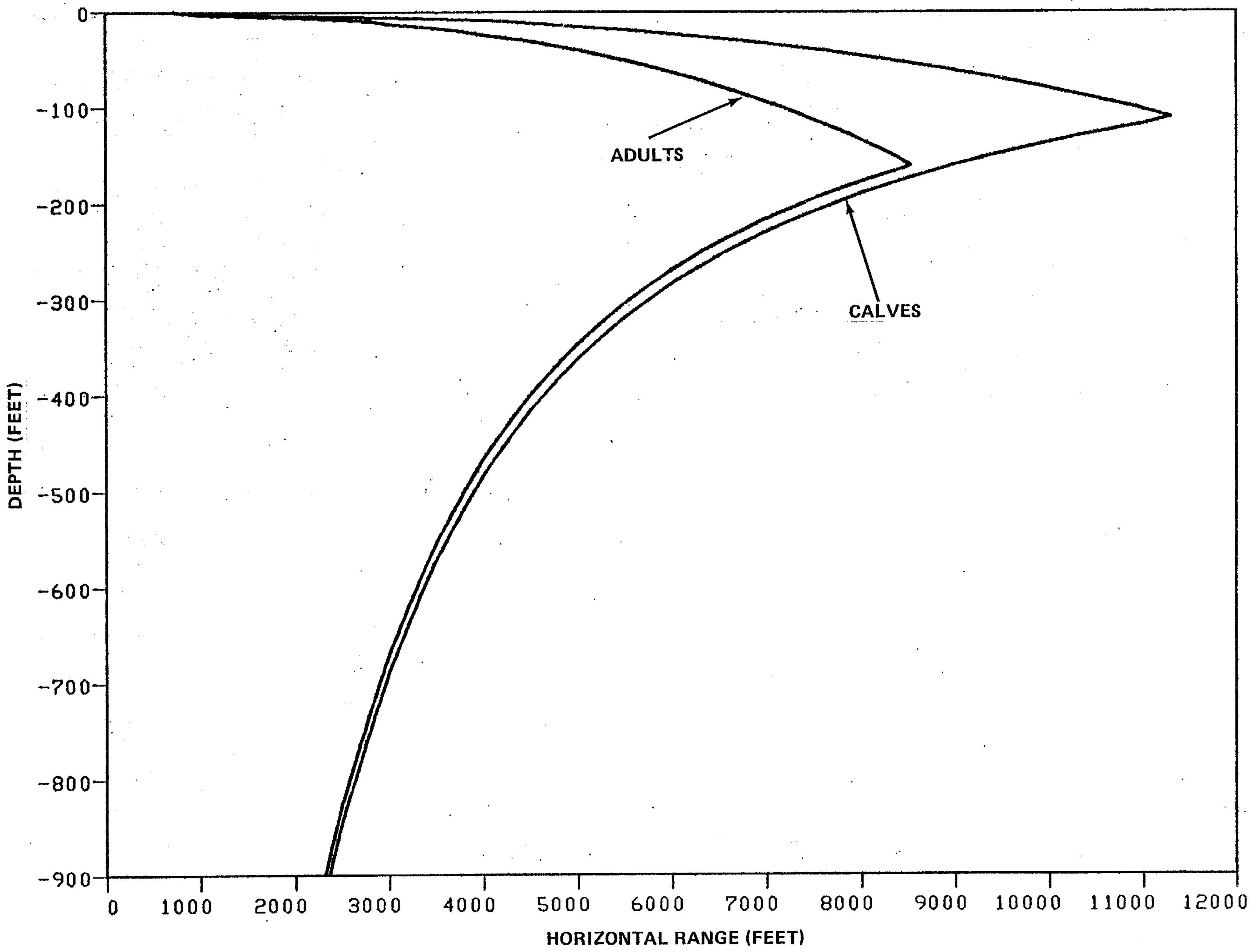

FIGURE 3.3.3. CONTOURS FOR SLIGHT INJURY TO PORPOISES: 40,000-LB CHARGE AT 200 FEET

3-4. MANATEES

These computations were done in response to a request from the Army Corps of Engineers for information on the effects of underwater blasting on manatees. A 12-pound explosive charge was used to represent the effect of charges weighing from 6 to 24 pounds. Computations were done for two charge depths, 5-feet and 40-feet, in order to bracket the situations ordinarily encountered by the Corps of Engineers; and for two mammal weights, 70-pounds (to represent calves), 1200-pounds (for juveniles and adults).

While the effects of the water surface are a major component of the computations, effects of bottom proximity are ignored. Bottom effects are considered to be of secondary importance, and, as yet, have not been considered in any of our environmental studies.

The results of these computations are presented in Figures 3.4.1 and 3.4.2, and are summarized in Table 3.4.1.

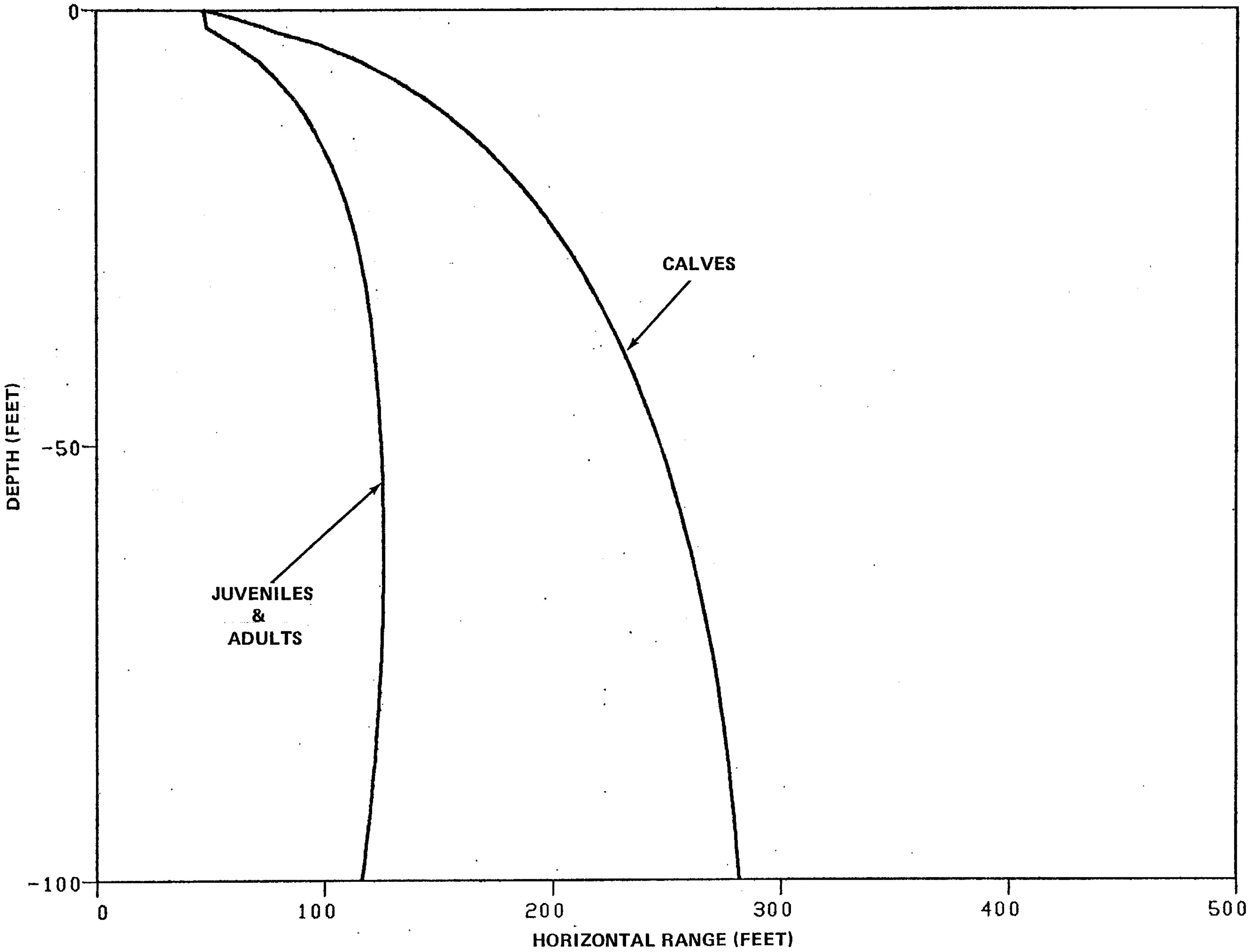

FIGURE 3.4.1. CONTOURS FOR SLIGHT INJURY TO MANATEES: 12-LB CHARGE AT 5-FT DEPTH

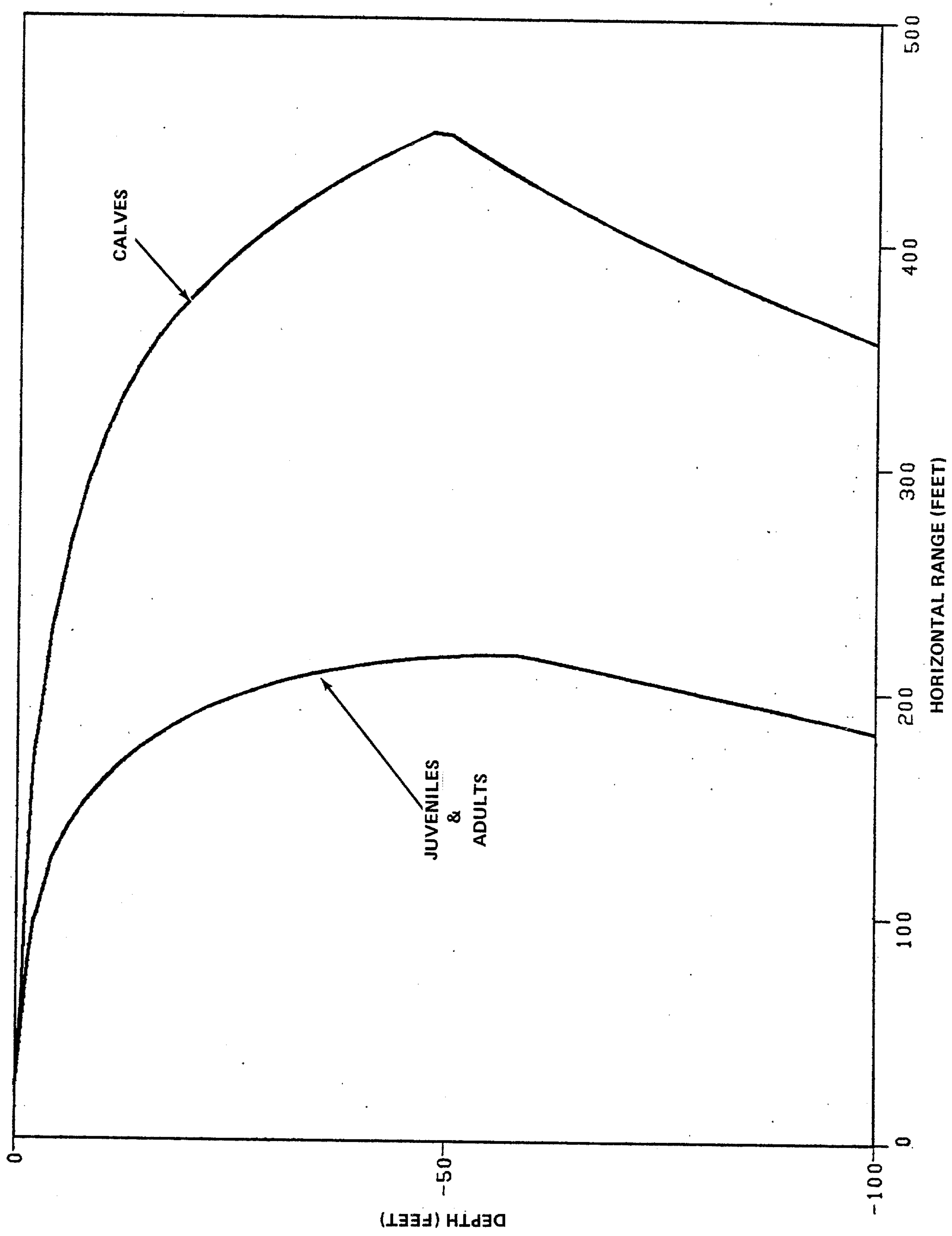

FIGURE 3.4.2. CONTOURS FOR SLIGHT INJURY TO MANATEES: 12-LB CHARGE AT 40-FT DEPTH

TABLE 3.4.1.- MAXIMUM HORIZONTAL EXTENT OF SLIGHT INJURIES TO MANATEES BY 12-POUND EXPLOSIONS[1]

Depth of Explosion (feet)	Predicted Horizontal Range: Juveniles and Adults[2] (feet)	Predicted Horizontal Range: Calves[3] (feet)
5	130	280
40	220	450

---

[1] For multiple blasts from submerged boreholes (simultaneous and/or time-delay), with 6 to 24 pounds explosive per hole, measure horizontal range to manatee from nearest borehole.

[2] Range for juveniles and adults computed using 1200-pound animal weight.

[3] Range for calves computed using 70-pound animal weight.

REFERENCES

1. Richmond, Donald R., Yelverton, John T., and Fletcher, E. Royce, "Far-Field Underwater-Blast Injuries Produced by Small Charges," Lovelace Foundation, DNA 3081T, 1973.

2. Yelverton, John T., et al, "Safe Distances from Underwater Explosions for Mammals and Birds," Lovelace Foundation, DNA 3114T, 1973.

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5. Goertner, John F., _Fish Killing Potential of a Cylindrical Charge Exploded Above the Water Surface_ NSWC/WOL TR 77-90, 1978.

6. Ommanney, F. D., _Lost Leviathan,_ Dodd, Mead and Co., New York, 1971.

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1. REPORT NUMBER NSWC TR 82-188	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) PREDICTION OF UNDERWATER EXPLOSION SAFE RANGES FOR SEA MAMMALS		5. TYPE OF REPORT & PERIOD COVERED Final Report
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) John F. Goertner		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Surface Weapons Center (CODE R14) White Oak, Silver Spring, Md 20910		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 6372IN;S0400SL;S0400SL:R14CA
11. CONTROLLING OFFICE NAME AND ADDRESS		12. REPORT DATE 16 August 1982
		13. NUMBER OF PAGES 38
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release, distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Underwater Explosions	Whales
Underwater Blast	Porpoises
Injuries	Dolphins
Mammals	Manatees

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report describes a method for the prediction of the water regions in the vicinity of an underwater explosion where significant injuries to sea mammals can occur. The method is based on an approximate scaling of underwater explosion test data obtained by the Lovelace Foundation using live sheep, dogs and monkeys. The scaling is based on the calculated radial oscillation responses of the lung cavity and of small bubbles of intestinal gas. At each point in the water the more significant of the two effects is used to define the predicted injury region.

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The method has been used in preparing Preliminary Environmental Assessments for explosion test programs. Results from several such computations done for sea mammals (whales, dolphins and manatees) are presented.

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