

CATHODIC PROTECTION MODELING  
OF NODES IN OFFSHORE  
STRUCTURES

By

MICHAEL RAYMOND HAROUN

Bachelor of Science in Chemical Engineering

Oklahoma State University

Stillwater, Oklahoma

1984

Submitted to the Faculty of the  
Graduate College of the  
Oklahoma State University  
in partial fulfillment of  
the requirements for  
the Degree of  
MASTER OF SCIENCE  
JULY, 1986

Thesis

1986

H292c

cop 2



CATHODIC PROTECTION MODELING  
OF NODES IN OFFSHORE  
STRUCTURES

Thesis Approved:

*Robert H. Hordening*

Thesis Adviser

*Mayis Seapan*

*Billy L. Cuyres*

*Norman N. Durham*

Dean of the Graduate College

1259878

## ABSTRACT

A three-dimensional computer model for analyzing the potential distribution on the metal surface and in the water surrounding nodes in offshore platforms was developed. The model is based on the Laplace equation as the governing equation and uses the finite difference method to solve the equation numerically. The model is the first of its kind and is unique because it is designed for microcomputers.

The model can model dozens of different node geometries. Most of these geometries have been tested for convergence problems and they are error free. The model is promising because it can expand to incorporate more node geometries.



## ACKNOWLEDGMENTS

I wish to express my sincere gratitude to all the people who assisted me in this work. I am grateful to my major adviser, Dr. Robert Heidersbach, for his guidance and much valued counsel. His determination and persistence made my software development possible.

I am also thankful to the other committee members, Dr. Ruth Erbar, and Dr. Mayis Seapan for their help and support in the course of this work. Special thanks for Dr. Ruth Erbar for her encouragement and her remarks.

Special thanks are due to Steve Wolfson from Shell development for his assistance and for his kind help in verifying the model output with the field data. I am also thankful to Steve Wolfson from Shell Development and Bill Coyle from Union Oil for providing me with drawings of the different node geometries used on offshore structures.

Special thanks are due to the School of Chemical Engineering for the financial support I received during the first year of my thesis work and to Shell Development, Union Oil, and Atlantic Richfield for funding my research project.

My father, my mother, and my girlfriend, Kaitsu Makela, deserve my deepest appreciation for their constant support and encouragement.

## TABLE OF CONTENTS

Chapter	Page
I. INTRODUCTION. . . . .	1
II. LITERATURE SEARCH . . . . .	3
Introduction . . . . .	3
Historical Background of Computers . . . . .	4
Corrosion Related Applications . . . . .	7
Database Systems. . . . .	7
Corrosion Rate Evaluation . . . . .	10
Corrosion Monitoring. . . . .	11
Computer Modeling . . . . .	13
Numerical Techniques . . . . .	13
Non-Numerical Techniques . . . . .	19
Suggested Additional Applications. . . . .	21
III. CATHODIC PROTECTION PRINCIPLES. . . . .	25
Introduction . . . . .	25
Basic Theory . . . . .	25
Design Considerations. . . . .	32
Design Procedure . . . . .	35
Anode Distribution . . . . .	36
Cathodic Protection Monitoring . . . . .	37
Conclusion . . . . .	38
IV. MODEL DESCRIPTION . . . . .	39
Introduction . . . . .	39
Mathematical Formulation . . . . .	40
Numerical Technique . . . . .	40
Mathematical Equation . . . . .	41
Boundary Conditions . . . . .	46
Water Resistivity . . . . .	50
Dynamic Mesh. . . . .	53
Anode Specifications. . . . .	54
Convergence Criteria. . . . .	57
Polarization Curves . . . . .	58
Shape Files . . . . .	62
Node Geometries . . . . .	64
Source Listing . . . . .	64
V. RESULTS AND DISCUSSION. . . . .	66

Chapter	Page
Introduction . . . . .	66
Input Data . . . . .	67
Potential Distribution in 3 Dimensions . . . . .	67
Two Dimensional Data Analysis. . . . .	70
Graphical Analysis . . . . .	71
Topographic Map . . . . .	71
Surface Map . . . . .	79
Validation of the Model. . . . .	82
Conclusion . . . . .	89
 VI. CONCLUSIONS AND RECOMMENDATIONS . . . . .	 90
Conclusions. . . . .	90
Recommendations. . . . .	91
 BIBLIOGRAPHY. . . . .	 94
 APPENDIXES. . . . .	 100
APPENDIX A - A SAMPLE OF CATHODIC PROTECTION DESIGN. . . . .	 101
APPENDIX B - SHAPE FILES . . . . .	108
APPENDIX C - LISTING AND FIGURES OF THE NODE GEOMETRIES. . . . .	 118
APPENDIX D - PROGRAM TREE STRUCTURE. . . . .	129

LIST OF TABLES

Table	Page
I. Galvanic Series of Some Commercial Metals and Alloys in Seawater. . . . .	31
II. Design Criteria for Cathodic Protection Systems . . . . .	33
III. A Sample of the Computer Output Showing the Input Data. . . . .	68
IV. A Listing of the Data Contained in a Shape File. . . . .	113

## LIST OF FIGURES

Figure	Page
1. Polarization Caused by an External Electron Supply. . . . .	27
2. A Picture of an Offshore Structure in the Sea . . . . .	29
3. A Schematic Diagram of Offshore Structure Showing the Locations of Node Geometries. . . . .	30
4. The Potential at Node P is Equal to the Average of the Six Surrounding Potential Values . . . . .	44
5. The Point of Interest is Located on the Face of Three-Dimensional Cube. . . . .	48
6. The Point of Interest is Located on the Edge of Three-Dimensional Cube. . . . .	48
7. The Point of Interest is Located at the Vertex of the Three-Dimensional Cube . . . . .	49
8. The Three Different Parts of a Three-Dimensional Cube Element. . . . .	51
9. The Cathode and the Anode as Represented in the Three-Dimensional Cubic Mesh. . . . .	56
10. The Effect of Increasing the Pressure (Water Depth) is a Slight Shift of Polarization Curve to the Right. . . . .	59
11. The Same Shift to the Right of the Polarization Curve Due to the Increase of Hydrostatic Pressure Except That the Temperature is at 10C . . . . .	60
12. A Plane Containing Data in Two-Dimensions Which is Perpendicular to the Z-axis. . . . .	72
13. The Topographic Map of the Potential Distribution for the Input Data Shown in Table III. . . . .	74
14. The Same Topographic Map of the Potential Distribution for the Input Data of Table II	

Figure	Page
but With a Small Contour Line Interval. . . . .	75
15. The Contour Lines of The Topographic Map Can be Labeled. . . . .	76
16. The Topographic Map in a Plane Located Further Away from the Anodes and Which Contains Areas That are Inadequately Protected . . . . .	78
17. The Surface Map of the Potential Distribution for the Input Data of Table III. The Rotation Angle is at 310 Degrees . . . . .	80
18. The Same Surface Map But Rotated at an Angle of 140 Degrees. . . . .	80
19. The Surface Map of the Potential Distribution at a Tilt Angle of 45 Degrees . . . . .	81
20. The Same Surface Map of the Potential Distribu- tion but Tilted at an Angle of 20 Degrees . . . .	81
21. The Surface Map of the Potential Distribution With a Height/Width Ratio of 1.0. . . . .	83
22. The Same Surface Map of the Potential Distribu- tion but With a Height/Width Ratio of 0.5 . . . .	83
23. The Surface Map of the Potential Distribution With a Skirt. . . . .	84
24. The Same Surface Map of the Potential Distribu- tion but Without a Skirt. . . . .	84
25. The Surface Map of the Potential Distribution With Grid Lines Parallel to the X-Axis. . . . .	85
26. The Surface Map but the Grid Lines are Parallel to the Y-Axis . . . . .	85
27. The Surface Map With Grid Lines Parallel to Both the X-Axis and the Y-Axis . . . . .	86
28. A Schematic Diagram of the Calibration Model. . . .	88
29. The Origin of the Three-Dimensional Cube Containing the Node Geometry is Located at the Lower Left Vertex of the Cube . . . . .	110
30. The Dots Represent the Locations of the Leg Coordinates in the Plane Perpendicular to the	

Figure	Page
Z-axis at $z=1$ . . . . .	112
31. The Dots Represent the Locations of the Leg and the Two Horizontal Braces in the Plane Perpen- dicular to the Z-axis at $Z=5$ . . . . .	112
32. A Graphical Representation of a Node Geometry Consisting of One Leg and Two Horizontal Braces. . . . .	114
33. The Source Listing of the BASIC Program that Created the Shape File Presented in Table IV. .	117

## NOMENCLATURE

d	- distance between nodes, ft
Dx	- distance increment along the x-axis, ft
Dy	- distance increment along the y-axis, ft
Dz	- distance increment along the z-axis, ft
E	- potential difference, volt
I	- Anode Output Current, ampere
$i_p$	- polarization current, mamp/ft <sup>2</sup>
L	- Anode Length, ft
P	- potential, volt
r	- equivalent radius, in
R	- resistance, ohm
s	- water resistivity, ohm-cm
T	- current output/anode, amp/anode
$\nabla$	- Laplacian operator



## CHAPTER I

### INTRODUCTION

Cathodic protection is a well-established means of controlling corrosion on offshore structures or any submerged installation. Advances in computer technology have allowed corrosion engineers to model complex marine structures using one of several numerical techniques. These numerical techniques are used to solve the governing differential equation of galvanic systems. The governing equation is the Laplace equation. Analytical techniques have failed to solve the Laplace equation because of the complexity of structure geometries.

Numerical techniques offer the advantage of speed and versatility and the ability to model any complex geometry. The drawback of these techniques is that they have been developed for large mainframe computers. Therefore, they are expensive to run and create communication problems between the corrosion engineer needing the information and the computer operator seeking to produce the information. The programs are not under control of the engineers but rather under the control of the queuing and delivery systems. The lack of commercial software capable of performing the same job has made the situation worse. All

of the above restraints have prevented the widespread use of computers for cathodic protection design.

The purpose of this research is to adapt existing numerical techniques such as the finite element, the finite difference, and the boundary integral method for use on a microcomputer. The objective is the development of a user-friendly and interactive package that can be used by corrosion engineers to design cathodic protection systems. The package offers the advantage of unlimited computer runs with no runtime expenses. Although the package does not have the elaborate capabilities of the larger mainframe programs, it is based on the same mathematical principles. The program is designed to run on IBM XT personal computers which are inexpensive and widely available. It is equipped with a database system containing several popular node geometries and can be expanded to include new node geometries.

## CHAPTER II

### LITERATURE SEARCH

Previous literature has presented the fundamentals of corrosion and corrosion control and monitoring. It has covered why and how metals corrode and what can be done to control corrosion. However, few papers mention the use of computers for corrosion detection and corrosion control. The intent of this chapter is to review the current uses of computers in corrosion control and monitoring, to offer a historical survey on computers and their usage in the corrosion field, and to suggest new applications for computers in corrosion control and monitoring.

#### Introduction

A major task in corrosion control and monitoring involves the acquisition of electrical or electrochemical data during the course of a survey. Routine calculations, data measurement, data manipulation, and design are the types of routine work that a corrosion engineer or technician must do. This routine handling of data can consume a major fraction of an engineer's time. The rapid and continuing development of computer technology can

greatly reduce this burden. With their low cost, high performance and ease of use, computers (especially microcomputers) provide extremely powerful techniques for data acquisition, numerical processing, data management, data communication, and modeling. Data can be collected, sorted, tabulated, and plotted automatically. This minimizes the possibility of human errors. Furthermore, physical storage space for large amounts of field data is no longer a problem. Nearly one million characters of data can be stored on an inexpensive magnetic disc. The modern computer can be easily interfaced with field apparatus to provide automated monitoring of data signals and/or control of input signals. A number of analog-to-digital (A/D) and digital-to-analog (D/A) converters are available to provide the communications hardware for interfacing. As a consequence, the human labor involved in data collection, collation, computation, storage and design is minimized.

#### Historical Background of Computers

The slide-rule can be considered to be the first tool available for routine multiplication and division. The concept of the slide rule is based on the logarithm of numbers. Since logarithms are compressed versions of their original numbers, by converting these into lengths on a scale or ruler, multiplication and division can be done by simply adding or subtracting the two lengths on the scale (1).

Though the slide rule is not a machine by itself, it does inspire the notion of a machine as a calculation aid. The first true machine capable of performing arithmetical functions appeared about a quarter of a century after logarithms around 1640. The inventor, Blaise Pascal, based his mechanical design on a set of interlocking cogs and wheels on various axles (1). The numbers were dialed and the results were displayed in a little window after the cogs and wheels inside rotated appropriately. The device, called a Pascaline, could add, subtract, multiply, or divide any two numbers and could therefore be called a calculation machine. This was followed by the difference machine, built in 1822 by the Englishman, Charles Babbage. This was a mechanical machine that could solve polynomial equations by calculating successive differences between sets of numbers. Although the machine was capable of doing just one job, the concept of the computer was born. A machine which could perform calculations of one kind could, in all probability, perform any kind of calculation.

The idea was left undisturbed until a century later when the German, Konrad Zuse, decided not only to design a universal computer, but also to build one (1). His models were based on binary calculating units and used electro-magnetic relays instead of mechanical switches. These were radical changes in computer design. The result was a machine that could perform any type of calculation and could be programmed to perform any mathematical task. The

computer was born. At the same time a calculator/ computer, called Mark 1, was being developed by Harvard University and IBM (2). It operated on a universal calculus and performed mathematical tasks. But it is the ENIAC, developed by the Moore School of Engineering at the University of Pennsylvania in 1946, that takes the honor of being the first true electronic computer. It contained the three essential parts of a computer: a central processing unit, a memory stage and an input/output device. This was followed by computers such as EDVAC, EDSAC, MANIAC, IAS, JOHNNIAC, and finally WHILWIND. The list can be further extended to include names of computers that have slight improvements over the original ones (2).

The invention of the transistor in 1948 at Bell Laboratories helped bring about the reduction in computer size and cost (3). Throughout the 1960's, transistors and other components were integrated into a single silicon chip. In 1975, ALTAIR was introduced, the first personal computer for use outside the industry (3). Office-size minicomputers and different types of microcomputers (desk-top, portable, pocket, etc) followed.

Computers were created for the basic need of performing mathematical operations at high speeds. Their application to a number of data computation, collection, and data storage, to include those related to corrosion, inevitably followed.

## Corrosion-Related Applications

Computers can have many applications in corrosion. They have been used for database systems, for calculations, for plotting data, for inspection and monitoring, and for modeling.

### Database Systems

Record keeping is necessary to evaluate progress, to maintain continuity, and to avoid duplication of effort. The volume of information and data which must be recorded is increasing exponentially, particularly in the engineering field. Corrosion engineers acquire large amounts of data and information in the study and evaluation of corrosion control measures. This is especially true where many parameters are measured and recorded. Records of geographical location and description, corrosion history, and corrosion control measures are maintained for future reference. Computers can simplify these tasks because of their tremendous speed in data storage, data retrieval, and data manipulation.

The use of computers as a database system in the corrosion field dates back to the late 1970's. The first technical paper on the use of computers for data collection and storage was presented at the Western Region Conference of the National Association of Corrosion Engineers (NACE), in 1964 (4). The paper, " Corrosion Control Evaluation and

Data Recording by Electronic Computer," discussed the use of electronic computers in data collection and storage. In 1958, an IBM 650 data processing computer was leased by Creole Petroleum Corporation for accounting and materials control (5). The computer was used as an electronic data processing (EDP) system to obtain efficient use of data on a network of submerged pipelines. With the EDP system, various correlations of corrosion data were made which permitted accurate evaluation of corrosion control measures and led to other methods for reducing maintenance costs.

In 1965, Rochester Gas and Electric Corporation used a standard punch card computer to store data from its pipe-to-soil potential surveys (6). Computer punch cards were used to analyze the conditions of buried pipelines and to keep a running tabulation of information on a specific pipeline. In 1967, Texas Eastern Transmission Corporation used a computer for data processing of 650 rectifiers protecting over 10,000 miles of pipe line (7). The computer system improved performance, efficiency, and saved money.

In recent years, microcomputers capable of performing the data handling tasks required for corrosion monitoring have become available. The cost of these units has dropped low enough to permit expanded use of these machines. However, data processing is not limited to computers. With today's technology, the same work done on a computer can be done on a programmable calculator. In his 1980 paper "The Programmable Electronic Calculator in Underground Corrosion



Related Activity," R.L. Seifert described how a programmable electronic calculator could be used to calculate and store network constants for underground pipelines (8).

The software needed to create database systems is available. An example is the software developed for making structure to soil surveys (9). The program is designed as an aid to the corrosion engineer or technician engaged in designing and maintaining cathodic protection systems for pipelines and related facilities. The program facilitates the entry of data by keyboard or automatic data collector and provides many options for searching and analyzing cathodic protection data.

However, software is not limited to data collection and analysis of pipelines but can be extended to other applications. Software has been developed for record handling for underground electrical transformer data (10). The method consists of computer programs for filing and recalling the data to provide an automated analysis and a case history for each transformer.

Software is also used for databases to provide corrosion information in the public domain. For example, a corrosion data program has been established by NACE and the National Bureau of Standards (NBS) to collect, evaluate, and disseminate the corrosion data which is presently scattered throughout the open literature and in the proprietary files of many companies and trade associations (11). A similar data base is the DECHEMA corrosion information system

developed in West Germany (12). This data bank provides information on the corrosion behavior of materials of construction in different areas of industry.

The list of computer applications as a database system can be extended further, but the above-cited examples are representative.

### Corrosion Rate Evaluation

One area where computers can be applied is the tedious and repetitive field of corrosion rate calculation. As a consequence, computer programs which calculate corrosion rates from many different sets of data are available. One such program calculates corrosion rates from sets of data such as (13): (1) resistance dataprobe; (2) weight loss coupon; (3) ion count; (4) linear polarization resistance method; and (5) Tafel extrapolation method. The program also outputs the corrosion rates in different units, namely: micrometer/y, mpy,  $g/m^2/day$ , mdd,  $microAmp/cm^2$ . The end result is a much faster operation for the corrosion engineer with fewer errors.

A similar short program calculates corrosion rates and electrochemical parameters from polarization data for a variety of corroding systems (14). These include activation controlled systems such as strong acids, sea water, and other environments with diffusion controlled reduction reactions and passive metal/corrosive systems. The Tafel constants in the program are used to determine inhibitor

mechanisms and to calculate the metal dissolution rate at any applied potential. It requires two minutes to execute on a low cost portable microcomputer. The program requires 3.5 K of memory which can be reduced to 2 K by omitting the remark statements. This low demand on memory requirements makes it possible for this program, or similar ones, to be used on any microcomputer after slight changes in the language syntax.

Another computer program has been developed for the analysis of polarization data obtained in the vicinity of the corrosion potential (15). It provides for the determination of anodic and cathodic Tafel slopes, polarization resistance, and corrosion current. It uses the Gauss-Newton method to generate a new set of parameter estimates and the process is repeated until the nonlinear residual error fails to change by more than a preset value.

The three programs mentioned in this section along with others make calculations and plots possible that would otherwise be ignored or approximated due to their time consuming nature.

### Corrosion Monitoring

The investigation of the extent and distribution of corrosion on metallic surfaces has long presented electrochemists and corrosion engineers with a difficult problem. Many electrochemical techniques for determining bulk corrosion rates have been devised, and some have been

used in attempts to elucidate the reaction mechanisms and the type of corrosion (pitting, crevice, uniform, etc ). An instrumental method that rapidly and economically determines the polarization resistance ( $R_p$ ) in the presence of a large solution resistance has many applications for corrosion monitoring. AC impedance techniques can accomplish this task since the high frequency limit of the impedance equals the solution resistance and the low frequency impedance approaches the DC limit and equals the sum of the solution resistance plus the polarization resistance (16). A computer program can determine the corrosion rate of a slowly corroding metal in the presence of a large solution resistance ( $R_s$ ). The program automatically determines  $R_s$  from the high frequency limit and the polarization resistance  $R_p$  using an integration approach. Computer-controlled AC impedance measurements systems are available for coated pipelines (17).

A different approach for automated corrosion monitoring of metals in solution can be achieved by using microprocessor- controlled potentiostats (18-20). Subsequent least-squares computer fitting of the polarization curve around the corrosion potential is possible (18). One system applies a potential step and measures the resulting current for a variable number of cycles; data are stored and manipulated by the computer (19).

One approach for monitoring surface corrosion uses a

microprocessor-based isopotential contouring system (21). A microprocessor-controlled scanning reference electrode is passed across a corroding specimen close to its surface, and the potential differences relative to another fixed reference electrode are recorded. The potential profile reflects the ion current density in the vicinity of the corroding surface and gives information about the location and magnitude of the surface corrosion sites.

Corrosion monitoring in power plants is achieved using a probe inserted in the process stream and a computer for the conversion of the probe signals into corrosion rates (22). One system measures the electrical resistance of a wire that becomes gradually thinner. The resistance measurement gives the value of the metal loss between two successive measurements and calculates the average corrosion rate. The system is applicable for steam condensers and high purity-water in high-temperature, high pressure conditions.

### Computer Modeling

#### Numerical Techniques

Many predictions of corrosion rates and estimates of adequate cathodic protection of structures have traditionally been based on trial and error case studies and sample exposure tests. Applying these results to real systems usually involves gross extrapolations from data

points, use of large safety factors, and on-going corrections and maintenance of the systems. Early analytical efforts to solve the Laplace equation--the governing equation for potential distributions in electrochemical cells--were successful but limited to cases of simple geometries and constant material properties (23-27). However, simple geometries seldom appear in real-world structures, and the electrochemical material properties are not constant with changing potential and current. Solutions can be applied to general geometries using numerical methods. These can accommodate varying inhomogeneous non-linear properties for electrolyte and constituent metals. Numerical methods have recently been employed in various levels of sophistication to solve the galvanic potential distribution problem. These methods include the finite element method, the finite difference method, and the boundary integral method.

The finite element method is a powerful tool for solving physical problems governed by a partial differential equation or an energy theorem, using a numerical procedure. This method has been applied to a number of galvanic corrosion (28) and cathodic protection problems (29,30). Munn described the use of the finite element method for the solution of the electric potential distribution and current fluxes near a multimetallic system submerged in an electrolyte (28). The model could handle general and arbitrary geometries and the effects of nonlinear

polarization behavior.

Lockheed adapted a general purpose finite element program called NASTRAN (NASA structural analysis) (29) to solve problems involving electrostatic applications and cathodic protection. The program uses the principle of conservation of energy to determine the strength and distribution of the energy field within the finite element model. It calculates the required current to maintain the minimum energy balance of each electrolyte element. The energy that enters the model at anode elements must leave at cathode elements. The advantages of this program over other programs is that shielding effects in nodes and other critical areas can be detected and, moreover, time-dependent polarization characteristics can be represented.

A second general purpose finite element program was presented by Casper and April in 1983 (30). The electrogalvanic fields, i.e., electric field intensity, current density, and potentials were calculated using the scalar Poisson equation. The ionic current in the electrolyte leaving the anode and arriving at the cathode were constrained to sum to zero over the metallic surface (based on spatial Kirchoff's law). The exact geometry and location of anodes, cathodes, and paint surfaces were incorporated in the mathematical model.

The finite difference method is a numerical discretization procedure for the approximate analysis of complex boundary value problems (31). The first time

iterative solutions of the difference form of the Laplace equation were applied was probably in 1964 (32). The method has been used for theoretical treatments of few electrode systems, but lately it is being used in offshore cathodic protection (31). Computerized finite difference analysis is useful in simulation and design of cathodic protection systems for offshore structures. It is also useful in cathodic protection monitoring, i.e. in the analysis of electric field strengths (IR drop), current density and potential readings.

The finite difference method also can be used to solve the Poisson equation. Munn used the finite difference method to solve the Poisson equation for the electrochemical potential distribution in an electrolyte containing an array of fixed-potential electrodes and electrodes with activation, passivation, and diffusion-controlled polarization kinetics (33). The results of the analysis were presented as a display of the potentials at selected coordinates or as a printed listing of the potentials at all nodal points in the electrolyte. The program was developed for operation on a low-cost microcomputer. As a consequence, the set of simultaneous equations was solved by the iteration method, because it is more efficient than other convergence methods (such as elimination, inversion, etc...) and requires less memory, both being important design considerations for microcomputers. Moreover, inhomogeneous electrolyte conductivities such as linear



gradients of electrolyte conductivity and layers of different conductivities can be added to the program (34).

The integral boundary equation method (also called boundary integral method) is similar to the finite element and finite difference methods in that it solves the Laplace equation to obtain the potential distributions in electrochemical cells. However, when the integral boundary equation method is employed, the Laplace equation is solved using Green's third formula which requires that any potential distribution satisfying the formula automatically satisfies the Laplace equation (35). Using proper boundary conditions, the solution of Green's third formula is the potential distribution in electrochemical cells. Fu and Chan showed that this numerical method is more efficient than either the finite element or the finite difference methods for homogeneous environments (35). The reason is that this method does not require modeling the electrolyte bodies in order to obtain the potential distribution on the surface of the structure. This saves computer time. Moreover, this method can be used for general applications by using a model generator and a post processor (36). A model generator is a versatile program capable of generating three dimensional element meshes for a variety of structures. It is used to calculate the positions and surface areas of each element and to store them in the computer's memory, along with material types for later use. A post processor is a program which can plot iso-potential

or iso-current density lines against the background of the element mesh, thus allowing the analysis of thousands of elements to be viewed graphically.

Another boundary element program has been developed to help corrosion engineers design cathodic protection systems (37). It uses nonlinear and dynamic cathodic boundary conditions to simulate real polarization conditions during the formation of calcareous deposits. Potential applications of the program include anode positioning, anode resistance, shielding effects, design safety margins, interference problems, simulation of node areas in offshore structures, and the use of coatings.

The applications of numerical techniques are not limited to simulation of marine structures. One potential application is the modeling of localized corrosion cells using the finite element method (38,39). The geometry of the cell is modeled using an element mesh, and the cell current distributions are calculated using the polarization curves of the materials in the cell as boundary conditions. Examples of instances where this modeling technique could be applied include galvanic corrosion in steam generators and concentration cells involving only grain boundaries and surrounding grains (38). The technique was actually used to calculate the preliminary galvanic corrosion rates during the chemical cleaning of a steam generator (40).

Modeling of corrosion cells can be further extended to include the capability of predicting long term corrosion

rates of nuclear waste isolation packages (41). In this case, a subroutine must be included in the program in order to calculate the chemical change with time in the crevice or the pit environment. The new concentrations are then used to calculate conductivities and to update the boundary conditions for the next time step. The procedure is repeated until a steady state condition is established, thus providing the desired answer.

#### Non-Numerical Techniques

Computer modeling is not restricted to the use of numerical techniques. Non-numerical techniques are also available. One non-numerical method was used to model water in cooling towers (42). It consisted of a computer model for each specific cooling system in the plant. Each program can be recalled instantly when conditions change or when the plant personnel decide to evaluate the effects of potential changes in operating parameters. Once the new operating data are entered, a revised operational report which contains a series of performance curves for scale, corrosion, and deposit control is obtained within minutes. Similar programs can be used to calculate supersaturation ratios to develop scaling index guidelines (43).

Computer modeling is also used to simulate intergranular corrosion (44,45). A computer program based on an improved chromium depletion theory is used to describe the time temperature-sensitization (TTS) diagrams of a

nickel-based alloy. The TTS diagrams are then used to examine the effect of thermal aging on the susceptibility to intergranular corrosion of low carbon Alloy 800.

Potential-pH (Pourbaix) diagrams can be calculated using computers (46-50). These diagrams are aids for corrosion prediction because they act as "road maps" providing direction for an experimental program. As such, they provide insights as to whether corrosion would occur during the course of the experiment.

Computer modeling can be used for the evaluation of anode resistance formulas (51) and for the design of state of-the-art cathodic protection systems (52). Strommen used a computer program to model a number of typical sacrificial anodes for different length/diameter ratios and for different operating conditions. Compared to the results of the most commonly employed formulas for the anode resistance, his work demonstrates that differences in environmental and operating conditions strongly affect the apparent anode resistance. A similar microcomputer program was developed by Cochran to optimize various anode/core lengths and end face geometries (52). It includes state of-the-art sacrificial-anode cathodic protection designs for offshore platforms based on classical equations. The design accounts for practical polarization current density, maintenance current density, current distribution, seawater resistivities, and sacrificial anode galvanic properties. Cathodic protection designs include sacrificial cathodic

protection designs for offshore pipelines (53) and jack-up rigs (54).

Cathodic protection modeling of coated tethers in Tension Leg Platforms (TLP) has been developed as a computer program (55). The author developed a microcomputer program to evaluate the maximum depth at which coated tethers in a TLP can be cathodically protected. The program provides several answers for tethers containing different percentages of holidays (i.e. coating defect areas). The answer is in the form of current density and potential distribution along the tether.

Computer modeling is becoming a powerful tool in corrosion. Advances in computer technology have made possible the mathematical formulation of complex physical problems. As a result, the design and analysis of cathodic protection systems or other systems is no longer a major obstacle.

#### Suggested Additional Applications

Previous sections indicate that corrosion-related uses of computers have included database systems, corrosion rate evaluation, inspection and monitoring, and modeling. Although more applications are being added to this list, the available corrosion-related applications are still inadequate. The solution of real world technical problems requires more than the manipulation of data at high speeds. Most corrosion problems are solved by corrosion experts who

have a large body of informal, judgemental, and empirical knowledge. Their decisions might be based partly on "experience", partly on laboratory generated data, and partly on personal judgement as to what may be the best solution. In any case, it is this expertise that is needed to solve any problem, including corrosion problems. Therefore, an attempt must be made to write computer programs that are able to generate answers or solutions to complex corrosion problems. In other words, it is necessary to exploit the computational capabilities of computers by writing programs that contain interpretive, diagnostic, and predictive algorithms based on the expertise of corrosion consultants. The end result is a computer that can think for itself (i.e. search through the database files, compare options, and make decisions). At this point, solutions to complex corrosion problems can be attempted by using the thinking power of the computer, so to speak.

This idea constitutes the basis of the artificial intelligence discipline which has received considerable attention in the past few years (2). The ability of a computer to use the relatively narrow knowledge of specialists in order to address a variety of technical problems is called an "expert system". Such systems already exist for many disciplines. As an example, PROSPECTOR is an expert system that provides consultation on problems arising in the field of mineral exploration (56). Another example is the expert system R1 designed to configure Digital

Equipment Corporation's VAX computer systems (i.e. spatial arrangement, cabling of various modules, etc). Once developed, such systems are proven to be very useful. In 1982, PROSPECTOR helped identify a large unknown deposit of Molybdenum in the vicinity of Mount Tolman in Washington, an estimated fortune of \$100 million.

If expert systems exist in many disciplines, then why not in the corrosion field? Expert systems should be developed to handle corrosion problems. Some of these systems already exist (57) and others are being introduced (58-62). The new systems should take into account the on line availability of information from chemists and others. It is a great help to interface the expert systems with such data banks. The systems should be flexible (i.e. rapidly and easily modifiable) and efficient (i.e. capable of adjusting to new conditions). The systems should also be written to include self-teaching routines --that is, once a problem is solved, the computer uses the learned rules and accumulated data to guide it in its next search.

This approach poses a big challenge and requires much work. Technical knowledge is difficult to encode because it is typically expressed in symbolic rather than numerical or analytical form (63). As such, technical means must be developed in order to represent symbolic knowledge in forms that can be conveniently manipulated by computers. Moreover, some people may object to the development of such expert systems. The very fact that these systems cost

hundreds of thousands of dollars to be developed is also a limiting factor (64). On the other hand, technology is constantly changing and what is impossible to do now can be feasible in the near future. The situation resembles the early introductions of the artificially intelligent chess board. H. Dreyfus, one of the most influential artificial intelligence researchers claimed "flat out" that artificial intelligence would never work and pointed out the best chess program of the day (1966) could be beaten by a ten-year old boy (2). Dreyfus subsequently lost to the same program.

If today's Seymour Cray X-MP is capable of 400 million operations per second, then future computers will be capable of 3 billion operations per second (65). To this end, the future is promising and as such, the development and the use of expert systems on a larger scale is only a question of time.



## CHAPTER III

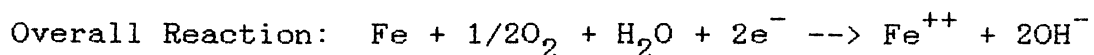
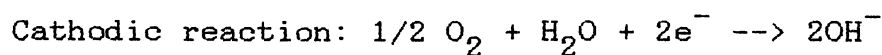
### CATHODIC PROTECTION PRINCIPLES

#### Introduction

Cathodic protection is an electrochemical technique used to protect metals (often iron or steel) from corroding in their natural environment. The technique consists of coupling the corroding metal structure to a more active metal. The active metal (anode), the metal structure (cathode), and the natural environment (electrolyte) form a galvanic couple. During the process, the active metal supplies electrons to the metal structure therefore suppressing its metal dissolution process. The anode corrodes preferentially to protect the more noble cathodic metal structure, hence the name "cathodic protection".

#### Basic Theory

The chemical reactions involved in the natural corrosion of iron in aerated water are the following (66):

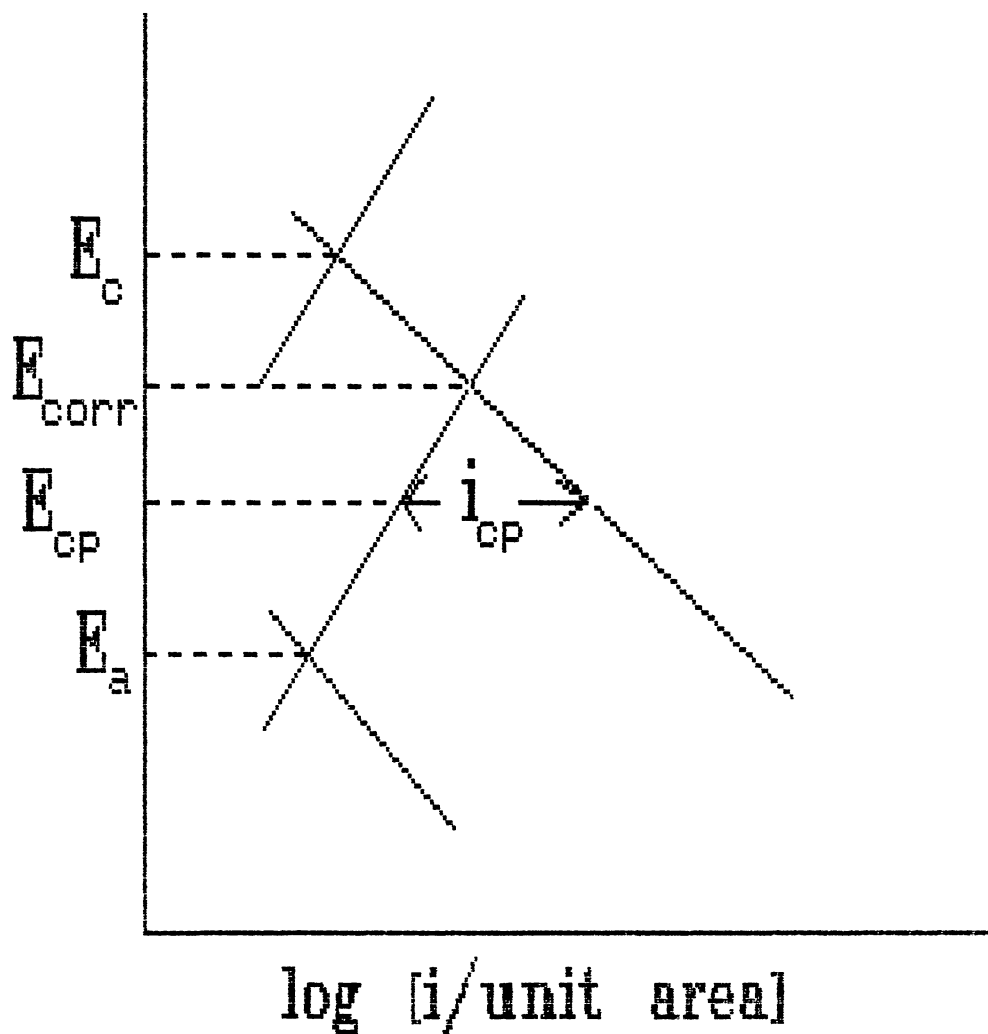


Iron produces electrons by anodic dissolution. These

electrons are consumed by simultaneous cathodic reactions. The overall reaction shows that the net result is the dissolution of iron by the net production of iron ions. At the corrosion potential  $E_{\text{corr}}$ , the potential at which natural corrosion occurs, the flow of electrons from anodic areas is exactly equal to the consumption of electrons at cathodic areas. To achieve cathodic protection, electrons must be provided from an outside source. The new source must meet the demands of the cathodic reaction in order to reduce the dissolution of the steel.

Figure 1 shows that when electrons are supplied externally, the corrosion potential shifts to lower levels. This means that if the corrosion potential is at a sufficiently negative value, iron becomes almost immune to corrosion in water and cathodic protection will be achieved. In seawater, a potential of  $-0.85$  volts when measured against the  $\text{Cu}/\text{CuSO}_4$  reference electrode (or  $-0.80$  volts versus the  $\text{Ag}/\text{AgCl}$  reference electrode) is considered to be a safe potential (67). Corrosion of steel in seawater will not occur at this potential, and this potential can be used as a protection criterion in cathodic protection designs.

Cathodic protection has been applied to offshore structures or marine installations. It can be applied by impressing current or by using sacrificial anodes (galvanic coupling). When the galvanic coupling method is used, the external electron source is provided by sacrificial anodes which are electrically connected to the corroding metal



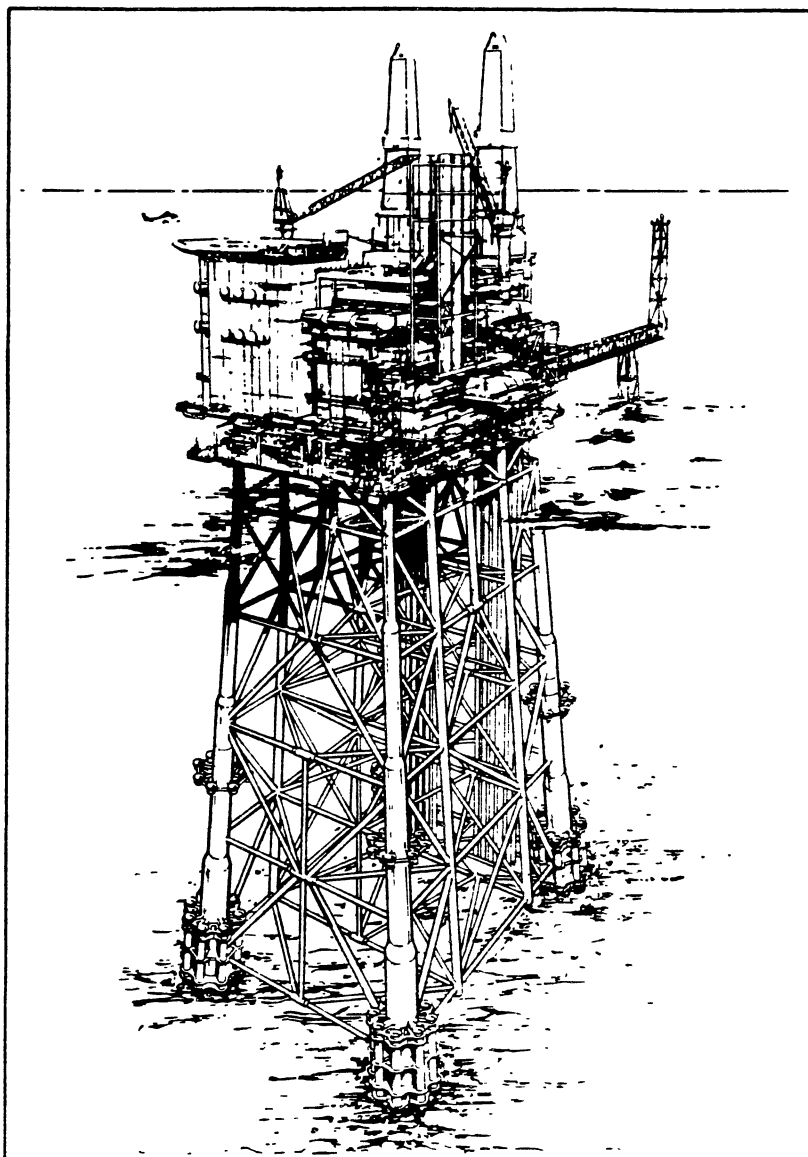
Source: M. G. Fontana and N. D. Greene, "Corrosion Engineering,"  
2nd Ed., New York: McGraw Hill Book Co., 1978.

Figure 1. Polarization Caused by an External Electron Supply

$E_c$  = Equilibrium Potential for Cathodic Reaction  
 $E_a$  = Equilibrium Potential for Anodic Reaction  
 $E_{cp}$  = Potential With Cathodic Protection  
 $i_{cp}$  = Cathodic Protection Current Density  
 $E_{corr}$  = Corrosion Potential

structures. These anodes are placed in the same environment these structures are placed in, seawater in this case. The seawater acts as the electrolyte in the electrical circuit. A picture of an offshore structure in the North Sea is shown in Figure 2. Figure 3 shows a schematic diagram of an offshore structure showing the locations of the structural nodes. Sacrificial anodes will be distributed evenly throughout the underwater structure to prevent corrosion.

Sacrificial anodes tend to corrode preferentially, because they are more chemically active than the steel cathodes. Magnesium, zinc, and aluminum, which are all more active than iron, as shown in Table I, are used as sacrificial anodes (66). Low consumption favors aluminum anodes for offshore platforms, where it is often desirable to limit the weight of the cathodic protection system. Zinc performs well in cold tap water and seawater where it corrodes freely without formation of a passivating film (68). Therefore, zinc anodes are chosen for offshore pipelines where the resulting extra weight over aluminum is an added advantage (68). Zinc is occasionally used for protection of onshore pipelines, but aluminum anodes are restricted primarily to offshore applications since most commercial anodes passivate in soil or mud. Magnesium is the preferred material in high resistivity applications (such as soil) due to its operating potential. The potentials provided by each of the materials are more than adequate to satisfy the criterion of establishing potentials



Source: H. J. Wind and K. W. Wiseman, "Brae 'B' Topside Design for Offshore Cycling in the North Sea," Offshore Technology Conference (1985).

Figure 2. A Picture of an Offshore Structure in the North Sea.

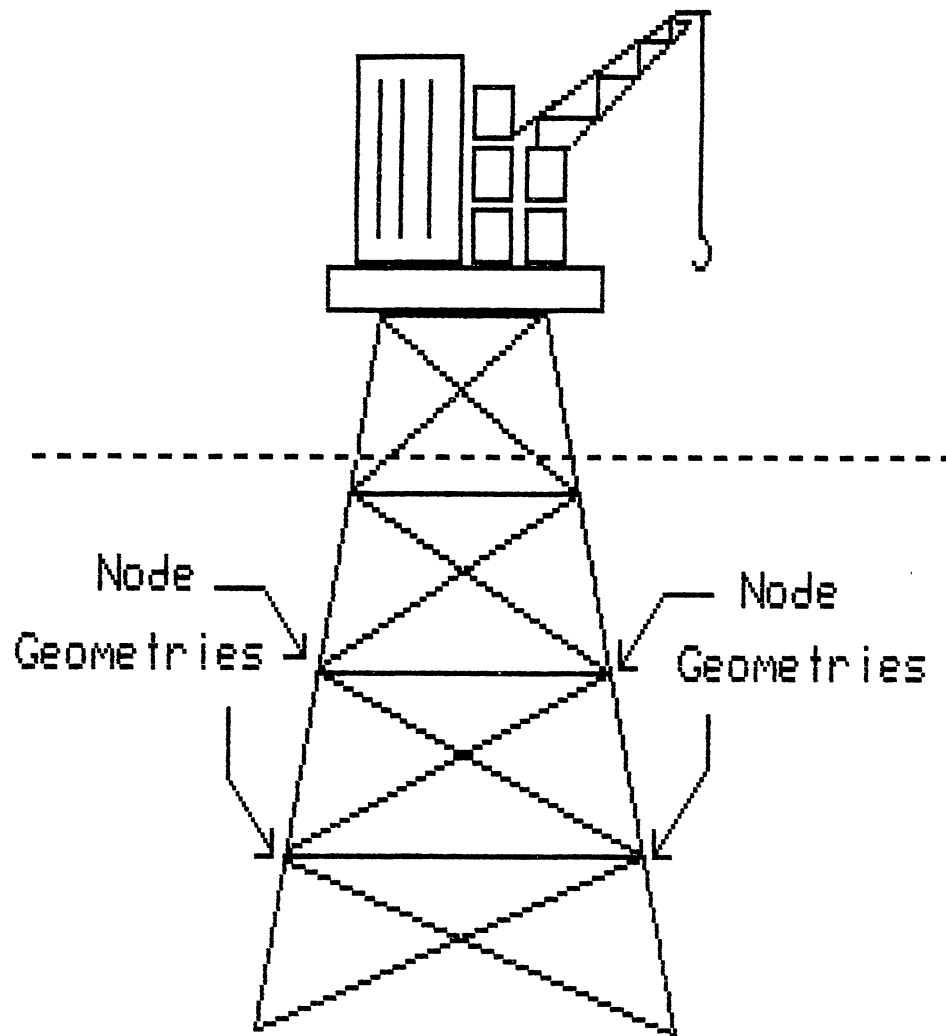


Figure 3. A Schematic Diagram of an Offshore Structure Showing the Locations of Node Geometries.

TABLE I

## GALVANIC SERIES OF SOME COMMERCIAL METALS AND ALLOYS IN SEAWATER

↑ Noble or cathodic	Platinum
	Gold
	Graphite
	Titanium
	Silver
	[Chlorimet 3 (62 Ni, 18 Cr, 18 Mo)
	[Hastelloy C (62 Ni, 17 Cr, 15 Mo)
	[18-8 Mo stainless steel (passive)
	[18-8 stainless steel (passive)
	[Chromium stainless steel 11-30% Cr (passive)
[Inconel (passive) (80 Ni, 13 Cr, 7 Fe)	
[Nickel (passive)	
Silver solder	
[Monel (70 Ni, 30 Cu)	
Cupronickels (60-90 Cu, 40-10 Ni)	
Bronzes (Cu-Sn)	
Copper	
[Brasses (Cu-Zn)	
[Chlorimet 2 (66 Ni, 32 Mo, 1 Fe)	
[Hastelloy B (60 Ni, 30 Mo, 6 Fe, 1 Mn)	
[Inconel (active)	
[Nickel (active)	
Tin	
Lead	
Lead-tin solders	
[18-8 Mo stainless steel (active)	
[18-8 stainless steel (active)	
Ni-Resist (high Ni cast iron)	
Chromium stainless steel, 13% Cr (active)	
[Cast iron	
[Steel or iron	
2024 aluminum (4.5 Cu, 1.5 Mg, 0.6 Mn)	
Active or anodic	Cadmium
	Commercially pure aluminum (1100)
	Zinc
↓	Magnesium and magnesium alloys

Source: M. G. Fontana and N. D. Greene, "Corrosion Engineering," 2nd Ed., New York: McGraw Hill Co. (1978).

of at least -0.85 volts between the corroding structure and a Cu/CuSO<sub>4</sub> reference electrode (or -0.80 volts vs Ag/AgCl) (68).

### Design Considerations

As a general rule, a sacrificial anode system is designed to deliver relatively small currents from a large number of anodes, as opposed to the impressed current system which is designed to deliver relatively large currents from a limited number of anodes. Since relatively small amounts of current must be evenly distributed throughout the entire installation of an offshore structure, the majority of offshore structures use sacrificial anodes to achieve cathodic protection. Other reasons include the lack of electrical power sources or hydrogen embrittlement problems associated with the use of impressed current systems which eliminates the impressed current option.

When using a sacrificial anode system, the maintenance currents vary from one location to another. Typical maintenance current values for different offshore locations can be found in Table II reproduced from NACE Standard RP-01-76 (67). Typical maintenance currents in the gulf of Mexico (5 mAmps/ft<sup>2</sup>) and in the Pacific Ocean off Southern California (8 mAmps/ft<sup>2</sup>), decreasing to 2 mAmps/ft<sup>2</sup> in the mud zone, are adequately satisfied with aluminum anodes containing zinc and mercury as alloying components (67). As a general rule the current required for cathodic



TABLE II  
DESIGN CRITERIA FOR CATHODIC PROTECTION SYSTEMS

Production Area	Water Resistivity <sup>(2)</sup> (ohm-cm)	Environmental Factors <sup>(1)</sup>		Lateral Water Flow	Typical Design Current Density <sup>(3)</sup>	
		Water Temp. (C)	Turbulence Factor (Wave Action)		mA/ft <sup>2</sup>	mA/m <sup>2</sup>
Gulf of Mexico	20	22	Moderate	Moderate	5-6	54-65
U.S. West Coast	24	15	Moderate	Moderate	7-10	76-106
Cook Inlet	50	2	Low	High	35-40	380-430
North Sea <sup>4</sup>	26-33	0-12	High	Moderate	8-20	86-216
Persian Gulf	15	30	Moderate	Low	5-8	54-86
Indonesia	19	24	Moderate	Moderate	5-6	54-65

Source: NACE Standard RP-01-76, "Corrosion Control of Steel, Fixed Offshore Platforms Associated With Petroleum Production," National Association of Corrosion Engineers (1983).

protection is directly proportional to water velocity and dissolved oxygen content but inversely proportional to the diameter of the cylindrical structural members (66). A small member will require a higher current density than a larger one at comparable oxygen concentrations and water velocities. High water velocities due to strong tidal action increase current requirements for cathodic protection of offshore platforms ( 42 mAmp/ft<sup>2</sup> in Cook Inlet, Alaska) which makes steel structures in such hostile environments cases for impressed current systems. Cathodic protection with impressed current is further favored in this location by the relatively high water resistivity (49 ohm-cm in Cook Inlet versus 22-25 ohm-cm in the Gulf of Mexico), which reduces current output per sacrificial anode.

One feature which makes cathodic protection of marine structures different from onshore practices is the buildup of calcareous deposits on seawater-exposed steel surfaces. The nature of the calcareous deposits is dependent on the prepolarization current density (68). The higher the initial current density supplied, the denser a coating will form in a shorter period of time. Once the coating is fully developed, the current requirement for complete cathodic protection will drop substantially, while the anodes will reach their ultimate throwing power (68). It should be noted, however, that if the prepolarization current is too low, protection potentials will be obtained only after a long time period (68). Calcareous deposits form on offshore

pipelines, but their effect on cathodic protection is much less dramatic since most pipelines are artificially coated (68).

### Design Procedure

The cathodic protection design procedure for an offshore platform follows the sequence of steps below:

- A- Selection of proper maintenance current.  $5 \text{ mAmp/ft}^2$  is commonly used in the Gulf of Mexico and  $8 \text{ mAmp/ft}^2$  is recommended for the Pacific (twice the amount in the splash zone, one quarter the amount in the mud zone).
- B- Calculation of respective surface areas and the addition of a safety factor (usually around 25%).
- C- Calculation of total amount of anode material required to guarantee a desired life assuming a certain anode capacity.
- D- Selection of a certain anode geometry and check using Dwight's equation for a single such anode whether the initial current density exceeds  $15 \text{ mAmps/ft}^2$  assuming a native potential of 0.45 volts between bare polarized steel and aluminum anodes.
- E- Judicious distribution of anodes on the steel assuming a throwing power of 25 feet in line of sight and placing anodes within 10 ft of all nodes.

The criterion for complete cathodic protection is a steel structure potential more negative than  $-0.80$  volts (i. e.  $-0.82$ ,  $-0.85$ , etc) at any point versus the Ag/AgCl reference electrode. A sample design of a sacrificial anode system for an offshore installation in the Gulf of Mexico is described in Appendix A. Step E of the design procedure is not included in Appendix A because of the extensive work involved (i. e., scale model, technical drawings, etc...). However, the general guidelines for the distribution of anodes on the steel are discussed next.

#### Anode Distribution

The final consideration concerns the positioning of anodes about the structure. They are placed within a specific distance from nodes (depending on the company's design), but elsewhere are assumed to protect steel in line of sight within a circle of 25 foot radius (68). Thus, areas shadowed by other structural elements may not be fully protected by any particular anode. Cathodic protection of well conductors, which are routinely inserted only after launching of the platform is, therefore, a special problem. In general, anodes are positioned throughout the platform in relation to the footage of steel to be protected. Thus, more anodes are clustered in the well conductor area. The increasing surface area with depth would be expected to result in a greater percentage of anodes at lower elevations. However, anode distribution is altered to

account for higher oxygen concentration and fluid velocity near the surface, partially offsetting the surface area trends. In order to minimize the lateral loads on the highly stressed vertical diagonals, often no anodes are placed on these members. Since the efficiency of most aluminum anodes is adversely affected when covered with mud, attaching anodes to structural members at the mudline should be avoided when unstable bottom conditions are anticipated (67).

#### Cathodic Protection Monitoring

Monitoring of the progressing steel polarization under the influence of cathodic protection is an excellent way to determine if full protection is achieved and to gather data for design of future cathodic protection systems. It generates base line information and allows adjustments of existing cathodic protection systems. The measurements used can be either structure potential or anode current output measurements (68). The following methods are used for placing measuring devices on the structure or in the water (68).

- Lowering the reference electrode from the surface
- Guy wire technique
- Divers
- Submersible vehicles
- Fixed monitoring systems

The locations for the potential measurements are:

- Shielded areas -- nodes, conductor guides.
- Selected anodes
- Number of general locations for adequate potential profile

The anode current output measurements use the same techniques as mentioned above.

### Conclusion

Cathodic protection is a well established means for marine corrosion control. It is an electrochemical technique based on the potential difference between two metals that are electrically connected and submerged in the same electrolyte. Conventional cathodic protection designs have proven to be valuable and effective in protecting marine structures.

## CHAPTER IV

### MODEL DESCRIPTION

#### Introduction

Numerical techniques have been used extensively to model cathodic protection systems. Most of the programs written in this area were designed for mainframe computers, where speed and memory requirements are not limiting factors. Most of these programs are not interactive because numerical techniques require the program to be run in a batch mode. Most often, these programs generate frustration to both the corrosion engineer and the computer operator, because neither one understands the other's job. This communication problem is made worse by wasting the research time on doing paper work, on transferring the computer results from one department to another, and spending huge amounts of money on computer runtime.

To avoid the above problems, a design tool was developed that is interactive and can be run on a microcomputer. The objective was a microcomputer package that was user friendly and cost effective. The package must be simple enough to be used by a corrosion engineer and yet maintain a level of sophistication to handle numerical modeling techniques. The following paragraphs explain how

such a model was developed and the mathematical formulation behind the model.

### Mathematical Formulation

#### Numerical Technique

The numerical model developed is based on the finite difference method. Many factors influenced the decision to choose the finite difference method over the finite element and the boundary element methods. It was found that the finite difference method is easier to program and requires less memory than the two other methods. Moreover, the system to be modeled is homogeneous and relatively simple in geometry and therefore does not require the use of the finite element or the boundary element method to provide a more refined element mesh. It was found that the finite element method is more time consuming than the finite difference method which is an important design consideration for microcomputer programs. The boundary element method has the same shortcomings as the finite element method. The only advantage of using the boundary element method is the fact that it does not require modeling the body of the liquid volume and is restricted to the cathode surface (69). Although the boundary element method provides faster solutions than the finite element method, it is still slower than the finite difference method. The boundary element method is as complex as the finite element method in



terms of programming and is more complex to encode than the finite difference method. For example, the finite difference method consists of taking the potential average of the surrounding nodes. However, the boundary element method requires building an element matrix for each three dimensional element in the mesh. Afterwards, these element matrices will be assembled into a global matrix before solving the potential values in the global matrix (70). This is a tedious procedure, time consuming, complex, and far from being as simple as the finite difference method.

As a conclusion, both the finite element and the boundary element methods are unsuitable for use in the actual model. Problems associated with memory requirements and execution time were found to be limiting factors for the two above methods. The finite difference method was used because of its reduced memory requirements, faster computer runtime, and its ease in programming. If the purpose of the model is to provide a rough prediction of the potential distribution in the three dimensional volume surrounding a structural node in an offshore platform, then the finite difference method is suitable and well equipped to provide an answer to the problem.

#### Mathematical Equation

The mathematical equation used in the model to represent the physical system is the Laplace equation. The Laplace equation is the governing equation for potential

distributions in electrochemical cells (28,29). When solved, it provides the values of the potential throughout the volume of the system being modeled. The Laplace equation has been used successfully to solve for the potential distribution in two dimensional systems (28,34, 33,35,39). No attempt has been made to model three dimensional systems on microcomputers, which makes this model unique in its category. The model can take a three dimensional cube in space containing a certain node geometry and calculate the potential distribution throughout the volume, including the cathode surface and the electrolyte. To explain how the model works, it is necessary to discuss how the finite difference method is used to solve the Laplace equation. The Laplace equation is represented by

$$\nabla^2 P = 0 \quad (3.1)$$

where,

P is the potential, in volts (33).

In rectangular coordinates, the Laplacian operator,  $\nabla^2$ , is written as (71)

$$\frac{d^2 P}{dx^2} + \frac{d^2 P}{dy^2} + \frac{d^2 P}{dz^2} = 0 \quad (3.2)$$

Using a Taylor series expansion about a point, the second order differential equation becomes (72)

$$P(x-Dx, y, z) = P(x, y, z) - \frac{Dx(dP)}{dx} + \frac{(Dx)^2(d^2P)}{2! dx^2} - \frac{(Dx)^3(d^3P)}{3! dx^3} + \dots \quad (3.3)$$

$$P(x+Dx, y, z) = P(x, y, z) + \frac{Dx(dP)}{dx} + \frac{(DX)^2(d^2P)}{2! dx^2} + \frac{(Dx)^3(d^3P)}{3! dx^3} + \dots \quad (3.4)$$

If all terms involving  $Dx$  to the third power are neglected, then Equations (3.2) and (3.3) may be added together to give:

$$P(x+Dx, y, z) + P(x-Dx, y, z) = 2P(x, y, z) + \frac{(Dx)^2 (d^2P)}{dx^2} \quad (3.5)$$

Rearranging the equation,

$$\frac{d^2P}{dx^2} = \frac{P(x-Dx, y, z) + P(x+Dx, y, z) - 2P(x, y, z)}{(Dx)^2} \quad (3.6)$$

$$\frac{d^2P}{dy^2} = \frac{P(x, y-Dy, z) + P(x, y+Dy, z) - 2P(x, y, z)}{(Dy)^2} \quad (3.7)$$

$$\frac{d^2P}{dz^2} = \frac{P(x, y, z-Dz) + P(x, y, z+Dz) - 2P(x, y, z)}{(Dz)^2} \quad (3.8)$$

If  $Dx=Dy=Dz$  then

$$\left\{ \begin{array}{l} P(x-Dx, y, z) + P(x+Dx, y, z) + \\ P(x, y-Dy, z) + P(x, y+Dy, z) + \\ P(x, y, z-Dz) + P(x, y, z+Dz) \end{array} \right\} = 6P(x, y, z) \quad (3.9)$$

$$P(x, y, z) = 1/6 \left\{ \begin{array}{l} P(x-Dx, y, z) + P(x+Dx, y, z) + \\ P(x, y-Dy, z) + P(x, y+Dy, z) + \\ P(x, y, z-Dz) + P(x, y, z+Dz) \end{array} \right\} \quad (3.10)$$

Solving for the potential at a point with the coordinates  $(x, y, z)$  is achieved by using Equation (3.10). The potential at point  $(x, y, z)$  is actually the average of the potentials at six points surrounding the point of interest as shown in Figure 4. Equation (3.10) applies for all the nodes inside the electrolyte body. The potential at a node located at the surface of the cathode cannot be calculated using equation (3.10). Rather a new equation is

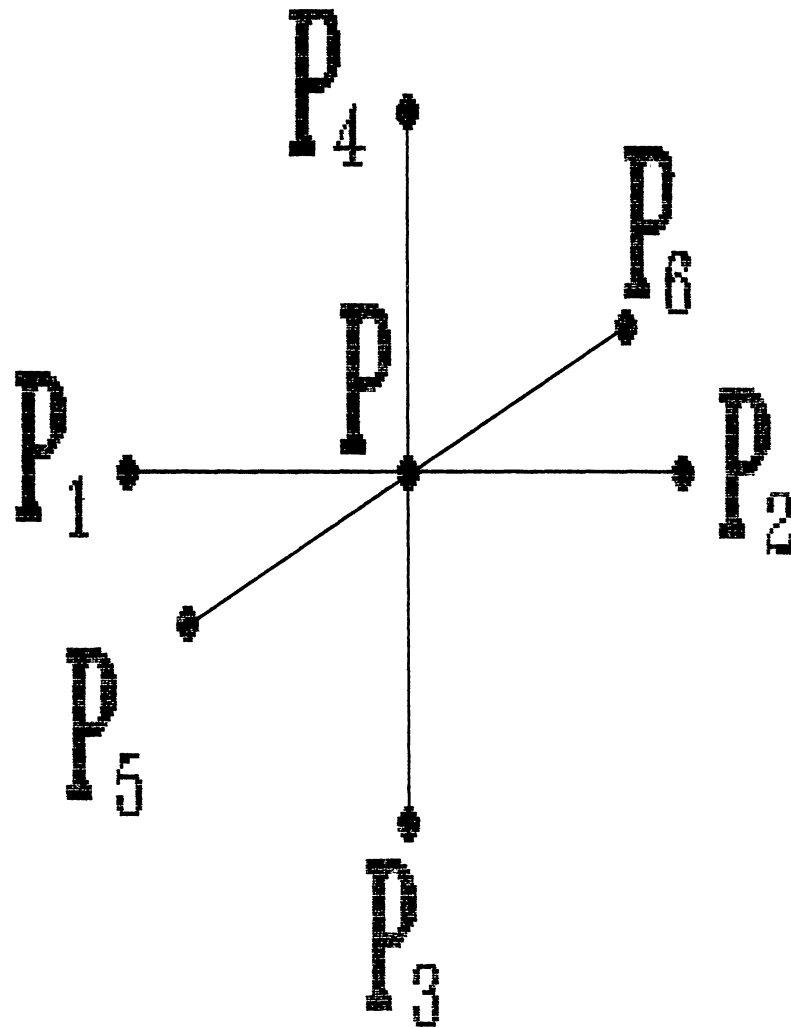


Figure 4. The Potential at Node  $P$  is Equal to the Average of the Six Surrounding Potential Values.

used called the Poisson equation (34).

$$\nabla(s\nabla P) + i_p = 0 \quad (3.11)$$

where  $s$  is the water resistivity, in ohm-cm.

Equation 3.11 is used because the polarization currents ( $i_p$ ) may enter or exit the cathode surface. The Poisson equation is similar to the Laplace equation except that there is a new term ( $i_p$ ) that accounts for the current entering or leaving the surface of the cathode. Assuming that  $s$  is constant, Equation (3.11) becomes

$$\nabla^2 P + i_p/s = 0 \quad (3.12)$$

which in rectangular coordinates becomes,

$$\frac{d^2 P}{dx^2} + \frac{d^2 P}{dy^2} + \frac{d^2 P}{dz^2} + \frac{i_p}{s} = 0 \quad (3.13)$$

Expanding the second order partial derivatives as before,

$$\left\{ \begin{array}{l} P(x-Dx, y, z) + P(x+Dx, y, z) + \\ P(x, y-Dy, z) + P(x, y+Dy, z) + \\ P(x, y, z-Dz) + P(x, y, z+Dz) \end{array} \right\} = 6P(x, y, z) - i_p/s \quad (3.14)$$

$$P(x, y, z) = 1/6 \left\{ \begin{array}{l} P(x-Dx, y, z) + P(x+Dx, y, z) + \\ P(x, y-Dy, z) + P(x, y+Dy, z) + \\ P(x, y, z-Dz) + P(x, y, z+Dz) \end{array} \right\} + i_p/s \quad (3.15)$$

Equation (3.15) solves for the potential at a point  $(x, y, z)$  on the cathode surface. The polarization current  $i_p$  is evaluated using a polarization curve. A polarization curve is an experimental (or theoretical) curve relating the potential of a cathode surface to the current density. Knowing the value of the potential at a certain point, the corresponding value of the current density at that same

point is calculated by simply looking up the value on the curve. These polarization curves are very useful because they allow the model to calculate the current density at the cathode surface. Once the polarization current is calculated, it is eventually used to calculate the potential at the cathode surface by using Equation (3.15).

### Boundary Conditions

Every numerical model requires specifying a set of boundary conditions. The boundary conditions are usually the values of the function (in this case, the function is the potential) at the boundaries of the physical system. These boundary conditions are necessary to allow the model to converge to a solution. Changing the boundary conditions will cause the model to generate a different solution.

The boundary conditions in the model are mirror image boundary conditions. This means that the potential of a point  $i$  at the boundary of the system must include in the average of the potentials at point  $(i)$  one or more fictitious points lying outside the physical system. These fictitious points are symmetrical to the actual points inside the physical system and are assumed to be equal to them in value. Since the model is a cubic volume made of cubic elements, there are three different cases of mirror image boundary conditions. These three different cases of boundary conditions are discussed next.

Boundary Condition (a): The point of interest  $(i)$  is

on the outer surface of the physical system or the three dimensional cube (i.e., the point is on the face of the cube as shown in Figure 5). In this case, of the six points needed in Equation (3.10) or (3.15) to solve for the potential at node (i), five are inside the physical system and the sixth point is a fictitious point. This fictitious point lies outside the physical system and is symmetrical and equal to one of the other five points. Therefore, of the six potential values needed to calculate the potential of the point at the face of the cube, two potential values are identical.

Boundary Condition (b): The point or node (i) is located on the side or the edge of the three dimensional cubic mesh as shown in Figure 6. Two fictitious points or nodes are needed to evaluate the potential at this node. Of the six surrounding potential values needed to calculate the potential at node (i), there are two sets of equipotential values.

Boundary Condition (c): The node or point (i) is located at the vertex of the three dimensional cubic mesh as shown in Figure 7. Three fictitious points are needed to evaluate the potential at the node. Of the six surrounding potential values needed to calculate the potential at node (i), there are three sets of equipotential values.

When used properly, these three different boundary conditions help evaluate the potential values at the boundaries of the physical system. A total of twenty seven

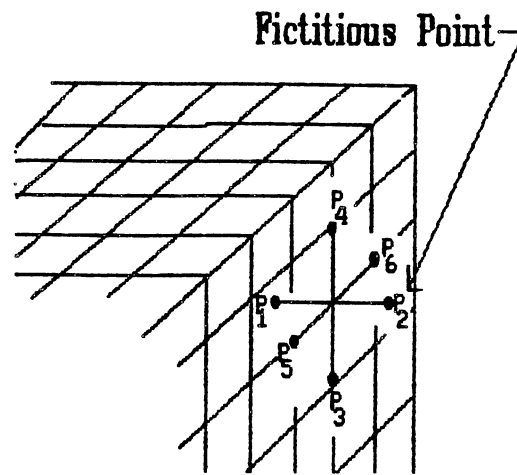


Figure 5. The Point of Interest is Located on the Face of the Three-Dimensional Cube.

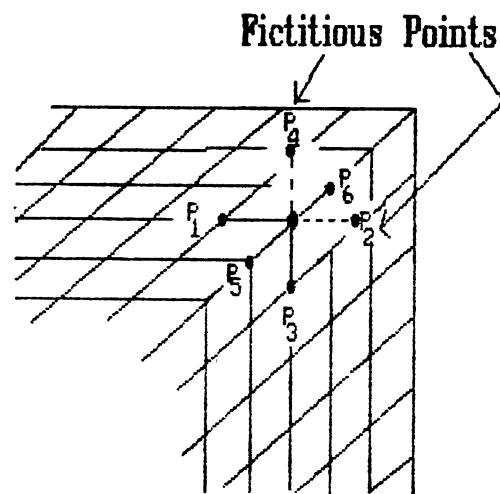


Figure 6. The Point Of Interest is Located on the Edge of the Three-Dimensional Cube.



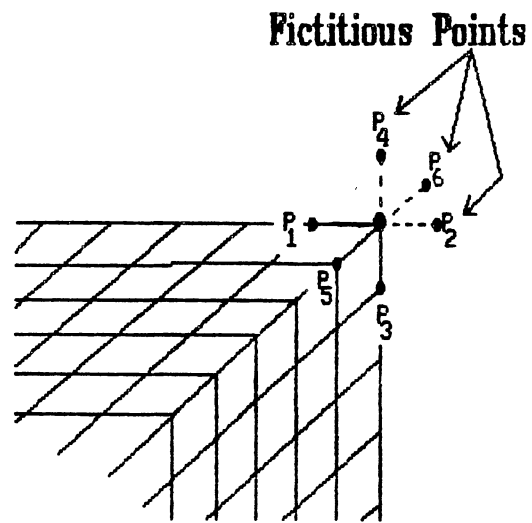


Figure 7. The Point of Interest is Located at the Vertex of the Three-Dimensional Cube.

equations are needed to include the three boundary conditions in the model. To be more specific, there is one equation that applies to the points or nodes inside the cubic mesh (i.e., Equation (3.10)). The remaining twenty six equations are used as follows:

- Six equations for the six faces of the 3-D cube.
- Twelve equations for the twelve edges of the 3-D cube.
- Eight equations for the eight vertices of the 3-D cube.

The different parts of the three dimensional cube are shown in Figure 8.

#### Water Resistivity

The water resistivity is used in the model in conjunction with the polarization current, i.e., Equation (3.14), to evaluate the potential at the nodes located at the cathode surface. In the model, the electrolyte is discretized into a 3 dimensional or axisymmetric array of nodes. The nodes are assumed to be connected to each other by resistors which represent the electrolyte. The resistance  $R$  between interior nodes is related to the water resistivity,  $s$ , by (33)

$$R = \frac{d s}{dxd} \quad \begin{array}{l} \text{(for a 3-D array of nodes} \\ \text{of } dx dx dx \text{ spacing)} \end{array} \quad (3.16)$$

Equation (3.16) is similar to the equation relating the resistance of a wire to its length and its cross section. The metal resistance in a wire increases with distance but decreases when the cross sectional area

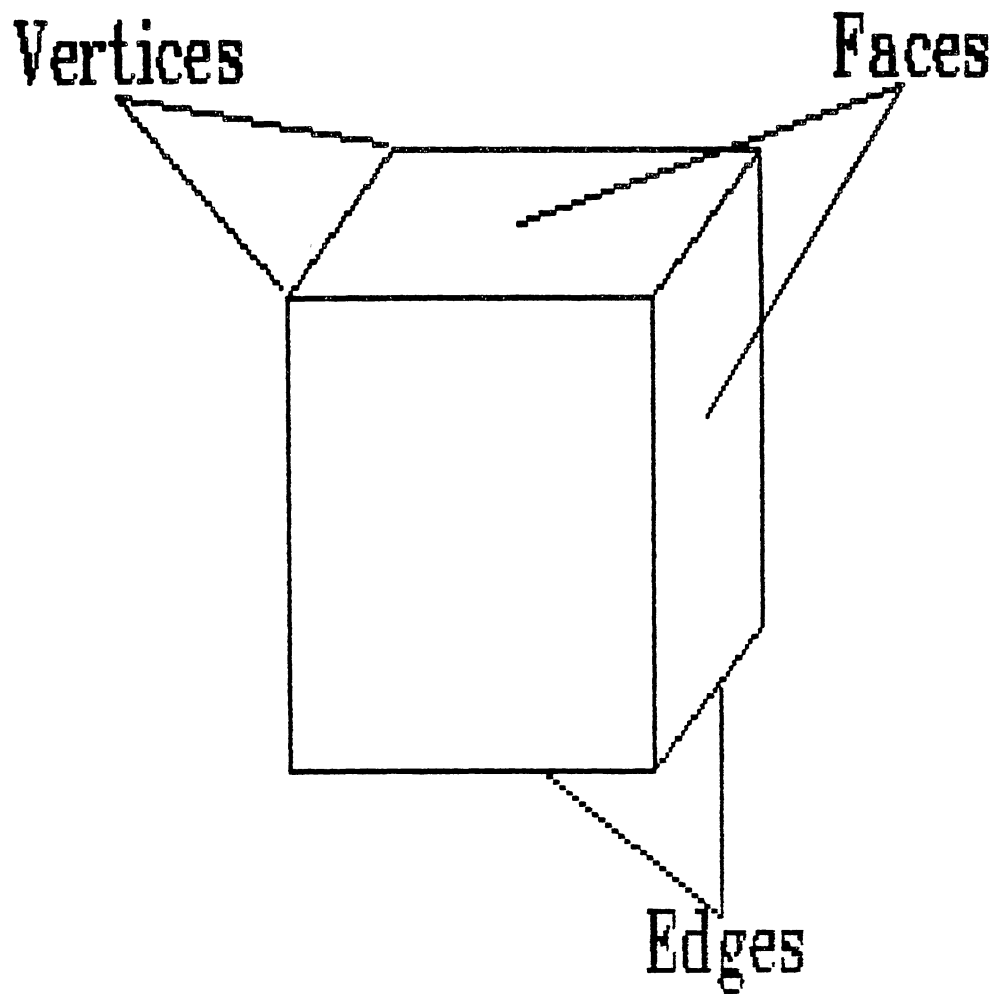


Figure 8. The Three Different Parts of a Three-Dimensional Cube Element.

increases. The same holds true for water except that the system is not a long thin wire but rather an element thin cube. Current will flow through the cross section of one element cube to the adjacent element cube. Simplifying Equation (3.16), the resistance becomes

$$R = s/d \quad (3.17)$$

When the cube size is increased, the total resistance decreases and vice versa. Equation (3.17) holds true for all the interior nodes. At the boundary, only half the volume of the cubic element is available and this fact should be taken into consideration. Therefore, at the boundaries, the distance in Equation (3.16) remains the same but the cross sectional area is reduced to half (33).

$$R = \frac{d s}{dx d/2} = \frac{2ds}{dx d} = \frac{2s}{d} \quad (3.18)$$

Equation (3.18) should be used with nodes located at the boundaries. It applies equally well to nodes that are on the external faces, the edges, or vertices of the cube. As a result, only two equations are needed to calculate the water resistance in the model. Equation (3.17) is used to evaluate the water resistance at the interior nodes. Equation (3.18) is used to evaluate the water resistance at the exterior nodes or the boundary nodes. Both equations are used in conjunction with Equation (3.15) to evaluate the potential of nodes at the cathode surface.

## Dynamic Mesh

The nodes or nodal points contained in the cubic model are stored in a three dimensional array. The size of the three dimensional array is 10x10x10. Each element of the array represents a node in the cubic model. Therefore, there is a total of 1000 nodal points distributed in the cubic model. Ten nodes exist in each direction, i.e., ten nodes in the x, y, and z direction. The number of nodes is limited to ten for practical reasons. First, the maximum number of nodes allowed in the IBM Basic interpreter is ten. This number can be safely used without exceeding the 64 K bytes of memory of the basic interpreter. However, the number of nodes can be brought up to 30 nodes in each direction once the basic source code is compiled. Using a three dimensional array of 30x30x30 requires 640 K bytes of RAM (Random Access Memory). Most microcomputers do not have this option. A more crucial consideration is the execution time of the software. With a three dimensional array of 10x10x10, execution time ranges between fifteen minutes and a maximum of two hours. Increasing the mesh size to 30x30x30 will increase the execution time by a factor of twenty seven. This in turn means that the execution time will range between seven and fifty four hours -- an operation which is both inconvenient and time consuming.

Increasing the mesh size does not mean more refined mesh elements. This is because of the way the model is set up. The mesh is a dynamic mesh, changing for every case or

every set of input data. In other words, the dimensions of the individual mesh elements are not constant but can increase or decrease in value. To make the mesh dynamic, the dimensions of each mesh element are set equal to the brace diameter. For a brace diameter of 2 ft, the spacing between nodes in the cubic mesh is equal to 2 ft in every direction. For a three dimensional array of 10x10x10, the distance between the first node and the last node is 18 ft in each direction, i.e., ten nodal points define 9 elements. For a brace diameter of 3 ft, the same distance is 27 ft and so forth. Therefore, increasing the mesh size does not make the mesh elements smaller but rather it makes the total cubic volume larger. For a brace diameter of 2 ft and an array of 30x30x30, the distance between the first node and the last node is no longer 18 ft but rather 57 ft in each direction. So whether the array is 10x10x10 or 30x30x30, the dimensions of each mesh element are still 2 ft.

In conclusion, a mesh size of 10x10x10 is used. The choice was made to insure fast execution times and reduced memory requirements.

#### Anode Specifications

Because the mesh is dynamic, the node spacing throughout the mesh is equal to the brace diameter. When the brace diameter is large enough to exceed 3 or 4 ft, then the node spacings are too large to accommodate the anode dimensions in a 3 dimensional fashion. In other words, the

anode cannot be represented in a three dimensional fashion because most anodes do not have a three feet diameter. To overcome this problem, the anode geometry was not assigned a volume but was limited to a line (1 dimensional representation). A line anode is represented by nodes on a straight line (Figure 9). On the contrary, a brace is represented by cubical mesh elements representing the circular brace diameter as shown in Figure 9. Representing an anode with a only a line rather than a volume does not reflect a true representation of the anode physical geometry. However, it is more realistic and logical than representing an anode with cubical elements.

The anode potential is needed as part of the input data. The potential at the anode is assumed to be constant throughout the anode surface. The anode potential is used in the model to calculate the potential distribution throughout the mesh. The current density of the anode or the current rate output per lbm is not needed because the Laplace equation models only the potential distribution. The only current densities to be accounted for are the current densities at the surface of the cathode. Theoretically, the sum of the current entering the cathode surface must be equal to the current leaving the anode surface. Since the Laplace equation does not provide any indication on the amount of current leaving the anode surface, it is assumed that it is equal to the amount of current entering the cathode surface. As a result, the

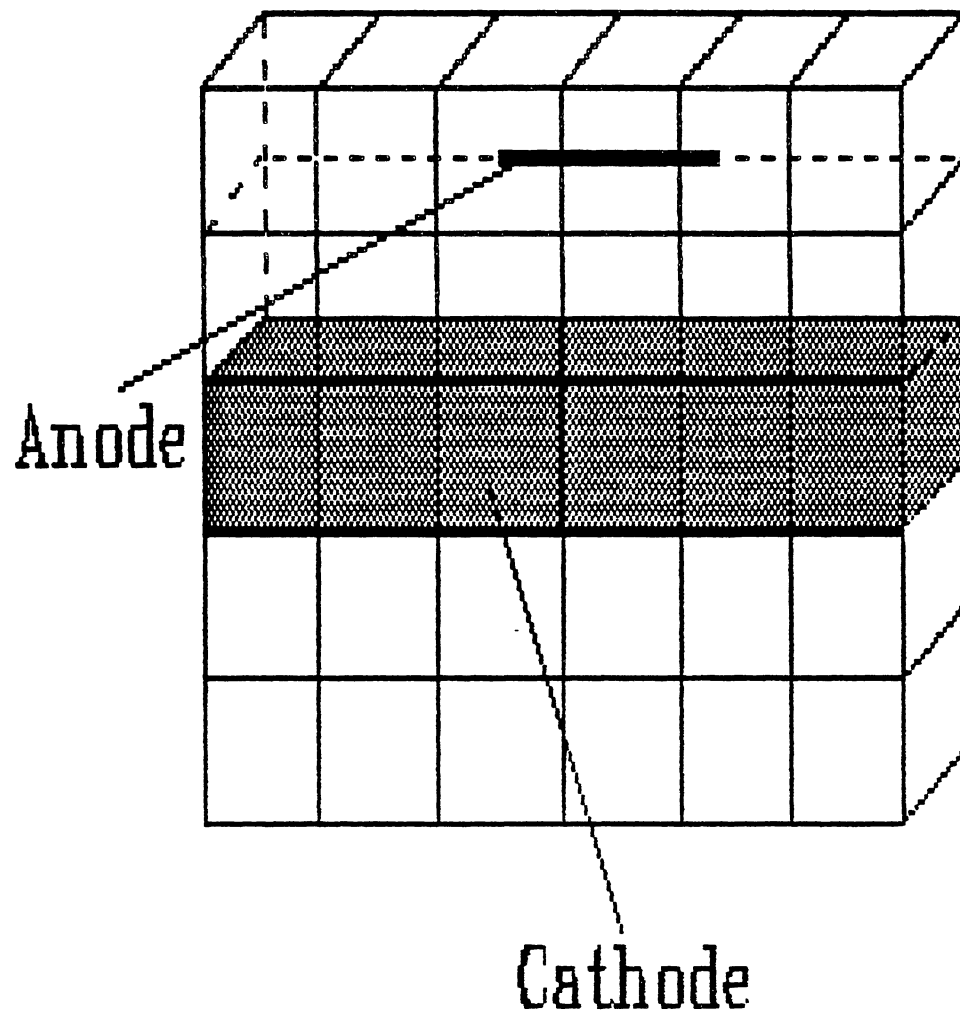


Figure 9. The Cathode and the Anode as Represented in the Three-Dimensional Cubic Mesh.



corrosion engineer can use the value of the total current entering the cathode system to determine the appropriate type of anode. The potential distribution throughout the mesh volume helps the corrosion engineer to place his anodes at an optimal distance from the weld area.

### Convergence Criteria

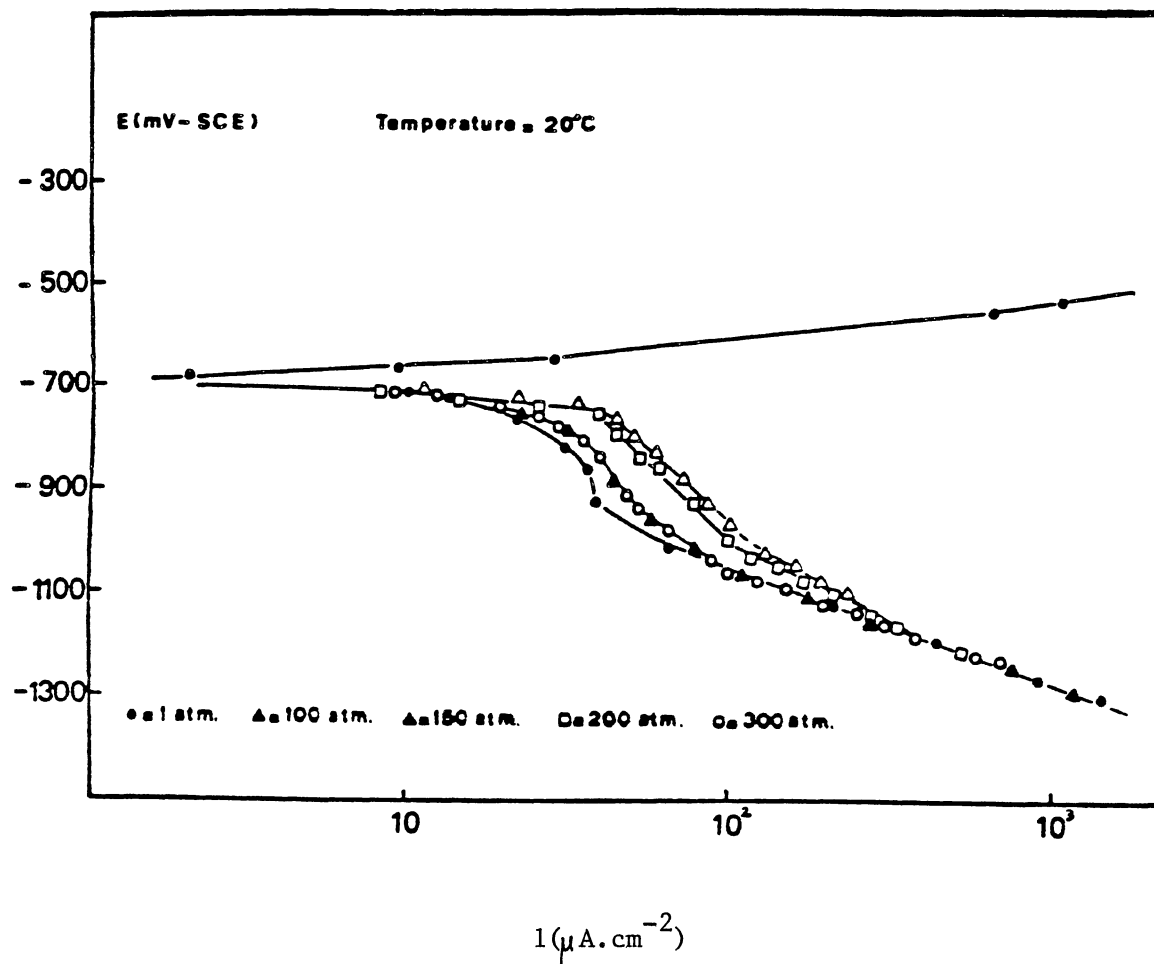
Using the finite difference method to solve for the Laplace equation generates an equation for each node in the three dimensional mesh. This results is a system of  $n$  linear equations with  $n$  number of unknowns. To solve the set of equations, several methods can be used. The method used in the model is the method of iteration (72). The choice was made because the microcomputer is available to do the number crunching. The way the iteration method works is simple. The first step involves assigning initial values to all the nodes. These initial values can be determined arbitrarily. However, if these initial values are chosen to be close to the solution values, then the solution will converge faster. The next step involves generating a set of new values based on the initial assigned values, using the system of  $n$  equations. This new set of values is used again to generate another new set of values. The process of generating new values based on a previous set of values is called an iteration. The iteration process is repeated until the values of the potential at each nodal point from one iteration to the next iteration do not differ by more

than a certain predetermined value. This predetermined value is called the convergence criteria. It is usually small enough so that the solution values are almost equal to the values of the previous iteration. Naturally, the smaller the convergence criteria the longer it will take the model to converge to a solution, and vice versa.

The iteration method is fast and reliable. It is fast because it is done on a microcomputer. It is reliable because the iteration method always converges to a solution even though the initial assigned values could be far from the true solution. There are always exceptions to the rules, and the same is true for the iteration method. The method may not converge if used with a set of equations which contains non-linear equations. However, this is not the case because all the equations used in the model are linear. Therefore, the model will always converge to a solution, no matter how long it takes to converge.

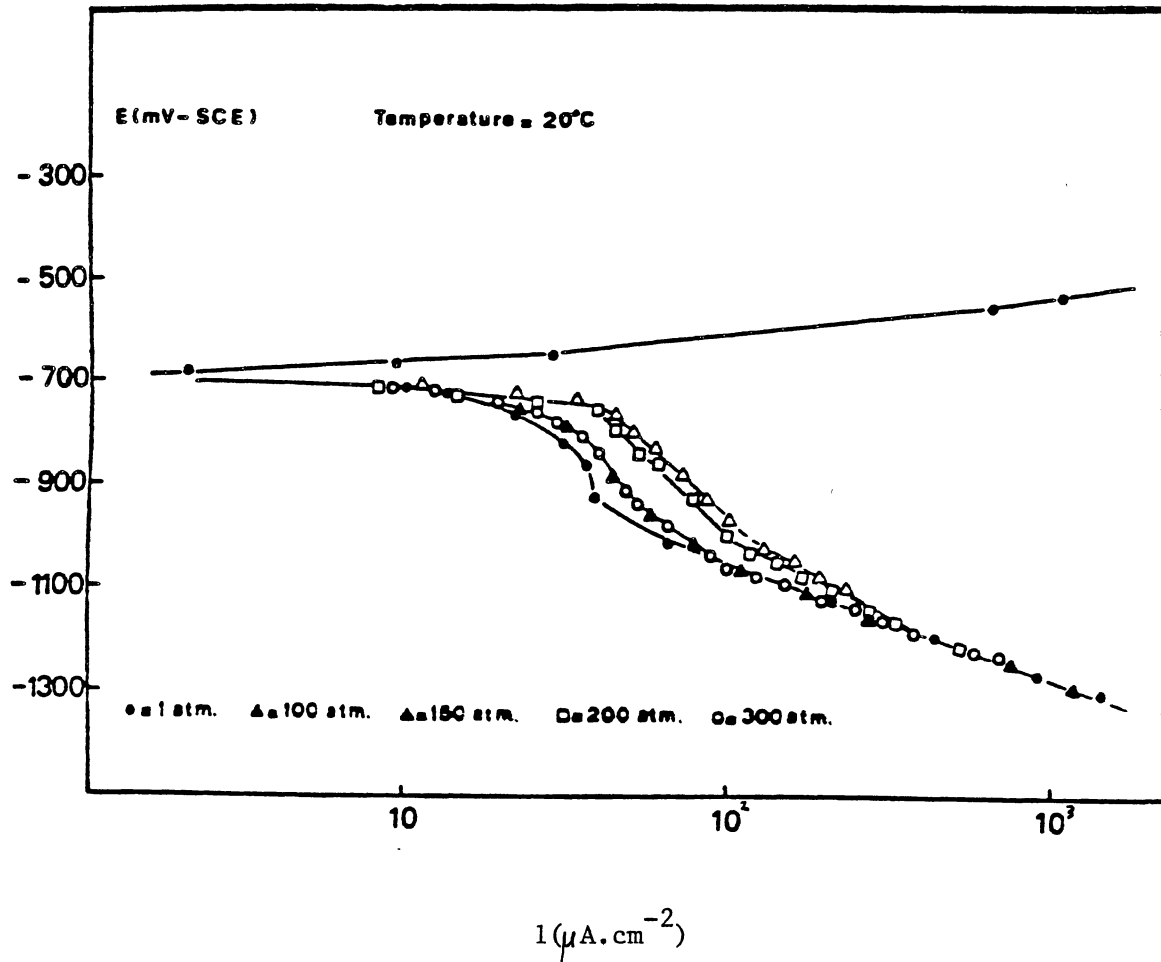
### Polarization Curves

As mentioned earlier, a polarization curve is an experimental (or theoretical) curve relating the potential of the cathode surface of a structure to the current density as shown in Figures 10 and 11. If the value of the potential at a point is known, then the corresponding current density can be evaluated by simply reading it from the curve. Polarization curves are useful because they allow the model to calculate the current density of the



Source: E. D. Mor and A. M. Beccaria, "The Influence of Hydrostatic Pressure on the Corrosion of Iron in Sea Water," Corrosion and Protection Offshore Communications Symposium International, Paper No. 124 (1979)

Figure 10. The Effect of Increasing the Pressure (Water Depth) is a Slight Shift of the Polarization Curve to the Right.



Source: E. D. Mor and A. M. Beccaria, "The Influence of Hydrostatic Pressure on the Corrosion of Iron in Sea Water," Corrosion and Protection Offshore Communications Symposium International, Paper No. 124 (1979)

Figure 11. The Same Shift to the Right of the Polarization Curve Due to the Increase of Hydrostatic Pressure Except that the Temperature is at 10C.

cathode surface at a certain potential. Polarization curves also provide information about the conditions of the actual physical system. In other words, the polarization curve is a true representation of the relation that exists between the potential and the current density of a cathode surface submerged in a conductive electrolyte and the environment conditions. These environmental conditions include the water temperature and pressure, the oxygen concentration, the water salinity, existing water currents, and surface finish of the cathode. All and each of these factors influences the relation between the potential and the current density of a submerged cathode. For example, Figures 10 and 11 show the influence of pressure and temperature on the polarization curve. The curves in Figure 10 represent polarization curves at different depths measured at a temperature of 20C. The curves in Figure 11 are measured at a temperature of 10C and represent polarization curves at different water depths ( or pressures). The net effect of the increase in pressure (or depth) in either Figure 10 or 11 is a slight shift of the polarization curve to the right. In addition, changing the temperature from 10C to 20C has also the effect of shifting the polarization curve to the right, as shown in Figures 10 and 11.

Therefore, an experimental polarization curve can be used as a design tool to predict the potential and the current density of the cathode for a given set of temperature, pressure, and water properties. Each set of

cathode and water properties produces a different polarization curve. Therefore, there can be hundreds of polarization curves representing hundreds of existing cathode conditions. If hundreds of polarization curves can exist, and they do exist, then one can create a database system based on the information (potential and current density values) retrieved from these polarization curves. Once the database system is created, it can be used with a numerical model to predict the potential distribution for most galvanic systems. Moreover, the model is not limited to time zero (launch time) but can be extended to account for galvanic systems that have been in the water for a certain period of time by using the corresponding polarization curve.

Polarization curves may not be the best way to relate the potential and the current density to existing water and cathode conditions. But, in the context in which they are used in this model, they are the only source of information that relates this theoretical model to the true world.

### Shape Files

A shape file is a data file containing information or data on the coordinates of the cathode in the x, y, and z direction. This information tells the program where exactly the cathode elements are located within the 3 dimensional cubic volume being analyzed. Once the coordinates of the cathode elements are recognized by the program, it will

include in its calculations the polarization currents entering the cathode surfaces. Another function of the shape file is to make the computer aware of the difference between the coordinates of the brace elements and the leg elements. This is needed because the brace diameter is usually different from the leg diameter. Therefore, the shape file will instruct the program to use the brace diameter at the brace elements and to use the leg diameter at the leg elements.

In general, a data file or a shape file is needed in every numerical model because numerical models need to be instructed about the locations or coordinates of each individual element. This is a basic requirement in all numerical models. Therefore, each geometry requires a specific data file which runs only with that specific geometry. To overcome this problem, a database was created that included shape files for twenty six different geometries. These geometries are the ones that are mostly used by the industry. The user can pick any shape file he wants by viewing it graphically on the screen. Then he can run the program for that particular geometry and analyze the output data. To make the program more interactive, the shape files do not contain information on the coordinates of the anodes. This means that the anode can move along the x-axis, the y-axis, or both. It is up to the user to specify the anode length and its distance from the weld area. This makes the program or the model interactive and

also user friendly.

The database system can be expandable to accommodate more geometries. It is up to the user to create his own shape files for geometries that are not included in menu of the program. An explanation and an example on how to create new shape files are included in Appendix B.

### Node Geometries

The node geometries are the structural nodes found in the submerged part of offshore structures and installations. It is referred to as a node geometry and should not be confused with the word "node" which is the mathematical word for all the points that forms the cubic mesh. The model incorporates twenty six different node geometries. A listing of these geometries along with their figures can be found in Appendix C. These geometries were chosen based on figures and drawings supplied by the sponsoring companies of the project. Each node geometry is represented numerically by a shape file. More node geometries can be included in the model if new shape files are created, as discussed in the previous section.

### Source Listing

The source listing of the program is not included in this thesis because of a confidentiality agreement between Oklahoma State University and the sponsoring companies. The source code will be made public after a certain time period



agreed upon by the concerned parties. However, a tree structure of the program is included in Appendix D. The program is composed of the main program menu PLATFORM and of eight subprograms. Four of the eight subprograms are commercial programs that were interfaced with the program PLATFORM to generate the graphics work.

## CHAPTER V

### RESULTS AND DISCUSSION

#### Introduction

Numerical models are used to simulate physical systems. The results obtained from these numerical models are used to predict how the physical system will behave under a certain set of conditions. In the same way, the numerical model PLATFORM tries to simulate the potential distribution in a three dimensional volume. The three dimensional volume contains a structural node of a specific node geometry and the surrounding water. Based on the results of the potential distribution, the corrosion engineer can change the location of the anodes to meet a minimum protection criteria of  $-0.78$  volt. The criteria is usually set by the NACE Recommended Practice RP-01-76 (1983 Revision) (67). To make the output data of the model easier to handle, they are displayed in a graphical fashion. A graphical representation of the results makes the analysis and the interpretation of the output data easier and simpler. The software PLATFORM can generate two dimensional and three dimensional plots of the potential distribution in the volume being analyzed.

## Input Data

Before discussing the output data, it is important to write about the different variables used in the input data. These input variables are listed in Table III. The input data can be divided into two types. In general, the first type consists of all the variables needed to run the program and obtain a solution of the potential in 3-dimensions. These variables include the anode length and potential, the anode distance from the node, the brace diameter, the leg diameter, the water resistivity, the potential convergence value, the type of polarization curve, and the shape file. After obtaining the solution, the graphical analysis of the data is in order. At this point, the second type of input variables is needed. These variables include the direction of the 2-dimensional plane (perpendicular to the x-axis, y-axis, or z-axis) and the distance of that plane from the axis origin.

Both types of input variables are needed to produce the final graphical analysis. The first type of input variables produces the 3-dimensional solution of the potential distribution. However, the second set is needed if any 2-dimensional analysis (graphical or not) is to be done.

## Potential Distribution in 3 Dimensions

Unlike most numerical models, this model is not

TABLE III

A SAMPLE OF THE COMPUTER OUTPUT SHOWING THE INPUT DATA

---

**INPUT DATA**

```

*****
The anode length, ft..... 8
The anode potential, volt..... -1.05
The anode distance from the node, ft (x-axis)..... 8
The anode distance from the node, ft (y-axis)..... 8
The brace diameter, ft..... 2
The leg diameter, ft..... 4
The water resistivity, ohm-cm..... 22
The potential convergence value, volt..... .001
Distance of plane from the axis origin is, ft..... 12
Total current entering the cathode surface, amp..... 9.66

```

**CURVE A** polarization curve was used

The chosen plane is perpendicular to the z-axis

The node geometry consists of:

1 ANODE ON EACH HORIZONTAL BRACE (X AND Y AXIS)

1 LEG AND 2 HORIZONTAL T-JOINTS

```

*****

```

---

limited to a two dimensional system. It is designed to model three dimensional systems. Therefore, the results of the model vary in three directions; along the x, y, and z direction. The results of the numerical model are given in terms of potential values. These potential values represent the potential distribution throughout the three dimensional cubic volume being analyzed. This cubic volume usually contains a structural node, a couple of anodes and the surrounding electrolyte. The potential distribution provides information about the potential on the surface of the cathode (the structural node), and throughout the electrolyte body. These results are important from a design point of view. The cathode potential must not exceed the potential criterion of -0.78 volt at any point on the structure surface. Therefore, the output data provides a listing of the potential values at all points inside the cubical volume including those points that are below the criterion value. To pinpoint these points, the corrosion engineer can either use graphical techniques or perform a volume search. Graphical analysis is possible with the software PLATFORM and it is easier to locate the areas with low potential values. A volume search is basically going through a list of numbers and indicating with a symbol such as an arrow, at those points that are below the minimum criterion. This task is not available in the software PLATFORM but can be done with any spreadsheet program. The most common spreadsheet is Lotus 123. The output data files

from PLATFORM are written in a format compatible with Lotus format. The file extension <.PRN> is also recognizable by Lotus. Therefore, the transfer of the output data file to Lotus should be easy and error free.

Whether it is a volume search or a graphical representation, the data analysis of the data helps the corrosion engineer to place the anodes at an optimal position. In turn, the optimal anode(s) position(s) should provide adequate cathodic protection of the steel surface including the weld area.

#### Two Dimensional Data Analysis

Before analyzing the output data graphically, the data must be written in a suitable format. As it is, the output data is provided along the x, y, and z direction. Any graphical representation of these data is cumbersome and almost impossible. In order to make the data available for graphical display, the data must be reduced from a three dimensional format into a two dimensional format. This can be done by dividing the three dimensional data into several two dimensional data sets. Each data set is a plane containing data in two directions. A plane can contain potential data along the x-axis and the y-axis, for example. This means that the plane is perpendicular to the z-axis since the z value is constant throughout the plane. As a result, a plane can be perpendicular to either the x-axis, the y-axis, or the z-axis depending on whether x, y, or z is

held constant. Moreover, two different planes that are perpendicular to an axis are parallel to each other. This is true because the mesh is made of regular cubic mesh elements.

Figure 12 shows a plane containing data in two dimensions and is perpendicular to the z-axis. The potential data provide information on the potential distribution in that plane, which is located at a certain distance from the axis origin. The two dimensional data contained within any plane can be analyzed graphically using topographic maps or surface maps.

### Graphical Analysis

Graphical representation of numerical data makes the data analysis easier and simpler. The software PLATFORM is equipped with graphics routines that produce topographic maps and surface maps. These routines are commercial routines that were interfaced with the main program PLATFORM to perform the graphic tasks. These maps make the interpretation of the potential data more efficient as discussed next.

#### Topographic Map

A topographic map is a map that contains contour lines describing a certain physical system. It is used mostly in geology where each contour line represents a set of points at the same altitude. Therefore, the topographic map

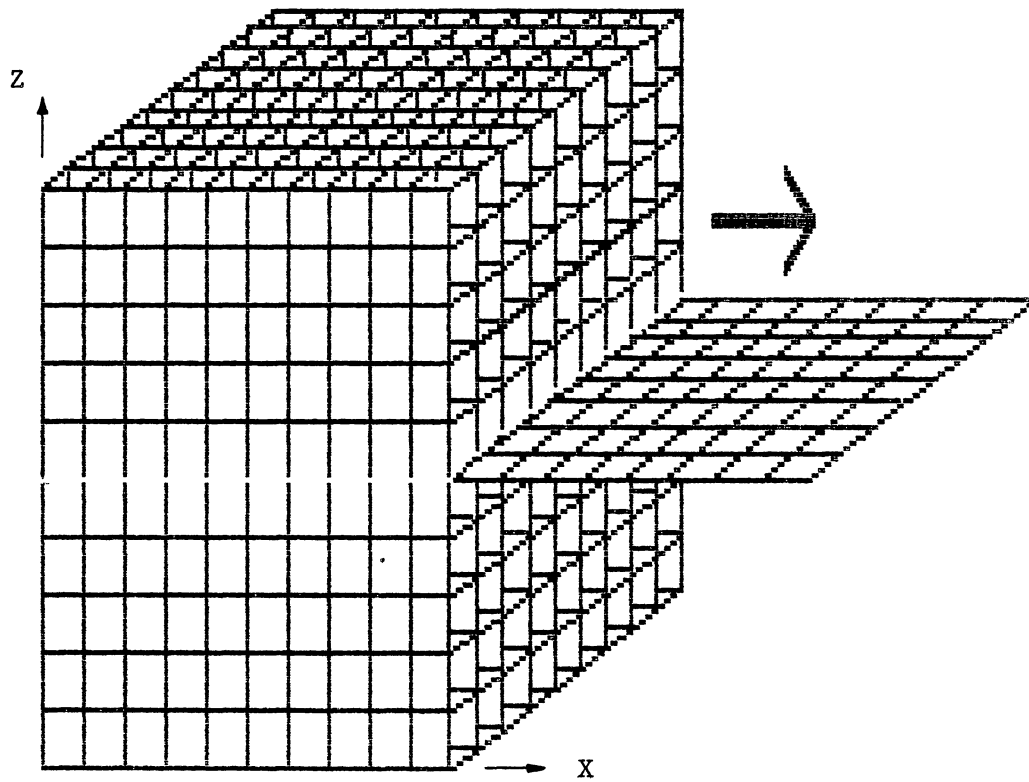


Figure 12. A Plane Containing Data in Two Dimensions Which is Perpendicular to the Z-Axis.



provides information on the altitude of a point and also on the elevation gradient or slope around that point. For example, a mountain can be represented by a set of almost concentric contour lines. The closer the contour lines, the steeper the gradient, and vice versa.

A topographic map can be used to provide information on the potential distribution within a surface or a plane. The contour lines are in this case isopotential lines or constant potential lines. By transferring the numerical data to a topographic map, the data analysis becomes systematic. One can read the potential value at almost any point in the system being analyzed just by reading it from the topographic map. One can also find out whether there is a steep or flat potential gradient next to a point of interest. This is important for areas close to the anodes. One can also look at the difference between the potential distribution at two different planes within the cubic volume. This is done by comparing their respective topographic maps.

The topographic maps in the software PLATFORM do not have a rigid format. They can be changed to include more contour lines. The user can also change the maximum and the minimum potential values. The map size can be changed as well as the number of labeled contour lines. The topographic map can be displayed on the screen or plotted on a dot matrix printer. The printer output is a high quality output resembling a plotter output. Figure 13, 14, and 15

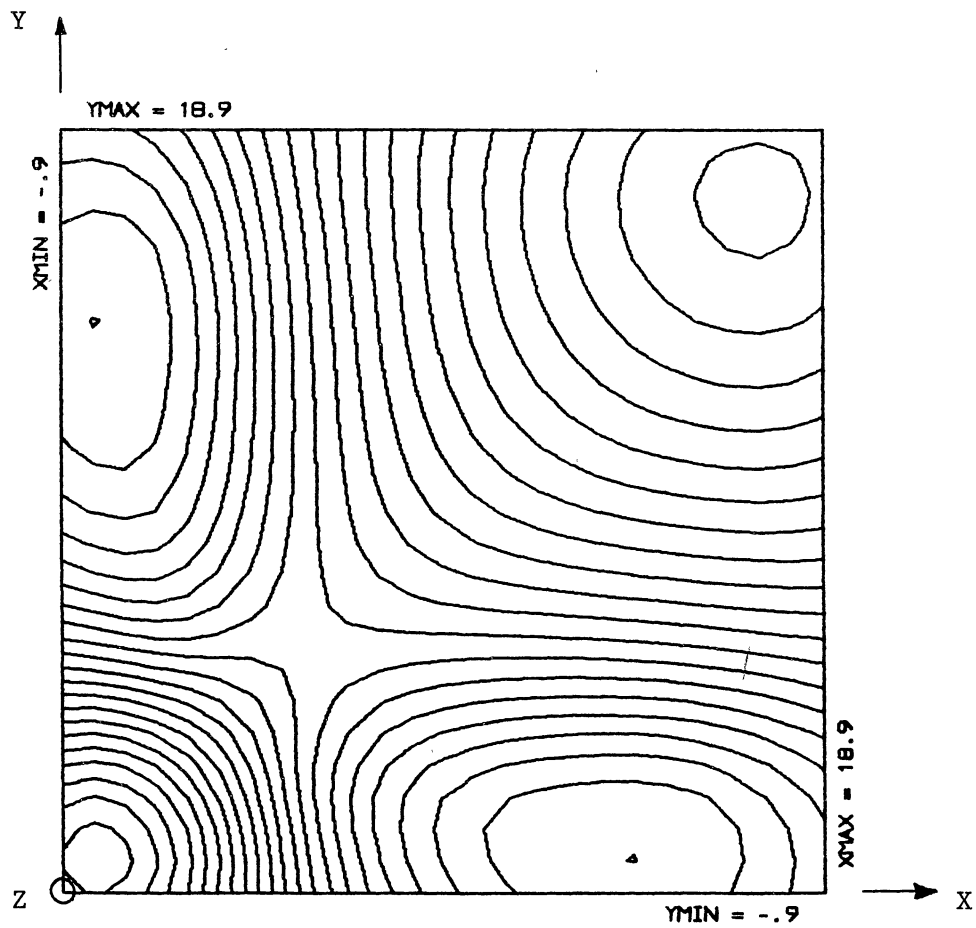


Figure 13. The Topographic Map of the Potential Distribution for the Input Data Shown in Table III. The Plane Containing the Potential Contour Lines is Perpendicular to the Z-Axis.

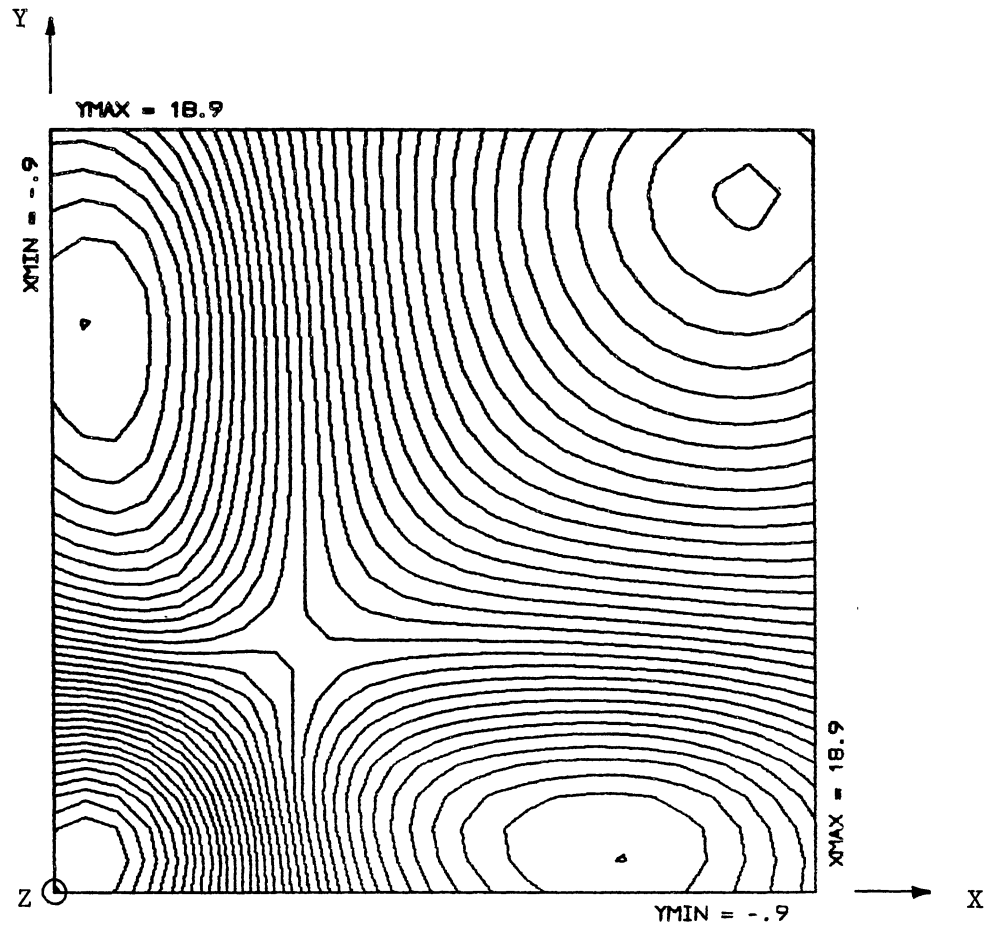


Figure 14. The Same Topographic Map of the Potential Distribution for the Input Data of Table III but With a Small Contour Line Interval.

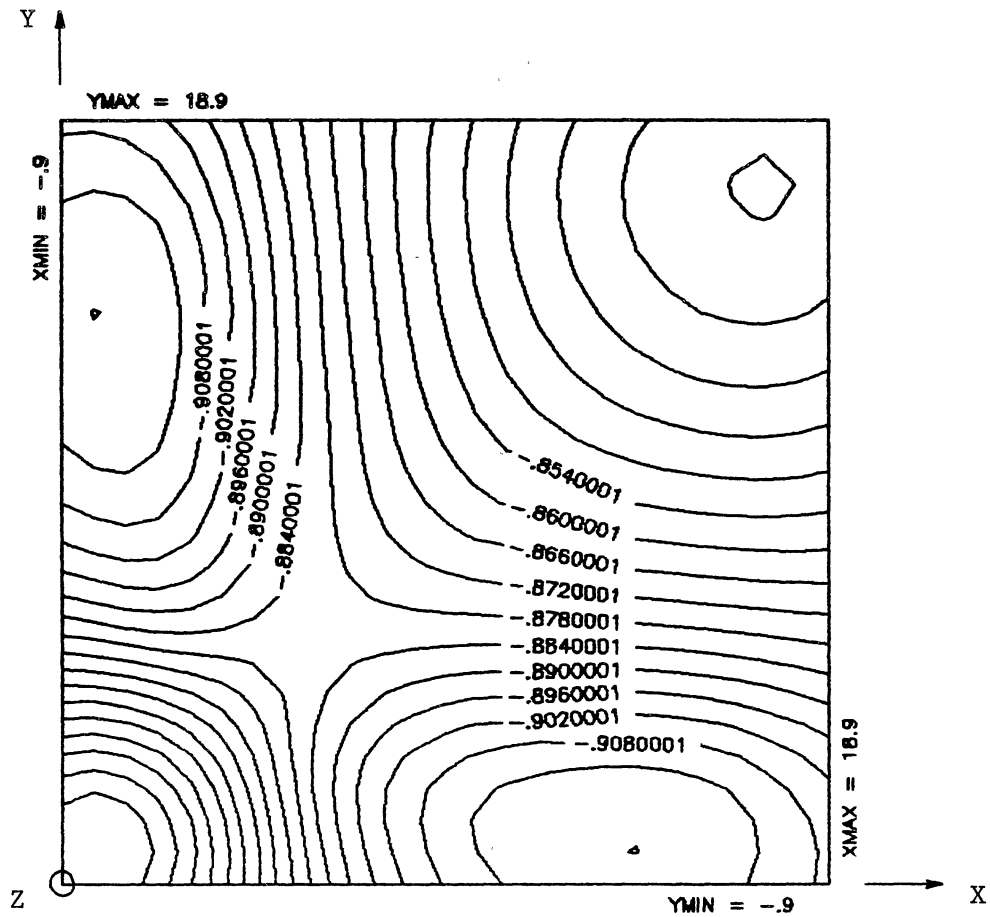


Figure 15. The Contour Lines of the Topographic Map Can be Labeled. The Above Topographic Map is for the Input Data of Table III.

show different versions of the same topographic map. Figure 13 is a topographic map of the potential distribution in a plane passing through the anodes and, therefore, is perpendicular to the z-axis. The input data used to generate the potential distribution is listed in Table III. Figure 14 is the same topographic map except that the contour interval between the contour lines was made smaller. This means that more contour lines are plotted in the same map. Figure 15 is the same topographic map except that the potential value of each line is printed on the map. Figure 16 is a topographic map for the same input data but the plane of interest is located further away from the anodes. The shaded parts of the map represent areas that are not adequately protected. At these areas, the potential is lower than  $-0.78$  volt vs.  $\text{Ag}/\text{AgCl}$ . Therefore, the anodes must be repositioned in order to achieve satisfactory protection.

One fact that needs to be mentioned is the effect of imposing boundary conditions on the cubic volume containing the structural node. This effect can be seen in Figures 13, 14, and 15 and is represented by the circular isopotential lines in the upper right corner and the lower left corner of the maps. These circular isopotential lines do not reflect a true behavior but rather represent the effect of imposing mathematical constraints on the model.

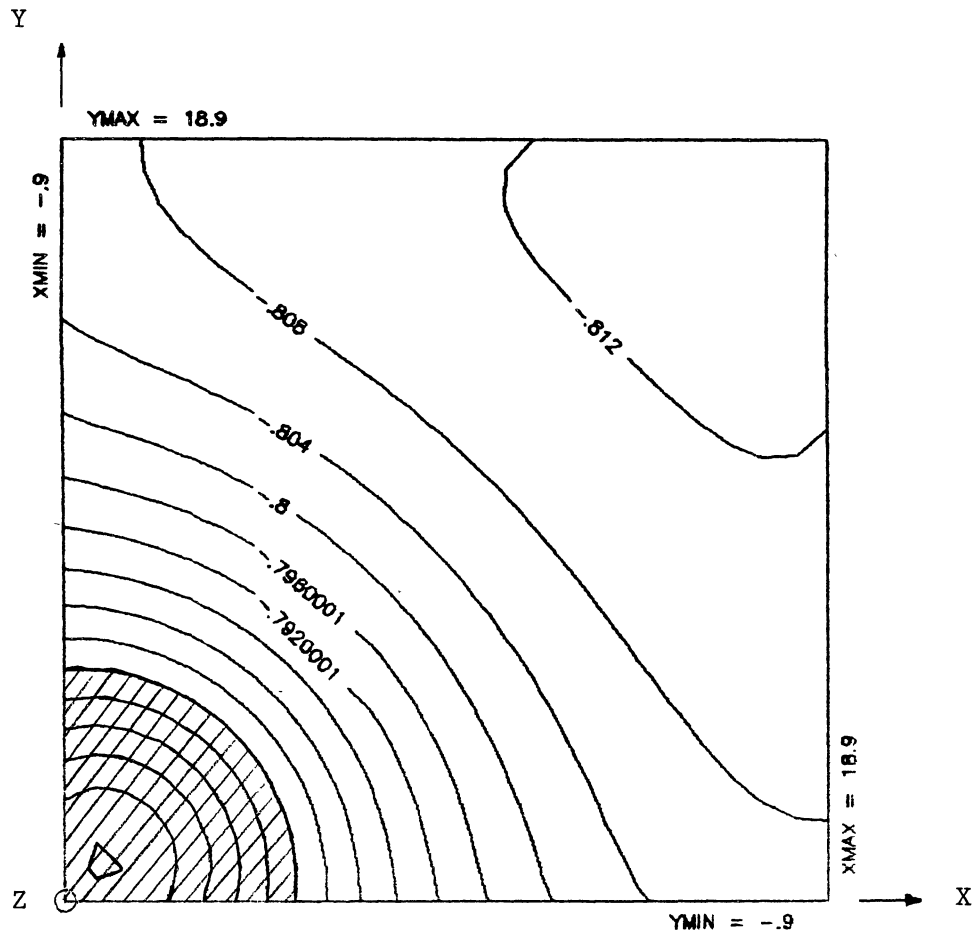


Figure 16. The Topographic Map in a Plane Located Further Away from the Anodes and Which Contains Areas That are Inadequately Protected (Shaded Areas).

## Surface Map

A surface map is a three dimensional representation of a topographic map. While the topographic map uses contour lines to represent a mountain for instance, the surface map is actually a plot of the mountain in three dimensions. The idea is to visualize where the top and the bottom points are on the topographic map. It also helps to locate in which direction are the potential gradients acting. In the software PLATFORM, the surface map will produce a three-dimensional representation of the potential distribution in a plane of interest. Apart from the fact that the surface maps are esthetically beautiful, they are a great help in cases where the topographic map is revealing complex information about the potential distribution. They definitely eliminate confusion when one is trying to visualize in his mind how a topographic map looks in three dimensions. Surface maps are helpful and can be used constructively to complement the data analysis of topographic maps.

The commercial routine that produces the surface maps offers different options for plotting the surface maps. The map size can be changed as well as the maximum and minimum values of the potential in the data. Since the surface map is a three dimensional plot, then the angle of rotation and the angle of tilt can also be changed as shown in Figures 17 to 20. The height to width ratio of the map can also be

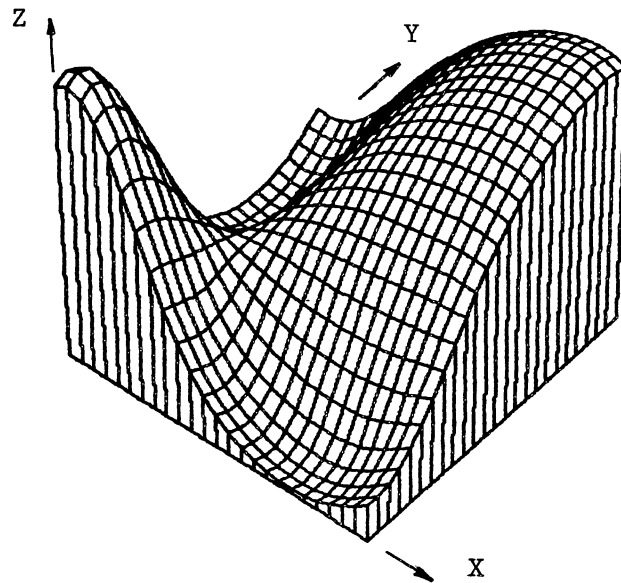


Figure 17. The Surface Map of the Potential Distribution for the Input Data of Table III. The Rotation Angle is at 310 Degrees.

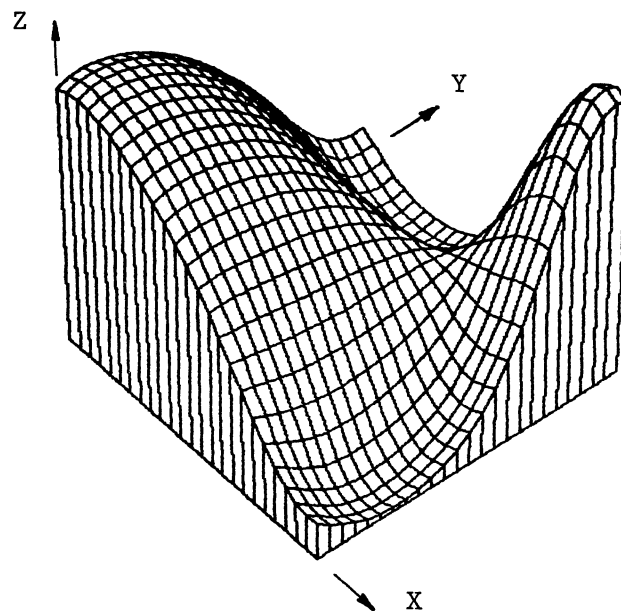


Figure 18. The Same Surface Map but Rotated at an Angle of 140 Degrees.



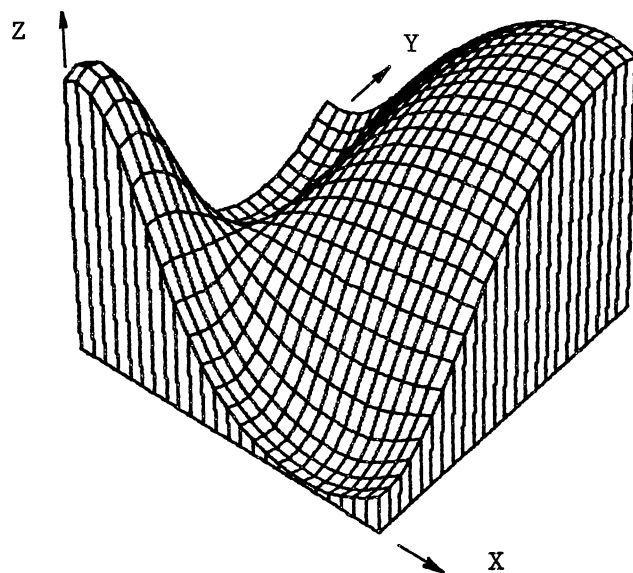


Figure 19. The Surface Map of the Potential Distribution at a Tilt Angle of 45 Degrees.

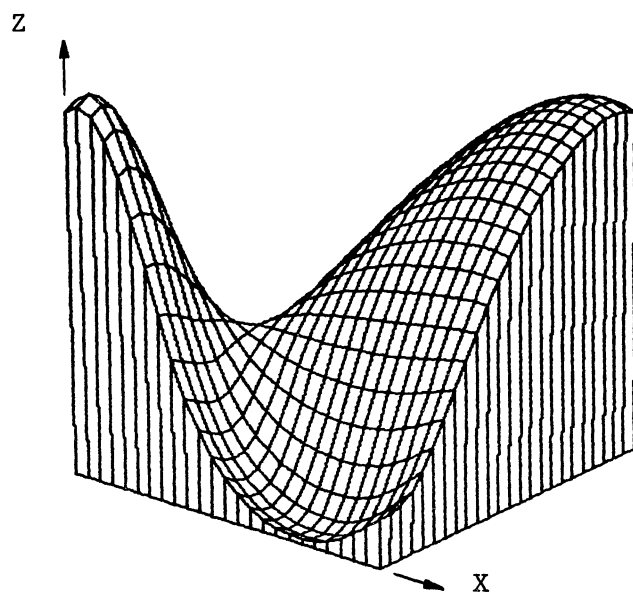


Figure 20. The Same Surface Map of the Potential Distribution but Tilted at an Angle of 20 Degrees.

altered as shown in Figure 21 and 22. The surface map can be plotted with or without a skirt as shown in Figures 23 and 24. The surface map can be plotted with lines that are either parallel to the x-axis, the y-axis, or both as shown in Figures 25, 26, and 27. All of the data shown graphically in Figures 17 to 27 are for the same set of data (Table III).

#### Validation of the Model

The results of the numerical model are typical of any numerical model simulating an electrochemical system governed by the Laplace equation. Fu (36), Munn (28), and De Carlo (29) showed similar behavior to the results of this model. Each one of their models simulated a galvanic system governed by the Laplace equation. Although the results of this model follows the same trend of results published in the literature, it does not mean that the output data of the model are valid. To validate the model, the theoretical data predicted by the program must be compared with field data.

One of the sponsoring companies was able to provide proprietary field data for model verification. The field data provided potential values for a structural node protected by two anodes. The structural node consisted of one leg and three horizontal T-joints as shown in Figure 28. The leg was six feet in diameter. Two of the horizontal braces had a diameter of twenty inch with the third brace

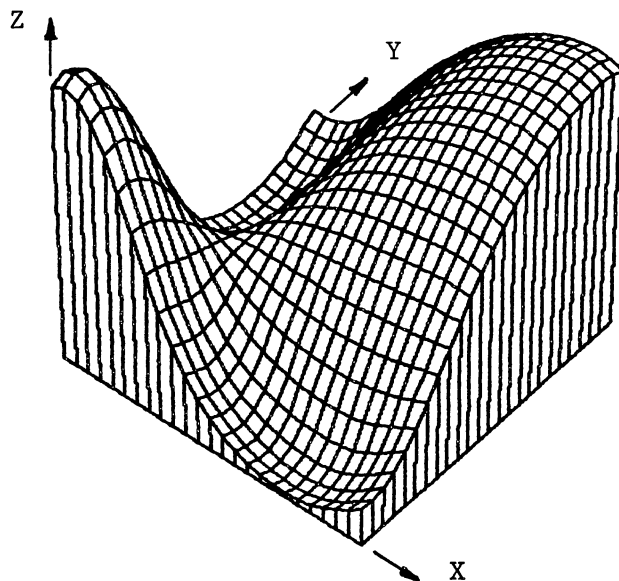


Figure 21. The Surface Map of the Potential Distribution With a Height/Width Ratio of 1.0.

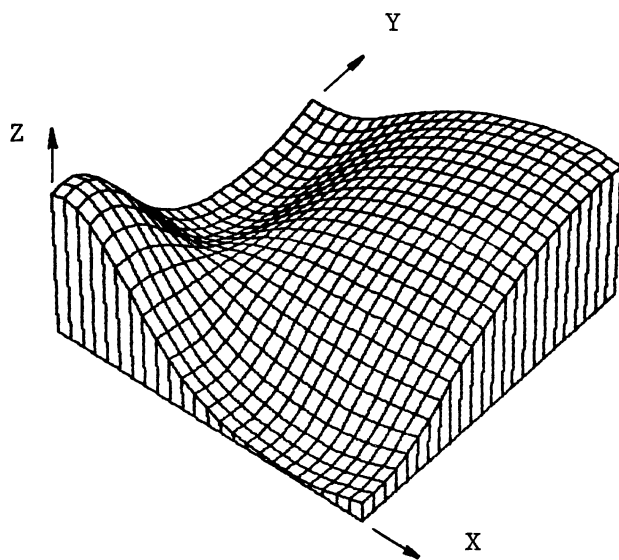


Figure 22. The Same Surface Map of the Potential Distribution but With a Height/Width Ratio of 0.5.

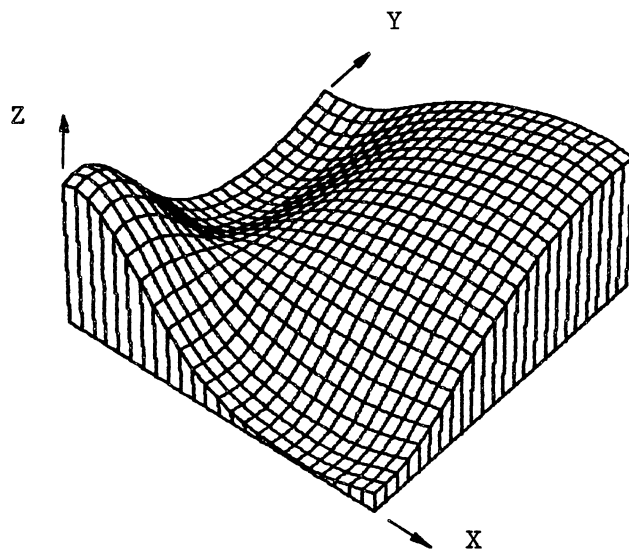


Figure 23. The Surface Map of the Potential Distribution With a Skirt.

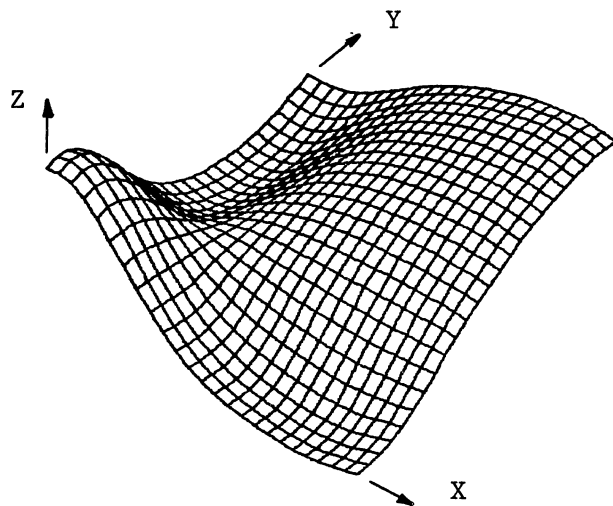


Figure 24. The Same Surface Map of the Potential Distribution but Without a Skirt.

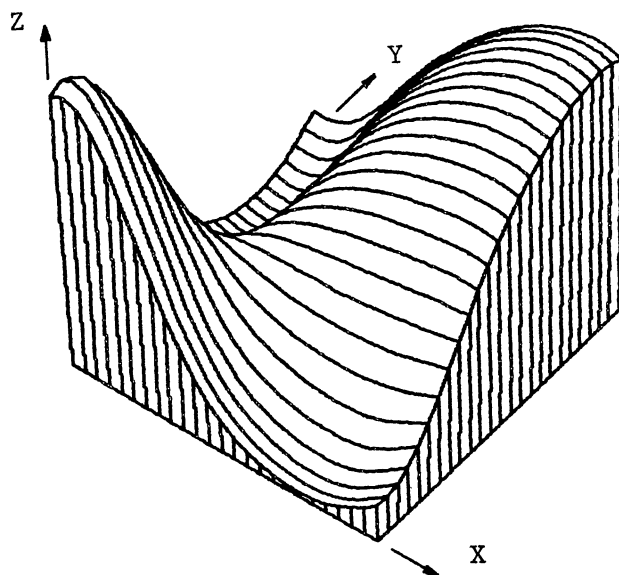


Figure 25. The Surface Map of the Potential Distribution With Grid Lines Parallel to the X-Axis.

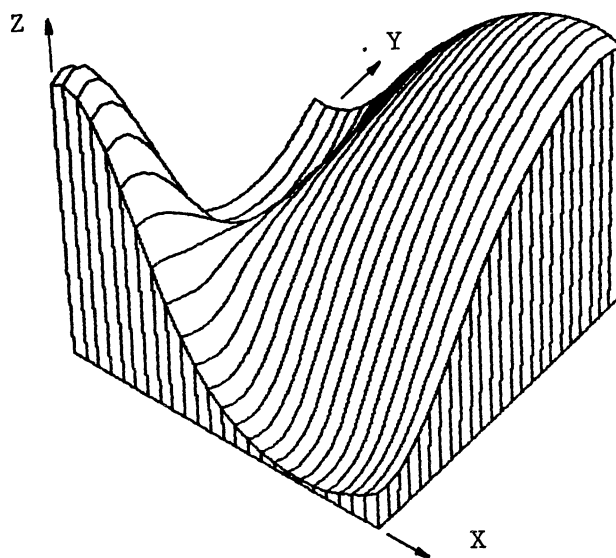


Figure 26. The Same Surface Map but the Grid Lines are Parallel to the Y-Axis.

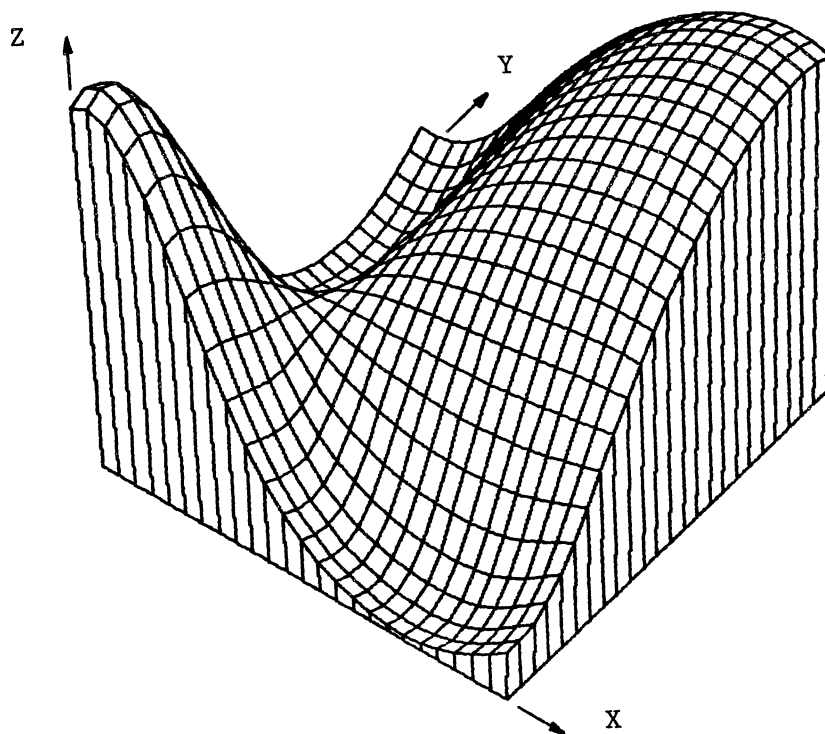


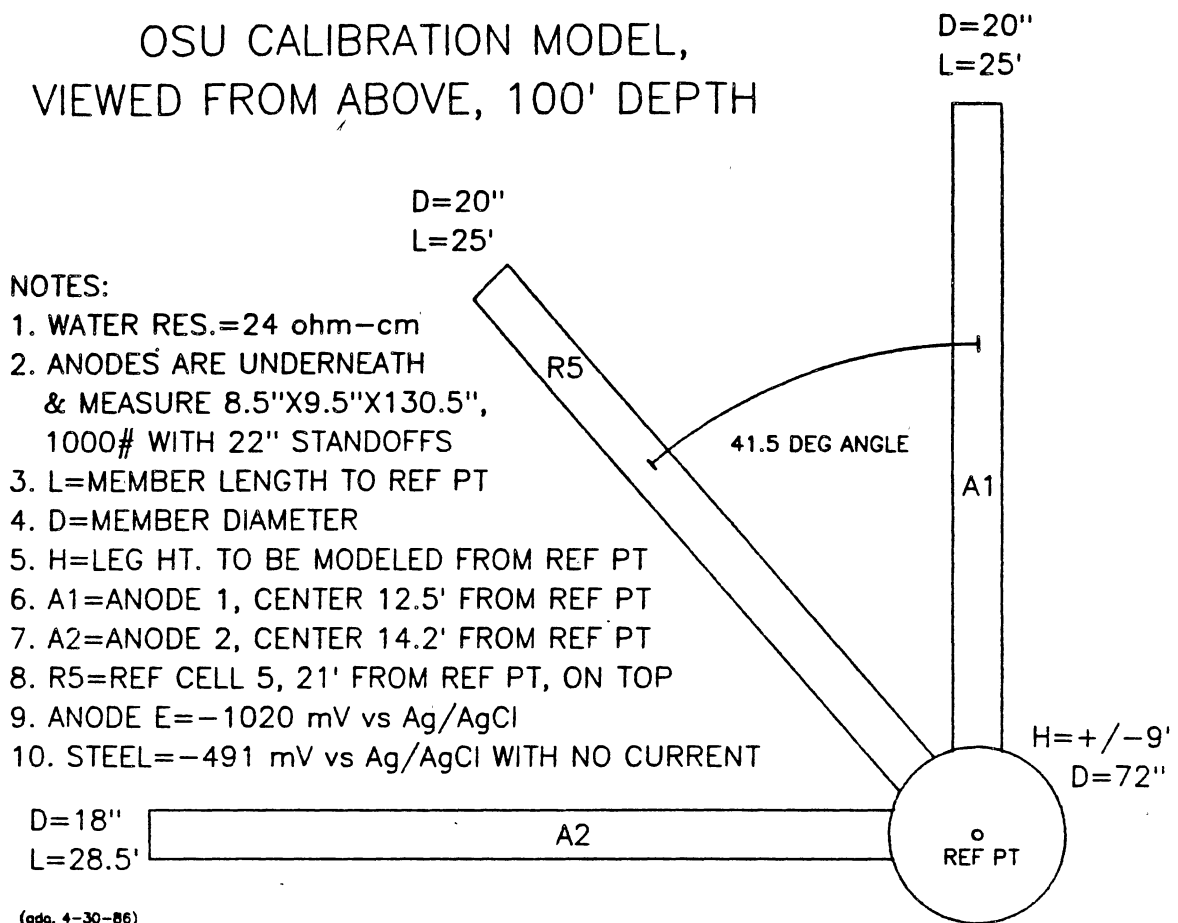
Figure 27. The Surface Map With Grid Lines Parallel to both the X-Axis and the Y-Axis.

having a diameter of eighteen inch. The reference cell R5 was located at a distance of twenty one feet from the reference point. Other pertinent data to the node geometry and anode specifications are shown in Figure 28.

In the first run, the same geometry dimensions of the different node members were used as input data. The results of the theoretical model, using the company's proprietary polarization curve, were within 30% of the field data. In the second run, the dimensions of the different members were adjusted to yield a surface area equal to the surface area of the actual structure. The potential results of the second run were within 20% of the field data. The current density results were within 1% of the field data. The purpose of the first run was to calculate the potential at the reference point R5. The purpose of the second run was to find out if the anode current output in the model was equal to the actual current output. This is why the different member dimensions were adjusted to yield a surface area equal to the surface area of the actual structure.

In the two runs, the model results were within 30% of the actual data. The validation process showed two facts. The first fact indicates that the model is valid and can predict results within 30% of the field data. The second fact indicated that the validity of the model depends on the validity of the polarization curve used in the model. This fact was based on the results of two other runs with the same input data but with a generic polarization curve. The

OSU CALIBRATION MODEL,  
VIEWED FROM ABOVE, 100' DEPTH



Source: A. D. Goolsby, Westhollow Research Center, Shell Development Company, 1986.

Figure 28. A Schematic Diagram of the Calibration Model.



generic polarization curve caused the model to yield results that were well off. The potential value in the first run was within 55% of the actual field datum. The current density in the second run was within 45% of the actual current density. Therefore, in future runs it is best to use a polarization curve which closely simulates the true conditions of the cathode.

### Conclusion

The numerical model described in this chapter was proved to be a valid model. A comparison of the theoretical results of the model with field data, provided by a sponsoring company, showed that the model results were within 30% of the actual data. The polarization curve used in the model has an important effect on the results. Therefore, it is important to choose the right polarization curve to simulate the cathode environment.

## CHAPTER VI

### CONCLUSIONS AND RECOMMENDATIONS

#### Conclusions

The numerical model PLATFORM is an interactive and user friendly model. It is designed to model three dimensional structural nodes in offshore platforms. It provides a solution for the potential distribution on the surface of the steel (cathode) and in the electrolyte body surrounding the node. The model is equipped with a database system that makes the numerical model interactive. The database consists of data files representing twenty six different node geometries. Each data file contains the coordinates of the cathode elements for the node geometry in question. The user can pick any geometry of his choice from the database and then solve for the potential distribution using the numerical model. The results of the program can be listed or displayed graphically. Two kinds of graphs are available for graphical analysis; topographic maps and surface maps. The topographic maps provide isopotential contour lines for any plane in either the x, y, and z direction. The surface map is a three dimensional representation of the topographic map. It is used when it becomes difficult to interpret the data in the topographic

map. Based on the graphical output, the user can change the anode locations to an optimal position to secure a proper cathodic protection of the steel surface. This is done to insure that the steel potential does not drop below  $-0.78$  volt vs. Ag/AgCl at any point on the steel surface. This minimum potential criteria is set by the NACE recommended practice RP-01-76 in the marine corrosion section.

The results of the model are valid. The theoretical data of the model were compared with field data from one of the sponsoring companies. The theoretical data were within 30% of the field data in the two cases. It was found that the model is dependent on the type of polarization curve used with the model. The closer the polarization curve represents the cathode conditions, the more accurate are the model results.

In all, the model is interactive and user friendly. It can be used as an effective design tool for cathodic protection systems. The results of the model can be used to predict the potential distribution for an existing structure or for a future one. Its capability to generate potential values in three dimensions and to graphically analyze the data makes it one of the few powerful tools available for cathodic protection design.

#### Recommendations

Every mathematical model has its own limitations. The same is true for this program. The following recommenda-

tions are in order if one one desires to make PLATFORM a more powerful and more useful program.

- The actual mesh size is limited to 10x10x10. The mesh size can be increased to 20x20x20 or even 30x30x30.

Increasing the mesh size means that the program can cover more surface area of the structure. This can be done by writing the computational part of the package (Input/Run section) in Fortran. The reason is that the Microsoft Fortran compiler allows the user to dynamically dimension his arrays to more than 10x10x10. The Fortran compiler can access the whole 640 Kilo bytes of random memory that can be available on a microcomputer (IBM XT).

- More node geometries can be added to the database system. This can be done by creating shape files for the new geometries. These shape files contain the coordinates of the cathode elements. Appendix B explains the procedure to create new shape files.

- The program is equipped to handle a maximum of two anodes in each node geometry. It is recommended that the program be modified to handle more than two anodes. It is also important to be able to place the anodes on non-horizontal braces such as the diagonals of a K-joint for example.

- In order to make the program more powerful, we suggest the following. Another version of PLATFORM can be created that runs in a batch mode. This means that the program will not prompt the user about the anode size(s), the anode location(s), or the anode distance(s) from the weld area.

Rather, the user will have to write a shape file that has a format different from the one discussed above. This new type of shape files will contain information not only about the coordinates of the cathode elements but about the coordinates of the anode elements as well. The new shape file allows the user to place any type of anode(s), any size of anode(s), and any distance of the anode(s) from the weld area. He can also use different cathode geometries such as pipelines or well conductors, and so forth. The program will only recognize the information provided in the shape file. The result is a more powerful program at the expense of labor time. The user will have to create a shape file for every single case he wants to analyze. This task can be time consuming and frustrating specially for novices in computer programming. However, this version of PLATFORM can be made available by changing a few sections in the source code.

- The fictitious points lying outside the boundaries of the cube were determined using the mirror image extrapolation technique. This method consists of assigning to the fictitious point(s) the value of the point which is in the opposite direction and is lying inside the cubic mesh. This method may be improved by taking into account the values of the rest of the points that are inside the cubic mesh. The idea is to use several values instead of one to extrapolate the value of the fictitious point(s).

## BIBLIOGRAPHY

1. R. C. Evans, *The Micro Millenium*, Viking Press, 2nd ed., New York (1980).
2. J. B. Rochester, J. Gautz, *The Naked Computer*, William Morrow and Company, Inc., New York (1983).
3. D. Z. Meilach, *Before You Buy a Computer*, Crown Publishers, Inc., New York (1983).
4. A. C. Toncre, "Corrosion Control Evaluation and Data Recording by Electronic Computer," presented at the NACE Western Region Conference, Phoenix, AZ, 1964.
5. A. C. Toncre, *Materials Protection*, Vol. 4, No. 7, p. 57 (1965).
6. R. H. Saunders, *Materials Protection*, Vol. 5, No. 3, p. 42 (1966).
7. G. S. Jones, Jr., *Pipe Line Industry*, Vol. 26, No. 10, p. 75 (1967).
8. R. L. Seifert, *Materials Performance*, Vol. 19, No. 10, p. 29 (1980).
9. *Mears Engineering Cathodic Protection Promotional Handouts*, Mears/CPG, Inc., Rosebush, Michigan, 1985.
10. P. D. Gamache, P. Sullivan, *Materials Protection*, Vol. 12, No. 3, p. 26 (1973).
11. A.C. Van Orden, G. M. Ugiansky, J. M. Rodriguez, E. Esalante, *J. Electrochemical Society*, Vol. 180, No. 9 (1985).
12. H. Puschmann, R. Eckermann, "Dechema Corrosion Data and Materials Data Bank," *International Congress on Metallic Corrosion*, 8th, p. 1963, 1981.
13. D. G. John, K. Hladky, *Materials Performance*, Vol. 19, No. 11, p. 42 (1980).
14. N. D. Greene, R. H. Ghandi, *Materials Performance*, Vol. 21, No. 7, p. 34 (1982).

15. S. M. Gerchakov, L. R. Udey, F. Mansfeld, *Corrosion*, Vol. 37, No. 12, p. 36 (1981).
16. M. Kendig, F. Mansfeld, *Corrosion*, Vol. 39, No. 11, p. 466 (1983).
17. J.D. Kellner, "Computer Controlled AC Impedance Measurements for the Evaluation of Anti-Corrosion Pipeline Coatings," *CORROSION/85*, Paper No. 73, National Association Of Corrosion Engineers, Houston, Texas, 1985.
18. L. F. G. Williams, R. J. Taylor, *Corrosion*, Vol. 38, No. 8, p. 425 (1982).
19. V. R. Wandruska, S. W. Orchard, A. Greeff, *Talanta*, Vol. 32, No. 4, p.307 (1985).
20. E. Sivieri, S. Rondinini, F. Bonino, *La Metallurgia Italiana*, Vol. 75, No. 7-8, p.515 (1983).
21. R. J. O'Halloran, L. F. G. Williams, C. P. Llyod, *Corrosion*, Vol. 40, No. 7, p. 344 (1984).
22. E. Diacci, R. Rizzi, C. Ronchetti, *Sci. Tech. Aerosp. Rep.*, 22(16), 1984.
23. J. T. J. Waber, *J. Electrochemical Society*, Vol. 101, No.6, p. 271 (1954).
24. J. T. Waber, M. J. Rosenbluth, *J. Electrochemical Society*, Vol. 102, No. 6, p. 344 (1955).
25. J. T. Waber, B. J. Fagan, *J. Electrochemical Society*, Vol. 103, No. 1, p. 64 (1956).
26. J. T. Waber, *J. Electrochemical Society*, Vol. 103, No. 10, p. 567 (1956).
27. E. Kenard, J. T. Waber, *J. Electrochemical Society*, Vol. 117, No. 7, p. 880 (1970).
28. R. S. Munn, *Materials Performance*, Vol. 21, No. 8, p. 29, (1982).
29. E. De Carlo, *Materials Performance*, Vol. 22, No. 7, p. 38 (1983).
30. R. G. Kasper, M. G. April, *Corrosion*, Vol. 39, No. 5, p. 181 (1983).
31. R. Strommen, A. Roland, *Materials Performance*, Vol. 20, No. 4, p.15 (1981).

32. R. N. Fleck, Numerical Evaluation of Current Distribution in Electrical Systems, MSc, Thesis, University of California, Sept., 1964.
33. R. S. Munn, J. H. Clark, "Simple Method for Prediction of Galvanic Corrosion Rates on Real Structures in Seawater Using Numerical Techniques on a Microcomputer," CORROSION/83, Paper No. 74, National Association of Corrosion Engineers, Houston, Texas, 1983.
34. R. S. Munn, "Numerical Corrosion Rate Prediction on Structures Immersed in Inhomogeneous Media," CORROSION/84, Paper No. 49, National Association of Corrosion Engineers, Houston, Texas, 1984.
35. J. N. Fu, J. S. K. Chow, Materials Performance, Vol. 21, No. 10, p. 9 (1982).
36. J. W. Fu, "Calculation of Cathodic Protection Potential and Current Distributions Using an Integral Equation Numerical Method," CORROSION/84, Paper No. 250, National Association of Corrosion Engineers, Houston, Texas, 1984.
37. P. O. Gartland, R. Johnsen, "COMPACS- Computer Modeling of Cathodic Protection Systems," CORROSION/85, Paper No. 319, National Association of Corrosion Engineers, Houston, Texas, 1985.
38. J. W. Fu, S. Chan, Corrosion, Vol. 40, No. 10, p.540 (1984).
39. J. W. Fu, Corrosion, Vol. 38, No. 5, p.295 (1982).
40. J. W. Fu, S. Chan, "Finite Element Modeling of Galvanic Corrosion During Chemical Cleaning of Westinghouse Series 51 Steam Generator," CORROSION/85, Paper No. 190, National Association of Corrosion Engineers, Houston, Texas, 1985.
41. J. W. Fu, S. Chan, "A Finite Element Modeling Method for Predicting Long Term Corrosion Rates," CORROSION/84, Paper No. 199, National Association of Corrosion Engineers, Houston, Teaxs, 1984.
42. B. P. Boffardi, G. W. Schweitzer, Materials Performance, Vol. 19, No. 12, p. 44 (1980).
43. L. Chen, D. T. Freese, W. R. Snyder, Materials Performance, Vol. 21, No. 12, p. 9 (1982).
44. A. Borello, S. Casadio, A. Saltelli, G. Scibona,



- Corrosion, Vol. 37, No. 9, p.498 (1981).
45. A. Borello, S. Casadio, A. Mignone, Corrosion, Vol. 39, No. 6, p. 247 (1983).
  46. D. C. Silverman, Corrosion, Vol. 38, No. 10, p. 541 (1982).
  47. J. C. Angus, C. T. Angus, J. Electrochemical Society, Vol. 132, No. 5, p. 1014 (1985).
  48. J. C. Angus, C. T. Angus, "Instructions For Potential-pH Diagram Generator", Case Western Reserve University, Chemical Engineering Department, April 1985.
  49. E. Verink, "Adaptation of a Computer Program for Pourbaix Diagrams to Personal Computers," in G. L. Liedl and K. S. Sree Harsha, editors, Computer Usage in Materials Education, The Metal Society, Warrendale, Pennsylvania, p. 123 (1985).
  50. M. Froning, M. Shanley, E. Verink, Corrosion Science, Vol. 16, No. 16, p. 371 (1976).
  51. R. Strommen, "Evaluation of Anode Resistance Formulas by Computer Analysis," CORROSION/84, Paper No. 253, National Association of Corrosion Engineers, Houston, Texas, 1984.
  52. J. Cochran, "Offshore Platform Cathodic Protection optimization Via Computer Use of Classical Equations," CORROSION/84, Paper No. 252, National Association of Corrosion Engineers, Houston, Texas, 1984.
  53. J. Cochran, "The Design of Cathodic Protection Systems of Offshore Pipelines in Varied Environments," CORROSION/84, Paper No. 333, National Association of Corrosion Engineers, Houston, Texas, 1984.
  54. J. Cochran, "New Mathematical Models for Designing Offshore Sacrificial Cathodic Protection Systems," Offshore Technology Conference, Paper No. 3858, Houston, Texas, 1980.
  55. M. Haroun, Cathodic Protection Modeling of Tethers in Tension Leg Platforms, Shell Development Company, Westhollow Research Center, Houston, Texas, Summer 1985.
  56. A. N. Campbell, V. F. Hollister, R. O. Duda, P. E. Hart, Science, Vol. 217, p. 927 (1982).
  57. C. Westcott, D. E. Williams, N. J. M. Wilkins, G. P.

- Marsh, J. N. Wanklyn, J. F. Croall, "Expert Systems - the Application of New Computer Methods to Corrosion Problems," Proceedings of the Electrochemical Society, Vol. 85-3, p. 190, 1985.
58. C. Westcott, D. Williams, J. Bernie, I. Croall, and S. Patel, "The Development and Application of Integrated Expert Systems and Databases for Corrosion Consultancy," CORROSION/86, Paper No. 54, National Association of Corrosion Engineers, Houston, Texas, 1986.
  59. E. H. Schmauch, and W. Thomason, "Expert Systems for Personal Computers," CORROSION/86, Paper No. 55, National Association of Corrosion Engineers, Houston, Texas, 1986.
  60. S. Marchand, A. Asphahani, and D. Carlson, "Computerized Expert Systems: Solving Corrosion Problems in Industrial Services," CORROSION/86, Paper No. 56, National Association of Corrosion Engineers, Houston, Texas, 1986.
  61. N. Pessal and J. J. Schreurs, "Development of Expert Systems by Corrosion Specialists," CORROSION/86, Paper No. 57, National Association of Corrosion Engineers, Houston, Texas, 1986.
  62. W. Bogaerts and M. Rijkaert, "Artificial Intelligence, Expert Systems and Computer-aided Engineering," CORROSION/86, Paper No. 58, National Association of Corrosion Engineers, Houston, Texas, 1986.
  63. P. E. Hart, "Expert Systems and Technological Problems," Proceedings of the Second International Conference on Foundations of Computer-Aided Process Design, Snowmass, Colorado, 1983.
  64. A. W. Westerberg, "Discussion Summary: Keynote Address," Proceedings of the Second International Conference on Foundations of Computer-Aided Process Design, Snowmass, Colorado, 1983.
  65. C. Edelineau, Materials Performance, Vol. 22, No. 10, p. 82 (1983).
  66. M. G. Fontana and N. D. Greene., "Corrosion Engineering," 2nd Ed., New York, McGraw Hill Co., 1978.
  67. NACE Standard RP-01-76, Corrosion Control of Steel, Fixed Offshore Platforms Associated with Petroleum Production, National Association of Corrosion Engineers, 1983.

68. Shell Development Company. Cathodic Protection Technical Training Manual, Westhollow Research Center, Houston, Texas, 1985.
69. M. Haroun, R. Erbar, and H. Heidersbach, "The Use of Computers in Corrosion Control and Monitoring," CORROSION/86, Paper No. 61, National Association of Corrosion Engineers, Houston, Texas, 1986.
70. L. R. Segerlind, "Applied Finite Element Analysis," 2nd Ed., New York, John Wiley and Sons, 1984.
71. R. B. Bird, W. E. Stewart, and E. N. Lightfoot, "Transport Phenomena," John Wiley and Sons, 1960.
72. J. D. Parker, J. H. Boggs, and E. F. Blick, "Introduction to Fluid Mechanics and Heat Transfer," 3rd Ed., Addison-Wesley Publishing Co., 1974.

APPENDIXES

**APPENDIX A**

**A SAMPLE OF CATHODIC PROTECTION DESIGN**

### SAMPLE DESIGN

The following is a sample of an offshore cathodic protection design procedure. The platform is in the Gulf of Mexico and the design parameters are similar to other Gulf platforms. These are:

- Maintenance current density = 5 mAmp/ft<sup>2</sup>
- Design life = 20 years
- Calculated surface area = 33484 ft<sup>2</sup> (water zone)  
= 47984 ft<sup>2</sup> (mud zone)
- Anode capacity = 1280 Amp-hr/lb
- Safety factor = 25%
- Water resistivity = 20 ohm-cm
- Assumed anode parameters = 725 lb net Aluminum weight  
8 ft long  
90.25 in<sup>2</sup> X-section area

Given these numbers, we first calculate the total current in the water zone and the mud zone:

$$\text{Current (water)} = \frac{(5 \text{ mAmp/ft}^2)(33484 \text{ ft}^2)}{1000} = 167.4 \text{ Amps}$$

$$\text{Current (mud)} = \frac{(5 \text{ mAmp/ft}^2)(47984 \text{ ft}^2)}{1000} = 95.9 \text{ Amps}$$

The next step is to evaluate the total weight of anode material required:

$$\begin{aligned} \text{Total Weight (water)} &= \frac{(167.4 \text{ Amps})(8760 \text{ hr/yr})(20 \text{ yrs})(1.25)}{(1280 \text{ Amp-hr/lb})} \\ &= 28641 \text{ lbs} \end{aligned}$$

$$\begin{aligned} \text{Total Weight (mud)} &= \frac{(95.9 \text{ Amps})(8760 \text{ hr/yr})(20 \text{ yrs})(1.25)}{(1280 \text{ Amp-hr/lb})} \\ &= 16408 \text{ lbs} \end{aligned}$$

At this stage, the number of anodes needed in each section can be evaluated:

$$\text{Number of anodes (water)} = (28641 \text{ lbs}) / (725 \text{ lb/Anode}) = 39.5$$

$$\text{Number of anodes (mud)} = (16408 \text{ lbs}) / (725 \text{ lb/Anode}) = 22.6$$

$$\text{Total Number of anodes} = 40 + 23 = 63$$

Sixty three anodes are needed to prepolarize the steel, or to provide the initial current density. The initial current density must be at least 15 mAmps/ft<sup>2</sup> to assure the buildup of an adequate calcareous deposit on the steel members. The total initial current output per anode is calculated using a potential of 0.45 volts between bare, unpolarized steel (-0.60 volt) and aluminum (-1.05 volt) and an anode resistance calculated from Dwight's equation for a single anode, since experience shows no significant interference between the various numbers of a multiple anode design.

$$\text{Resistance} = \frac{s}{2(\text{PI})(L)} (\ln 4L/r - 1) \quad , \text{ Dwight Equation}$$

where,

L = anode length, in

PI = 3.14159

s = Water Resistivity, ohm-cm

r = Equivalent Radius, in

For shapes other than cylindrical shapes

r = SQRT(Cross Sectional area/PI)

In this case, the anode has a trapezoidal cross section and the equivalent radius is calculated using the equivalent radius formula:

$$r = \text{SQRT}(90.25/\text{PI})$$

$$r = 5.36 \text{ in}$$

$$\text{Resistance} = \frac{(20 \text{ ohm-cm})}{96 \text{ in}} (\ln(4)(96)/5.36 - 1)$$

$$\text{Resistance} = 0.0427 \text{ ohms}$$

The initial current output of the anode is determined next.

$$I = E/\text{Resistance}$$

where,

$$E = 1.05 - 0.60 = 0.45 \text{ volts, potential difference}$$

$$\text{Resistance} = 0.0427 \text{ ohms}$$

$$I = 0.45 \text{ volts} / 0.0427 \text{ ohms} = 10.54 \text{ Amps}$$

The initial structure current density is determined as follows:

$$\begin{aligned} \text{Current Density} &= \frac{(10.54 \text{ Amps/Anode})(63 \text{ Anodes})}{33484 \text{ ft}^2} \\ &= 0.0198 \text{ Amp/ft}^2 = 19.8 \text{ mAmp/ft}^2 \end{aligned}$$

A current of 19.8 mAmp/ft<sup>2</sup> is considered to be an adequate current density for the buildup of a calcareous deposit which leads to a satisfactory polarization of steel.

Fully polarized steel develops a potential more negative than -0.780 volt against the Ag/AgCl reference electrode and will, therefore, establish a potential drop of 0.20 to 0.25 volt versus aluminum anodes. Using the 0.20 to



0.25 volt potential drop for Ohm's law and calculating the anode resistance with Dwight's equation based on anode dimensions at 40 to 50% consumption will then result in a maintenance current density which is roughly half the value of the calculated initial one. Therefore, if the steel is polarized to -0.80 volt vs. Ag/AgCl, the current output of the anode is

$$I = E/\text{Resistance}$$

where,

$$E = 1.05 - 0.8 = 0.25 \text{ volts}$$

$$\text{Resistance} = 0.0441 \text{ ohm (derated anode radius based on a 10\% reduction of the initial radius)}$$

$$I = 0.25/0.0441 = 5.6 \text{ Amps}$$

The actual potential drop between structural steel cathode and aluminum anodes at some time after launching the platform is estimated as the difference between the given aluminum versus Ag/AgCl potential and the average of polarized steel potentials as measured with Ag/AgCl reference electrodes at various locations of the structure. The true current output per anode is, therefore, available for predicting the life of the cathodic protection system given the capacity of 725 lb aluminum anodes, namely,

$$\text{Life} = \frac{(1280 \text{ Amp hr/lb})(725 \text{ lb/Anode})}{(8760 \text{ hr/yr})(T \text{ Amp/Anode})}$$

which leads to the life in years for T amps current output per anode as follows:

$$\text{Life} = 106/T \text{ years}$$

Based on a current of 5.6 Amp, the design life of the cathodic protection system is

$$\text{Life} = 106/5.6 = 18.9 \text{ years}$$

Since the required design life is 20 years, then another anode geometry should be chosen.

### 2nd iteration

Suppose that the new anode has the following anode characteristics:

$$\text{Length} = 10 \text{ ft} = 120 \text{ in}$$

$$\text{Radius} = 6 \text{ in}$$

$$\text{weight} = 1135 \text{ lb}$$

$$\text{Anode Capacity} = 1280 \text{ Amp-hr/lb}$$

The total number of anodes needed based on the surface area of the water and the mud sections is

$$\text{Nbe of Anodes (water)} = (28641 \text{ lb}) / (1135 \text{ lb/Anode}) = 25.2$$

$$\text{Nbe of Anodes (mud)} = (16408 \text{ lb}) / (1135 \text{ lb/Anode}) = 14.4$$

$$\text{Total Number of Anodes} = 26 + 15 = 41$$

The resistance of one anode using Dwight's equation is

$$\begin{aligned} \text{Resistance} &= \frac{20}{2(\text{PI})(120)} (\ln(4)(120)/6 - 1) \\ &= 0.03532 \text{ ohm} \end{aligned}$$

The initial total current output based on a potential drop of 0.45 volt is

$$\begin{aligned} I &= E/\text{Resistance} \\ &= 0.25/0.03532 = 12.74 \text{ Amps} \end{aligned}$$

The structure current density is now evaluated and is equal

to

$$\begin{aligned} \text{Current Density} &= \frac{(12.74 \text{ Amps/Anode})(41 \text{ Anodes})}{33484 \text{ ft}^2} \\ &= 0.0156 \text{ Amp/ft}^2 = 15.6 \text{ mAmp/ft}^2 \end{aligned}$$

An initial structure current density of 15.6 mAmp/ft<sup>2</sup> is acceptable. A more conservative design will allow for a higher number. Next, the anode resistance is calculated based on a derated radius of 5.4 in (10 % reduction).

$$\begin{aligned} \text{Resistance} &= \frac{20}{2(\text{PI})(120)} (\ln(4)(120)/5.4 - 1) \\ &= 0.036420 \text{ ohm} \end{aligned}$$

Using a potential drop of 0.25 volt, the total maintenance current available is

$$\begin{aligned} I &= 0.25/0.036420 \\ &= 6.86 \text{ Amps (almost half the initial value)} \end{aligned}$$

Based on a current of 6.86 Amps, the design life of the cathodic protection system is

$$\begin{aligned} \text{Life} &= \frac{(1280 \text{ Amp-hr/lb})(1135 \text{ lb/Anode})}{(8760 \text{ hr/yr})(6.86 \text{ Amps/Anode})} \\ &= 24.2 \text{ years} \end{aligned}$$

Therefore, the design is acceptable.

**APPENDIX B**

**SHAPE FILES**

## SHAPE FILES

A shape file contains information about the coordinates of the cathode elements. To create new shape files the user must supply information about the coordinates of the cathode elements of the new geometry. Once the new shape file is created, then it can be used with the program PLATFORM to model the potential distribution of the new geometry. Before attempting to create a new shape file, one must understand how the model works. This section will explain how the model works. It will also provide an example of a shape file and its corresponding file in BASIC.

The three-dimensional cube containing the node geometry has ten nodal points along the x, y, and z axis. The origin of the axis system is at the lower left vertice of the cube as shown in Figure 29. The program maps the nodal points in the cube to look for the cathode points. It starts at the axis origin at  $x=1$ ,  $y=1$ , and  $z=1$ . First it moves along the x-axis at  $y=1$  and  $z=1$ . Once the program reaches  $x=10$ , it updates  $y$  which is now equal to 2 and moves again along the x-axis. This is done for all the  $y$  values from 1 to 10. Once the program reaches  $x=10$  and  $y=10$  it updates the third coordinate  $z$  to 2. The same procedure starts all over again and is repeated for all the values of  $z$  from 1 to 10.

To enter the coordinates of the cathode elements, one

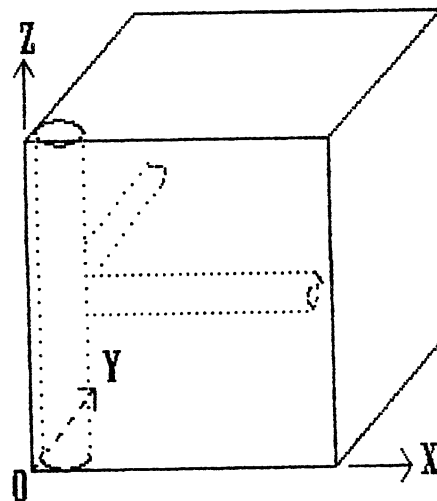


Figure 29. The Origin of the Three-Dimensional Cube Containing the Node Geometry is Located at the Lower Left Vertex of the Cube.

must follow the above format. The coordinates must be entered in a consecutive fashion. The first point in the file must have the lowest coordinate values (for example, 1, 1, 1) and the last point in the shape file must have the largest coordinate value (for example, 10, 10, 10). Therefore, the user must start at the first plane at  $z=1$ . In that plane, he must determine the coordinates of the cathode nodal points. Figure 30 shows the locations of the points representing the leg in the plane at  $z=1$ . The values are entered in the shape file, and the same operation is repeated for the plane at  $z=2$ . The planes at  $z=5$  and  $z=6$  contain the nodal points of the brace elements. Figure 31 shows the locations of the nodal points for the leg and for the two horizontal braces. Once all the planes from  $z=1$  to 10 are mapped for the cathode points, the shape file is complete. This procedure is explained better in the following example.

Table IV is a listing of the data contained in a shape file for a geometry consisting of one leg and two horizontal braces. The node geometry is shown in Figure 32. The shape file is a consecutive listing of the cathode coordinates and is arranged in data sets. Each data set contains four data points. The first datum is a negative number informing the computer whether the nodal point belongs to the leg or to the brace. The following three numbers in the data set are the coordinates of the nodal point along the  $x, y$ , and  $z$  axis. However, the first two data sets do not contain a

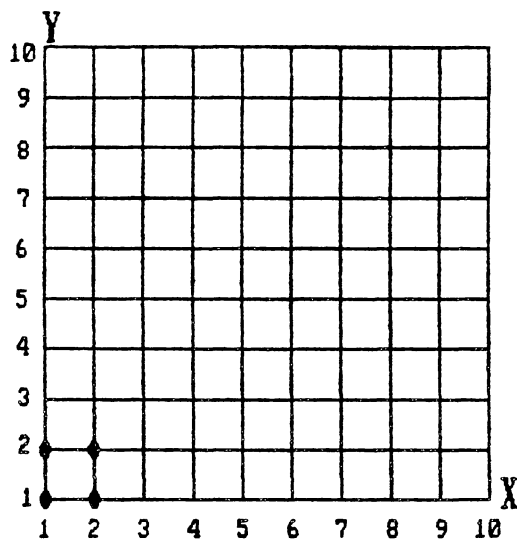


Figure 30. The Dots Represent the Locations of the Leg Coordinates in the Plane Perpendicular to the Z-Axis at  $Z=1$ .

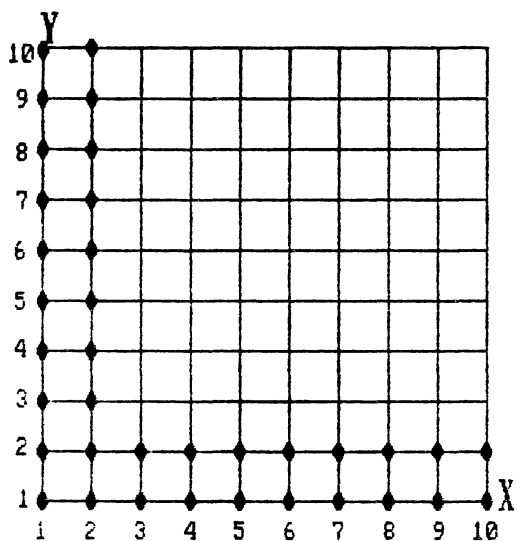


Figure 31. The Dots Represent the Locations of the Leg and the Two Horizontal Braces in the Plane Perpendicular to the Z-Axis at  $Z=5$ .



TABLE IV

A LISTING OF THE DATA CONTAINED IN A SHAPE FILE

---

1,0,2,7	-1,1,6,5	-1,1,10,6
1 leg and 2 horizontal T-joints,??	-1,2,6,5	-1,2,10,6
-2,1,1,1	-1,1,7,5	-2,1,1,7
-2,2,1,1	-1,2,7,5	-2,2,1,7
-2,1,2,1	-1,1,8,5	-2,1,2,7
-2,2,2,1	-1,2,8,5	-2,2,2,7
-2,1,1,2	-1,1,9,5	-2,1,1,8
-2,2,1,2	-1,2,9,5	-2,2,1,8
-2,1,2,2	-1,1,10,5	-2,1,2,8
-2,2,2,2	-1,2,10,5	-2,2,2,8
-2,1,1,3	-2,1,1,6	-2,1,1,9
-2,2,1,3	-2,2,1,6	-2,2,1,9
-2,1,2,3	-1,3,1,6	-2,1,2,9
-2,2,2,3	-1,4,1,6	-2,2,2,9
-2,1,1,4	-1,5,1,6	-2,1,1,10
-2,2,1,4	-1,6,1,6	-2,2,1,10
-2,1,2,4	-1,7,1,6	-2,1,2,10
-2,2,2,4	-1,8,1,6	-2,2,2,10
-2,1,1,5	-1,9,1,6	0,0,0,0
-2,2,1,5	-1,10,1,6	
-1,3,1,5	-2,1,2,6	
-1,4,1,5	-2,2,2,6	
-1,5,1,5	-1,3,2,6	
-1,6,1,5	-1,4,2,6	
-1,7,1,5	-1,5,2,6	
-1,8,1,5	-1,6,2,6	
-1,9,1,5	-1,7,2,6	
-1,10,1,5	-1,8,2,6	
-2,1,2,5	-1,9,2,6	
-2,2,2,5	-1,10,2,6	
-1,3,2,5	-1,1,3,6	
-1,4,2,5	-1,2,3,6	
-1,5,2,5	-1,1,4,6	
-1,6,2,5	-1,2,4,6	
-1,7,2,5	-1,1,5,6	
-1,8,2,5	-1,2,5,6	
-1,9,2,5	-1,1,6,6	
-1,10,2,5	-1,2,6,6	
-1,1,3,5	-1,1,7,6	
-1,2,3,5	-1,2,7,6	
-1,1,4,5	-1,1,8,6	
-1,2,4,5	-1,2,8,6	
-1,1,5,5	-1,1,9,6	
-1,2,5,5	-1,2,9,6	

---

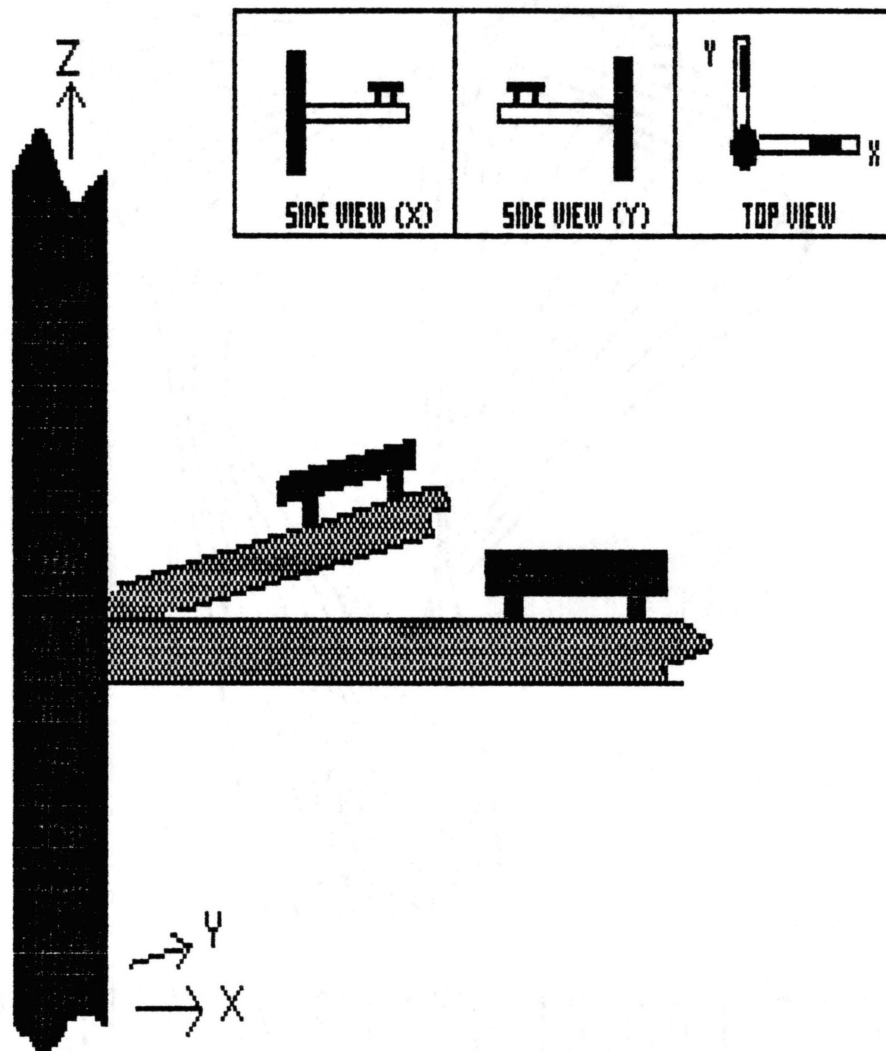


Figure 32. A Graphical Representation of a Node Geometry Consisting of One Leg and Two Horizontal Braces.

negative number and they are used for a different purpose. They provide information about the number of anodes and their locations. We will go through the first couple of data sets and elaborate more about the function of each number in the shape file.

#### Data Set 1

1 is a flag to indicate the anode type:

Anode type=1, anode on the x-axis

Anode type=2, anode on the y-axis

Anode type=3, anode on both the x-axis and y-axis

0 is the anode coordinate along the x-axis

2 is the anode coordinate along the y-axis

7 is the anode coordinate along the z-axis

#### Data Set 2

"One Anode and Two Horizontal Braces,?,?" is text information about the node geometry. A total of three comments separated by commas is allowed. The question mark, "?", is ignored by the program and is used to replace missing comments.

#### Data Set 3

-2 is a flag to indicate that the point belongs to the leg.

1 is the coordinate of the leg along the x-axis.

1 is the coordinate of the leg along the y-axis.

1 is the coordinate of the leg along the z-axis.

#### Data Set 4

-2 is a flag to indicate that the point belongs to the leg.

2 is the coordinate of the leg along the x-axis.

1 is the coordinate of the leg along the y-axis.

1 is the coordinate of the leg along the z-axis.

#### Data Set 5

-2 is a flag to indicate that the point belongs to the leg.

1 is the coordinate of the leg along the x-axis.

2 is the coordinate of the leg along the y-axis.

1 is the coordinate of the leg along the z-axis.

#### Data Set 6

-2 is a flag to indicate that the point belongs to the leg.

1 is the coordinate of the leg along the x-axis.

2 is the coordinate of the leg along the y-axis.

1 is the coordinate of the leg along the z-axis.

Data set 7 through 18 contain the same information on the leg coordinates in the planes at  $z=2, 3,$  and  $4$ . The planes at  $z=5$  and  $z=6$  contain the coordinates of the braces. Data sets 19 to 90 cover the coordinates of all the leg and the two horizontal braces in the cube. Data sets 91 to 105 contain the coordinates of the leg in the planes at  $z=7, 8, 9,$  and  $10$ . The last data set contains four zeros. This informs the program that it reached the end of the shape file.

The source listing of the program that created the shape file that we just discussed is shown in Figure 33. It can be adjusted to create new shape files. The source code is very simple and therefore can be modified without any major problem.

```

5 COLOR 14,0:CLS:KEY
OFF
10 ANDTYPE=1:AND1=0:AND2=2:AND3=7
20 OPEN "c:a1.shp" FOR OUTPUT AS #1
30 WRITE #1,ANDTYPE,AND1,AND2,AND3
35 PRINT #1,"1 leg and 2 horizontal T-joints";",";"?";",";"?"
40 FOR I=1 TO 105
50 READ COND,A,B,C
60 WRITE #1,COND,A,B,C
70 '***** 16 data points *****
80 DATA -2,1,1,1,-2,2,1,1,-2,1,2,1,-2,2,2,1
90 DATA -2,1,1,2,-2,2,1,2,-2,1,2,2,-2,2,2,2
100 DATA -2,1,1,3,-2,2,1,3,-2,1,2,3,-2,2,2,3
110 DATA -2,1,1,4,-2,2,1,4,-2,1,2,4,-2,2,2,4
120 '-----
130 '***** 2HT, 72 data points *****
140 DATA -2,1,1,5,-2,2,1,5,-1,3,1,5,-1,4,1,5,-1,5,1,5,-1,6,1,5,-1,7,1,5,-1,8,1,5
,-1,9,1,5,-1,10,1,5
150 DATA -2,1,2,5,-2,2,2,5,-1,3,2,5,-1,4,2,5,-1,5,2,5,-1,6,2,5,-1,7,2,5,-1,8,2,5
,-1,9,2,5,-1,10,2,5
160 DATA -1,1,3,5,-1,2,3,5,-1,1,4,5,-1,2,4,5,-1,1,5,5,-1,2,5,5,-1,1,6,5,-1,2,6,5
,-1,1,7,5,-1,2,7,5,-1,1,8,5,-1,2,8,5,-1,1,9,5,-1,2,9,5,-1,1,10,5,-1,2,10,5
170 DATA -2,1,1,6,-2,2,1,6,-1,3,1,6,-1,4,1,6,-1,5,1,6,-1,6,1,6,-1,7,1,6,-1,8,1,6
,-1,9,1,6,-1,10,1,6
180 DATA -2,1,2,6,-2,2,2,6,-1,3,2,6,-1,4,2,6,-1,5,2,6,-1,6,2,6,-1,7,2,6,-1,8,2,6
,-1,9,2,6,-1,10,2,6
190 DATA -1,1,3,6,-1,2,3,6,-1,1,4,6,-1,2,4,6,-1,1,5,6,-1,2,5,6,-1,1,6,6,-1,2,6,6
,-1,1,7,6,-1,2,7,6,-1,1,8,6,-1,2,8,6,-1,1,9,6,-1,2,9,6,-1,1,10,6,-1,2,10,6
200 '-----
210 '***** 17 data points *****
220 DATA -2,1,1,7,-2,2,1,7,-2,1,2,7,-2,2,2,7
230 DATA -2,1,1,8,-2,2,1,8,-2,1,2,8,-2,2,2,8
240 DATA -2,1,1,9,-2,2,1,9,-2,1,2,9,-2,2,2,9
250 DATA -2,1,1,10,-2,2,1,10,-2,1,2,10,-2,2,2,10,0,0,0,0
260 '-----
270 NEXT I
280 CLOSE #1

```

Figure 33. The Source Listing of the BASIC Program That Created the Shape File Presented in Table IV.

APPENDIX C

LISTING AND FIGURES OF THE  
NODE GEOMETRIES

## NODE GEOMETRIES

The figures in this appendix represent the twenty six different node geometries used in the program PLATFORM. Each figure is intended to give the user a rough idea on the geometry of the structural node. The figures are preceded by a list describing each geometry. Each number in the list corresponds to a similar number in each figure as follows:

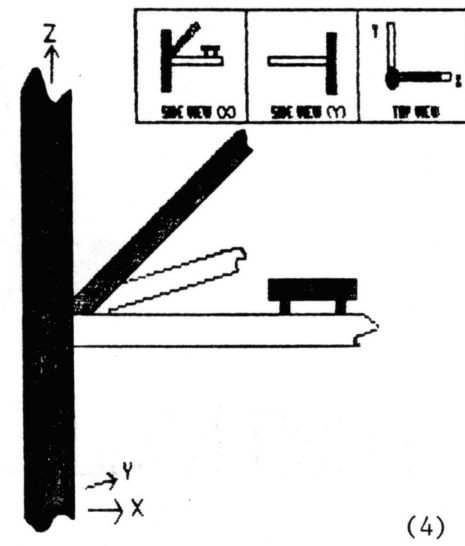
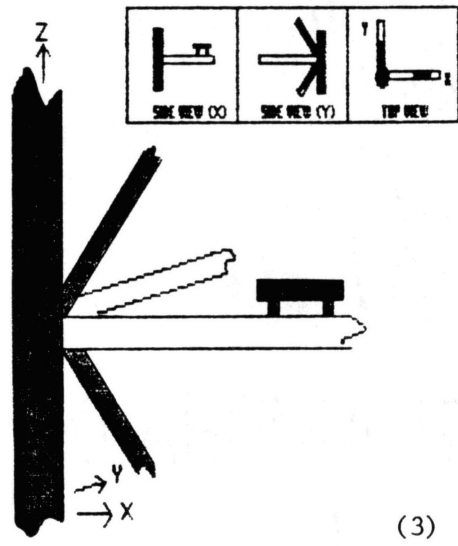
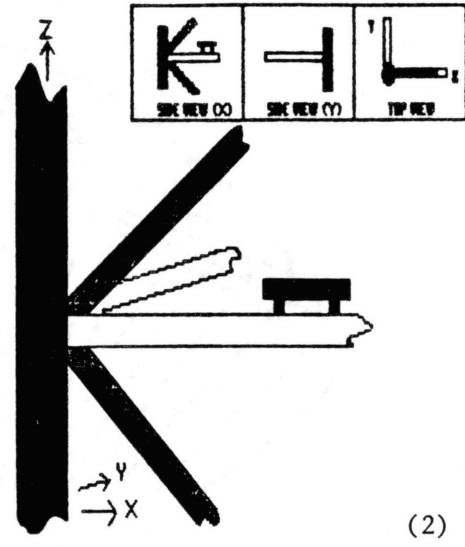
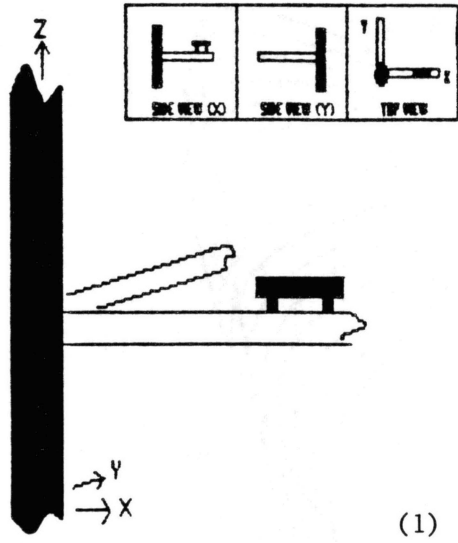
- 1- 2 horizontal T-joints
- 2- 2 horizontal T-joints and 1 K-joint along the x-axis
- 3- 2 horizontal T-joints and 1 K-joint along the y-axis
- 4- 2 horizontal T-joints and 1/2 K-joint along the x-axis pointing upward.
- 5- 2 horizontal T-joints and 1/2 K-joint along the y-axis pointing upward.
- 6- 2 horizontal T-joints and 1/2 K-joint along the x-axis pointing downward.
- 7- 2 horizontal T-joints and 1/2 K-joint along the y-axis pointing downward.
- 8- 2 horizontal T-joints and 1 K-joint along the x-axis and 1 K-joint along the y-axis.
- 9- 2 horizontal T-joints and 1 K-joint along the x-axis and 1/2 K-joint along the y-axis pointing downward.
- 10- 2 horizontal T-joints and 1 K-joint along the x-axis

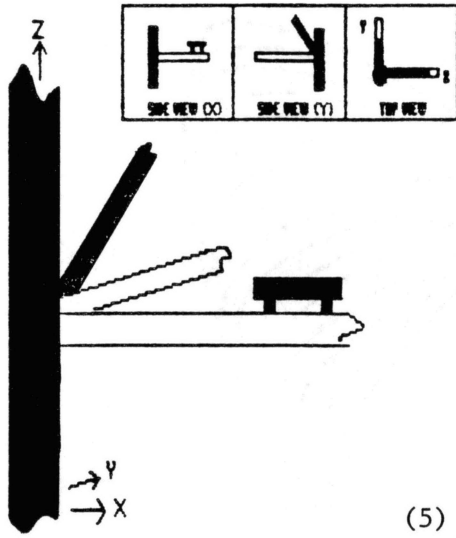
- and  $1/2$  K-joint along the y-axis pointing upward.
- 11- 2 horizontal T-joints and  $1/2$  K-joint along the x-axis pointing downward and 1 K-joint along the y-axis.
- 12- 2 horizontal T-joints and  $1/2$  K-joint along the x-axis pointing upward and 1 K-joint along the y-axis.
- 13- 2 horizontal T-joints and  $1/2$  K-joint along the x-axis pointing upward and  $1/2$  K-joint along the y-axis pointing upward.
- 14- 2 horizontal T-joints and  $1/2$  K-joint along the x-axis pointing downward and  $1/2$  K-joint along the y-axis pointing downward.
- 15- 2 horizontal T-joints and  $1/2$  K-joint along the x-axis pointing downward and  $1/2$  K-joint along the y-axis pointing upward.
- 16- 2 horizontal T-joints and  $1/2$  K-joint along the x-axis pointing upward and  $1/2$  K-joint along the y-axis pointing downward.
- 17- 1 horizontal T-joint and 1 K-joint along the x-axis and 1 K-joint along the y-axis.
- 18- 1 horizontal T-joint and 1 K-joint along the x-axis and  $1/2$  K-joint along the y-axis pointing downward.
- 19- 1 horizontal T-joint and 1 K-joint along the x-axis and  $1/2$  K-joint along the y-axis pointing upward.
- 20- 1 horizontal T-joint and  $1/2$  K-joint along the x-axis pointing downward and 1 K-joint along the y-axis.
- 21- 1 horizontal T-joint and  $1/2$  K-joint along the x-axis pointing upward and 1 K-joint along the y-axis.



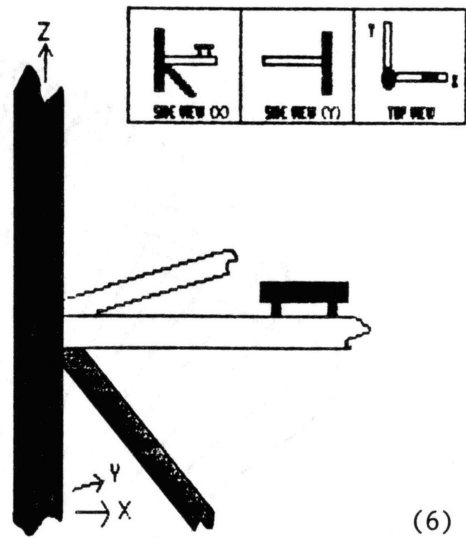
- 22- 1 horizontal T-joint and 1/2 K-joint along the x-axis pointing upward and 1/2 K-joint along the y-axis pointing upward.
- 23- 1 horizontal T-joint and 1/2 K-joint along the x-axis pointing downward and 1/2 K-joint along the y-axis pointing downward.
- 24- 1 horizontal T-joint and 1/2 K-joint along the x-axis pointing downward and 1/2 K-joint along the y-axis pointing upward.
- 25- 1 horizontal T-joint and 1/2 K-joint along the x-axis pointing upward and 1/2 K-joint along the y-axis pointing downward.
- 26- 1 horizontal T-joint and 1 K-joint along the x-axis.

These geometries are the same for the case where the anode is on the brace along the x-axis or where the anode is on the brace along the y-axis. Therefore, there are 26 geometries for either case. However, when there are two anodes with one anode on each axis (x and y axis) there are only 17 geometries. This is because one of the two horizontal T-joints will be missing in the geometry and there will be no place to put the second anode.

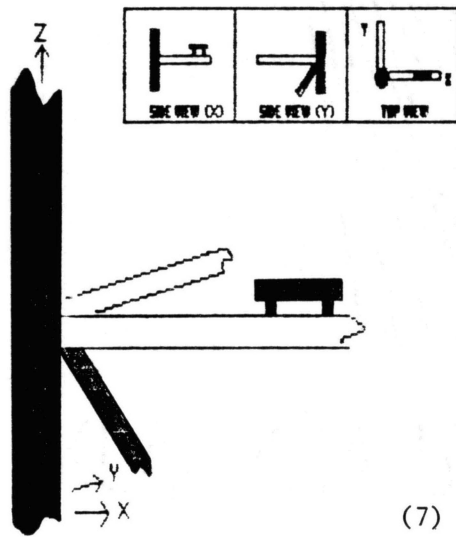




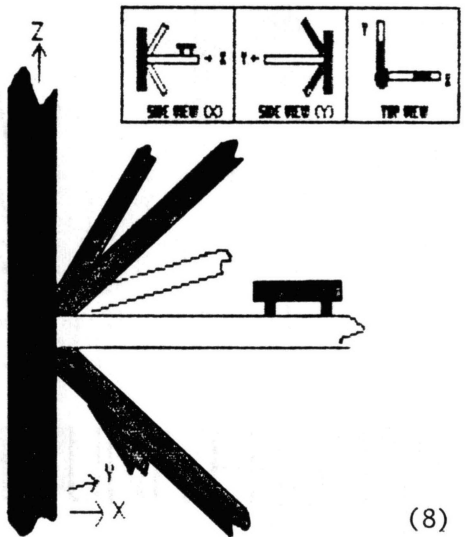
(5)



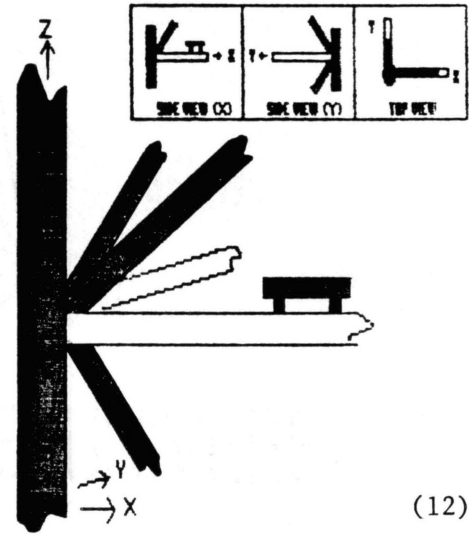
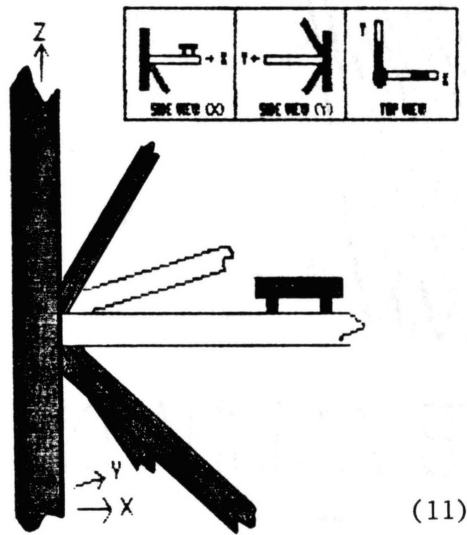
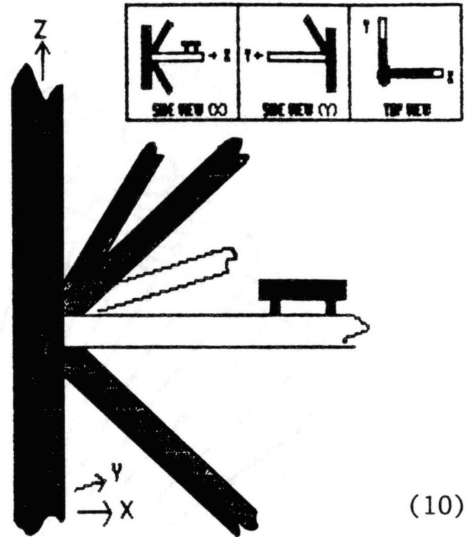
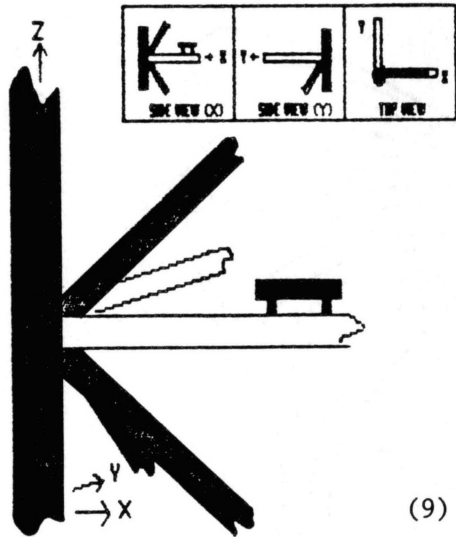
(6)

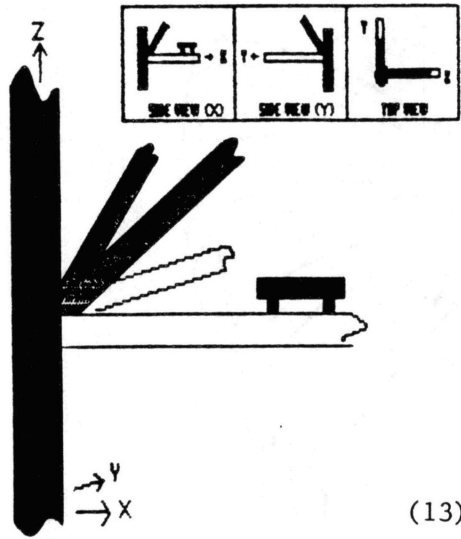


(7)

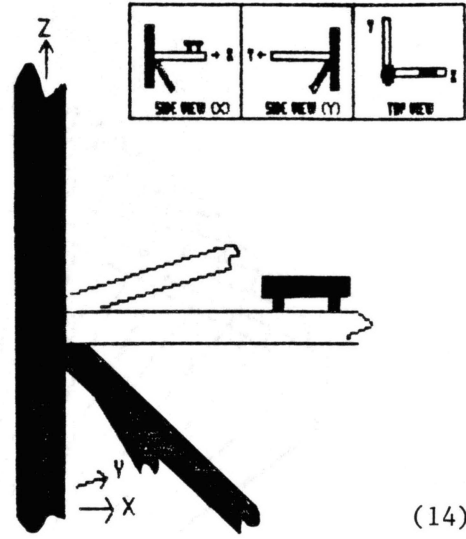


(8)

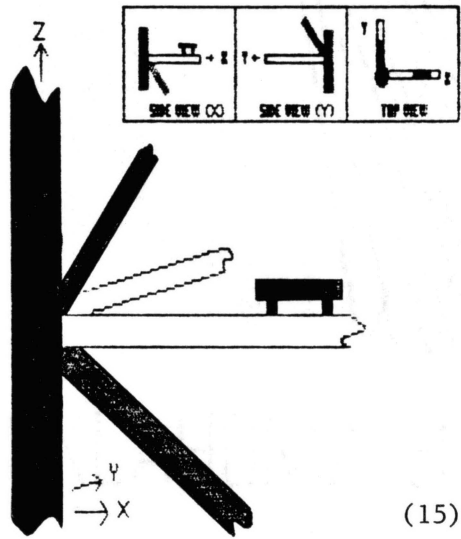




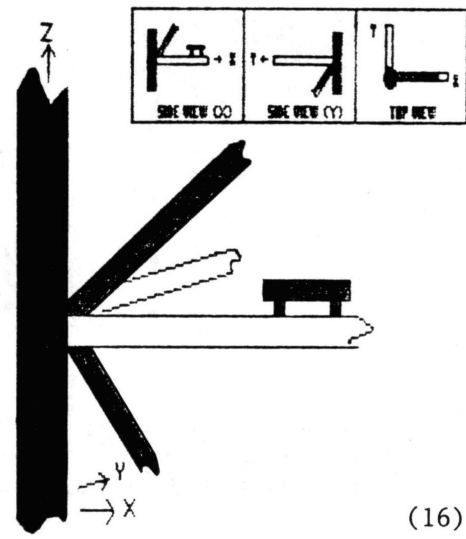
(13)



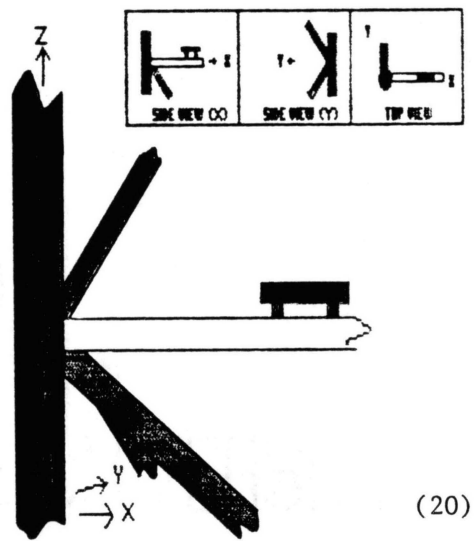
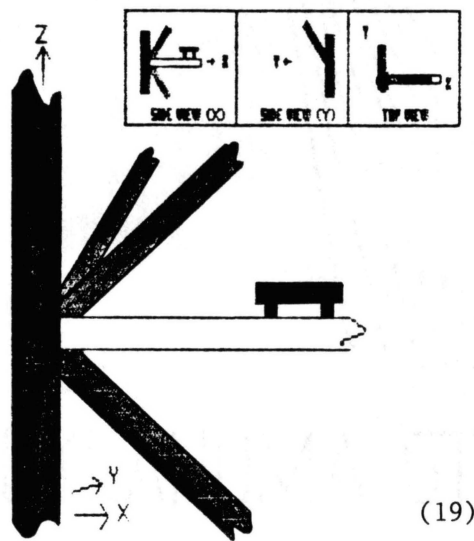
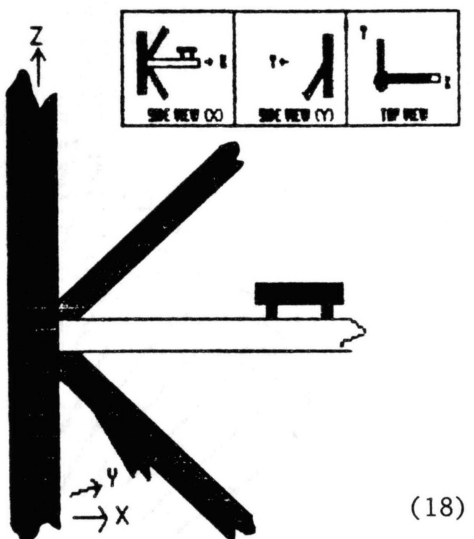
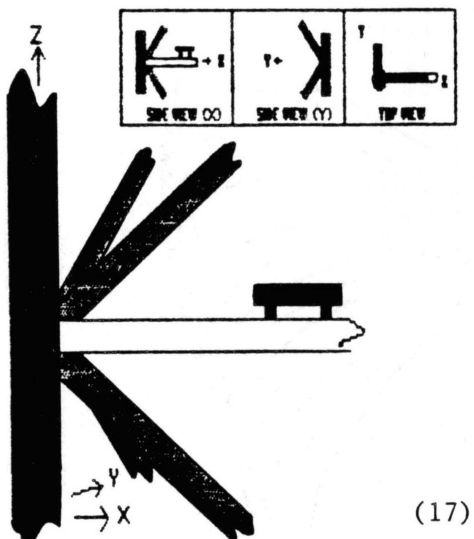
(14)

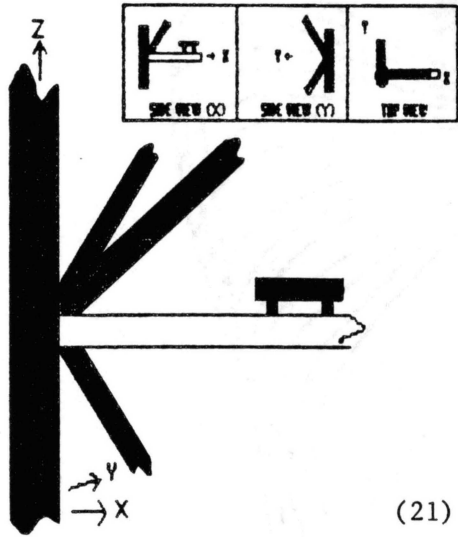


(15)

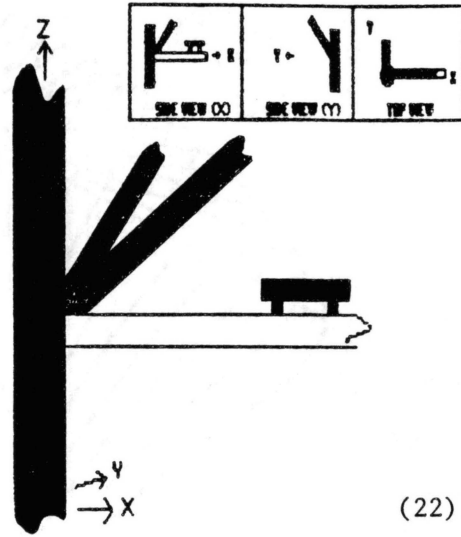


(16)

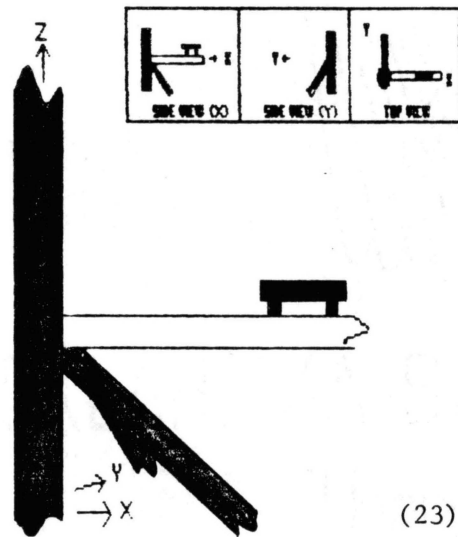




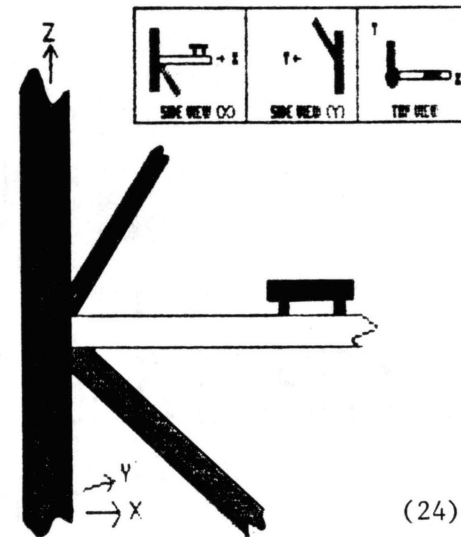
(21)



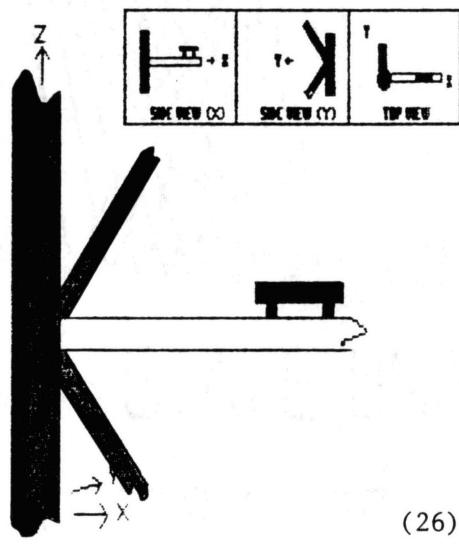
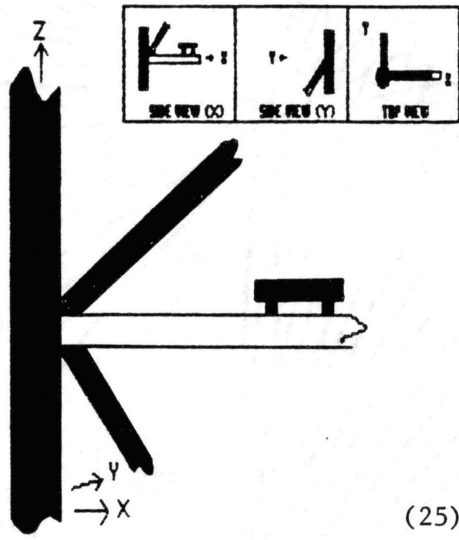
(22)



(23)



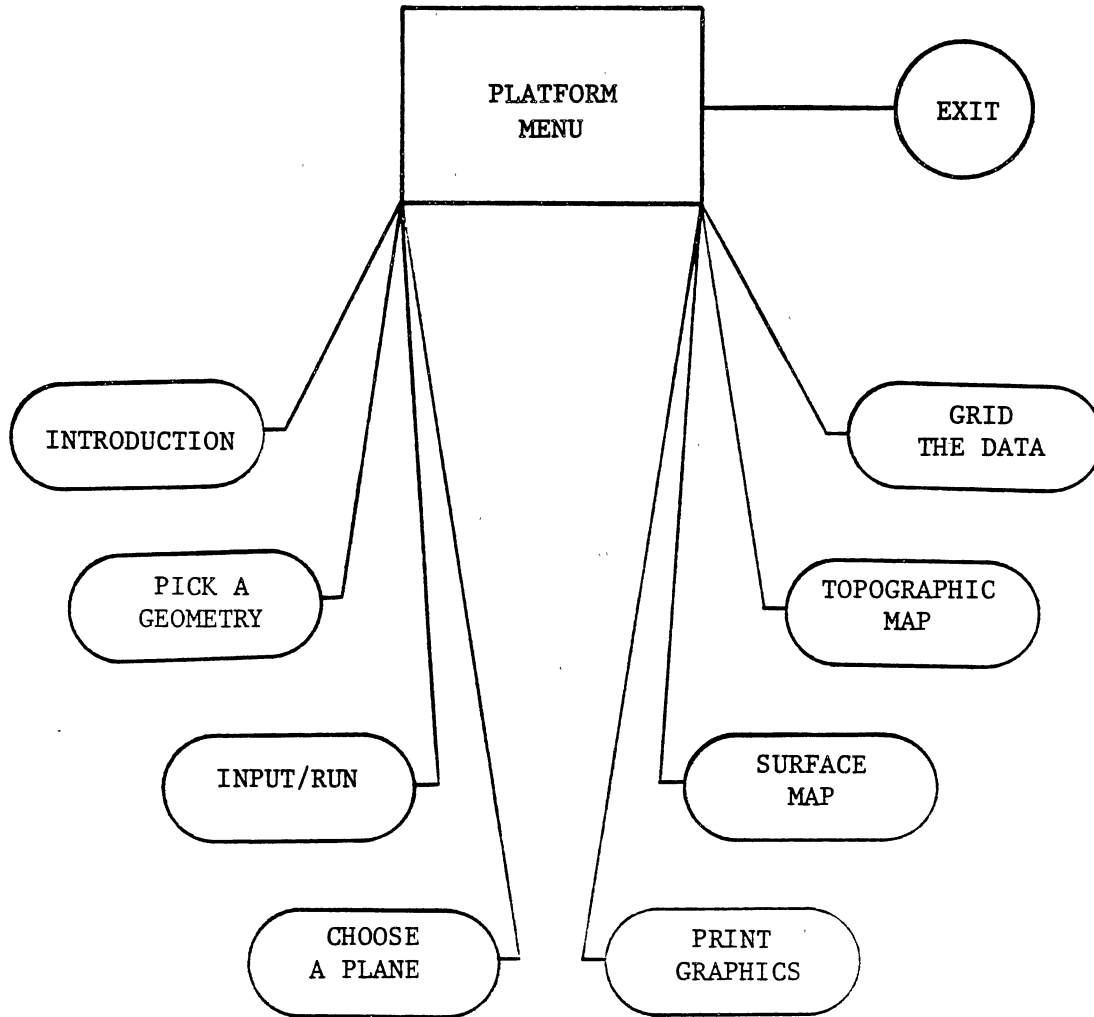
(24)





**APPENDIX D**

**PROGRAM TREE STRUCTURE**



THE TREE STRUCTURE OF THE PROGRAM PLATFORM

VITA

Michael Raymond Haroun

Candidate for the Degree of  
Master of Science

Thesis: CATHODIC PROTECTION MODELING OF NODES IN OFFSHORE  
STRUCTURES

Major Field: Chemical Engineering

Biographical:

Personal Data: Born in Makene, Sierra Leone, July 18,  
1960, son of Raymond and Clautilde Haroun.

Education: Graduated from College des Freres Mont La  
Salle High School, Ain Saade, Lebanon, in May  
1978; received the Bachelor of Science Degree in  
Chemical Engineering from Oklahoma State  
University in May, 1984; completed the  
requirements for the Master of Science in Chemical  
Engineering at Oklahoma State University in July,  
1986.

Professional Experience: French Instructor, Foreign  
Language Department, Oklahoma State University,  
January 1984 through May 1984; Teaching Assistant,  
Engineering Science Department, Oklahoma State  
University, August 1984 to May 1985; Corrosion  
Engineer, Shell Development Company, Houston, May  
1985 to August 1985; Research Assistant, School of  
Chemical Engineering, Oklahoma State University,  
August 1985 to present.