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OFFSHORE TECHNOLOGY REPORT - OTO 98 002

Shock Risk to Swimmers and Divers from an Electrical Field

Date of Issue : April 1998

Health & Safety Executive

FOREWORD

This report is published by the Health and Safety Executive as part of a programme of work which was commissioned in support of the Offshore Safety Division's (OSD) diving research strategy. The full programme of work covers the period from the late 1970's to 1997; some reports from the programme have hitherto not been published.

Some research was sponsored by the Department of Energy prior to the transfer of their responsibilities for offshore safety to the Health and Safety Executive. Other studies were originally commissioned by OSD for internal use. It has now been decided to issue the reports relating to this work so that the information they contain is in the public domain.

In view of the extended period of the research programme, some reports may contain information or recommendations which have been superseded. The structure of others may not meet the standard now expected of an Offshore Technology series report. Nevertheless it is HSE's intention that all such documents should be in the public domain.

Health and Safety Executive
January 1998

Note:- The Department of Energy funded ERA Technology Limited to prepare a Code of Practice for the Safe Use of Electricity Under Water and a Technical Committee was created to assess the information available, on which to base the Code.

This technical paper is one of several prepared by ERA Technology Limited for use by the Technical Committee. It has been made available to help those readers of the Code who want to refer to this background information.

No attempt has been made to edit the paper and so some minor inconsistencies may be found if compared with the Code.

A list of the Technical Papers as they appear in Appendix C of the Code will be found at the back of this paper.

Also, some 300 references have been accumulated in the course of this project.

Any queries concerning this paper or other references should be sent to:-

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Copies of the Code are available from:-

CIRIA Underwater Engineering Group
6 Storey's Gate
LONDON SW1P 3AU
Tel: 01 211 8891 (Price £12)

SHOCK RISK TO SWIMMERS AND DIVERS FROM ELECTRIC FIELD IN THE WATER.

January 1981

1 BACKGROUND.

In many types of electrical equipment used underwater, passage of electric current into the water cannot be prevented. For example, cathodic protection systems operate by passing current through the water continuously. Large electric motors and cables may pass a heavy current into the water for a fraction of a second whenever a fault occurs. Swimmers and divers incur a risk of shock if they enter the field generated by such equipment. But, since the field falls off with distance, there i[illegible]rtain safe distance beyond which the shock can be tolerated. It is [illegible] possible to provide protection by means of a barrier erected at or beyond the safe distance. This report provides a method of assessing safe distances.

For the present purposes, a SWIMMER is taken to mean a person who is in contact with the water over the whole of the surface of his body. A DIVER is a person who is wearing a diving suit that has the effect of restricting contact with the water to certain parts of the body only (for example the hands). Different diving suits provide different degrees of protection against contact with the water and so provide different degrees of protection against shock. This report provides the basis for a method of assessing the protection factors of diving suits.

2. SWIMMER IN UNIFORM FIELD

In order to render the problem tractable, it is considered to be possible to represent a swimmer by a conducting ellipsoid. The following cases are treated:

(i) A swimmer with arms at his sides is represented by an ellipsoid in which the three axes are of different length.

(ii) A swimmer with arms outstretched, to give maximum distance between hands and feet, is represented by an ellipsoid of revolution.

The problem to be solved is that of determining the current density inside the conducting ellipsoid when the latter is introduced into a conducting medium which, in the absence of the ellipsoid, is carrying current which is uniform in density and direction at all points. The problem can be solved by analogy with a corresponding magnetic problem, namely that of determining the magnetic flux density inside a magnetic ellipsoid when introduced into a uniform magnetic field. Solutions to this problem are well known and are expressed in terms of "demagnetising factors", values of which have been listed for ellipsoids of all shapes.*+ The problem is simplified by the fact that, although the presence of the ellipsoid distorts the external field, nevertheless the field inside the ellipsoid is uniform. The basic relations are as follows:

a = minor semi-axis of ellipsoid, m
b = intermediate semi-axis of ellipsoid, m
c = major " " " " , m
D_a= demagnetising factor in direction of minor axis
D_b= " " " " " intermediate axis
D_c= " " " " " major "
i_o= current density in the water in absence of ellipsoid, A/m^2
E_o= voltage gradient " " " " " " " , V/m
i = current density in ellipsoid, A/m^2
E = voltage gradient " " , V/m
σ_o= conductivity of the water, S/m
σ = " " " ellipsoid, S/m
$\kappa = \sigma/\sigma_o$

For the general ellipsoid : $c > b > a$
For the ellipsoid of revolution: $c > r = a = b$

The three demagnetisation factors are connected by the following relation:

$$D_a + D_b + D_c = 1 \qquad \text{-(1)}$$

The current density and the voltage gradient inside the ellipsoid are given by :

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* E.C. Stoner, "Demagnetising Factors for Ellipsoids" pp 803-821, Ser 7, Vol 36, No 263, Dec 1945

\+ J.A. Osborn, "Demagnetising Factors of the General Ellipsoid", Physical Review, Vol 67, Nos 11 and 12, pp 351-357, 1st/15th June 1945.

$$\frac{i}{i_o} = \frac{\kappa}{1+(\kappa-1)D} \tag{2}$$

$$\frac{E}{E_o} = \frac{1}{1+(\kappa-1)D} \tag{3}$$

where D is the demagnetisation factor appropriate to the orientation of the ellipsoid with respect to the direction of the field in the water.

In the numerical evaluation of equations (2) and (3) the electrical resistivity of the swimmer's body is taken to be $1/\sigma = 3.5$ Ωm.

Case A

Swimmer with arms at his sides
General ellipsoid
Field in direction of minor axis (from chest to back)
$b/a = 1.5$ $c/\sqrt{ab} = 5$
$D_a = 0.566$

Case B

Swimmer with arms at his sides
General ellipsoid
Field in direction of intermediate axis (from arm to arm through chest)
$b/a = 1.5$ $c/\sqrt{ab} = 5$
$D_b = 0.378$

Case C

Swimmer with arms at his sides
General ellipsoid
Field in direction of major axis (from head to feet)
$b/a = 1.5$ $c/\sqrt{ab} = 5$
$D_c = 0.056$

Case R

Swimmer with arms outstretched .
Ellipsoid of revolution
Field in direction of minor axis (across chest)

$c/r = 7$
$D_r = 0.483$

Case S

Swimmer with arms outstretched
Ellipsoid of revolution
Field in direction of major axis (from hands to feet)

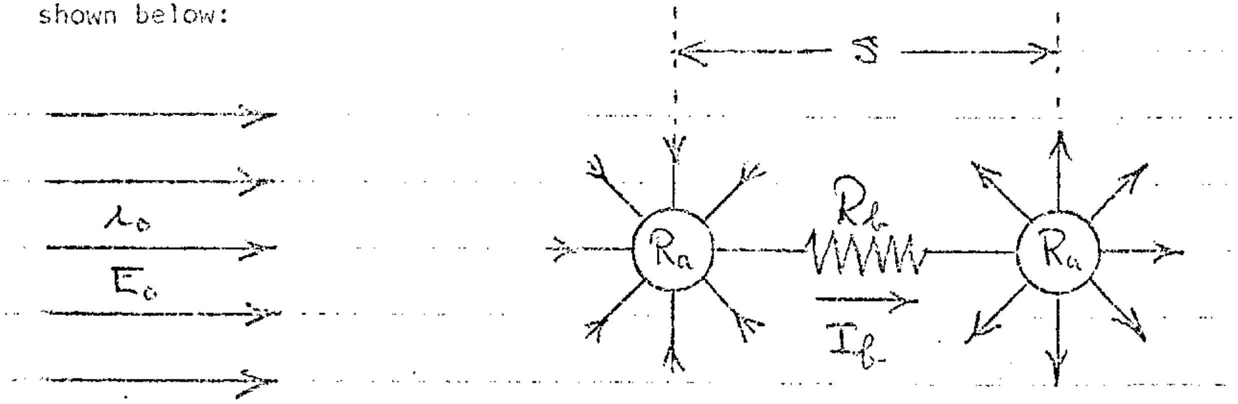
$c/r = 7$
$D_s = 0.034$

Values of i/io and E/Eo, derived from equations (2) and (3) and from the demagnetisation factors listed above, are plotted in Figures 1 and 2 for a range of water resistivities. It should be noted that sea water may be taken to have a resistivity of $1/\sigma_o = 0.25$ Ωm, whereas freshwater covers the range 10Ωm - 10 kΩm.

These curves show that the most dangerous condition for sea water is Case A, where the direction of the field is from chest to back. For fresh water, the most dangerous condition is Case S, where the swimmer has his hands outstretched and the direction of the field is from hands to feet. In sea water the voltage gradient in the swimmer's body can be up to 2.1 X the voltage gradient in the water. In freshwater the current density in the swimmer's body can be up to 30 X the current density in the water.

3. DIVER IN UNIFORM FIELD

For the purposes of this analysis, a "standard diver" is a diver having his hands exposed to the water but having the remainder of his body insulated from the water by his diving suit. The hands may be represented by equivalent spherical electrodes, each having the same surface area as the hand. The water displaced by the diver's body has to be disregarded. But, since only the worst case will be considered in which the arms are fully outstretched in opposite directions, it can be expected that the effect of the displaced water will be small. The conditions are then as shown below:



s = span between divers hands, m

a = equivalent radius of diver's hand, m

R_a = hand resistance into the water, Ω

R_b = diver's body resistance, hand/hand, Ω

σ_o = conductivity of the water, s/m

i_o = current density in the water, in the absence of the diver, A/m^2

E_o = voltage gradient in the water, in the absence of the diver, V/m

I_b = current through the diver's body, A

V_o = voltage across the span s in the absence of the diver = $E_o s$, V

V_b = voltage across the diver = $I_b R_b$, V

A_b = cross-sectional area of diver's body at chest, m^2

i_b = current density through diver's chest, A/m^2

The diver's hand resistance (from hand to water) is given by:

$$R_a = \frac{1}{4\pi\sigma_o a} \quad \text{------------------------------------}(4)$$

The current through the diver's body is given by:

$$\frac{I_b}{i_o} = \frac{s}{\sigma_o(R_b+2R_a)} = \frac{s}{\sigma_o R_b + \frac{1}{2\pi a}} \quad \text{------------------------------------}(5)$$

The voltage across the diver's hands is given by:

$$\frac{V_b}{V_o} = \frac{R_b}{R_b+2R_a} \simeq \frac{2\pi\sigma_o a R_b}{1+2\pi\sigma_o a R_b} \quad \text{------------------------------------}(6)$$

The current density through the diver's chest is given by:

$$\frac{i_b}{i_o} = \frac{s}{A_b\sigma_o(R_b+2R_a)} = \frac{s}{A_b(\sigma_o R_b + \frac{1}{2\pi a})} \quad \text{--------------------------(7)}$$

The numerical values taken for the evaluation of these relations are as follows:

Span between diver's hands	$s = 1.7$ m
Surface area of diver's hand	0.035 m^2
Equivalent radius of diver's hand	$a = 0.053$ m
Diver's body resistance (hand/hand)	$R_b = 500$ ohm
Cross-sectional area of diver's chest	$A_b = 0.08$ m^2

Values of I_b/i_o, V_b/V_o, and i_b/i_o derived from equations (5), (6) and (7), are plotted in Figures 3, 4 and 5 for a range of water resistivities. These curves show the following properties.

(i) In sea water, the voltage across the diver's hands is equal to the voltage in the water in his absence. In fresh water, the voltage across the diver's hands can vary from 100% down to 2% of the voltage in the water.

(ii) In sea water, the cross-section of water from which current is diverted into the diver is only 8.5 cm^2. In fresh water, it can vary from 300 cm^2 to 5000 cm^2.

(iii) In sea water, the current density in the diver's chest is only 1% of the current density in the water. In freshwater, it can vary from 40% to 700%.

4. PROTECTION FACTOR OF DIVING SUIT

In the preceding sections relations have been derived for the ratio of the current density in a swimmer's body to the current density in the water (equation 2) and for the ratio of the current density in a standard diver's body to the current density in the water (equation 7). Figures 1 and 5 show that, under all conditions, the current density in the diver's body is less than that in the swimmer's body. The ratio of these two current densities may be taken as a measure of the protection provided by the diving suit.

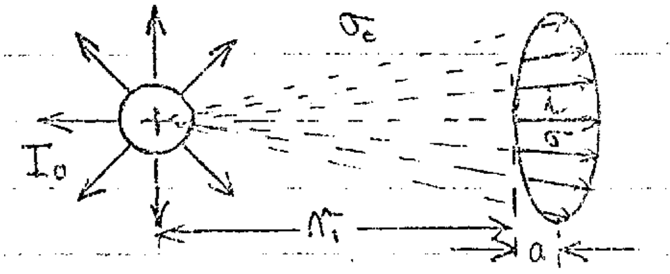
The protection factor of the "standard" diving suit (i.e. a suit that exposes only the hands to the water), derived in this way, is shown plotted against water resistivity in Figure 6. The values shown in Figure 6 are obtained by taking the orientation of the swimmer as that which gives the highest current density in his body (Case A for sea water; Case S for fresh water). It will be seen that the protection factor is 14 : 1 for sea water and varies from 7 : 1 to 4 : 1 for fresh water.

For diving suits of types other than the standard, the protection factor cannot easily be calculated. But protection factors can be determined by experiment, using the standard suit as a reference.

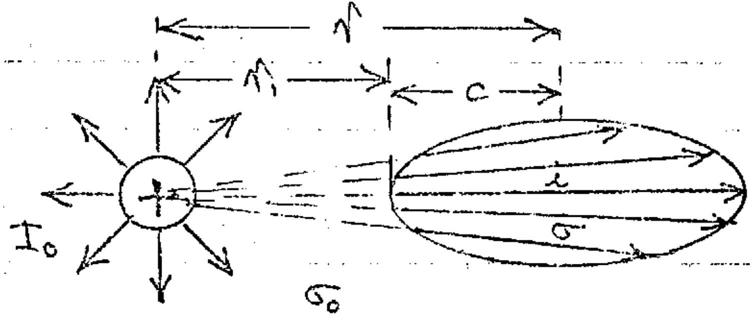
5. SWIMMER IN DIVERGENT FIELD

It is assumed that current is emitted into the water from a point source. In practice the source will have finite dimensions. The analysis will then be valid only if the distance of the swimmer from the source is appreciably greater than its dimensions.

In the absence of the swimmer, the current in the water will be radially outwards from the source. When the swimmer is present (and representing him as an ellipsoid) the field in the water will be distorted, but the field in his body will be radially outwards from the point source. Only the most severe cases are taken, namely Case A for sea water and Case S for fresh water. In both these cases the swimmer's heart is located close to the centre of the ellipsoid. Hence the current density at the centre of the ellipsoid may be taken. The systems are as shown below.



CASE A



CASE S

r_1 = distance of nearest point on diver's body from the point source of current, m

a = minor semi-axis of ellipsoid, m

c = major semi-axis of ellipsoid, m

r = distance of centre of ellipsoid from the point source of source of current = $r_1 + a$ (Case A)= $r_1 + c$(Case S), m

In the absence of the ellipsoid, the current density in the water at the point corresponding to the centre of the ellipsoid is given by:

$$i_o = \frac{I_o}{4\pi r^2}$$

The current density at the centre of the ellipsoid is therefore given by:

$$\frac{i}{I_o} = \frac{\kappa}{4\pi r^2(1+(\kappa-1)D)} \text{--} (8)$$

It follows that the diver's body current is given by:

$$\underline{\text{CASE A:}}\quad \frac{I_b}{I_o} = \frac{\kappa A_b}{4\pi(r_1+a)^2(1+(\kappa-1)D_a)} \text{---------------------} (9)$$

$$\underline{\text{CASE S:}}\quad \frac{I_b}{I_o} = \frac{\kappa A_b}{4\pi(r_1+c)^2(1+(\kappa-1)D_s)} \text{-----------------------} (10)$$

Hence the minimum safe distance is given by:

$$\underline{\text{CASE A:}}\quad r_1 = \sqrt{\frac{\kappa A_b I_o}{4\pi(1+(\kappa-1)D_a)I_b}} - a \text{ -----------------------} (11)$$

$$\underline{\text{CASE S:}}\quad r_1 = \sqrt{\frac{\kappa A_b I_o}{4\pi(1+(\kappa-1)D_s)I_b}} - c \text{ ------------------------} (12)$$

where I_b = maximum safe shock current.

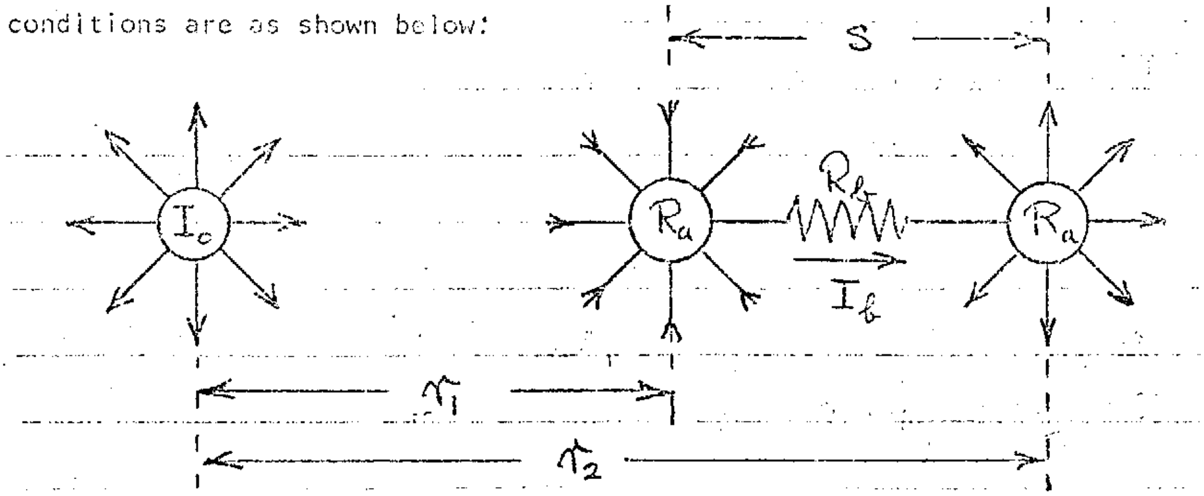
The numerical values taken for the evaluation of these relations are as follows:

Minor semi-axis of ellipsoid, Case A: $a = 0.14$ m
Major " " " Case S: $c = 1.12$ m
Demagnetising factor of ellipsoid, Case A: $D_a = 0.566$
" " " Case S: $D_s = 0.034$
Resistivity of swimmer's body: $1/\sigma = 3.5$ ohm-m
Cross-sectional area of swimmer's chest: $A_b = 0.08$ m^2

Values of the minimum safe distance r_1 derived from equations (11) and (12), are plotted in Figure 7 for ranges of water resistivity and maximum safe shock current.

6. DIVER IN DIVERGENT FIELD

It is assumed that current is emitted into the water from a point source. Since the source will have finite dimensions in practice, the analysis is valid only if the distance of the diver from the source is appreciably greater than its dimensions. The analysis applied to a "standard diver", and the effect of the water displaced by the diver is disregarded. The conditions are as shown below:



r_1 = distance of diver's nearest hand from the point source of current, m

r_2 = distance of diver's farthest hand from the point source of current, m

I_o = current emitted into the water by the point source, A

Other parameters are as specified in Section 3.

The diver's hand resistance (from hand to water) is given by equation (4).

In the absence of the diver, the voltage across the span s is given by:

$$V_o = \frac{I_o}{4\pi\sigma_o}\left(\frac{1}{r_1} - \frac{1}{r_2}\right) \text{------------------------------} (13)$$

Th [illegible]ent through the diver's body is given by:

$$I_b = \frac{V_o}{R_b + 2R_a} \text{------------------------------------} (14)$$

Hence:

$$\frac{I_b}{I_o} = \frac{a\left(\frac{1}{r_1} - \frac{1}{r_2}\right)}{2(1 + 2\pi\sigma_o a R_b)} \text{-----------------------------------} (15)$$

Taking the worst case, when $r_2 - r_1 = s$, the minimum safe distance is given by :

$$r_1 \approx \frac{s}{2}\left[\sqrt{1 + \frac{2aI_o}{sI_b(1 + 2\pi\sigma_o a R_b)}} - 1\right] \text{--------} (16)$$

where I_b = maximum safe shock current.

The numerical values taken for the evaluation of this relation are:

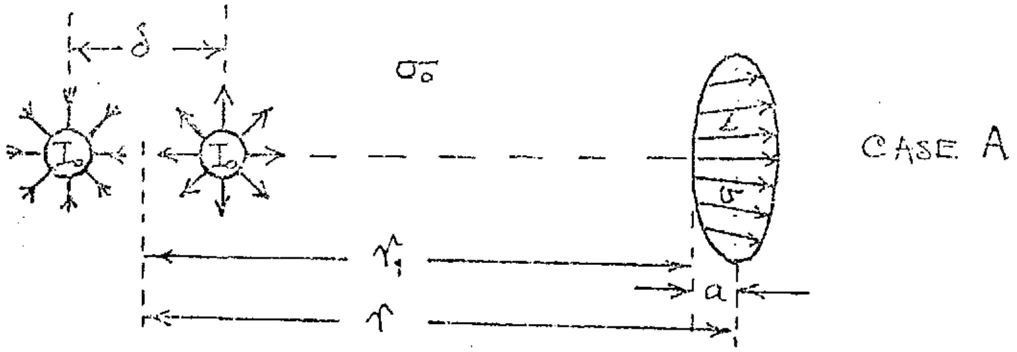
Span between diver's hands:	$s=1.7$ m
Surface area of diver's hand:	0.035 m^2
Equivalent radius of diver's hand:	$a=0.053$ m
Diver's body resistance (hand/hand):	$R_b=500$ ohm

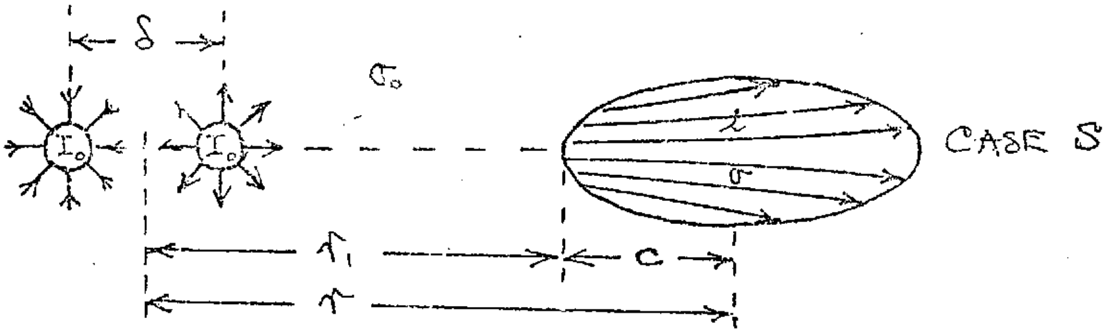
Values of the minimum safe distance r_1, derived from equation (16), are plotted in Figure 8 for ranges of water resistivity and maximum safe shock current.

7. SWIMMER IN FIELD FROM CURRENT DIPOLE.

When current flows in the water from a severed cable, current will flow into the water from one or more of the exposed conductors and out of the water into another of the exposed conductors. For cables carrying direct current or single-phase alternating current, the current source in the water may be regarded as a current dipole. For cables carrying 3-phase alternating current current source would have to be regarded as a current tripole. S the analysis required for the latter is much more complex, only the case of the current dipole is considered here.

It can be shown that, at a given distance, the strongest field from a current dipole occurs at points on its axis. Representing the swimmer by an ellipsoid, as previously, the systems are as shown below.





I_o = current passed through the water, A

δ = separation of the +ve and -ve current sources, m

a = minor semi-axis of ellipsoid, m

c = major semi-axis of ellipsoid, m

r = distance of centre of ellipsoid from centre of current dipole, m

r_1 = distance of nearest point on ellipsoid from centre of current dipole m

r_1 = r-a (Case A)

r_1 = r-c (Case S)

In the absence of the ellipsoid, the current density in the water at the point corresponding to the centre of the ellipsoid is given by:

$$i_o = \frac{I_o \delta}{2\pi r^3} \quad \text{------------------------------------(17)}$$

The current density at the centre of the ellipsoid is therefore given by:

$$\frac{i}{I_o} = \frac{\kappa\delta}{2\pi r^3 \ \{1+(\kappa-1)D\}} \quad \text{------------------------------------(18)}$$

It follows that the diver's body current is:

CASE A

$$\frac{I_b}{I_o} \quad \frac{\kappa A_b \delta}{2\pi(r_1+a)^3\{1+(\kappa-1)Da\}} \quad \text{------------------------------------(19)}$$

CASE S

$$\frac{I_b}{I_o} = \frac{\kappa A_b \delta}{2\pi(r_1+c)^3\{1+(\kappa-1)Ds\}} \quad \text{------------------------------------(20)}$$

Hence minimum safe distance is given by:

CASE A

$$r_1 = \left[\frac{\kappa A_b I_o \delta}{2\pi Ib\{1+(\kappa-1)Da\}}\right]^{\frac{1}{3}} - a \quad \text{------------------------------(21)}$$

CASE 5

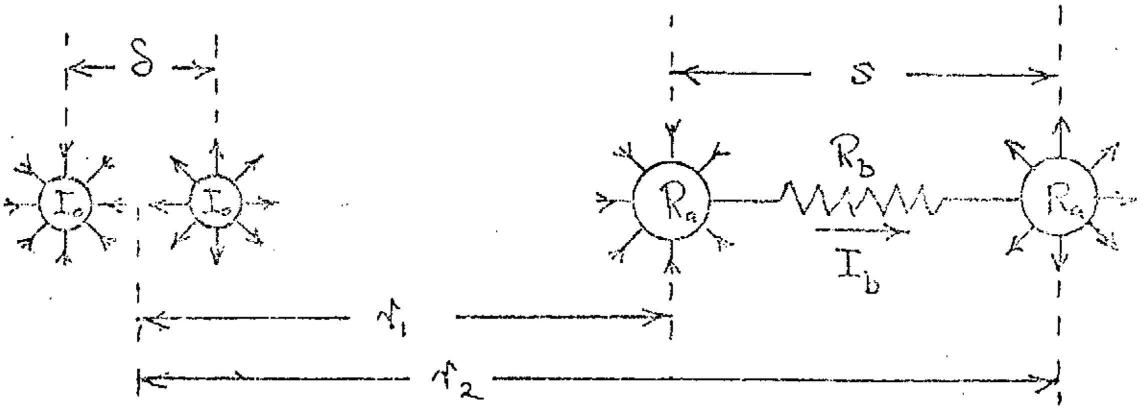
$$r_1 = \left[\frac{\kappa A_b I_o \delta}{2\pi I_b \{1+(\kappa-1)D_s\}}\right]^{\frac{1}{3}} - c \qquad \text{------------------------------(22)}$$

where I_b = maximum safe shock current

Values of the minimum safe distance r. derived from equations (21) and (22) are plotted in Figures 9 and 10.

8. DIVER IN FIELD FROM CURRENT DIPOLE

The system is as shown below:



I_o = current passed through the water, A

δ = separation of the +ve and -ve current sources, m

s = separation of diver's hands, m

r_1 = distance of diver's nearest hand from centre of current dipole, m

r_2 = distance of diver's furthest hand from centre of current dipole, m

S = $r_2 - r_1$

In the absence of the diver, the voltage across the span s is given by:

$$V_o = \frac{I_o \delta}{4\pi\sigma_o}\left(\frac{1}{r_1^{\,2}} - \frac{1}{r_2^{\,2}}\right) \qquad \text{------------------------------(23)}$$

substituting

$$r_2 = r_1 + s$$

$$\frac{4\pi\sigma_o V_o}{I_o\delta} = \frac{s(2r_1 + s)}{r_1^{\,2}(r_1 + s)^2} \tag{24}$$

The current through the diver's body is given by equation (14). Hence the minimum safe distance is given by:

$$\sigma_o = \frac{1}{2\pi a R_b}\left\{\frac{as(2r_1+s)I_o\delta}{2r_1^{\,2}(r_1+s)^2 I_b} - 1\right\} \tag{25}$$

Values of minimum safe distance, derived from equation (25), are plotted in Figures 11 and 12.

(7) A diving suit which exposes only the divers hands reduces the electric shock by 14 times for seawater and between 4 and 7 times for freshwater.

(8) The safe distance of approach to a single current source is 4 - 10 times smaller for a diver in sea water than for a swimmer. In fresh water, the safe distance for a diver is 2 - 3 times less than for a swimmer.

(9) The safe distance of approach to a current dipole is less than for a single current source of the same current magnitude, and falls progressively as the separation of the two current sources in the dipole is reduced.

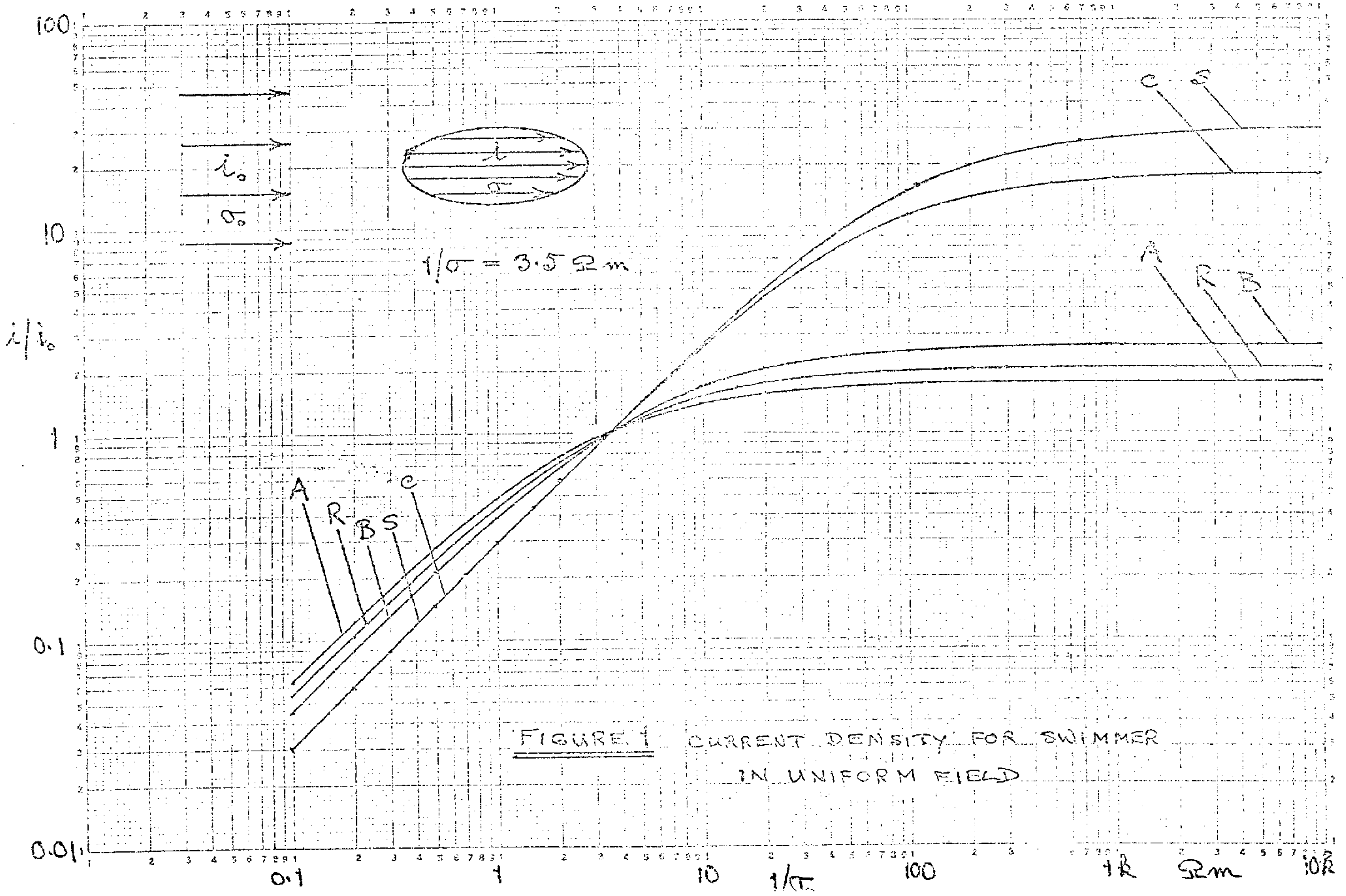


FIGURE 1 CURRENT DENSITY FOR SWIMMER IN UNIFORM FIELD

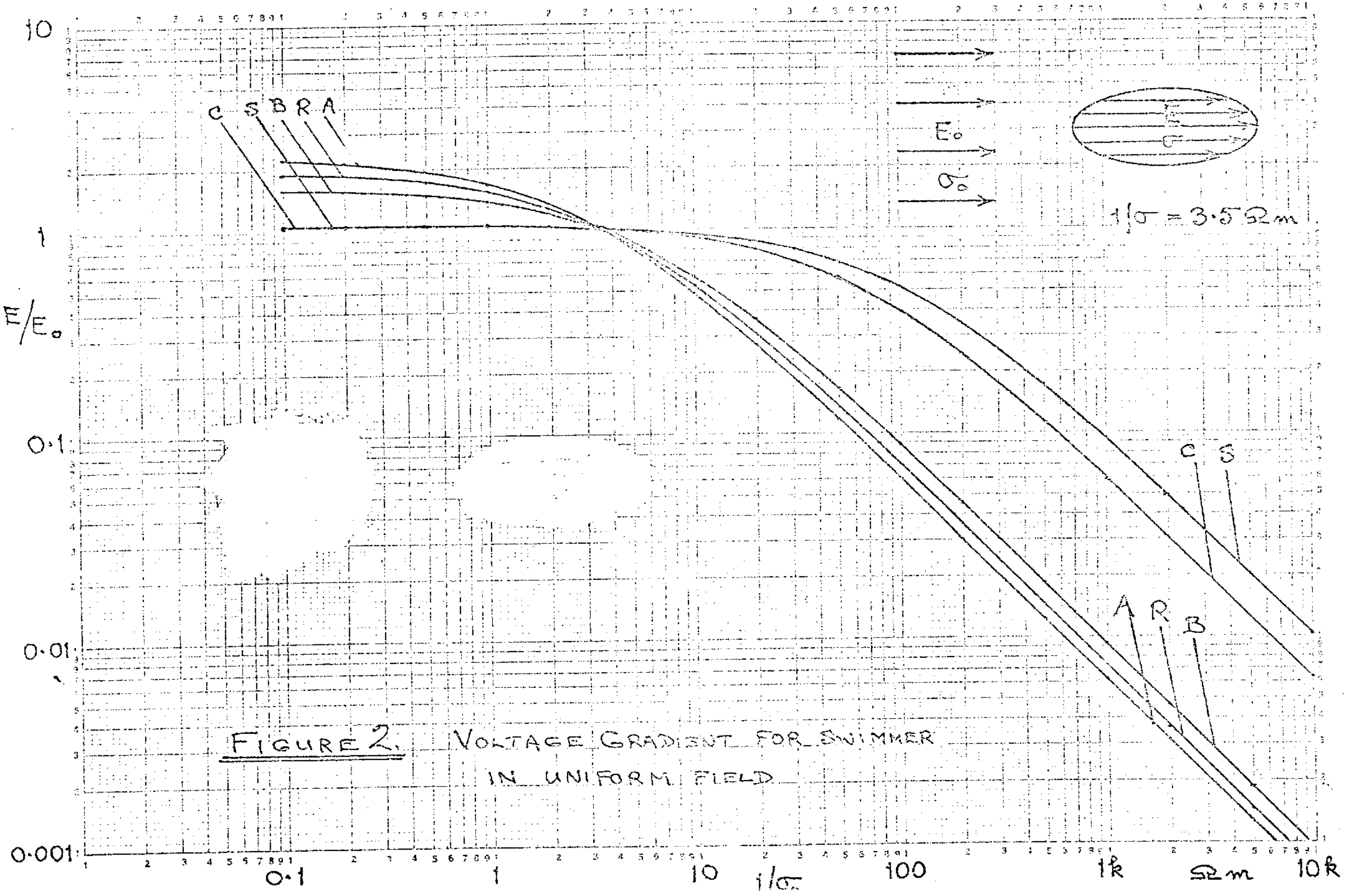


FIGURE 2. VOLTAGE GRADIENT FOR SWIMMER IN UNIFORM FIELD

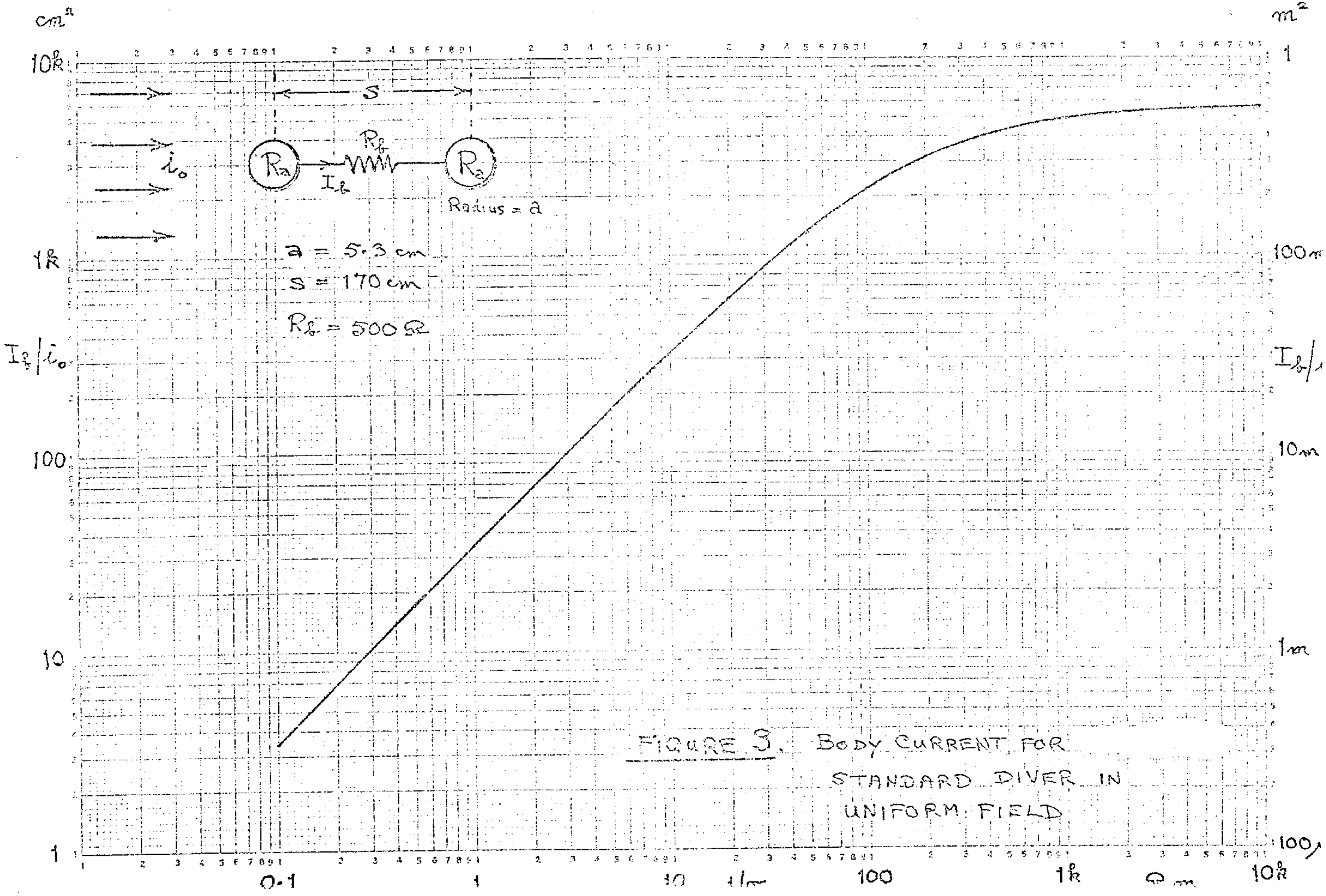


FIGURE 3. BODY CURRENT FOR STANDARD DIVER IN UNIFORM FIELD

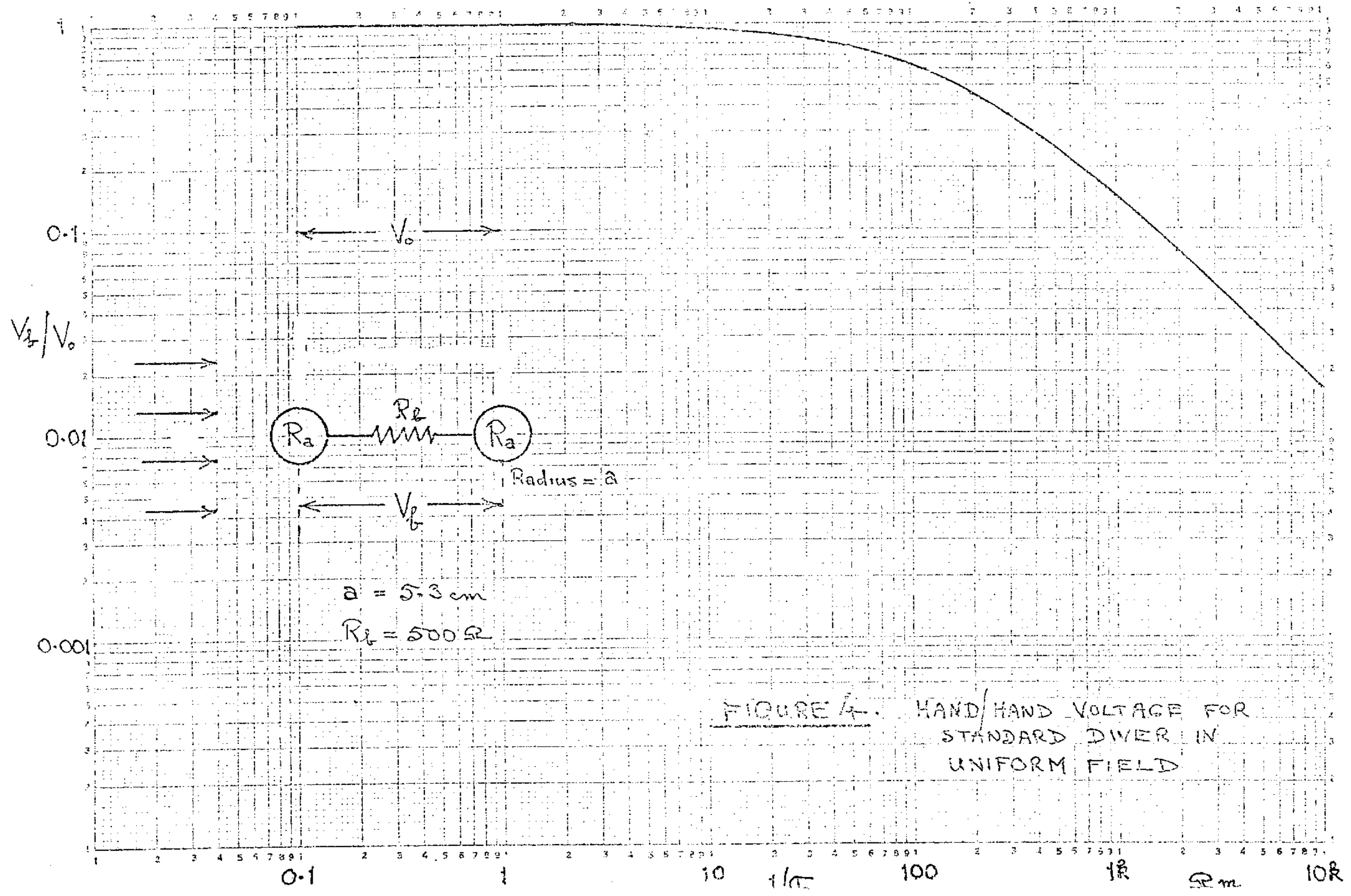


FIGURE 4. HAND/HAND VOLTAGE FOR STANDARD DIVER IN UNIFORM FIELD

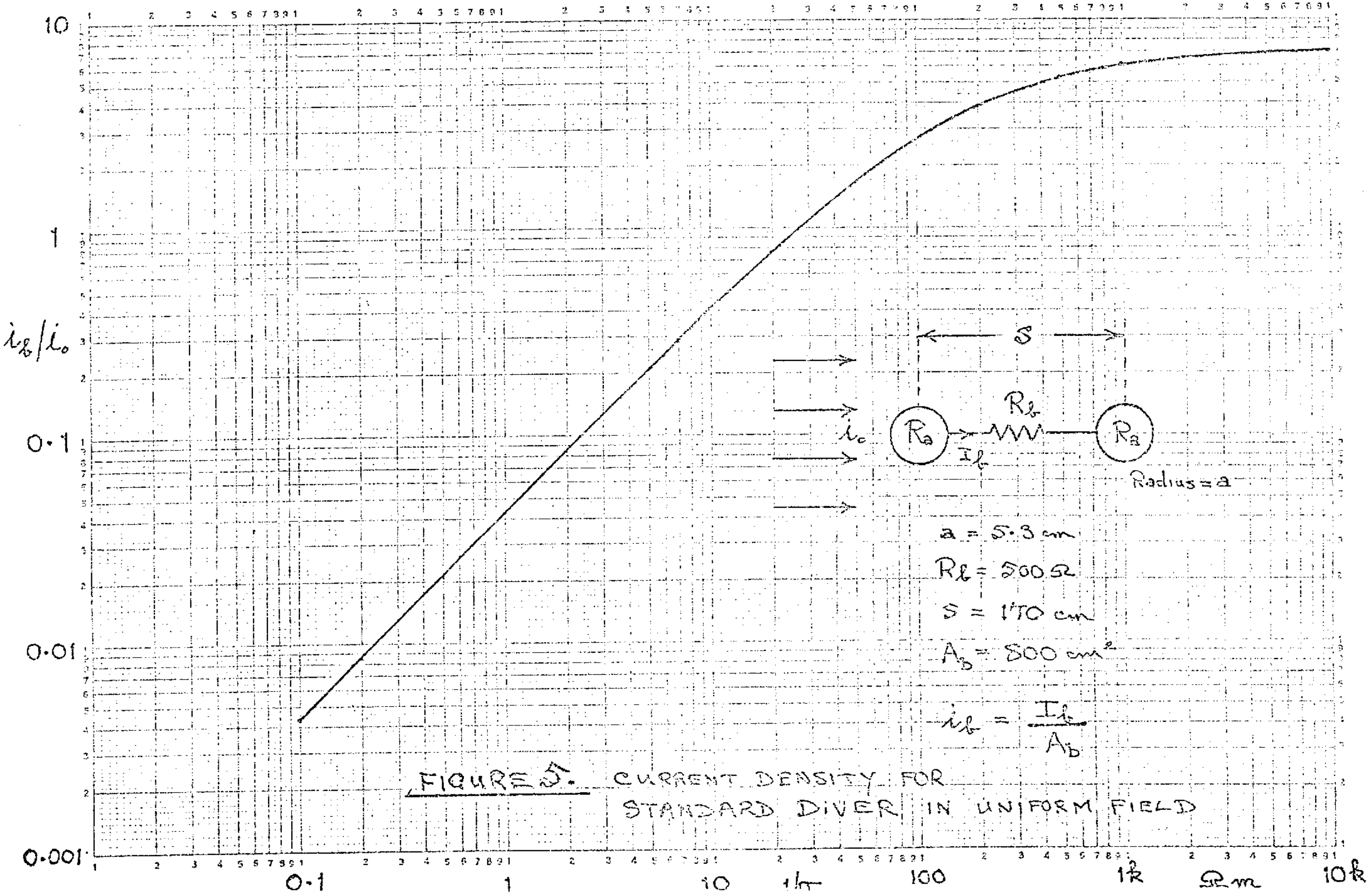


FIGURE 5. CURRENT DENSITY FOR STANDARD DIVER IN UNIFORM FIELD

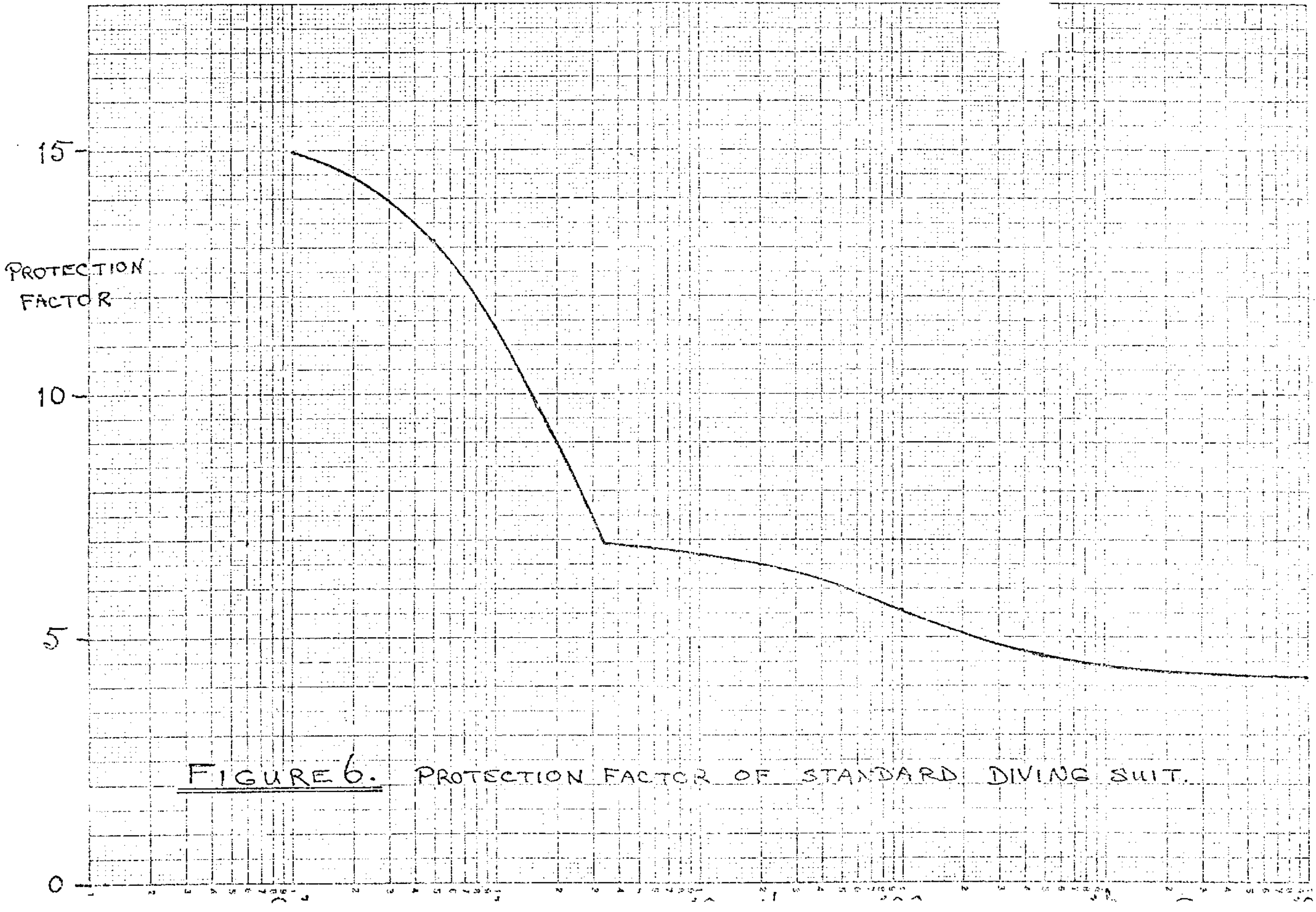


FIGURE 6. PROTECTION FACTOR OF STANDARD DIVING SUIT.

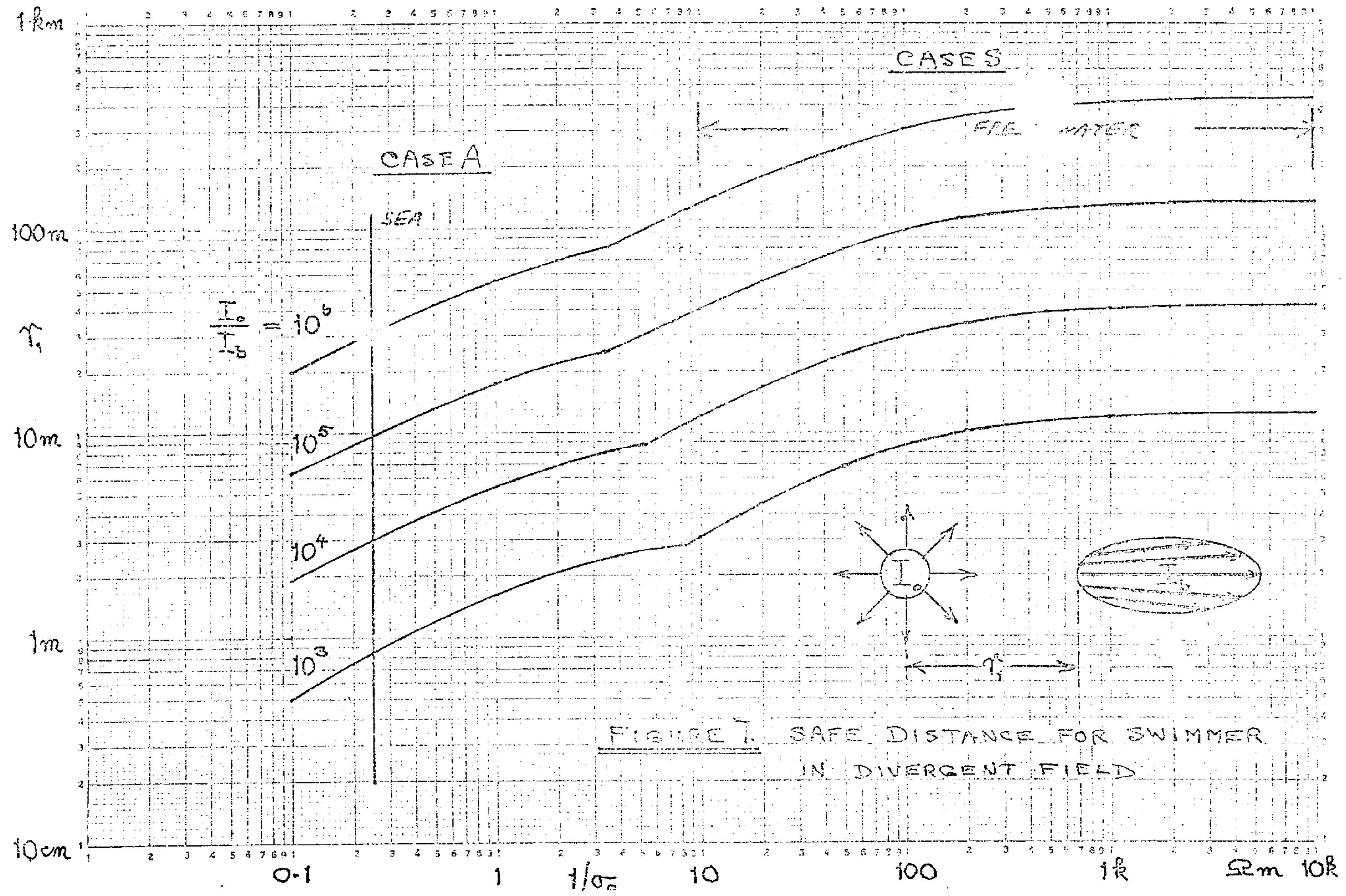


FIGURE 7. SAFE DISTANCE FOR SWIMMER IN DIVERGENT FIELD

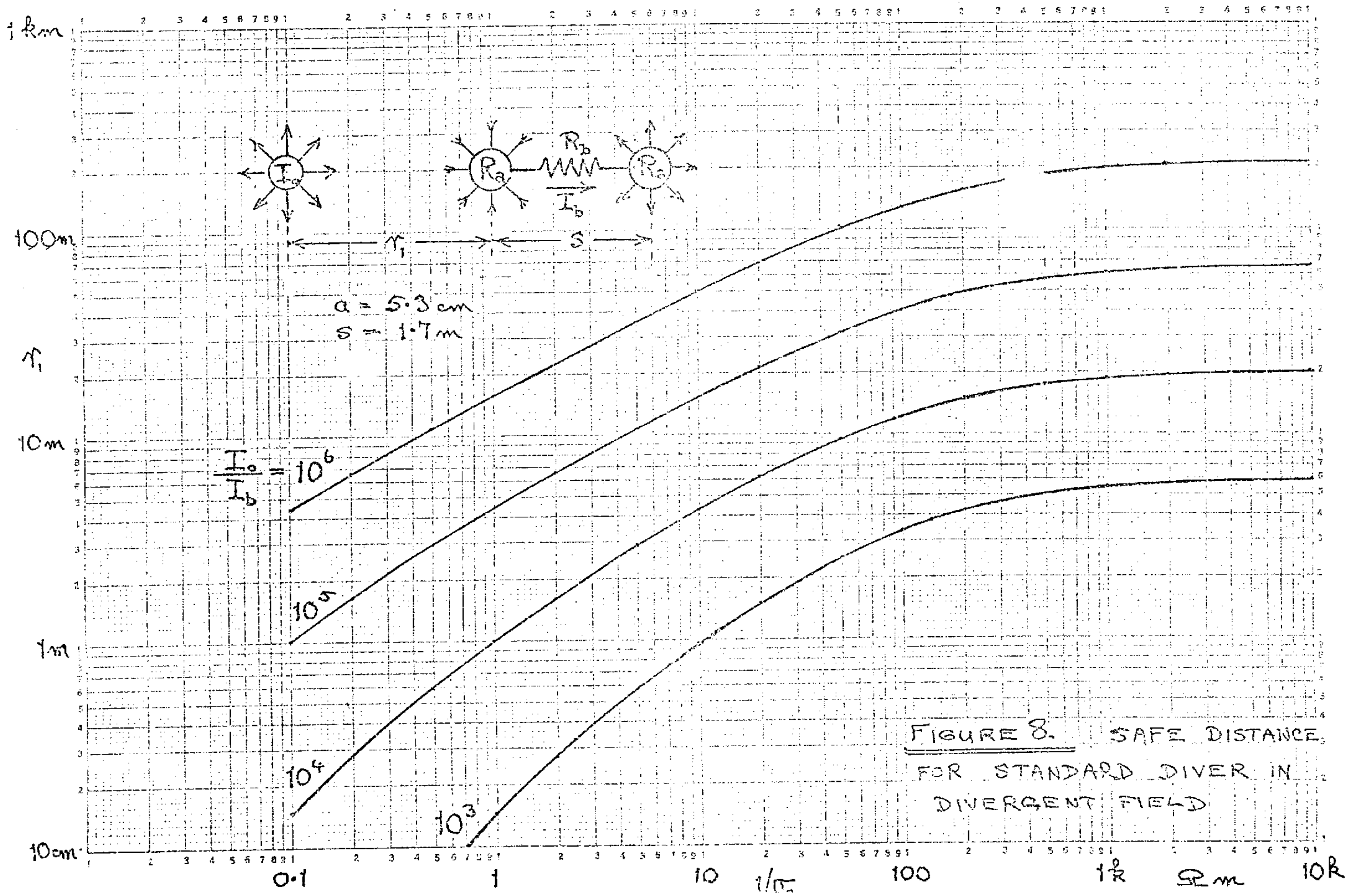


FIGURE 8. SAFE DISTANCE FOR STANDARD DIVER IN DIVERGENT FIELD

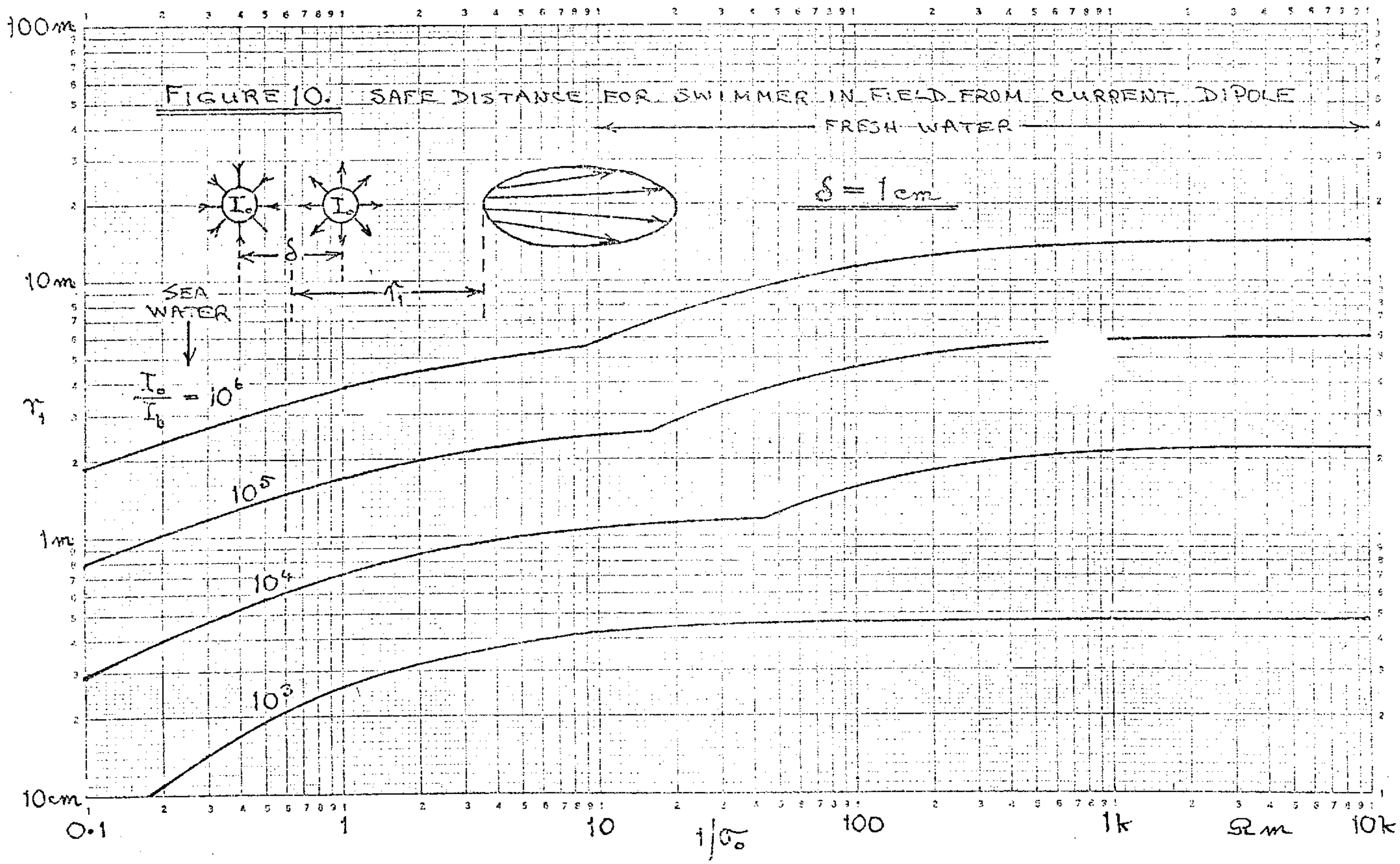
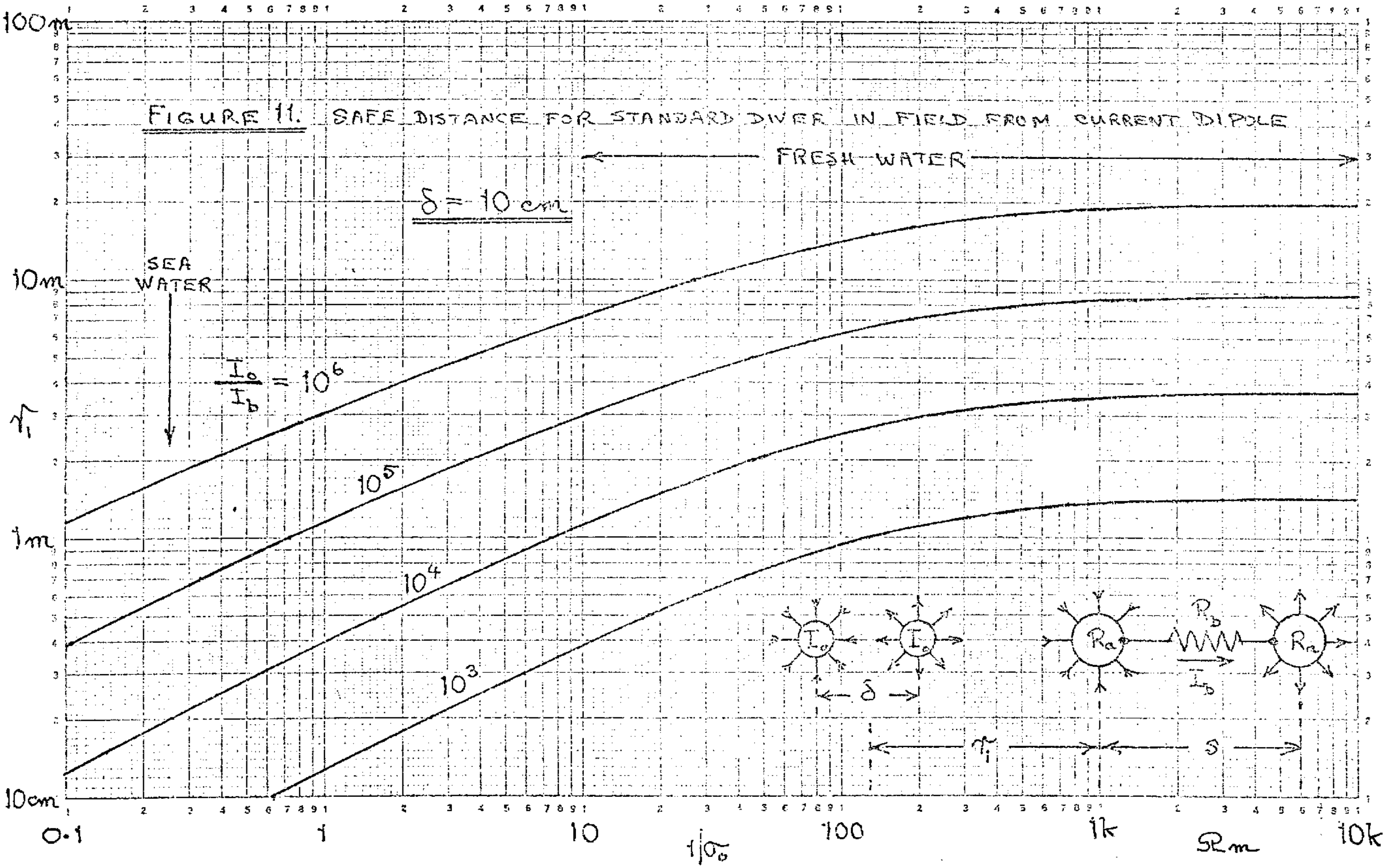


FIGURE 10. SAFE DISTANCE FOR SWIMMER IN FIELD FROM CURRENT DIPOLE

FIGURE 11. SAFE DISTANCE FOR STANDARD DIVER IN FIELD FROM CURRENT DIPOLE



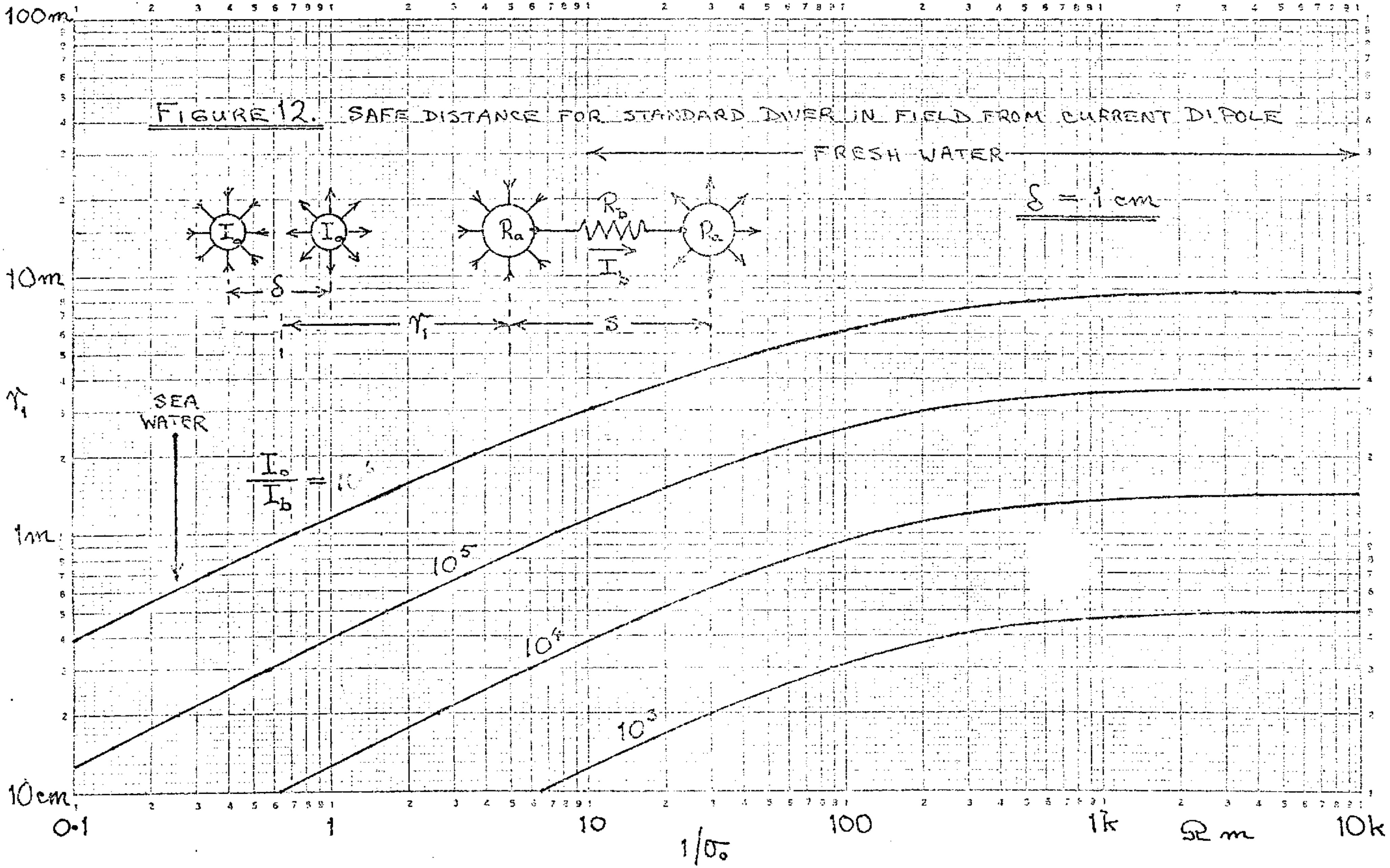


FIGURE 12. SAFE DISTANCE FOR STANDARD DIVER IN FIELD FROM CURRENT DIPOLE

TECHNICAL REFERENCE PAPERS AS LISTED IN APPENDIX C OF THE DEPARTMENT OF ENERGY'S CODE OF PRACTICE FOR THE SAFE USE OF ELECTRICITY UNDERWATER.

1. Protection of divers against electric shock — physiological criteria, ERA Report 77-1063, June 1977, OT-R-8272.
2. Shock risk to swimmers and divers from an electrical field, Project ref 0367/TC/65, September 1980, OT-R-8273.
3. Calculation of safe distance from an electrically [illegible] object in water, Project ref 0367/TC/70, January 1981, OT-R-8274.
4. Methods of protection against electric shock under water — earth-leakage circuit-breakers, Project ref 0367/TC/20, September 1979, OT-R-8275.
5. Protection against electric shock under water — line-insulation circuit-breakers, Project ref 0367/TC/21, September 1979, OT-R-8276.
6. Inherently safe systems, Project ref 0367/TC/23 (revised), December 1979, OT-R-8277.
7. Warning of electrical fields in water, Project ref 0367/TC/26B, December 1979, OT-R-8278.
8. Protection against shock from arc welding and cutting sets, Project ref 0367/TC/26A, December 1979, OT-R-8279.
9. An assessment of toxic gases from overheated electrical equipment, Project ref 0367/12, January 1979, OT-R-8280.
10. Emission of toxic gases from electrical equipment, Project ref 0367/TC/5, July 1979, OT-R-8281.
11. Application of fatal concentrations and toxicity index from Defence Standard 61-12/18 and Naval Engineering Standard 713, Project ref 0367/TC/29, January 1980, OT-R-8282.
12. Polymeric materials commonly used in electrical equipment with calculations of their possible toxicity, Project ref 0367/TC/29 (appendix), January 1980, OT-R-8283.
13. Review of the requirements for explosion-protected electrical equipment under water: flammability characteristics of gases and vapours, Project ref 0367/TC/49, OT-R-8284.
14. Requirements for explosion-protected electrical equipment under water: relevance of current standards for surface industry applications, Project ref 0367/TC/54, August 1980, OT-R-8285.
15. Requirements for explosion-protected electrical equipment under water: assessment of flammability limits, Project ref 0367/TC/63, October 1980, OT-R-8286.

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