An Investigation of the Equivalent Resistance, Power Requirements and Field Characteristics of Electric Fishing Electrodes

R&D Technical Report W2-076/TR

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This report should be read in conjunction with R&D Technical Report W2-054/TR Best Practice Guidelines for Electric Fishing Operations. The detailed information on power requirements and effective capture field sizes will form part of a field manual for electric fishing operations which will be distributed to all staff engaged in directing electric fishing operations in the field.

Keywords
Electric fishing, equivalent electrode resistance, voltage gradient.

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Thanks to Luke Scott for setting up the equipment and assistance with measuring the electrical outputs.

EXECUTIVE SUMMARY

The relationship between the diameter of ring anodes and their equivalent electrical resistance has been measured for a range of anode designs currently in use by workers in the UK. In addition, equivalent resistance values have been measured for two designs of cathode.

Measured values did not correspond well with published methods of calculating equivalent electrode resistance by theoretical means.

The empirical relationship between anode ring diameter, water conductivity and equivalent resistance has been modelled. Results from the modelled data are within 1% of the data measured.

Knowledge of the equivalent electrode resistance has also enabled a model to be constructed to determine the input power required to energise an electric fishing system for a range of water conductivities and applied anode voltages.

Voltage field measurements have also been mapped for a range of anode ring sizes and these too have been modelled over a range of input voltage values.

KEYWORDS

Electric fishing, equivalent electrode resistance, voltage gradient.

1. INTRODUCTION

Knowledge of the electrical resistance of the electrode system used in electric fishing is both fundamental to understanding the effects of the electrodes and vital if it is required to determine the power required to energise the electrodes. Likewise, knowledge of the size of the electrical field produced by differing electrode shapes and designs is essential if the correct energising voltage (i.e. one that is not damaging to fish) is to be used for electrodes of differing diameters. Current European Standards for electric fishing (EN 14011:2003) also confer an onus of care on the electric fishing operator regarding not damaging fish during electric fishing operations. Thus, information regarding non-harmful waveforms and field intensity is of increasing importance.

With the exception of very high conductivity water (>1000 μScm^{-1}) available power from the generator is rarely an issue when using pulsed direct current (pdc) waveforms. However, concerns regarding the potential for fish injury caused by using pdc has led to a general recommendation that direct current (dc) should be used wherever possible (Beaumont *et al.* 2002). If large anode diameters and high-applied voltages are used when fishing with dc however overloading of generators can occur at even moderate water conductivities. Knowledge of the required power input for the electrode array will overcome this potentially hazardous situation.

When describing the electrical resistance of electric fishing electrode (anode and cathode) systems the term equivalent electrical resistance is used. The electrodes themselves, being made from a conductive metal (usually Aluminium, Stainless Steel or Copper), linked to connectors by means of copper cables, have a very low electrical resistance. Even with very long cables, the value of resistance from the connector to any point on the anode or cathode may be expected to be less than 0.25 Ohm. If the electrodes were to come into electrical contact, then the total circuit resistance between the two connectors would be the sum of the two individual electrode resistances, e.g. 2 * 0.25 Ohms = 0.5 Ohms. However, when two electrodes are separated in a volume of water, the electrical resistance between the electrode connectors is a function of <u>two</u> components. One component is the sum of the two individual electrode resistances (e.g. 0.5 Ohms in the example above), the other, and major component, is a function of the conductivity of the water, the spacing of the electrodes, and the dimensions and geometry of the electrodes. Orientation of the electrodes has only a minor impact upon their equivalent resistance provided that; the spacing of the electrodes is large compared to the dimensions of the electrodes; the volume of water is large compared with the spacing; and the electrodes are not close to boundaries such as surface, bottom or sides of the vessel (or river). Thus, the resistance of electrodes in water is equivalent to a higher value than that of the electrodes alone.

Novotny and Priegel (1974) described a theoretical relationship between these parameters to evaluate the “Electrode Equivalent Resistance” (Equation 1).

$$R = {}^{f(\gamma)}\!\big/_{K\sigma_w} \qquad \text{Equation 1}$$

where, for a circular or ring shaped electrode made from round or tube shaped material:

$$\gamma = {}^{t}\!/_{d} \qquad \text{Equation 2}$$

Where: t = diameter (gauge) of ring material
d = ring diameter
σ_w = water conductivity (Scm^{-1})
K = principal electrode dimension (for a ring = diameter)
f(γ) is ascertained from a graph of electrode resistance factors for different electrode shapes (Figure 1).

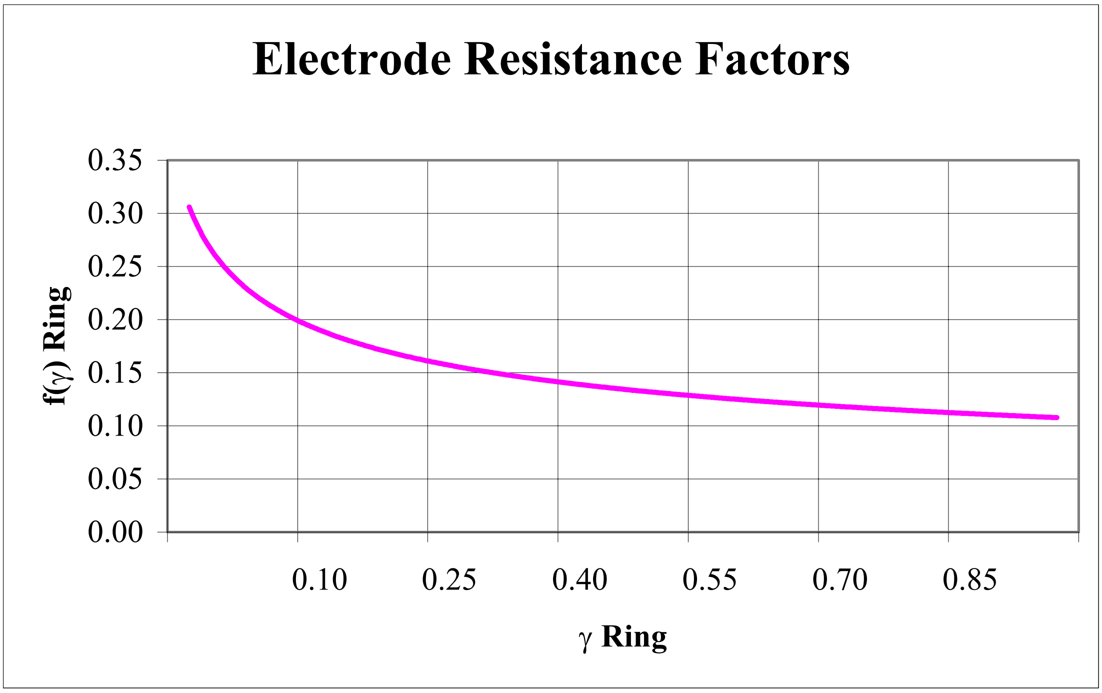

Figure 1 **Electrode resistance factors for ring electrode shapes (adapted from Novotny and Priegel 1974)**

This relationship is the one most commonly used in theoretical calculations of electrode resistance. In the principle manual used by the US Fish and Wildlife Service however (Kolz *et al.* 1998), the metric for "t" in equation 2 (where it equals diameter) is replaced with the metric circumference.

In addition to the theoretical work of Novotny & Priegel (1974), Kolz (1993) gives some empirical equivalent resistance values for differing electrode shapes. Only values for two ring diameters of electrode are given however and it is not clear whether water conductivity values are ambient or specific values, thus limiting the use of the information.

All the above theoretical calculations are cumbersome however and all electric fishing teaching recommends the actual measurement of the equivalent resistance of an electrode. Where it is wished to use electrodes of unknown electrical resistance however, a simple method of ascertaining its resistance would be a useful tool.

As with equivalent electrical resistance, knowledge of the effective voltage field of any electrode is important when setting up electric fishing systems. Whilst Kolz (1989) uses *Power Density* as the definitive term to describe the intensity of electric fishing effects, in the UK *Voltage Gradient* is a more common parameter used to quantify the effectiveness of the electrical fields' ability to elicit a response from fish. This is commonly expressed as the potential gradient found in the water (Vcm^{-1}). The voltage gradient at any given point for any given electrode configuration is independent of water conductivity provided the applied voltage is kept constant (Cuinat 1967). However, the power needed to supply that constant voltage will vary with water conductivity, as the water conductivity will affect the equivalent resistance of the electrodes. For a given electrode the voltage gradient is also directly proportional to the input voltage of the electrode. Thus, once determined for one electrode at one applied voltage the gradient value can be extrapolated to any given input voltage for that electrode.

Cuinat (1967) considered that the electrical characteristics of the commonly used ring anode could be adequately described by the electrical characteristics of hemispheres, with the metric for the diameter of the ring anode (d) being replaced by the radius of a hemisphere having the equivalent electrical characteristics (r_e). From this it is possible to calculate the voltage required to be applied to the electrode to produce a particular voltage gradient at any distance from any sized anode.

$$Va = E_D * \frac{D^2}{r_e} \qquad \text{Equation 3}$$

Where:
Va = applied anode potential (Volts)
E_D = voltage gradient at distance D
D = the distance between the centre of the anode and a point in the water
r_e = Radius of hemispherical anode having an electrical resistance equivalent to the anode ring diameter.

As voltage gradient is independent of conductivity equation 3 can be used to calculate the distance away from the anode that various voltage gradients occur for differing applied voltage at the anode.

$$D = \sqrt{V * \left(\frac{r_e}{E_D}\right)} \qquad \text{Equation 4}$$

Cuinat (1967) obtained the value for r_e for a ring electrode by a look-up table, however it can be represented by the formula

$$r_e = 1.39 * \left(d^{0.61}\right) \qquad \text{Equation 5}$$

Where: d = ring anode diameter

Equation 4 therefore becomes

$$D = \sqrt{\frac{V * \left(1.39 * d^{0.61}\right)}{E_D}} \qquad \text{Equation 6}$$

As with the theoretical calculations of equivalent electrode resistance however, empirical measurement is the best way to accurately assess voltage gradient characteristics of electrodes.

Regarding the actual “best” diameter of electrode to be used, the basic rule regarding anode size is “use as large a diameter as possible”. Not only are voltage gradients close to the anode lower with large rings (for a given applied voltage) but also power requirements per m^2 of fishing zone are reduced (Cuinat 1967). Within this ideal, restrictions will be based upon having sufficient power to energise the anodes and the physical size of the stream to be fished. Within the UK the most common anode sizes are in the range 250 – 400 mm (Beaumont *et al.* 2002). Lamarque (1990) however considered that in water of 30 - 500 μScm^{-1} conductivity electrodes of 600 mm ring diameter, 20 mm tube diameter were effective. Likewise, Cuinat (1967) gives information regarding 600 mm diameter anodes noting however [whilst anodes greater than 400 mm are rarely used] “it would be advantageous to use electrodes larger than this”. These large anodes (correctly powered) should give a good taxis field yet a small tetanising field and thus be less damaging [to fish] than smaller electrodes.

The only empirical data for such large anodes is given in Cuinat (1967) and Beaumont *et al.* (2002) noted that further investigation of the ease of use and voltage fields produced by large (>400 mm) electrodes would be useful. It was also noted that within the Agency the majority of anodes are of one or two designs and that these “standard” anodes, fitted with a range of diameter heads, should have their resistance empirically measured in order to assist in calculating power requirements.

The objectives of this study therefore were to:

1. Achieve an accurate model (based on empirical measurements) to predict the power required to energise electric fishing electrodes of differing physical properties in different water conductivities.

2. Map effective (0.1 – 1.0 Vcm^{-1}) one-dimensional linear voltage gradients produced by a variety of anode designs.

3. Investigate the implications of varying applied voltage upon field (voltage gradient) characteristics.

4. Trial the ease of use and electrical characteristics of the novel large anode design described in Beaumont *et al.* (2002)

2. METHODS

A range of electrode sizes (Figure 2) was constructed from stainless steel and their effective electrical resistance empirically measured. Electrodes designs represented anodes (ring shaped) and cathodes (braid and mesh plates). The diameter and gauge (ring thickness) for the anodes used are shown in Table 1.

Table 1 Anode sizes assessed

Diameter	Ring Thickness		
100 mm	6 mm		
200 mm	6 mm	10 mm	20 mm
400 mm *	6 mm	10 mm	20 mm
600 mm	6 mm	10 mm	20 mm
600 mm	10 mm thickness with spacers and central fixing for anode pole.		

* = Reference anode diameter

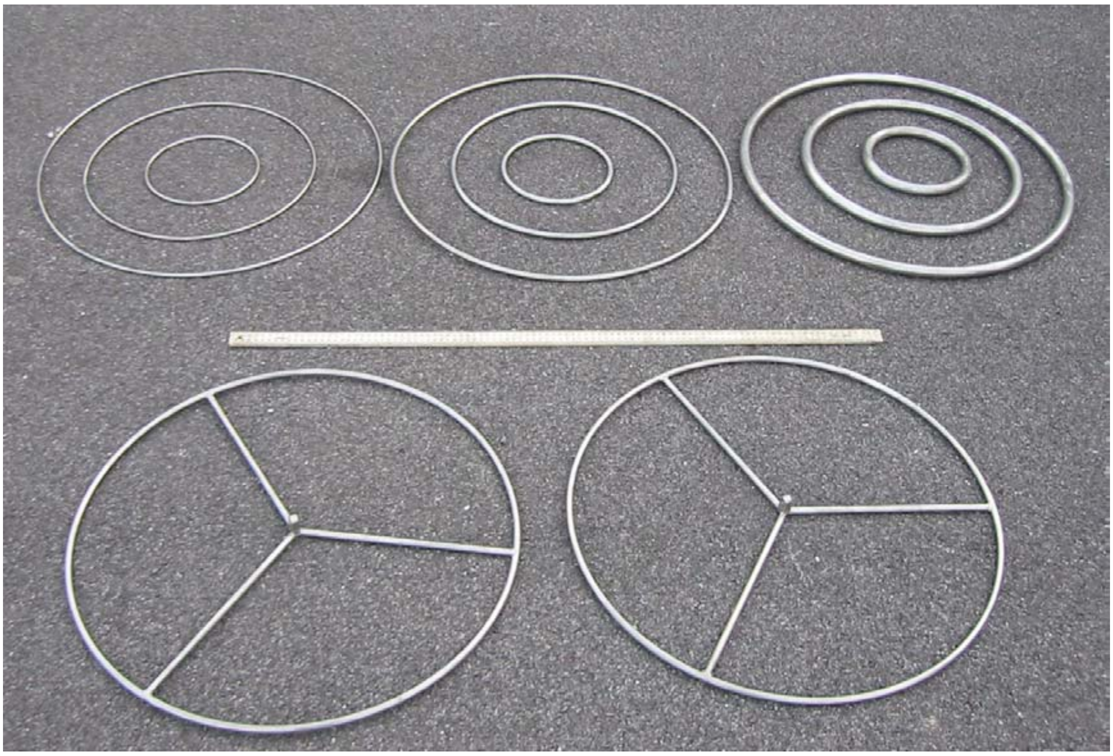

Figure 2 Anode sizes tested, not including Pulse box manufacturers designs. Top row left to right 6 mm, 10 mm and 20 mm gauge 200 mm, 400 mm and 600 mm size anodes, Lower row novel anode design

In addition to the range of standard anode sizes measured, examples of anode ring designs used by pulse box manufacturers were also tested. Anode rings on electrodes supplied by Electracatch, Millstream and Intelysis (Figure 3) plus others not currently in common use in the UK were removed from the handles and tested in the manner described above.

Figure 3 Pulse box manufacturers anode designs. Left to right, Electracatch; Millstream; Intelysis

The electrodes were suspended from a non-conductive cradle (Figure 4) in a semi-natural stream (Figure 5 and 6). Effective resistance of the anodes was measured by applying a known low voltage dc potential across a pair of electrodes and measuring the circuit current. Electrodes were periodically agitated to prevent the build up of gas bubbles (from electrolytic action) on the electrode surfaces affecting the resistance characteristics. Measurements were taken both with the anode suspended at the water surface and with it suspended at 500 mm depth (water depth was *c.*1500 mm). These two depths were chosen to represent the highest resistance value that could be generated (at the surface) and the usual maximum operating depth (thus the minimum resistance and maximum power required values likely to be encountered).

For reasons of safety, most of the electrical measurements were carried out using a low voltage (50 V dc) source. By undertaking tests at low voltage, the electric shock hazards associated with this work were virtually eliminated. As the effects being measured were linear with reference to the applied voltage values obtained could be scaled up to any given voltage. In order to verify this however a limited number of tests were carried out using a high voltage (150 – 300 V dc) source.

The power source for the low voltage tests was a bank of four 12 V 33 Ah sealed lead acid batteries, series connected to give a nominal supply voltage of 48 V dc. The interconnections to the batteries and to the electrode cables were made by means of waterproof (IP68) connectors and all other interconnections were made within a waterproof enclosure (IP66). The cables used were Arctic grade 3 core 1.5 mm^2 rated to 500 V.

The power source for the high voltage tests was an Intelisys FMII bankside fishing system powered by a 1 kVA Honda generator. The Intelisys controller was set to supply dc at a range of voltages. The standard anode and cathode cables were used, but a connection was made to the anode-fixing stud so that the full range of electrodes could be tested using the same cable and connection system that was used in the low voltage tests. Safety was ensured when handling the electrodes both by the standard Intelisys "dead-mans" safety switch and, additionally, by isolating the electrode by means of an in-line waterproof connector (IP68) before making any adjustments or changes to the electrode. A single 750 mm long copper braid (25 mm x 5 mm) cathode was used.

Electrical coupling between electrodes was assessed by positioning two 600 mm diameter electrodes 8 m apart in the stream and energising them with *c.*50 V dc (one ring thus becoming the anode and the other the cathode). Voltage gradient between the two electrodes was measured to determine if significant inter-electrode electrical coupling between the electrodes was taking place; the 600 mm electrodes having the largest field and thus the being the most likely to be coupled.

For all tests, water flow was negligible and total water depth at the site of the electrical measurements was *c.*1.5 m.

Specific water conductivity was measured using a laboratory calibrated Ciba-Corning Checkmate #90 conductivity meter. Specific conductivity was 558 μScm^{-1} at 5.8 C, from this ambient conductivity was calculated to be 350 μScm^{-1}.

From the voltage and current readings the effective electrode resistance was calculated from equation 7:

$$2R_{ref} = \frac{V}{I} \qquad \text{Equation 7}$$

Where: R_{ref} = reference anode resistance,
V = voltage
I = current (amps)

Thereafter single electrodes of differing diameter and thickness were substituted for one of the reference electrodes and the effective resistance of the new electrode calculated using Equation 8.

$$R_x = \left(\frac{V}{I}\right) - R_{ref} \qquad \text{Equation 8}$$

where: R_x = the resistance of the new electrode
R_{ref} = reference anode resistance

Figure 4 Mesh design cathode suspended in non-conducting cradle

In the case of the novel anode configuration (Table 1 Figure 2), these were constructed as proposed in the Best Practice Report (Beaumont *et al.* 2002). Equivalent resistance was measured as above and, in addition, the practicalities of the design evaluated (the ring being mounted on the Intelysis design anode poles).

The measurements above were used to construct a model of physical electrode characteristics and equivalent resistance. This empirical model for anode resistance was evaluated against the theoretical models of electrode resistance for torus shaped electrodes described by Novotny and Priegel (1973) and Kolz *et al.* (1998).

From either the calculated or the measured data of the electrode resistance it is possible to calculate the power required to energise the electrodes for a range of voltage values (Equation 9).

$$Power = V^2 / R \qquad \text{Equation 9}$$

Where V= Circuit voltage
R= circuit resistance

An electrode's resistance however will vary with water conductivity. If measured for a specific value of water conductivity and then used in water having a different conductivity, the electrode's resistance will change in inverse proportion (equation 10) to the two values of water conductivity (Kolz 1993).

$$\left[\frac{R_2}{R_1}\right] = \left[\frac{c_1}{c_2}\right] \qquad \text{Equation 10}$$

Where: R_1 is the resistance of the electrode in the water having a conductivity equal to c_1,
R_2 is the resistance of the electrode in the original water having a conductivity of c_2.

Therefore, the resistance of an electrode can be calculated for any value of water conductivity once its resistance is experimentally determined for water of known conductivity using Equation 11.

$$R_2 = \frac{(R_1 * c_1)}{c_2}$$

Equation 11

The equivalent resistance values at differing water conductivities were thus also used to calculate the power required to energise differing electrode types using equation 9.

The power value derived from equation 9 however needs to be corrected for adverse power factor. The Power Factor of the electric fishing control box will depend upon the circuitry within the unit. Adverse power factor occurs in ac - input power converters of the type used in electric fishing control boxes due to the non-linear nature of the rectifier/capacitor input circuit. This results in an input current with a high harmonic content. These harmonic components do not contribute to the power since they do not have corresponding components in the input voltage waveform. It is technically feasible to design circuitry with unity power factor with little detriment to conversion efficiency, however the added complexity would be likely to increase the cost of the power converter by 50%. In practice, with currently available equipment, it may be anticipated that power factor may be as low as 0.6. This value therefore has been used in the calculations of Input VA required to energise the electrodes.

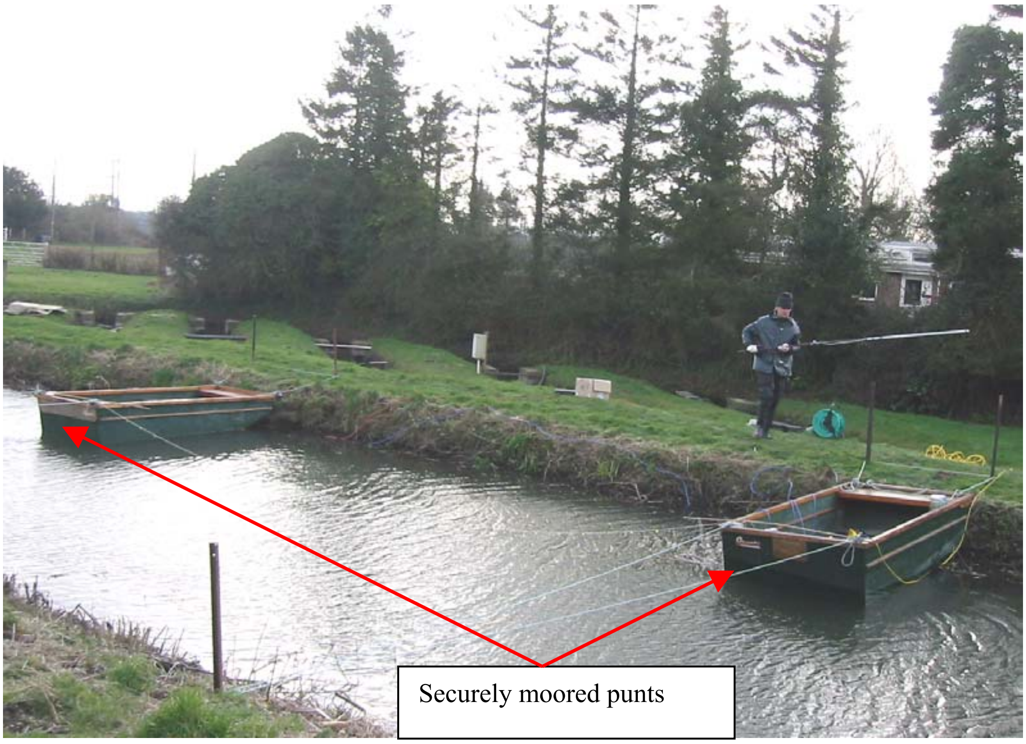

Figure 5 Experimental set up

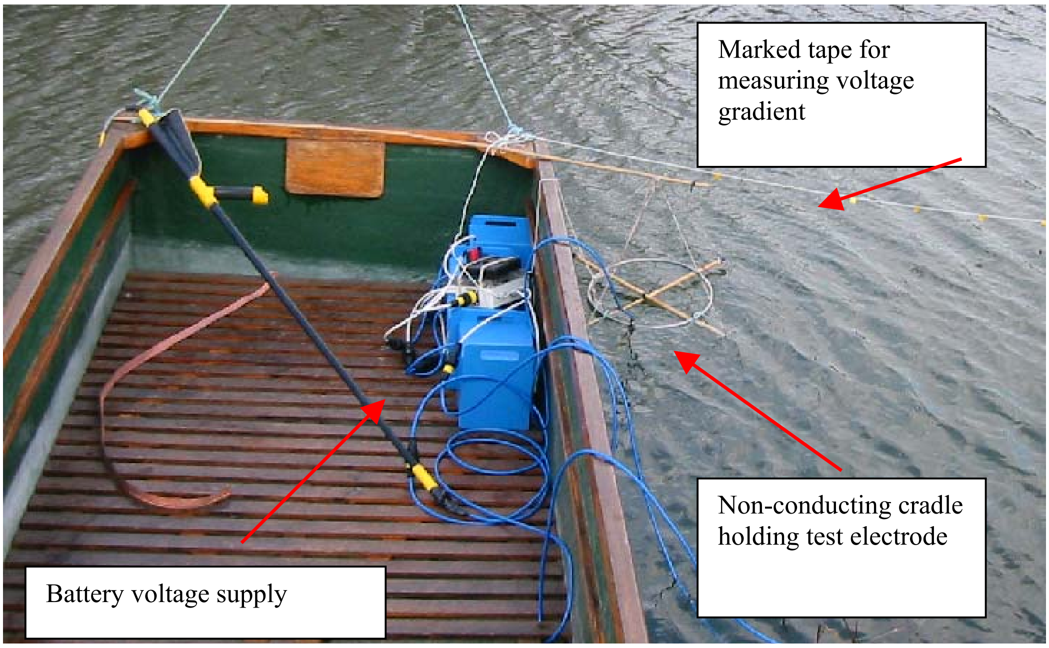

Figure 6 Detail of experimental set up

Cathode resistance was measured using similar methodology to that used to measure the anode resistance. Measurements were taken at the water surface and with the cathode resting on the stream bed (as per usual electric fishing practice). Cathode types and sizes are shown in Figure 7 and were:

1/. 750 mm long 25 x 5 mm copper braid
2/. One 500 mm x 500 mm mesh sheet with 6 mm hexagonal perforations.
3/. Two 500 mm x 500 mm mesh sheets as above connected in parallel, positioned with 500 mm separation.

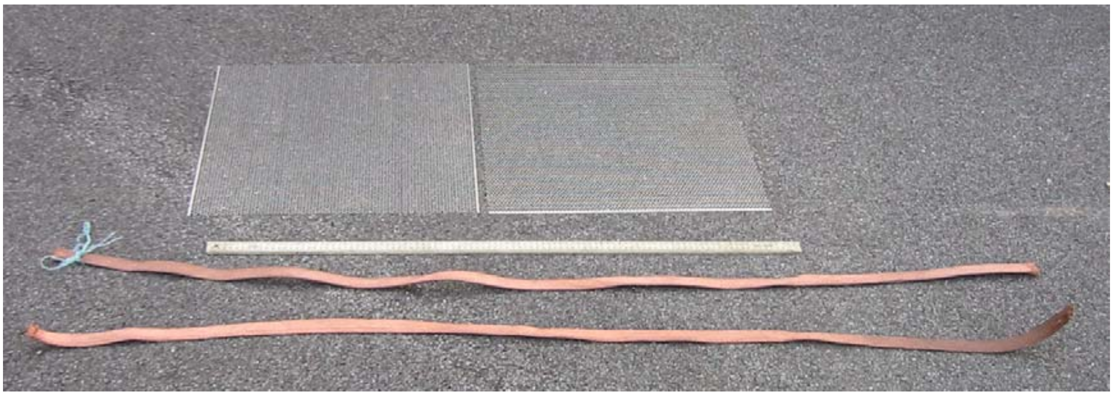

Figure 7 Cathode types and sizes evaluated

2.1 Voltage Gradient (E)

Linear voltage gradients (Vcm^{-1}) from four diameters of anode (100 mm, 200 mm, 400 mm and 600 mm) were measured. A simple field strength probe with an electrode separation of 100 mm was used to measure electric field strength in the water. This probe was used with a Digital Volt Meter to give a direct reading of the voltage over 100 mm. At the measurement point, the probe was aligned to maximise the reading at each position to determine the maximum field strength. For a given voltage, the voltage gradient produced by a standard anode will remain constant irrespective of the water conductivity (Kolz 1993, Beaumont *et al.* 2002 Appendix 3) thus correction for water conductivity was not required.

3. RESULTS

The linear voltage gradient between two 600 mm ring electrodes is shown in Figure 8. In an idealised situation when measuring voltage gradient between two identical electrodes the graph would have at least two values on the minima and be symmetrical. Figure 8 shows that some asymmetry in values did occur (probably due to local variations in river bed conductivity) and that a low gradient plateau was not present. Values measured at the minima however are very low and thus only minimal electrical coupling between electrodes was likely.

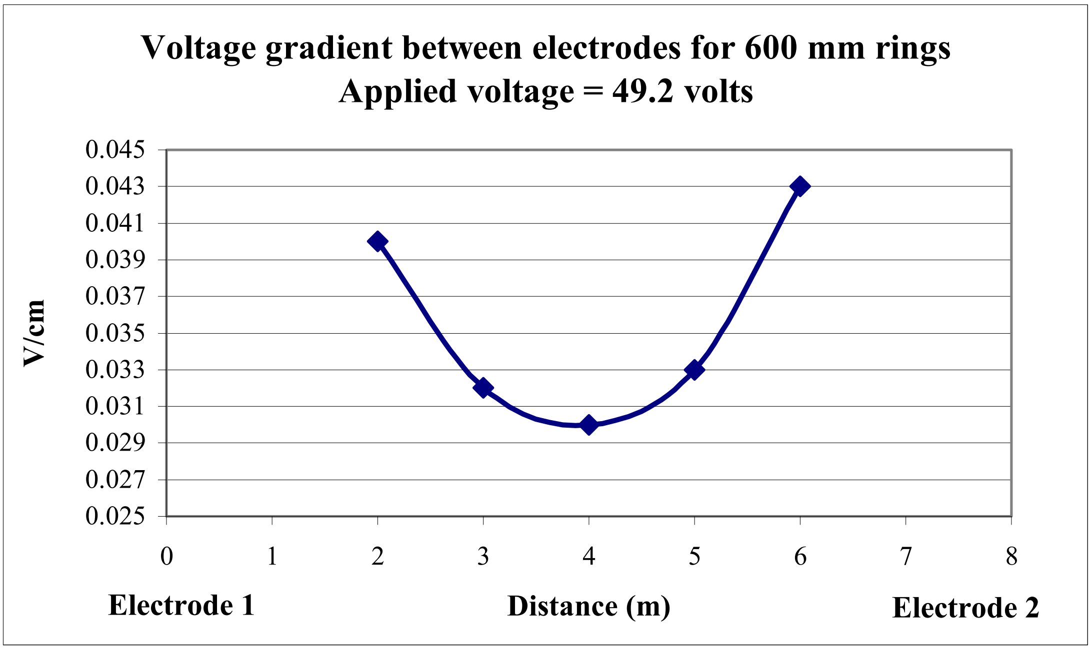

Figure 8 Inter-electrode voltage gradient between two 600 mm rings at 8 m separation

3.1 Equivalent Electrode Resistance

Full details and results of the electrical measurements are shown in Appendix I and II. Results are stratified into those taken at the water surface and those taken at 500 mm depth. These two depths simulating the most common depths at which electric fishing anodes are used. Data for a range of ring electrode sizes taken at 500 mm depth were extrapolated to a range of different conductivities and these are shown in Table 2. Data for braid and mesh electrodes are similarly extrapolated (Table 3) using values obtained when the electrodes were in contact with the bottom of the stream; as would be more usual for cathodes.

The effect on the electrode resistance of differing gauges (thicknesses) of ring thickness was evaluated. Although higher resistances were found with smaller gauge material, differences were minimal (Figure 9).

Table 2 Equivalent resistance for a range of ring electrodes and water conductivities

ANODE SIZE (mm)		MEASURED VALUES (Ω)	CALCULATED RESISTANCE AT DIFFERENT AMBIENT CONDUCTIVITIES (Ω)					
Diameter	**Gauge**	**At 350 µScm^{-1}, 5.8^{o}C**	**At 100 µScm^{-1}**	**At 200 µScm^{-1}**	**At 500 µScm^{-1}**	**At 1000 µScm^{-1}**	**At 1500 µScm^{-1}**	**At 2000 µScm^{-1}**
400	6	28.37	99.30	49.65	19.86	9.93	6.62	4.96
100	6	73.23	256.30	128.15	51.26	25.63	17.09	12.82
200	6	47.00	164.51	82.25	32.90	16.45	10.97	8.23
600	6	22.03	77.10	38.55	15.42	7.71	5.14	3.86
400	10	27.10	94.84	47.42	18.97	9.48	6.32	4.74
200	10	43.89	153.61	76.81	30.72	15.36	10.24	7.68
600	10	20.62	72.16	36.08	14.43	7.22	4.81	3.61
400	20	24.90	87.15	43.58	17.43	8.72	5.81	4.36
600	20	18.66	65.32	32.66	13.06	6.53	4.35	3.27
600	10	18.76	65.66	32.83	13.13	6.57	4.38	3.28
290 #	6	24.41	85.44	42.72	17.09	8.54	5.70	4.27
325 $	12	30.17	105.60	52.80	21.12	10.56	7.04	5.28
380 £	15	27.46	96.11	48.06	19.22	9.61	6.41	4.81

= Intelysis design (stainless steel)
$ = Electracatch design (stainless steel)
£ = Millstream design (copper)

Table 3 **Electrode resistance for a range of cathode sizes and water conductivities**

CATHODE TYPE		MEASURED VALUES (Ω)	CALCULATED RESISTANCE AT DIFFERENT AMBIENT CONDUCTIVITIES (Ω)					
Diameter	**Gauge**	**At 350 µScm^{-1}, 5.8^{o}C**	**At 100 µScm^{-1}**	**At 200 µScm^{-1}**	**At 500 µScm^{-1}**	**At 1000 µScm^{-1}**	**At 1500 µScm^{-1}**	**At 2000 µScm^{-1}**
Braid	750 mm	24.2	84.70	42.35	16.94	8.47	5.65	4.24
Mesh	600 x 600 mm	21.5	75.25	37.63	15.05	7.53	5.02	3.76
Mesh x2	600 x 600 mm	8.7	30.45	15.23	6.09	3.05	2.03	1.52

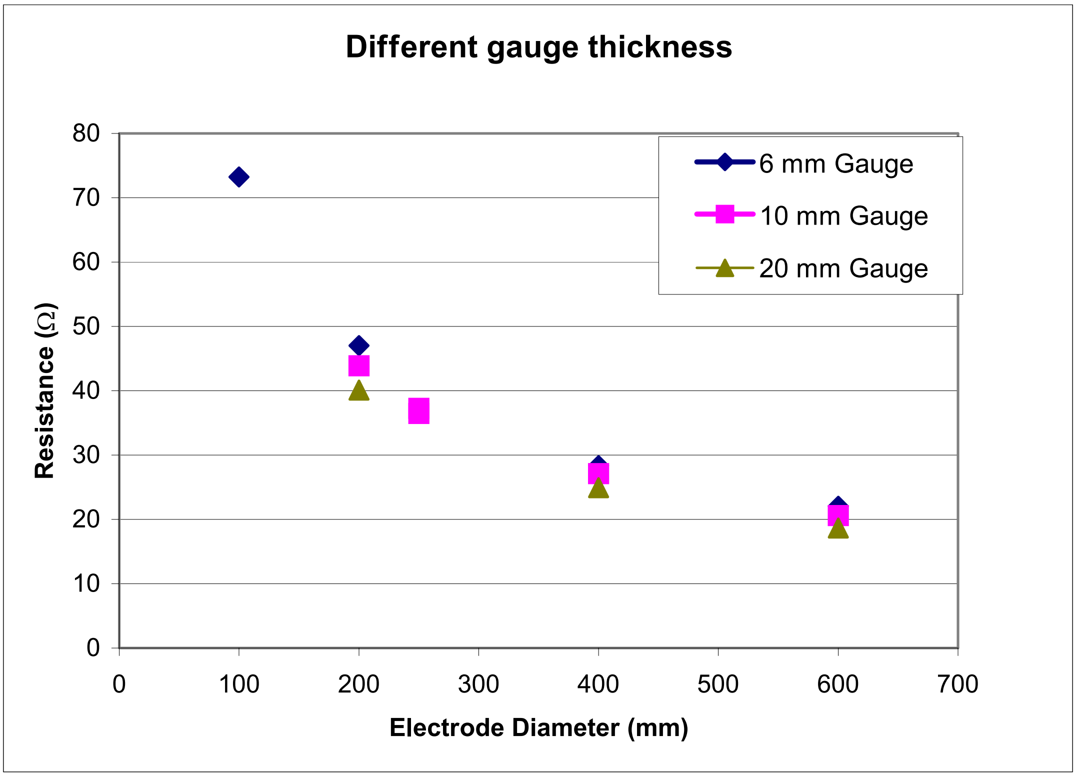

Figure 9 Equivalent resistance values for different gauges of electrode

As gauge of ring material had minimal effect on the readings, data for all gauges were combined for calculating resistance values at the surface and at 500 mm depth. Equivalent electrode resistance was found to be higher when measured at the surface when compared with the 500 mm depth measurements (Figure 10). Measurements at 500 mm depth being on average 70% of those measured at the surface.

Equivalent electrode resistance was found to consist of a power law relationship with electrode diameter.

For an electrode at the surface:

$$\mathrm{Req} = 3076\ D^{-0.74} \quad R^2 = 0.93 \ p = <0.001 \qquad \text{Equation 12}$$

For an electrode at 500 mm depth:

$$\mathrm{Req} = 1956\ D^{-0.72} \quad R^2 = 0.98 \ p = <0.001 \qquad \text{Equation 13}$$

Thus equations 11 and 12 can be use to calculate the equivalent electrical resistance of any diameter electrode and then adjusted according to the conductivity of the water in which it is being used using equation 10.

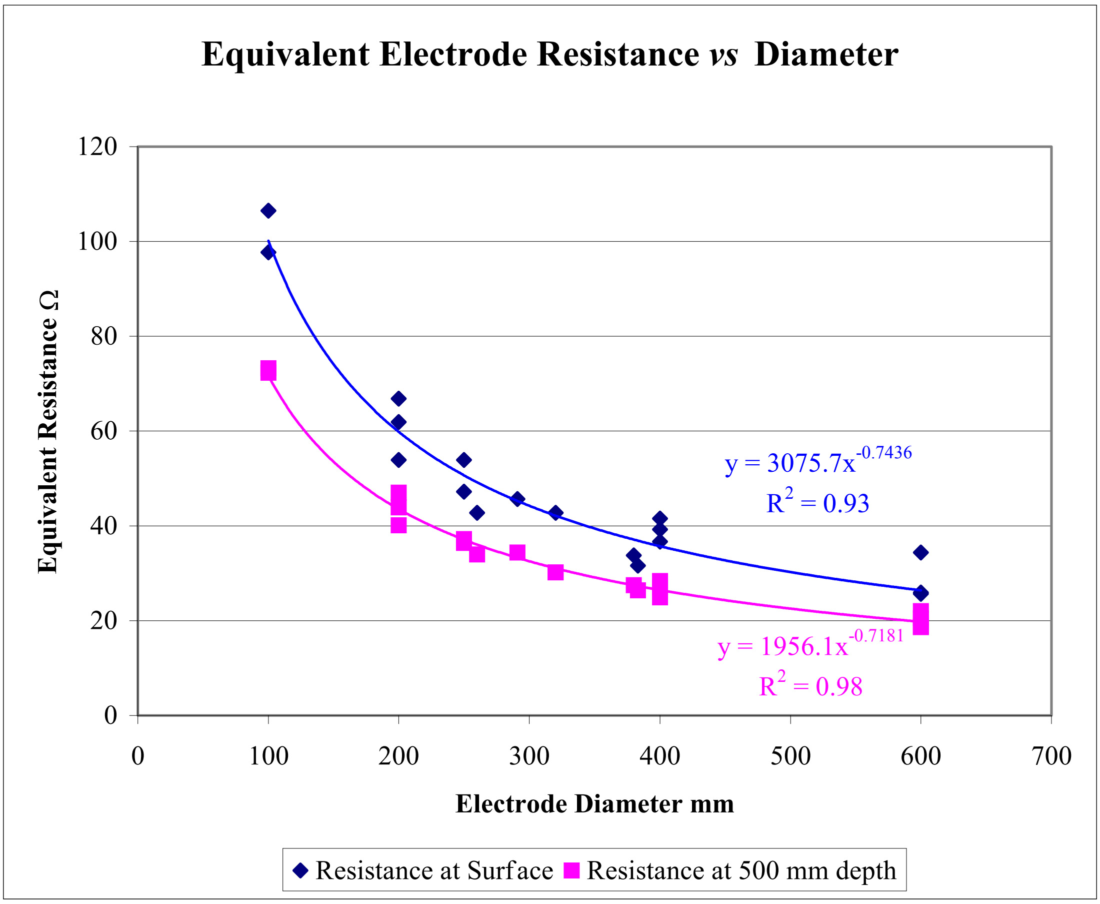

Figure 10 **Relationship between ring diameter and equivalent resistance measured at surface and at 500 mm depth**

Measured values of resistance (at 500 mm depth) were compared with values calculated by the method proposed by Novotny and Priegel (1974) and Kolz *et al.* (1998). Data has been stratified into the three thicknesses of electrode measured and values for the metric "t" of both diameter and circumference has been used (Figures 11 - 13).

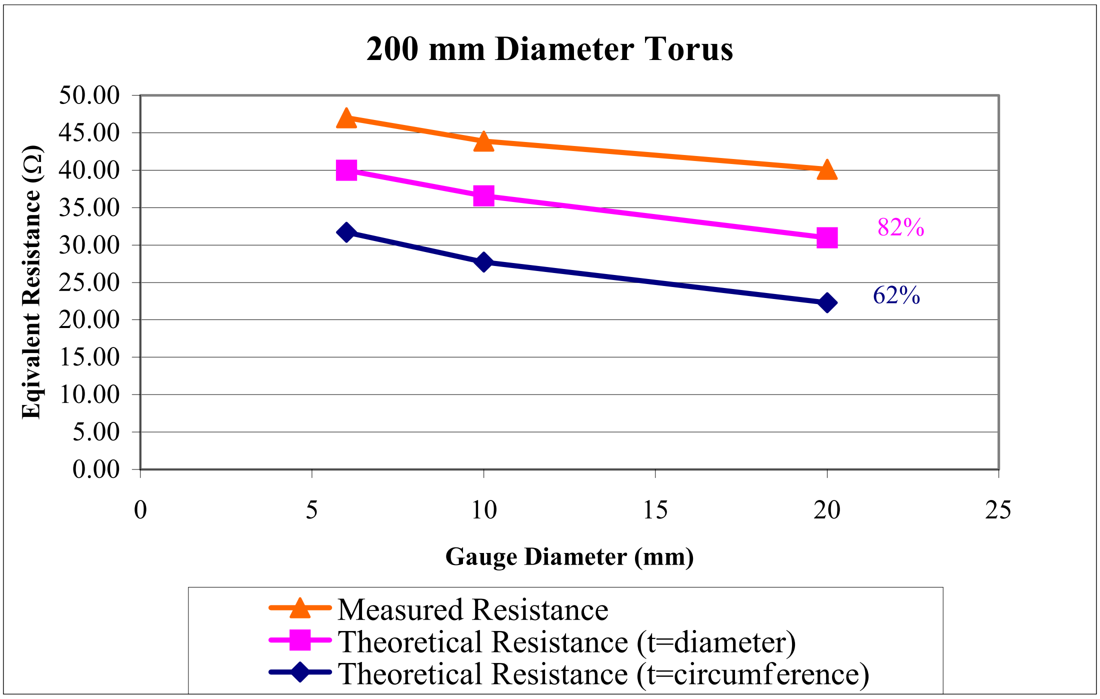

Figure 11 Comparison of measured and calculated resistance values for 200 mm ring anode

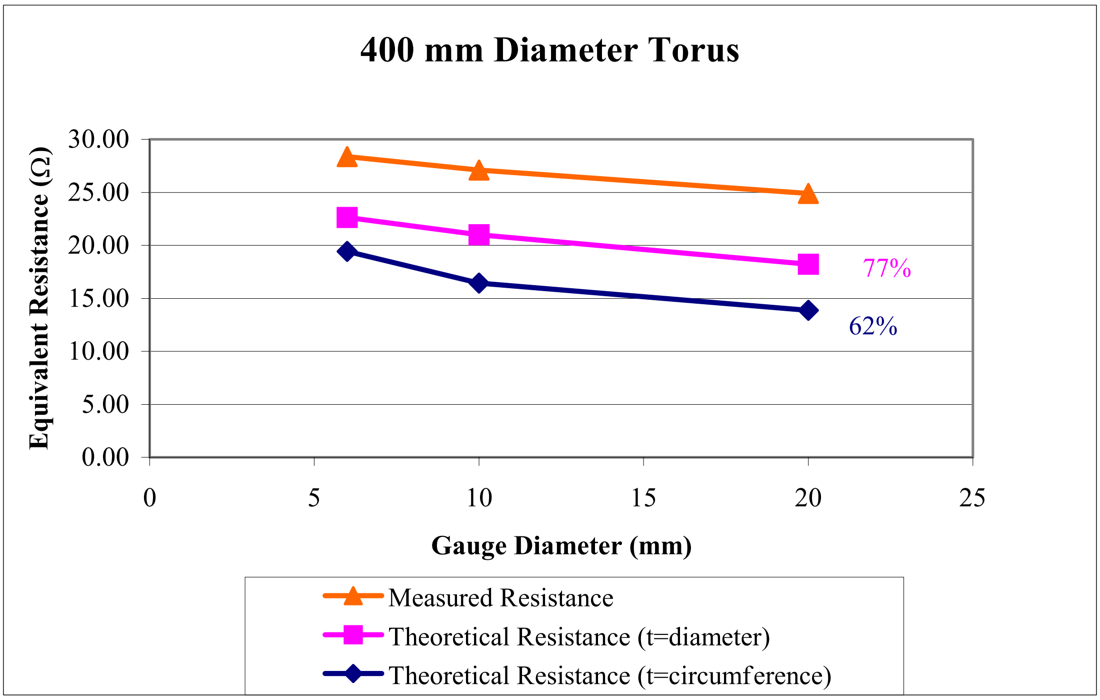

Figure 12 Comparison of measured and calculated resistance values for 400 mm ring anode

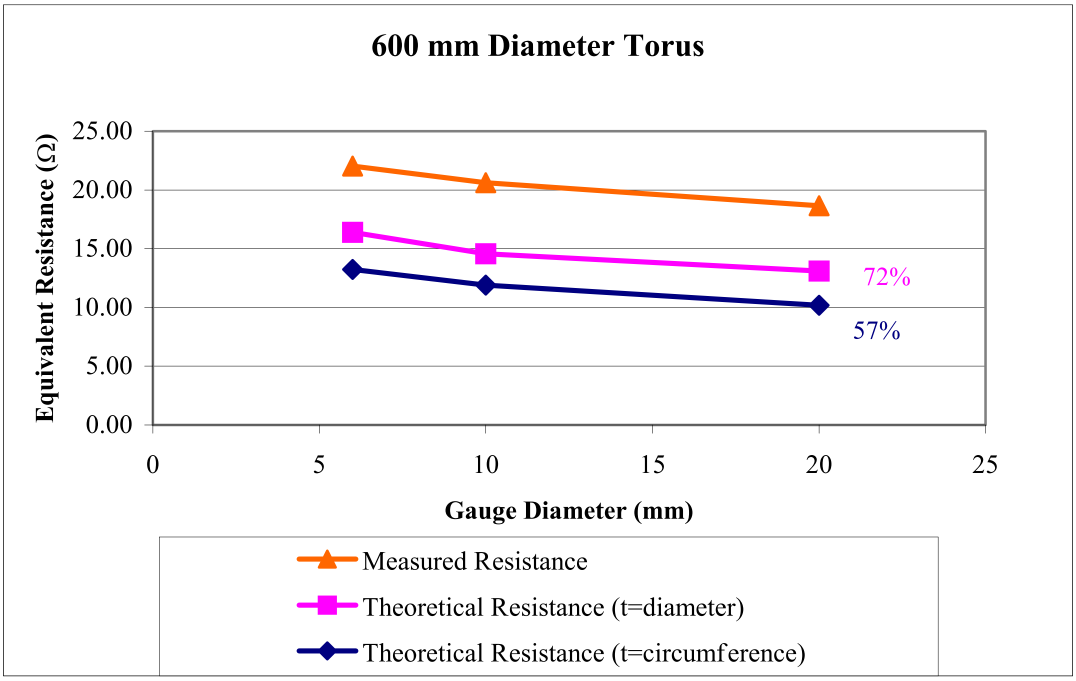

Figure 13 **Comparison of measured and calculated resistance values for 600 mm ring anode**

As can be seen, the Novotny and Priegel (1974) values are closer to the measured values than are the values calculated from the US Fish & Wildlife equation. Both however are still some way off the actual values measured. Novotny and Priegel (1974) also consider the effects of shallow water operation on the resistance values of the electrodes. They consider that the equations given (Equations 1 and 2) are those for electrodes "far removed from boundaries (water surface and bottom)" and that a surface correction factor of two should be used to correct for the increase in resistance experienced by an electrode at the surface. When this correction factor is applied to the data results are still considerably distant from the measured data, however the US F&W data are on average only 25% greater than the measured data.

The equation derived from the measurements carried out for this work results in values of 99% of the measured data given in Appendix II.

Equivalent resistance values of the cathode designs (Table 3) indicated that the 750 mm braid was of similar effectiveness as the single 600 mm x 600 mm mesh. Twin, mesh cathodes resulted in approximately halving the equivalent resistance values for single, mesh cathodes. Surface measurements resulted in the twin mesh having *c.*50% of the single mesh equivalent resistance value and when measured on the bottom of the stream values were 40% of the single mesh values.

3.2 Power Requirements

Resistance values at differing water conductivities have been used to construct graphs of the input power (VA) required for different electrode configurations at differing values of applied voltage. Anode sizes of 100 mm diameter x 6 mm gauge, 200 mm diameter x 10 mm gauge, 400 mm diameter x 10 mm gauge and 600 mm diameter x 10 mm gauge have been used and for all cases it has been assumed that a 750 mm copper braid has been used as the cathode (Figures 14 - 17). Note that the data presented are for dc input voltage.

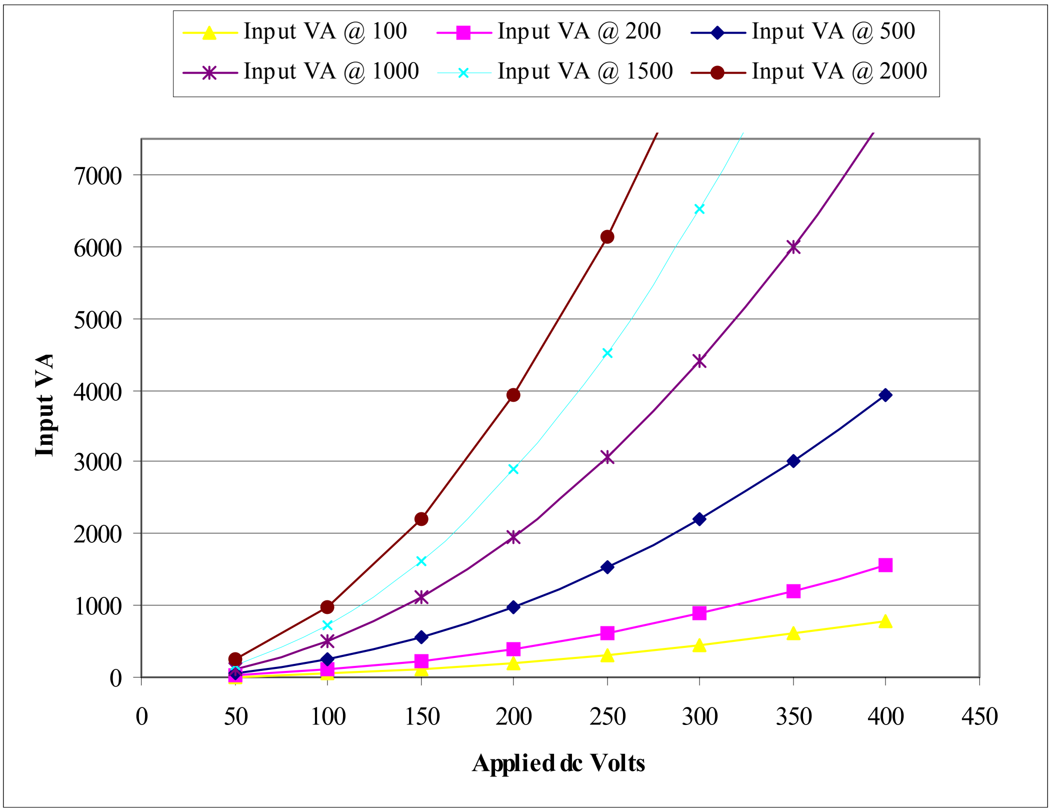

Figure 14 Input VA required to energise a 100 mm x 6 mm ring (plus cathode) at different water conductivity values (100 µScm^{-1} to 2000 µScm^{-1})

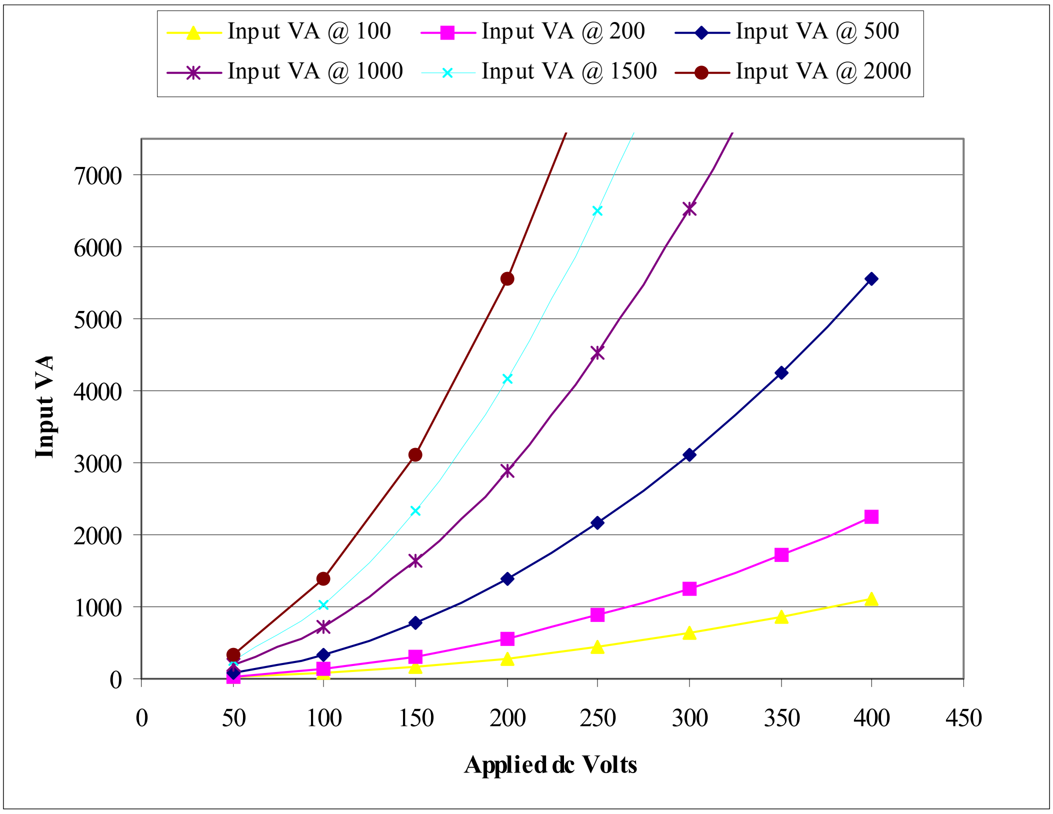

Figure 15 Input VA required to energise a 200 mm x 10 mm ring (plus cathode) at different water conductivity values (100 µScm^{-1} to 2000 µScm^{-1})

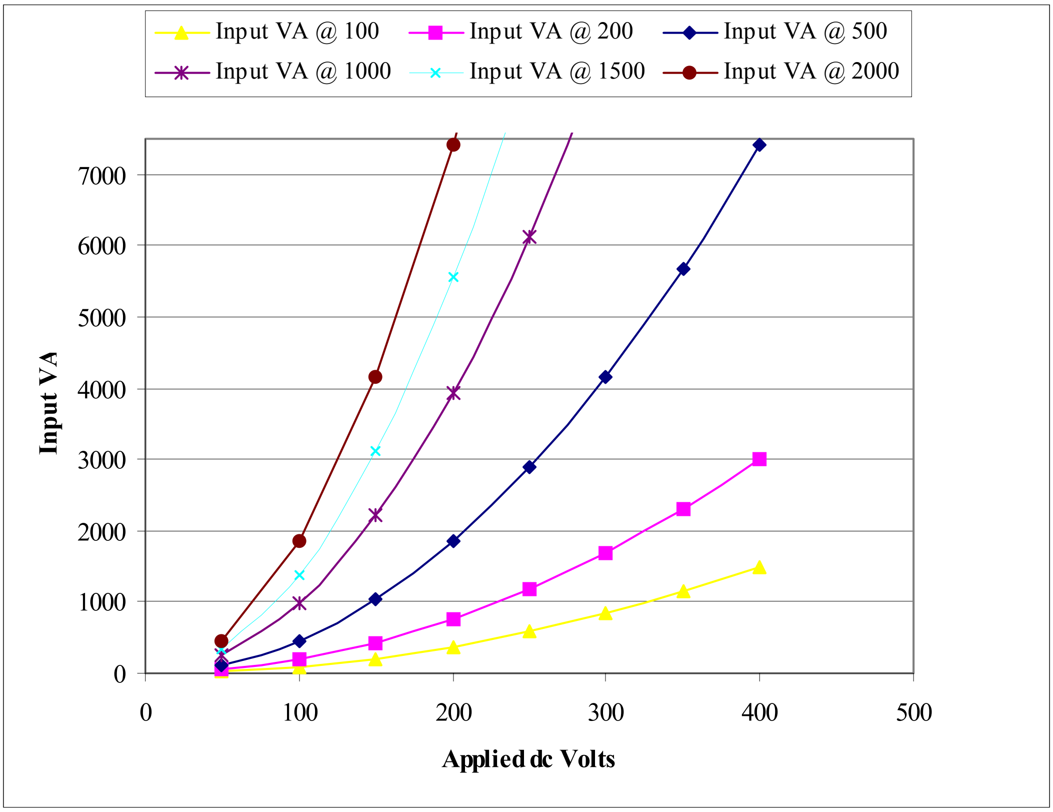

Figure 16 Input VA required to energise a 400 mm x 10 mm ring (plus cathode) at different water conductivity values (100 µScm^{-1} to 2000 µScm^{-1})

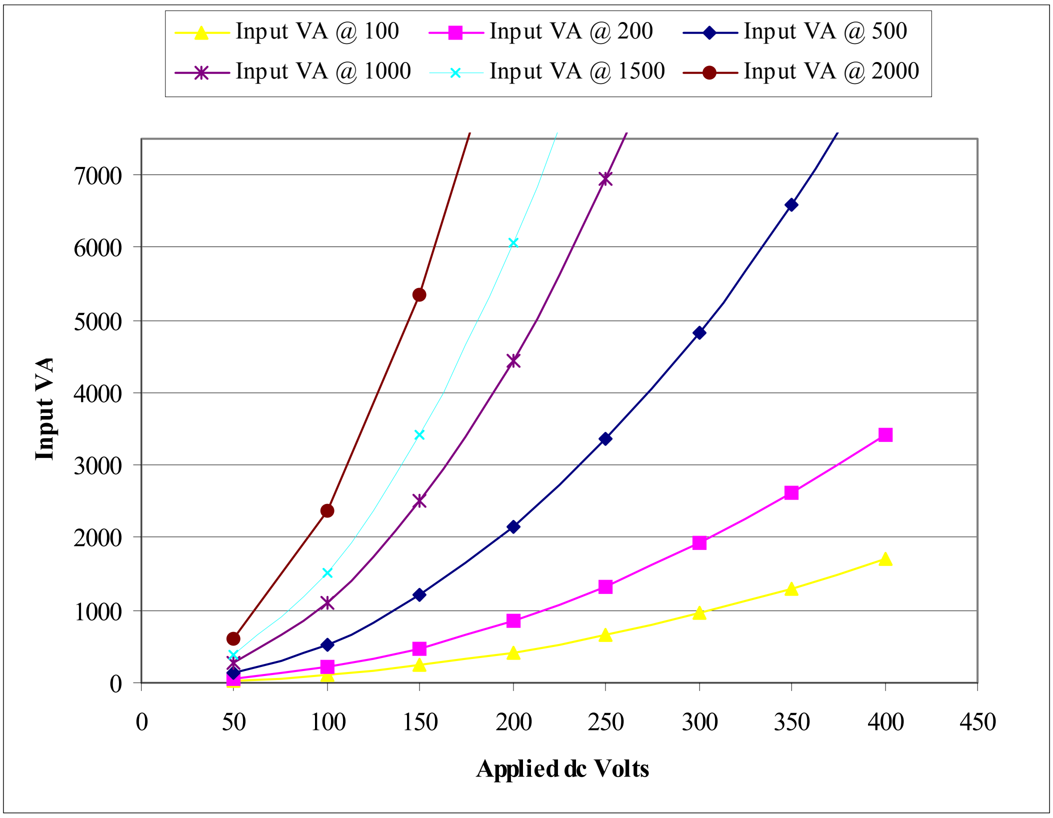

Figure 17 Input VA required to energise a 600 mm x 10 mm ring (plus cathode) at different water conductivity values (100 µScm^{-1} to 2000 µScm^{-1})

If using pdc, input VA is proportional to the duty cycle being used. Required input VA for pdc waveforms can therefore be calculated. Where pulse box output is only shown as pulse width (milliseconds) Appendix III can be used to ascertain the duty cycle (to the nearest 5%) for differing frequencies and pulse widths.

The relationship between input VA required and input voltage, electrode diameter, water conductivity and duty cycle has been modelled for ring shaped anodes and can be represented by the equation:

$$InputVA = \left[\frac{V^2}{Ra + Rc}\right] * \left[\frac{1}{P * 100}\right] * DC$$

Equation 14

For water depth of 500 mm

$$Ra = \frac{1956.1 * (D^{-0.72})}{350} * C_w$$

Equation 15

and

$$Rc = \frac{Cr}{350} * C_w$$

Equation 16

Where:
V = applied voltage applied at anode
Ra = Anode resistance
Rc = Cathode resistance
DC = % Duty Cycle (if pdc is used)
C_w = Ambient Conductivity of the water
Cr = Cathode resistance @ 350 μScm^{-1} (from Appendix II)
P = Power conversion factor (0.6)

Equations 14 to 16 have been combined into an Excel spreadsheet (Appendix IV) where, when input variables are entered, the input VA for both dc and pdc output are automatically calculated.

This spreadsheet has also been extrapolated to twin anode situations by using the equation for calculating resistance in parallel circuits.

$$\text{Req} = \frac{R_1 * R_r}{R_1 + R_2}$$

Equation 17

Where
Req = circuit resistance
R_1 = equivalent resistance of anode 1
R_2 = equivalent resistance of anode 2

In reality actual measurements of twin anode circuits result in measurements slightly higher than that predicted by theory. This is due to electrical coupling between the electrodes: electrical theory assuming perfect isolation of each resistor whereas in realty the twin anodes are often in relatively close proximity to each other.

For all the above spreadsheet calculations choice of cathode design is limited to either the 750 mm copper braid, a single 500 x 500 mm mesh sheet or a double 500 x 500 mm mesh sheet. It has been assumed that twin cathodes will also be used for the twin anode situation.

3.3 Voltage Gradient (E)

Voltage gradients were measured from 100 mm, 200 mm, 400 mm and 600 mm diameter ring electrodes (with 750 mm braid cathode positioned at right angles to the measured axis). These data were extrapolated for a range of input voltage values. Values for the threshold values of 0.1 V/cm (commonly considered the lower limit for dc taxis), 0.2 V/cm, 0.5 V/cm and 1.0 V/cm (commonly considered the threshold at which dc tetanus occurs) are shown in figures 18 – 21.

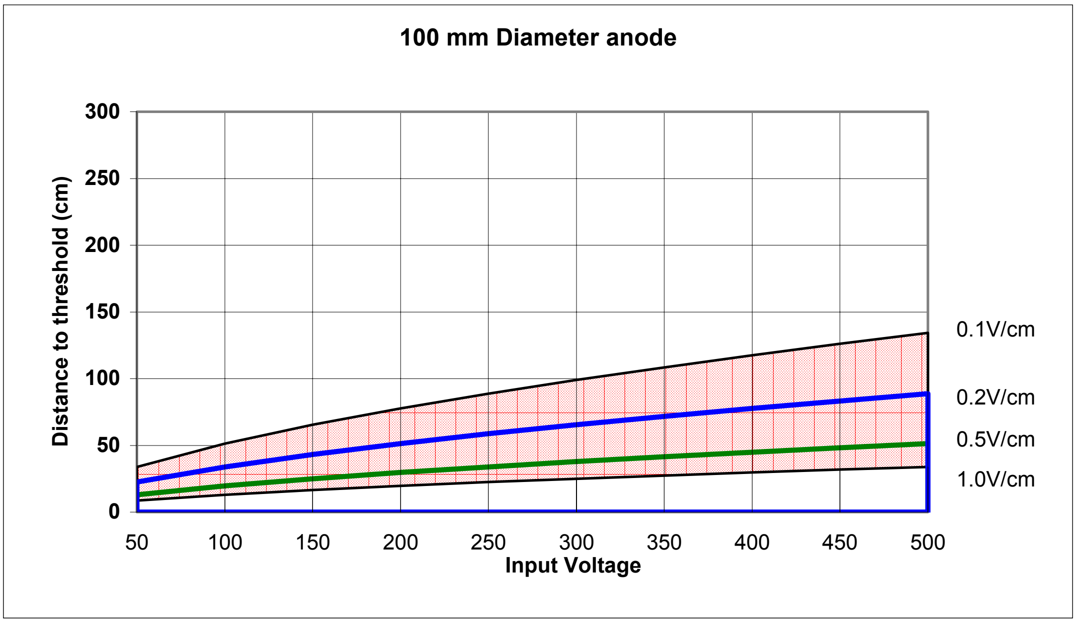

Figure 18 Threshold distances for 0.1, 0.2, 0.5 and 1.0 V/cm thresholds at differing input voltage values for a 100 mm diameter ring anode

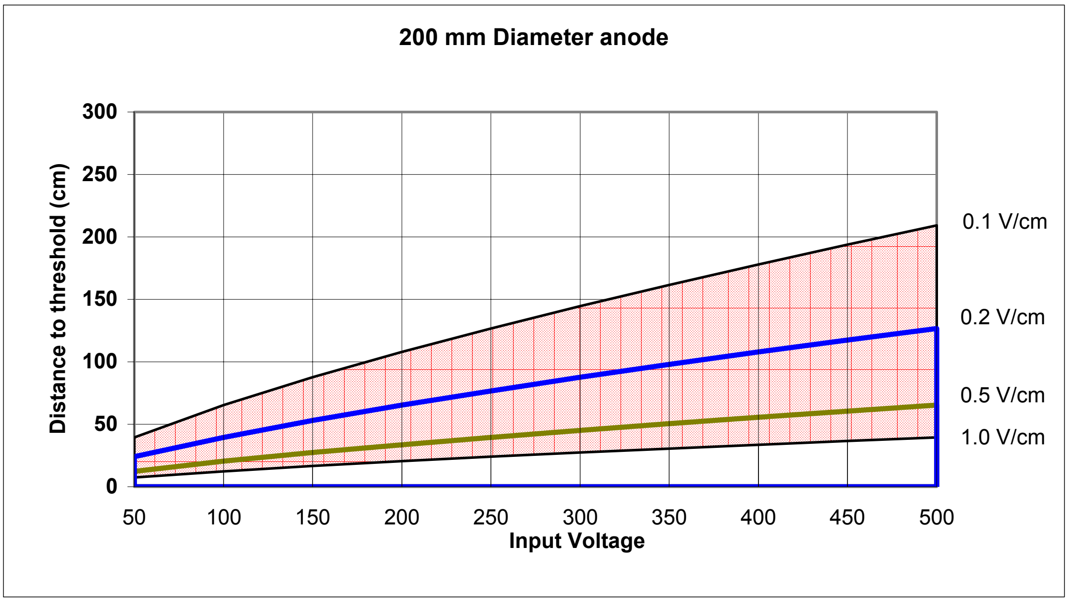

Figure 19 Threshold distances for 0.1, 0.2, 0.5 and 1.0 V/cm thresholds at differing input voltage values for a 200 mm diameter ring anode

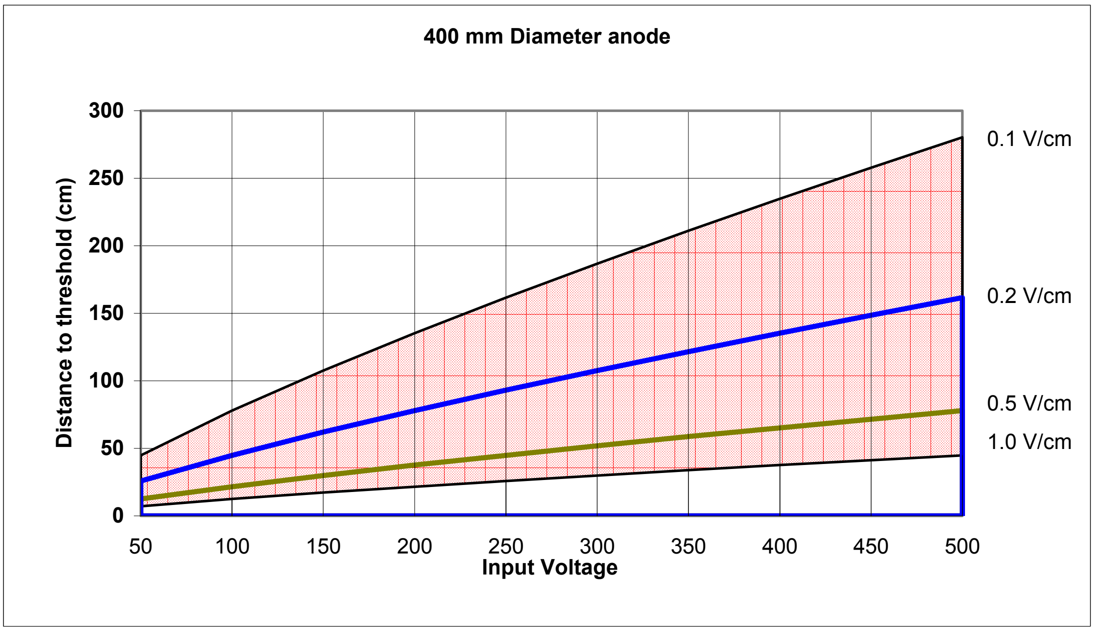

Figure 20 **Threshold distances for 0.1, 0.2, 0.5 and 1.0 V/cm thresholds at differing input voltage values for a 400 mm diameter ring anode**

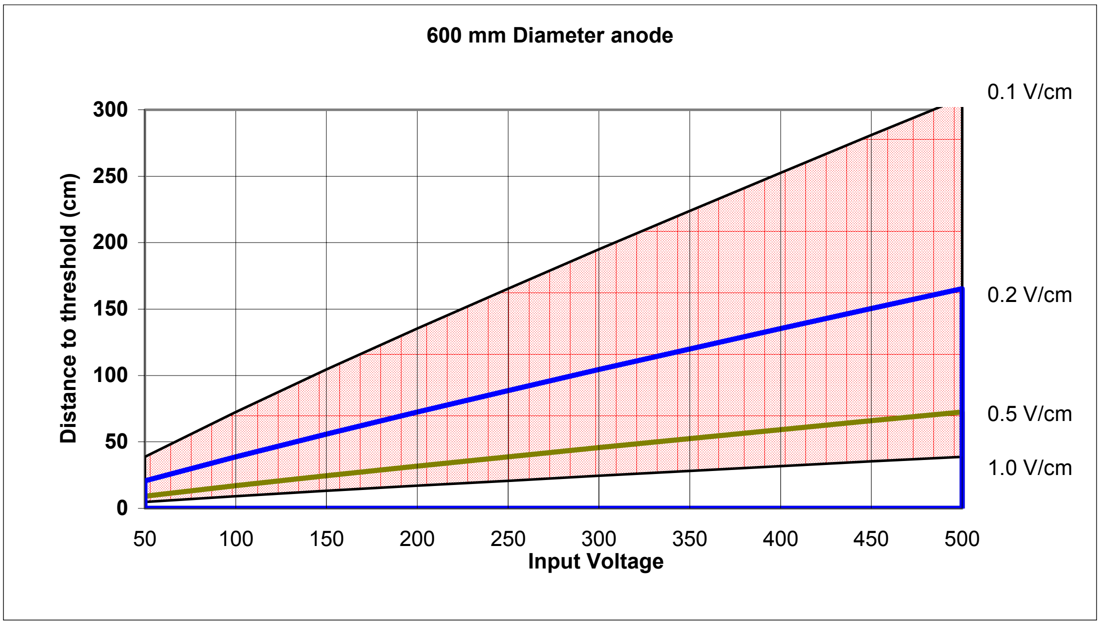

Figure 21 **Threshold distances for 0.1, 0.2, 0.5 and 1.0 V/cm thresholds at differing input voltage values for a 600 mm diameter ring anode**

Voltage gradient data for differing anode sizes from this study were compared with data calculated using equation 6 (derived from Cuinat 1967). For the 0.1 V/cm gradient equation 6 gave a fair approximation of the values obtained in this study. The data being, on average, 130% of the values obtained in this study, with a trend for data derived from equation 6 to correspond less at lower applied voltages compared with higher applied voltages. At values for 1.0 V/cm however, agreement between data derived from equation 6 and this study was poor (on average 170%). Thus, data derived from equation 6 does not appear suitable for use in determining voltage gradient distances.

3.4 Novel Anode Assessment

An assessment of the ergonomics of using the novel anode design showed that whilst the size of the electrode was not a problem and in use, the anode design had some advantages over the usual anode design (lack of rotational force) the design was too heavy to use for electric fishing. A construction using thin walled stainless steel or aluminium tube may overcome this problem.

4. DISCUSSION

The graph of voltage gradient between the 600 mm electrodes (Figure 8) indicated minimal inter-electrode coupling was taking place. However some of the voltage gradient results from the 600 mm electrodes show readings less than would be anticipated by comparison with the results of the smaller electrodes (Figure 21). If some inter-electrode coupling were taking place then this would also have had an effect on the current readings when measuring the equivalent resistance values of the large electrodes (see Figure A3.7 in Beaumont *et al.* 2002 regarding current values at low inter-electrode separation). No such effect was apparent however (Figures 9 and 10) thus indicating that if electrode coupling was occurring its effect was minimal.

The effect of anode gauge thickness was not significant over the range of thicknesses measured. However there was some effect of depth on the measured resistance. Novotny and Priegel (1974) recommend doubling the equivalent resistance of an electrode measured at the surface to correct for surface effect. At the two depths used in this report however the deeper measurements were only 70% of the surface measurements. This discrepancy is to be expected as Novotny and Priegel's data refer to electrodes only being half submerged whereas in this work the "surface" measurements were taken with the electrodes completely submerged. Data from the 500 mm depth have been used in the subsequent extrapolation of data as the data both more realistically represents the depth at which an anode is held during electric fishing and because they provide a "worse case" scenario for determining power requirements (the lower the equivalent electrode resistance the more power is required).

Results from this study show that the variation of equivalent resistance of electrodes with diameter can be described by a power law equation ($p=<0.001$). Further, it has been shown that neither the Novotny and Priegel (1974) equation nor the variation of that equation described in Kolz *et al.* (1998) are particularly accurate in determining actual equivalent resistance values. The fact that the graphic calculation of $f(\gamma)$ for most ring electrode sizes in common use requires interpretation of the far left hand side of the graph (Figure 1) can only add to the likelihood of error using this method. The application of a simple conductivity correction to the relationship found in this study will allow a more accurate determination of theoretical values to be obtained for any diameter of anode in any water conductivity.

Equivalent resistance of the single mesh sheet and the braid were very similar this is in contrast to Beaumont *et al.* (2002) where it was found that generally braid cathodes had a far more intense voltage gradient than mesh cathodes. The reason for the discrepancy between the two findings is not certain but could be due to the differing mesh size and overall size of the various types of cathode used in the two studies. It should also be noted that Beaumont *et al.* (2002) measured voltage gradient and whilst low gradients should be associated with low equivalent resistance, the physical shape of the electrode will affect the gradient far more than the equivalent resistance.

The equivalent resistance of the twin mesh cathode configuration was greater than predicted from resistance theory. This was probably due to inter-electrode coupling at the 500 mm separation used.

The input power requirement for different anode diameters at different applied dc voltages has been modelled and is presented in a series of "look-up" graphs. From these it is possible to ascertain the size generator required to power the electric fishing system (assuming a standard braid cathode and 0.6 Power Factor conversion) at different input voltage values at a range of different water conductivities. Whilst figures shown represent power required when using dc, the percentage of the power being used by pdc can be determined by applying a correction to the dc data based on the percentage of the power (% duty cycle) being used when compared to dc. Graphs have been truncated at 7.5 kVA as this represents the maximum generator size (based on weight and physical size of generator) it is feasible to use in a "field" situation (and then only in boat mounted situation). Few Agency fishery groups have generators above 3 kVA however (Beaumont *et al.* 2002) and for practical purposes where manual transportation is used a 3 kVA generator (dry weight *c.*60 Kg) should probably be used as an upper limit for generator size.

Power input required to operate electric fishing gear using standard anode and cathode designs and dc waveform is very high. If 3.0 kVA is the likely upper limit of generator size suitable for portable field use and 250 V input the likely minimum applied voltage required, a water conductivity of 500 μS^{-1} is the probable upper limit for dc electric fishing (using a single 400 mm diameter anode and 750 mm braid cathode).

Voltage gradients of four different diameters of simple anode design at different input voltage values have been determined. Values for 0.1 V/cm, 0.2 V/cm, 0.5 V/cm and 1.0 V/cm have been used as threshold values as these encompass the published data regarding the minimum (0.1 V/cm) and maximum (1.0 V/cm) values that should be used for dc electric fishing (Lamarque 1967, Cuinat 1967, Kolz and Reynolds 1989, Kolz *et al.* 1998). Note however that data on voltage gradients required for pdc electric fishing indicate that higher gradients may be required for this waveform compared to dc fields. Measurements were taken using a simple stainless steel anode with a 750 mm copper braid cathode.

It should be noted that the voltage gradient at a point near to an electrode in a given water conductivity is dependant upon the total current flowing through the electrode. If the total current is reduced, then the voltage gradient will also be reduced. Such a reduction in current could be achieved either by reducing the applied voltage, or by increasing the resistance of the other electrode. Thus, the voltage gradient adjacent to an anode would, in general, change if the cathode geometry (and hence resistance) changed. In the ideal electric fishing scenario, the cathode resistance is very much less than the anode resistance hence, small changes in the cathode resistance would have little effect on the total current or on the voltage gradient close to the anode. The use in this study of the simple anode design and relatively standard cathode however should minimise differences for most UK applications.

Over a range of voltage gradient thresholds data calculated using equation 6 (derived from Cuinat 1967) showed poor agreement with the data obtained from the measured and calculated values from this study. Values derived from equation 6 ranged between 130% of this study's findings (for 0.1 V/cm gradient) to 170% for the 1.0 V/cm gradient threshold.

Data from this study have been incorporated into a spreadsheet model that graphically displays input power required and anode voltage gradient thresholds (E). On inputting details of anode diameter, cathode type, output voltage required and duty cycle, an output of the power required to energise the fishing system is shown for both dc (the left y-axis of the graph) and pdc (the right y-axis of the graph) fishing output. The spreadsheet includes twin anode (and twin cathode) electric fishing systems. Whilst anode resistance is calculated from the diameter of the ring, the resistance value for the cathode (two cathodes for the twin anode calculations) is entered from a list of values for differing cathode types.

Information regarding anode voltage gradient for the chosen anode size is shown on a separate graph and shows the distance to the 0.1 V/cm, 0.2 V/cm and 1.0 V/cm thresholds.
A disc containing the spreadsheet is incorporated into the report together with screen grabs of the spreadsheet (Appendix IV). The spreadsheet requires Microsoft Excel® to run.

The results from this study gives information that both elucidates equivalent resistance values for a size range of electrodes and gives information about specific anode designs currently in use in the UK. Measurements have been taken at depths that represent the real life situation of electric fishing and thus results are directly applicable to the type of classical electric fishing used by researchers and managers. The results allow equivalent electrode resistance to be calculated with a high degree of certainty without recourse to graphic extrapolations. No evaluations of "Wisconsin ring" designs of anode have been undertaken: these are often unique in their design and thus require measuring empirically.

Data from this study now make it possible to predict with a high degree of certainty the likely distance to specific voltage gradient thresholds. However, whilst a reasonable amount of data exists regarding the dc voltage gradient thresholds required to elicit a response from a fish, little is known about what those values (to maximise fish capture and minimise fish injury) should be for pdc. With dc fields being impractical to use in water conductivity of above *c*. 500 μScm^{-1} (due to high power requirements) research on thresholds required for pdc is urgently required.

5. REFERENCES

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Kolz A L and Reynolds J B (1989) Electrofishing, A Power Related Phenomenon US Fish and Wildlife service. Fish and Wildlife Technical Report 22 pp 1-25.

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Novotny D W and Priegel G R (1974) Electrofishing boats. Improved designs and operational guidelines to increase the effectiveness of boom shockers. Tech. Bull. 74. Dep. Natural Resources Madison Wisconsin

APPENDIX I MEASURED ELECTRODE EQUIVALENT RESISTANCE VALUES

Temperature 5.8^{o}C, Ambient Conductivity 350 μS^{-1}

Measurement Depth	Electrode 1		Electrode 2		Applied Volts (V)	Measured Amps	Calculated Bulk Resistance	Electrode 2 Resistance
	Diam	Gauge	Diam	Gauge				
Surface	400	6	400	6	51.00	0.65	78.46	**39.23**
Surface	400	6	100	6	51.00	0.35	145.71	**106.48**
Surface	400	6	200	6	50.90	0.48	106.04	**106.04**
Surface	400	6	600	6	50.80	0.69	73.62	**73.62**
Surface	400	10	400	10	50.70	0.61	83.11	**41.56**
Surface	400	10	200	10	50.70	0.49	103.47	**103.47**
Surface	400	10	600	10	50.40	0.75	67.20	**67.20**
Surface	400	20	400	20	50.60	0.69	73.33	**36.67**
Surface	400	20	600	20	50.30	0.86	58.49	**58.49**
Surface	600	10	600	10	50.30	0.97	51.86	**25.93**
Surface	100	6	100	6	50.80	0.26	195.38	**97.69**
Surface	400	10	250	10	50.60	0.57	88.77	**88.77**
Surface	400	10	383 (Intelysis)	12	50.50	0.69	73.19	**73.19**
Surface	400	10	291 (Intelysis)	6	50.60	0.58	87.24	**87.24**

Measurement Depth	Electrode 1		Electrode 2		Applied Volts (V)	Measured Amps	Calculated Bulk Resistance	Electrode 2 Resistance
	Diam	Gauge	Diam	Gauge				
Surface	400	10	320 (Electracatch)	12	50.60	0.60	84.33	**84.33**
Surface	400	10	260 (Millstream)	15	50.60	0.60	84.33	**84.33**
Surface	400	10	380 (Millstream)	15	50.50	0.67	75.37	**75.37**
Surface	400	10	200	20	50.60	0.53	95.47	**95.47**
Surface	400	10	250	10	50.60	0.53	95.47	**95.47**
Surface	braid		braid		50.60	1.15	44.00	**22.00**
Surface	mesh		mesh		50.50	0.97	52.06	**26.03**
Surface	braid		Mesh x2		50.40	1.44	35.00	**13.00**

APPENDIX II MEASURED ELECTRODE EQUIVALENT RESISTANCE VALUES

Temperature 5.8°C, Ambient Conductivity 350 μS^{-1}

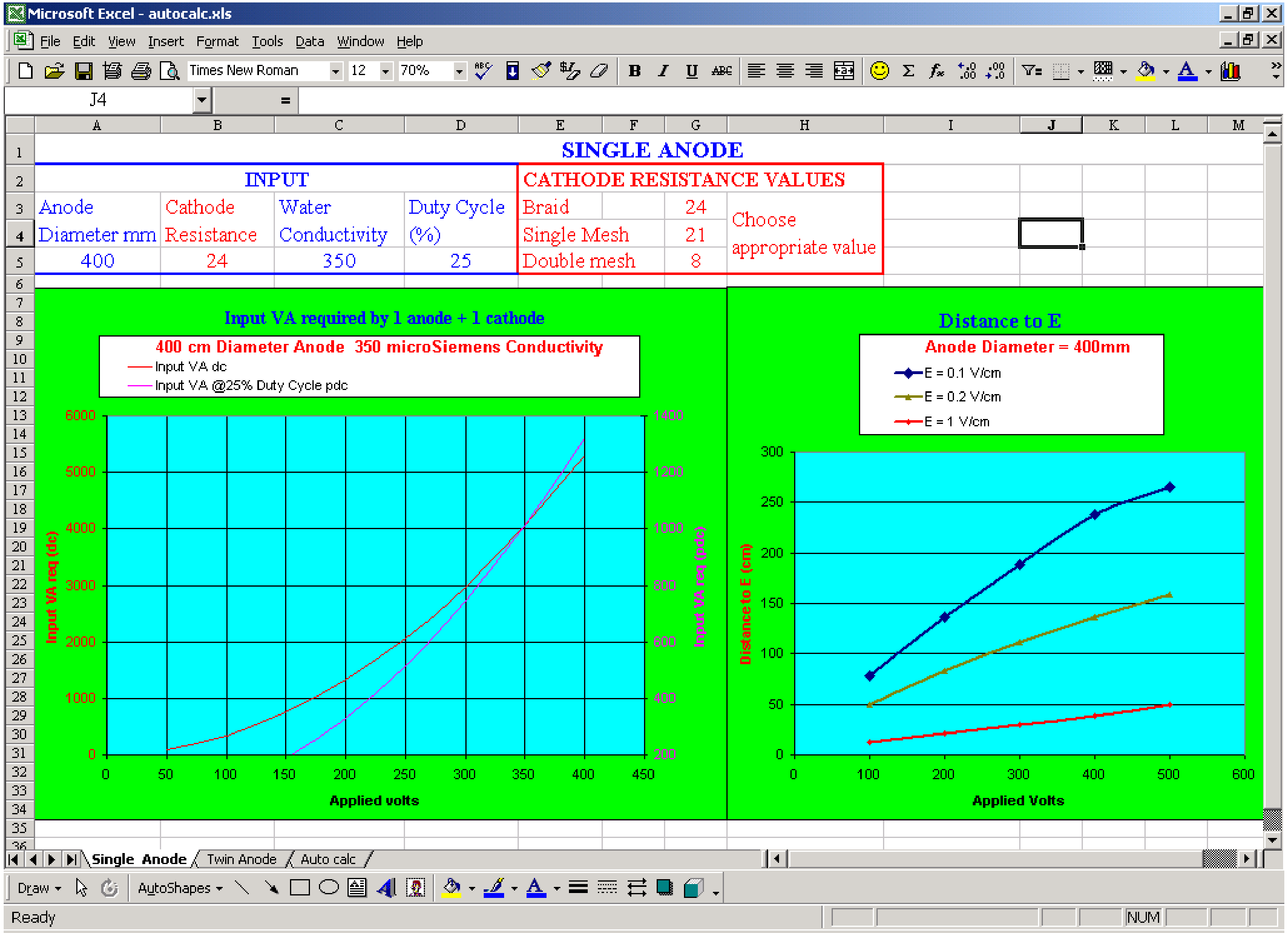
Measurement Depth	Electrode 1		Electrode 2		Applied Volts (V)	Measured Amps	Calculated Bulk Resistance	Electrode 2 Resistance
	Diam	Gauge	Diam	Gauge				
500 mm depth	400	6	400	6	50.5	0.89	56.742	**28.371**
500 mm depth	400	6	100	6	50.8	0.50	101.600	**101.600**
500 mm depth	400	6	200	6	50.5	0.67	75.373	**75.373**
500 mm depth	400	6	600	6	50.4	1.00	50.400	**50.400**
500 mm depth	400	10	400	10	50.4	0.93	54.194	**27.097**
500 mm depth	400	10	200	10	50.4	0.71	70.986	**43.889**
500 mm depth	400	10	600	10	50.1	1.05	47.714	**20.618**
500 mm depth	400	20	400	20	50.3	1.01	49.802	**24.901**
500 mm depth	400	20	600	20	50.1	1.15	43.565	**18.664**
500 mm depth	600	10	600	10	49.90	1.33	37.52	**18.759**
500 mm depth	100	6	100	6	50.60	0.35	144.57	**72.286**
500 mm depth	400	10	250	10	50.20	0.78	64.36	**64.359**
500 mm depth	400	10	383 (Intelysis)	12	50.30	0.94	53.51	**53.511**
500 mm depth	400	10	291 (Intelysis)	6	50.40	0.82	61.46	**61.463**

Measurement Depth	Electrode 1		Electrode 2		Applied Volts (V)	Measured Amps	Calculated Bulk Resistance	Electrode 2 Resistance
	Diam	Gauge	Diam	Gauge				
500 mm depth	400	10	320 (Electracatch)	12	50.40	0.88	57.27	**57.273**
500 mm depth	400	10	260 (Millstream)	15	50.10	0.82	61.10	**61.098**
500 mm depth	400	10	380 (Millstream)	15	50.20	0.92	54.57	**54.565**
500 mm depth	400	10	200	20	50.40	0.75	67.20	**67.200**
500 mm depth	400	10	250	10	50.20	0.79	63.54	**63.544**
Bottom	Braid		Braid		49.80	1.03	48.35	**24.175**
500 mm depth	Mesh		Mesh		50.00	1.40	35.71	**17.857**
Bottom	Mesh		Mesh		49.80	1.16	42.93	**21.466**
300 mm	Braid		Mesh x2		49.90	1.55	32.19	**8.019**
Bottom	Braid		Mesh x2		49.40	1.50	32.93	**8.759**

APPENDIX III DUTY CYCLE/PULSE WIDTH CONVERSION

Frequency (Hz)		5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
		Pulse Width (ms)																			
Duty Cycle %	**5**	10	5	3	3	2	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	10	20	10	7	5	4	3	3	3	2	2	2	2	2	1	1	1	1	1	1	1
	15	30	15	10	8	6	5	4	4	3	3	3	3	2	2	2	2	2	2	2	2
	20	40	20	13	10	8	7	6	5	4	4	4	3	3	3	3	3	2	2	2	2
	25	50	25	17	13	10	8	7	6	6	5	5	4	4	4	3	3	3	3	3	3
	30	60	30	20	15	12	10	9	8	7	6	5	5	5	4	4	4	4	3	3	3
	35	70	35	23	18	14	12	10	9	8	7	6	6	5	5	5	4	4	4	4	4
	40	80	40	27	20	16	13	11	10	9	8	7	7	6	6	5	5	5	4	4	4
	45	90	45	30	23	18	15	13	11	10	9	8	8	7	6	6	6	5	5	5	5
	50	100	50	33	25	20	17	14	13	11	10	9	8	8	7	7	6	6	6	5	5
	55	110	55	37	28	22	18	16	14	12	11	10	9	8	8	7	7	6	6	6	6
	60	120	60	40	30	24	20	17	15	13	12	11	10	9	9	8	8	7	7	6	6
	65	130	65	43	33	26	22	19	16	14	13	12	11	10	9	9	8	8	7	7	7
	70	140	70	47	35	28	23	20	18	16	14	13	12	11	10	9	9	8	8	7	7
	75	150	75	50	38	30	25	21	19	17	15	14	13	12	11	10	9	9	8	8	8
	80	160	80	53	40	32	27	23	20	18	16	15	13	12	11	11	10	9	9	8	8
	85	170	85	57	43	34	28	24	21	19	17	15	14	13	12	11	11	10	9	9	9
	90	180	90	60	45	36	30	26	23	20	18	16	15	14	13	12	11	11	10	9	9
	95	190	95	63	48	38	32	27	24	21	19	17	16	15	14	13	12	11	11	10	10

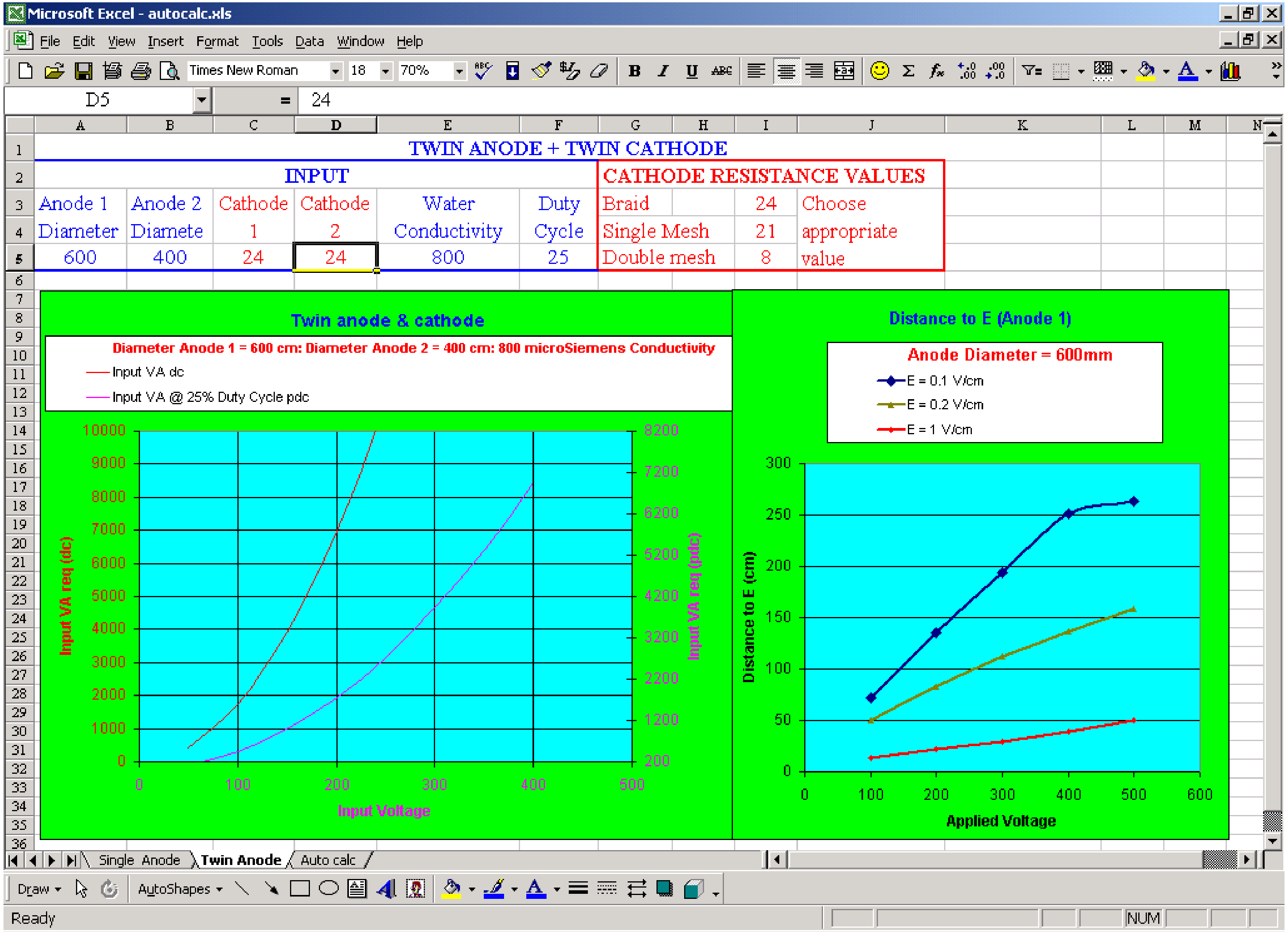
APPENDIX IV OUTPUT POWER AND VOLTAGE GRADIENT MODEL



SINGLE ANODE

INPUT			
Anode Diameter mm	Cathode Resistance	Water Conductivity	Duty Cycle (%)
400	24	350	25

CATHODE RESISTANCE VALUES		
Braid	24	Choose appropriate value
Single Mesh	21	
Double mesh	8	



TWIN ANODE + TWIN CATHODE									
INPUT						CATHODE RESISTANCE VALUES			
Anode 1	Anode 2	Cathode	Cathode	Water	Duty	Braid		24	Choose
Diameter	Diamete	1	2	Conductivity	Cycle	Single Mesh		21	appropriate
600	400	24	24	800	25	Double mesh		8	value