PAPER NUMBER

297

Corrosion 86

The International Corrosion Forum Devoted Exclusively to the Protection and Performance of Materials

March 17-21, 1986
Albert Thomas Convention Center
Houston, Texas

COMPUTERMODELING AND IN-SITU CURRENT DENSITY MEASUREMENTS PROVE A NEED FOR REVISION OF OFFSHORE CP DESIGN CRITERIA.

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SUMMARY.

During recent years there has been a trend towards development and application of current density monitoring equipment in combination with potential measurements on the North Sea structures. In the same period there has also been a strong development of numerical methods for computer modeling of offshore cathodic protection systems. This paper presents results obtained with such modern techniques in monitoring of North Sea platforms. In particular the results demonstrates that the current density requirements for CP in the North Sea are considerably lower than normally anticipated. It is furthermore shown that the sacrificial anode weight may be reduced by introducing changes in the design rules, taking these findings into account.

INTRODUCTION.

External corrosion represent a threat to the continued safe operation of large offshore structures for the production of oil and gas. Cathodic protection(CP) of fixed offshore structures and pipelines by using sacrificial anodes, impressed current or a combination of both, have proved to be an efficient and economical method to reduce or avoid such hazards.

In the case of submarine pipelines, CP is normally combined with coatings. In addition to the primary advantage of corrosion protection, the coating effectively reduce the current required for CP, and accordingly reduce the sacrificial anode weight required to protect exposed steel. Less frequently, coatings are applied on platform structures. The major advantages of coatings in this latter case have been improved rate of polarization and reduced weight loads and drag forces acting on the structures.

Unfortunately there has been a large number of incidents of unsatisfactory performance of cathodic protection systems since the first structures were placed in the North Sea some 15 years ago. The incidents referred to, comprise problems which have appeared shortly after the structures were launched, as well as deficiencies developed over the first few years of operation and which eventually have created needs for rectification. Included are hardware failures, e.g. of impressed current anodes of unsatisfactory mechanical design to resist the loads of rough sea states. A considerable number, however, are simply caused by unsatisfactory CP and anode design or distributions. Thus unfavourable changes in the potential levels of the structures have been observed, often starting to appear at nodes, risers, at conductors or conductor guides and other complex and critical areas of the structures.

At an early stage already it was obvious that the design methods and/or criteria adopted for the North Sea, on the basis of experience in the US and elsewhere, were far from adequate. Such inadequate protection experienced in this early phase was soon rectified, simply by increasing the number of anodes. This was reflected in the CP design criteria which soon showed current density requirements for protection of 110 mA/m² - 130 mA/m², compared to the early figures of typically 80 mA/m².

Over the last decade there have been lengthy discussions and numerous papers presented on CP design methods, procedures and criteria. Not least there has been a considerable development of the technology, including the development of advanced computerized methods for CP modeling and design analysis, and of modern current density/field gradient monitoring systems for inspection of offshore cathodic protection. Increasing use of this modern technology as well as evaluations and measurements using more basic or traditional methods, have strongly indicated that there is room for optimization in offshore CP design.(It is referred to references 1-8). Such optimization relates to improvements in sacrificial anode design and distributions as well as to sacrificial anode weight.I.e. there is room for considerable optimization(reduction) of sacrificial anode weight, still allowing for improvements in the level of protection of the structures.

METHODS USED IN MONITORING AND EVALUATION OF OFFSHORE CP SYSTEMS.

Computer Modeling.

One of the most significant developments in this area made in later years, refers to the computerized modeling techniques developed for the analysis of offshore cathodic protection systems. Computer programs developed include applications of methods such as the finite difference, the finite element and more recently the boundary element methods. As opposed to the traditional CP design procedures which are based on a few simple formulae and certain rules of thumb, these new methods allow for detailed analysis of potential and current density distributions all over the structures including nodes, pile guides etc and other complex and criticial sections.

Examples of results have been shown in fig. 1, obtained using a boundary element-based package including advanced colour graphics for display of the resultant distribution of potential and current densities. The program includes procedures for handling the formation of calcareous deposits and time-dependent polarization effects, and has capabilities for modeling very large and complex structures.

Particularly of interest in this regard is the use of such programs in analysis of CP and current density(CD) or field gradient readings. An example of such analysis by curve-fitting of theoretically calculated to a measured field gradient curve is shown in fig. 5 for a sacrificial bracelet anode. Thus the program is used to obtain relatively accurate figures for current output from sacrificial anodes and cathodic current densities on exposed steel. Combined with potential readings this provides the basic performance data for a CP system.

Current Density and CP Monitoring Equipment.

Over the last few years there has been an increasing application of equipment for electric field strength/current density monitoring in CP surveys of North Sea Structures. Probes for ROV and diver operations are used to measure simultaneously the potential and the electric field strength at exposed steel, at typical stand-off anodes, at sacrificial bracelet anodes on pipelines etc(see figs. 2 - 5). The most sensitive system for such purposes is based on a pair of rotating electrodes described previously (1, 8). If the geometry is not too complex a pair of fixed reference electrodes may also be used.

Obviously there is a strong reduction in the field strength and in local current density with increasing distance from the anode surface. Accordingly there is a need to relate the reading, obtained at a specified distance from the anode, back to the anode surface. This is achieved by comparison of measured field strength values with figures obtained from computer modeling of the same anode geometry as already described above. By modeling of the anodes for different conditions, i.e. for different current output levels, the output from an anode is found simply by comparison of the readings with tabulated figures for known current output.

In monitoring of platform anodes, readings are obtained at well defined positions, i.e. at specified distance from the anode surface. For this purpose the probe is provided with a support or spacing piece. Preferably this should be manufactured to keep the probe at 10-15 cm distance from the anode surface, to avoid too strong effects of local variations over the anode surface in the anodic current density. When monitoring long, rod-shaped offshore anodes, 2-3 readings per anode may therefore be required to obtain results of good reliability. Still efficiency is maintained with a typical figure of 15-20 anodes monitored per hour.

Surveys of submarine pipelines are normally conducted using ROVs and manned submersibles with the probe carried in front of the vehicle. The electric field strength variations along the pipeline are continuously monitored and logged on a diskette or other suitable medium. A typical peak on such a profile, obtained on passing an anode bracelet of a 36« North Sea pipeline is already shown in fig 5.

Polarization Tests.

Another system also developed recently allows for polarization tests to be carried out in-situ on submerged structures. The system principle which has been patented is based on a probe as shown in fig. 6. This includes a reference electrode, a counter electrode, an auxilliary electrode and a rubber bell to seal off these electrodes from all but a small section of the structure to be polarized/monitored. When connected via cable to a potentiostat this opens up for the full range of corrosion forecasting capabilities inherent in polarization curves and various polarization techniques.

The system is used for measuring local current densities on sacrificial anodes, on cathodically protected steel in sea water etc. E.g in this latter case the procedure would be as follows:

- Measure the potential of the CP protected steel with the probe at a short distance from the surface.
- Place the probe on to the surface of the steel and maintain the potential(cathodic protection) by supplying the current required from the counter electrode of the probe.(replacing the current flow

from the sacrificial anode).
The current supplied from the C-electrode to maintain the protective level of this steel section is thus read on a meter.

For a sacrificial anode the current flow is reversed compared to the example of a steel surface.

In practice the best results have been obtained by applying an additional 10 mV cathodic polarization of the steel compared to the initial potential reading(10 mV anodic polarization in the case of monitoring an anodically polarized surface, e.g. an anode).

Potential Measurements.

In the early days of cathodic protection a few potential readings only were normally taken to check the level of protection, e.g. by lowering a half cell into the sea from the platform deck. Such procedures are unsatisfactory for assessing the CP performance. However, additional information may be extracted from potential measurements if properly planned. Sets of potential readings of relatively high density. e.g. such that attenuation curves at anodes or depolarization effects at a node corner are clearly displayed, may allow for detailed and reliable analysis to extract current density data.

NORTH SEA APPLICATIONS AND RESULTS

Monitoring equipment based on the rotating T-sensor principle(1,9) and the computer modeling analysis technique have been used on a large number of North Sea platforms for monitoring CP performance. This includes work on relatively small as well as medium sized and larger steel platforms in water depths up to 150 m approx. In several instances the CP/CD surveys have comprised more or less the complete platforms while in other cases sections and special structural elements like pile-guides, pile-sleeves, risers etc have been surveyed only.

From this variety of surveys there are available tens of thousands of simultaneous readings of potentials(CP) and current densities(CD) locally, for cathodically protected steel and a somewhat lower number of readings for sacrificial anodes of the more common aluminium qualities and zinc. Major results have been summarized for steel and for sacrificial anodes as follows:

Current Density Requirements for CP of steel in Seawater.

Simultaneous readings of CP and CD, mixed from a considerable number of platforms, all protected by sacrificial anodes, have been plotted in an E-i-diagram as shown in fig.7. Potential wise the readings ranged(approximately) from -550 mV to -1100 mV vs. Ag/AgCl, with a large portion of the figures between -850 to -1000 mV. The current density figures ranged from as low as 10 mA/m^2(approx) up to beyond 300 mA/m^2 locally. Typical average figures for the current density readings are around 50-70 mA/m^2. Of interest is also the observation that for small platforms of low complexity the average cathodic current density has been even lower, i.e. less than 50 mA/m^2 and that the «typical potential levels» have been more negative than -900 mV vs. Ag/AgCl. On the other hand for large and complex structures, the average cathodic current density has been on the high side of the figures quoted above, i.e. typically 70-80 mA/m^2. This behaviour may most probably be explained as follows:

- For the large and complex structures as opposed to smaller and geometrically simpler, it has been difficult to design the CP systems to avoid shadow effects etc. and to achieve quick and efficient polarization. This reflects a slower rate of formation of calcareous deposits due to less optimal distribution and accordingly a slower drop in the current density than observed for the smaller and less complicated structures. In line with this observation, the larger and more complex structures that were surveyed showed a much higher frequency of readings of unprotected or marginally protected areas.
  The unprotected areas were found in narrow corners, in pile guides, pile sleeves, in complex nodes etc. This also explains the «nose» on the E-i-curve at the potential level of -800 mV to -900 mV(fig.7). The sections or spots of the structures within this potential range have had a history of slower rate of polarization and an inferior quality of the coating(calcareous deposits) than sections polarized to -900 mV to -1000 mV vs. Ag/AgCl.

Accuracy of the Readings.

The dependability of these readings may be evaluated in different ways:

1. Comparison of anodic and cathodic readings. CD readings were normally also carried out on a large number of sacrificial anodes. The anodic current densities were integrated over all sacrificial anodes for the structure and compared with the cathodic current, integrated over the whole steel surface of the structure. In all surveys the difference between Ia and Ic was normally less than 5% and never beyond approx 10%
2. CD surveys have also been carried out on structures with impressed current and hybrid systems, included shunted anodes. Normally there has been very good agreement between this type of CD readings and independent readings via shunts. Likewise, average current densities obtained have been in very good agreement with the average figure obtained on the basis of impressed anode output. This was for example the case in the survey of the Murchison Platform published previously. Also for this survey the average cathodic current density was on the low side of 60 mA/m^2. (See fig. 8).
3. Even for platforms which have shown marginal or unsatisfactory protection, major sections with most of the surface have been very well protected with potentials around -900 to -950 mV, and with anode driving force of the order of 100 mV. This suggests that the typical output from the majority of the sacrificial anodes is less than 50% of the «design output» which corresponds to typically 130 mA/m^2. Only in some areas of the structures are there anodes of high drain «to cope with local problems».(Only few examples have been seen which deviate from this experience). Accordingly this is also in good agreement with the CD data quoted above.

Potential Readings on Steel.

As demonstrated in the CP readings as well as in computer calculations, distribution phenomena over a structure may introduce considerable «cathodic IR-drops» e.g. close to a node, reducing the driving force for the anode. Potential measurements on the steel platforms showed such cathodic IR drops, denoted Ec in fig. 9, to range from a few mV at smaller nodes to beyond a 100 mV at pile sleeves. This needs to be taken into account in CP design(2,6,10).

Sacrificial Anode Performance.

In accordance with the readings presented above for steel, the typical average output from the sacrificial platform anodes was less than half of the (max) design output. However, despite this observation the potential of the anodes was very often unsatisfactory when compared with specifications. An unexpectedly high number of AlZnIn anodes showed potentials in the range -990 to -1040 mV with average figures e.g. around -1010 mV vs. Ag/AgCl. This average might vary from one platform to another. The spread in the readings was high, and sets of data have ranged from -950 to -1100 mV vs. Ag/AgCl. Other Al-alloys have shown the same tendency. (See figure 10).
(The readings were normally taken with the reference electrode at a distance of 10 cm from the surface, and have been corrected for the IR-drop).

CONSEQUENCES FOR CP DESIGN.

As opposed to the trend in the 1970'ies towards higher current density requirements for CP in the North Sea, there is now a solid evidence that the CD required for protection of submerged steel is in the order of 50% only of the figures specified in various recommended practises. Such evidence is available from a number of different sources and includes comprehensive offshore experience data and in-situ measurements.

The low current density requirements documented provides the necessary basis for a similar optimization (reduction) of sacrificial anode weight, i.e. a weight reduction of 50% approx. The author will stress, however, that such a dramatic reduction is not recommended for several reasons. A reduction to 70-80 mA/m² of the average «maintenance current density», which is the basis for sacrificial anode weight calculations, is considered realistic at this stage for the Mid to Northern North Sea.

Despite the fact that the sacrificial CP Systems have been overdesigned in terms of weight, some platform structures have shown marginally or underprotected sections as quoted above. I.e. the anodes have not been designed to supply the amount of current required for protection. The analysis has shown that the anodes should be designed with a different geometry or increased surface area per unit weight to allow for an increased putput per unit weight(10). I.e. the design must be such that the sacrificial output capacity at least is maintained at the same level as of to-days traditional design or higher.

In this respect it should again be remembered that real sacrifical anode output normally is considerably lower than calculated when using the traditional procedures and formulae. As documented in the data quoted above, the reason for this in practice can be attributed to a strongly reduced driving force:

Reduction in driving force by 50 mV-100 mV due to cathodic IR drops at nodes, pileguides etc.
Reduction in driving force by 40-80 mV to make up for anode closed circuit potentials more positive than specified.

When using traditional CP design procedures the following change is recommended.

Anode output (Ia) to be calculated as:

$$Ia = \frac{Ec - Ea - \Delta Ec}{Ra} \quad (1)$$

where Ec = protection potential for steel (-800 mV vs. Ag/AgCl).

Ea = anode closed circuit potential (to be on the safe side of *real* performance data).

ΔEc = safety factor to account for potential distribution (shadow effects or cathodic IR-drops) over the structure.

Ra = anode resistance according to Dwight or other relevant formula.

Such a change in the design procedures will promote an increase in the anode surface area and in anode output as per the requirements above.

An alternative procedure suggested recently tends to promote a change in the same direction. This latter proposal involves an increase in the initial and the final current densities, which is the basis for calculation of the anode output capacity for the initial and the final stages of anode life. At the same time the mean current density is reduced allowing for a similar reduction in sacrificial anode weight.

The former method using equation(1) above is, however, considered advantageous as this will make a better correspondance between real current densities on the structures and the calculated. While using the latter method the current densities applied in the calculations are unrealistically high compared to real current densities on the structures. This will of course make it more complicated to make use of and compare current density measurements/performance data obtained on the structures and the design current densities.

Before introducing any changes in the CP design procedures, it should be stressed, however, once more that a thorough evaluation should be made taking into consideration all aspects of CP including not only the theoretical design, but also practical problems related to manufacture and installation of anodes etc.

In no circumstance is it recommended to reduce the current density requirements for design and continue using other CP design parameters and procedures unchanged.

At the present a more detailed statistical analysis of the collected CP data, and a thorough evaluation of the CP design procedures is carried out by CorrOcean on behalf of several oil companies in Norway.

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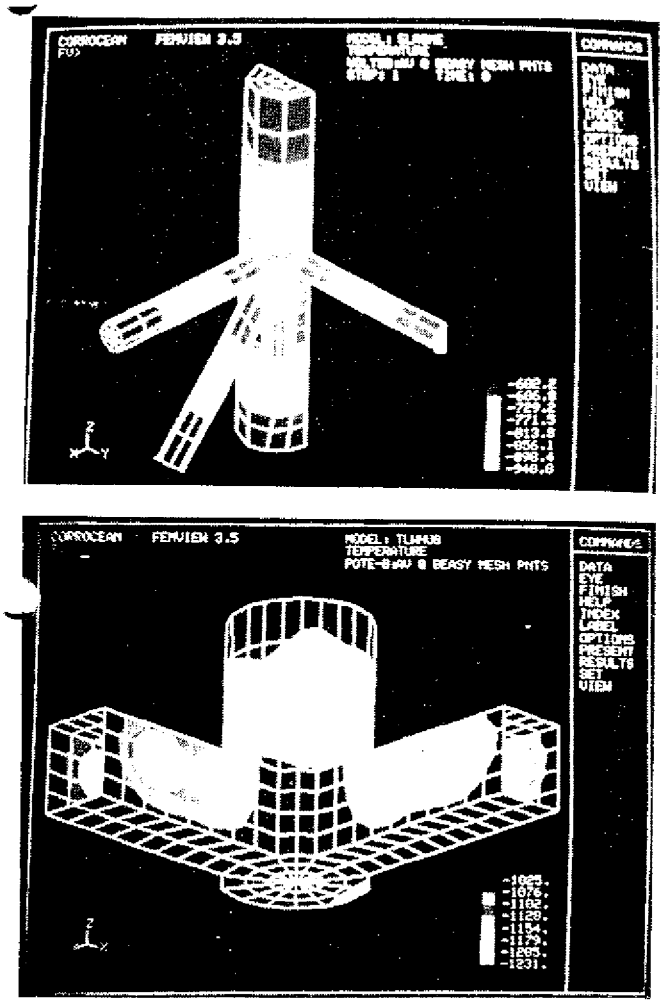

Figure 1. *Results from computer calculations showing the potential distribution using colour graphics.*

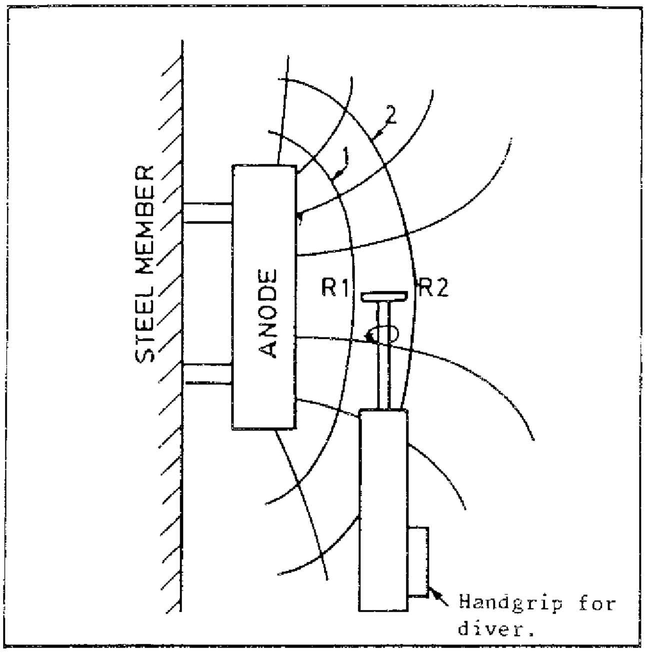

Figure 2. *Sensors for electric fieldstrength/current density monitoring of sacrificial anodes, steel etc.*

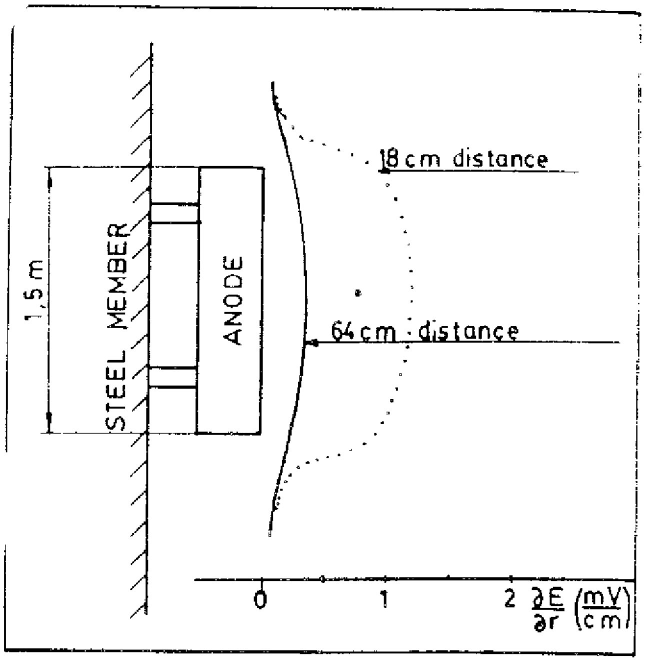

Figure 3. *Field strength values for two different distances from the anode surface. Results from computer modeling.*

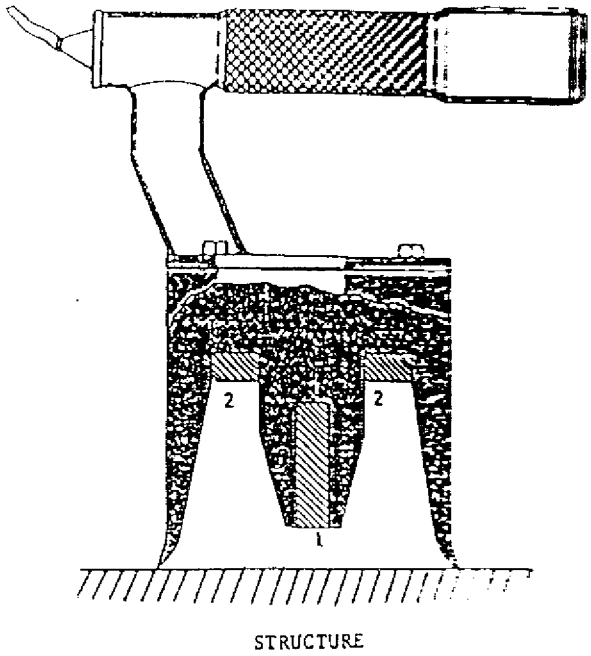

Figure 6. *The CPD Probe for in-situ polarization measurements. Electrodes no 1 and 2 are a reference and a counter electrode respective*

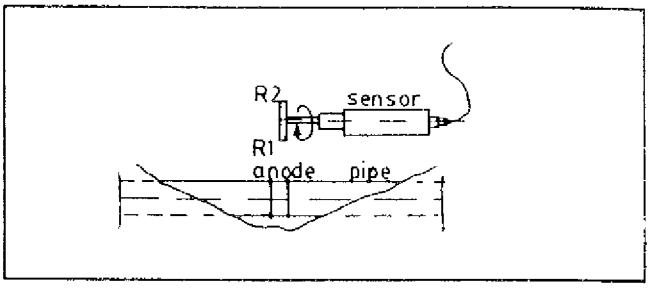

Figure 4. *Sensor for electric field strength monitoring along submarine pipeline.*

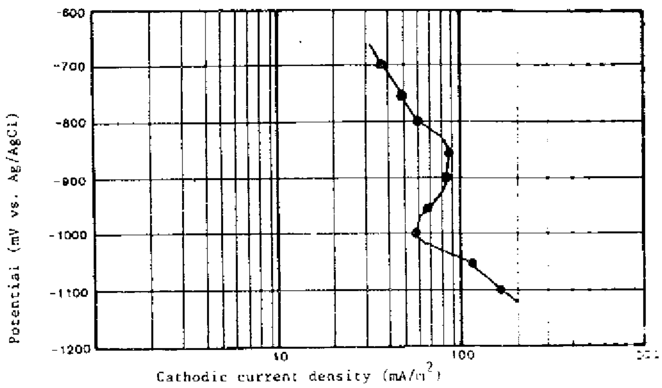

Figure 7. *A very large number of simultaneous readings of current density and potential have been obtained in-situ on offshore steel platforms. This curve shows average current densities for various potential levels.*

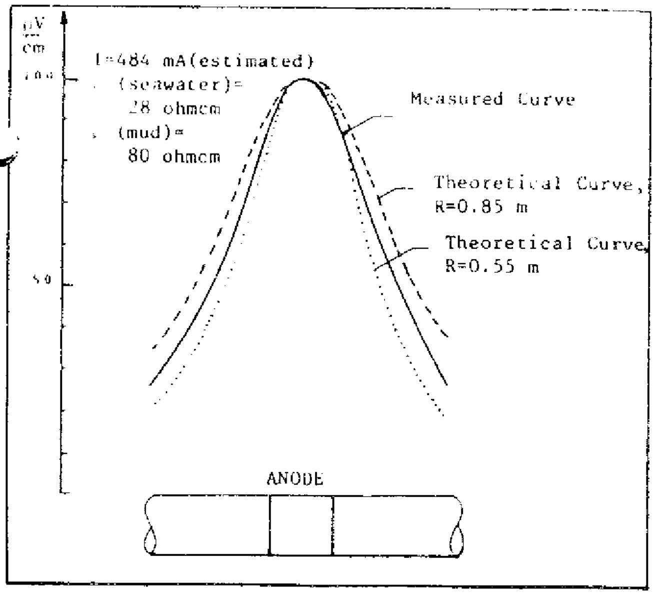

Figure 5. *Measured and calculated field strength values at a bracelet on a 36-in. pipeline.*