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ECONOMIC EFFECTS OF METALLIC CORROSION IN THE UNITED STATES—

(Appendix B)

A Report to NBS
by
Battelle Columbus Laboratories

ECONOMIC EFFECTS OF METALLIC CORROSION IN THE UNITED STATES

- - - A Three Part Study for Congress - - -

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ECONOMIC EFFECTS OF METALLIC CORROSION IN THE UNITED STATES—Appendix B

Part II

+ Special publication

A Report to NBS by Battelle Columbus Laboratories

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FOREWORD

From the beginning of formal discussions on this study in the fall of 1976, many people and organizations were contacted. Through them the information necessary to estimate effects of corrosion was gathered. The cooperation from industry, government, professional societies, and trade organizations was excellent.

All corrosion effects were expressed as changes to coefficients and elements in the Corrosion Input/Output Model. Supportive material for cost estimates reported here, i.e., Input/Output Tables, and a compilation of all adjustments for corrosion effects with their cause, are on file at Battelle's Columbus Laboratories and copies were sent to the National Bureau of Standards.

An advisory Panel participated throughout the study:

Dr. Seymour L. Blum
The MITRE Corporation

Mr. C. P. Dillon
C.P. Dillon and Associates

Dr. Mars G. Fontana
Materials Technology Institute of the Chemical Process Industries, Inc.

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General Motors Corporation

Their valuable contributions, review, and guidance are gratefully acknowledged.

Significant contributions were made by Dr. E. B. Berman of the MITRE Corporation, who was an economic consultant to National Bureau of Standards for this study.

The National Bureau of Standards staff actively participated in many aspects of the study, including the preliminary planning, definitions, and the data gathering efforts. Dr. L. H. Bennett, Dr. J. Kruger, Dr. E. Passaglia, and Dr. H. Yakowitz are specifically acknowledged for their worthy contributions. Also contributing from NBS were J. Ambrose, Y. Bertocci, J. Carroll, B. Christ, E. Escalante, W. Gerhold, A. Melmed, F. Ogburn, R. Parker, C. Reimann, A. Ruff, G. Ugiansky and J. Young.

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THE ECONOMIC EFFECT OF CORROSION IN THE UNITED STATES

by

J. H. Payer, D. G. Dippold, W. K. Boyd,
W. E. Berry, E. W. Brooman,
A. R. Buhr, and W. H. Fisher

SUMMARY

The purpose of this study was to determine the economic effect of corrosion in the United States. A valid estimate of the cost of corrosion is necessary if government and industry are to make rational choices of what resources and approaches should be used to reduce wastage. The results provide a basis for development of technological, legislative, and other initiatives to promote effective economic savings.

It was beyond the scope of the present study to develop or evaluate alternative proposals to reduce corroson costs, e.g., methods to increase replacement lives of capital equipment or to reduce maintenance and repair costs. Data gathered and procedures developed to estimate corrosion costs are applicable, however, to the detailed analysis required for evaluation of alternatives.

The working definition of cost of corrosion was the *increment* of total costs incurred because corrosion exists. Corrosion costs include both capital costs, e.g., costs of replacement of plant and equipment, and operating costs, e.g., cost of maintenance, repair, and corrosion control. The study was confined to corrosion of metals and did not consider deterioration of other engineering materials, e.g., concrete, plastics, glass, wood, and refractories.

Corrosion has a major impact on the economy of the U.S. Effort expended for corrosion control and in production of goods for replacement or repair because of corrosion would be available for alternate uses if corrosion losses were reduced. Of particular importance in these times of materials/energy shortages and need for conservation, is the irrecoverable losses of expensive and strategic metals: chromium, nickel, molybdenum, zinc, aluminum, etc. Dollar value of technical expertise and labor losses are approximately ten times that of material losses.

A modified form of Battelle's national Input/Output Model provided the methodological framework for estimation of corrosion costs. The Corrosion Input/Output Model permitted analysis of interindustry relationships in the national economy and attribution of relative costs to specific segments of the conomy.

Each industrial sector is viewed as a user and as a producer of goods and services. Analysis was performed by a team of economic and corrosion experts. The application of Input/Output analysis resulted in more comprehensive and detailed treatment of national corrosion costs than for any previous estimates.

Total costs for corrosion were separated into avoidable and unavoidable costs. The former was defined as those costs amenable to reduction by the most economically effective use of presently available corrosion control technology. Reduction of the latter requires technological advance.

For 1975 as the base year, total costs of corrosion were estimated to be 4.9 percent of Gross National Product (GNP). Approximately 40 percent of total costs (2.9 percent GNP) were estimated to be avoidable, i.e., amenable to reduction by presently available corrosion control technology. Dollar value of resources (materials, labor, energy, and technical capabilities) ascribed to corrosion-related activities were:

Total Costs to U.S.	$82 Billion
Avoidable Costs	$33 Billion
Unavoidable Costs	$49 Billion.

The significance of these estimates is that they provide a reference point for the impact on corrosion against which the relative impact of other factors affecting the economy can be compared.

Total costs were allocated to segments of the economy. A series of indicators express corrosion costs on a dollar basis and as percent of sales for total and avoidable costs.

The importance of identifying the source of costs and the wide variation from industry to industry of the predominant elements of corrosion costs are illustrated by results of analysis for several industrial sectors. For the livestock industry, approximately 95 percent of total costs ($1100M) were the result of adjusting the average replacement life of capital from 14 years to 21 years if corrosion were not a factor, and less than 5 percent of total costs were the result of corrosion-related maintenance. For the Fabricated Structural Metal industry, greater than 95 percent of total corrosion costs ($1150M) resulted from costs for providing corrosion protection to the industry's product, i.e., metallic coatings, corrosion resistant metals, cathodic protection, and organic coatings. For the Industrial Chemical Industry approximately 65 percent of total costs ($690M) were ascribed to operating costs and 35 percent to capital. Operating costs resulted from corrosion-related maintenance and repair and purchases of corrosion inhibitor, whereas capital costs resulted from corrosion effects on replacement lives of equipment and on production capacity.

Input/Output analysis, which provided the methodological framework for this study, permitted detailed and comprehensive treatment of all elements of the costs of corrosion. Production costs, capital costs, changes in replacement lives, etc. were treated in a coordinated and systematic manner. The methodology applied and developed in this study can be used to study the effects of other forms of wastage to the economy.

Data gathered and procedures developed in this study provide a sound basis for technological assessments. The principal attribute of Input/Output analysis is the determination of *indirect,* as well as *direct* consequences of technological change. The corrosion I/O Model can be used to assess proposed means to reduce costs.

1 INTRODUCTION

The potential savings to the United States economy by improved corrosion prevention and control are well recognized. The economic effect of corrosion is that labor, materials, technical expertise, and energy are used which would be available for alternative uses were it not for corrosion. The National Commission on Materials Policy concluded that one of the ''most obvious opportunities for material economy is control of corrosion''.

While several estimates were made over the years, there has been no focused and concentrated effort directed to determine the cost of corrosion to the U.S. based on a sound technical-economic method. Some of these studies were the work of individuals who had little or no background in economics or econometrics and who made no serious attempt to gather extensive amounts of data. Other studies, for example, the Hoar Report on Cost of Corrosion for the U.K., have involved committees set up by governmental agencies and have used voluntary workers unable to devote concentrated efforts. These past efforts have suffered from some or all of the following: (1) a limited data base, (b) a loosely structured definition of the cost of corrosion, and (c) limited use of economic analysis techniques.

A valid estimate of the cost of corrosion is necessary if government and industry are to make rational choices of what resources and approaches should be brought to bear to reduce losses. This information provides a basis for developing technological, legislative, and other initiatives to promote effective economic savings. Battelle's Columbus Laboratories conducted this study to determine the economic effect of corrosion in the U.S. The Study, sponsored by The National Bureau of Standards (NBS), was a joint effort of economists and corrosion specialists from the two laboratories. Congress initiated the study by directive to NBS.

The working definition of cost of corrosion for this study was the *increment* of total costs incurred by the *user* because of corrosion. This definition, discussed in detail later, includes both capital costs, e.g., costs of replacement of plant and equipment, and operating costs, e.g., costs of maintenance, repair, and corrosion control. The study was confined to corrosion of metals and did not consider deterioration of other engineering materials, e.g., concrete, plastics, glass, wood, and refractories.

Total costs of corrosion were divided into avoidable and unavoidable costs. The former is defined as those costs which can be avoided by the most economically effective use of presently available corrosion prevention and control technology. The latter require technological advances prior to realization of cost reductions.

In estimating corrosion costs, a modified form of Battelle's national Input/Output model provides the methodological framework for the study. This model permits analysis of interindustry relationships in the national economy. A total of 130 industrial sectors were included, e.g., petroleum refining, engines and turbines, water transportation, and electric power. Each sector was viewed as a user and as a producer of goods or services. This methodology allowed the determination of relative costs of corrosion in each sector as well as cost of corrosion for the entire economy.

Results and procedures of the study are presented in this report. In Section 2, the impact of corrosion on the U.S. economy, the approach taken in this study, and several principal concepts used throughout the study are presented and discussed. A description of Input/Output analysis and the specific features, used in the application to the determination of the costs of corrosion are discussed in Section 3. Data gathering procedure, treatment of each element of costs of corrosion, and description of estimates of corrosion costs are presented in Section 4. In Section 5, results of the study are reported. Total costs of corrosion were divided into avoidable and unavoidable portions and relative costs attributed to each sector of the economy. The results section also includes a discussion of uncertainty in estimates, and uses of Input/Output analysis for technological assessment.

Three areas were identified for more detailed analysis: Federal government, electric power generation, and personally owned automobiles. Costs of corrosion in these areas are discussed in Appendices A, B, and C, respectively. A glossary of terms is presented in Section 7, and a list of industrial sector titles for the I/O model is presented in Appendix D.

2 BACKGROUND

2.1 Impact of Corrosion on U.S. Economy

Corrosion has a major impact on the economy of the U.S. Efforts expended for corrosion control and in the production of goods for replacement or repair because of corrosion would be available for alternative uses if corrosion losses were reduced. Of particular importance, in these times of materials/energy shortages and need for conservation, are the irrecoverable losses of expensive and strategic metals, e.g., chromium, nickel, molybdenum, zinc, and aluminum. The dollar value of technical expertise and labor losses are approximately ten times that of material losses.

The magnitude of corrosion cost is astonishing. In 1949, the annual cost of corrosion to the U.S. was estimated by Uhlig[29] to be $5.5 billion. A more recent estimate in 1972, by a task group of The Federation of Materials Societies estimated the U.S. losses because of corrosion to be on the order of $15 Billion per year. It was further estimated that approximately $5 Billion of the total loss was recoverable through application of corrosion control techniques already developed and available for use.

A survey of corrosion costs to the United Kingdom* estimated an annual cost equal to 3.5% of the gross national product. It was estimated that a saving of approximately one quarter of these costs could be achieved with better use of current knowledge and techniques.

The impact of corrosion is more, however, than that measured in dollars alone. Materials limitations are among the pacing constraints to further technological advance in key segments of the economy: fossil energy production, electric power generation, aerospace, transportation, and construction. Present technology is limited because materials are not available for more severe service or costs of suitable materials are prohibitive. Increased corrosion resistance is at or near the top of lists for desired materials' properties.

In a broader sense, corrosion is a form of wastage. Materials are depleted by degradation modes such as corrosion, in the same manner as illness affects people, and inefficiency affects energy. The use of resources (materials, labor, technical expertise, and energy) is necessary to the economy just as food and oxygen are necessary to sustain life.

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*Report of the Committee on Corrosion and Protection; T. P. Hoar, Chairman; Department of Trade and Industry; Her Majesty's Stationery Office; London; 1971.

It is the wasteful and inefficient use of resources that is deplorable and must be reduced, and corrosion is a principal contributor to the wasteful use of resources. The forms of waste can be separated into those which are amenable to reduction by presently available technology (avoidable) and those which are not (unavoidable). Reduction of avoidable wastage requires technology transfer and implementation, while reduction of unavoidable wastage requires technological advance.

In order to implement effective cost reduction programs on a rational basis, valid estimates of the magnitude of corrosion costs and the relative distribution of those costs among segments of the economy are essential. The purpose of this study was to develop this information.

2.2 Approach to Determination of Costs of Corrosion

The approach to determine the economic effect of corrosion in the U.S. was first, to determine an inventory of items which corrode. The inventory comprised two categories: (1) Producer capital, i.e., plants and equipment for production of goods and services for sale and (2) Social capital and infrastructure, which includes all items not included in producer capital, e.g., defense material, highways and related structures, personal passenger cars, personal houses and appliances, and public buildings.

Secondly, a definition of cost of corrosion was developed that contained elements of cost which were measurable and amenable to study. Some elements included were maintenance and repair, corrosion prevention and control, replacement life, and excess capacity for scheduled downtime. Thirdly, the inventory of corrodibles was analyzed for each element of corrosion cost. Fourthly, the economic effect of corrosion, defined as use of capital, materials, energy, labor, and technical expertise that would be available for alternative uses if corrosion was not a factor, was determined.

Total corrosion costs were separated into avoidable and unavoidable costs. The former was defined as those costs amenable to reduction by presently available corrosion control technology. Reduction of the latter requires technological advance. In addition, the portion of total costs attributed to each segment of the economy was determined.

A modified form of Battelle's National Input/Output Model provided the methodological framework for the study. This model describes interindustry relationships in the national economy. A total of 130 industrial sectors were included, e.g., petroleum refining, engines and turbines manufacturing, water transportion, and electric power generation. Each sector was treated as both a user und a producer.

In order to determine the portion of economic activity ascribed to corrosion, three scenarios were investivated by Input/Output analysis: World I—The economy as it exists, World II—The economy with all activity ascribed to corrosion removed, and World III—The economy with universal use of best corrosion control practice. The difference between World I and World II provided an estimate of total cost of corrosion, and the difference between World I and World III provided an estimate of avoidable costs of corrosion. Indicators were developed using input/output analysis to attribute relative costs to segments of the economy.

Analysis was performed by a team of economic and corrosion experts. Estimates of effects of corrosion were based on available data and technical judgment. Information was gathered from open literature, technical reports, and interviews with technical experts. An Advisory Panel, a peer group of corrosion experts, was established to provide guidance throughout the study.

2.3 Principal Concepts

A number of principal concepts were developed and/or adopted for use in the determination of the cost of corrosion. These are presented below.

2.3.1 Definition of Cost of Corrosion

Although a broader definition is often chosen, for this study corrosion was restricted to metals only. Environmental degradation of other non-metallic engineering materials was excluded, e.g., concrete, wood, refractories, plastic, and glass. Corrosion was defined as degradation of metals where the environment, aqueous or gaseous, contributed to the mode of degradation. In addition to general or local metal wastage by dissolution, other processes included were stress-corrosion cracking, corrosion fatigue, erosion-corrosion, oxidation, sulfidation, etc. Degradation processes in which the environment was not a factor were excluded, e.g., creep, mechanical damage, and stress rupture.

The cost of corrosion was defined as that *increment* of total cost incurred because corrosion exists. Conversely, what costs would not be incurred if corrosion did not exist? Each segment of the economy was viewed as a producer and as a user of goods and services.

For a manufacturer, corrosion costs are incurred in the manufacturing process in several ways. First, the inputs required for his product (materials, energy, labor, and technical expertise) are affected by corrosion. For example, a product is painted for corrosion protection, a corrosion resistant metal is chosen in place of carbon steel for corrosion protection, technical service is required to design and install cathodic protection on a product, or additional heat treatment is required to relieve stresses for protection against stress-corrosion cracking.

Secondly, other operating costs are affected by corrosion. For example, corrosion inhibitors and water treatment costs are incurred to control corrosion of the plant and equipment, portions of maintenance and repair costs are attributed to corrosion, and corrosion specialists are employed to implement a corrosion control program.

Thirdly, capital costs are incurred because of corrosion. The replacement life of equipment required in the manufacturing process is decreased by corrosion. For an operation which runs continuously, excess capacity is required to allow for scheduled downtime for corrosion-related maintenance. In other instances, redundant equipment is kept to allow maintenance on one unit while processing continues with another unit in service.

For an end-user, e.g., a private citizen, corrosion costs are incurred for purchases of corrosion prevention and control products, maintenance and repair, and premature replacement.

Elements of the cost of corrosion were identified to provide a convenient check-list for consistent treatment of costs in all segments of the economy. These elements are presented and described in the following section. While in many instances costs were clearly and exclusively ascribed to corrosion, certain costs were incurred for multiple reasons and technical judgment was used to allocate costs for corrosion and non-corrosion. Examples of the former are costs for coatings on buried, steel pipelines and costs for cathodic protection on ships' hulls; both are corrosion costs exclusively. An example of the latter is the cost of painting exposed surfaces on automobiles. Fenders, hoods, etc., are painted for corrosion protection and aesthetics. In this instance, one-half of the painting costs were ascribed to corrosion. Similar judgments were made in other areas where multi-purpose operations were encountered.

2.3.2 Elements of the Cost of Corrosion

Ten elements of the cost of corrosion were identified. Estimating procedures for each is presented in Section 4.2. All segments of the economy were analyzed for the following elements:

2.3.2.1 Replacement of Equipment and Buildings. Equipment and buildings are replaced because of corrosion, wear, obsolescence, etc. Corrosion contributed to cost when the replacement life was less than it would have been if corrosion did not exist. Conceptually, the value of replacement life is the average number of years an item is used prior to replacement in a given segment of the economy. The replacement life of similar items in similar service can vary from industry to industry.

2.3.2.2 Loss of Product. This element of cost includes loss of valuable product because of leaks in equipment, contamination by corrosion products of solutions requiring high purity, and scrap losses during storage or shipping of items which corrode.

2.3.2.3 Maintenance and Repair. The portion of maintenance and repair costs ascribed to corrosion are included in this element. Both scheduled and unscheduled activities are included.

2.3.2.4 Excess Capacity. Excess plant capacity is considered a cost only for operations which are scheduled for continuous operation where portions of scheduled downtime could be ascribed to corrosion. For non-continuous operations, lost production because of corrosion was not considered as a cost of corrosion since the production could be recovered in normal off periods. This element accounts for additional plant capacity (capital stock) because of corrosion.

2.3.2.5 Redundant Equipment. This element, like excess capacity, accounts for additional plant equipment (capital stock) required because of corrosion. Specific items, e.g., large fans and pumps, are backed-up by identical redundant items to allow processing to continue while one is being maintained.

2.3.2.6 Corrosion Control. Costs for corrosion control and prevention included costs for corrosion inhibitors, organic coatings, metallic coatings and platings, and cathodic protection.

2.3.2.7 Technical Support. Costs for corrosion-related research and development, engineering, and other technical support were included in this element.

2.3.2.8 Design. The incremental increase in costs of materials of construction selected (for corrosion resistance or protection against product contamination by corrosion products) over the costs of materials if corrosion was not a factor, was included in this element. In addition, costs ascribed to incorporation of a corrosion allowance and costs for special processing, e.g., stress relief or shot peening, were included.

2.3.2.9 Insurance. Of costs for insurance premiums to protect against losses ascribed to corrosion only those costs for writing and administering the policy were included. Charges which are to build a reserve to cover claims are not included because these costs are balanced by claims and there is no net cost.

2.3.2.10 Parts and Equipment Inventory. The costs of parts or equipment for a corrosion inventory are not included in this element. Only costs for handling and storage of the inventory are included.

2.3.3 Avoidable and Unavoidable Costs

Total costs of corrosion are defined as all costs above those incurred if corrosion did not exist. Although this definition has a hypothetical and unachievable basis, i.e., corrosion does exist, it is a well defined, static base against which the state of the real world can be measured. An analogy is the comparison of engines with the maximum efficiency, Carnot cycle engine.

It is also useful to separate total costs into avoidable and unavoidable portions. Procedures to estimate avoidable costs of corrosion are described in Section 4.3. Costs which are amenable to reduction by the most economically efficient use of presently available corrosion control technology are defined as avoidable costs. Those which are not amenable to reduction by presently available technology are unavoidable.

For example, consider the costs of a corrugated-steel roof on a warehouse. If corrosion did not exist, an uncoated steel roof would be selected and last for the life of the warehouse. Any corrosion-related costs incurred over the construction costs for the no corrosion base case are included in the total cost of corrosion: increased cost of roofing material and installation, maintenance costs, or premature replacement costs. Assume that a galvanized steel roof provides sufficient corrosion resistance so the roof lasts for the life of the building and requires no additional maintenance. Then this would be the best corrosion control alternative, and incremental costs of galvanized steel over uncoated steel are the unavoidable costs. If an uncoated roof was installed, high maintenance and replacement costs would be realized over the life of the building. All costs above that of original construction would be included in total costs. Avoidable costs would be those above the cost of a galvanized steel roof.

This concept is important because different approaches are required to reduce the two types of costs. Unavoidable costs require technological advance before reduction can be realized. In the above example, this would be a more cost effective alternative to steel than galvanized steel. A program to develop a less expensive coating would be one way to proceed. For avoidable costs, reduction is achieved by technology transfer and implementation. First, determine why a galvanized steel roof was not selected, and secondly, take necessary action to encourage its selection for future warehouses.

2.3.4 Best Corrosion Control Practice

Best corrosion control practice is defined as the most economically effective and efficient use of resources to control corrosion with presently available technology. This practice defines the division between avoidable and unavoidable costs. It does not imply that corrosion is stopped at all costs or that all equipment is gold-plated.

2.3.5 Input/Ouptut Analysis

Input/Output analysis provided the methodological framework for this study. The methodology is described in detail in Section 3.

Battelle's National Input/Output Model describes interindustry transactions in the economy. For each of 130 industrial sectors, the I/O Model quantitatively describes:

(1) Resources (material, labor, energy, value added) required to produce its product or service. The dollar value of inputs required from each industrial sector are given.

(2) Plant and equipment requirements to produce its product or service. The capital stock required from each capital producing sector is given.

(3) Replacement rates for each type of capital stock (plant and equipment) required in the production process. Replacement lives are determined for the capital stock in each industry sector.

Economic activity of private consumers, the Federal Government, State and Local Government and other components of final demand are also described.

The I/O Model provided the detail and comprehensiveness for treatment of all the elements of the cost of corrosion. Production costs, capital costs, change in replacement lives, etc. could be treated in a coordinated and systematic manner. The analysis provided a measure of total costs of corrosion separated into avoidable and unavoidable costs and a relative measure of the allocation of costs among the industrial sectors.

2.3.6 Direct and Indirect Costs

Direct costs are costs an industrial sector acrues as it purchases inputs and produces its products, while indirect costs are those accrued in producing the inputs to a particular production process, and the costs of producing inputs to the inputs, etc., until additional costs become negligible.

2.3.7 World I, World II, and World III

To determine total, avoidable, and unavoidable costs of corrosion, three scenarios were constructed. First, the economy as it exists (World I); Secondly, the economy as it would exist if corrosion did not exist (World II); and Thirdly, the economy as it would exist if all segments of the economy used best corrosion-control practice (World III). An Input/Output Model was constructed to describe each economy. Costs of corrosion were determined by differences between the three worlds.

Starting with a modification of Battelle's National Input/Output Model as a description of World I, adjustments were made to account for all economic activity associated with corrosion and World II was constructed. Similarly, adjustments were made to account for all activity associated with best corrosion control practice and World III was constructed. Procedures for determination of costs of corrosion and adjustments for World II and World III are presented in Section 4.

Differences between World I (existing economy) and World II (economy with no corrosion) determined the total cost of corrosion, while differences between World I and World III (economy with best corrosion-control practice) determined avoidable costs of corrosion. Unavoidable costs were calculated from total costs minus avoidable costs.

2.3.8 Ex-Ante Approach for Estimation

The ex-ante approach was used both in determination of World I and in estimation of parameters for World II and World III. The essence of this procedure for estimation is that the process relies upon expert knowledge and judgment rather than data surveys and statistical analyses. Through adoption of this approach, all available data can be assimilated and applied to determine necessary parameters. The procedure is discussed in Section 3.3.5.

3 METHODOLOGY

3.1 Introduction

The many cost elements, both capital and operating, associated with the existence of corrosion affect the economy in complex ways. The purpose of the Input/Output model is to put those costs into a logical structure so that their implications may be traced. For example, the fact that the replacement life of a piece of capital equipment is less in the present environment than it would be in a corrosion-free environment indicates that annual replacement of that equipment potentially may be reduced. A reduction in the annual replacement, or purchase, of certain capital equipment would result in both direct and indirect reductions in the requirements for labor, material, energy, and other capital. Those reductions would then result in subsequent reductions of their own.

In order to capture all of these effects, we have chosen to utilize a modification of Battelle's existing national input-output model. At the beginning of this study, Battelle already had an existing 127 sector input-output model. Several modifications and expansions of that model were made in the course of the study. A number of industrial sectors were disaggregated into more detailed sectors. A replacement life matrix indicating the range of replacement lives for each kind of capital used by each industrial sector was added. A special mechanism, called the social savings row, was added, and special algorithms for allocating the cost of corrosion to specific industrial sectors were devised.

Input-output analysis, pioneered by Leontief, and the modified Battelle model are ideally suited for use in estimating the total direct and indirect costs of corrosion for a number of reasons. The model is quite detailed. In the form used in this study, it consists of 130 economic sectors, each of which is represented by a production function consisting of the respective inputs from each of the 130 sectors plus value added. As a result, relatively detailed industry corrosion cost data may be incorporated into the model for simulation purposes.

The model is comprehensive. It has sufficient components to allow all the aspects of corrosion costs (e.g., production costs, capital costs, reductions in replacement lives, excess capital capacity, etc.) to be considered in the analysis. Because of the model's structure, all of these aspects may be considered in a highly coordinated and systematic manner.

The model is simultaneous so that it is able to account for both direct and indirect effects of certain changes in the economy. This ability to account for direct and indirect effects is critical if one is to estimate the total costs of corrosion to the society.

Because the model simultaneously determines equilibrium values, comparative static analysis is an obvious application. And the corrosion problem is one very amenable to comparative static analysis. The costs of corrosion in the existing world are compared to corrosion costs in each of two hypothetical worlds: one in which no corrosion exists and thus the costs are zero; and one in which ''best practice'' corrosion control methods are used.

And finally, since the model consists of process sectors described in terms of ''ex ante'' parameters, it is well suited to ''ex ante'' changes describing worlds II and III.* The process orientation is important since it allows technical experts to concentrate on specific production processes necessary to produce a given output. The ex ante derivation of parameters frees these experts from the burden of statistical analysis for which little or no data exists.

The input-output model used in this study can be separated into three basic components: the direct technical coefficient matrix, the capital-to-output coefficient matrix, and the final demands. The relationship which ties all three components together is

$$X = AX + BGX + BRX + \overline{FD} \qquad (1)$$

where

X is a vector of total output

A is a matrix of direct technical coefficients

B is a matrix of capital/output coefficients

G is a diagonal matrix of industry growth rates

R is a matrix of capital replacement rates

$\overline{FD}$ is stipulated final demand (excludes gross private domestic investment)

Equation (1) states that an industry's total output is distributed among intermediate consumers, purchasers of capital (for both growth and replacement), and final consumers. The term AX is the output consumed by intermediate users, BGX is the output which is allocated to growth capital, BRX is the output allocated to replacement of worn out capital, and $\overline{FD}$ is the output accruing to final consumers. Equation (1) may be solved for total output, X, by the following:

$$X = [I-A-B(G+R)]^{-1}\ \overline{FD} \qquad (2)$$

where

$[I-A-B(G+R)]^{-1}$ is an inverse matrix.

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*Ex ante refers to a process for estimating model parameters. The process relies upon expert knowledge and judgment rather than data surveys and statistical analyses as in the ex post approach. The ex ante approach is discussed in more detail in Section 3.3.5.

Equation (2) is basic to the input-output formulation used in this study and is often termed a ''dynamic inverse''. The dynamic inverse combines the capital coefficients (BG&BR) with the direct technical coefficients (A); it treats the capital coefficients, actually stock coefficients, as if they are flow coefficients, and thus as if capital purchases are a function of stipulated final demand. This formulation causes no problems as long as the economy is assumed to be growing at its long term rate of change, as was assumed in this study. If, however, one is simulating other than a constant, long term rate of growth, the formulation will cause faulty estimates of capital formation.

3.2 Assumptions

Certain assumptions are implicit in the model and they should be identified. They include

- Linearity assumption
- Homogeneous product assumption
- Inelasticity
- Steady growth assumption
- Average technology assumption
- Full employment trend

3.2.1 Linearity Assumption

The linearity assumption states that an industry's inputs are directly proportional to its output. In other words there are no economies or diseconomies of scale; input requirements are not related to the size of the firm, volume of output, etc.

3.2.2 Homogeneous Product Assumption

Each sector in the input-output model is assumed to produce one homogeneous product bundle. A lack of homogeneity would imply that a sector's product mix may change in that very diverse products requiring diverse production technologies are produced by the same sector. Although changing product mixes and different production processes may exist in reality, they are difficult to deal with in the input-output model. As a result we assume that each sector produces a slowly changing average product mix.

3.2.3 Inelasticity of Substitution Assumption

It is assumed in the model that there is no substitution among inputs by any given producing sector. This assumption is necessary primarily because price changes are difficult to measure and cross elasticities of substitution do not exist for the many items in the input-output model.

3.2.4 Steady Growth Assumption

We assume in the model that any goods or services demanded can be and have been supplied, and that all of the model sectors have been changing at their long term rate of change for a long time.

3.2.5 Average Technology

Implicit in the model is the assumption that an industry's production function may be represented by average 1975 technology. This assumption is embodied in the fact that the 1975, ex ante direct technical coefficient matrix reflects the average technology considered to be in effect in that year.

3.2.6 Full Employment Assumption

In estimating the model's stipulated final demands we assumed that 1975 was a full employment year, using the term ''full employment'' to mean full employment of all resources. As a result the final demands and output levels are somewhat higher than those actually experienced during 1975. The essence of this assumption is that it allows us to measure the full potential capacity of the economy and thus the full costs of corrosion. The dollar costs of corrosion, as measured by the input-output model, therefore, are those which would occur if the economy were operating at full capacity. In percentage terms (costs as percent of GNP), however, the costs of corrosion should differ very little between the two situations.

The three components of the model, the A matrix, the capital matrix, and the final demands may now be described in turn.

3.3 The ''A'' Matrix

The ''A'' matrix is sometimes called the matrix of direct technical coefficients. The cells in this matrix indicate the dollars worth of inputs required from the row sector in order for the column sector to produce one dollar's worth of output. Three rows (value added, social savings, and imports, all discussed at a later time) are outside the matrix and as a result are not involved directly in the inversion of the A matrix.

Since the coefficients are in terms of proportions, the column sum of the A matrix plus the sum of value added, imports and social savings is equal to one. The sum of the column coefficients in the A matrix is equal to the column sector's use of domestic intermediate inputs per dollar of its own output. In world I if the cells of the matrix and the value added and import rows are filled with their dollar, or transaction values, the column sums are equal to the column industry's total input and also equal to the industry's total output.

3.3.1 Value Added

Value added refers to the value which a particular manufacturing process adds to the inputs it purchases; this value is included in the final product value of the process. Specifically value added includes wages and salaries, profits, rent, taxes, interest, and depreciation charges which accrue to a sector as it produces its goods or services.

In the model, value added appears as an exogenous row of coefficients, one for each column sector in the A matrix and as a row of dollar values in the transactions table. Each of the coefficients indicates the total dollars of value added which the column sector accrues for each dollar of final output it produces. The value added values in the transaction table indicate the total dollars of value which the respective column sectors add in producing their total output.

3.3.2 Social Savings

The cost to the economy of corrosion was measured in terms of the reduction in GNP that would take place if our world were corrosion free. This is to say that labor and resources are being used to overcome the effects of corrosion which would not be used – and therefore could be directed toward some other purpose – in the absence of corrosion.

One important factor which must be taken into account is that, given the absence of corrosion or given the application of optimal anticorrosion practices (however defined), industrial technologies would be different from those currently employed in the real world. If these differences in technology are entered into the model in the usual manner (alteration of the proportionate structure of the subject sector's direct technical coefficients, followed by renormalization of the entire column) the simulation would automatically reallocate GNP, but it would not measure the amount by which it would be *reduced or increased*.

In order, therefore, to have a better indication of the impacts of technological changes implicit in moving from the real world to a no-corrosion world or to an optimal-corrosion-control world , an innovation has been undertaken. A new row has been added to the transactions table and to the A-matrix that is called ''Social Savings''. In the tables this row is *outside* the intermediate matrix (like Value Added) so that it only enters the inverse through its indirect influence on the sizes of all the intermediate direct coefficients. In the World I (real world) tables, this row is always empty. In going from World I to either of the other two (hypothetical) worlds, any changes made in specific cells in a column of coefficients are balanced by the entry added into this row.

For instance, if a move from World I to World II causes a reduction in one material input (coefficient) and a smaller increase in another, the positive entry into Social Savings exactly equals the net change. Thus the column sum still equals unity *without renormalization*. As a result of this feature, when the transactions table has been derived, the net row sum of Social Savings will indicate the amount of GNP which has (if positive) been made available for other use, or (if negative) the amount by which GNP in other uses has been reduced.

3.3.3 Foreign Trade

Imports of goods and services include both the importation of intermediate and final demand goods and services. Typically these imports have been incorporated in the input-output model as a double row across the intermediate matrix (''A'' matrix) and final demand sector, with exports as a final demand subvector. In this typical formulation one import row consolidates all imports required as inputs to the respective column sector and not directly substitutable for U.S. outputs. The second (or ''transferred'') imports row shows all imports essentially substitutable for the column sector's output; these latter imports are treated as being purchased as inputs by the column sector, which then distributes them with its output across its own output row. This transferred import, like secondary transfers among producing sectors, destroys the technological integrity of the A-matrix.

In the Battelle model, only noncompetitive imports were included as a row across the table. Competitive imports were placed as a negative column of final demand entries. Thus, competitive imports were treated as reducing the final demands for similar U.S. output; and all the noncompetitive imports of inputs to each producing sector were consolidated into an intermediate row (with a corresponding row across final demand). While theoretically simple and correct, especially in a country in which imports constitute relatively small proportions of total supply, the convention introduces the danger of a serious anomaly. Where imports for intermediate use (e.g., crude petroleum) were large relative to total final demand, there was a danger that total final demand (net after imports) would become heavily negative and lead to extremely low or negative total outputs.

In order to preclude this danger, we have modified the above convention. All imports are carried as a row outside the intermediate and inverted matrices. Total input thus becomes:

$$TI = TDI+DVA+IM \tag{3}$$

where

TI is total input

TDI is total domestic intermediate input

DVA is domestic value added

IM is imports.

Every direct coefficient in the A-matrix is thereby made technologically correct, regardless of whether or not the inputs are domestic or imported. After solving for total output, an import column can be calculated for information purposes by multiplying each sector's output by the sector's import coefficient. These calculated values can then be added as a column to the table so that

$$TDO = TIO+TFD-IM \tag{4}$$

and

$$TDO = TDI=TI-IM \tag{5}$$

where

TDO is total domestic output

TIO is total intermediate output

TFD is total final demand

TI is total inputs.

3.3.4 Disaggregations

Certain sectors of the model have been specially disaggregated for this study. Since the corrosion of concern is that which affects only metals, the metal sectors are one group of particular interest. As a result the original four metal sectors have been disaggregated into fourteen more detailed sectors. In addition, it was felt important to be able to separate paints and allied products; coatings and plating; and maintenance and repair construction into corrosion prevention and noncorrosion prevention components. The original three sectors were thus disaggregated into seven more detailed sectors (the original sector which contained coatings and platings also contained another group of sundry outputs so that three new sectors resulted from the original).

The model disaggregations have been derived through an ex ante as opposed to an ex post approach. The ex ante approach, discussed in detail below, is well suited to the particular problem at hand because of the lack of formal data in many cases.

3.3.5 The Ex Ante Approach

The ex ante approach to the determination of input-output coefficients has been designed for the explicit purpose of taking fullest account of the impacts of technological change on interindustry relationships.

The analysis in this study has been performed for the year 1975. The latest national survey table is for the year 1967.* An alternative way of estimating the 1975 input-output model coefficients was thus necessary.

There are several ways of establishing a matrix of direct technical coefficients that presumably reflect target-year technologies.

- A matrix from a past year can be assumed to describe a future year with no further change
- A matrix for a past year can be assumed to describe the future year after adjustments for relative price changes
- For a selected group of coefficients assumed likely to undergo technological change, technological forecasts can be made, and all other coefficients conformed to them
- Estimates can be made of the marginal dollar totals (total intermediate output, and total intermediate input) for every productive sector. Then the dollar flows can be adjusted by means of a double proportionally method (RAS) to conform to the new marginal values; and new coefficients can be derived.
- An extrapolation into the future can be made by standard econometric methods, if comparable coefficients matrices are available for two or more past years
- A technological forecast to one or more target years can be made for each sector in the I/O table and converted into coefficient form.

All of the above methods have been used in making coefficient forecasts. The first three are probably used most often. The coefficients used in this study have been derived using the last method, the ''ex ante'' approach. In general the method consists of generating a preliminary matrix of direct technical coefficients for each target year through use of whatever method or combination of methods (from the first five on the list) is feasible. The preliminary coefficients are then subject to intensive cell-by-cell review by members of a group of experts, the selection of whom is crucial to the effectiveness of the approach. Then the final coefficient forms are established and normalized.

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*U.S. Department of Commerce, Bureau of Economic Analysis, *Input-Output Structure of the U.S. Economy: 1967*, U.S. Government Printing Office, Washington, D.C., 1974.

The above process was used both in disaggregating existing sectors in the model and in estimating parameters for worlds II and III, two hypothetical environments in which no corrosion exists (II) and in which best corrosion control practices are used (III).

3.4 Capital Matrix

Private capital, plant and equipment used in the production of goods and services, must meet the following conditions: it must not be transformed during the production process; it must last in excess of one year. In the input-output model it is estimated through use of the capital matrix.

The capital matrix, as is true for the flow matrix, is a 130 by 130 matrix of ''ex ante'' coefficients measuring a relationship to output. Where the flow coefficients measure dollars worth of inputs per dollar of output, the capital coefficients measure dollars worth of capital per dollar of output. Sectors listed across the top of the matrix indicate capital users; sectors listed down the side of the matrix indicate capital producers. Since all sectors are users but not producers of capital, a great many zero rows exist in the matrix.

In brief, the capital matrix is used to indicate the amount and type of capital (measured in terms of current cost) necessary to support various levels of production. It is explained in greater detail below.

3.4.1 The General Concept of the Capital Module

Private fixed capital formation (PFCF) is one of the standard components of GNP and provides one of the seven subvectors of final demand in the I/O context. PFCF is the *private* demand from the entire economy for the structures and machinery used in production and for the structures (residential) used by consumers.

The formation of new plant-and-equipment capital by industry can be thought of as triggered by need for growth, by need for replacement (of wornout or obsolete capital), or by government requirements (e.g., for environmental protection). By *growth*, we refer primarily to the growth of demand for an industry's output, regardless of whether the demand be final or intermediate, foreign or domestic. By *replacement* we refer both to replacements due to technological change — usually almost impossible to isolate, as will be shown — and to replacements which arise because of the age structure of existing capital. Capital changes that result from governmental regulations probably are best estimated with reference to policy directives and added to our modular estimates. We will not discuss them further in this report.

In order to estimate the amounts of new capital which each capital-using sector will purchase from each capital-producing sector (aside from the response to government regulations) during a given year, we need to have five bodies of data:

- The stipulated (noncapital) final demands which each sector must satisfy ($\overline{FD}$)
- The capacity growth rate matrix (G)
- The capital replacement rate matrix (R)
- The matrix of direct technical coefficients (A)
- The matrix of capital coefficients (B).

To the extent required for understanding, each of these will be discussed at greater length, below; at this point, we will take each as defined and indicate the general computational program of the capital module.

In standard matrix notation, the Leontief I/O system of equations can be written

$$X - XA = FD \tag{6}$$

where

X = total output

A = the direct coefficients matrix

FD = total final demand.

We can rephrase this statement to read: total output must always exactly cover both intermediate input requirements and final demands. This is a truism, primarily because net increases in inventories of unsold output are treated as final demand.

In the steady growth case, when we wish to account for investment demand separately, Equation (6) can be rewritten

$$X - XA - X\overline{B} = \overline{FD} \tag{7}$$

where

$\overline{B}$ = total capital coefficients matrix

$\overline{FD}$ = total stipulated (noncapital) final demand.

and

$$\overline{B} = B(G + R)$$

with

B = the standard capital coefficient matrix (expressed in the form of ratios of capital stock to output)

G = matrix of annual growth rates of total capacity (capital)

R = matrix of annual replacement rates of capital.

This allows us to rewrite Equation (7)

$$X - XA - XBG - XBR = \overline{FD} \tag{8}$$

Given exogenous means of determining g and r (the individual growth and replacements rates), this is the modified form of the Leontief equation from which the *dynamic inverse* is derived. It is this relationship that provides the logic of the capital module. Before going into the actual derivations and relationships of the module, however, we need to review the concept of capital that underlies the original derivation of the B-matrix.

3.4.2 The B-Matrix

The capital coefficients used in this exercise differ from the usual statistical coefficients in that they are *stock,* rather than flow, coefficients.

In this context, all capital coefficients may be described as a set of ratios that sum to the capital output ratio of the *capital-using* industry – i.e., the dollars-worth of capital required to produce $1.00 per year of industry output. The structure of the set of ratios is determined by the proportionate parts of that total capital which are provided by the several capital-producing industries. What we term capital-flow ratios are derived from statistics of capital sales and purchases in a given calendar year. They need never relate meaningfully to the technologically required structure of productive plant and equipment. In contrast, capital-stock ratios are derived in terms of the proportionate composition of a meaningful productive unit. They describe engineering necessities.

A capital stock matrix, however, can be defined in several different ways. It can be an *accumulated* stock matrix, structured in terms of the kinds of capital (regardless of age and/or relative degrees of obsolescence) currently in use in a real situation. Or it can be a *best-practice* stock matrix, structured in terms of optimal engineering requirements. The B-matrix used in this case is a best-practice, balanced-expansion, stock matrix in that it assumes optimal engineering requirements but *no* excess capacities.* In order to increase an industry's output by one percent, every capital input must

*The concept of best practice in the capital stock matrix and average technology in the flow, or A matrix, are not necessarily incompatible, although certain inconsistencies should be pointed out. Since the values in the capital matrix are really marginal values, they could well reflect a best practice technological distribution and cost of growth capital and not contradict an average practice flow matrix. In computing replacement capital, however, the marginal coefficients are used as stock coefficients. Thus if the actual distribution of capital has changed over time, the marginal, best practice coefficients will result in an incorrect distribution of replacement capital.

increase by one percent. This means that when we use the associated capital-output ratios to convert total outputs to ''total capital already in place'', we implicitly assume that all plant and equipment is optimal from an engineering point of view. Another way of stating this is that we express capacity in terms of its *current replacement cost* rather than either its *original cost* or its *current book value*.

The B-matrix used in this study is defined in terms of 130 Sector detail. It defines complete process-related capital structures, including necessary infrastructures (e.g., the transmission lines of electrical utilities); and it contains allowances for capital requirements of effluent control of major pollutants but not necessarily that called for by governmental regulations.

In the I/O sense, the capital matrix (B-matrix) shows how much capital the column sector (capital-using) will purchase from each row sector (capital-producing) in order to create new capacity to produce one dollar's worth of output per year. It is expressed in 1975 dollars and price relationships; it reflects 1970-75 best-practices.

3.4.3 The Growth Matrix

In order to determine how much new capacity must be formed in order to keep up with the growth demands we derive the ratio g from first approximation growth rates of total output (X). If K = capacity, g may be derived for a given sector as

$$g = \frac{K_1 - K_0}{K_0} \tag{9}$$

If we substitute a comparable ratio based on X (defined as the total output of the sector in an economy in which capital formation is approximated) we allow changes in K to be approximated in terms of the direct plus indirect growths of general demand. Therefore

$$g = \frac{\overline{X}_1 - \overline{X}_0}{\overline{X}_0} \tag{10}$$

In our actual program, X is taken from our full employment trend tables. Also, since we are working with 5-year interval estimates, we have reformulated g to use estimates for the two successive quinquennial years:

$$g_{75} = \left[\frac{\overline{X}_{75}}{\overline{X}_{70}}\right]^{1/5} - 1 \tag{11}$$

If a given value of g is negative – that is, if total output declines – we compare the value of g with the corresponding value of r (see below). If, ignoring signs, $g \leq r$, the sum $g+r$ will be positive or zero; and neither value is changed. But if, again ignoring signs, $g > r$, the sum $(g+r)$ will be negative. This implies that the sector is disinvesting and is supplying capital to other sectors – a very unlikely situation. Therefore, in such cases, g is set equal to r, so that the sum $(g+r)$ is arbitrarily forced to zero. The values of g for each sector are then entered as the diagonal row in the g matrix; all off diagonal elements are zero.

In estimating capital formations in 1975, for example, $\overline{FD}_{75}$ (estimated *non*capital final demand in 1975) is used, along with the modified dynamic inverse, to calculate the final values of total output.

3.4.4 The Replacement Matrix

Since we have no precise vintage composition of total capital, we assume that the age-structure of each capital-using industry's existent stock of capital results from its steady growth at rate g. Replacement rates would therefore be a function of the growth rate and the replacement life of that stock. We have used the Internal Revenue Service's *Bulletin F* as our source of the replacement life expectancies of each sector's plant and equipment.

The replacement rate (r) for each sector is taken as a joint function of both replacement life expectancy and sector growth. The R matrix is a *full* matrix, like the B matrix. It is derived in turn from a corresponding matrix of replacement lives (U) by the following procedure.

Working from entries of depreciation life *Bulletin F*, every cell U_{ij} corresponding with a nonzero cell in B is assigned a replacement life expentancy value. The assigned value may take the form of a given number of years or of a range of years. Average annual growth rates for each column sector, g_j, are derived in the above manner and used to describe the entire cycle of replacement lives.

Assuming smooth growth, the current stock of worn-out capital would be that which was formed for reasons of both growth and replacement in the first year of a period u years long. If we let K_t represent capital stock value in year t, we can designate the value in the first year of the period as K_0. The total value of the current capital stock can be designated as ΣK, defined as

$$\Sigma K = K_0 + K_1 + K_2 - - - + K_{u-1} \tag{12}$$

where K_0, K_1, . . . is the growth and replacement capital purchased in year 0, 1, 2, . . . respectively and U is the life to first replacement of the capital stock.

Then by definition, the annual replacement rate of capital, r, for a given sector becomes $r = K_0/\Sigma K$.

If we calculate K_1, K_2, through K_{u-1} in terms of K_0, given the annual growth rate of the sector, g, they become

$$K_1 = K_0 * (1 + g)^1$$

$$K_2 = K_0 * (1 + g)^2$$

$$\vdots$$

$$K_{u-1} = K_0 * (1 + g)^{u-1} \tag{13}$$

Since K_0 is common to all terms

$$r = K_{0/\Sigma K} = \frac{1}{1 + (1 + g) + (1 + g)^2 + --- + (1 + g)^{u-1}} \tag{14}$$

This can be transformed, for ease of calculation, into

$$r = \frac{g}{(1 + g)^u - 1} \tag{15}$$

In setting up the replacement matrix, R, we establish a value of r_{ij} for each corresponding value of u_{ij}. If a given cell has a single replacement life (e.g., 5 years) there will be only a single replacement rate. However, if a particular cell is shown as having a range of replacement lives (e.g., 5-10 years) there will be a range of replacement rates (one for 5 years, one for 6 years, and so on); and the corresponding single value entered in the R-matrix will be the simple mean of these replacement rates.

3.4.5 The Modified Dynamic Inverse

It will be recalled that our capital equation was stated

$$X - XA - XBG - XBR = \overline{FD} \tag{16}$$

This can be rephrased

$$X = [I - (A + B(G + R))]^{-1} * \overline{FD} \tag{17}$$

In this form, given the constraints mentioned in a previous section (i.e., the economy growing at its long term rates of change), the equation permits the computation of total output (X) from the data sources which have been discussed.

3.4.6 The Final Capital Matrices

After total outputs (X) have been computed via the dynamic inverse and the stipulated final demand, the detailed capital transactions matrices are computed from the following relationships

Growth capital	= XBG
Replacement capital	= XBR
Total capital	= Growth capital + Replacement capital.

In matrix form, these tables provide capital market data that show how much capital goods must be purchased by each capital-using sector from each capital-producing sector, if the capacity of the economy is to satisfy all final demands.

The column of row sums of the total capital matrix enters the PFCF column in the final demand vector of the I/O transactions table. When the total capital matrix is added, cell-by-cell, to the intermediate and other final transactions matrix of the I/O table, this provides us with a complete market profile for every row sector, regardless of the nature of its output.

3.5 Final Demands

Final demands account for the third major component of the input-output model. They represent the final disposition of goods and services produced by the economy.

Specifically, the stipulated final demands used in this study may be separated into expenditures for:

- Personal Consumption
- Government (federal, state, local) purchases
- Exports
- Net inventory change.

Normally, the sum of the final demands is equivalent to GNP. In this study, however, the stipulated final demands must be adjusted in order to achieve a sum equivalent to GNP; the adjustments include *adding* gross private domestic investment to and *subtracting* imports from the sum of the above categories.

3.5.1 Generation of Stipulated Final Demands ($\overline{FD}$)

The optimal potential path of the stipulated final demands ($\overline{FD}$) – that associated with the term ''full employment'' – is assumed a function of two main determinants, the working-age population and the average technology with which it works.* The working age population has been defined as all persons between the ages of 18 and 65 – regardless of whether employed or even whether in the ''labor force'', as usually defined.

The other determinant of $\overline{FD}$ in this module is the trend in productivity, measured as real (1975 dollar) GNP per person 18-64.

In order to reflect conditions of full employment: The forecasting trend-line for GNP per person 18-64 has been fitted to the peak series values of 1950-70. Thus, the fitted line represents the best performance of the U.S. economy during the post war decades. Projected values from this trend have been multiplied by projections of the 18-64 year old population to obtain tentative estimates of aggregate GNP in constant 1975 dollars. The population projections are produced within the model via a cohort-survival projection technique.

3.5.1.1 Composition of GNP. Total GNP by itself is of little use in the model. It must be separated into the specific components included in $\overline{FD}$ before it can be used in any detailed analysis. Each of the components of $\overline{FD}$, personal consumption, government purchases, exports, and net inventory change is discussed below.

3.5.1.2 The Consumption Module. It will be recalled that total population by age is projected with a cohort-survival technique. Based upon historical and forecast family formation statistics, the numbers of families of given sizes by age of head of household were then forecast. These data then were combined with information on income characteristics** to provide a three-dimensional matrix of families by income by age of head and by size. This matrix is shown conceptually in Figure 1.

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*Since 1975 is now history, it is no longer a forecast year. However, the 1975 values for stipulated final demand used in the model are forecast values in the sense that they are valued which were forecasted to have occurred if the economy had experienced full employment of resources and a long term, steady rate of growth.

**For forecasting purposes, spending behavior relative to income is estimated in terms of eight ''income behavior'' classes, the mean family incomes of which vary over time. For instance, in 1970 the average income of two person Class 1 families was $5,493; it is expected to rise to $6,920 (in 1970 dollars) by 1985. For Class 8, corrcsponding averages are $29,764 adn $37,499.

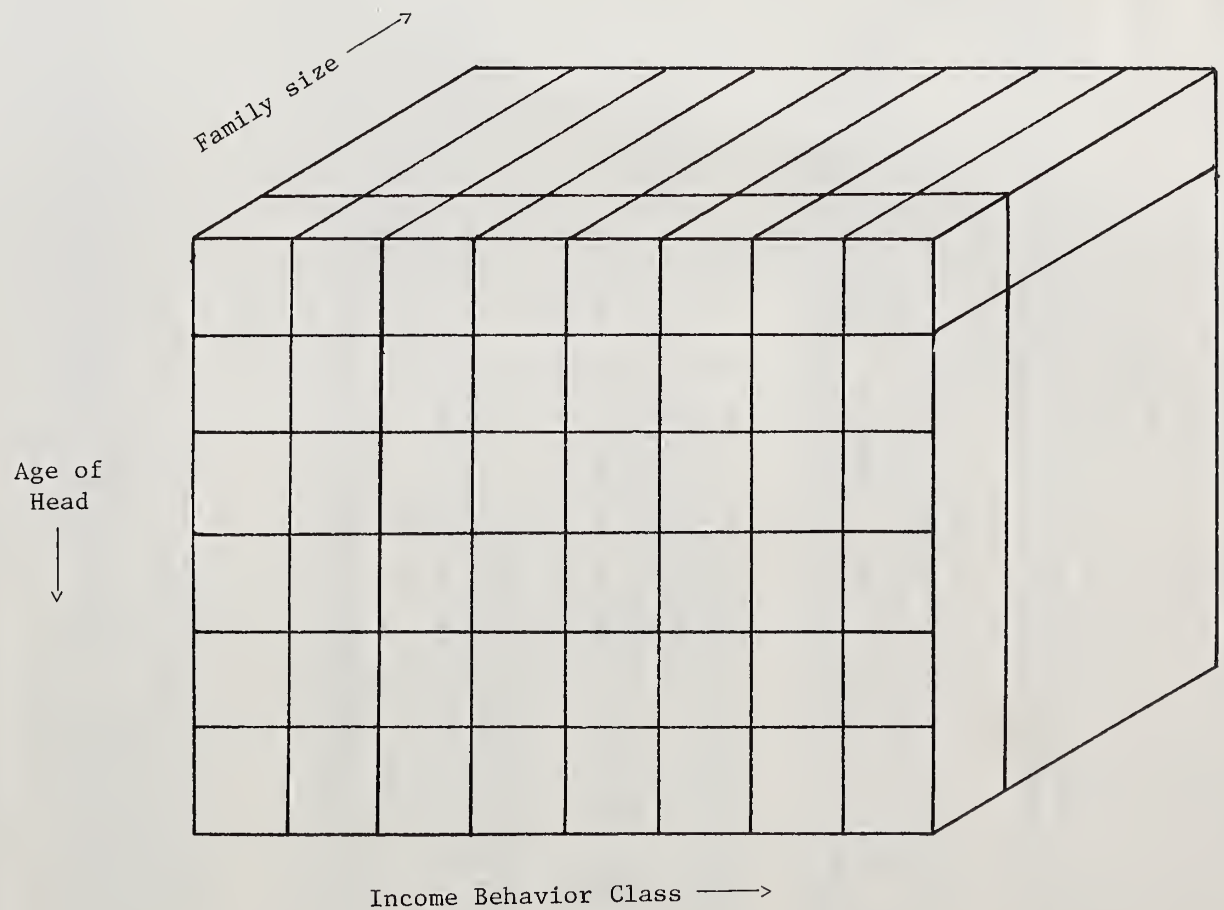

FIGURE 1. CONSUMER PROFILE--INCOME, HOUSEHOLD AGE-OF-HEAD, FAMILY SIZE MATRIX

A separate analysis was made of how families with different income and size characteristics spend their income on each of 42 major categories of consumption goods and services. The estimates are expressed as regression equations which show how much the average family in a given income class and of a given size will spend in a year on a specific expenditure category. After being aggregated across all family size categories, the 42 categories have been disaggregated into 180 detailed classes of consumer expenditures for each of the eight income behavior classes of family. At this point, the total consumption expenditure of all families has been calculated in detail. It must then be converted from a consumption framework to a producer-sector framework for incorporation into the I/O table.

In order to enter the PCE column of the I/O table's final demand sector, total consumer expenditures on the 180 items must undergo considerable transformation. First, it must be converted from consumer market terms into producer-prices. This is done by removing from what the consumer pays the transportation and trade margins that have been added in calculating retail prices. Then, the producer-values of the goods consumed must be ascribed to the industry in which they were produced, while the transportation and trade margins must be accumulated and ascribed to the transportation industry and to wholesale retail trade.

3.5.1.3 Other Final Demands. In order to deal with these other final demands in an expeditious and reasonably precise manner, we had to make many assumptions about the characteristics of the target years. For instance, the assumption of peacetime full employment meant that governmental expenditures (especially at the federal level) would not be complicated by emergency programs, either those required by a wartime situation or those required for the relief of unemployment.

What constitutes a ''normal'' foreign trade situation in a world currently characterized by international inflation and recurrent problems in foreign exchanges? For model purposes, we have assumed a very small U.S. trade surplus in each of the target years. The general composition of exports has been assumed to follow recent historical patterns with some exception.

In general, the computations of this module have been quite simple. Total GNP has been distributed according to historical structures derived either from the corresponding final demand subvectors of the 1958 and 1963 U.S. I/O tables or from the detailed time series of the National Income and Product Accounts. This procedure was followed for government expenditures and gross exports. Imports, as discussed in a previous section, have been entered as a row in the ''A Matrix'' so that they appear in final demand only in an information sense.

3.5.1.4 Inventory Change. Inventory change is an item which poses some conceptual problems. As a result, the item is discussed separately. Official statistics on net inventory changes show the amounts by which inventories grew or declined in a given past period, regardless of the kinds of inventory or the reason for the change. Generally speaking, industry inventory statistics are reported in terms of the industry that holds the inventory. If they are to be useful for I/O analysis, however, they must be stated in terms of the industry that produced the goods held in inventory, regardless of held in inventory, regardless of by whom.

Inventories held by an industry can rise (or fall) because its decision makers expect an increase (decrease) in the demands for its output; or they can do so because previous output decisions were mistakenly too big (low) because of excessive and unrealistic optimism (pessimism). In other words, a change in inventories can come about either because of changed expectations about the future or because of a past ''goof'' by management. The first is theoretically acceptable and should be incorporated into our model, if possible; the second is not and should not be.

Since official statistics cannot distinguish these two sources of inventory change and so must include them both, there is no valid way of econometrically forecasting future inventory changes, *by industry*, through their use. Instead, we have estimated aggregate inventory change as a function of average changes in noninventory final demands. In order to obtain a distribution of this total over the 130 industrial sectors of our table, we have applied the same general approach to each row sector, and then normalized the results to the estimated total.

3.5.2 Disaggregations

As was the case with the direct technical coefficient matrix, certain of the previously existing cells within the final demand vectors were disaggregated. The original four metal sectors which intersected final demand were separated into fourteen sectors; the paints and allied products sector was disaggregated into a corrosion prevention and noncorrosion prevention component; the coatings and plating sector was disaggregated into corrosion prevention, noncorrosion related, and all other sectors; the maintenance and repair construction sector was disaggregated into a corrosion control and noncorrosion related sectors.

As in the previous cases, the disaggregations were performed using expert knowledge and judgment and any available data.*

*An example of the data used is the 1967 national input-output table published by the Bureau of Economic Analysis. This table is more detailed than the Battelle model (367 sectors compared to 130) and thus offered data allowing us to disaggregate some of our more aggre ated sectors.

3.5.3 Durable Goods

Social capital/infrastructure is defined as consisting of final demand durable goods lasting in excess of one year and which do not change form during their use, e.g., automobiles, battleships, airplanes, etc. The annual purchase of these items by individuals and government is shown in each of three final demand vectors: personal consumption, federal government expenditures, and state and local government expenditures.

Originally social capital and infrastructure were to be inventoried, actually counted physically, and multiplied by an average unit price in order to arrive at a dollar value for the total existing stock. Upon investigation, however, it was discovered that an actual inventory was impractical for a number of reasons. For one, very little data are available which indicate the numbers of various social capital items in existence at any particular time. The data which do exist (primarily government inventories) are not centrally collected and thus presented a severe time and cost problem. Finally, average price data, if they existed at all, were suspect. For example, government inventories reflect an average unit price but not necessarily a replacement price; and often, because of the degree of sector aggregation, it was impractical to derive an average sector unit price.

As a result of the difficulties involved, an alternative approach was taken to the problem of estimating the value of the social capital infrastructure stock. This approach is based on the fact that the annual purchase of social capital/infrastructure items is a function of the item's replacement life and the historical rate at which demand for those items has changed.

The estimation begins with the identity that the purchase from a social capital producing sector (the annual purchase is the value falling in the appropriate cell in FD) in year t is equivalent to purchases for replacement plus purchases for the growth occurring between year t-1 and t.

$$\begin{array}{l}\text{Annual Purchase of} \\ \text{Social Capital}_t\end{array} = \begin{array}{l}\text{Replacement Purchases}_t + \\ \text{Growth Purchases}_{t-1,t}\end{array} \tag{18}$$

The purchases for growth are equal to the stock of capital in year t-1, SK_{t-1}, multiplied by the rate of growth, g, from t-1 to t.

$$\text{Growth Purchases}_{t-1,t} = g\ (SK_{t-1}) \tag{19}$$

Since we are interested in the present stock of social capital, SK_t, (19) may be transformed by using the following equivalent for the variable SK_{t-1}:

$$SK_t = (1 + g)\ SK_{t-1} \tag{20}$$

and

$$SK_{t-1} = SK_t/(1 + g) \tag{21}$$

Then Equation (19) may be rewritten as

$$\text{Growth Purchases}_{t-1,t} = \frac{g\ SK_t}{1 + g} \tag{22}$$

As has already been described in the section of the capital matrix, the annual replacement rate of a durable good, the production of which has been growing at its long term rate of g per year and which has a replacement life of u years, may be represented as:

$$r = \frac{g}{(1 + g)^u - 1} \tag{23}$$

The annual replacement of social capital in year t is then equal to the stock of capital in year t multiplied by the replacement rate

$$\text{Replacement Purchases}_t = SK_t \frac{g}{(1 + g)^u - 1} = (SK_t)(r) \tag{24}$$

Substituting equations (22) and (24) into (18) we then get

$$\text{Annual Purchase of Social Capital} = \frac{(g)(SK_t)}{(1 + g)} + (SK_t)(r) \tag{25}$$

Since we are interested in the value of capital stock in year t, SK_t, and since the annual purchase of said capital is known (the values are those occurring in the appropriate find demand cells), we may solve for SK_t

$$SK_t = \frac{\text{Annual Purchase of Social Capital})(1 + g)}{r(1 + g) + g} \tag{26}$$

The use of (26) allowed us to estimate the stocks of social capital held by individuals, federal government, and state/local governments.

3.6 Specific Industry Cost Parameters

The methodology for describing the aggregate costs of corrosion to the U.S. has already been described. Operating technology, capital plant and equipment requirements, replacement lives, and stipulated final demands are estimated for each sector of the model in the present environment and hypothesized environments in which no corrosion and best corrosion control practices exist respectively. The values are then used with the model to determine the aggregate costs of corrosion to the society (these costs, the sum of the values accumulated in the social savings row, reflect that portion of GNP being consumed as a result of corrosion).

It is important, however, that we carry the analysis further and devise an indicator of how the total cost is allocated among the individual sectors of the economy. A methodology was developed which provides four different sector cost parameters: the direct cost of corrosion per unit of output; the total direct costs of corrosion per sector; the direct and indirect cost of corrosion per unit of output; and the total direct and indirect cost of corrosion for each sector.*

3.6.1 Direct Cost of Corrosion Per Unit of Output

Each sector's direct per unit cost of corrosion is obtained by comparing production requirements per unit of output between worlds I and II and I and III.

Production requirements per unit of output are defined as the sum of the intermediate requirements of production (direct technical coefficients including value added) per unit of the producing sector's output; capital requirements per unit of the producing sectors output multiplied by the sector's growth rate; and the annual replacement of capital per unit of production. The sum of these components represents a total requirement necessary to produce a unit of a given sector's output. The difference between the world I, II, and III sums then provides an indication of the direct, per unit production costs of corrosion for each sector. The process may be represented mathematically by the following steps.

Step 1. Calculate the direct requirements per unit of production

$$\tau_{wj} = 1 + g_j C_{wj} + \rho_{wj} - SS_{w,j};\ (w = 1,2,3) \tag{27}$$

where

g_j is the annual rate of growth of sector j's output
$SS_{w,j}$ is the social savings entry for sector j in world w (SS_j is zero for world I)
C_{wj} is the total capital/output ratio for sector j in world w
ρ_{wj} is the total annual replacement of capital required to produce one unit of section j's output in world w.

In this formulation, $1-SS_{w,j}$ is equal to the sum of direct technical coefficients plus value added, and is a more convenient way of obtaining that sum.

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*The methodology described in this section is primarily the contribution of Edward B. Berman, of the Mitre Corporation.

Step 2. Calculate total direct per unit costs

$$\tau_{1j} - \tau_{2j}$$

Step 3. Calculate reducible direct per unit costs

$$\tau_{1j} - \tau_{3j}$$

The value SS_{wj} is a specially devised account for keeping track of various corrosion related expenses. It includes any reductions in operating costs. Those reductions relate both to intermediate inputs and value added. The input changes are determined through industry surveys, the value added adjustments are estimated as is explained in the following discussion.

3.6.1.1 Value-Added Adjustments. A number of adjustments to each industry's value added coefficient may be necessary in moving from World I to II and III. Those adjustments have all been grouped into a common term Z_{wj}. The value Z_{wj} is to be subtracted from sector j world I value-added in order to obtain sector j, World W (W=2,3) value added. After the value added is subtracted from World I value added, it is added to row sector, SS, world w, sector j. SS is the cumulation of net corrosion savings in the column of direct technical coefficients. Z_{wj} is defined as:

$$Z_{wj} = A_{wj} + \Delta_{wj}; \; (w = 2,3) \tag{28}$$

$$A_{wj} = (C_{1j} - C_{wj})n; \; (w = 2,3) \tag{29}$$

The average prime interest rate in 1975 approximates n, perhaps adjusted upwards to reflect the fact that some firms cannot obtain capital at the prime interest rate. A_{wj} represents the reduction in the cost of holding capital for the fact that the total capital requirement is reduced.

$$\Delta_{wj} = (D_{1j} - D_{wj}) - (\rho_{1j} - \rho_{wj}); \; (w = 2,3). \tag{30}$$

This represents the reduction in net accumulation of the depreciation account. D measures the gross use of capital and also the gross accumulation in the depreciation account, and ρ measures the value of replacement accounted for in final demand. The difference $D-\rho$ thus represents the net accumulation in the depreciation account, and Δ represents the reduction in that net accumulation in going from world 1 to world 2 and 3.

The annual replacement of capital used by sector j in world w, ρ_{wj}, is defined as

$$\rho_{wj} = \sum_i r_{wij} \, c_{wij} \tag{31}$$

where

r_{wij} is the world w annual replacement rate of capital produced by sector i and used by sector j
c_{wij} is the world w capital produced by sector i and required to produce a unit of sector j's output.

Since the average replacement rate RR, applicable to sector j's total capital is equal to

$$RR_{wj} = \rho_{wj}/C_{wj} \tag{32}$$

where

C_{wj} is the total capital/output ratio of sector j

and since, as shown in The Replacement Matrix section,

$$RR_{wj} = \frac{g_j}{(1 + g_j)^U - 1} \tag{33}$$

where

g is the growth rate of sector j
U is the world w average replacement life of capital used by sector j.

We may combine Equations (32) and (33) and solve for U_{wj}, the average replacement life of all capital used by sector j.

$$U_{wj} = \ln \left[\frac{gC_{wj} + \rho_{wj}}{\rho_{wj}}\right] \div \left[\ln(1 + g)\right] \tag{34}$$

It is now possible to calculate D_{wj}, the straight life depreciation of capital owned by sector j

$$D_{wj} = \frac{C_{wj}}{U_{wj}} \tag{35}$$

3.6.2 Total Direct Costs of Corrosion

Since the sector sums obtained in the preceding section represent the direct per unit requirements, all that is necessary to obtain total requirements for each sector is to multiply the respective sums by the sector's World I total output. World I total output is used as the multiplicand for each of the World I, II, and III sums of per unit of production requirements in order to insure results which are consistent and comparable. As described in the previous section, the differences between World I and II and World I and III are then calculated. These differences reflect the total direct costs of corrosion.

3.6.3 Direct and Indirect per Unit Costs of Corrosion

The direct and indirect costs are obtained by calculating the total direct and indirect requirements needed to produce the vectors of direct requirements discussed in the preceding sections. The calculation involves multiplying the vectors of direct requirements associated with each sector by the appropriate World I, II, or III inverse.* The resulting vectors are then summed and for each sector the World II sum is subtracted from the World I sum and the World III sum subtracted from the World I sum. Mathematically the procedure may be represented by the following steps:

Step 1. Form a column vector V_{wj} of which the ith row is defined as follows:

$$V_{wij} = a_{wij} + g_j c_{wij} + r_{wij} c_{wij}; \; (w = 1,2,3) \tag{36}$$

where

V_{wij} is the ith row of vector V_{wj},

a_{wij} is the direct technical coefficient, world w, row i, column j.

g_j is the growth rate for sector j

c_{wij} is the capital supplied by sector i to sector j per unit of j's output in world w

r_{wij} is annual replacement by j of capital supplied by i (capital per unit if j's output) in world w

Step 2: Form the matrix product:

$$[I - A]_w^{-1} V_{wj} = X_{wj} \tag{37}$$

where

$[I - A]_w^{-1}$ is the inverse matrix for world w

X_{wj} is the resulting output vector corresponding to sector j.

Step 3: Sum columns X_{wj}:

$$\tilde{X}_{wj} = \sum_i X_{wij} \tag{38}$$

where

X_{wij} is the ith row of X_{wj}.

*The inverse referred to here is the $(I-A)^{-1}$ inverse not the dynamic inverse, $(I-A-BR-BG)^{-1}$.

Step 4: Calculate total direct and indirect per unit cost

$$\tilde{X}_{1j} - \tilde{X}_{2j}.$$

Step 5: Calculate reducible direct and indirect per unit cost

$$\tilde{X}_{1j} - \tilde{X}_{3j}.$$

3.6.4 Total Direct and Indirect Costs of Corrosion

The total direct and indirect costs are calculated in a way analogous to the calculation of total direct costs. The outputs of steps 4 and 5 are multiplied by the corresponding world I sector output.

4 DETERMINATION OF COSTS OF CORROSION

In this section the procedures and methodology for determination of costs of corrosion are presented. First a general description of the data gathering is presented. Secondly, procedures for determining coefficients to account for the various elements of corrosion are presented. Thirdly, the procedure for determining avoidable cost of corrosion are discussed, and fourthly all coefficient adjustments made are discussed on an industry by industry basis.

4.1 Data Gathering Procedure

In order to determine the cost of corrosion, data were required in four specific areas:

(1) Inputs required to produce a product

(2) Capital equipment required to produce a product

(3) Replacement lives of the capital equipment

(4) Final demands for the product.

These areas are described for each sector in a portion of the I/O Model: the ''A'' matrix or flow matrix, the ''B'' matrix or capital/outnut matrix, the replacement lives matrix, and the final demand vector, respectively. More specifically, data were required to guide adjustments of values in each of the above four parts of the model of the economy as it presently exists (World I) for each of two conditions: the economy if corrosion was not a factor (World II) and the economy if best corrosion practice were universally applied (World III).

Information required is identified by the principal questions which were asked.

The flow matrix (''A'' matrix) is a matrix of coefficients which describes the inputs necessary to produce a product. The dollars worth of each row industry's product necessary to produce $1 worth of the column industry's output is described by the coefficients. Principal questions here were: What inputs are affected by corrosion?, How would the inputs change if corrosion were not a factor?, and How would the inputs change if ''best corrosion practice'' were used?

The capital/output matrix (''B'' matrix) describes the capital required by an industry to produce its products. The coefficients describe the dollars worth of capital stock which must be provided by the row industry for the column industry to produce $1 worth of output per year. Principal questions here were: Is there excess capacity within the industry because of corrosion? and Is there any redundant capital because of corrosion? and if so, how would the amounts of excess capacity and/or redundant equipment be affected if ''best corrosion practice'' were used?

For replacement lives two principal questions were asked: How would the replacement lives of capital produced or used by your industry change if corrosion were not a factor? and How would the replacement lives of capital used or produced by your industry change if''best corrosion practice'' were used?

For final demand, the two principal questions were: Does corrosion affect the final demand of your product? and How would final purchases of your product change if''best corrosion practice' were used? The above questions were central to the entire data gathering operation.

Ultimately, all the information was reduced to coefficient and range changes. In their final form, World II and World III flow coefficient adjustments were stated as percentages of the corresponding World I coefficient. Capital/output coefficient adjustments were expressed as a percentage excess capacity for an entire industry or as percentage of specific World I coefficient for redundant equipment adjustments. Replacement life adjustments were expressed as a change in the range of years, i.e., 10 to 30 years for World I could be changed to 20 to 30 years for World II. Final demand changes were expressed as percentage change of World I values.

In general, analysis was done on an industry by industry basis, viewing each industry both as a user of goods and as a producer of goods. Like sectors were grouped and an individual assigned the responsibility of coordinating data gathering for the group. A flow diagram for the procedure to collect and process cost of corrosion data is presented in Figure 2. In the initial analysis stage, a general description of the industrial sector was determined from the list of Standard Industrial Classifications (SIC) and a priority assigned to the sector based on the effect of corrosion on the product and the production process. A sector plan was then prepared identifying likely sources of information and contacts to be made. During the preliminary stages, the World I matrices were reviewed to identify coefficients significantly affected by corrosion. Data gathering was carried out through interviewing knowledgeable individuals associated with the industry, reviewing the literature, and consulting technical experts. Finally, data were reduced to the required model format by review with BCL economists and necessary follow-up.

In most instances data were not readily available in the required format of percentage changes. Directly applicable information would indicate corrosion related costs as a percentage of the industries total output (total sales) and the origins and relative magnitudes of that cost, for example:

Corrosion Cost = 10% Total Sales

50% Corrosion Cost — Paints

30% Corrosion Cost — Stainless Steel

20% Corrosion Cost — Maintenance and Repair

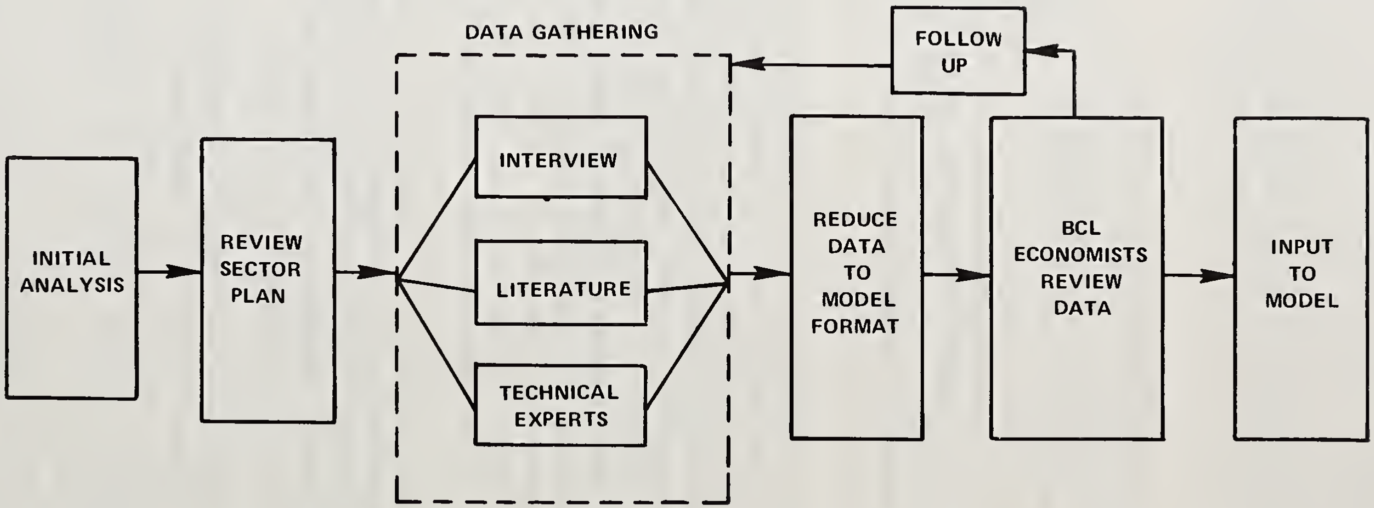

FIGURE 2. PROCEDURE TO COLLECT AND PROCESS COST OF CORROSION DATA

With this information, adjustments could be made to the appropriate sector inputs. When only a total cost was available, technical judgment based on experience from similar sectors or a knowledge of corrosion processes active in the industry was used to distribute total cost among the appropriate sectors.

Several meetings were held throughout the study to provide continuity and consistency of data processing. Information from individual sectors was reviewed and methods to handle various elements of costs of corrosion were developed through interaction of corrosion and economics experts. For consistency, all final coefficient adjustments were made by the same team of corrosion and economic experts based on input from all data gatherers.

4.2 Procedure for Coefficient Determination

The working definition for cost of corrosion was; That *increment* of total cost incurred by the *u*ser because of corrosion. The test question was ''What portions of the elements of total cost are incurred because corrosion exists?''. Portions of ten elements of cost were identified as being affected by corrosion. These elements are presented in Table 1 with a summary of procedure of treatment in the I/O Model. Each is discussed further in the remainder of this section.

Several items were excluded from the cost of corrosion in this study. Loss of life and loss of goodwill were not considered because they involved value judgment which cannot be defined rigorously in an economic sense. Catastrophic, one-time costs were not treated in the study except as these costs influence the overall industry behavior. Processes where oxidation of metals is favorable were not considered costs of corrosion, e.g., pickling of hot-rolled steel. Environmental deterioration of nonmetallics were not considered in the cost of corrosion, except where they are used as corrosion protection for metals, e.g., paint on steel. Subsequent costs as a consequence of corrosion failure or product loss, e.g., oil spill cleanup, fire damage, or air pollution, were not treated in this study. Finally, advertising and marketing costs for corrosion were not counted because no change in costs was anticipated. If corrosion resistance were not used in marketing, another attribute of the product would be chosen.

4.2.1 Replacement of Equipment or Buildings

The first element of cost of corrosion to be discussed is replacement of equipment or buildings. An example of this cost is the premature replacement of a pressure vessel containing corrosive fluids

TABLE 1. ELEMENTS OF COST OF CORROSION AND METHOD OF TREATMENT

Element of Cost	Example	Portion for Corrosion	Treatment in Model
1.0 Replacement of Equipment or Buildings	Corroded Pressure Vessel	All	Increase replacement life to next limiting factor, e.g., wear, obsolescense
2.0 Loss of Product	Corrosion Leak	All	Excess capacity, reduce capital requirements
	Corrosion Contamination of Product	All	
	Corrosion During Storage		For producer plant: excess capacity, reduce capital requirements For user: adjust input of producing sector
3.0 Maintenance and Repair	Repair Corroded Corrugated Metal Roof	All	For items supplied by construction sectors (19.01 to 19.04), separate input of 19.05 into corrosion and noncorrosion portions
	Weld Overlay of Chemical Reaction Tank	All	
	Repair Pump Handling Corrosive Slurry - Erosion and Corrosion	Partial	For equipment not supplied by construction, adjust input of producing sector, e.g., fabricated structural metal products
4.0 Excess Capacity	Scheduled Downtime for Plant in Continuous Operation, e.g., Petroleum Refinery	Partial	Reduce capital requirements by percent downtime ascribed to corrosion
5.0 Redundant Equipment	Installation of Three Large Fans, Where Two are Required During Operation	Partial	Reduce dollar amount of capital item required by portion of redundancy ascribed to corrosion, e.g., corrosion portion of 33 percent
6.0 Corrosion Control			
6.1 Inhibitors	Injection of Oil Wells	All	Reduce input by amount of inhibitors
6.2 Organic Coatings	Coal Tar on Exterior of Underground Pipeline	All	Separate 5.12 points and allied products into corrosion and noncorrosion
	Paint on Wooden Furniture	None	
	Topcoat on Automobile -- Aesthetics and Corrosion	Partial	
	Zinc-Rich Paint on Automobile	All	
6.3 Metallic Coatings	Galvanized Steel Siding	All	Separate coatings and platings into 8A07 corrosion and 8B07 noncorrosion
	Chrome Plated Faucets -- Aesthetic and Corrosion	Partial	
6.4 Cathodic Protection	C.P. of Underground Pipelines	All	Adjust input of 20.05, other business and professional services into sector constructing item (DTC)
7.0 Engineering, Research and Development Testing	Corrosion Resistant Alloy Development	All	Adjust input of user sector for input from sector supplying service, or user value added for self-supplied service
	Materials Selection	Partial	
	Corrosion Monitoring and Control	All	
8.0 Design			
8.1 Material of Construction for structural integrity	Stainless Steel for Corrosive Application	All	For producer of item reduce input of SS and increase input of mild steel, reflecting material substitution
	Stainless Steel for High Temperature Mechanical Properties	None	No Change
8.2 Material of Construction for Product Purity	High Alloy to Prevent Corrosion Products Contamination, e.g., Drug Industry	All	For producer of item reduce input of alloy and increase input of mild steel
8.3 Corrosion Allowance	Thicker Wall for Corrosion	All	Reduce input of metal to producer of item
8.4 Special Processing for Corrosion Resistance	Stress Relief, Shot Peening, Special Heat Treatment (e.g., Al Alloys) for Corrosion	All	Adjust inputs of producing sector for inputs required
9.0 INSURANCE	Portion of Premiums on Policy to Protect Against Loss Because of Corrosion (To cover charge of writing and administering policy -- not protection amount)	All	Adjust input of insurance to using sector
10.0 PARTS AND EQUIPMENT INVENTORY	Pumps Kept on Hand for Maintenance, e.g., Chemical Plant Inventory	Partial	Parts and equipment are accounted for in replacement life and input of producer to user Cost of storage -- adjusted value added of industry storing

Excluded From Cost of Corrosion

1.0 Loss of Life
2.0 Loss of Cood Will
3.0 Catastrophic - One Time Costs
4.0 Processes Where Oxidation of Metal is Favorable, e.g., Pickling Hot-Rolled Steel
5.0 Environmental Deterioration of Nonmetallics
6.0 Costs as Consequence of Corrosion Failure or Product Loss, e.g., Oil Spill Clean-up, Fire Damage, Air Pollution
7.0 Advertising and Marketing for Corrosion

because of corrosion. Corrosion costs of this type were treated in the I/O Model by adjusting the replacement life of the corroded capital to the next limiting factor. It was recognized that capital is replaced for reasons other than corrosion, e.g., wear and obsolescence, and adjustments were only made where corrosion was judged to result in premature replacement.

While the concept of premature failure because of corrosion is clearly defined, it proved to be one of the most difficult elements to treat quantitatively. Difficulties arose from the facts that there was a paucity of data on replacement lives of capital equipment and that each capital producing sector in the I/O Model produces a bundle of goods. A consequence of the latter is that even with the detail provided by separating the productive economy into 130 sectors, each capital producing sector produces a number of products which in some cases were quite diverse with respect to the effects of corrosion.

As a starting base, in World I, a range or single value for replacement life in years was assigned to each capital producing sector based upon Internal Revenue Service data for depreciation rates from Bulletin F. These replacement lives do not represent actual lives in service.

The following procedure was used to estimate changes in replacement lives from the base range because of corrosion. First, industrial sectors which produce goods affected by corrosion were identified. Thus, several capital producing sectors were eliminated from further consideration, e.g., the industry producing wooden furniture. Secondly, the effect of corrosion on replacement life was estimated to be minor, moderate, or major; Similarly, estimates were made for effect of best corrosion practice on replacement life. Thirdly, the base range for replacement lives (World I) was changed to reflect the relative impact of corrosion (World II) and best corrosion practice (World III).

The procedure allowed changes to be made in a consistent manner with identification of relative magnitude of corrosion effects, when no service life information was available. Judgments of magnitude of corrosion effects were made based on general knowledge of types of capital equipment, their materials of construction, and severity of corrosion in service.

Capital producing sectors whose products were affected by corrosion could be divided roughly into two groups. Sectors in one group produced capital which was exposed to similar service and environments regardless of the sector in which it was used, e.g., automobiles. The other group comprised sectors whose capital was exposed to widely varying service conditions depending upon the sector in which it was used, e.g., pumps. For the former, a general guideline could be established describing the extent to which useful lives were affected by corrosion, and these guidelines could be applied to all column sectors using the capital. The latter required a column by column analysis where useful lives were based upon the severity of corrosion in the column industry.

A compilation of all sectors in which replacement life adjustments were made is presented in Table 2. The capital producing sector is identified by numer with the type of items affected by corrosion. The extent of corrosion effect, the impact of best corrosion practice, and typical replacement life adjustments are presented. For example, Sector 8.04 produces heating equipment (except electrical) which includes boilers, furnaces, incinerators, and radiators. The effect of corrosion and impact of best corrosion practice on replacement lives of this equipment was judged to be major. A typical base replacement life range of 15 to 20 years in World I was adjusted to 25 to 30 years in World II and to 20 to 25 years in World III. Adjustments listed in the table are typical; changes for a particular column industry may be different.

The ranges of replacement lives and changes from World I and World II or World III do not reflect actual service lives but rather magnitudes of the effects of corrosion. Because of the lack of quantitative data for replacement lives and the effect of corrosion on replacement lives, estimates of costs associated with this element have a greater degree of uncertainty than that of other elements.

4.2.2 Loss of Product

Examples of this cost of corrosion are loss of valuable product through a corrosion leak, contamination by corrosion products of solutions requiring high purity, and corrosion damage to products during storage or shipping. Where loss of product affected a producing sector the cost was treated as lost capacity and all capital output coefficients were reduced by the precentage to which corrosion affected overall capacity. When a user industry was affected, these costs were treated by reducing the input from the industry providing the lost goods by the percentage of total input lost because of corrosion.

4.2.3 Maintenance and Repair

Examples of this element of the cost of corrosion are repair of a corroded corrugated metal roof, weld overlay of a chemical reaction tank, and the repair of a pump handling corrosive slurries. Only the portion of costs attributable to corrosion were of interest and where more than one effect was contributing to maintenance and repair, e.g., corrosion and wear, only a portion of the cost was ascribed to corrosion.

TABLE 2. REPLACEMENT LIFE ADJUSTMENTS

Capital Producing Sector	Types of Items Affected By Corrosion	Extent Corrosion Affect	Best Practice Impact	Replacement Life Range, Years Base*	With No Corrosion	With Best Practice
8.02	Metal Barrels, Drums, and Pails	Minor	Minor	4-10	6-10	5-10
8.04	Heating, Equipment (except electric) - Boilers, Furnaces Incinerators Radiators	Major	Major	15-20	25-30	20-25
8.05	Fabricated Structural Metal-Steel Joist, Expansion Joints, Transmission Towers, Condensors, Culvert, Pressure Vessels, Siding, Bins	Major	Major	3-25 15-30	20-25 20-35	12-25 20-30
8C07	General Hardware, Wire Products, Springs, Valves, Pipe Fittings, Fabricated Pipe	Major	Moderate	10-20 18-25	20-20 25-25	12-20 20-25
9.01	Engines and Turbines - Gas And Steam Turbines, Turbine Generator Set Units, Diesel Engines, Interior Combustion, Excludes Auto and Aircraft	Minor/ Moderate	Minor	17-25 20-25	25-25 25-25	20-25 22-25
9.02	General Industrial Machinery And Equipment - Mechanical Power Transmission, Process Furnaces And Ovens, Pumps, Compressors, Blowers, and Fans	Major	Major	10-25	20-25	15-25
10.01	Farm Machinery	Moderate	Minor	5-15	12-15	8-15
10.02	Construction Machinery	Minor	Minor	2-30 2-20	6-30 6-20	4-30 4-20
10.03	Mining Machinery	Minor	Minor	8-50 8-25	15-50 12-25	10-50 10-25
10.04	Oil Field Machinery	Moderate	Minor	3-25	15-25	7-25
10.05	Material Handling Equipment	Minor	Minor	7-30	12-30	9-30
10.08	Special Industry Machinery	Major	Major	15-25	20-30	20-25
11A01	Automobiles	Moderate	Moderate	3-5	6-8	4-7
11B01	Trucks, Buses	Moderate/ Minor	Minor	4-8	6-8	5-8
11.02	Aircraft, Aircraft Engines, Auxilliary Equipment	Minor	Minor	5	5-5	---
11.03	Ship Building And Repair	Major	Moderate	20-33	30-33	25-33
11.04	Railroad Equipment	Major	Major	17-25	25-35	25-30
12.03	Industrial Controls, Transformers, Bus Bars, Switch Gear	Minor	Minor	10-20 15-20	12-20 18-20	----- 16-20
12.04	Electric Lamps and Fixtures, Conduits and Fittings	Minor	Minor	15-25	17-25	16-25
13.01	Service Industry Machinery - Air Conditioning Units, Refrigeration Units, Dehumidifiers	Major	Moderate	10-25	15-25	12-25
13.02	Household Appliances- Washing Machines, Water Heaters, Refrigerators, Fans, Dishwashing Machines	Moderate	Minor	10-25	12-25	-----
13.03	Radio, TV, and Communication Equipment - Antenna, Radar	Minor	Minor	25	26	-----
14.01	Scientific Instruments, Measures, And Controls	Minor	Minor	15-30	17-30	-----

* Base replacement life range taken from allowable IRS depreciation lives report in Bulletin F, not actual service lives. Similarly, changes reflect magnitude of corrosion effect and not actual service life changes.

In the I/O Model maintenance and repair costs are treated as inputs to the using industry from the industry supplying maintenance and repair. For items supplied by the construction sectors (19.01 to 19.04), maintenance and repair is supplied by sector 19.05 Maintenance and Repair Construction. For equipment not supplied by construction sectors, the sector which produces the goods supplies the maintenance and repair. For example, maintenance on buildings is supplied by sector 19.05 and maintenance on engines and turbines is supplied by sector 9.01.

To determine maintenance and repair construction, corrosion costs sector 19.05 inputs to column industries were disaggregated into 19A05 – Corrosion Related Maintenance and Repair Construction and 19B05–Noncorrosion Related Maintenance and Repair Construction. This disaggregation was carried out in the World I ''A'' matrix. For equipment not supplied by construction, adjustments were made in the A matrix for World II and World III to account for the percentage of input from the producing sector ascribed to corrosion related maintenance and repair. Methods used to estimate these costs are discussed below.

As a starting basis, estimates of total maintenance costs for various industrial sectors were available from several sources. Compilations of maintenance costs described as percentage of total operating costs or as percentage of total sales were found in both technical and trade journals. For example, a report in *Chemical Week*, July 9, 1975, reported maintenance cost for chemical process industries. The cost data were taken from Form 10-K that public corporations file annually with the Securities and Exchange Commission. Maintenance costs for 34 major companies total 5.9 billion dollars in 1974 and were presented as total maintenance dollars spent, percent of sales, percent of net income, and percent of fixed assets both at cost and after depreciation. Another source, Aries and Newton in *Chemical Engineering Cost Estimation*, McGraw Hill, 1955, reported that maintenance costs for the chemical industries expressed as percent of fixed capital costs range from 2 to 4 percent for simple light use industries up to 8 to 10 percent for complicated severe chemical usage. In addition to sources of this type, individual companies when interviewed often had reliable estimates of total maintenance costs and their distribution.

The principal needs for this study were to determine the portion of total maintenance costs ascribed to corrosion and the distribution of these corrosion costs among industrial sectors providing inputs.

Data for the portion of maintenance costs because of corrosion were available for several industries. For example, compilation of Office of Pipeline Safety statistics for 1970 to 1975, indicated that 15 percent of the leaks in gas transmission pipelines were caused by corrosion, and 46 percent of leaks in gas distribution systems were corrosion related. A survey of operators of offshore platforms in the oil and gas industry conducted by NACE ascribed 1 to 2 percent of installed platform costs for corrosion maintenance. Another study conducted by NACE ascribed 90 percent of well casing replacements to corrosion. Results reported in 1973 by DuPont on 4 years of failures recorded by cause found 55.2 percent of piping and equipment failures to be due to corrosion. Similar data of corrosion maintenance costs were found in other sectors.

Where corrosion costs were not considered to be significant, most industries estimated corrosion related maintenance to be 1, 2, or 5 percent of total maintenance. In many cases these estimates were ''best guess with little or no substantiating evidence'', however, in instances where data were available 1 to 5 percent of total maintenance for corrosion was substantiated as being quite reasonable as a lower bound.

4.2.3.1 Maintenance and Repair Construction. Sector 19.05 Maintenance and Repair Construction was disaggregated into corrosion and non-corrosion activities. The procedure to estimate the portion of 19.05 which was corrosion related was to begin by ranking the 130 industrial sectors as to the impact of corrosion on their maintenance. The rankings were determined by technical experts based upon a general knowledge of the processes within each industrial sector and the extent to which plant and equipment were affected by corrosion in those processes. For example, a chemical processing plant handling highly corrosive fluids has higher corrosion related maintenance costs than a small manufacturing facility. Similarly, plants and equipment exposed to highly corrosive industrial or marine atmospheres require more corrosion related maintenance than those exposed to a more benign, rural atmosphere.

Next, estimates were made for the percentage corrosion in each rank. These latter estimates were keyed to particular industries where information was available. Based on information gathered from interviews with industrial experts and published information, the following set of percentages for corrosion were estimated:

2A05 - Crude petroleum	30 percent
2B05 - Natural gas	30 percent
4.07 - Pulp and paper	50 percent
5.01 - Petroleum refining	40 percent
6.01 - Glass and glass Products	6 percent
6.04 - Other nonmetallic mineral products	6 percent
17.06 - Pipelines	20 percent
20.05 - Other business and professional services	10 percent

Using these estimates as a guide percentages were assigned to the other industries.

Estimates for each group of industrial sectors are presented in Table 3. The coefficient in the World I ''A'' matrix for input of maintenance and repair construction (Sector 19.05) to the column industry was separated into corrosion and non-corrosion portions using these estimates.

4.2.3.2 Maintenance and Repair Equipment. Maintenance and repair of equipment for corrosion, which is handled in the I/O Model as inputs from the sector which produces the equipment, was estimated by three alternative methods: (1) Total maintenance supplied by the producing sector was estimated and then the percentage of total maintenance for corrosion was estimated, (2) An estimate was made of total percent corrosion maintenance for a sector and then distributed among the appropriate sectors supplying maintenance, and (3) An estimate of dollar value of corrosion maintenance for an entire sector or specific equipment in a sector was used to make coefficients adjustments. The alternatives are listed in their order of preference for this study, but all were used depending upon data available.

For sectors which produced no corrodible products, inputs for maintenance were readily identified, e.g., input from sector 9.02—General Industrial Machinery and Equipment to the chemical industry must be all for maintenance of equipment because machinery and equipment are not found in products of the chemical industry. For sectors which produce corrodible products, inputs can be either for maintenance or for inclusion in products produced, e.g., inputs of Sector 9.02— General Industrial Machinery and Equipment to the ship and boat building industry can either be for maintenance or part of the ship produced.

When distribution of a total cost among appropriate sectors was required, the distribution was made based on knowledge of the corrosion maintenance required for specific types of equipment and the dollar value of that type of equipment in the capital of the particular industry.

Information on percent corrosion related maintenance for items of equipment in various industries was obtained through published data, interviews with industrial experts responsible for corrosion maintenance and control, and interviews with producers of equipment. In many cases data from detailed studies and careful analysis were available while in others estimates were made based on experience and general knowledge without specific data. Table 4 presents some of the data on corrosion related cost for maintenance of equipment. Estimates of percentage for corrosion are listed for various types of equipment in petroleum refineries, steel plants, and chemical process plants. Similar data were gathered for other industries or specific equipment in other industries.

TABLE 3. ESTIMATES FOR DISAGGREGATION OF SECTOR 19.05 MAINTENANCE AND REPAIR CONSTRUCTION INTO 19A05 CORROSION RELATED AND 19B05 NONCORROSION RELATED

	Sector Group	Percent Maintenance and Repair Construction for Corrosion
1.0	Agriculture, Forestry and Fishery	5% Agriculture, 10% Fishery
2.0	Extraction of Mineral Resources	10% Mining, 30% Gas and Oil
3.0	Manufacture of Food, Leather and Textile Products	10% Food, 5% Textile
4.0	Wood and Paper Products	50% Pulp and Paper, 5% Lumber and Furniture
5.0	Petroleum and Chemical Products	40% Petroleum Refining, 30% Industrail Chemicals, 20% Drugs, 10% Tires
6.0	Stone, Clay, and Glass Products	6% Glass, 6% Stone
7.0	Primary Metals and Manufacturers	25% Ferrous, 20 to 40% Nonferrous
8.0	Fabricated Metal Products	20% Coating and Plating, 5% all other
9.0	General Machinery and Components	5% All Sectors
10.0	Specialized Machinery	10% Oil Field, 5% all other
11.0	Transportation Equipment	20% Ships, 10 all other
12.0	General Electrical Apparatus	5% All Sectors
13.0	Special Electrical Apparatus	5% All Sectors
14.0	Scientific and Measuring Devices	10% Photographic, 5% all others
15.0	Business Machines and Supplies	5% All Sectors
16.0	Miscellaneous Manufacturers	5% All Sectors
17.0	Transportation	15% Water, 10% Air, 5% Railroad
18.0	Public Utilities	20% Gas, 10% all others
19.0	Construction	10% All Sectors
20.0	Trade and Business Services	5% Wholesale/Retail Trade
21.0	Other Services	15% Personal Auto, 10% Hotels and Lodging, 5% Printing
22.0	Government Enterprises	10% Post Office

TABLE 4. ESTIMATES OF CORROSION PORTION (PERCENT) OF TOTAL MAINTENANCE COSTS FOR EQUIPMENT

Item	Crude Distillation Unit of Refinery[1]	Steel Industry[2]	Chemical Plant[3]	Chemical Plant[4]	Refinery Complex[5]
Industrial Controls		15	20		15
Electrical		25	20		
Pumps			90	↑	5
Reactors/Vessels	45				
Tanks			15		80
Heat Exchangers	90				
Furnaces	80				
Piping	100		85	55.2%	95
Valves			85	Piping and	50
Mechanical Equipment		5	10	Equipment Failures	5
Engines and Turbines		15		↓	2
General	40				

(1) N. J. Landis, Corrosion, 16, 479C, 1960.

(2) Estimate of Mechanical Foreman and Engineering Department of Integrated Steel Plant.

(3) Estimate of Head of Department with responsibility for materials selection and related problems for variety of chemical plants.

(4) J. A. Collins and M. L. Monack; Materials Protection and Performance; 12, 11, 1973.

(5) Concensus of group responsible for maintenance and repair at a large refinery complex.

Where no data were available for a particular industry estimates were made based on a general knowledge of the severity of corrosion in the industry and experience from sectors with similar service where data were available.

This procedure which comprised gathering specific data in selected industries and generalizing the estimates to industries where no other data were available is illustrated in two examples presented below.

First, treatment of maintenance costs in the ship building industry provide an example of the procedure for estimating total costs of corrosion and distributing it among the appropriate sectors. In this industry data were available from a major ship building yard which indicated that total maintenance was 3 percent of sales. Further, 10 percent of total plant and equipment maintenance was ascribed to corrosion. Additional information was provided which broke down total maintenance by types of equipment maintained. Thus all the information necessary to estimate and distribute costs was available.

In the second example, only a total dollar estimate for corrosion maintenance was available. For Sector 21.05—Auto Repair and Services, $5.1 Billion per year was ascribed to corrosion maintenance. When compared to the total output of Sector 21.05, this dollar value indicated that approximately 25 percent of the sector activities were corrosion related. This factor was applied to estimate corrosion related maintenance from Sector 21.05 in all industries.

4.2.4 Excess Capacity

Excess capacity was considered as a cost of corrosion only in those instances where plants and equipment were run on a continuous basis with scheduled downtime. Lost production time on facilities which were not scheduled for continuous service was not considered as a cost of corrosion. Sector 5.01—Petroleum Refining provides an example where a portion of excess capacity was ascribed to corrosion. Petroleum refineries are designed and operated at 95 percent of plant capacity with 5 percent scheduled downtime. Analysis of the requirements for and operations carried out during scheduled downtime indicated that downtime could be reduced approximately 50 percent were corrosion not a factor. Consequently, an excess capacity of 2 percent in the Petroleum Refinery Industry was ascribed to corrosion, and capital coefficients for the entire industry were reduced by this factor in World II. In other words, if corrosion were not a factor the entire capital in place in petroleum refineries could be reduced by 2 percent.

4.2.5 Redundant Equipment

When processes are designed to run continuously, it is standard design practice to install redundant equipment on large ancillary items which require regular maintenance. This practice allows the processing to continue while one of the redundant items is out of service for maintenance. Three large fans, motors, or pumps are typically installed in a plant where two are required for continual operation.

In many instances a portion of the redundant equipment can be ascribed to corrosion. These costs were treated in the I/O Model by first, identifying redundant equipment in an industry; secondly, estimating the percentage of capital of that type in the industry; and thirdly, estimating the percentage of redundancy which could be ascribed to corrosion. This procedure supplied the necessary information for adjustment of the capital/output coefficient for the row industry producing the capital in the column industry using the redundant capital.

4.2.6 Corrosion Control

4.2.6.1. Corrosion Inhibitors and Water Treatment. Corrosion inhibitors are used extensively for the control of corrosion in many industries. Identification of industries using inhibitors, the major applications of ihnibitors, and some cost information were found in *Corrosion Inhibitors* published by National Association Corrosion Engineers. Cost associated with the purchase of inhibitors were treated in this study by making adjustments to the inputs from Chemical Sectors 5.03 and 5.06 to the industry using inhibitors.

In many cases, where inhibitors were a large portion of the chemicals purchased by an industry a direct estimate could be made of the percentage of total chemical purchases accounted for by corrosion inhibitors. For example, technical experts in their respective industries estimated the percentage of corrosion inhibitor purchases of total chemical purchases were

40 percent in Sector 2A05	Crude Petroleum Production
20 percent in Sector 2B05	Natural Gas Production
40 percent in Sector 5.01	Petroleum Refining
50 percent in Sector 17.06	Pipeline

Inputs from sections 5.03 and 5.06 were adjusted by these percentages.

In other cases a direct estimate was not available, or corrosion inhibitors made up only a small portion of the total purchases of chemicals. Then, direct estimate of the purchases of corrosion inhibitors was made. Basis for these estimates was an estimated value of total water treatment purchases in 1975 and a breakdown of the total by general industrial classifications. These dollar estimates were distributed among the appropriate industrial sectors. For example, it was estimated that the primary metals industries purchased $80M of corrosion inhibitors and water treatment, and that 60 percent of these purchases were by the ferrous metals industries. Thus, $48M was distributed among the five ferrous metals sectors, 7A01 through 7E01. Distribution was made based upon the ratio of the sector's total output. This procedure was used to estimate the cost of inhibitors in Sectors 4.07 — Pulp and Paper, 3X01 — Food and Kindred Products, 3X04 — Fabricated Textile Products, all chemical sectors, and all primary metal sectors.

4.2.6.2. Organic and Metallic Coatings and Platings. Corrosion costs associated with protective coatings were treated by disaggregating Sector 5.12 — Paints and Allied Products into Sector 5A12 — corrosion related and 5B12 — non-corrosion related and disaggregating Sector 8.07 — Metallic Coatings and Platings into Sector 8A07 — corrosion related and 8B07 — non-corrosion related. These disaggregations were carried out in the World I flow matrix.

A distinction is made in the treatment of coatings in the I/O Model for coatings which are applied to the product of an industry and for coatings used for maintenance within the industry. Coatings applied to a product are treated as direct input to the sector manufacturing the product, while maintenance coatings are supplied by the sector that produced the capital item being maintained. The latter are treated as an input from the capital producing sector to the user column.

The treatment of coatings in the auto industry illustrates the distinction. The auto industry applies organic coatings to its product, automobiles, and it was estimated that 50 percent of the organic coatings applied to automobiles was for corrosion protection. In the flow matrix the column industry, Sector 11A01—Automobiles, has an input from the row industry, Sector 5A12—Paints and Allied Products. Equal inputs from both disaggregated sectors, 5A12—Corrosion and 5B12—Non-corrosion, constitute the entire purchases of paints and allied products by the auto industry.

Maintenance painting is treated as follows. The buildings of an auto plant are painted (along with other maintenance) by Sector 19.05—Maintenance and Repair Construction. Similarly, machinery in the auto plant is painted (and otherwise maintained) by the producing industry, e.g., 9.02—General Industrial Machinery. The cost of painting is included in the input from the respective capital producing sector.

Determination of the portion of coatings to be ascribed to corrosion is straightforward in many instances, e.g., external coating on buried pipelines is all for corrosion protection, and painting of wooden furniture is all non-corrosion related. Other instances were encountered where ascribing portions for corrosion and non-corrosion was not as straightforward, e.g., the painting of automobiles where visible sheet metal is primed and top coated both for corrosion protection and aesthetics. In the latter case judgment was required to disaggregate painting costs.

The procedure used to disaggregate coatings into corrosion and non-corrosion was to have technical experts knowledgeable in coatings and corrosion review the capital producing sectors which had inputs from either organic or metallic coating and plating sectors. Based on examination of Standard Industrial Classifications for the capital producing sectors a determination was made of the products being coated. From a knowledge of (1) the products being coated, (SIC information), (2) types of coatings being applied (combined experience of experts), and (3) need for corrosion protection of the products (combined experience of experts) a judgment of the percentage of coating to be ascribed to corrosion was made. Corroborative statistics were used where available, for example, ''The Compilation of Industrial or Chemical Coatings by End Use in 1974''. The percentage of coating ascribed to corrosion protection used for the disaggregation of organic coatings and metallic coatings are listed in Table 5.

4.2.6.3. Cathodic Protection. Cathodic protection services, materials, and equipment were treated as part of Sector 20.05—Other Business and Professional Services. Magnesium, zinc, aluminum, other materials, and equipment required for cathodic protection were treated as inputs to Sector 20.05, and in turn Sector 20.05 provided cathodic protection service to industries constructing or producing the item to be protected. For example, it was estimated that 6500 tons of zinc are used annually for sacrificial anodes in cathodic protection systems. This zinc appears as an input to Sector 20.05. Cathodic protection is applied by the ship building industry to protect ships hulls and internal tank surfaces from corrosion. Cost of this cathodic protection are treated as inputs from Sector 20.05 to the ship building industries Sector 11.03. Cost for cathodic protection of municipal water storage tanks are treated as an input from Sector 20.05 to the industry constructing water storage tanks, namely Sector 19.03—New Construction, Public Utilities.

With the above procedure nearly all cathodic protection is treated in the construction sectors. Public Utilities are the largest users of cathodic protection with other users including transportation sectors, gas and oil, chemical process industries, and ships. To treat these costs, an estimate of total sales (output) of the cathodic protection industry was made, and this amount was distributed among the construction sectors. Distribution was made based upon the proportion of

TABLE 5. ESTIMATES OF PERCENTAGE OF COATINGS ASCRIBED TO CORROSION PROTECTION *

	Industry Applying Coating to Their Product	Organic 5A12 Corr.	Coatings 5B12 Non-Corr.	Metallic Coatings and Platings 8A07 Corr.	8B07 Non-Corr.
1.03	Forestry and Fishery Products	0	100	0	0
3.05	Fabrics, Yarns and Threads	0	100	0	0
4X01	Lumber Mills, Plywood, Wooden Containers	5	95	0	0
4.03	Lumber & Wood Products, Except Cont.	5	95	0	0
4X05	Furniture and Fixtures	50	50	60	40
5X07	Plastics Materials & Organic Man-made	0	0	0	9
5.15	Manufactured Plastics Products	0	100	0	100
6.01	Glass and Glass Products	0	0	0	100
7A01	Mild Steel - Carbon Steel	100	0	100	0
7B01	Low Alloy Steel	100	0	100	0
7C01	Alloy Steel	100	0	0	0
7D01	Stainless Steel	100	0	0	0
7.02	Primary Copper	0	0	75	25
7.03	Primary Aluminum	0	0	75	25
7F04	AU, AC, PT, PD	0	0	0	100
8.01	Metal Cans	90	10	90	10
8.02	Metal Barrels, Drums and Pails	90	10	67	33
8.03	Metal Sanitary Ware & Plumbing Fittings	90	10	67	33
8.04	Nonelectric Heating Equipment	90	10	67	33
8.05	Fabricated Structural Metal Products	95	5	75	25
8.06	Screw Machine Prod. etc., & Stampings	75	25	75	25
8A07	Coating and Plating, Corr.	75	25	0	0
8B07	Coating and Plating, N-Corr.	80	20	0	0
8C07	All Others	95	5	75	25
9.01	Engines and Turbines	90	10	50	50
9.02	General Industrial Machinery & Equip.	94	6	25	75
9.03	Machine Shop Products	0	0	15	85
10.01	Farm Machinery	85	15	30	70
10.02	Construction Machinery	90	10	50	50
10.03	Mining Machinery	90	10	50	50
10.04	Oil Field Machinery	90	10	67	33
10.05	Materials Handling Mach., Except Trucks	80	20	25	75
19.04	New Construction, Highway and Other	50	50	0	0
19A05	Maintenance & Repair Construction, Corr.	50	50	0	0
19B05	Maintenance & Repair Construction, N-Corr.	0	100	0	0
20101	Wholesale and Retail Trade	50	50	0	0
20X02	Finance, Insurance, Real Estate, Advertising	50	50	0	0
20.05	Other Business & Professional Services	26	74	0	0
21.04	Personal & Repair Services, Except Auto	40	60	50	50
21.05	Automobile Repair and Services	60	40	75	25
21.06	Amusements	17	83	0	0

	Industry Applying Coating to Their Product	Organic 5A12 Corr.	Coatings 5B12 Non-Corr.	Metallic Coatings and Platings 8A07 Corr.	8B07 Non-Corr.
10.06	Industrial Trucks and Tractors	70	30	50	50
10.07	Metalworking Machinery	100	0	60	40
10.08	Special Industry Machinery	70	30	60	40
11A01	Automobiles	50	50	30	70
11B01	Trucks, Buses, etc.	58	42	60	40
11.02	Aircraft and Parts	80	20	50	50
11.03	Ship and Boat Building & Repair	75	25	75	25
11.04	Locomotives & Rail and Streetcars	75	25	33	67
11.05	Motorcycles, Bicycles, Trailer Coaches, etc.	50	50	50	50
12.01	Electrical Measuring Instruments	75	25	40	60
12.02	Electric Motors and Generators	60	40	40	60
12.03	Industrial Controls, Transformers, etc.	50	50	40	60
12X04	Electric Lamps and Fixtures	20	80	33	67
12.06	Electronic Components and Accessories	10	90	70	30
12.07	Miscellaneous Electrical Machinery	27	73	40	60
13.01	Service Industry Machinery	60	40	75	25
13.02	Household Appliances	85	15	60	40
13.03	Radio, T.V., and Communication Equip.	50	50	60	40
14.01	Scientific Instru., Meas. and Controls	75	25	60	40
14.02	Medical, Surgical, Dental Instru. and Supplies	70	30	75	25
14.03	Watches, Clocks and Parts	0	0	75	25
14.04	Optical and Ophthalmic Goods	0	0	5	95
14.05	Photographic Equipment and Supplies	37	63	30	70
15.01	Computing and Related Machines	39	61	60	40
15.02	All Other Office and Business Machines	50	50	60	40
15.03	Office Supplies	0	0	60	40
16.01	Ordnance and Accessories	80	20	70	30
16.02	Other Miscellaneous Products	50	50	67	33
19.01	New Construction, Nonfarm Residences	25	75	0	0
19.02	New Construction, Nonresidential Bldgs.	40	60	0	0
19.03	New Construction, Public Utility	60	40	0	0

* Based on Technical Judgement.

capital produced by each construction sector for the sectors using cathodic protection, e.g., all chemical plant production is done by Sector 19.02, and greater than 95 percent of construction of public utilities is done by Sector 19.03. Following this procedure an estimated $145 M was distributed:

20 percent to Sector 19.02

75 percent to Sector 19.03

5 percent to Sector 19.04.

In cases such as ship building, a direct estimate of the percentage of constructed costs for cathodic protection could be made. Published data reported that sacrificial cathodic protection on a $20 Million tanker cost approximately $10,000 while impressed current cathodic protection systems cost approximately $50,000. Thus, cathodic protection cost represents from 0.05 percent to 0.25 percent of tanker cost. The lower number in this range was chosen as all ships and boats do not have cathodic protection installed. On this basis, cathodic protection costs to the ship building industry were estimated to be 0.05 percent of the total output of the Ship and Boat Building Industry, and input from Sector 20.05 was adjusted accordingly.

4.2.7 Research and Development, Engineering and Other Technical Support

Corrosion costs are incurred for technical support to improve corrosion resistance of products and to carry out corrosion maintenance and control programs. The corrosion related technical support can be in the form of research and development, engineering, testing, inspection, consulting, and other services. These corrosion costs are treated in the I/O Model by adjustments of inputs to the sector receiving the technical support from Sector 20.05—Other Business and Professional Services or Row 25.00—Value Added.

Estimates were available for research and development costs by various industries expressed as percent of total sales (*Business Week*, ''Where Private Industry Puts Its Research Money'', June 28, 1976). These data were used to estimate Research and Development expenditures for all industrial sectors in the I/O Model. Next, the percentage of Research and Development cost for corrosion was estimated. These estimates are listed in Table 6; only sectors where a portion of Research and Development cost was ascribed to corrosion are listed. A multiplier was assigned to each industry to account for other technical support for corrosion in addition to Research and Development.

TABLE 6. CORROSION RELATED TECHNICAL SUPPORT COSTS RESEARCH AND DEVELOPMENT, ENGINEERING, AND TESTING

	Sector	Percent Sales For R&D	Percent R&D for Corrosion	Multiplier For Engineering and Other Technical Support	Net Coefficient Adjustment
2.01	Iron and Ferroalloys Ores	0.012	0.1	2	0.000024
2.02	Copper Ores	0.012	0.1	2	0.000024
2.03	Nonferrous Ores, Except Copper	0.012	0.1	2	0.000024
2A05	Crude Petroleum	0.004	5	2	0.0004
2B05	Natural Gas	0.004	5	2	0.0004
4.07	Pulp, Paper and Paper Products, Except Containers	0.008	0.1	2	0.000016
5.01	Petroleum Refining and Related Products	0.013	1	3	0.00039
5.03	Industrial Inorganic and Organic Chemicals	0.026	1	3	0.00078
5.04	Fertilizers	0.026	1	3	0.00078
5.05	Agricultural Chemicals, Except Fertilizers	0.026	1	3	0.00078
5.06	Miscellaneous Chemical Products	0.026	1	3	0.00078
5A12	Paints and Allied Products, Corr	0.012	50	2	0.012
7A01	Mild Steel - Carbon Steel	0.006	10	2	0.0012
7B01	Low Alloy Steel	0.006	10	2	0.0012
7C01	Alloy Steel	0.006	10	2	0.0012
7D01	Stainless Steel	0.006	60	2	0.0072
7E01	Cone	0.006	1	2	0.00012
7.02	Primary Copper	0.012	20	2	0.0048
7.03	Primary Aluminum	0.012	10	2	0.0024
7A04	NI, Ni Alloys, CO	0.012	20	2	0.0048
7B04	Zinc	0.012	1	2	0.00024
7C04	Magnesium	0.012	0.1	2	0.000024
7D04	Lead	0.012	0.1	2	0.000024
7E04	TI, TA, ZR	0.012	0.1	2	0.000024
7F04	AU, AG, PT, PD	0.012	0.1	2	0.000024
7G04	All Others	0.012	0.1	2	0.000024
8.01	Metal Cans	0.011	10	1	0.0011
8.02	Metal Barrels, Drums and Pails	0.011	10	1	0.0011
8.03	Metal Sanitary Ware and Plumbing Fittings	0.012	0.1	2	0.000024
8.04	Nonelectric Heating Equipment	0.012	0.1	3	0.000036
8.05	Fabricated Structural Metal Produc Products	0.012	0.1	3	0.000036
8A07	Coating and Plating, Corr	0.026	50	2	0.026
9.01	Engines and Turbines	0.017	1	3	0.00051
9.02	General Industrial Machinery and Equipment	0.017	1	3	0.00051
9.03	Machine Shop Products	0.017	1	2	0.000034
10.01	Farm Machinery	0.024	0.1	3	0.000072
10.02	Construction Machinery	0.024	0.1	3	0.000072
10.03	Mining Machinery	0.017	0.1	3	0.000051
10.04	Oil Field Machinery	0.017	0.1	3	0.000051
10.08	Special Industry Machinery	0.024	0.5	3	0.00036
11A01	Automobiles	0.027	0.1	2	0.000054
11B01	Trucks, Buses, etc.	0.027	0.1	2	0.000054
11.02	Aircraft and Parts	0.032	1	2	0.00064
11.03	Ship and Boat Building and Repair	0.01	0.1	2	0.00002
11.04	Locomotives and Rail and Streetcars	0.01	0.1	2	0.00002
11.05	Motorcycles, Bicycles, Trailer Coaches, etc.	0.01	0.1	2	0.00002
13.02	Household Appliances	0.012	0.1	2	0.000024
14.02	Medical, Surgical, Dental Instruments and Supplies	0.054	0.1	1	0.000054
15.01	Computing and Related Machines	0.056	0.1	2	0.00011
16.01	Ordnance and Accessories	0.02	0.1	3	0.00006
17.01	Railroads and Related Services	0.003	0.1	2	0.000006
17.02	Local and Other Highway Passenger Transport	0.003	0.1	2	0.000006
17.03	Motor Freight	0.003	0.1	2	0.000006
17.04	Water Transportation	0.003	0.1	2	0.000006
17.05	Air Transport	0.003	0.1	2	0.000006
17.06	Pipelines	0.003	0.1	2	0.000006
17.07	Transportation Services	0.003	0.1	2	0.000006
18.01	Telecommunication	0.019	1	2	0.00038
18.02	Electric Power	0.003	0.1	2	0.000006
18.03	Gas	0.003	0.1	2	0.000006

(1) Business Week, "Where Private Industry Puts Its Research Money", June 28, 1976.

The multiplication product of these three estimates yielded the final net coefficient adjustment to be made for the sector to account for corrosion related technical support. For example, Sector 7.02–Primary Copper was estimated to spend 1.2 percent of every sales dollar for research and development of which 20 percent was ascribed to corrosion. A multiplier of 2 was assigned to this sector meaning that it was estimated that research and development cost accounted for 50 percent of the technical support for corrosion. The net coefficient adjustment resulting from these estimates was 0.0048. Therefore, the overall estimate was that for every sales dollar of the Primary Copper industry 0.0048 dollars are used for corrosion technical support. This coefficient multiplied by the total output of the sector provides the total cost of corrosion technical support.

4.2.8 Design

Four aspects are considered in this element of corrosion: material of construction for corrosion resistance, material of construction for product purity, corrosion allowance, and special processing for corrosion resistance. Selecting a more corrosion resistant metal is a basic method of corrosion control. The incremental cost of corrosion resistant metal over that of the metal which would be chosen were corrosion not a factor, typically mild steel, is a cost of corrosion.

These costs were treated in the sector of the producer of the item by shifting dollar purchases from the input of corrosion resistant metal to the input of the lower priced alternative metal. For example, consider a chemical process industry which uses stainless steel pressure vessels when mild steel pressure vessels would be chosen if corrosion were not a factor. The cost of corrosion is treated as if the Fabricated Structural Metal Sector, producers of pressure vessels, purchased mild steel to construct a vessel and not stainless steel. Thus, dollar purchases by the Fabricated Structural Metal Sector of stainless steel are reduced, purchases of mild steel are increased, and the cost differential is transferred to the social savings row in the flow matrix.

A dollar per pound conversion ratio was used to make all metal shifts for corrosion purposes, i.e., the dollars worth of stainless steel no longer purchased was converted to pounds of stainless steel and an equal weight of mild steel was purchased. The dollar difference between the two purchases was treated as the cost of corrosion. These are simplifing assumptions used for this study and for specific items should not be used in practice. The price ratio used for metal conversions were mild steel 1.00, low alloy steel 1.35, alloy steel 2.50, stainless steel 7.50, copper 8.65, aluminum 5.36, and nickel and nickel alloys 19.00.

Consequences of this conversion procedure are that differences in design thicknesses using different metals, differences in densities of different metals, and differences in fabrication costs are not considered.

Mild steel was considered to be the basic material of construction with corrosion resistant materials selected in place of mild steel where required. For sectors producing metallic items, metal inputs were examined, and conversions from purchase of corrosion resistant metals to mild steel were made where warranted. The portion of metal inputs ascribed to corrosion was estimated based upon analysis of the products manufactured by a sector and the service in which products would be used. Estimates were based on experience, information from materials producers, and information from equipment manufacturers.

It is standard design practice to incorporate a corrosion allowance for many applications. These costs were treated in the I/O Model by a reduction of metal input to the sector producing the item to account for metal used for corrosion allowance. For example, in the ship building industry it was estimated that 20 percent of steel usage was for specified corrosion allowance of steel plate and structual members. Thus, if corrosion were not a factor, steel purchases by the ship building industry would be reduced by 20 percent.

Special processing of metal and alloys is often required to provide corrosion resistance. Included under the heading of special processing are stress relief treatments, shot peening, and special heat treatment such as used for aluminum alloys. Incremental costs for special processing were considered to be a cost of corrosion . Treatment in the I/O Model was to reduce inputs to the metal producing sector for special processing and reduce capital coefficients of the metal producing sector to account for equipment required for special processing.

4.2.9 Insurance

Portions of insurance premiums to protect against loss because of corrosion are a legitimate cost of corrosion. The costs of corrosion are those to cover the expenses of writing and administering the policy and do not include those charges which go to covering claims. These costs are treated in the I/O Model by reducing the input of the insurance sector to the purchasing sector.

4.2.10 Parts and Equipment Inventory

The cost of maintaining an inventory of spare parts and equipment for corrosion is considered a cost of corrosion. Only the cost of handling and storing the items are considered here, because costs of the inventory itself are handled by replacement and flow matrix coefficients. Costs for maintaining the inventory are treated by transferring the cost from the industry's value added to social savings.

4.3 Avoidable Costs of Corrosion—Best Corrosion Control Practice

Determination of the avoidable and unavoidable portions of the total cost of corrosion is of primary interest in evaluating the present state of circumstances and in developing programs to reduce corrosion cost. Avoidable costs are those amenable to reduction by presently available corrosion prevention and control technology. In this context, the definition of best corrosion-control practice does not imply a gold-plated world, but rather a world in which resources are used economically and efficiently to control corrosion.

The division of total corrosion costs into avoidable and unavoidable makes an important distinction and can provide guidance in the assignment of priorities to educational or research and development efforts. Avoidable costs are amenable to reduction by present technology and are impacted upon by increased technology transfer, increased awareness, and incentives to save. For example, high maintenance costs and early replacement of a steel marine structure because of inadequate cathodic protection is an avoidable cost of corrosion. Unavoidable costs are not amenable to present technology and require technological advance for reductions to be realized. The costs for a sound, maintenance painting program to protect structures from atmospheric corrosion are presently unavoidable. Development of improved coating systems is a potential means for savings to be realized.

Determination of avoidable cost of corrosion was one of the more difficult areas of this study for two reasons. First, a definition of best practice readily measurable in economic terms was difficult to develop. Secondly, data for avoidable costs of corrosion were very limited. Except in isolated instances *standards* of best practice do not exist. A decision on which is the ''best'' alternative is complex and can vary widely within an industry or even within a company.

In addition to the many technical, material factors which impact on best corrosion practice, a number of economic parameters must also be considered as described in NACE publication RP-02-72, ''Direct Calculation of Economic Appraisals of Corrosion Control Measures''. The economic parameters include return on investment, discounted cash flow, present worth of money, and future worth of money.

4.3.1 Approach Adopted for Avoidable Costs

Determination of avoidable cost of corrosion was achieved by the construction of a third set of all components in the I/O Model (World III). The treatment and general procedures were the same as those for constructing,World II, where corrosion was not a factor. Moreover, adjustments made to construct World II provided a basis for estimating World III adjustments.

Avoidable costs of corrosion were considered to be significant in only two areas: (1) Maintenance and repair and (2) Replacement. Other changes in inputs for World II were considered to be best practice. Therefore no changes from World I values were made in coatings, platings, cathodic protection, corrosion resistant metals, etc. Also, adjustment to capital/output coefficients in World II were made to account for redundant equipment and excess capacity. These adjustments were considered to be best practice and no changes were made for World III.

It should be recognized that the above are simplifying assumptions and changes in purchases such as paints and metallic coatings are likely to be affected by use of best practice. However, for a first order approximation the assumptions are valid. Costs of corrosion control materials and labor in many cases do not increase, but best practice is achieved at no additional costs through improved procedures and implementation.

4.3.2 Treatment of Avoidable Costs in I/O Model

Adjustments for World III from World I values were confined to two areas: the A matrix to account for corrosion related maintenance and the replacement life matrix to account for reduction in replacement lives because of avoidable corrosion.

Coefficient adjustments in the A matrix to account for *total* corrosion-related maintenance costs were made in World II. To estimate avoidable corrosion maintenance costs, a best practice rating was determined for each industrial sector, a percentage avoidable costs factor assigned to each rating, and the resulting industry-specific rating applied to corrosion maintenance costs of that industry.

Best practice ratings were determined by a qualitative comparison of industrial sectors as to their incentive or pressure to use best corrosion practice and their responsiveness or capacity to use best corrosion practice. Each industrial sector was rated high, medium, or low in both categories. A best practice rating was determined by the average of ranking in the two categories by assigning 1.0 to low rating, 2.0 to moderate rating, and 3.0 to high rating. For example, Sector 1.01—Livestock and Livestock Products was given rankings of moderate incentive and low responsiveness for a best practice rating of 1.5.

Qualitative ratings for incentive and responsiveness were based on the following considerations. Factors considered in the rating of industries for incentive or pressure to use best practice included

(1) Relationship of profits to corrosion cost—industries whose profits are affected directly by corrosion costs or who incur large magnitude corrosion costs have a high incentive to use best practice,

(2) Quality of product,

(3) Awareness of corrosion,

(4) Regulation,

(5) Safety,

(6) Personal responsibility, and

(7) Consequences of failure.

Factors considered in rating for responsiveness included

(1) Size of companies,

(2) Level of technology,

(3) Availability of corrosion expertise,

(4) Time frame over which cost are incurred,

(5) Complexity of the problem and

(6) Administrative system through which practices are implemented.

In both categories, any one of the considerations could be overriding in assignment of a rating. For example, industries handling toxic gases have a high incentive to prevent corrosion related leaks regardless of other consideration. Dominant considerations in incentive ratings were effect of corrosion on profits and accountability for corrosion failures. Whereas, dominant consideration in responsiveness rating were size of the company and availability of corrosion expertise. A complete list of best practice ratings for all industrial sectors is presented in Table 7.

Percentage avoidable corrosion related maintenance costs corresponding to best practice ratings were:

3.0—5 percent avoidable
2.5—15 percent avoidable
2.0—25 percent avoidable
1.5—35 percent avoidable
1.0—45 percent avoidable.

These arbitrary ratings are considered to be realistic based upon maintenance cost savings achieved in specific instances on going to

TABLE 7. BEST PRACTICE RATINGS FOR INDUSTRIAL SECTORS

	Sector Identification	Incentive	Responsive	Best Practice Rating
1.01	Livestock and Livestock Products	0	–	1.5
1.02	Field and Orchard Crops	0	–	1.5
1.03	Forestry and Fishery Products	0	–	1.5
1.04	Services to Agriculture, Forestry and Fishery	0	–	1.5
2.01	Iron and Ferroalloys Ores	0	–	1.5
2.02	Copper Ores	0	–	1.5
2.03	Nonferrous Ores, Except Copper	0	–	1.5
2A04	Underground Coal Mining	0	–	1.5
2B04	Strip Coal Mining	0	–	1.5
2C04	Other Coal Mining	0	–	1.5
2A05	Crude Petroleum	+	+	3.0
2B05	Natural Gas	+	+	3.0
2.06	Stone and Clays	0	–	1.5
2.07	Chemical and Fertilizer Minerals	0	0	2.0
3X01	Food and Kindred Products, Tobacco	+	–	2.0
3.03	Leather Tanning and Industrial Leather Products	–	–	1.0
3X04	Misc. Leather and Fabricated Textile Products	–	–	1.0
3.05	Fabrics, Yarns and Threads	–	–	1.0
3.07	Tire Cord and Misc. Textile Goods	–	–	1.0
4X01	Lumber Mills, Plywood, Wooden Containers	–	–	1.0
4.03	Lumber and Wood Products, Except Containers	–	–	1.0
4X05	Furniture and Fixtures	–	–	1.0
4X07	Pulp, Paper and Paper Products, Except Containers	+	0	2.5
4X08	Paperboard Containers and Boxes	–	–	1.0
5.01	Petroleum Refining and Related Products	+	+	3.0
5.02	Paving Mixtures and Asphalt Products	–	–	1.0
5.03	Industrial Inorganic and Organic Chemicals	+	+	3.0
5.04	Fertilizers	+	+	3.0
5.05	Agricultural Chemicals, Except Fertilizers	+	+	3.0
5.06	Miscellaneous Chemical Products	+	+	3.0
5X07	Plastics Materials and Organic Man-made	+	0	2.5

	Sector Identification	Incentive	Responsive	Best Practice Rating
5X09	Drugs	+	0	2.5
5X10	Cleaning and Toilet Preparations	+	0	2.5
5A12	Paints and Allied Products, Corr.	0	–	1.5
5B12	Paints and Allied Products, N-Corr.	0	–	1.5
5B13	Tires and Inner Tubes	0	–	1.5
5B14	All Other Rubber Products	0	–	1.5
5B15	Manufactured Plastics Products	0	–	1.5
6.01	Glass and Glass Products	+	0	2.5
6.02	Hydraulic Cement, Lime and Gypsum Products	0	–	1.5
6.03	Clay and Cement Products and Refractories	0	–	1.5
6.04	All Other Stone & Nonmetallic Mineral Products	0	–	1.5
7A01	Mild Steel - Carbon Steel	+	+	3.0
7B01	Low Alloy Steel	+	+	3.0
7C01	Alloy Steel	+	+	3.0
7D01	Stainless Steel	+	+	3.0
7E01	Coke	+	+	3.0
7.02	Primary Copper	+	+	3.0
7.03	Primary Aluminum	+	+	3.0
7A04	NI, NI Alloys, CO	+	+	3.0
7B04	Zinc	0	0	2.0
7C04	Magnesium	+	+	3.0
7D04	Lead	0	0	2.0
7E04	TI, TA, ZR	+	0	2.5
7F04	AU, AG, PT, PD	+	+	3.0
7G04	All Others	+	0	2.5
8.01	Metal Cans	0	0	2.0
8.02	Metal Barrels, Drums and Pails	0	0	2.0
8.03	Metal Sanitary Ware & Plumbing Fittings	0	0	2.0
8.04	Nonelectric Heating Equipment	0	0	2.0
8.05	Fabricated Structural Metal Products	0	0	2.0
8.06	Screw Machine Products, etc., & Stampings	0	0	2.0
8A07	Coating and Plating, Corr.	0	0	2.0
8B07	Coating and Plating, N-Corr.	0	0	2.0
8C01	All Others	0	0	2.0

TABLE 7. (CONTINUED)

	Sector Identification	Incentive	Responsive	Best Practice Rating
9.01	Engines and Turbines	0	0	2.0
9.02	General Industrial Machinery & Equipment	0	0	2.0
9.03	Machine Shop Products	0	0	2.0
10.01	Farm Machinery	0	0	2.0
10.02	Construction Machinery	0	0	2.0
10.03	Mining Machinery	0	0	2.0
10.04	Oil Field Machinery	0	0	2.0
10.05	Materials Handling Machinery, Except Trucks	0	0	2.0
10.06	Industrial Trucks and Tractors	0	0	2.0
10.07	Metalworking Machinery	0	0	2.0
10.08	Special Industry Machinery	0	0	2.0
11A01	Automobiles	+	+	3.0
11B01	Trucks, Buses, etc.	+	+	3.0
11.02	Aircraft and Parts	+	+	3.0
11.03	Ship and Boat Building and Repair	0	0	2.0
11.04	Locomotives and Rail and Streetcars	0	0	2.0
11.05	Motorcycles, Bicycles, Trailer Coaches, etc.	+	0	2.5
12.01	Electrical Measuring Instruments	0	0	2.0
12.02	Electric Motors and Generators	0	0	2.0
12.03	Industrial Controls, Transformers, etc.	0	0	2.0
12X04	Electric Lamps and Fixtures	0	0	2.0
12.06	Electronic Components and Accessories	0	0	2.0
12.07	Miscellaneous Electrical Machinery	0	0	2.0
13.01	Service Industry Machinery	0	0	2.0
13.02	Household Appliances	+	0	2.5
13.03	Radio, T.V., and Communication Equipment	0	0	2.0
14.01	Scientific Instruments, Measures and Controls	+	0	2.5
14.02	Medical, Surgical, Dental Instruments and Supplies	+	0	2.5
14.03	Watches, Clocks and Parts	+	0	2.5
14.04	Optical and Ophthalmic Goods	+	0	2.5
14.05	Photographic Equipment and Supplies	+	0	2.5
21.08	Educational Services and Nonprofit Organizations	–	–	1.0
22.01	Post Office	0	0	2.0

	Sector Identification	Incentive	Responsive	Best Practice Rating
15.01	Computing and Related Machines	+	0	2.5
15.02	All Other Office and Business Machines	0	0	2.0
15.03	Offic Supplies			--
16.01	Ordnance and Accessories	+	0	2.5
16.02	Other Miscellaneous Products	0	0	2.0
17.01	Railroads and Related Services	0	0	2.0
17.02	Local and Other Highway Passenger Transport	0	0	2.0
17.03	Motor Freight and Warehousing	0	0	2.0
17.04	Water Transportation	0	0	2.0
17.05	Air Transport	+	0	2.5
17.06	Pipelines	+	0	2.5
17.07	Transportation Services	0	0	2.0
18.01	Telecommunication	+	+	3.0
18.02	Electric Power	+	0	2.5
18.03	Gas	+	0	2.5
18.04	Water and Sanitary Services	0	0	2.0
19.01	New Construction, Nonfarm Residences	–	–	1.0
19.02	New Construction, Nonresidential Buildings	0	0	2.0
19.03	New Construction, Public Utility	0	0	2.0
19.04	New Construction, Highway and Other	0	0	2.0
19A05	Maintenance & Repair Construction, Corr.	0	0	2.0
19B01	Maintenance & Repair Construction, N-Corr.	0	0	2.0
20.01	Wholesale and Retail Trade	–	–	1.0
20X02	Finance, Insurance, Real Estate, Advertising	–	–	1.0
20.05	Other Business & Professional Services	0	0	2.0
21.01	Printing and Publishing	0	0	2.0
21.02	Radio and Television Broadcasting	–	–	1.0
21.03	Hotels and Lodging Places	0	–	1.5
21.04	Personal & Repair Services, Except Auto	0	0	2.0
21.05	Automobile Repair and Services	0	0	2.0
21.06	Amusements	0	–	1.5
21.07	Medical and Health Services	0	–	1.5

KEY:
+ High (3.0)
0 Moderate (2.0)
– Low (1.0)

improved corrosion-control procedures and estimates of technical experts. The upper limit of 45 percent avoidable costs is probably conservative. A 5 percent avoidable costs figure was ascribed to those industries considered to be using best practice because even in these industries best practice is not universally applied.

The procedure for adjustment of replacement lives was discussed previously in the section on replacement of equipment or buildings. The approach was to identify all sectors producing goods whose replacement lives were affected by corrosion, and to make adjustments in the replacement life range from World I to account for the impact of best corrosion practice.

4.4 Description of Industry by Industry Coefficient Adjustments

In this section, adjustments made in Input/Output Model coefficients are described for cause for adjustments identified and each segment of the economy.

4.4.1 Agriculture, Forestry, and Fishery

Four sectors are included in this group: 1.01—Livestock and Livestock Products, 1.02—Field and Orchard Crops, 1.03—Forestry and Fishery Products, and 1.04—Services to Agriculture, Forestry, and Fishery. No items are produced which corrode and corrosion is not generally recognized as a significant problem in the industry. The industries are quite diverse and depend primarily upon equipment and structure suppliers for the introduction of new corrosion prevention and control procedures. Major forms of corrosion encountered are atmospheric corrosion throughout the industries and marine corrosion in the fishery industry.

No specific data were available for these industries and estimates for coefficient adjustments in the I/O Model were based on data from other industries and general knowledge of the forms of corrosion and corrosion severity within these industries. Inputs to the industries were adjusted for corrosion maintenance. Capital coefficients were unchanged as no evidence was found for either excess capacity or redundant equipment. Replacement lives of several types of equipment are affected by corrosion and adjustments were made accordingly.

All industries in this sector were given a best practice rating of 1.5 based on a moderate incentive and low responsiveness.

4.4.2 Extraction of Mineral Resources

The ten sectors included here were divided into a Solid Minerals Group and Gas and Oil. Eight sectors are included in the first group: 2.01—Iron and Ferro-Alloys, Ores, 2.02—Copper Ores, 2.03—Nonferrous Ores, Execpt Copper, 2A04—Underground Coal Mining, 2B04—Strip Coal Mining, 2C04—Other Coal Mining, 2.06—Stone and Clays, and 2.07—Chemical and Fertilizer Minerals. Two sectors, 2A05—Crude Petroleum and 2B05—Natural Gas comprise the second group.

4.4.2.1 Solid Minerals. No items which corrode are produced in these sectors and corrosion is not generally recognized as a significant problem. Establishments are engaged primarily in mining, beneficiating, milling, and otherwise preparing ores, coal, stone and clay, and chemical and fertilizer minerals. Many of the establishments are quite diversified and primarily depend upon equipment suppliers and contractors to provide corrosion protection for plant and equipment.

Corrosion problems are encountered in the beneficiation and preparation of ores where aqueous processes are used. Acidic or brine solutions encountered in these areas can be extremely corrosive. In addition to corrosive aqueous solutions, atmospheric corrosion affects maintenance and replacement lives of plant and equipment. Corrosion-related maintenance costs are higher in iron and ferroalloy ores, non-ferrous ores, chemical and fertilizer minerals, and underground coal mining than in strip and other coal mining sectors and the stone and clay sector because of the increased contact with aqueous solutions in the prior sectors.

No specific data were available for maintenance costs in these industries and estimates for coefficient adjustments in the I/O Model were based on data from other industries and general knowledge of the forms of corrosion and corrosion severity in these industries. Inputs to the industry were adjusted for corrosion maintenance in all sectors and for corrosion-related grinding rod and ball replacements in the ore and chemical mineral sectors. Based on published information, 30 percent of the steel ball and rod usage in iron ore processing can be attributed to corrosion (Reference: A. W. Lui and G. R. Hoey, *Materials Performance*, 15, 9, September, 1976. This corrosion cost can be eliminated by the use of inorganic inhibitors. This cost was generalized to other sectors with similar usage and adjustment made to input of steel ball and rod. Capital coefficients were unchanged as no evidence was found for either excess capacity or redundant equipment. Replacement lives of several types of equipment are affected by corrosion and adjustments were made accordingly.

All industries in this group were judged to have moderate incentive for best practice and low responsiveness except for 2.07—Chemical and Fertilizer Minerals, which was judged to be moderate in both categories. Best practice ratings were 1.5 for all industries except 2.07 which had a rating of 2.0.

4.4.2.2 Gas and Oil. Sectors 2A05–Crude Petroleum and 2B05–Natural Gas include establishments primarily engaged in operating oil and gas field properties. Such activities include exploration for petroleum and natural gas; drilling, completing, and equipping wells; operations of separators, emulsion breakers, desilting equipment; and all other activities incident to making oil and gas marketable up to the point of shipment from the producing property. Sector 2A05 also includes production of oil through the mining and extraction of oil from oil shale and oil sands. No items which corrode are produced by the industries; however, costs for corrosion maintenance and control are substantial. The industries are aware of corrosion costs and considerable effort is expended to control corrosion. Primary materials of construction are mild steel, carbon steel, and low alloy steel. Protective coatings, inhibitors, and cathodic protection are used to control corrosion.

Corrosion costs in these industries are expected to rise dramatically for two reasons. First, an increased proportion of production will be coming from offshore sites where corrosion control and corrosion maintenance costs increase substantially over those for onshore production. Secondly, more gas and oil are being produced from fields which contain high amounts of corrosives, principally hydrogen sulfide, carbon dioxide, and brines. Both of these factors lead to an increased usage of higher quality coatings, cathodic protection, inhibitors, and more corrosion resistant alloys.

Estimates for costs of corrosion were developed from interviews with industrial experts, results of surveys and studies by the industry, and interviews with suppliers of corrosion related materials to the gas and oil industry. Considerable attention has been paid to corrosion costs in these industries and several detailed studies of costs were available in the open literature. Prime sources were the results of a special study by the editorial staff of *Petroleum Engineer International* on down-hole equipment repairs and replacement costs,[81] a survey of oil and gas well corrosion costs by NACE Technical Unit Committee T-1H,[203] a review of well casing corrosion in the oil industry,[233] and a survey of practices and cost of corrosion control of offshore platforms.[112]

Coefficient adjustments were made in the two sectors to account for corrosion related inputs to each sector and changes in replacement lives. No adjustments were made in the capital for the industries, because no evidence was found for excess capacity or redundant equipment.

Corrosion inhibitors were estimated to comprise 40 percent of total chemical purchases by the oil industry and 20 percent of chemical purchases by the gas industry. The former estimate was based on data from the surveys listed above, while the latter estimate was based on chemical purchases by a company judged to be typical of the entire industry.

A major portion of corrosion costs in these industries was for corrosion-related maintenance. Adjustment in maintenance coefficients were made based on data from a survey of repair and equipment costs which found 75 percent of maintenance to be related to corrosion and wear. As no breakdown of this number was available, wear and corrosion were estimated to make equal contributions. The resulting 37 percent of maintenance costs ascribed to corrosion were consistent with estimates made by industry experts. Adjustments for maintenance on electrical components and instruments were made based on experience from the chemical industries.

Additional adjustments were made to coefficients for Sectors 20.05 and 25.00 to account for corrosion related research and development, engineering, inspection and testing.

Replacement lives of several types of capital equipment are affected by corrosion and appropriate adjustments were made. Best practice ratings for both industries were 3.0 based on high incentive and high responsiveness.

4.4.3 Manufacture of Food, Leather, and Textile Products

This group includes five sectors:

3X01—Food and Kindred Products, Tobacco;
3.03—Leather Tanning and Industrial Leather Products;
3X04—Miscellaneous Leather and Fabricated Textile Products;
3.05—Fabrics, Yarns, and Threads; and
3.07—Tire Cord and Miscellaneous Textile Goods.

With the exception of Sector 3X01, no goods which corrode are produced in these industries. Corrosion of metal food containers and contamination of product are of concern in Sector 3X01. Companies in 3X01 rely primarily upon container suppliers to provide corrosion-resistant materials. In the remaining sectors, corrosion is given a low priority.

No specific data were available for these sectors, and coefficient adjustments were made based on data from other sectors and a general knowledge of corrosion in these industries. Input to the industries were adjusted for corrosion maintenance only. Capital was not affected since no evidence for excess capacity or redundant equipment was found. Replacement lives were adjusted based on information for other sectors.

Best practice rating for Sector 3X01 was 2.0 based on (1) High incentive for corrosion control because of the importance of product purity and shelf life and (2) Low responsiveness. Best practice ratings in the remaining sectors were 1.0 based on low incentive and low responsiveness.

4.4.4 Wood and Paper Products

Five sectors are included in this group: 4X01–Lumber Mills, Plywood, Wood Containers; 4.03–Lumber and Wood Products, except containers; 4X05–Furniture and Fixtures; 4.07–Pulp, Paper and Paper Products, except containers; and 4.08– -Paperboard Containers and Boxes. The output of these industries is generally non-metallic, and consequently there is no corrosion of items produced. The only exception is that metal furniture and fixtures are included as a portion of Sector 4X05. Corrosion of the latter, particularly in outdoor exposure, is encountered.

Significant corrosion costs occur primarily in sectors where corrosive liquids or vapors are associated with the processing. Corrosive liquids are limited to Sector 4.07–Pulp and Paper and corrosive vapors are limited to 4X01–Kiln Drying of Lumber. The presence of corrosive vapors increases corrosion costs in the kiln drying of lumber; fans are particularly susceptible. Discussions with industry experts confirmed that corrosion costs were not a significant portion of plant maintenance and operating costs, except in Sector 4.07–Pulp and Paper.

Thus, emphasis was on estimating costs of corrosion to the pulp and paper industry. Data for the industry were collected from a plant visit, a visit to TAPPI (The Technical Association of the Pulp and Paper Industry), discussion with industry experts in the U.S. and Canada, from the open literature and reports. An extensive study of corrosion costs in the pulp and paper industry was carried out in Canada in 1968, under the auspices of the Pulp and Paper Research Institute of Canada. This study is reported in ''Estimated Costs Due to Corrosion in Canadian Pulp and Paper Mills'' by K. M. Thompson (Technical Section Proceedings, Canadian Pulp and Paper Association, D51, 1970). This study was combined with Worldwide 1971 Production Data by M. F. Davy and W. A. Mueller in an article entitled ''Pulp and Paper Industry Worldwide Corrosion Costs'' published in the NACE Book: *Pulp and Paper Industry Corrosion Problems*, 1974. From all of the above sources corrosion costs for the pulp and paper industry were estimated to be $360 Million annually, based on 50 million tons of air-dried pulp and paper product. Approximately 60 percent of this total was ascribed to be operating cost with the remainder ascribed to capital cost.

Inputs to the industries for corrosion maintenance were adjusted based on data from other sectors. For all sectors except 4.07 corrosion maintenance costs were judged to be low; a small increase was made in corrosion maintenance for 4X01 to account for corrosive fumes in kiln drying of lumber. Sector 4.07 containing aqueous pulp and paper processes was treated as an industrial chemical process.

In addition to corrosion-related maintenance adjustments, in Sector 4X05 the portion of paints ascribed to corrosion protection (50 percent of total) and the portion of corrosion protection platings and coatings (60 percent of total) were adjusted. Further, coefficient adjustments were made for the cost differential between corrosion-resistant metals, primarily aluminum, and mild steel. These latter coefficient adjustments accounted for corrosion protection costs in the manufacture of metal furniture and fixtures.

In Sector 4.07—Pulp and Paper Products, 10 percent of the capital stock, supplied by Sector 10.08—Special Industrial Machinery, was ascribed to be redundant equipment for corrosion purposes. This accounts for duplicate suction press rolls which are kept to allow continual operation of the plant. No other redundant equipment or excess capacity was noted in the sectors of this group.

Information gathered indicates that the replacement lives of capital equipment supplied by Sector 9.02—General Industrial Machinery and Equipment and Sector 10.08—Special Industrial Machinery are significantly affected by corrosion. Replacement lives of other equipment in this sector and other sectors of this group can also be affected by corrosion and adjustments were made accordingly.

Sector 4.07 was given a best practice rating of 2.5 based on high incentive and moderate responsiveness; all other sectors in the group were given best practice ratings of 1.0 based on low incentive and low responsiveness.

4.4.5 Petroleum and Chemical Products

Fourteen sectors are included in the petroleum and chemical products group. No items are produced which corrode. The impact of corrosion costs on this group of industries covers a broad range from minor to major. To better define this industry variation, a number of corrosion parameters were determined for each industry. The qualitative ranking in each of these areas are presented in Table 8. Based on technical judgment, each industry was ranked high, medium, or low for

(1) Its incentive to account for and address corrosion costs

(2) Its ability to respond to corrosion costs

(3) The level of technology

(4) The overall corrosivity of the environment in the industry

(5) The percentage of corrosion related building and plant maintenance from Sector 19A05

(6) The corrosion related maintenance costs on equipment.

The variation from high rankings in all categories for industrial chemicals and petroleum refining to low rankings in nearly all categories for paving products, rubber products, and manufactured plastic products is apparent. This overall ranking was used in two

TABLE 8. QUALITATIVE RANKING OF CORROSION PARAMETERS IN PETROLEUM AND CHEMICAL PRODUCTS INDUSTRIES

	Industry	Incentive	Responsiveness	Level of Technology	Corrosivity	19A05 percent Corrosion M & R	Corrosion Related Maintenance of Equipment	Best Practice Rating
5.01	Petroleum Refining and Related Products	+	+	+	+	40	High	3.0
5.02	Paving Mixtures and Asphalt Products	-	-	-	-	10	Low	1.0
5.03	Industrial Inorganic and Organic Chemicals	+	+	+	+	30	High	3.0
5.04	Fertilizers	+	+	+	+	20	High	3.0
5.05	Agricultural Chemicals, Except Fertilizers	+	+	+	+	20	High	3.0
5.06	Miscellaneous Chemical Products	+	+	+	+	20	High	3.0
5X07	Plastics Materials and Organic Man-made	+	0	+	0	10	Moderate	2.5
5.09	Drugs	+	0	+	+	20	Moderate	2.5
5X10	Cleaning and Toilet Preparations	+	0	+	0	20	High	2.5
5 A/B 12	Paints and Allied Products, Corr. and N. Corr.	0	-	-	-	10	Low	1.5
5.13	Tires and Inner Tubes	0	-	0	-	10	Low	1.5
5.14	All Other Rubber Products	0	-	-	-	10	Low	1.5
5.15	Manufactured Plastics Products	0	-	-	-	10	Low	1.5

KEY: + High

0 Moderate

\- Low

ways: (1) To provide guidance for setting priorities for emphasis in this study and (2) To provide guidance for coefficient adjustments based on the severity of corrosion in each industry.

Corrosion costs in the industries are confined to costs of corrosion control and corrosion related maintenance, repair, and replacement. Forms of corrosion control used in the industries are coatings, inhibitors, corrosion-resistant metals, metallic coatings, cathodic protection, and design for corrosion control. Those industries with high rankings in the parameters of Table 8, are aware of corrosion costs and exert considerable effort to control costs. Estimates for corrosion costs for this study were based on extensive interviews with industrial experts and several studies reported in the open literature. Prime sources were a detailed study of costs in a petroleum refinery by Landis,[48] a study of refinery costs by Sherwood,[13] and a study of the causes of failure in chemical process industries by Collins and Monack.[404] In addition to the above, suppliers of the corrosion related items to the petroleum and chemical industries were interviewed.

Coefficient adjustments were made in the sectors for inputs of corrosion inhibitors, corrosion-related maintenance, and corrosion-related technical support.

Costs associated with corrosion inhibitors and water treatment were estimated as a proportion of the input of chemicals to the particular industry where possible or by distribution of an estimated dollar value of corrosion inhibitors where data for a direct estimate were unavailable. An example of the former was the treatment of corrosion inhibitors to the petroleum refining industry (Sector 5.01). It was estimated that corrosion inhibitors comprised 40 percent of total chemical purchases by Sector 5.01 based on data from the survey by Landis and by review of chemical purchases of a large petroleum refinery over a 1 year period. Procedure for distributing the estimate of total dollars of corrosion inhibitor purchases by all chemical industries into the individual sectors is discussed in Section 4.2.6.1, Treatment of Corrosion Inhibitor and Water Treatment Costs.

The basis for adjustments for maintenance costs in the chemical industries is discussed in Section 4.2.32—Maintenance and Repair Equipment Costs. Specific data available for the chemical process and petroleum refining industries were used to estimate corrosion related costs for various types of equipment in the other sectors.

Several process units in Sectors 5.01, 5.03, 5.05, and 5.06 are run continuously. It is standard procedure in the industries to have scheduled down-time for maintenance of approximately 5 percent of total capacity, and significant portions of the down-time can be attributed to corrosion-related maintenance and repair. Consequently, a 2 percent excess capacity was ascribed to the above industries for corrosion and capital/output coefficients were adjusted.

In addition to the above adjustment to capital/output coefficients, adjustments were made to account for redundant equipment in Sector 9.02—Pumps and Fans and Sector 12.02—Motors. Standard design practice calls for installation of three large units from these sectors where two are required for operation. This allows for continuous processing while a fan or motor is being maintained. Adjustment to account for this redundancy was made in Sectors 5.01, 5.03, 5.04, 5.05, 5.06, and 5X10.

Replacement lives of several types of capital equipment are significantly affected in the petroleum and chemical industries and appropriate adjustments were made. Best practice ratings for each of the industries based on incentive and responsiveness were listed in Table 8.

4.4.6 Stone, Clay, and Glass Products

Four sectors are included in this group: 6.01—Glass and Glass Products; 6.02—Hydraulic Cement, Lime and Gypsum Products; 6.03—Clay and Cement Products and Refractories; and 6.04—All Other Stone and Non-metallic Mineral Products. No items which corrode are produced in these sectors.

Sector 6.01—Glass and Glass Products is a rather homogeneous sector with similar corrosion problems experienced throughout. Corrosion costs arise from handling of water, primarily cooling waters; from enhanced attack due to elevated temperatures; and from handling of hydrochloric and hydrofluoric acid fumes produced in etching and other surface treatments. The latter causes extensive corrosion of duct work. Corrosion inhibitors, organic and metallic coatings, corrosion-resistant metals, and cathodic protection are used by the industry to control corrosion.

Coefficient adjustments in the I/O Model were based upon interviews with industrial experts and data from other industries. Inputs to Sector 6.01 were adjusted for (1) Corrosion inhibitors-based upon scaling up an estimate of corrosion inhibitor usage by a company and (2) Corrosion-related maintenance cost. Total corrosion-related maintenance costs were estimated by an industry expert to be approximately 0.2 percent of sales. Capital coefficients were unchanged as no evidence was found for either excess capacity or redundant equipment.

Corrosion affects the replacement life of several components throughout the glass and glass products industry. An industry expert estimated the replacement life of pipe systems could be doubled if it were not for corrosion. Also the replacement life of pumps is shortened by corrosion. It was also estimated that replacement life of buildings and machinery were determined by obsolescence, and corrosion was not a factor for these items.

Sector 6.02, 6.03, and 6.04 are all affected by corrosion and wear. With the exception of production of refractories as a portion of Sector 6.03, the principal operations in these industries are grinding and material handling. Coefficient adjustments were made based on the estimate that corrosion costs in the industry are a small percentage of total maintenance costs and data from other industries. Inputs to the industry were adjusted for corrosion maintenance.

Capital coefficients were unchanged as no evidence was found for either excess capacity or redundant equipment. Replacement lives of several types of equipment are affected by corrosion and adjustments were made accordingly.

Best practice ratings for these industries were 2.5 for Sector 6.01—Glass and Glass Products, based on high incentive and moderate responsiveness; and 1.5 for Sectors 6.02, 6.03, and 6.04 based on moderate incentive and low responsiveness.

4.4.7 Primary Ferrous Metals and Manufacturers

This major group includes establishments engaged in the smelting and refining of ferrous metals from ore, pig, or scrap; in the rolling, drawing, and alloying of ferrous metals; in the manufacture of castings, forgings, and other basic products of ferrous metals; and in the manufacture of nails, spikes, and insulated wire and cable. The group also includes the production of coke. Ferrous metals are disaggregated into five sectors: 7A01—Mild Steel-Carbon Steel, 7B01—Low Alloy Steel, 7C01—Alloy Steel, 7D01—Stainless Steel, and 7E01—Coke. American Iron and Steel Institute steel grade definitions were used for identifications of each sector.

Costs of corrosion in these sectors are incurred for both providing corrosion protection to the metals supplied and for corrosion of plant and equipment during production. Corrosion has heavy impact on the industry and considerable effort is expended within the industries to improve corrosion resistance of products. Plant and equipment corrosion costs are substantial because of exposure to atmospheric corrosion in highly industrial areas and processes which expose equipment to high temperatures, corrosive vapors, and corrosive solutions. Corrosion protection for products is supplied by organic coatings, metallic coatings, chemical composition of metal, and metallurgical structure control. Corrosion of plant and equipment is controlled through the use of organic coatings, metallic coatings, corrosion inhibitors, design, and use of corrosion resistant alloys.

Coefficient adjustments were made in the sectors to account for the use of corrosion resistant coatings, inhibitors, maintenance costs, and technical support. Corrosion inhibitors and corrosion related water treatment costs were handled by distributing $48 Million for annual purchases of these items among the five sectors based on total dollar output. Estimate of total purchases was based on a study of industrial water treatment purchases. Inputs to the ferrous metals industries from Sector 5.03—Industrial Inorganic Chemicals were adjusted according to these dollar estimates.

Both metallic and organic coatings are used in the ferrous metals industry to provide corrosion protection for products. Adjustments were made for inputs of Sectors 5A12—Paints and Allied Products for Corrosion and 8A07—Coatings and Plating for Corrosion based on the premise that essentially all coatings applied to ferrous metals are for corrosion protection. Metal inputs to Sector 8A07 coatings and platings for corrosion used in the steel industry were 65,000 tons of zinc per year for galvanized steel, 5,000 tons of aluminum per year for hot-dip aluminized steel, and 2,300 tons of tin per year for tin plate steel.

Corrosion related maintenance costs were estimated based on input from mechanical foremen and engineering departments of a major integrated steel plant. Their estimates of corrosion related maintenance for various items were as follows:

Industrial controls—15 percent
Electrical Instruments—25 percent
Mechanical Equipment—5 percent
Engines and Turbines—15 percent.

Corrosion related plant and building maintenance costs were estimated to be 20 percent for mild steel, low alloy steel, and alloy steel industries; 5 percent for the stainless steel industry; and 30 percent for coke industries.

Estimates for corrosion related technical support were determined by information on percent of sales for research and development and for percent of research for corrosion.

Many of the processes in ferrous metals manufacture are continuous and capacity is reduced by scheduled down-time. None of this scheduled down-time could be ascribed to corrosion. While considerable corrosion related maintenance and repair is performed during these down-times the time required for repairs is not related to corrosion. Adjustments were made to capital coefficients for capital supplied by Sector 9.02—Pumps and Fans and Sector 12.02—Motors to account for corrosion related redundant equipment. Redundancy arises from the standard design practice of installing three large units from these sectors when two are required for continuous operations. The third unit allows maintenance without interrupting continuous operation. Replacement lives of several types of capital equipment throughout the plants are affected by corrosion and appropriate adjustments were made.

Best practice ratings for all five sectors in this group were 3.0 based on high incentive and high responsiveness.

4.4.8 Primary Non-Ferrous Metals and Manufacturers

Sectors included in this group are 7.02—Primary Copper, 7.03—Primary Aluminum, 7A04—Ni and Ni Alloys and Cobalt, 7B04—Zinc, 7C04—Magnesium, 7D04—Lead, 7E04—Titanium, Tantalum and Zirconium, 7F04—Silver, Gold, Platinum, and Palladium and 7G04—All Other. The costs, of corrosion in these sectors are related to materials degradation and maintenance of equipment used in producing primary metal from various ores. The amount of corrosion occurring is strongly dependent on the type of ore being processed. For example, sulfide ores are usually roasted to form an oxide. In this process large amounts of SO_3, which are highly corrosive to plant equipment and buildings, are produced. This necessitates the extensive use of stainless steels for process equipment and structures. For example, smelter exhaust stacks are made of Type 316 stainless steel to overcome the corrosive effects of sulfuric acid condensation on the sides of the stack. Those primary metal producers where the process is highly corrosive include copper, zinc, nickel, and lead. Data furnished by one copper and one nickel producer indicate that 15 percent of maintenance costs can be attributed to corrosion.

Another area which has relatively high corrosion costs is aluminum production. The fluoride salts involved in the electrorefining of aluminum ore result in severe corrosion to building and other equipment located in the refining area. Similarly to estimates for the copper, nickel, zinc, and lead industries, corrosion costs are estimated by the aluminum industry to be approximately 15 percent of the total maintenance budgets.

In contrast, many hydrometallurgical processes for refining of ores more nearly resemble moderately corrosive chemical processes. The primary metal producers in this area are producers of magnesium, precious metals and others. For these industries no data were available for corrosion cost from producers. Coefficient adjustments were made on the basis of data pertaining to maintenance, and useful life of equipment in moderately corrosive chemical processes which were assumed to have similar corrosion experience.

Likewise, data for the extent of corrosion caused maintenance were not available for Sector 7E04—Titanium, Tantalum and Zirconium. From discussion with experts in titanium, zirconium, and tantalum production it was concluded that maintenance costs for corrosion in the steel industry were probably quite comparable to theirs; therefore, coefficients in 7E04 were adjusted to reflect experience similar to that in the steel industry.

Estimates were obtained for the portion of research and development which is directly related to improving corrosion performance, to understand corrosion mechanisms or to testing new alloys. The data obtained suggest that for the primary metal producers about 1.2 percent of sales is allocated to research and development. Discussion with research managers in laboratories of a large copper and aluminum producer, a nickel and precious metal producer, and an aluminum producer revealed research and development dollars spent on corrosion varied considerably between metal producers. Approximately 20 percent of the research and development conducted by the copper and nickel producers is directly concerned with corrosion. The aluminum industry on the other hand spends about 10 percent of its research and development budget for corrosion, while the zinc industry spends only 1 percent. It was estimated that other non-ferrous primary metal producers spend between 0.1 and 0.2 percent of their research and development budget for corrosion related studies.

4.4.9 Fabricated Metal Products

Nine sectors are included in this group: 8.01—Metal Cans, 8.02—Metal Barrels, Drums and Pails, 8.03—Metal Sanitary Wear and Plumbing Fittings, 8.04—Non-Electric Heating Equipment, 8.05—Fabricated Metal Structural Products, 8.06—Screw Machine Products and Stampings, 8A07—Coating and Plating, Corrosion, 8B07—Coating and Plating, Non-corrosion, and 8C07—Miscellaneous Fabricated Metal Products. With the exception of the coating and plating sectors, industries in this group have low corrosion maintenance, repair, and replacement costs. The coatings and platings industry has substantial corrosion related operating costs because of handling highly corrosive fluids and vapors. Primary emphasis was placed upon changes of inputs to products for corrosion resistance. Corrosion protection for products is provided by organic coatings, metallic coatings, and the use of corrosion resistant metals.

Coefficient adjustments for input of paint and allied products to the fabricated metal products industries were made based on the technical judgment that 90 percent of paints and allied products were to provide corrosion protection in Sectors 8.01, 8.02, 8.03, and 8.04; 95 percent for corrosion protection in Sector 8.05; 75 percent for corrosion protection in Sectors 8.06, 8A07, 8B07; and 95 percent for corrosion protection in Sector 8C07. Similar adjustments were made for the use of metallic coatings in platings in the industry, where 95 percent of the use of metallic coatings was ascribed to corrosion protection for Sector 8.01—Metal Cans and between 50 and 75 percent of the use of metallic coatings was ascribed to corrosion protection for the remaining industries.

Metal inputs to the industries were reviewed and adjustments made to account for use of corrosion resistant metal. In Sectors 8.01 and 8.02, all use of aluminum and stainless steel was ascribed to corrosion. In Sector 8.03, all usage of aluminum, stainless steel, alloy steel, and high strength low alloy steel was attributed to corrosion, but only fifty percent of the use of copper was ascribed to corrosion because considerable amounts of copper piping are used for ease of installation as well as corrosion resistance.

Adjustments for Sector 8.04 were the same as for Sector 8.03 with an additional adjustment to account for 10 percent of mild steel usage as corrosion allowance in products. For Sector 8.05—Fabricated Structural Metal Products all usage of alloy, and high-strength low-alloy steels was attributed to corrosion. However, stainless steel, copper, and aluminum are used for both corrosion resistance and ornamental or architectural purposes; accordingly 50 percent, 25 percent, and 50 percent of these metals was ascribed to corrosion, respectively. In Sector 8.06 all usage of aluminum, copper, stainless steel, alloy steel, and high-strength low-alloy steel was attributed to corrosion resistance. In Sector 8C07—Miscellaneous Fabricated Metal Products, the following percentages of metal usage were ascribed to corrosion resistance:

Low Alloy Steel—100 percent
Alloy Steel—50 percent
Stainless Steel—50 percent
Copper—90 percent
Nickel and Nickel Alloys—100 percent.

Corrosion related maintenance in all Sectors except coatings and platings was estimated to be low and adjustments were made based on information from other sectors. Corrosion related maintenance in Sectors 8A07 and 8B07—Coatings and Platings was made based on data from the industrial chemical sector.

Capital coefficients were unchanged as no evidence was found for either excess capacity or redundant equipment. Replacement lives of several types of equipment are affected by corrosion and adjustments were made accordingly.

All industries in this group were judged to have moderate incentives for best practice and moderate responsiveness with resulting best practice ratings of 2.0.

4.4.10 General Machinery and Components

Three sectors are included in this group: 9.01—Engines and Turbines, 9.02—General Industrial Machinery and Equipment, and 9.03—Machine Shop Products. Corrosion related operating costs in these industries were considered to be low and major emphasis was placed upon determining changes in inputs to the industries for corrosion protection for products. Inputs for corrosion resistance are paints and allied products, corrosion resistant metals, and coating and platings. Greater than 90 percent of the use of paints and allied products in Sectors 9.01 and 9.02 was ascribed to corrosion protection. Portions of the usage of coatings and platings in Sectors 9.01, 9.02, and 9.03 were ascribed to be 50 percent, 20 percent, and 15 percent for corrosion resistance, respectively.

Adjustments were made to account for use of corrosion resistant metals in Sector 9.01—Engines and Turbines. Corrosion was judged to account for:

100 percent of Low Alloy Steel
50 percent of Alloy Steel
50 percent of Copper
50 percent of Aluminum

In addition, 30 percent of the dollar purchases of stainless steel and 75 percent of the dollar purchases of nickel and nickel alloys were ascribed to costs for higher priced alloys for corrosion resistance. In other words, lower priced alloys from these categories could be used if corrosion were not a factor. In Section 9.02—General Industrial Machinery and Equipment, the following percentages of usage was ascribed to corrosion resistance:

Low Alloy Steel—100 percent
Alloy Steel—50 percent
Stainless Steel—75 percent
Copper—50 percent
Aluminum—75 percent
Nickel and Nickel Alloys—75 percent.

Similarly in Sector 9.03 the following adjustments were made:

Low Alloy Steel—100 percent
Alloy Steel—50 percent
Stainless Steel—75 percent
Aluminum—75 percent.

Corrosion related maintenance was estimated to be low and adjustments were made based on experience from other sectors. Additional adjustments were made to account for corrosion-related technical support.

Capital coefficients were unchanged, as no evidence was found for either excess capacity or redundant equipment. Replacement lives of several types of equipment are affected by corrosion and adjustments were made accordingly.

Best practice ratings for industries in this group were 2.0 based on moderate incentive and moderate responsiveness.

4.4.11 Specialized Machinery

Eight sectors are included in this group: 10.01—Farm Machinery, 10.02—Construction Machinery, 10.03—Mining Machinery, 10.04—Oil Field Machinery, 10.05—Oil Materials Handling Machinery, except trucks, 10.06—Industrial Trucks and Tractors, 10.07—Metal Working Machinery, and 10.08—Special Industry Machinery. Corrosion-related costs in these industries are incurred for providing corrosion protection in products and corrosion-related maintenance, repair, and replacement costs. Corrosion resistance is provided for products by the use of organic coatings, metallic coatings, and corrosion resistant metals.

Adjustments for inputs of paints and allied products and coatings and platings were based on technical judgment. Nearly all of the use of organic coatings was ascribed to corrosion protection, and approximately 1/2 to 2/3 of the use of metallic coatings and platings was ascribed to corrosion protection. Breakdowns estimated for each sector are presented in the section describing adjustments for coatings and platings.

Adjustments were also made to the inputs of corrosion-resistant metals into each of the sectors. Metal uses ascribed to corrosion-resistance were:

Low Alloy Steel—100 percent
Stainless Steel—100 percent
Alloy Steel—50 percent
Copper—90 percent
Aluminum—75 percent
Nickel Alloys—90 percent.

In Sector 10.02—Construction Machinery, 10.03—Mining Machinery, and 10.04—Oil Field Machinery, further adjustments were made in the use of mild steel of 1 percent, 1 percent, and 5 percent, respectively to account for the incorporation of corrosion allowance in the construction of machinery by these sectors.

Maintenance cost adjustments in each of the sectors were determined based on estimates of total maintenance costs and estimates of portions of total maintenance related to corrosion. The latter estimates were based on knowledge of severity of corrosion in the manufacturing processes of each sector and experience of other sectors. Further adjustments were made to account for technical support based on procedures previously described.

Capital coefficients were unchanged as no evidence was found for excess capacity or redundant equipment. Replacement lives of several types of equipment are affected by corrosion and adjustments were made accordingly.

Best practice ratings for all sectors in this group were 2.0 based on moderate incentive and moderate responsiveness.

4.4.12 Motor Vehicles and Miscellaneous Transportation Equipment

Three sectors are included in the group: 11A01—Automobiles, 11B01—Trucks, Buses, etc., and 11.05—Motorcycles, Bicycles, Trailer Coaches, and Miscellaneous Transportation Equipment. Primary interest in these sectors is in the inputs to each sector for corrosion protection of products. Operating corrosion costs for these industries are low. Sector 11A01–Automobiles was the subject of a more detailed study, and corrosion costs for personally owned automobiles are discussed in Appendix C.

There is a need for corrosion protection on products produced by these industries because visible and non-visible components corrode, affecting both aesthetic appearance and operation. Various forms of prevention and corrosion control are utilized including:, (1) Internal and External Coatings, (2) Modifications in design, (3) Inhibitors, (4) Alternate Materials, (5) Testing and development of new corrosion materials. Major corrosion costs ascribed to these industries are for (1) Organic and metallic coatings and platings, (2) Use of corrosion resistant materials, (3) Research and development and other technical support, and (4) Maintenance, replacement, and repair.

Significant portions of inputs to the industry can be ascribed to corrosion in several areas. Adjustments were made in the inputs from Sector 5.01–Petroleum Refining and Related Products and Sector 5.06–Miscellaneous Chemical Products to account for use of corrosion preventive waxes and lubricants and corrosion-inhibited radiator coolant, respectively. Fifty percent of all organic coatings was ascribed to corrosion protection in Sectors 11A01 and 11.05; and 50 percent of organic coatings was ascribed to corrosion protection in Sector 11B01. These adjustments account for a portion of the primer and top coat costs which are applied for both corrosion prevention and aesthetics, all of the use of zinc rich paints, and all of the use of other organic coatings on underbody parts. Portions of metallic coatings and platings ascribed to corrosion protection for each of the sectors were 11A01–30 percent, 11B01–60 percent, and 11.05–50 percent.

Metal inputs to the motor vehicle industries are significantly affected by corrosion considerations. In Sectors 11A01 and 11B01 the following proportions of metal usage were ascribed to corrosion protection:

Low Alloy Steel–50 percent
Alloy Steel–50 percent
Stainless Steel–100 percent
Copper–10 percent.

Use of aluminum alloys for corrosion resistance was estimated to be 25 percent in Sector 11A01 and 75 percent in Sector 11B01. Similar estimates for Sector 11.05 were:

Low Alloy Steel–100 percent
Alloy Steel–50 percent
Stainless Steel–100 percent
Copper–95 percent
Aluminum–50 percent.

In all cases corrosion resistant metals were substituted for mild steel.

Corrosion-related maintenance costs in these sectors were considered to be low and adjustments were made based on experience from other sectors.

Capital coefficients were unchanged as no evidence was found for either excess capacity or redundant equipment. Replacement lives for several types of equipment are affected by corrosion and adjustments were made accordingly.

Best practice ratings for Sector 11A01 and 11B01 were 3.0 based on high incentive and high responsiveness. Best practice rating for 11.05 was 2.5, based on high incentive and moderate responsiveness.

4.4.13 Aircraft and Air Transporation

Two sectors are included in this group: 11.02—Aircraft and Parts and 17.05—Air Transport. The former includes establishment for the manufacture of aircraft and parts, including aircraft engines. The latter provides air transportation services for passengers and cargo.

The combined aircraft fleet of the United States' airlines excluding charter companies total 2400 planes of which 2250 are jets. This number is made up of a wide variety of types including two-engine aircraft; three-engine 727; four-engine aircraft, 707 and DC-8; and the jumbo jets represented by 747, DC-10, and L-1011's. In a given year the industry spends about $1.5 Billion for parts and $6.5 Billion for salaries. The Air Transport Association in Washington has compiled extensive data pertaining to the industries' performance; however, data for maintenance costs related to corrosion were not readily available. On the other hand, maintenance and performance costs per block hour for different types of aircraft as compiled by the airline carriers are regularly published in Air Transport World. In addition, each of the large air carriers keeps extensive records of both air frame and engine maintenance costs with a breakdown of that portion attributable to corrosion.

In the course of this survey, maintenance managers of six of the largest air carriers were contacted for pertinent data. Excellent cooperation was obtained. In general, the data supplied by each company are in good agreement. However, the commercial airline corrosion costs when compared with the military appear to be quite low. For example, data from the air carriers suggest that corrosion-related maintenance ranges between 2 and 2.5 percent of the total maintenance budget. The Air Force, on the otherhand, spends 20-30 percent of maintenance appropriations for corrosion. Similarly, an order of magnitude difference in costs per airplane is reported. For example, the corrosion-related costs in the commercial fleet averages beteen $3,000 and $3,500 per aircraft. For the military, the range is $15,000 to $30,000 per aircraft, depending on the type. The larger the military aircraft, the higher the corrosion-related maintenance costs.

This is also true for the airline companies where the average cost of corrosion is $1.59/flight hour for 727 aircraft compared with about $2.88/flight hour for the larger 747 aircraft.

A portion of the difference in corrosion costs between the military and commercial airlines can be attributed to the different modes of operation and the useful aircraft life. Military data show that older aircraft have higher corrosion costs. Many of the aircraft in the military are much more than 10 years old which is the replacement life for commercial carriers. Another difference between the military and commercial aircraft is flying time. Military aircraft spend most of the time on the ground while commercial aircraft fly 8 to 10 hours per day. However, the major difference appears to be in the accounting procedures. It is believed that commercial airline accounting procedures are such that most corrosion related costs are not identified as such.

Two techniques were employed to obtain a rationale for total corrosion related maintenance for the commercial airline industry. First, based on the available data, corrosion related maintenance data indicated the average corrosion cost per flight hour to be $1.59. Assuming an aircraft flies 10 hours per day for 300 days per year, the corrosion-related cost per aircraft per year is $4,770. This compares favorably with the $3,000 to $3,500 reported by several airlines. Based on a total fleet of 2400 aircraft, the corrosion-related costs for the industry range from $7,200,000 to $11,448,000 per year. The airlines indicate this is between 2 and 2.5 percent of maintenance budgets.

Secondly, if one assumes that 1 percent of the monies spent for parts ($1.5 Billion) is for corrosion this amounts to $15,000,000 per year. One percent of parts was identified by Navy as being attributed to corrosion. It is also reasonable and perhaps conservative to estimate that the total labor costs attributed to corrosion are approximately 0.1 percent of the total labor dollars or $6,500,000. From this analysis, the cost per airplane per year for corrosion amounts to $8,950, which compares favorably with military aircraft cost data.

Coefficient adjustments for inputs to Sector 11.02 were made to account for inputs to provide corrosion protection to products and also to account for corrosion-related maintenance within the industry itself. It was estimated that 80 percent of the purchases of paints and allied products and 50 percent of the metallic coatings and platings are corrosion-related. Ten percent of the use of stainless steel, in lieu of carbon steel, was ascribed to corrosion. In addition, 30 percent of the sales of nickel and nickel alloys to this industry were ascribed to purchasing more costly corrosion-resistant alloys from this sector.

Corrosion-related maintenance costs in the industry were judged to be low and adjustments were made based on experience from other sectors. An estimate of technical support for corrosion was based on procedures as in other sectors.

Coefficient adjustments in Sector 17.05 were made to account for corrosion-related maintenance and technical support. Corrosion accounts for a significant portion of maintenance costs and estimates were made based on information from commercial airlines and analysis in the federal sector. An estimate of corrosion related technical support was determined by procedures as in other sectors.

Capital coefficients in both sectors were unchanged as no evidence was found for either excess capacity or redundant equipment. Replacement lives of several types of equipment are affected and appropriate adjustments were made.

Best practice ratings for Sector 11.02 was 3.0 based on high incentive and high responsiveness, and best practice rating for Sector 17.05 was 2.5 based on high incentive and moderate responsiveness.

4.4.14 Water Transportation Services and Equipment

Two sectors are included in this group: 11.03—Ship and Boat Building and Repair, and 17.04—Water Transportation. The former is involved in construction of ships and boats, while the latter provides transportation services. Significant costs are incurred in corrosion protection during operation and construction and corrosion maintenance during operation due to exposure to corrosive marine environments. Primary material of construction in ship building is carbon steel, although, other corrosion-resistant metals are used. Organic and metallic coatings are used extensively for corrosion protection of carbon steel.

In addition to discussions with industry experts, two articles were prime sources used to evaluate costs of corrosion in the ship building industry: (1) An article by Soltz[147] discussed major corrosion problems encountered by a large steamship company and outlined several procedures for corrosion control and (2) An article by Turlee, et al[72] presented results of an economic analysis of tanker operation.

In general, four major areas for corrosion costs on ships were identified: Steel renewal and replacement, piping and valve maintenance, boiler maintenance, and mechanical equipment maintenance. Primary emphasis in this study was to evaluate: (1) Costs incurred during ship construction for corrosion prevention and control and (2) Operating expenses including maintenance costs for corrosion.

Coefficient adjustments in Sector 11.03—Ship and Boat Building were made to account for inputs to provide corrosion protection for ships built by the industry and also to account for corrosion-related maintenance for the ship building industry itself. Inputs for corrosion protection to ships include organic coatings, corrosion resistant metals, corrosion allowance for mild steel, and cathodic protection.

It was estimated that 75 percent of the organic coatings used on ships are for corrosion protection. Adjustments of metal inputs to Sector 11.03 were made to account for the use of corrosion resistant metal. The following percentages of metal inputs were ascribed to corrosion related usage:

Low Alloy Steel—75 percent
Alloy Steel—25 percent
Stainless Steel—100 percent
Copper—90 percent
Aluminum—50 percent.

In addition, 20 percent of the usage of mild steel for ship building was ascribed to corrosion allowance. This estimate was based on information in the articles by Soltz(197) and Pearly(72) which identify specified corrosion allowance for various structural steel members in ships. Input of cathodic protection from Sector 20.05—Other Business and Professional Services was estimated to be 0.05 percent of total construction cost.

Based on data from a major ship building yard, corrosion related maintenance costs for the ship building industry were estimated to be 10 percent of total plant and equipment maintenance, which in turn was estimated to be 3 percent of total sales. These corrosion related costs were distributed among the appropriate sectors providing maintenance to the ship building industry. Corrosion related technical support was estimated as in other sectors and an adjustment made to input from Sector 25.00—Value Added.

Capital coefficients were unchanged as no evidence was found for either excess capacity or redundant equipment. Replacement lives of several types of equipment are affected by corrosion and adjustments were made accordingly.

Coefficient adjustments for Sector 17.04—Water Transporation were made to account for corrosion related maintenance and operation costs. Fuel requirements for ships are increased by rough hulls, which increase can be attributed partially to corrosion. Accordingly, fuel usage by the industry was estimated to be 0.1 percent greater because of corrosion.

Corrosion related maintenance is a significant part of overall maintenance because equipment is exposed to highly corrosive seawater and marine atmospheres. Increased use of sulfur bearing fuels further increases corrosion costs. Estimates for portions of total maintenance ascribed to corrosion were:

Fabricated Structural Metal Products—90 percent
General Industrial Machinery and Equipment—20 percent
Material Handling Machinery—20 percent
Miscellaneous Electrical Machinery—20 percent.

Based on data from a major ship building yard, 20 percent of all maintenance provided by the yard is attributed to corrosion. Corrosion related technical support was estimated as in other sectors and adjustments made to input from 25.00—Value Added.

A corrosion-related, overall excess capacity of 0.25 percent was estimated for the water transportation industry to account for load carrying capacity reduction (by weight of steel for corrosion allowance), and in some cases, rust scale buildup and loss of product in scale. No evidence of redundant equipment was found in this industry.

Replacement lives of several types of equipment are affected by corrosion and adjustments were made accordingly. The replacement life of ships is significantly affected by corrosion and the replacement life range was shifted from the base of 30 to 60 years to 50 to 60 years, if corrosion was not a factor; and to 40 to 60 years, if best corrosion practice was used.

Best practice ratings for both industries in this group were 2.0 based on moderate incentive and moderate responsiveness.

4.4.15 Railroad and Equipment Related Services

Two sectors are included in this group: 11.04—Locomotives and Rail and Streetcars and 17.01—Railraod and Related Services. The former sector is involved in construction of railroad equipment, while the latter provides transportation services. Costs of corrosion in these sectors are predominantly for corrosion control in the construction of railroad equipment and maintenance for corrosion damage of equipment. Corrosion related costs for the roadbed and track are minor.

Primary materials of construction for railroad equipment are mild steel and high-strength, low-alloy steel, although stainless steels are used to a significant extent in tank cars handling corrosive materials and in passenger train cars. Organic and metallic coatings are used primarily for corrosion protection of mild steel.

A breakdown of the types of railroad equipment is presented in Table 9. The statistics were taken from ''Yearbook of Railroad Facts: 1977 Edition'' published by the Economics and Finance Department of the Association of American Railroads.

Corrosion decreases the replacement life and increases operating maintenance costs for covered and uncovered hopper cars, gondola cars, tank cars, and passenger train cars. An extreme example of the effects of corrosion is that covered hopper cars in service carrying copper ore concentrate can have a replacement life of 8 months as opposed to 30 to 35 years for an identical car in non-corrosive service. Application of protective organic coatings to the interior of hopper cars can

TABLE 9. RAILROAD EQUIPMENT IN SERVICE IN 1976

Type	Total Number
Box Cars	473,953
Covered Hoppers	230,069
Flat Cars	141,781
Refrigerator Cars	98,017
Stock Cars	3,637
Gondola Cars	185,776
Hopper Cars	365,526
Tank Cars	168,018
Other Freight Cars	32,250
Passenger Train Cars	6,471
Locomotives	27,573

significantly decrease corrosion at an initial cost of approximately 10 percent on a $40,000 covered hopper car. Replacing steel roofs on hopper cars can cost approximately $5,000 per car. It is estimated that the total annual maintenance costs for freight cars to the railroad industry is $2.3 Billion. While the largest single maintenance item is replacement and reworking of wheels, which have very little corrosion costs involved, a significant portion of the remaining maintenance costs can be attributed to corrosion.

Coefficient adjustments were made in the two sectors on the basis of (1) Change in inputs to each sector and (2) Change in replacement lives of capital in the sectors; no adjustments were made in the capital for the industries since no evidence was found for excess capacity or redundant equipment.

In Sector 11.04, adjustments were made to account for input of corrosion protection materials for car construction and for corrosion maintenance in the industry. Inputs adjusted included corrosion paints, corrosion platings and coatings, and metal inputs. It was estimated that 1 percent of mild steel use was for corrosion-related steel replacement. Conversion of other metals to mild steel use were made as follows: 80 percent conversion of low alloy steels, including copper steels and high strength, low alloy steels for corrosion resistance, 50 percent conversion of alloy steel used for corrosion and wear resistance, 100 percent conversion of stainless steel used exclusively for corrosion protection, 50 percent conversion of copper, and 80 percent conversion of aluminum used for corrosion resistance and weight savings.

Input coefficients for maintenance in Sector 11.04 were reduced 10 percent to account for corrosion related maintenance based on data in other sectors and discussions with industry experts. This proportion for corrosion maintenance is somewhat higher than that for general manufacturing industries to account for the heavy equipment and exposure to more severe atmospheric corrosion.

In Sector 17.01, adjustments were made to input coefficients to account for corrosion related maintenance. Estimates were made based on data for other sectors.

Replacement lives of railroad cars supplied by Sector 11.04 to Sector 17.01 are significantly affected by corrosion. Based on the breakdown of types of equipment in service in 1976, it was estimated that approximately 55 percent of cars in service are affected by corrosion. It was further estimated that the replacement life was doubled when corrosion service was not encountered. Furthermore, presently available corrosion technology can be applied to realize this increased life. Accordingly, replacement lives of capital equipment supplied by Sector 11.04 to Sector 17.01 were changed from the base value of 28 years to 35 years if corrosion was not a factor, and to 34 years if best corrosion practice was implemented.

Best corrosion practice ratings for both sectors was 2.0 based on moderate incentive and moderate responsiveness.

4.4.16 General Electrical Apparatus

Six sectors are included in this group: 12.01—Electrical Measuring Instruments, 12.02—Electrical Motors and Generators, 12.02—Industrial Controls, Transformers, Etc., 12X04—Electric Lamps and Fixtures, 12.06—Electronic Components and Accessories, and 12.07—Miscellaneous Electrical Machinery. Primary interests in these sectors were in the inputs used by the industries to provide corrosion protection for their products. Corrosion protection is provided by organic coatings, metallic coatings and platings, the use of corrosion resistant metals, and corrosion inhibitors during shipping and storage. Corrosion related maintenance and repair costs within each industry were judged to be low.

Coefficient adjustments of inputs to Sectors 12.01, 12.03, and 12.06 were made for vapor phase corrosion inhibitors from Sector 5.03—Industrial Inorganic and Organic Chemicals and for packaging materials from Sector 5.15 to provide for corrosion protection during shipping and storage. These adjustments were based on data for Sector 15.01—Computing and Related Machines, where similar corrosion protection is required.

Portions of inputs from paints and allied products and coatings and platings ascribed to corrosion for each of these industries were presented in the sector describing procedures for these adjustments.

Portions of organic coatings ascribed to corrosion range from 10 percent for Sector 12.06—Electronic Components to 75 percent for Sector 12.01—Electrical Measuring Instruments, and portions of coatings and platings ascribed to corrosion ranged from 33 percent for Sector 12X04—Electrical Components and Accessories.

Significant usage of corrosion resistant metals was identified in these sectors and appropriate adjustments were made in coefficients. The following portions of usage for materials was ascribed to corrosion protection for products:

Low Alloy Steel—100 percent
Alloy Steel—25 percent
Stainless Steel-100 percent
Aluminum—50 percent.

In all cases, corrosion resistant materials were substituted for mild steel.

Corrosion-related maintenance costs are low for these sectors. Adjustments to coefficients for corrosion related maintenance were made based on estimates of (1) 2.4 percent of sales of maintenance and (2) 5 percent maintenance costs for corrosion purposes. This amount was then distributed among the appropriate sectors providing maintenance.

Capital coefficients were unchanged, as no evidence was found for either excess capacity or redundant equipment. Replacement lives of several types of equipment are affected by corrosion and adjustments were made accordingly.

Best practice ratings for all sectors in this group were 2.0 based on moderate incentive and moderate responsiveness.

4.4.17 Special Electrical Apparatus

Three sectors are included in this group: 13.01—Service Industry Machinery, 13.02—Home Appliances, 13.03—Radio, TV, Communication Equipment. Primary emphasis was placed on inputs to each industry for corrosion protection of products manufactured. Corrosion protection to products is provided through the use of organic coatings, metallic coatings and platings, corrosion resistant metals, and in the case of water heaters in Sector 13.02, cathodic protection. Corrosion-related maintenance costs in the manufacturing operations were judged to be low.

Portions of organic coating usage for corrosion protection of products were 60 percent in Sector 13.01, 85 percent in Sector 13.02 and 50 percent in Sector 13.03. Portions of metallic coatings and platings ascribed to corrosion were 75 percent in Sector 13.01, 60 percent in Sector 13.02, and 60 percent Sector 13.03. Further coefficient adjustments were made in Sector 13.03 to account for purchases from Sector 5.03, 5.06, and 5.15 to account for vapor phase inhibitor and packaging to provide corrosion protection during shipping and storage.

Metal inputs to each of the sectors are significantly affected by the need to provide corrosion protection in manufactured products. In Sector 13.01 and 13.03, all use of low alloy steel, alloy steel, stainless steel, and aluminum was attributed to corrosion protection. In Sector 13.02 all use of low alloy steel, alloy steel, and stainless steel was attributed to corrosion. Fifty percent of the use of copper, aluminum, and nickel and nickel alloys was ascribed to corrosion resistance. In all cases corrosion resistant metals were substituted for the use of mild steel. Inputs of Sector 20.05—Other Business and Professional Services was adjusted in Sector 13.02 to account for the use of magnesium in the cathodic protection of water heaters.

Corrosion related maintenance costs in each of the industries were considered to be low and adjustments were made based on experience in other sectors.

Capital coefficients were unchanged and no evidence was found for either excess capacity or redundant equipment. Replacement lives of several types of equipment are affected by corrosion and adjustments were made accordingly.

Best practice rating for Sector 13.01 and 13.03 were 2.0 based on moderate incentive and moderate responsiveness. Best practice rating for Sector 13.02 was 2.5 based on high incentive and moderate responsiveness.

4.4.18 Scientific and Measuring Devices

Five sectors are included in this group: 14.01—Scientific Insturments, Measures and Controls, 14.02—Medical, Surgical, Dental Instruments and Supplies, 14.03—Watches, Clocks and Parts, 14.04—Optical and Ophthalmic Goods, and 14.05—Photographic Equipment and Supplies. Major areas of costs of corrosion in these sectors are for corrosion protection in the products manufactured and corrosion protection during shipping. Corrosion related maintenance in these sectors is low except for some aqueous processing in the photographic sector. For corrosion protection during shipping, vapor phase inhibitors and plastic packaging are used. Coatings, platings, and corrosion-resistant metals are used for corrosion protection in manufactured products.

No specific data were available for these industries and estimates for coefficient adjustments in the I/O Model were based on data from other sectors. Inputs of industrial chemicals and manufactured plastic products for corrosion protection during shipping were estimated to be 10 percent of purchases for Sectors 14.01, 14.02, 14.03, and 14.04, and 1 percent of purchases for Sectors 14.05.

Three adjustments were made to account for inputs for corrosion protection in manufactured products. These were based on estimates of the corrosion related costs of (1) painting, (2) metallic plating and coating, and (3) the cost differential between mild steel and the corrosion-resistant metals used, i.e., aluminum, stainless steel, alloy steel, and low alloy steel.

In addition, the portion of corrosion related maintenance of plants and equipment in these sectors was estimated. Portions ascribed to corrosion maintenance were somewhat higher in Sector 14.05–Photographic Equipment and Supplies to account for handling aqueous solutions in this industry.

Capital coefficients were unchanged and no evidence was found for either excess capacity or redundant equipment. Replacement lives of equipment in these industries were not judged to be significantly affected by corrosion.

All industries in this group were given a best practice rating of 2.5 based on high incentive and low responsiveness.

4.4.19 Business Machines and Supplies

Three sectors comprise this group: 15.01–Computing and Related Machines, 15.02–All Other Office and Business Machines, and 15.03–Office Supplies. The last sector is a dummy sector for the I/O Model and no changes are warranted for the corrosion study. Corrosion costs for the prior two industries are predominantly for corrosion protection in the construction of products and corrosion protection during shipping. Corrosion related maintenance costs to the industries themselves are estimated to be minor.

Two industry sources estimated cost of corrosion to be 2 percent of product cost in Sector 15.01. Corrosion costs were broken down as: Painting–17 percent, Plating–35 percent, Electronic Construction and Packaging–43 percent, and Shipping–5 percent. An industry source estimated corrosion cost in Sector 15.02 to be 1.5 percent of product manufacturing cost.

Inputs for corrosion protection in Sector 15.01 were identified as vapor phase inhibitors for protection during shipping, plastics used for packaging for corrosion protection, use of corrosion-resistant metals, corrosion-protection paints, and corrosion-protection platings. An industrial expert estimated that 50 percent of industrial chemicals and 50 percent of plastic purchases could be ascribed to corrosion protection. Further, 40 percent of costs for painting; 60 percent for costs of plating; and all use of aluminum, stainless steel, and high-strength, low alloy steel were ascribed to corrosion protection.

Adjustments in machinery sectors for corrosion related maintenance were based on experience and data from other sectors. Similar coefficient adjustments were made in Sector 15.02.

Capital coefficients were unchanged as no evidence was found for either excess capacity or redundant equipment. Replacement lives of equipment were not judged to be significantly affected by corrosion.

Best practice rating for the Computing and Related Machinery sector was 2.5 based on high incentive and moderate responsiveness, while best practice rating for the Other Office and Business Machine Sector was 2.0 based on moderate incentive and responsiveness.

4.4.20 Miscellaneous Manufacturers

Two sectors are included in this group: 16.01—Ordnance and Accessories and 16.02—Other Miscellaneous Products. The former includes establishments engaged in manufacturing artillery, small arms, and related equipment; ammunition; tanks and specialized tank parts; fighting and fire-control equipment; and miscellaneous ordnance and accessories. The latter sector includes establishments primarily engaged in manufacturing products not classified in any other manufacturing group. Industries in this sector fall into the following categories: jewelry, silverware and plated wear; musical instruments; toys, sporting and athletic goods; pens, pencils, and other office and artists' materials; buttons, costume novelties, miscellaneous notions; brooms and brushes; morticians' goods; and other miscellaneous manufacturing industries.

Costs of corrosion in this sector are incurred for both corrosion protection of products and corrosion related maintenance, repair, and replacement.

In Sector 16.01, coefficient adjustments were made to account for corrosion protection of products during storage and shipping, namely, the use of vapor phase inhibitors and special packaging purchases from Sectors 5.06 and 5.15, respectively.

Organic coatings for corrosion protection were estimated to be 80 percent of total paint usage, and corrosion related metallic coatings and platings were estimated to be 75 percent of the total usage.

All of the use of low alloy steel and stainless steel in this industry was attribued to corrosion resistance as a substitute for mild steel. Similarly, 20 percent of the use of aluminum was ascribed to corrosion resistance for canisters and containers with the remainder for non-corrosion applications such as weight savings. All of the usage of titanium, tantalum, and zirconium from Sector 7E04 was ascribed to corrosion resistance.

An estimate of technical support for corrosion was made as in other sectors. Corrosion related maintenance in this industry was judged to be low, and coefficient adjustments were made based on experience from other sectors.

Sector 16.02 is a widely diverse sector and coefficient adjustments were made based on experience in other sectors. Input adjustments for corrosion resistance of products were made to account for the use of organic coatings (50 percent of total usage), metallic coatings (67 percent of total usage), and use of corrosion-resistant metals in place of mild steel. The following percentages of total metal usage were ascribed to corrosion resistance: Low Alloy Steel—100 percent, Alloy Steel—25 percent, Stainless Steel—100 percent, Copper—75 percent, and Aluminum—50 percent.

Corrosion related maintenance was judged to be low and adjustments were made based on experience from other sectors.

No changes in capital coefficients were made as no evidence for excess capacity or redundant equipment was found. Replacement lives of several types of equipment are affected by corrosion and appropriate adjustments were made.

Best practice rating for Sector 16.01 was 2.5 based on high incentive and moderate responsiveness, and best practice rating for Sector 16.02 was 2.0 based on moderate incentive and moderate responsiveness.

4.4.21 Highway Passenger Transport, Motor Freight and Warehousing, and Transportation Services

Three sectors are included in this group: 17.02—Local and Other Highway Passenger Transport, 17.03—Motor Freight and Warehousing, 17.07—Transportation Services. Sector 17.02 includes companies primarily engaged in furnishing local and surburban passenger transportation by rail, coach, or Motorbus Line. Also included are companies engaged in furnishing highway passenger transportation and companies furnishing highway passenger terminal maintenance or facilities. Intercity bus lines are included in this sector. Sector 17.03 includes establishments furnishing local or long distance trucking, transfer, and draying services, or engaged in the storing of farm products, furniture, and other household goods, or commercial goods of any nature. Operation of terminal facilities for handling freight is also included in this sector. Sector 17.07 includes companies engaged in freight forwarding, establishments engaged in arrangements of transportation, and miscellaneous services incidental to transportation, e.g., inspection and weighing services, packing and crating, and fixed facilities for motor vehicle transportation.

No items which corrode are produced in this group. Only corrosion related costs in operation, replacement, and repair are of concern in this study. Major corrosion costs are related to maintenance of vehicles used to provide transportation services.

Information as a basis for estimates of corrosion related maintenance costs was obtained from interviews with major trucking firms, operators of buslines, input from the detailed analysis sector, and past experience with corrosion problems for automobiles, trucks, and buses. Overall, corrosion was not judged to play a major role in the maintenance of equipment in these sectors.

Coefficient adjustments to inputs were made to account for corrosion related maintenance and technical support. In addition 50 percent of the chemical purchases in Sector 17.02 and Sector 17.03 were ascribed to corrosion control in the form of inhibited radiator coolant.

Adjustment of coefficients for maintenance were based on information from industry experts and experience in other sectors. Treatment of technical support for corrosion was as in other industries.

Capital coefficients were unchanged as no evidence was found for either excess capacity or redundant equipment. Replacement lives of several types of equipment are affected by corrosion and ajustments were made accordingly.

Best practice ratings for all sectors in this group were 2.0 based on moderate incentive and moderate responsiveness.

4.4.22 Pipelines

Sector 17.06—Pipelines includes companies engaged in the pipeline transportation of petroleum and other commodities, except natural gas. Pipelines for crude petroleum and refined products of petroleum comprise the bulk of this industry. No items which corrode are produced and inputs to the industry are not greatly affected because of corrosion. Capital which corrodes includes pipelines, pump stations, and ancillary equipment.

The industry is aware of corrosion, and in general employs specialists to monitor and conduct corrosion control programs. Forms of corrosion prevention and control are organic coatings, cathodic protection, inhibitors, and removal of water and corrodents, e.g., hydrogen sulfide and carbon dioxide. Cost for application for organic coatings, labor to monitor corrosion control, and repair of corrosion damage are the major contributions to the costs of corrosion.

Coefficient adjustments were made based on interviews with industry experts, suppliers of corrosion related goods to the pipeline industry, and extensive experience in corrosion related problems in the pipeline industry. It was estimated that 50 percent of the chemical purchases by the industry are for corrosion control. Further adjustments were made for corrosion related maintenance based on information from operators of pipelines. Estimates of technical support for corrosion were made as in other industries and adjustments made to Sector 25.00—Value Added.

No evidence was found for excess capacity within the industry. The capital coefficient for Sector 9.02 input to the pipeline industry was adjusted at account for redundant pumps in pump stations. Standard design practice is to install three pumps where two are required for continuous operation. Fifty percent of the redundant pumps are ascribed to corrosion. Replacement lives of several types of equipment are affected by corrosion and ajustments were made accordingly.

Best practice rating for Sector 17.06 was 2.5 based on high incentive and moderate responsiveness.

4.4.23 Public Utilities

Four sectors are included in this group: 18.01—Telecommunication, 18.02—Electric Power, 18.03—Gas, and 18.04—Water and Sanitary Services. Each is discussed separately below.

4.4.23.1 Telecommunication. Sector 18.01—Telecommunication includes companies furnishing point-to-point communications services by wire or radio intended to be received aurally or visually; and radio broadcasting and television. Services for the exchange or recording of messages are also included.

Major causes of corrosion costs in this industry are atmospheric corrosion of transmission towers and lines, corrosion of buried cables, and air oxidation. The latter is a special case associated with deterioration of switching components and relays which ''arc'' during activation.

No specific data were available for this industry and estimates for coefficient adjustments were based on data from other industries and a general knowledge of the forms and severity of corrosion within this industry. Inputs to the industry were adjusted for corrosion maintenance and research and development. No evidence was found for either excess capacity or redundant equipment and thus, capital coefficients were not changed.

Best practice rating for the industry was 3.0 based on high incentive and high responsiveness.

4.4.23.2 Electric Power. Sector 18.02—Electric Power includes companies engaged in the generation, transmission, and/or distribution of electricity. Such companies (or systems) may be combinations of any of the above services.

This industry is treated in detail in Appendix B of this report. Specific data were found for costs in the nuclear power generation; in other cases expert opinion and judgment were used to estimate coefficients adjustments. Inputs to the industry were adjusted for maintenance, chemicals, and research and development. Corrosion related maintentnace is a major factor in the power industry as is described in Appendix B. By its very nature, the power industry must maintain excess capacity. A portion of this excess capacity can be related to corrosion caused outages, and thus capital coefficients have been adjusted accordingly.

Best practice rating for the industry was 2.5 based on high incentive and moderate responsiveness.

4.4.23.3 Gas. Sector 18.03—Gas includes companies and systems engaged in transmission, storage, and/or distribution of natural gas for sale. In addition, companies engaged in the manufacture or distribution of L.P. gas are included.

No items which corrode are produced by these companies, but corrosion maintenance and control contribute significantly to overall costs in each of three major facets of the industry; natural gas transmission pipelines, gas storage, and distribution systems. Carbon steel is the primary material of construction throughout the industry. Organic coatings, cathodic protection, and corrosion inhibitors are used to control corrosion.

Natural gas transmission pipelines transport gas across the country from production fields, primarily in the South and Southwest, to major user regions, the Northest and Midwest. Corrosion affects the buried pipelines, compressor stations, and auxiliary equipment. A compilation of cause of leaks in gas transmission from 1970 to 1975 gives the following percentage breakdown:

Corrosion—14.9 percent
Outside Force (e.g., backhoes puncturing the pipeline)—
56.3 percent
Materials Failure—16.9 percent
Construction Defect—5.0 percent
Other—6.9 percent.

Corrosion protection is included during construction by external organic coatings and cathodic protection. These represent approximately 5-10 percent and 0.05 percent of pipeline construction costs, respectively. Operating costs attributable to corrosion are costs for portions of maintenance, inhibitors for internal corrosion control, sulfur removal from gas, and portions of inspection and testing. Useful life of a pipeline would be indefinite if corrosion was not a factor, since it is the only significant mode of degradation of pipelines.

Gas is typically stored in underground storage reservoirs. In 1975, there were approximately 350 underground reservoirs in the U.S. with approximately 15,000 associated wells. Corrosion control of storage wells is accomplished through the use of coatings, inhibitors, corrosion allowance and cathodic protection. Two prime sources of information for corrosion costs in this area were (1) results of a survey by the National Association of Corrosion Engineers and the American Gas Association[414] and (2) a paper by Push and Beasley[411].

Corrosion costs in gas distribution systems result from maintenance, coatings, inhibitors, and cathodic protection. Compilation of cause of leaks in distribution systems of the gas industry for 1970 and 1975 indicate that 46 percent of leaks were caused by corrosion.

Wise[410] reviewed corrosion costs associated with a moderate sized distribution system. Corrosion control costs for construction as percent of total investment were coatings—8 percent, cathodic protection—2 percent, and electrical insulation—2 percent. Operating costs for cathodic protection were 0.46 percent of investment protected.

Chemicals purchased by the industry include odorants, glycol for dehydration, and corrosion inhibitors. The latter were estimated to be approximately 5 percent of total chemical purchases.

Coefficient adjustments were made for inputs to the industry to account for corrosion inhibitors, corrosion related maintenance, and technical support for corrosion control. No excess capacity was identified in this industry; however, the capital coefficient for engines and turbines was reduced to account for redundant equipment in compressor stations.

Replacement lives of much of the capital equipment are affected by corrosion and adjustments were made accordingly.

Best practice corrosion rating for the industry was 2.5 based on high incentive and moderate responsiveness.

<u>4.4.23.4 Water and Sanitary Services.</u> Sector 18.04—Water and Sanitary Services includes systems primarily engaged in distribution of water for sale for domestic, commercial, and industrial use (except irrigation); systems engaged in the collection, treatment, and disposal of wastes conducted through a sewer system; systems engaged in the collection and disposal (but not transport) of refuse by processing or destruction; and other sanitary services such as sweeping, mosquito control, and malaria control. The industry relies heavily on plumbing systems and chemical plant type operations.

Specific data were scarce for this industry and estimates for coefficient adjustments in the model are based on data from other industries and general knowledge of the forms and severity of corrosion within this industry.

Inputs to the industry were adjusted for electric power, gas, maintenance and corrosion inhibitors. Fuel and power adjustments were based on the widespread use of pumps. Published information indicates that pumping horsepower requirements increase about 20 percent for roughened pipes. Estimates that corrosion accounts for about 40 percent of roughening and that about 50 percent of the electricity and gas used by the industry is for pumping results in a 4 percent change (20% x 40% x 50%) in these two direct technical coefficients. Similarly, the appropriate capital coefficient (Sector 9.02) also was adjusted by 4 percent to account for extra pump capacity required because of corrosion.

Best practice rating for the industry was 2.0 based on moderate incentive and moderate responsiveness.

4.4.24 Construction

Six sectors are included in this group: 19.01—New Construction, Nonfarm Residences, 19.02—New Construction, Nonresidential Buildings, 19.03—New Construction, Public Utility, 19.04—New Construction, Highway and Other, 19A05—Maintenance and Repair Construction, Corrosion, and 19B05—Maintenance and Repair Construction, Noncorrosion.

Sector 19.01 includes establishments engaged in construction of residential homes and apartments; farm buildings and homes are excluded. Sector 19.02 includes establishments engaged in construction of non-residential buildings. This includes office buildings, public buildings, factories, and other types of buildings used for purposes other than in farming and residence. Sector 19.03 includes establishments engaged in construction of public utility infrastructure, not including buildings used by public utilities. Infrastructure required by the telecommunications, transportation, power, gas, and water industries includes railroads, high-tension power lines, cities' service poles, antennae, and pipelines. Sector 19.04 includes establishments engaged in construction primarily of streets and roads with all necessary appendages, e.g., bridges, and guard rails. Construction items also included in this sector are dams and jetties, drainage ditches, farm construction, improvements to the land, and well drilling. The largest single activity in this sector is construction of highways. Sectors 19A05 and 19B05 provide the maintenance and repair for all items constructed by the above sectors. They do not provide maintenance and repair for specialized machinery and equipment within the construction.

Corrosion related costs for these sectors were judged to be low and primary emphasis was placed upon the inputs to construction sectors for corrosion protection of items constructed.

Coefficient adjustment in Sector 19.01—Construction, Nonfarm Residences were made to account for inputs for corrosion protection of constructed items and for corrosion related maintenance in the industry itself. The latter was judged to be low based on input from construction companies. Coefficient adjustments were made based on experience in other sectors.

It was estimated that 25 percent of the paints and allied products used in this industry are for corrosion protection. Inputs of primary metals to the industry were also adjusted for corrosion resistant usage. Fifty percent of the use of copper by the industry was judged to be for corrosion. Copper is used for both electrical wiring and plumbing. Use of copper in plumbing is primarily for corrosion, although in large projects copper is selected also because of the ease of installation when compared with threaded steel pipe. Corrosion is not a factor in the selection of copper for electrical applications. All of the use of aluminum was ascribed to corrosion resistance. In both cases, more corrosion-resistant materials were used as a substitute for mild steel.

Coefficient adjustments in Sector 19.02—New Construction, Nonresidential Buildings were made to account for inputs for corrosion protection in constructed items and to account for corrosion related maintenance within the industry itself.

Corrosion related maintenance costs were judged to be low and coefficient adjustments were made based on experience from other sectors.

It was estimated that 40 percent of the paints and allied products used by this sector were for corrosion protection. Adjustments in the use of corrosion-resistant metals were made based on estimates of portions of metal usage for corrosion as follows:

Low Alloy Steel—100 percent
Alloy Steel—75 percent
Stainless Steel—100 percent
Primary Copper—90 percent
Aluminum—100 percent.

Input from Sector 20.05—Other Business and Professional Services was adjusted to account for an estimated $29 Million of cathodic protection installed by Sector 19.02.

For Sector 19.03—New Construction, Public Utility, coefficient adjustments were made to inputs to account for corrosion protection in constructed items and for corrosion related maintenance in the industry itself.

Similarly to the other construction sectors, corrosion related maintenance was judged to be a small percentage of total maintenance and coefficient adjustments were estimated based on experience from other sectors.

It was estimated that 60 percent of the use of organic coatings in this sector were for corrosion protection. The following portions of metal inputs were judged to be for corrosion:

Low Alloy Steel—100 percent
Alloy Steel—75 percent
Stainless Steel—100 percent
Copper—90 percent
Aluminum—100 percent
Nickel and Nickel Alloys—100 percent.

All corrosion resistant metal usage was assumed to be in place of mild steel. Input from Sector 20.05—Other Business and Professional Services was adjusted to account for the estimated $108 Million of cathodic protection installed by this industry.

Similar coefficient adjustments were made in Sector 19.04—New Construction, Highway and Other. Corrosion related maintenance was judged to be low and adjustments were made based on information from other sectors. It was estimated that 50 percent of the paints and allied products used was for corrosion protection. The following adjustments were estimated for corrosion related inputs:

Low Alloy Steel—100 percent
Alloy Steel—75 percent
Stainless Steel-100 percent
Copper—90 percent
Alluminum—100 percent.

Input from Sector 20.05—Other Business and Professional Services was adjusted to account for an estimated $7 Million for cathodic protection installed by this sector.

Sectors 19A05 and 19B05—Maintenance and Repair Construction, Corrosion and Noncorrosion, were treated similarly. Inputs to both industries can be ascribed to corrosion protection on items repaired and for corrosion related maintenance to the industries themselves. It was estimated that 50 percent of the paints and allied products used by Sector 19A05 was for corrosion protection. The following proportions of metal inputs was ascribed to be for metal corrosion resistance in both sectors:

Low Alloy Steel—100 percent
Alloy Steel—75 percent
Stainless Steel—100 percent
Copper—90 percent
Aluminum—100 percent.

Input of Sector 20.05—Other Business and Professional Services to Sector 19A05 was adjusted to account for cathodic protection based on estimates in the other construction sectors.

Capital coefficients were unchanged in all sectors as no evidence was found for either excess capacity or redundant equipment. Replacement lives of several types of equipment are affected by corrosion and adjustments were made accordingly.

Best practice ratings for all sectors were 2.0 based on moderate incentive and moderate responsiveness.

4.4.25 Trade and Business Services

This group comprises four sectors: 20.01—Wholesale and Retail Trade, 20X02—Finance, Insurance, Real Estate, Advertising, 20.05—Other Businesses and Professional Services, and 20.06—Business Travel, Entertainment, and Gifts. Sectors 20.01 and 20X02 are diverse industries and produce no corrosible goods. Corrosion is not recognized as a significant problem nor addressed directly by the industries.

Sector 20.05 is also a diversified industry containing many different functions. Of particular interest to this study is the cathodic protection services which are included in this sector. Cathodic protection coefficients have been discussed in another section of this report. Sector 20.06—Business Travel is a dummy sector constructed for the I/O model and no coefficient adjustments for the corrosion study are warranted.

Coefficient adjustments for 20.01 and 20X02 were made based on data for laboratories and office buildings. Inputs to the industry were adjusted for corrosion maintenance only and no capital coefficient adjustments were made. No evidence of excess capacity or redundant equipment was found.

Replacement lives of some equipment for buildings is affected by corrosion and adjustments were made.

Similar adjustments to those for Sectors 20.01 and 20X02 were made in Sector 20.05 with additional adjustments to account for cathodic protection services.

Best practice ratings for 20.01 and 20X02 were 1.0 based on low incentive and low responsiveness. Best practice rating for 20.05 was 2.0 based on moderate incentive and moderate responsiveness.

4.4.26 Other Services

Eight sectors are included in this group: 21.01—Printing and Publishing, 21.02 Radio and Television Broadcasting, 21.03-Hotels and Lodging Places, 21.04 Personal and Repair Services, except auto, 21.05 Automobile Repair Services, 21.06-Amusements, 21.07-Medical and Health Services, and 21.08-Educational Services and Nonprofit Organizations. With the exception of the repair sectors, 21.04 and 21.05, all sectors in this group produce no items which corrode. In the former sectors corrosion is not recognized as a significant problem and is not addressed directly by the industries. Inputs to these industries were adjusted for corrosion maintenance based on data for office buildings and laboratories. Capital was not affected as no evidence for excess capacity or redundant equipment was found. Best practice ratings based on incentive and responsiveness were

Printing Publishing—2.0
Radio and Television—1.0
Hotels and Lodging Places—1.5
Amusements—1.5
Medical and Health—1.5
Eucational Services—1.0.

Adjustments in Sector 21.04-Personal and Repair Services and 21.05—Auto Repair and Services were made to account for both corrosion maintenance within the sectors as well as inputs of materials used in corrosion related repairs. For both sectors the use of paints and metallic coatings for corrosion were estimated. Capital was not affected as no evidence of excess capacity or redundant equipment was found.

Best practice ratings for 21.04 and 21.05 were 2.0 based on moderate incentive and moderate responsiveness.

4.4.27 Government Enterprise—Post Office

Sector 22.01—Post Office produces no items which corrode, and corrosion is not judged to be a major problem in the Post Office.

Inputs were adjusted for corrosion related maintenance, based on data from other sectors. Predominant items in the maintenance budget are for autos and trucks, and fixed structures. Capital coefficients were unchanged as no evidence was found for either excess capacity or redundant equipment.

Replacement lives of several types of equipment are affected by corrosion and adjustments were made accordingly.

A best practice rating of 2.0 was given to the Post Office based on moderate incentive and moderate responsiveness.

4.4.28 Final Demands

Final demand comprises six components: personal consumption expenditures (PCE), private capital formation, exports, federal government expenditures, state and local government expenditures, and net inventory change. Adjustments discussed in this section concern personal consumption expenditures, federal government expenditures, and state and local government expenditures. Adjustments to private capital formation have previously been discussed, and net export and net inventory changes are disregarded for this study. Adjustments in final demand are analagous to those in the industrial sectors, i.e., adjustments in consumption levels of non-durable goods and services (paints, coatings, inhibitors, etc.), redundant capital because of corrosion, and adjustments in replacement lives of durable goods.

4.4.28.1 Changes in Non-Durable Goods. Non-durable goods are defined as goods that last less than 1 year, change form in the consumption process, or are intangible. Three non-durables: paints, coatings and platings, and maintenance and repair construction were treated as in the flow matrix, and inputs from these sectors were separated into corrosion and non-corrosion portions. Other adjustments are discussed below for each of the three components of final demand of interest here.

4.4.28.1.1 Other Adjustments for Personal Consumption Expenditures. Other adjustments in Personal Consumption Expenditures were made to account for corrosion related maintenance and protection. Purchases from Sector 5.06 were adjusted to account for the approximately $180 million of radiator coolant bought for automobiles annually. The bulk of these purchases is made to retain sufficient corrosion inhibitor concentration in automobile cooling systems. Purchases from Sectors 10.01 — Farm Machinery, 11.03 — Ship and Boat Building, and 13.03 - Radio and Television and Communication Equipment were adjusted to account for corrosion related purchase of repair parts. Estimates for corrosion related parts and purchases were made based on experience in the comparable industrial sector or direct estimate. Finally, adjustments were made in purchases from Sectors 21.04 - Personal and Repair Services, except auto and Sector 21.05 - Automobile Repair and Services based on experience from industrial sectors. Corrosion related costs in these sectors were estimated to be 1 percent and 25 percent, respectively.

4.4.28.1.2 Other Adjustments for Federal Government Expenditures. Adjustments were made in Federal Government Expenditures to account for corrosion related maintenance and control. Purchases from Sector 5.06 - Miscellaneous Chemical Products were adjusted to account for corrosion costs based on experience from other sectors and distribution of estimates for water treatment, corrosion inhibitors, and radiator coolant. The result was that 6 percent of purchases from Sector 5.06 were attributed to corrosion. Adjustments were made in the purchases of paints and allied products based on an estimate that 40 percent of paints and allied products were for corrosion protection.

Purchases of corrosion-resistant metals as substitute for mild steel were estimated to be the following percentages of total purchases:

Low-Alloy steel - 100 percent
Alloy Steel - 75 percent
Stainless Steel - 100 percent
Copper - 90 percent
Aluminum - 50 percent.

Purchases of coatings and platings were adjusted based on the estimate that 60 percent of coatings and platings were purchased for corrosion resistance. Purchases from Sector 20.05—Other Business and Professional Services were adjusted based on the estimate that approximately $10 million of corrosion related technical support is purchased annually.

Corrosion related maintenance costs for aircraft, ships, ordnance, and communication equipment were treated as follows. Where an estimate of total corrosion related costs was available, supplied labor was removed from Row 23.02 - Government Industry; the Government Industry cell indicates all wages and salaries paid by the federal government. All materials and the remaining labor were distributed among industrial sectors which supplied them. For example, analysis of federal government expenditures on corrosion related aircraft maintenance indicated annual expenditures of $833 million for labor, and $153 million for material. The former was allotted to Row 23.02 - Government Industry and the latter, $153 million was distributed

70 percent to aircraft and parts
20 percent to electronic components
10 percent to paints.

The distribution of materials was based on information from the commercial airline sector.

Maintenance on ships was treated somewhat differently in that approximately one-half of ship repair is contracted to privately owned shipyards, and the other half done in government owned shipyards. As a result, one-half of the government expenditures for ship repairs was allocated to the ship building and repair sector while the other half was distributed as follows:

30% - Government Supplied Labor to Row 23.02—Government Industry
70% - Materials Distributed to Sectors
  35% - Miscellaneous Fabricated Metal Products
  6% - Engines and Turbines
  3% - General Industrial Machine and Equipment
  1% - Non-Electric Heating Equipment
  55% - Mild Steel.

Distribution of materials was based on the distribution of inputs to the ship building industry.

Where no estimates were available for corrosion related maintenance on types of capital equipment, estimates were made based on experience from the comparable industrial sector with the assumption that corrosion related maintenance costs per dollar for like capital would be similar in both cases.

4.7.28.1.3 Other Adjustments for State and Local Government Expenditures. State and local government expenditures were adjusted in a similar manner to the federal government expenditures. Purchases from Sector 5.06 - Miscellaneous Chemical Products were adjusted based on an estimate of use of corrosion inhibitors. Corrosion related paints and allied products were estimated to be 25 percent of total purchases. Use of corrosion resistant metals in place of mild steel were judged to be the following percentages of total purchases:

Low Alloy Steel - 100 percent
Alloy Steel - 75 percent
Stainless Steel - 100 percent
Copper - 90 percent
Aluminum - 50 percent.

Corrosion related maintenance expenditures were handled as in the federal government.

4.4.28.2 Adjustments to Durable Goods. Adjustment to inventory of durable goods in the final demand sectors were made similarily to that in the industrial sectors, i.e., considerations were excess capacity, redundant equipment, and changes in useful lives.

No excess capacity as a result of corrosion was identified in the final demands. Two redundant equipment changes were identified from analysis of the federal sector presented in Appendix A. It was estimated that 6 percent of federal government-owned aircraft and parts and 0.5 percent of federal-owned ordnance and accessories can be ascribed to corrosion.

Replacement lives of durable goods in final demand were adjusted on the same basis as used in the industrial sectors. Relative changes were made to the base replacement life estimate to account for effects of corrosion. Where available specific information for corrosion effects in final demand sectors was used. Where no specific data were available, it was assumed that replacement lives for durables purchased by final consumers were the same as those estimated for industrial sectors.

5 COSTS OF CORROSION: ANALYSES OF RESULTS

There are two aspects of corrosion costs which have been determined by this study. They are (1) Quantification of total costs to the economy and (2) Attribution of costs to specific industrial sectors. The first aspect is economy-wide in its significance, dealing with measurements of the resources which our society devotes to the corrosion problem that would be available for other uses if (1) there were no corrosion, or (2) every segment of the economy followed ''best practices'' (as defined) in dealing with corrosion. The second aspect is more sectorally specific. It deals with a determination of which industrial sectors are most affected by corrosion. This aspect of the study provides a data base to guide decisions of where corrective actions and/or where anticorrosion R&D efforts can best be taken.

These results are presented below with a discussion of uncertainty of the estimates and of uses of the I/O model for technology assessment.

5.1 Quantification of Total Costs

The total cost of corrosion to the U.S. economy may be viewed as *the total value of resources* (including labor, energy, embodied materials, and technical/managerial expertise) that the economy consumes because of corrosion. Viewed in a different way, it consists of the value of resources that, in the absence of corrosion as a destructive force, would be available for other uses. Viewed in a third way, it may be thought of as the difference in Gross National Product (GNP) between a real world in which corrosion exists and an alternative world which would be corrosion-free, with nothing else changed.

Estimates of the total cost of corrosion to the United States in 1975 were

Total Cost of Corrosion	\$82B
Intermediate Cost	\$24B
Final Demand Cost	\$58B

The sum is made up of two subtotals. Final demand cost measures the reduction in final demand purchaess by consumers, investors and governments that would be realized in a corrosion-free situation. Intermediate cost measures the reduction in resource requirements that would become technologically feasible if productive processes no longer needed to take corrosion into account.

Portions contributing to final demand costs included \$23B attributed to private consumer expenditures, \$8B attributed to Federal Government expenditures, and \$3B attributed to state and local government expenditures.

The total cost of corrosion, $82B, constituted 4.9 percent of Gross National Product (GNP). This is based on GNP of $1677B for World I (the economy with corrosion) in the Input/Output analysis.

Total cost of corrosion was broken down into avoidable and unavoidable costs. Avoidable costs are the total value of resources that are amenable to savings by application of best corrosion control practice. Estimates were

Avoidable Cost of Corrosion	$33B
Unavoidable Cost of Corrosion	$49B

Avoidable cost is made up of $31B for final demand purchases and $2B for intermediate costs. Based on a GNP of $1677B, avoidable costs constitute 2.0 percent of GNP and unavoidable costs constitute 2.9 percent of GNP. Thus, approximately 40 percent of total costs of corrosion are avoidable costs.

5.2 Sectoral Attributions of Costs

As a basis for industrial analysis, Input/Output technique was used to attribute relative costs of corrosion to specific segments of the economy. A major reason for choice of the I/O Model as the device for quantifying (measuring) corrosion costs in the U.S. was that this model is uniquely capable of tracing the indirect costs of corrosion as well as those costs directly borne by each sector. For instance, if the metal can industry uses aluminum to control corrosion, this means that different (larger) amounts of energy must be consumed in making aluminum than in making steel; but either more or less energy (as the case may be) might be consumed in mining, because of the need to capture a different mix of metallic ores. Thus, there would be a net indirect change in resources used in other sectors than metal cans that would be attributable to this anti-corrosion activity.

One way of tracing sectoral attributions of corrosion costs would be by cell-by-cell analyses of the matrices which comprise the I/O Model. However this is a rather unwieldy and involved procedure that requires a great deal of technical expertise on the part of the analyst to trace aspects of costs in detail. A more direct approach was made possible by the development of ''Industry Indicators''. These indicators provide a relative measure of the impact of corrosion on specific sectors of the economy.

5.2.1 Industry Indicators and Examples of Their Use

There are eight different Industry Indicators for each sector, four measuring total cost of corrosion and four measuring avoidable cost of corrosion. In each of these groups, two measure direct costs attributable to the sector and two measure the sum of direct plus indirect costs attributable to corrosion. Costs are expressed first on a cost per unit basis (i.e., cents worth of corrosion cost per dollar of output value) and second on a total dollar cost of corrosion basis (i.e., cost per unit multiplied by total value of output in World I).

The eight industry indicators are

(1) Total Direct per Unit Cost

(2) Total Direct Aggregate Cost

(3) Total Direct/Indirect per Unit Cost

(4) Total Direct/Indirect Aggregate Cost

(5) Avoidable Direct per Unit Cost

(6) Avoidable Direct Aggregate Cost

(7) Avoidable Direct/Indirect per Unit Cost

(8) Avoidable Direct/Indirect Aggregate Cost.

The terms used in these eight titles have the following meanings: ''Total'' indicates total costs of corrosion, avoidable and unavoidable, combined. ''Avoidable'' indicates only those costs which are amenable to savings by the adoption of current best anti-corrosion practices. ''Direct/Indirect'' indicates the summation of (a) the direct costs of the sector, (b) the indirect (or supporting) costs borne by other sectors, and (c) the interactive effects on the sector's output of changes made in its own and other sector's activities. ''Per Unit'' indicates average costs per dollar's worth of sector output. ''Aggregate'' indicates the total costs for the entirety of sector output.

Each of the indicators has relevance and best choice for comparison is determined by the issue being analyzed. For instance, a sector could have high per unit costs of corrosion, but, because its value of output was very low, account for a small aggregate cost of corrosion.

The Industry Indicators for all 130 industrial sectors are presented in Table 10. Five examples of uses of indicators are discribed below.

Example 1: From column 1 of the table it can be determined that Sector 8C07—Miscellaneous Fabricated Metal Products and Sector 19.03—New Construction, Public Utility have the highest total direct costs of corrosion per unit. For both these sectors costs of corrosion are more than 8 cents on each dollar of output. However, from column 5, Sector 8C07 has avoidable direct cost per unit of only 0.05 cents per dollar of output, while Sector 19.03 has avoidable costs of 1.24 cents per dollar of output. In other words, universal application of best corrosion practice would have only small impact on the fabricated metal products sector and would do little to further reduce the corrosion costs associated with its activity. The public utility construction sector, however, would be significantly affected and corrosion costs associated with its activity would be reduced by a substantial amount.

TABLE 10. INDUSTRY INDICATORS OF COST OF CORROSION

	TOTAL COSTS OF CORROSION (WORLD I MINUS WORLD II)				REDUCIBLE COSTS OF CORROSION (WORLD I MINUS WORLD III)			
	DIRECT		DIRECT AND INDIRECT		DIRECT		DIRECT AND INDIRECT	
	PER UNIT ($)	TOTAL (Mil $)	PER UNIT ($)	TOTAL (Mil $)	PER UNIT ($)	TOTAL (Mil $)	PER UNIT ($)	TOTAL (Mil $)
1.01 LIVESTK+LIVESTK PROD	0.0258	1086.10	0.0644	2710.74	0.0159	671.35	0.0347	146 .26
1.02 FIELD + ORCHARD CROP	0.0215	1377.67	0.0523	3349.98	0.013	833.85	0.0276	1771.53
1.03 FORESTRY + FISHERY P	0.0191	96.79	0.0448	226.28	0.0103	52.	0.02.3	1 .51
1.04 AGRI. FORST + FISH S	0.0290	141.48	0.0739	360.59	0.0125	61.13	0.0239	116.62
2.01 IRON + FERROALLOY O	0.0334	164.80	0.0762	376.71	0.0159	78.72	0.0315	155.84
2.02 COPPER ORES	0.0566	84.66	0.1251	187.09	0.0237	35.45	0.0478	71.45
2. 3 NONFERROUS ORES, EXP	0.0361	78.15	0.0812	175.87	0.0186	4 .36	0.0378	81.82
2A04 UNDERGROUND COAL MIN	0.0284	177.43	0.0662	413.78	0.0121	75.54	0.0245	153. 3
2B04 STRIP COAL MINING	0.0151	89.58	0.0433	256.18	0.0062	36.75	0.0134	79.43
2C.4 OTHER COAL MINING	0.0184	4.36	0.0477	11.28	0.0098	2.31	0.020	4.73
2A05 CRUDE PETROLEUM	0.0142	329.60	0.0272	630.74	0.0 4	92.43	0.0068	158.19
2B05 NATURAL GAS	0.0151	93.21	0.0301	185.12	0.0041	25.21	0.0071	43.65
2.06 STONE + CLAY MINING	0.0186	103. 1	0.0502	277.77	0.0079	43.54	0.016	88.81
2.07 CHEM + FERTLZR MINER	0.0195	34.24	0.0416	72.94	0.0072	12.69	0.0138	24.33
3X01 FOOD+KINDRD PROD, TOB	0.0037	701.58	0.0191	3619.69	0.002	374.82	0.0052	98 .
3.03 LETHR TAN+IND LETHR	0.0028	8.20	0.0158	46.25	0.00 3	.96	0.002	5.80
3X04 MISC.LEATH+FAB TEXT	0.0011	79.29	0.0104	734.37	0.0 04	31.21	0.0019	135.
3.05 FABRICS, YARNS + THR	0.0017	41.80	0.0165	415.76	0.0009	21.81	0.003	75.96
3.07 TIRE CORD+MISC TEXT	0.0009	3.39	0.0141	60.23	0. 5	2. 5	0.0024	1 .41
4X01 LUMBER MILL, PLYWD, WD	0.0043	59.38	0.0184	255.01	0.0021	29.24	0.0056	77.94
4.03 LMBR+WOOD PRD EX CON	0.0040	42.96	0.0195	210.25	0.0021	23.05	0.0056	6 .59
4X05 FURNITURE+FIXTURES	0.0400	622.90	0.0858	1335.08	0.0 6	8.04	0.0027	41.81
4.07 PULP+PAPR PRD EX CON	0.0181	561.47	0.0440	1369.06	0.0033	102.35	0.0073	227.5
4.08 PAPERBRD CONTAINERS+	0.0015	17.11	0.0236	274.23	0.0008	8.96	0.0037	43. 2
5.01 PETROL REFNS + RELTD	0.0165	1 53.87	0.0382	2440.12	0. 13	8 .79	0. 33	2 7.67
5. 2 PAVING MIX+ASPHALT P	0.0048	23.09	0.0236	113.71	0.0028	13.46	0.0 59	28.53
5.03 INDUSTRL INORG+ORG C	0.0216	691.70	0.0432	1382.38	0.0028	90.73	0.0058	184.87
5.04 FERTILIZERS	0.0072	28.88	0.0211	84.66	0. .8	3.74	0. 25	1 .15
5.05 AGRI CHEM EX FERTLZR	0.0071	10.16	0.0212	30.32	0.001	1.43	0.0026	3.69
5.06 MISC CHEM PRD	0.0212	127. 1	0.0477	285.42	0.0 38	22.77	0.0079	47.51
5X07 PLAS.MATLS+ORG.MANMA	0.0067	96.14	0.0342	493.48	0.0 36	52.35	0.0 68	97.4
5.09 DRUGS	0.0056	58.77	0.0166	173.92	0.0021	21.74	0.0043	45.23
5X10 CLEANING+TOILET PREP	0.0093	123. 1	0.0281	370.07	0.0 14	17.92	0.0 35	46.22
5A12 PAINTS+ALLIED PRD, CO	0.0214	40.98	0.039	74.80	0.0 33	6.37	0.0073	13.9
5B12 PAINTS+ALLIED PRD, NC	0.0206	75.33	0.0347	126.80	0.0 31	11.25	0.0066	24.30
5.13 TIRES + INNERTUBES	0.0023	15.35	0.0147	97.45	0.0005	3.23	0.002	13.38
5.14 OTHR RUBBER PRD	0.0036	23. 3	0.0186	120.10	0.0011	6.77	0.003	19.38
5.15 MANUFAC PLASTICS PRD	0.0 31	33.33	0.0162	179.93	0. .14	15.05	0.0033	36.78
6.01 GLASS + GLASS PRD	0.0052	33.23	0.0219	139.90	0.0011	7.30	0.0034	21.45
6.02 CEMENT+LIME+GYPSUM P	0.0030	9.52	0.020	63.80	0.0 15	5.15	0.005	15.83
6.03 CLAY+CEMENT PRD+REFR	0.0 71	92.64	0.0318	415.73	0. 34	44.29	0.0079	103.29
6.04 OTHR NONMET MINERAL	0.0045	23. 2	0.0216	108.95	0.0 18	9.18	0.0 45	22.69
7A01 MILD STEEL-CARBON ST	0.0223	916.56	0.0469	1923.58	0.0 18	73.57	0.0 52	212.37
7B01 LOW ALLOY STEEL	0.0213	23.57	0.0701	54.45	0. 19	3.40	0.0048	8.75

TABLE 10. (Continued)

	TOTAL COSTS OF CORROSION (WORLD I MINUS WORLD II)				REDUCIBLE COSTS OF CORROSION (WORLD I MINUS WORLD III)			
	DIRECT		DIRECT AND INDIRECT		DIRECT		DIRECT AND INDIRECT	
	PER UNIT ($)	TOTAL (Mil $)	PER UNIT ($)	TOTAL (Mil $)	PER UNIT ($)	TOTAL (Mil $)	PER UNIT ($)	TOTAL (Mil $)
7C01 ALLOY STEEL	0.0120	53.70	0.0275	123.70	0.0019	8.31	0.0047	21.28
7D01 STAINLESS STEEL	0.0262	51.13	0.0274	69.24	0.0020	5.01	0.0041	1 .37
7E01 COKE	0.0091	55.75	0.0355	218.16	0.0018	11.05	0.0075	46.07
7.02 PRIMARY COPPER	0.0152	191.38	0.0509	639.38	0.0006	7.88	0.0049	62.13
7.03 PRIMARY ALUMINUM	0.0103	101.13	0.0323	317.92	0.0014	13.56	0.0039	38.53
7A04 NI, NI ALLOYS. CO	0.0052	21.50	0.0144	50.00	0.0004	1.27	0.0021	6.99
7B04 ZINC	0.0026	2.27	0.0109	9.61	0.0007	0.61	0.0023	2.01
7C04 MAGNESIUM	0.0048	4.92	0.0180	18.67	0.0005	0.53	0.0020	2.06
7D04 LEAD	0.0020	2.75	0.0153	21.12	0.0006	0.86	0.0032	4.38
7E04 TI, TA, ZR	0.0047	8.20	0.0219	38.13	0.0009	1.58	0.0034	5.93
7F04 AU, AG, PT, PD	0.0095	22.56	0.0360	85.38	0.0008	1.82	0.0029	6.81
7G04 ALL OTHERS	0.0033	4.31	0.0171	22.52	0.0007	0.93	0.0028	3.73
8.01 METAL CANS	0.0415	194.44	0.1036	485.07	0.0033	1.62	0.002[illegible]	9.45
8.02 METAL BARRELS,DRUM+P	0.0559	43.03	0.1284	98.88	0.0003	0.20	0.002[illegible]	1.54
8.03 MET SANIT+PLUMBING P	0.0701	83.16	0.1961	232.68	0.0003	0.34	0.0019	2.25
8.04 NONELEC HEATING EQUI	0.0477	113.84	0.1213	289.84	0.0014	3.27	0.0039	9.22
8.05 FAB STRUCTURAL METAL	0.0568	1153.10	0.1314	2668.79	0.0005	9.24	0.002[illegible]	41.02
8.06 SCREW MACH PRO+STAMP	0.0721	855.60	0.1714	2032.98	0.0004	4.18	0.0018	21.50
8A07 COATNG+PLATNG, COR	0.0619	281.44	0.0782	355.70	0.0033	14.91	0.0069	31.14
8B07 COATNG+PLATNG.NCOR	0.0383	150.40	0.0841	324.81	0.0034	13.16	0.007[illegible]	27.22
8C07 MISC.FABR.METAL PROD	0.0738	683.37	0.182	1684.15	0.00[illegible]5	4.23	0.002[illegible]	18.38
9.01 ENGINES + TURBINES	0.0227	178.15	0.0656	515.40	0.0007	5.66	0.0022	17.15
9.02 GEN INDUS MACH+EQUIP	0.0430	784.23	0.1127	2056.50	0.0014	25.38	0.0035	63.12
9.03 MACHINE SHOP PRD	0.0059	32.12	0.0205	112.31	0.00[illegible]8	4.13	0.0021	11.28
10.01 FARM MACHINERY	0.0160	109.59	0.0607	416.28	0.0004	2.57	0.002	13.96
10.02 CONSTRUCTION MACHINE	0.0292	192.64	0.0819	539.63	0.0003	2.30	0.0018	12.[illegible]9
10.03 MINING MACHINERY	0.0412	31.34	0.1003	77.69	0.0003	[illegible].27	0.0018	1.39
10.04 OIL FIELD MACHINERY	0.0278	18.66	0.0689	46.18	0.0004	[illegible].24	0.0014	[illegible].93
10.05 MTRL-HNDLNG MACH EX	0.0181	130.42	0.0561	405.14	0.0003	2.21	0.0014	10.12
10.06 INDUST TRUCKS + TRAC	0.0147	19.50	0.0551	72.98	0.0004	[illegible].52	0.0021	2.78
10.07 METAL WORKING MACHIN	0.0137	171.20	0.0431	536.82	0.0004	4.87	0.0015	18.15
10.08 SPECL INDSTRY MACHIN	0.0467	586.[illegible]4	0.1061	1329.97	0.0004	4.43	0.0015	18.74
11A01 AUTOMOBILES	0.0221	2206.38	0.0885	8819.28	0.001[illegible]	98.29	0.0033	325.56
11B01 TRUCKS,BUSES,ETC.	0.0175	576.59	0.0582	1913.13	0.0009	30.77	0.0026	85.96
11.02 AIRCRAFT + PARTS	0.0080	336.94	0.0357	1501.85	0.0003	13.64	0.0014	58.05
11.03 SHIP+BOAT BLDG + REP	0.0213	125.08	0.0672	394.11	0.0006	3.45	0.0022	12.84
11.04 LOCOMTVS+RAIL+ST CAR	0.0340	149.25	0.0977	423.57	0.0014	6.26	0.0043	18.89
11.05 CYCLES,TRAILERS, ETC	0.0262	89.00	0.0756	256.30	0.0009	3.20	0.0028	9.36
12.01 ELEC MEASURING INSTR	0.0067	33.05	0.0311	153.56	0.0005	2.42	0.001[illegible]	7.68
12.02 ELEC MOTORS + GENERA	0.0142	63.56	0.0452	202.80	0.00[illegible]3	1.20	0.0016	7.12
12.03 INDUSTRL CONTROLS,ET	0.0108	100.60	0.0353	329.74	0.0003	2.68	0.0015	13.92
12X04 ELEC.LAMPS+FIXTURES	0.0173	125.21	0.0537	384.85	0.0003	1.94	0.0017	12.1[illegible]
12.06 ELECTRNC COMPNTS+ACC	0.0341	341.76	0.0871	872.96	0.00[illegible]4	4.41	0.002[illegible]	21.86
12.07 MISC ELECTRICAL MACH	0.0037	20.35	0.0253	142.82	0.0003	1.79	0.0017	9.71

TABLE 10. (Continued)

	TOTAL COSTS OF CORROSION (WORLD I MINUS WORLD II)				REDUCIBLE COSTS OF CORROSION (WORLD I MINUS WORLD III)			
	DIRECT		DIRECT AND INDIRECT		DIRECT		DIRECT AND INDIRECT	
	PER UNIT ($)	TOTAL (Mil $)	PER UNIT ($)	TOTAL (Mil $)	PER UNIT ($)	TOTAL (Mil $)	PER UNIT ($)	TOTAL (Mil $)
13.01 SERVC INDUSTRY MACHI	0.0234	182.94	0.0752	587.71	0.0010	7.90	0.0035	27.74
13.02 HOUSEHOLD APPLIANCES	0.2565	463.73	0.1307	1073.55	0.0005	4.28	0.0025	20.91
13.03 RADIO,TV+COMMUN EQUI	0.0394	294.19	0.0381	1188.42	0.0003	9.94	0.0014	44.18
14.01 SCIENTIFIC INSTRMNTS	0.0255	176.70	0.0735	508.55	0.0003	2.05	0.0018	12.4[illegible]
14.02 MED,SURGCL,DENTAL IN	0.0073	14.19	0.0269	52.33	0.0001	0.24	0.0013	2.57
14.03 WATCHES,CLOCKS + PAR	0.0083	7.62	0.0259	23.69	0.0001	0.12	0.0011	.93
14.04 OPTICAL+OPTHALMIC GO	0.0016	2.23	0.0148	20.99	0.0001	0.14	0.0010	1.46
14.05 PHOTO EQUIP + SUPPLI	0.0088	49.14	0.0295	165.45	0.0002	1.16	0.0013	7.21
15.01 COMPUTING+RELAT MACH	0.0083	92.29	0.0419	465.40	0.0004	4.07	0.0015	16.92
15.02 OTHR OFFICE+BUSIN MA	0.0299	142.93	0.0531	253.57	0.0005	2.19	0.0016	7.57
15.03 OFFICE SUPPLIES	.0000	.00	0.0246	173.16	.0000	.0	0.0022	15.39
16.01 ORDNANCE + ACCESSORI	0.0171	307.75	0.0438	790.11	0.0014	24.55	0.0031	54.33
16.02 OTHR MISC PRD	0.0196	348.15	0.0549	974.30	0.0004	7.23	0.0018	32.23
17.01 RAILROADS+RELATD SER	0.0282	576.31	0.0824	1685.38	0.0111	226.86	0.0224	457.85
17.02 LOCAL+HIGHWAY PASSNG	0.0310	540.39	0.0763	1328.57	0.0162	282.00	0.0370	643.66
17.03 MOTOR FREIGHT+WAREHO	0.0300	808.18	0.0764	2056.18	0.0118	318.48	0.0270	725.89
17.04 WATER TRANSPORTATION	0.0352	266.19	0.0851	644.13	0.0125	94.39	0.0233	176.55
17.05 AIR TRANSPORT	0.0352	380.18	0.0874	942.85	0.0054	58.24	0.0129	139.74
17.06 PIPE LINES	0.0429	59.50	0.1142	158.24	0.0127	17.63	0.0264	36.56
17.07 TRANSPORTATION SERVI	0.0160	18.56	0.0407	47.37	0.0078	9.09	0.0179	2[illegible].84
18.01 TELECOMMUNICATION	0.0133	447.00	0.0600	2011.79	0.0014	45.59	0.0037	123.21
18.02 ELECTRIC POWER	0.1008	4106.11	0.1130	4603.12	0.0003	120.30	0.0066	267.41
18.03 GAS	0.0084	251.00	0.0392	1176.08	0.0017	50.53	0.0046	138.30
18.04 WATER + SANITARY SER	0.0492	411.14	0.1009	843.06	0.0119	99.30	0.0221	184.01
19.01 NEW CONST,NONFARM RE	0.0111	571.22	0.0452	2743.51	0.0051	308.76	0.0125	760.79
19.02 NEW CONST,NONRESID B	0.0139	796.04	0.0610	3502.67	0.0036	206.26	0.0086	496.63
19.03 NEW CONST,PUBLIC UTI	0.0779	1976.62	0.2208	5606.32	0.0124	315.38	0.0271	688.47
19.04 NEW CONST,HIGHWAY+OT	0.0255	652.50	0.0756	1935.22	0.0131	335.12	0.0285	728.91
19A05 MAINT+REPR CONST,COR	0.0483	269.50	0.1168	652.40	0.0059	32.98	0.0135	75.22
19B05 MAINT+REPR CONST.NCO	0.0139	846.88	0.0457	2784.85	0.0059	358.50	0.0134	815.02
20.01 WHOLESALE+RETAIL TRA	0.0211	5441.38	0.0567	14620.20	0.0126	3251.67	0.0289	7438.91
20X02 FINANC,INS,REAL E,AG	0.0051	1257.47	0.0165	4061.97	0.0027	668.64	0.0065	1604.33
20.05 OTHR BUS+PROF SERVIC	0.0122	702.69	0.0340	1960.60	0.0056	322.82	0.0136	781.48
20.06 BUS TRAVEL,ENTER+GIF	.0000	.00	0.0199	381.36	.0000	.00	0.0035	67.63
21.01 PRINTING + PUBLISHIN	0.0017	40.40	0.0143	347.47	0.0009	21.61	0.0028	68.48
21.02 RADIO + TV BROADCAST	0.0076	1.10	0.0237	3.43	0.0015	.21	0.0039	.56
21.03 HOTELS + LODGING PLA	0.0275	415.49	0.0703	1063.65	0.0133	201.46	0.0292	441.52
21.04 PERSNL+REPAR SERV,EX	0.0226	831.18	0.0646	2375.85	0.0111	408.50	0.0252	928.48
21.05 AUTOMOBILE REPAIR+SE	0.0413	826.10	0.1102	2202.42	0.0141	281.34	0.0317	634.47
21.06 AMUSEMENTS	0.0133	49.08	0.0171	252.40	0.0016	24.21	0.0046	68. 1
21.07 MEDICAL + HEALTH SER	0.0045	199.89	0.0186	816.76	0.0024	105.69	0.0056	248.25
21.08 EDUCAT SERVC+NONPROF	0.0030	184.27	0.0153	943.43	0.0016	100.56	0.0041	248.37
22.01 POST OFFICE	0.0147	157.81	0.0435	465.81	0.0087	85.75	0.0187	199.84
TOTAL		45266.33		126019.49		11895.04		27717.99

Example 2: A similar analysis can be made based on indicators in column 2 of Table 10. Sector 20.01–Wholesale and Retail Trade and Sector 18.02–Electric Power have the largest total amounts of direct corrosion cost, $5.4 Billion and $4.1 Billion, respectively. Referring again to column 5, and comparing these values with column 1, we find that Sector 18.02 has avoidable unit costs of 0.3 cents per dollar of output (approximately 1/30th of total direct corrosion costs per unit) and Sector 20.01 has reducible unit costs of 1.3 cents per dollar of output (approximately 1/2 the total direct corrosion costs per unit). From column 6, avoidable costs for the trade sector are greater than $3 Billion, while avoidable costs for the Electric Power Sector are only $120 Million.

Example 3: A third type of analysis involves sector decisions concerning R&D activity versus adoption of best practices as a means of reducing corrosion costs. Using columns 1 and 5, we find that Sector 8C07–Miscellaneous Fabricated Metal Products which was used in Example 1, can also be viewed in a somewhat different context. Nearly all the direct corrosion costs per unit (7.4 cents per dollar of output) are unavoidable costs and require technological advance for savings to be realized; moreover, potential savings are great.

In contrast, Sector 6.02, Cement, Lime, and Gypsum Products, would be affected to a minor degree only by any anti-corrosion activity. Its total direct costs per unit are shown to be 0.7 cents per dollar of output; half of this is reducible by adoption of best practices; and half could be reduced only by technological advance.

Example 4: In order to suggest industrial priorities for the allocation of anti-corrosion resources, sectors can be arrayed in terms of their proportionate contributions to total unavoidable aggregate direct/indirect costs (column 4 minus column 8). This can be done by establishing sector-to-total economy ratios. For instance:

$$\text{Sector 11A01/Total Economy} = \frac{8819.28 - 325.56}{126019.49 - 27727.99}$$

$$= 8493.72/98301.50$$

$$= .0864$$

Similarly

$$\text{Sector 20.01/Total Economy} = \frac{14620.20 - 7438.91}{98301.50}$$

$$= 7181.29/98301.50$$

$$= .0731$$

Therefore, while Sector 20.01-Wholesale and Retail Trade had greater total costs of corrosion than Sector 11.01-Automobiles, its unavoidable costs are lower.

Example 5: Another allocation criterion can be based on unavoidable costs that are directly related to each sector. First, differences between columns 1 and 5 are taken:

Sector 11A01: .0221 - .0010 = .0211

Sector 20.01: .0211 - .0126 = .0085.

Secondly, these values are expressed as ratios to the corresponding per unit averages for the total economy (Σ column 2/World I total output less Σ column 6/World I total output):

Total Economy = .0162 - .0043 = .0119

Making this conversion, we obtain

Sector 11A01 = .0211/.0119 = 1.773

Sector 20.01 = .0085/.0119 = .7143.

Thirdly, the allocation measure is adjusted by multiplying these values by the corresponding values in Example 4. The normalized allocation parameters then become:

Sector 11A01 = .0864 x 1.77 = .1529

Sector 20.01 = .0731 x .714 = .0522.

These parameters can be calculated for every sector and normalized to sum to unity. Whatever values the normalized ratios might have, by this criterion Sector 11A01 would be viewed as being three times as effective as Sector 20.01 trade in ability to utilize anti-corrosion resources.

While the parameters presented above provide guidance as to priorities, other factors such as potential returns and pay-back periods enter into analyses of this sort. Detailed analysis of the source of costs and their impact is necessary in addition to analysis of the parameters.

5.2.2 Analysis of Industry Indicators

A better appreciation of the industry indicators can be gained through analysis of the components from which they are constructed. An industry indicator is a relative measure of the requirements attributed to corrosion for the industry to produce $1 of its product per year.

Four components of the indicators are presented in Figure 3. First, there are corrosion effects on inputs required to make a product. These effects are reflected in changes to coefficients in the flow matrix and include costs of coatings and platings, corrosion inhibitors, maintenance and repair, corrosion resistant metals, and cathodic protection. Secondly, replacement of capital stock in the industry is affected by corrosion through changes in replacement lives of equipment and through changes in capital requirements because of excess capacity or redundant equipment. Thirdly, capital stock for growth is affected by corrosion through changes in replacement lives. Fourthly, value added activity of the industry is affected by corrosion through changes of inputs (e.g., research and development and technical services) and changes in depreciation of capital. The sum of the four components, calculated from input/output model data, is the Industry Indicator.

Industry Indicators provide a relative ranking of industries. Alternative criteria for ranking include:

> To what industries are greatest *direct cost of corrosion as percent of sales* attributed?
>
> To what industries are greatest *direct dollar costs of corrosion* attributed?
>
> What portion of costs attributed to an industry are *avoidable?* and what portion are *unavoidable*?
>
> What *percent of all avoidable costs* are attributed to each industry?
>
> What *unavoidable costs* are attributed to each industry?

Sectors with the highest Industry Indicators for total cost of corrosion are presented in Table 11. Sectors with the highest Industry Indicators for avoidable costs are listed in Table 12.

Industries to which highest total costs of corrosion are attributed based on percent sales include copper ore mining, manufacturing industries, public utilities, and public utilities construction. For highest total cost on a dollar basis, industries with large total sales appear on the list: Wholesale and Retail Trade, Automobile Manufacturers, Livestock, and Petroleum Refining.

The list of sectors with highest industry indicators for avoidable costs changes considerably from that for total costs. Based on percent of sales; Livestock and Agriculture, Mining, Transportation, Construction, and Trade and Business Services are attributed the highest costs. On a dollar basis, the list remains the same except mining industries no longer appear and the Food Industry and Pulp and Paper Industry are added. No major differences are observed on comparing lists for direct avoidable costs with that for direct and indirect avoidable costs.

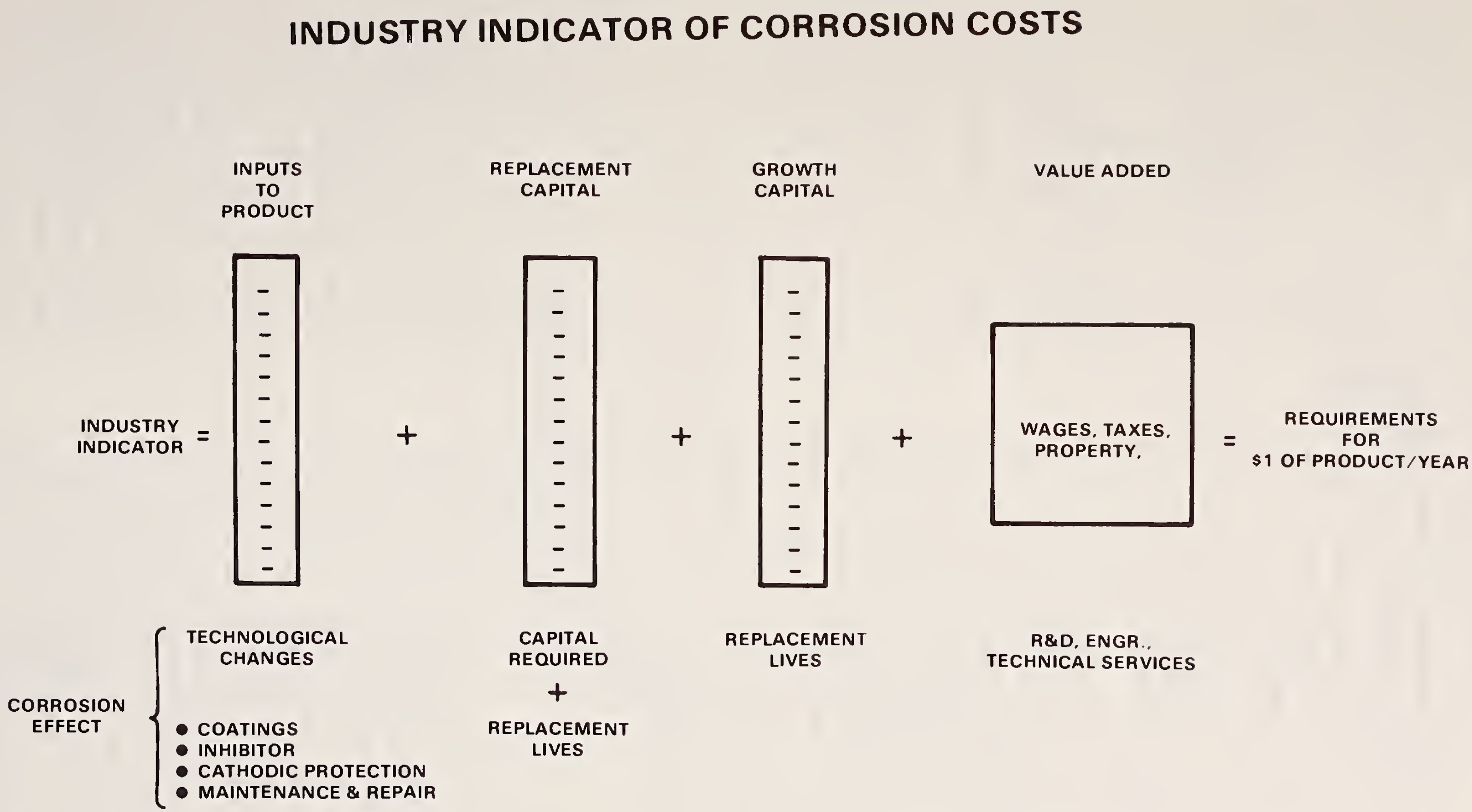

FIGURE 3. COMPONENTS OF INDUSTRY INDICATORS FOR CORROSION COSTS

TABLE 11. SECTORS WITH HIGHEST INDUSTRY INDICATORS FOR TOTAL COST*

Sector		% Sales	Sector		$M
Direct Costs					
2.02	Copper Ores	5.6	1.01	Livestock + Livestk Prod	1100
4X05	Furniture + Fixtures	4	1.02	Field + Orchard Crop	1400
8.01	Metal Cans	4	5.01	Petrol Refng + Reltd	1100
8.02	Metal Barrels, Drum + P	5.5	7A01	Mild Steel-Carbon St	900
8.03	Met Sanit + Plumbing P	7	8.05	Fab Structural Metal	1200
8.04	Non Electric Heating Equipment	4.7	11A01	Automobiles	2200
8.05	Fab Structural Metal	5.7	18.02	Electric Power	4100
8.06	Screw Mach Prd + Stamp	7.2	19.03	New Const, Public Uti	2000
8A07	Coating + Plating, Cor	6.1	20.01	Wholesale + Retail Tra	5400
8C07	Miscellaneous, Fabr. Metal Prod	7.4	20X02	Financ, Ins, Real E, Ad	1300
9.02	General Indus Mach + Equipment	4.3			
10.03	Mining Machinery	4			
10.08	Special Industry Machin	4.1			
13.02	Household Appliances	5.7			
17.06	Pipe Lines	4.3			
18.02	Electric Power	10			
18.04	Water + Sanitary Ser	4.9			
19.03	New Const, Public Uti	7.8			
19A05	Main + Repr Const, Cor	4.8			
21.05	Automobile Repair + Se	4.1			
Direct + Indirect Costs					
2.02	Copper Ores	12	1.01	Livestk + Livestk Prod	2700
8.01	Metal Cans	10	1.02	Field + Orchard Crop	3300
8.02	Metal Barrels, Drum + P	13	3X01	Food + Kindrd Prod, Tob	3600
8.03	Met Sanit + Plumbing P	20	5.01	Petrol Refng + Reltd	2400
8.04	NonElec Heating Equi	12	8.05	Fab Structural Metal	2600
8.05	Fab Structural Metal	13	8.06	Screw Mach Prd + Stamp	2000
8.06	Screw Mach Prd + Stamp	17	9.02	Gen Indus Mach + Equip	2100
8C07	Misc. Fabr. Metal Prod	18	11A01	Automobiles	8800
9.02	Gen Indus Mach + Equip	11	17.03	Motor Freight + Wareho	2000
10.03	Mining Machinery	10	18.01	Telecommunication	2000
10.08	Specl Indstry Machin	11	19.01	New Const, NonFarm Re	2700
13.02	Household Applicances	13	19.02	New Const, NonResid B	3500
17.06	Pipe Lines	11	19.03	New Const, Public Uti	5600
18.02	Electric Power	11	19B05	Maint + Repr Const, NCO	2700
18.04	Water + Sanitary Ser	10	20.01	Wholesale + Retail Tra	14600
19.03	New Const, Public Uti	22	20X02	Financ, Ins, Real E, Ad	4000
19A05	Maint + Repr Const, Cor	12	21.04	Persnl + Repar Serv, Ex	2400
21.05	Automobile Repair + Se	11	21.05	Automobile Repair + Se	2200

* Relative costs attributed to industrial sectors

TABLE 12. SECTORS WITH HIGHEST INDUSTRY INDICATORS FOR AVOIDABLE COSTS*

Sector		% Sales	Sector		$M
		Direct Costs			
1.01	Livestk + Livestk Prod	1.6	1.01	Livestk + Livestk Prod	700
1.02	Field + Orchard Crop	1.3	1.02	Field + Orchard Crop	800
1.03	Forestry + Fishery P	1.0	3X01	Food + Kindrd Prod, Tob	400
1.04	Agri, Forst + Fish S	1.3	4.07	Pulp + Papr Prd Ex Con	100
2.01	Iron + Ferroalloys O	1.6	17.01	Railroads + Relatd Ser	200
2.02	Copper Ores	2.4	17.02	Local + Highway Passng	300
2A04	Underground Coal Min	1.9	17.03	Motor Freight + Wareho	300
2B04	Strip Coal Mining	1.2	18.02	Electric Power	100
17.01	Railroads + Relatd Ser	1.1	19.01	New Const, NonFarm Re	300
17.02	Local + Highway Passng	1.6	19.02	New Const, NonResid B	200
17.05	Air Transport	1.2	19.03	New Const, Public Uti	300
17.04	Water Transportation	1.3	19.04	New Const, Highway + OT	300
17.06	Pipe Lines	1.3	19B05	Maint + Repr Const, NCO	400
18.04	Water + Sanitary Ser	1.2	20.01	Wholesale + Retail Tra	3300
19.03	New Const, Public Uti	1.2	20X02	Financ, Ins, Real E, Ad	700
19.04	New Const, Highway + OT	1.3	21.05	Automobile Repair + Se	300
20.01	Wholesale + Retail Tra	1.3	20.05	Othr Bus + Prof Servic	300
21.04	Persnl + Repar Serv, Ex	1.1	21.04	Persnl + Repar Serv, Ex	400
21.05	Automobile Repair + Se	1.3	21.03	Hotels + Lodging Pla	200
			21.07	Medical + Health Ser	100
			21.08	Educat Servc + NonProf	100
		Direct + Indirect Costs			
1.01	Livestk + Livestk Prod	3.5	1.01	Livestk + Livestk Prod	1500
1.02	Field + Orchard Crop	2.8	1.02	Field + Orchard Crop	1800
1.03	Forestry + Fishery P	2.0	3X01	Food + Kindrd Prod, Tob	1000
1.04	Agri, Forst + Fish S	2.4	4X01	Lumber Mill, Plywd, Wd	200
2.01	Iron + Ferroalloys O	3.2	5.01	Petrol Refng + Reltd	200
2.02	Copper Ores	4.8	7A01	Mild Steel-Carbon St	200
2.03	Nonferrous Ores, Exp	3.8	11A01	Automobiles	300
2A04	Underground Coal Min	2.5	17.01	Railroads + Relatd Ser	500
2C04	Other Coal Mining	2.0	17.02	Local + Highway Passng	600
17.01	Railroads + Relatd Ser	2.2	17.03	Motor Freight + Wareho	700
17.02	Local + Highway Passng	3.7	18.02	Electric Power	300
17.03	Motor Freight + Wareho	2.7	19.01	New Const, NonFarm Re	800
17.04	Water Transportation	2.3	19.02	New Const, NonResid B	500
17.06	Pipe Lines	2.6	19.03	New Const, Public Uti	700
18.04	Water + Sanitary Ser	2.2	19.04	New Const, Highway + OT	700
19.03	New Const, Public Uti	2.7	19B05	Maint + Repr Const, NCO	800
19.04	New Const, Highway + OT	2.9	20.01	Wholesale + Retail Tra	7000
20.01	Wholesale + Retail Tra	2.9	20X02	Financ, Ins, Real E, Ad	1600
21.03	Hotels + Lodging Pla	2.9	20.05	Othr Bus + Prof Servic	800
21.04	Persnl + Repar Serv, Ex	2.5	21.03	Hotels + Lodging Pla	400
21.05	Automobile Repair + Se	3.1	21.04	Persnl + Repar Serv, Ex	900
			21.05	Automobile Repair + Se	600
			21.07	Medical + Health Ser	200
			21.08	Educat Servc + NonProf	200

* Relative costs attributed to industrial sectors

By analyzing the input/output matrices and compilation of adjustments made for corrosion, the components of an Industry Indicator can be determined. This provides necessary information on the source of costs attributed to the industry. To illustrate the usefulness of this procedure, the components of Industry Indicators were calculated for five industries:

Sector 1.01—Livestock and Livestock Products

Sector 5.03—Industrial Chemicals

Sector 8.05—Fabricated Structural Products

Sector 19.03—Public Utility Construction

Sector 20.01—Wholesale and Retail Trade.

These industries provide a broad spectrum of activities, and illustrate that the major source of costs can vary significantly from industry to industry.

Breakdowns of each direct Industry Indicator into its components for the five sample sectors are shown schematically in Figures 4 through 8. Areas of the two circles are proportional to magnitudes of total costs and avoidable costs, respectively. The portion of each cost resulting from changes in requirements for (1) Inputs to the production process, (2) Replacement capital, (3) Growth capital, and (4) Value added are identified. In addition, sources of change from the analysis are identified, e.g., change in use of inhibitors, change in maintenance and repair requirements, and change in replacement life of capital equipment.

For Sector 1.01—Livestock and Livestock Products, Industry Indicators for Total Direct Costs and Avoidable Direct Costs were $1086 M and $671 M, respectively. As shown in Figure 4, the major contribution to Total and Avoidable Costs was from adjustment of replacement lives in the analysis. Average replacement lives for all capital in Sector 1.01 was 14 years in World I, 21 years in World II, and 18 years in World III. These changes in replacement lives resulted in a slight change in value added. A small portion, approximately 4 percent, of total direct costs resulted from input adjustments to account for corrosion related maintenance and repair.

For Sector 5.03—Industrial Chemicals, Industry Indicators for Total Direct Costs and Avoidable Direct Costs were $692 M and $91 M, respectively. A breakdown of these indicators is shown in Figure 5.

The largest contribution to total costs resulted from adjustments to inputs. Furthermore, adjustments for inhibitors and water treatment accounted for approximately 20 percent of this portion of costs with adjustments for maintenance and repair accounting for the remainder. Other contributions to direct costs were (1) Replacement capital resulting from changes in useful lives and an estimated 2 percent excess capacity for the industry, (2) Growth capital resulting from excess capacity, and (3) value added resulting from adjustments to technical service inputs and capital requirements.

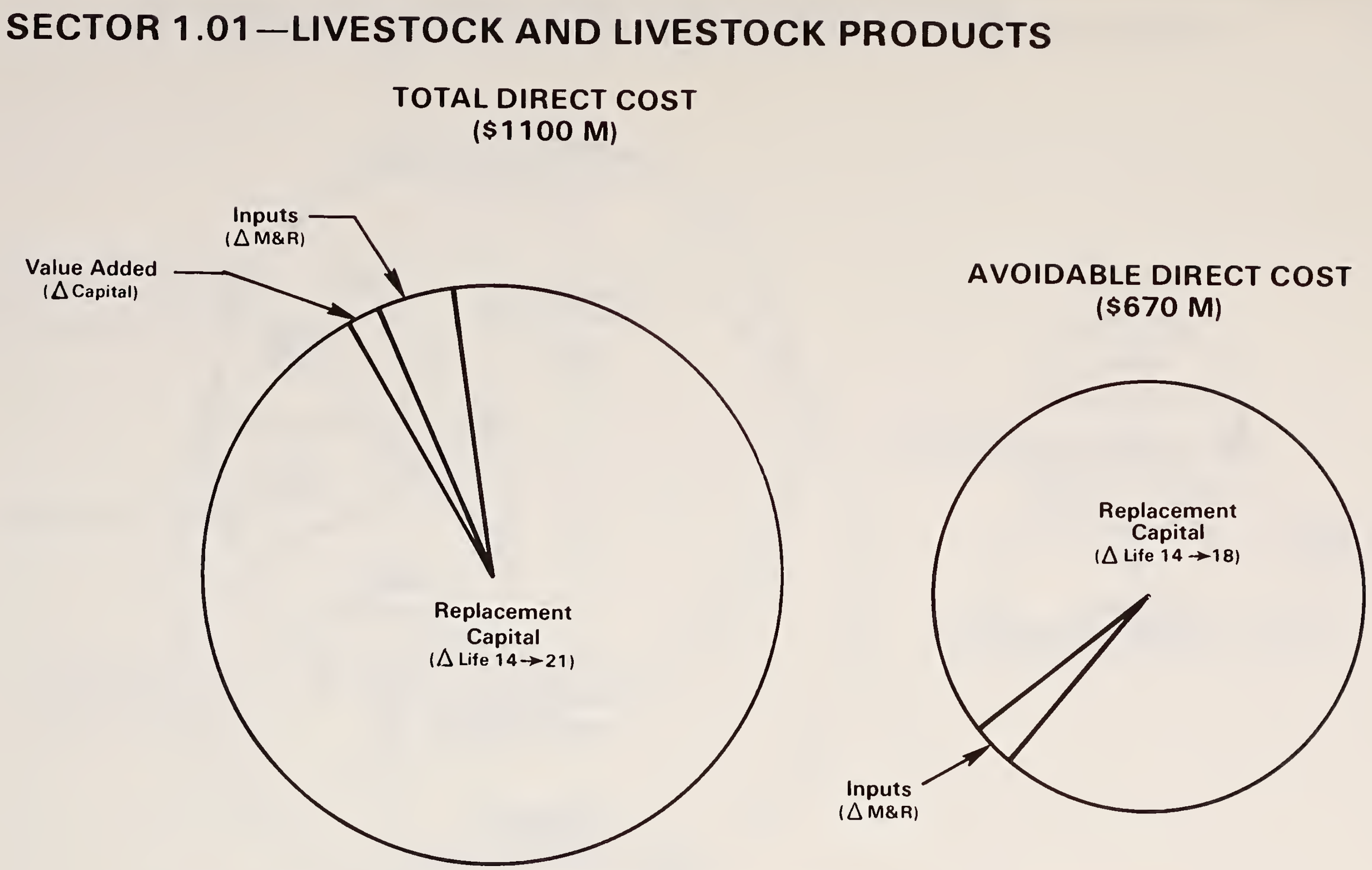

FIGURE 4. BREAKDOWN OF DIRECT INDUSTRY INDICATOR FOR SECTOR 1.01 - LIVESTOCK AND LIVESTOCK PRODUCTS

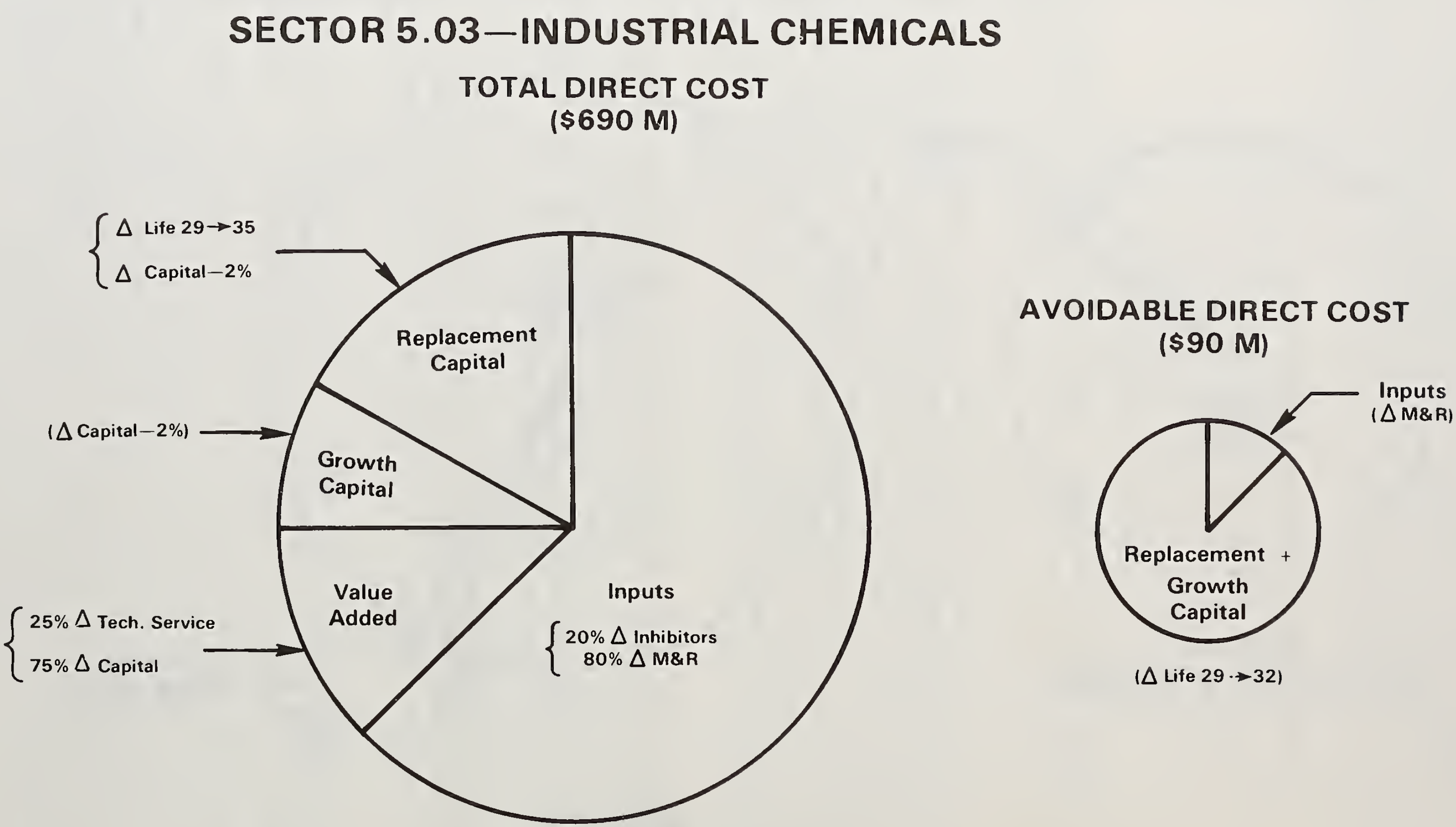

FIGURE 5. BREAKDOWN OF DIRECT INDUSTRY INDICATOR FOR SECTOR 5.3 - INDUSTRIAL CHEMICALS

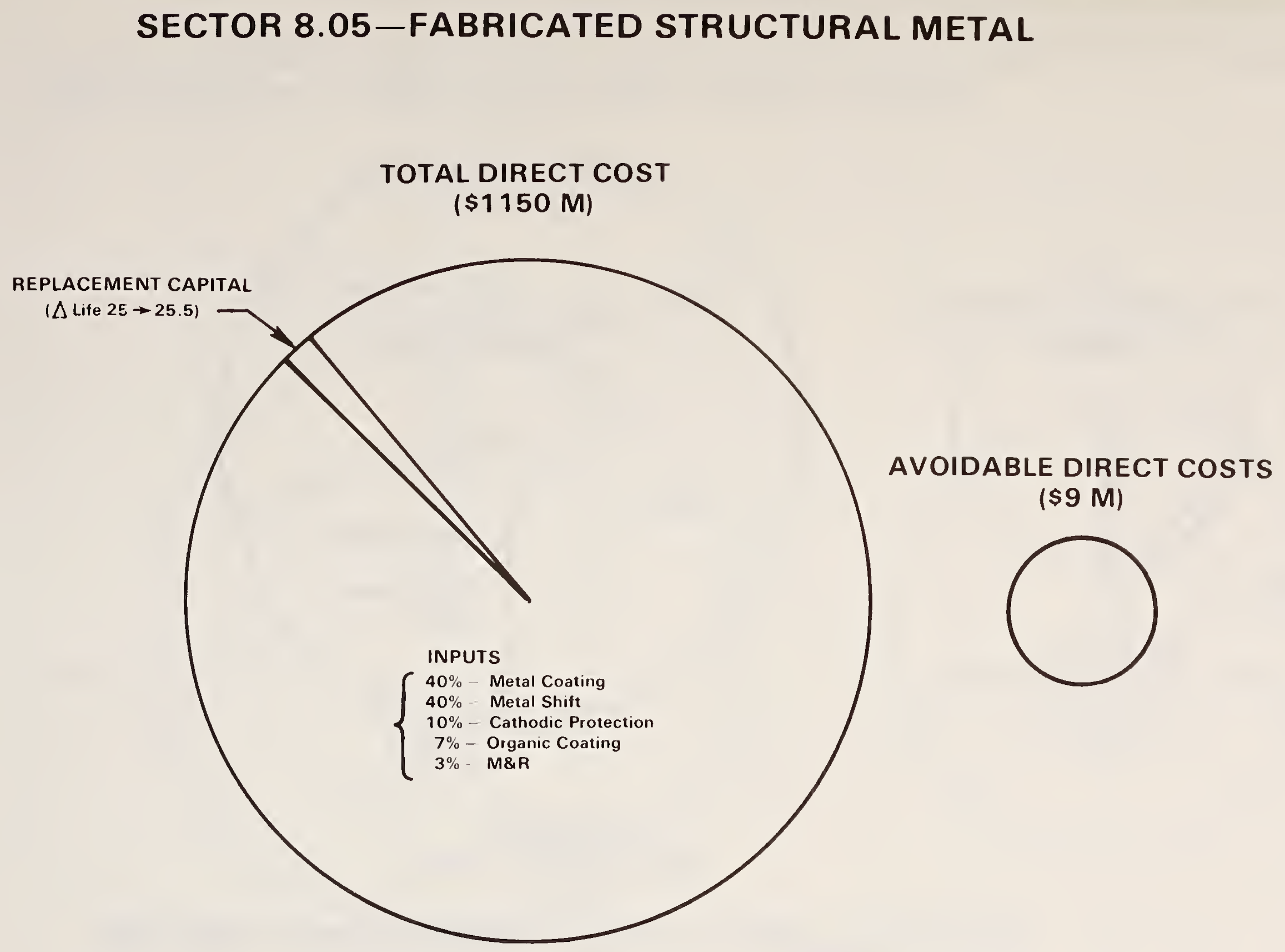

FIGURE 6. BREAKDOWN OF DIRECT INDUSTRY INDICATOR FOR SECTOR 8.05 - FABRICATED STRUCTURAL METAL

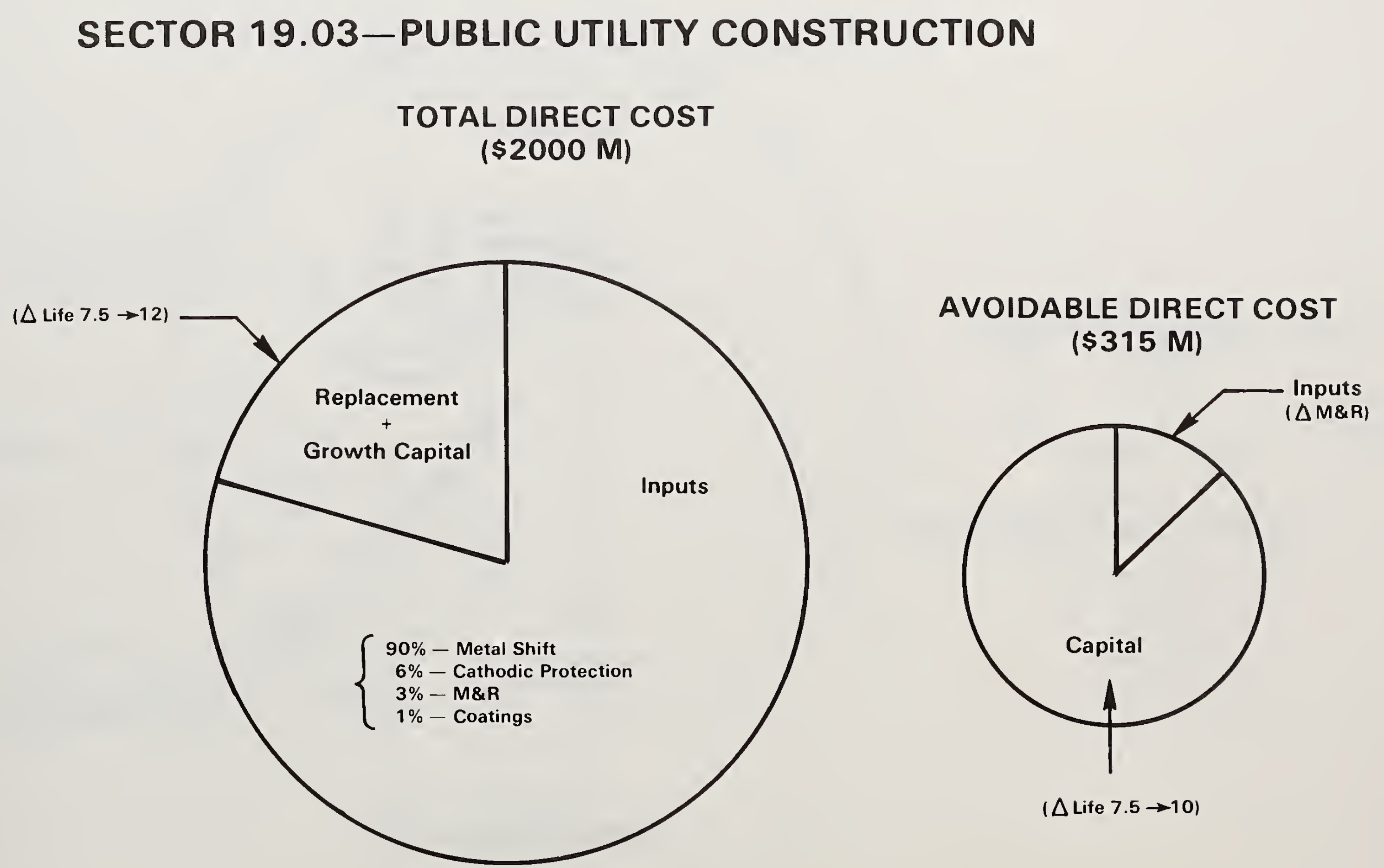

FIGURE 7. BREAKDOWN OF DIRECT INDUSTRY INDICATOR FOR SECTOR 19.03 - PUBLIC UTILITY CONSTRUCTION

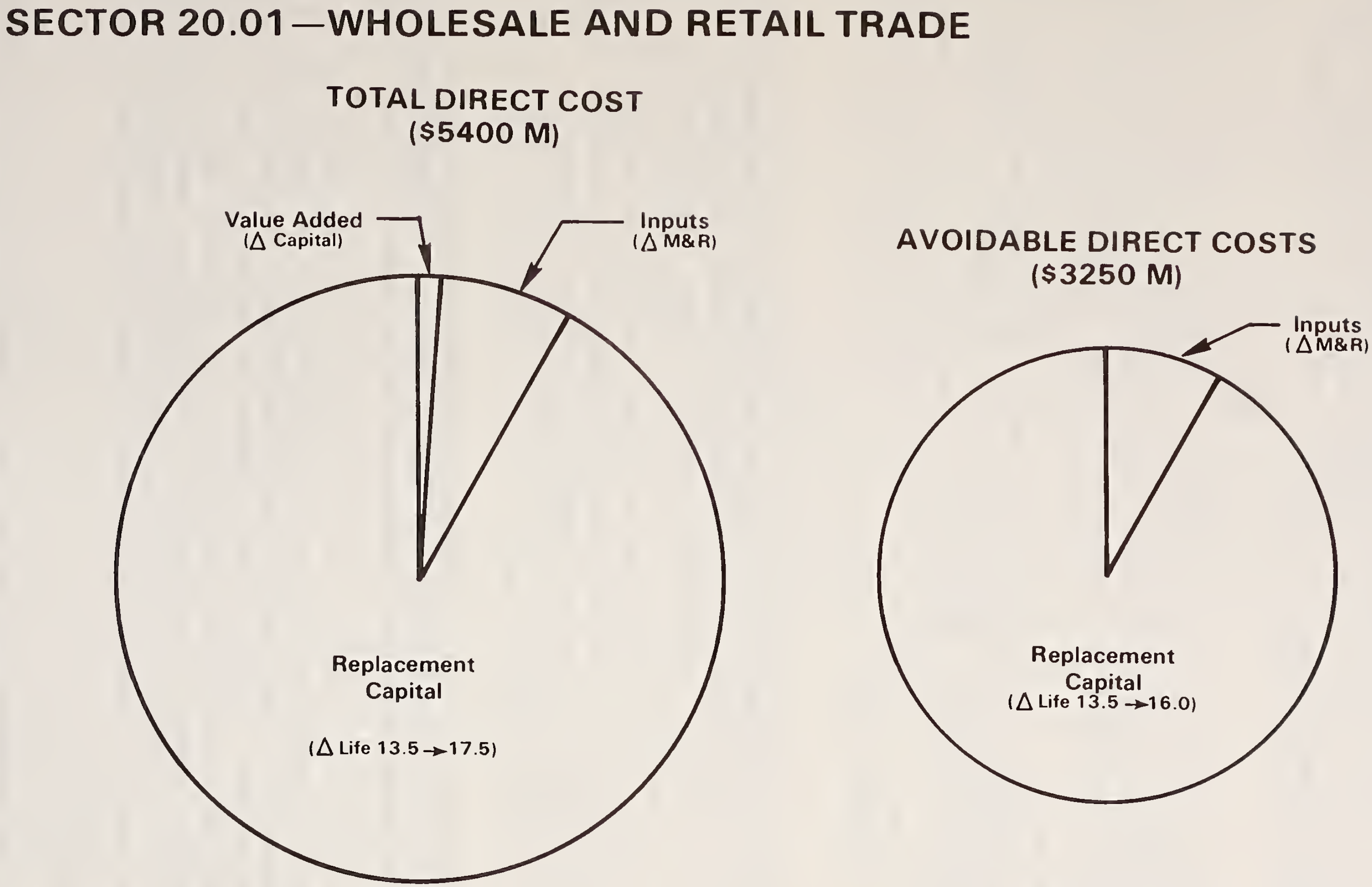

FIGURE 8. BREAKDOWN OF DIRECT INDUSTRY INDICATOR FOR SECTOR 20.01 - WHOLESALE AND RETAIL TRADE

Avoidable costs, which are less than 15 percent of Total Costs, comprise primarily growth and replacement capital costs with a smaller contribution from inputs. The former results from changes made to replacement lives, while the latter results from adjustments to maintenance and repair inputs.

Industry Indicators for Sector 8.05—Fabricated Structural Metal were $1153 M for Total Direct Costs and $9 M for Avoidable Costs. As shown in Figure 6, except for a small contribution from capital requirements resulting from change in replacement lives, total costs are the result of adjustments to inputs. Further breakdown indicates that 97% of adjustments to inputs were to account for incorporation of corrosion protection in the products of this industry. Corrosion protection was provided by metal coatings, use of corrosion resistant metal, cathodic protection, and organic coatings. Maintenance and repair inputs made only a slight contribution.

In contrast to results for Sector 1.01—Livestock and Livestock Produts, Avoidable Costs for Sector 8.05 are less than 1 percent total costs.

For Sector 19.03—Public Utility Construction, Industry Indicators were $1977 M for Total Direct Costs and $315 M for Avoidable Direct Costs. As shown in Figure 7, total costs are ascribed primarily to adjustments to inputs. Approximately 97% of input adjustments were attributed to incorporation of corrosion protection in items constructed: 90% use of corrosion resistant metals, 6% cathodic protection, and 1% coatings. Maintenance and repair input accounted for only 3% of this portion of costs. Change of average replacement life from 7.5 to 12 years resulted in replacement and growth costs and the remainder of total direct costs.

Avoidable Costs were attributed to changes in capital requirements and changes to maintenance and repair inputs. Avoidable Costs accounted for approximately 15 percent of total costs for this industry.

Industry Indicators for Sector 20.01—Wholesale and Retail Trade were $5441 M for Total Direct Costs and $3251 M for Avoidable Direct Costs. Breakdown of these costs shown in Figure 8 identifies the source of these costs. Both Total and Avoidable Costs are primarily attributed to changes in replacement capital costs resulting from adjustment of replacement lives from 13.5 years for World I to 17.5 years for World II and to 16 years for World III. Adjustments of inputs for maintenance and repair account for the remainder of costs in the industry.

The five examples presented above demonstrate the relationship between adjustments made to elements of the Input/Output model and results of cost of corrosion. Analysis of this type identifies sources of costs attributed to an industrial sector and a relative measure of the impact of adjustments on costs.

5.2.3 Costs of Corrosion for Components of Final Demand

Costs attributed to the industrial sectors were discussed in the previous section. A measure of impact of corrosion on components of final demand is available from dollar values indicated in social savings (row 27.00 of I/O Transaction Tones).

Total costs for personal consumption expenditures, the private consumer activity, were $22.8 B with avoidable costs of $15.9 B. Total costs for federal government expenditures were $8.1 B with $1.7 B as avoidable costs. Total costs for state and local government were $2.9 B with avoidable costs of $0.9 B.

Sources of these costs for each of the final demand components were discussed in section 4.4.28. The costs resulted from changes in purchases of non-durable goods and services, redundant capital, and corrosion effects on replacement lives of capital.

5.3 Uncertainty

Uncertainty in the model's results may be attributed to uncertainty associated with each of the model's component parts:

- The A matrix
- The capital matrix
- The stipulated final demands.

5.3.1 A Matrix Uncertainty

The A matrix consists of the direct technical coefficients, of which there are n^2, n being the number of sectors in the matrix. Each of the n^2 cells is subject to measurement error which may ultimately find its way into the model's results. In the case of world I, this A matrix generated error is likely to be more evenly distributed than in the world II and III cases. The reason the world I A matrix errors are likely to be more evenly distributed is that the n columns of coefficients in world I are all normalized to unity. The normalization acts to prevent the errors in the individual cells from being accumulated in the residual cell, in this case, value added. In the world II and III cases, the errors are not normalized but rather collected in the social savings cell as a residual.

In spite of the fact that the world II and III coefficient errors are not normalized, those errors tend to converge when they are translated into the inverse since (1) all the errors are less than one, and (2) the inverse of the (I-A) matrix may be estimated as

$$I + A + A^2 + A^3 + \ldots + A^\infty$$

Additionally, certain sensitivity testing of input-output models suggests that the model's outputs are relatively insensitive to errors in the direct technical coefficients.* For example, using various order matrices, Stevens and Trainer found that a mean error of 26 percent in the matrix coefficients resulted in a mean U value of .067 for the total output levels.** The testing was performed on matrices ranging from orders of 10, 25, 50, and 100 while the errors in the coefficients were selected randomly from normal distributions with standard deviations of either 10, 20, 30, or 40 percent of the original coefficient value.

5.3.2 Capital Matrix Uncertainty

The capital matrix when used in conjunction with the remainder of the model results in gross private domestic investment. There are various sources of errors which may affect these final levels of investment. Errors in the capital coefficients themselves likely exist but unfortunately there is seemingly no way of determining the magnitude of those errors. Capital replacement rates and growth rates also involve errors and again it is difficult to estimate their absolute magnitude. It is also difficult to state analytically what the implications of those errors are upon the models final output. Replacement capital coefficients are determined by multiplying the capital coefficients by their replacement rates. The replacement rate is estimated as

$$RR = \left\{ g[(g+1)^u - 1]^{-1} \right\}$$

where RR is the capital replacement rate

g is the growth rate for a specific type of capital

u is the replacement life of a specific type of capital

Thus any error in the ultimate replacement capital coefficient becomes a function of the error in the capital coefficients multiplied by the error in the replacement rate which is itself a complex function of the errors in replacement life and growth rates.

However, since the capital replacement and growth coefficients are combined with the direct technical coefficients in the dynamic inverse, $(I-A-BR-BG)^{-1}$, and since the term (A+ BR + BG) is generally *less* than one, the errors would seem to converge for the calculation of

*Stevens, Benjamin H., and Glynnis A., Trainer, ''Error Generation in Regional Input-Output Analysis and its Implications for Non-Survey Models,'' Regional Science Research Institute, April 14, 1977.

** $U = [\sum_i (P_i - A_i)^2 / \sum_i A_i^2]^{\frac{1}{2}}$

A_i = Actual or exact output of sector i

P_i = Predicted or estimated output of sector i given the errors.

total ouputs in a way analogous to the errors in the direct technical coefficients. If, however, (A + BR + BG) is *greater* than *one*, unlikely in this case, the errors would not converge but rather increase during the inversion process.

5.3.3 Stipulated Final Demand Uncertainty

Errors in stipulated final demand for World I arise primarily from the estimation procedure which is described in the methodology section. Again, little is known of their magnitude except that the value estimated as full employment GNP is approximately 2 to 3 percent greater than actual GNP for 1975. Since we are measuring full employment GNP it is difficult to determine the errors implicit in the difference. Errors in Worlds II and III derive from both the errors in the World I estimate and the methods used to make the Worlds II and III adjustments to the World I levels of stipulated final demand. The adjustments included

- ex ante adjustments for redundancy of social capital infrastructure and for other corrosion related consumption
- adjustments to social capital infrastructure replacement lives which are translated into changes in the rate at which the items are replaced.

Finally, the adjusted stipulated final demands were used to actually drive the model so that errors in this final demand component probably are more significant in terms of the model's final results than are the errors in other model components. However, while these errors will tend to affect the *absolute* sizes of both the GNP estimates and the estimates of corrosion cost, and in the same directions, they probably have less influence on the resulting estimates of the *relative* significance of corrosion costs. The relative estimates, i.e., costs as percent of GNP or relative costs among industrial sectors, are more certain than absolute dollar value estimates.

5.3.4 Total Costs of Corrosion Uncertainty

Given the uncertainty in the model's component parts and in its output, the cost of corrosion estimates will also embody uncertainty. We feel that uncertainty will tend to result in an underestimation of the total costs for the following reasons:

(1) Where specific information has not been obtained, U.S. averages will tend to be used. This means that special situations, so far as high corrosion is concerned, will tend to be understated, more often than not, if not specifically quantified in the field.

(2) The coefficient adjustments that must be made in going from World I to World II are generally made by subtracting a corrosion-related portion from the entries into specific cells. These cells must not and cannot be reduced below zero. Therefore, if the World I coefficient is large enough to cover or more than cover the full correction, it will be made; however, if the coefficient is *not* large enough to cover the full correction, only a partial adjustment will be possible. Given random errors in the cell values, results will be biased in one direction, only—toward understatement of the World I - World II differential.

(3) There are a large number of small instances of corrosion (e.g., corrosion of umbrella ribs or of small appliances) which cannot be specifically accounted for. No attempt has been made to estimate their aggregate impact and incorporate it into the model, because such a correction would destroy the integrity of an interdependent model of this kind. Although these are individually small costs, they are not included in the estimates. Their aggregate value and their contribution to the understatement of corrosion costs is not known but likely to be significant.

(4) There are some subtle and intangible costs of corrosion (e.g., engineering attempts to reduce it or its effects in designing items that are not conspicuously vulnerable) that undoubtedly occur, but cannot be estimated and ascribed to a particular sector. These will be systematically omitted from the World I - World II adjustments.

(5) Where specific estimates have been made of World I/World II differentials, we have tried to make accurate estimates rather than to estimate on the high side. Thus, these estimates probably are subject to random rather than biased errors. Given the ''conservatism'' of the I/O model, we can say that the net impact of these errors will be low *and* random—i.e., in a narrow ± range. All the systematic errors (items 1-4, above), on the other hand, will tend to bias in the negative direction, and will therefore lead to a high probability of understating the total cost of corrosion.

(6) When we turn to the distribution of total cost between avoidable and unavoidable, i.e., World III, we cannot say with any assurance what bias, if any, will be injected. The World III corrections logically could range from the same negative errors of World II to zero bias. There is no reason to believe that they would systematically tend in the opposite direction. This would imply that both total and avoidable corrosion costs would be understated (though not necessarily to the same degree), making the unavoidable costs more nearly correct than either of the other two.

The degree of certainty of estimates of the effect of elements of corrosion cost discussed in section 4.2 ranges widely. Estimating procedures were described and should be judged individually. Clearly, estimates of corrosion costs for maintenance and repair, where detailed studies were available and total maintenance costs were reasonably well established, are more certain than estimates of costs based on changes in replacement lives, where specific data were unavailable and a more qualitative approach was necessary.

The supporting data in components of the I/O model and rationale of estimates of corrosion effects provide a means to determine the source of significant costs of interest. By tracing these costs and performing further analysis, it is possible to evaluate the estimates and to make refinements where warranted.

5.4 Input/Output Model As A Means Of Technology Assessment

Technology assessments were not included within the scope of this study, but data gathered and procedures developed provide a sound basis for such activities. The principal attribute of the I/O analysis is the determination of *indirect* as well as *direct* consequences of technological change. The corrosion I/O model, used here to determine costs of corrosion, can be used to assess proposed means to reduce costs.

In contrast to procedures to determine total effect of corrosion where technologies of all industrial sectors were changed simultaneously, only those adjustments specific to the proposed technology would be entered into present technology (World I) values. The consequences of alternative proposals can thus be determined.

To illustrate this procedure, a hypothetical example is chosen; a two-fold increase in the use or galvanized steel for automobiles. In the World I Input/Output tables, ''motor vehicles and parts'' is a row and a column in which all parameters are fitted to the real world. In order to measure the social and industrial impacts of this increased use of galvanized steel, an alternative world (World IA) is created.

The first change introduced is in the motor vehicle column of the A-matrix (the column of input coefficients). Here inputs are shifted from mild steel to galvanized steel with an off-setting entry into Row 27.00 (Social Saving) to account for differences in real (resource) costs. If this change alters other inputs, as well (e.g., labor or energy use in auto manufactures), then these changes are also made.

In the final demand vector as well as in the input columns of other industries, the change in materials may directly alter the relative purchases of motor vehicles and parts and of automobile repairs and services. These changes in input coefficients are also determined. Similarly the change in materials may affect replacement lives of cars in various uses.

When all the differences have been incorporated into the World IA tables that are ascribed to the material alteration, the transaction table is determined and compared with the World I base. Differences between the two worlds introduced by the scenario provide the bases of the assessment of the proposed technology. A result of the analysis may be that present galvanized-steel production capacity in the U.S. would have to be increased to meet the new demand.

Other simulations are possible, by means of which various alternatives to reduce corrosion costs may be evaluated.

6 CONCLUSIONS

Corrosion has a major impact on the economy of the U.S. Reduction of the wastage of resources by decreasing corrosion costs is an effective means to provide materials, energy, labor, and technical expertise for alternate uses.

Costs of corrosion in the United States in 1975 were estimated to be

Total Costs to U.S.	\$82 Billion
Avoidable Costs	\$33 Billion
Unavoidable Costs	\$49 Billion

Total costs were 4.9 percent of Gross National Product (GNP). Avoidable costs were 2.0 percent of GNP, and unavoidable costs were 2.9 percent of GNP. Thus, approximately 40 percent of total costs were estimated to be avoidable, i.e., amenable to reduction by presently available corrosion control technology.

Total costs of corrosion are comprised of (1) final demand costs of \$58 B, a measure of the final demand purchases by consumers, investors, and governments because of corrosion and (2) intermediate output of \$28 B, a measure of the resource requirements for productive processes because of corrosion. Final demand costs include \$23 B for personal consumer expenditures, \$8 B for federal government expenditures, and \$3 B for state and local government expenditures.

These estimates should not be taken as absolute, but rather as the best available measurement of the economic effect of corrosion. Their significance is that they provide a reference point for the impact of corrosion against which the relative impact of other factors affecting the economy can be compared. By this means, priorities and allocation of resources to reduce costs can be established in a rational manner. The results indicate that large potential savings are present for both unavoidable costs (requiring technological advance for reduction) and avoidable costs (requiring technology transfer and implementation for reduction).

The second objective of the study, after total costs were determined, was to allocate total cost to individual segments of the economy. This allocation is necessary to identify areas where potential savings are the greatest and, therefore, provide guidance for cost-reduction efforts. A set of indicators was developed to ascribe relative costs of corrosion to industrial sectors of the economy. A series of indicators express corrosion costs of an industry on a dollar basis and as percent of sales for total corrosion costs and avoidable corrosion costs.

The source of costs to an industry can be determined by analysis of the foundational data for estimates of costs. The approach of cost reduction efforts will depend greatly on the source of costs.

Several industrial sectors were analyzed, and costs were attributed to operating costs (resource requirements to produce the industries product or service) and to capital costs (plant and equipment requirements for the production process). These analyses illustrated, (1) The importance of identifying the source of costs and (2) The wide variation from industry to industry of predominant element of cost, e.g., maintenance costs, corrosion control costs, and replacement life costs. Three examples are reviewed here.

For the livestock industry, approximately 95 percent of total costs $1100M were the result of adjusting the average replacement life of capital from 14 years to 21 years if corrosion were not a factor, and less than 5 percent of total costs were the result of corrosion-related maintenance. For the Fabricated Structural Metal industry, greater than 95 percent of total corrosion costs of $1150M resulted from costs for providing corrosion protection to the industries product, i.e., metallic coatings, corrosion resistant metals, cathodic protection, and organic coatings. For the Industrial Chemical Industry approximately 65 percent of total costs of $690M were ascribed to operating costs and 35 percent to capital. Operating costs resulted from corrosion-related maintenance and repair and purchases of corrosion inhibitor, whereas capital costs resulted from corrosion effects on replacement lives of equipment and production capacity.

Input/Output analysis, which provided the methodological framework for this study, permitted detailed and comprehensive treatment of all elements of the costs of corrosion. Production costs, capital costs, changes in replacement lives, etc. were treated in a coordinated and systematic manner. The methodology applied and developed in this study can be used to study the effects of other forms of wastage to the economy.

Data gathered and procedures developed in this study provide a sound basis for technological assessments. The principal attribute of Input/Output analysis is the determination of *indirect*, as well as *direct* consequences of technological change. The corrosion I/O Model can be used to assess proposed means to reduce costs. Through simulations alternatives to reduce corrosion costs can be evaluated.

7 GLOSSARY

A Matrix: matrix, also called the flow matrix, of direct technical coefficients; the value of each coefficient indicates the dollar's worth of inputs from the row sector necessary to produce one dollar's worth of the column sector's output.

Annual Replacement Rate: the average, annual rate at which existing capital stock (private or social) is replaced.

Avoidable Cost of Corrosion: that portion of the total costs of corrosion which could be avoided if best corrosion control practices were used.

B Matrix: a matrix of capital-to-output coefficients; also called the capital matrix.

Best Corrosion Control Practice: the most economically effective and efficient use of labor, materials, energy, and technical expertise possible with presently available corrosion control technology.

Capital: in the context of this study, this term refers only to physical plant and/or equipment that is not directly consumed or changed in form, but is used in the production of goods and services, either for sale or for consumption. By general usage, all items of capital have a replacement life of one year or more.

Capital-Output-Coefficient: the value of capital equipment required by an industry in order for it to produce one dollar's worth of output. The coefficient is measured in terms of capital replacement value and at the using sector's full capacity.

Capital Matrix: a matrix of capital-to-output coefficients; also called the B Matrix. Each cell indicates the value of capital produced by the row sector and used by the column sector.

Cell: a single value of entry in a matrix or vector. A cell is defined as the intersection of a row and column.

Corrosion: the degradation of metals because of interaction with aqueous or gaseous environment, e.g., aqueous corrosion, stress corrosion cracking, corrosion fatigue, erosion-corrosion, oxidation, and sulfidation. Non-metallics are excluded from the more general definition of corrosion for this study.

Depreciation: the incremental decrease in the value of capital because of wear, aging or obsolescence.

Diagonal Matrix: a matrix which contains values only in the diagonal cells, with zeros in all off-diagonal cells.

Direct Technical Coefficient Matrix: also called the A Matrix; matrix of values which indicate dollar's worth of input from the row sector required to produce one dollar's worth of the column sector's output.

Direct Costs: the costs on industrial sector accrues as it purchases inputs and produces its products.

Disaggregation: the separation of an industrial sector (in the input-output sense) into two or more of its component parts; the sector's row and column in each of the input-output model matrices is separated into two or more component rows and columns.

Durable Goods: products which last in excess of one year and which do not change form during their use.

Dynamic Inverse: a transformation of a matrix containing direct technical coefficients, capital replacement requirements, and capital growth requirements $(I\text{-}A\text{-}BG\text{-}BR)^{-1}$.

Econometric Model: a mathematical representation of an economic system.

Ex ante: a process of determining model parameters through use of expert knowledge and opinion rather than through the manipulation of existing statistics.

Ex post: estimating model parameters through use of historical, existing statistics.

Final Consumers: consist of private individuals purchasing for their own satisfaction, governments, private investors, and parties receiving U.S. exports.

Final Demand: in national income accounting terms, the consumption attributable to private investors, individuals purchasing for their own private use, governments, net inventory change, and net exports.

Flow Coefficient: also called direct technical coefficient. Dollar's worth of inputs required from a given industry for some other industry to produce one dollar's worth of output.

G Matrix: a diagonal matrix of industrial sector growth rates.

GNP: the gross national product, that is, the value of the final output of an economy, measured without double counting.

Growth Capital: annual capital equipment purchases which may be attributed to the fact that the economy is growing.

Input-Output: a particular methodology used in modeling an economic system. It consists of a set of simultaneous equations which may be solved for the system's total output.

Indirect Costs: the costs which accrue in producing the inputs to a particular production process, and the costs of producing the inputs to the inputs until the additional costs become negligible.

Industry Indicator: a special index used in this study to help assign relative total costs of corrosion to individual industrial sectors.

Intermediate Consumers: those industries purchasing products which are to be transformed into different products.

Inverse: a transformation of the A Matrix. Each cell in the inverse indicates the total dollar's worth of inputs from the row sector necessary in order for the column sector to deliver one dollar's worth of output to its own final demand.

Inversion: the process by which a matrix is transformed into its inverse.

Input: a necessary element in the production of a sector's output. In general, inputs consist of raw materials, energy, intermediate-components, supplies, purchased services, and value added. The total value of a sector's inputs is equal to the value of its output.

Matrix: a table made up of rows and columns. In mathematics, a ''short-hand'' way of expressing a set of simultaneous equations.

Output: the result of the productive process. The totality of goods and services produced and sold by a sector. The value of a sector's output is equal to the total value of all its inputs.

Private Fixed Capital Formation: the annual purchase of capital (plant and equipment) by private investors for reasons of growth and replacement.

Privately Owned Social Capital: equipment, structures, and other durable goods owned and used by individuals for their own enjoyment.

Process Sectors: industrial sectors of the input-output model which use one technological process to produce a homogeneous product (or group of products).

R Matrix: a matrix of annual average capital replacement rates; each cell indicates the average annual replacement of capital produced by the row sector and used by the column sector.

Replacement Capital: annual capital purchases which are made to replace obsolete or worn out plant and equipment.

Replacement Life: the time to first replacement of a piece of capital equipment.

Sector: an industry or group of industries that is treated as a productive unit in an input-output table.

Social Capital/Infrastructure: plant, equipment, and structures, purchased and used by private individuals and/or government. These items last in excess of one year and do not change form during their use, e.g., highways, bridges, and navigational aids.

Social Savings: an accounting mechanism in the modified input-output model used in this study. The social savings accounts for real resources being consumed and value added accruing because corrosion exists.

Stipulated Final Demand: the value of goods and services which accrue to individuals, government, net inventory change, and exports.

Stock Coefficient: also called capital coefficient; indicates the value of capital stock of a certain type required for an industry to produce an additional dollar of its output.

Total Cost of Corrosion: the total resources consumed in our economy because of the fact that corrosion exists.

Total Output: the value of the total goods or services produced by some industrial sector.

Unavoidable Cost of Corrosion: that portion of the total cost of corrosion which cannot be reduced by application of best corrosion control practice.

Value Added: the additional value accruing to a sector's inputs as they are fashioned into the product itself; included are wages, salaries, rents, profits, interest, taxes, and depreciation. It can also be defined as the value of the productive factors contributed by the industry itself, rather than purchased from other industries.

Vector: a single row or column of values.

World I: the present environment and economy as they now exist.

World II: a hypothetical environment and economy in which no corrosion exists.

World III: a hypothetical economy in which best corrosion control practices exist and are universally applied.

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APPENDIX A

CORROSION COSTS IN THE FEDERAL GOVERNMENT*

1 INTRODUCTION

The Federal Government is the owner of a large amount of capital equipment that is subject to corrosion, and large amounts of money are spent yearly to protect that capital from corrosion. Generally speaking, agencies of the Government are very much aware of their corrosion prevention costs, and several important studies have been carried out on these costs, particularly in the Department of Defense. However, to do a thorough study of the costs of corrosion in the Federal Government would mean that each agency would have to be studied individually. Each agency has custody of its own equipment, and maintenance and repair costs would have to be obtained from each of them. Within the time and effort available for this study this was impossible. Hence the strategy that was followed was to investigate those agencies that own specialized capital, and those that own a large amount of capital from which extrapolation could be made to the total costs for the Federal Govenment. This meant a heavy concentration on the Department of Defense, for this Department owns the largest share of the capital owned by the Federal Govenment. Fortunately, this is also the Department that has, in many cases, the most reliable cost data.

The agencies from which data were obtained were the three services of the Department of Defense, NASA, the U.S. Coast Guard, the GSA, the Legislative Branch, and the National Bureau of Standards. Corrosion costs data were not available in all cases. Where not available, estimates of corrosion costs were made from the available data by ourselves, guided in most cases by data from those agencies for which corrosion costs data were available.

The costs we have collected are primarily maintenance and repair costs. Where appropriate, capital redundancy information was also collected, as well as capital lifetimes. However, no attempt was made to obtain added first costs because of corrosion. These would be reflected as changes in inputs to the appropriate capital producing sector in any case, and not as changes in Federal capital acquisition expenditures. The data for World II are, generally speaking, based on previously reported surveys or studies whereas data for World III involve a great deal of subjective judgment.

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*Section prepared by Elio Passaglia—NBS with assistance from W.K. Boyd—Battelle-Columbus Laboratories.

2 CAPITAL EQUIPMENT OF THE U.S. GOVERNMENT

A complete inventory of the capital equipment of the U.S. Government was not available. However, all the real property (buildings, structures and land) at book value is given in Reference 1, which has many other valuable data as well. Real property and personal property (all property other than real property) for the Department of Defense is given in Reference 2. Reference 3 gives statistics on highways, which are, however, property of the States. Reference 4 gives valuable information of various kinds.

An overall inventory of the capital of the U.S. Government, at 1975 replacement prices, is given in Table A-1. This was calculated by Battelle from yearly purchases, expected lifetime and rate of growth. The inventory is broken down into dollars of capital from each capital-producing, industrial sector in the I/O Model. In Tables A-2 and A-3 we have collected all items of inventory with a value greater than three billion dollars. Table A-2 gives real property, which accounts for 36.3% of total capital owned by the U.S. Government. Table A-3 gives the remainder. The capital listed in these two tables accounts for 97.6% of the capital owned.

With these two tables in mind, the strategy that was followed for the Federal Government was as follows. Corrosion costs were collected on real property and those items of capital equipment where the Federal experience is expected to be unique. This is in the military. The particular items chosen were aircraft (29.2% of total capital), ships (8.4%) and ordnance and accessories (9.5%). In monetary value, these four items of capital equipment account for 83.4% of the capital owned by the U.S. Govenment. Their fraction of the corrosion costs is expected to be at least that great. Corrosion costs for the remainder of the items in Table A-1 and Table A-3 were not studied specifically for the Federal Government, but were estimated from the results of other portions of the study.

3 AIRCRAFT

The major owners of aircraft in the Federal Government are the Air Force, the Navy, the Army (primarily helicopters) and the Coast Guard. Detailed study was carried out for the Navy, the Air Force, and the Coast Guard. The Army costs were estimated from the information obtained from the Navy and the Air Force. Data obtained from each of these agencies are discussed below.

TABLE A-1. CALCULATED INVENTORY OF CAPITAL OF THE FEDERAL GOVERNMENT

Capital Producing Sector	$ - M
4x05 Furniture + Fixtures	2165.72
8.02 Metal Barrels, Drum + Pails	47.79
8.04 Nonelectric Heating Equipment	82.42
8.05 Fab Structural Metal Prd	1079.59
8C07 All Others	726.91
9.01 Engines + Turbines	4501.54
9.02 General Industrial Machinery + Equipment	5082.07
10.01 Farm Machinery	232.02
10.02 Construction Machinery	1626.83
10.03 Mining Machinery	47.10
10.04 Oil Field Machinery	7.82
10.05 Material-Handling Mach Ex Truc	107.58
10.06 Industrial Trucks + Tractors	1070.40
10.07 Metal Working Machinery	1732.91
10.08 Special Industry Machinery	385.30
11A01 Automobiles	3165.10
11B01 Trucks, Buses, etc.	4061.80
11.02 Aircraft + Parts	194714.05
11.03 Ship + Boat Building + Repairs	56367.33
11.04 Locomotives + Rail + Street Cars	242.04
11.05 Cycles, Trailers, etc.	20.15
12.01 Electric Measuring Instruments	4250.08
12.02 Electric Motors + Generators	3208.85
12x04 Electric Lamps + Fixtures	526.80
12.07 Miscellaneous Electrical Machinery	1995.19
13.01 Service Industry Machinery	905.97
13.02 Household Appliances	218.54
13.03 Radio, TV + Communication Equipment	57668.07
14.01 Scientific Instruments, etc.	7874.81
14.02 Medical, Surgical, Dental Instruments	867.24
14.03 Watches, Clocks + Parts	27.70
14.04 Optical + Opthalmic Goods	323.49
14.05 Photo Equipment + Supplies	2981.01
15.01 Computing + Related Machines	4310.96
15.02 Other Office + Business Machines	731.08
16.01 Ordnance + Accessories	63293.16
16.02 Other Miscellaneous Products	185.32
19.01 New Construction, Nonfarm Resid	11804.11
19.02 New Construction, Nonresid Build	40481.49
19.04 New Construction, Highway + Other	189817.86

TABLE A-2. REAL PROPERTY, U.S. GOVERNMENT

Sector	Amount-M$	% Total
19.01 Residential	11,804	1.77
19.03 Building, Non Res.	40,481	6.07
19.04 Highway and Other	189,817	28.47
TOTAL	242,102	36.32

TABLE A-3. PERSONAL PROPERTY

Sector	Amount-M$	% Total
9.01 Engines & Turbines	4,501	0.68
9.02 General Industrial	5,082	0.76
11A01 Autos	3,165	0.47
11001 Trucks, etc.	4,061	0.61
1101 Aircraft	194,714	29.2
1103 Ships & Boats	56,367	8.4
1201 Elec. Meas. Inst.	4,250	0.64
13.03 Communication Equipment	57,668	8.65
14.01 Scientific Instruments	7,875	1.18
15.01 Computers	4,311	0.65
16.01 Ordnance and Accessories	63,293	9.49
TOTAL	408,496	61.3

3.1 Navy, World II

3.1.1 Maintenance and Repair

Costs for the corrosion portion of maintenance and repair were derived from discussions with several experts from the Naval Air Systems Command. The maintenance and repair figures are given in Table A-4. These are divided up as to costs incurred for maintenance and repair in the depot and in the field. The latter in turn are broken down for scheduled maintenance and unscheduled maintenance and repair. Since scheduled maintenance for corrosion is accurately specified, and unscheduled mairtenance is the subject of a thorough study, these estimates are considered quite firm.

3.1.2 Capital Redundancy and Lifetimes

We estimate that 5-8% of the time Navy aircraft are not available because they are undergoing maintenance and repair for corrosion. Hence, we conclude that the Navy aircraft have a redundancy of 5-8% because of corrosion. All discussions with Navy personnel have indicated that aircraft are not replaced because of corrosion, but because of obsolescence. Hence, it is concluded that aircraft lifetime is not influenced by corrosion.

3.2 Air Force, World II

3.2.1 Maintenance and Repair

Costs of corrosion of aircraft were obtained in discussions with experts from the Air Force Materials Laboratory. Based on these discussions estimates are made for corrosion maintenance expenditures. Corrosion costs are also available from two other sources: FY-76 Aircraft Maintenance Costs[5] and USAF Corrosion Data, Manhours Expended for Corrosion Inspection and Treatment.[6] From various sources it is possible to obtain a range of estimates for corrosion costs for aircraft.

Maintenance costs were expended in depots and in the field (see Table A-4). Reference 5 gives a complete breakdown of the fraction of maintenance expenditures expended for corrosion for each type of AF aircraft. These data are summarized in Table A-5. From this it is estimated that 27.3% of total maintenance man-hours are expended for corrosion. Reference 5 also gives the overall maintenance costs for depot repair and maintenance. The product then gives the corrosion costs incurred in depot repair and maintenance. These are given in Table A-6 along with field costs.

TABLE A-4. SUMMARY OF CORROSION COSTS - NAVY AIRCRAFT

Depot Costs		M$
Air-Frame	0.1 x 199 M/year	19.9
Engines, assume	0.25 x 88 M/year	22
Other Equipment	0.1 x 344 year	34.4
Total Depot		76.3
Field Costs		
This applies to ∿ 5,000 airplanes		
Scheduled maintenance		
Man-power		
$\frac{32}{28}$ x 5000 x 365 x 15		31.3
Materials @ 10%		3.1
Unscheduled Maintenance		
206, 565 x 12 x 15 =		37.2
Materials @ 10%		3.7
Total Field		75.3
	GRAND TOTAL	151.6

TABLE A-5. PORTION OF MAINTENANCE EXPENDITURES FOR CORROSION FOR DIFFERENT TYPES OF AIR FORCE AIRCRAFT

Aircraft	No	% Corrosion	No. Hours/Corr.	Total
F/FB 111	445	5-10%	176	2,347
B52	?	20%	8,800	44,000
F106	249	17-20%	807	4,362
F105	247	8-9%	613	7,222
F102	223	0(?)~10	773	7,730
F100	518	24%	644	2,683
F4	1,640	15%	678	4,520
A-7	346	13%	416	3,200
C141	280	30%	2,760	9,200
C135	762	23%	2,459	10,691
C5	79	60%	15,535	25,892
C118	93	58%	2,146	3,700
C130	662	23%	8,980	39,043
T29/C131	436	50%	280	560
	5,981		45,067	165,150

$$\frac{45,067}{165,150} = 0.273 \text{ Corrosion Fraction}$$

Developing the field costs is a more difficult matter. Reference 5 gives no data on field costs for corrosion. However, it gives the total appropriation for field maintenance, the total number of field and depot personnel, and the total field and depot maintence costs for the F-4 aircraft. Unfortunately, these are three different rates, being 3.0, 1.37 and 1.53, taking depot warehouse costs at $20/hour and field warehouse costs at $15/hour as recommended by AFML. Moreover, from Reference 6 it is possible to derive that 25% of field maintenance costs are expended for corrosion, as compared to the 27.3% derived from Reference 5 for depot work. These numbers are remarkably similar. From these various data and the known depot maintenance costs, it is possible to derive a series of estimates for the field costs, and hence the total costs. These are given in Table A-6.

This gives a very wide range of estimates. However, following discussions with Air Force personnel, we discard the high costs. These result from the large ratio of appropriation for field work as compared to depot work. We accept the lower estimate for two reasons: (1) the field depot man-hour ratio and the field/depot costs for the F-4 are quite similar, and (2) the Navy experience (Table A-4) shows depot costs and field costs to be very similar. A representative figure of $750 M/year was decided upon. This is essentially determined by the relatively firm figures for the F-4.

3.2.2 Redundancy and Lifetime

The redundancy is estimated to be at the upper end of the Navy figures, since a greater fraction of maintenance and repair expenditures is used for corrosion. Hence a figure of 8% redundancy is estimated.

As with the Navy, no change in lifetime of aircraft is anticipated because of corrosion.

3.3 Coast Guard

The Coast Guard provided us with detailed maintenance and repair expenses for aircraft. From these we derived corrosion costs. The results are shown in Table A-7, where we have used the fraction of maintenance and repair expenses for corrosion that we obtained for the Air Force fleet to make the estimate.

It is to be noted that field maintenance for the Coast Guard is carried out largely by crew members, and their labor is not separately accounted for, as it is for the Navy and the Air Force. Hence, to place the Coast Guard expenditures on a comparable basis to those of the Navy and the Air Force, the field labor expenditures were increased until materials represented 20% of total maintenance costs. This was for the comparison made in the next section.

No data were derived for redundancy or lifetimes.

TABLE A-6. AF AIRCRAFT CORROSION MAINTENANCE COSTS

	$, Million
(a) DEPOT	
From AFML	300 - 450*
Calculated from Ref. (5)	300
(b) FIELD	
From AFML	300*
Using fraction from (5)	
Scaled by appropriation	900
Scaled by MH	411
Scaled by F-4	459
Using fraction from (6)	
Scaled by appropriation	824
Scaled by MH	376
Scaled by F-4	420
Total and Range	600 - 1,350

* Includes materials @ 20% of labor

Average decided with CT Lynch = $750 M

TABLE A-7. COAST GUARD, AIRCRAFT

	Total, \$K	% Corr	Corrosion Cost \$K
Field			
Labor	30	25	7.5
Matls.	1,472		368
Depot			
Labor	4,952	25	1,238
Matls.	1,238		309
		TOTAL	1,922

$$\text{Cost per aircraft} = \frac{1922}{172} = \$11{,}200/\text{year}$$

Cost per aircraft, scaled for field labor = 19,700/year

3.4 Comparison of Navy and Air Force Figures

Table A-8 gives a comparison of the corrosion maintenance costs for Navy and Air Force aircraft. In this table, costs are given for each service in terms of dollars spent per year per aircraft. It is seen that the Air Force spends about 2.5 times as much per aircraft as does the Navy. The reason for this is made clear in Table A-5. There it can be seen that the larger aircraft, like the C135, the C5 and the C118 require a considerably higher proportion of maintenance expenditures for corrosion control than do the smaler aircraft. Indeed, for the F-4 aircraft, the experience is quite similar to the figures given in Table A-4 for depot repair for the Navy. Hence it is concluded that the ratio of per-aircraft yearly corrosion maintenance costs for the Air Force and the Navy is in the expected direction, although its accuracy cannot be assessed.

The table also gives the yearly maintenance costs per dollar of inventory value as given in Reference 2. However, here no ratio is given since this is much harder to interpret.

3.5 Total Aircraft Costs, Federal Government

Table A-9 gives the total corrosion maintenance costs for aircraft for the Federal Government. The figures for the Army are not part of

TABLE A-8. COMPARISON OF NAVY AND AF AIRCRAFT CORROSION MAINTENANCE COSTS

	NAVY	AF	AF/NAVY
Total cost, M$/year	152	750	
No. of Aircraft	6,475	12,425	
Cost per aircraft, $/year	23,500	60,360	2.5
Dollar value of aircraft, B$	18.3	31.2	
Cost per year per dollar value, $/$year	0.0083	0.0240	

TABLE A-9. AIRCRAFT, CORROSION MAINTENANCE COST

	Book Value $B	Labor $M	Materials $M
Navy	18.2	137	14.5
Air Force	31.2	625	125
Army	4.7	69*	13
Coast Guard		2	.6
TOTAL		833	153

* Scaled from Navy and AF Sum.

an independent estimate, but were scaled on the basis of the inventory value from the Navy and Air Force experience. The total corrosion maintenance costs for aircraft in the Federal Govenment are approximately one billion dollars per year.

4 SHIPS AND BOATS

The two organizations investigated for corrosion maintenance costs were the Coast Guard and the Navy.

4.1 Coast Guard

The Coast Guard provided detailed figures for total repair and maintenance for cutters and boats. From the aspect of the overall expenditures for the Federal Government, the expenditures for boats were sufficiently small that they were not analyzed. However, from the figures provided on cutters, an estimate of the fraction of maintenance and repair expenditures for corrosion was made and was later used for the analysis of the Navy figures. Hence these were analyzed in detail.

The costs for cutters are given in Tables A-10 and A-11. Table A-10 is for maintenance and repairs in dry-dock and yards (labelled ''Depot'' to make them consistent with Tables A-4, A-5, and A-6). Table A-11 gives similar figures for maintenance and repair in the field, and totals. In each table the total maintenance and repair figures were provided by the Coast Guard. The portion attributable to corrosion is our estimate. How this was done is described in the following paragraphs.

The two first columns of Table A-10 give the total maintenance and repair costs expended in depots. These are broken down into categories of ''Dry-docking and Underbody'',''Propulsion'', ''Auxiliary Systems'' and ''Hull''. It is this detailed breakdown that permits an estimate of the fraction of these costs that is attributable to corrosion.

Drydocking and underbody work on ships is done to remove fouling and not because of corrosion. Hence none of these costs were attributed to corrosion.

For propulsion systems the following analysis was used. Reference 7 is a thorough study of maintenance and repair expenses for the propulsion systems on LST's. From the data assessed during this study, Peterson derived that 29% of the labor and materials used for maintenance of these propulsion systems were required because of corrosion. These data are not published but were made available to us by Mr. Peterson. The figure of 29% was used both for propulsion and for auxiliary systems.

TABLE A-10. COAST GUARD CUTTER - DEPOT

	Dollars in Thousands				
	Labor	Matls	Corrosion	Corr. Labor	Corr. Matls
Drydocking and Underbody	5,930	130	0	0	0
Propulsion	2,425	1,126	0.29	703	326
Auxiliary Systems	2,620	852	0.29	759	247
Hull	2,354	311	1.00	2,354	311
TOTAL	13,331	2,421		3,816	884

Corr. Labor = 29%

Corr. Matls = 36%

Corrosion Total = 30%

For hull repair and maintenance in the depot, the total amount was attributed to corrosion. Accident repair is accounted for separately from these figures.

Fractions of maintenance expenditures attributable to corrosion in the field were derived in a similar fashion, but 25% of hull work was attributed to corrosion. There is, of course, no underbody work in the field. It is also to be noted that the time of crew members spent on maintenance and repair is not counted.

From these figures it is estimated that approximately 30% of depot maintenance and repair expenses are attributable to corrosion, and about half the field expenses.

The total corrosion maintenance costs are given in the bottom part of Table A-11. The overall fraction of maintenance and repair expenses is approximately 35%.

TABLE A-11. COAST GUARD CUTTER - FIELD

Dollars in Thousands

	Labor[1/]	Matls	Total	%C	Corrosion Cost
Propulsion	118	1,231	1,349	29	391
Auxiliary	153	1,758	1,911	29	554
Hull & Structures	412	2,080	2,552	75	1,869
TOTAL	683	5,129	5,812		2,859 (49%)

[1/] Does not include CG Personnel

Corrosion Costs

Dollars in Thousands

	Field		Depot		Total
	Labor	Matls	Labor	Matls	
Propulsion	34	357	703	326	1,420
Auxiliary	44	510	759	247	1,560
Hull	309	1,560	2,354	311	4,534
TOTAL	387	2,427	3,816	884	7,514

4.2 Navy Ships

Corrosion maintenance costs for Navy Ships were the most difficult to obtain and should be considered as representing only an estimate based on available data.

The Navy maintains a ''3M'' (Maintenance and Materials Management) accounting system for maintenance and repair costs. From this system, some costs for maintenance of six classes of ships, accounting for a total of 184 ships, are reported in the ''Ships Data Book Operations and Support Costs, FY 1975''. These data are shown in Table A-12. Costs are collected in three categories: Direct Organizational Costs, which is for work performed aboard ship; Intermediate Costs, which is work performed by the fleet tenders; and Depot Costs. These costs are well documented for these 184 ships. The method selected to scale these costs upward to the total fleet of 535 ships is described in the following paragraphs.

The Direct Organizational Costs and the Intermediate Repair Costs were considered to be costs that did not fluctuate greatly over time since they are primarily for small, routine tasks. Hence for these two costs, the scaling upward to the total fleet was accomplished by multiplying the figures shown in Table A-12 by the ratio 535/184. This implicitly assumes that the costs on all ships would be comparable to this group of 184. In the absence of other directly applicable data, no other assumption could be made.

It was felt that a similar procedure could not be justified for the depot costs which were large and variable. It is reported to us[12] that on the average ships came into the depot for maintenance and repair about once every three years. It does not follow that one third of each class of ships comes into the depot every year for repair. Indeed, an inspection of the variation in the figures for the various classes of ships shown in Table A-12 shows that this almost certainly is not the case. Hence the data indicate that a simple scaling of depot costs as was done for the other costs could be seriously in error.

In an attempt to establish the costs for depot repair of Navy ships, Navy budget documents[13] were consulted. From the figures given on page 766, Reference 13, it is estimated that a lower limit on ships depot maintenance is $693 M for FY 1975. This probably overlooks other ships depot maintenance expenses accounted elsewhere in the budget. On page 593, Reference 13, figures for ships maintenance and modernization as well as other Navy depot maintenance are given. From these it is estimated that some fraction of $2165 M representing ship maintenance and modernization is properly ship depot maintenance for FY 1975. It is estimated that about 50% or $1000 M may be used for maintenance and repair. Thus it is concluded that the expenditures for

TABLE A-12. SAMPLE SHIPS MAINTENANCE COSTS

Information	CV Carrier	AS Sub Tender	LPH Land Platf. heli.	DDG Destroyer	FF Frigate	SSBM Sub	
Type	1	2	3	4	5	6	Total
# Ships	15	15	7	40	66	41	184
1) Direct Organizational Repair Costs (10^6\$)							
a) Labor, maintenance	2.5	1.5	1.3	0.5	3.0	2.2	11
b) All material, total	100	105	13	110	35	80	443
c) Consumables	1.9	1.2	.14	.6	1.3	.2	5.3
d) Reported spare parts	.22	4.3	.21	1.6	8.6	25	40
e) All spare parts includes (d)	11	11	1.2	.6	16	34	74
2) Intermediate Repair (tender) costs (10^6\$)							
a) Labor, maintenance	1.2	4.0	1.6	12	2.0	8.2	29
b) All Material	0.2	2.2	.35	.8	.5	2.5	6.5
c) All Reported spare parts	~0	2.7	.1	.84	.72	22	26.3
3) Depot Repair Costs (10^6\$)							
a) Labor, Maintenance	NA	NA	7	48	60	NA	115
b) Total, Labor & Materials	10	0.3	27	218	213	6	474

ships depot maintenance are between about \$700 M and \$1000 M for FY 1975. This range is somewhat larger than the result in Table A-12 because of actions involving other ships and hence not accounted for in that sample.

The total figures and the corrosion costs are given in Table A-13. To make the estimates, an overall 30% of maintenance costs were attributed to corrosion. That fraction is consistent with the figures developed from the Coast Guard considering the high fraction of the total maintenance costs expended in depot actions. Of the costs listed in Table A-12 for Organizational and Tender actions, only those connected with corrosion-susceptible actions were used. These involve labor and spare parts costs of \$148 M for organizational actions and \$160 M for Tender actions, after scaling to a fleet size of 535 ships. A figure of \$1000 M for total depot repair was used, the upper end of the range given above.

TABLE A-13. MAINTENANCE AND REPAIR

Navy Estimated (535 Ships)

	Materials (10^6\$)	Labor (10^6\$)	Total (10^6\$)	Ratio (Matls/ Labor)	Corrosion Costs (10^6\$) @ 30%
Fleet (Organizational) Level	\$ 116	\$ 32	\$ 148	3.6	\$ 44
Tender (IMA) Level	75	85	160	0.9	48
Depot Level	750	250	1,000	3.0	300
Total	941	367	1,308	2.6	392
Corrosion Costs @ 30%	282	110	392		

The total figure for corrosion maintenance on Navy ships is therefore estimated to be $392 M with the labor and materials breakdown shown in Table A-13. This is subject to a great deal of uncertainty, the magnitude of which cannot be well estimated.

5 ORDNANCE AND ACCESSORIES

The U.S. Army has an enormous inventory of ordnance and accessories which are subject to corrosion. This amounts to some 9.5% of the personal property owned by the government (63,293 billion dollars).

In an attempt to establish which percentage of maintenance costs can be attributed to corrosion several different areas within the Army and DOD were contacted. No data were derived for corrosion related maintenance, redundancy or lifetimes. In the absence of data estimates were made on the basis of data available from related sectors. Adjustments made on this basis to the coefficients ascribed the cost of corrosion as $307 M. This amount appears to be somewhat conservative in light of corrosion costs in other military operations.

6 REAL PROPERTY

6.1 Introduction and Structure of Study

As can be seen from Table A-2, real property in the form of buildings and other structures (but not including land), comprises 36% of the total capital owned by the Federal Government. The inventory of this property is given in Reference 1 by agency and by type. The inventory is a highly variable one. Reference 1 lists ten different types of buildings and sixteen different types of structures and facilities. To do a complete and thorough study of the corrosion costs for all these different types of buildings and structures and facilities would mean visiting every agency for every type, and this was not possible within the resources and time available. What was done basically was to use data available from the Department of Defense, and to deduce the costs for the remainder of the Federal Government from the costs for the DOD, with checks made where possible from the data obtained from other agencies. The agencies that were studied were the DOD, NASA, GSA, the Coast Guard, NBS, and Post Office.

The Department of Defense is the single largest property owner in the Federal Government. Tables A-14 and A-15 give respectively the book value of the inventory of the buildings and of structures and facilities for the DOD and the remainder of the Federal Government, omitting that portion, such as TVA, that do not form part of general

TABLE A-14. COMPARISON OF DOD AND ALL FEDERAL BLDGS (NOT INCLUDING POSTAL SERVICE)

	DOD ($M)	Other ($M)
Housing	6,849	552
Service	6,243	678
Office	1,566	2,805
R & D	1,455	2,634
Industrial	1,205	1,543
Hospitals	817	1,483
Storage	1,618	563
School	1,534	248
Other Inst.	183	333
Prisons	1	60
TOTAL	21,471	10,899
%	66%	34%

Government. The data are taken from Reference 1. It can be seen from these tables that the DOD has custody of 66% of the inventory value of buildings, and 70% of inventory of structures and facilities. Reference 1 also shows that on the basis of floor area, the DOD has custody of 73% of the buildings, which implies that the overall age distribution of DOD buildings is approximately the same as that of the rest of the Federal Government, but slightly older. Thus, to the accuracy with which other data are available in this study, we can say that the DOD has custody of 70% of the buildings and of the structures and facilities owned by the Federal Government. Hence, what was done was to identify the corrosion costs for real property in the DOD, and to scale them up to the total Federal Government by dividing by 0.70. This assumes that the costs in the DOD are approximately the same as in the remainder of the Federal Government. As will be seen, this is not a bad assumption.

TABLE A-15. STRUCTURES AND FACILITIES

Unit	DOD	Other (B$)
Power Dev. & Distri.	3.43	.008
Flood	6.04	0.294 DOI: 0.105 DOT 0.103 Other
Utility	4.01	2.14
Roads & Bridges	1.52	3.14
Reclamation & Irrigation	.063	2.35 (DOI)
Airfield Pavements	2.192	.105
Misc. Military	1.971	.003
SERvice	1.821	.002
R & D	.551	0.255
Storage (except buildings)	.931	0.046
Mon. & Mem.		0.270
Harbor & Port	.676	0.123
Industrial	.121	0.126
Railraods	.392	0.147
Nav. & Traffic Aids	.173	0.167
Comm. Syst.	.348	0.222
Total (%)	24.24 (70.5)	10.106

6.2 Corrosion Maintenance Costs for Real Property in the DOD

A thorough study of corrosion maintenance costs was carried out by C. Hahin of the Army Construction Engineering Research Laboratory[8]. In this study, Hahin investigated real-property maintenance and repair expenditures, both in-house and on contract, at four Air Force installations and three Army installations. By investigating each individual item of work performed and discussing each with the individual performing the work, he was able to estimate what portion of each was attributable to corrosion. This in turn was categorized by the type of system, such as plumbing, heating systems, refrigeration and air conditioning, etc. From these data Hahin was able to develop a comprehensive corrosion costs prediction model relating various environmental factors such as SO_2 content of the atmosphere, soil resistivity, etc., to characteristics of the installations like length of buried pipe, total building surface area, etc.

Hahin's model can in principle predict the corrosion cost quite accurately. However, the large volume of data necessary on the various installations was not available to us and hence could not be used. Fortunately, Hahin also calculated the fraction of all operations and maintenance expenditures that were due to corrosion for each of the bases. Hence, the approach that was adopted was to multiply the total operations and maintenance expenditures for the Air Force and the Army by these fractions to obtain the total cost of corrosion maintenance actions for these two services. The results obtained are, of course, a grosser estimate than would have been obtained using Hahin's methodology. The results are shown in Table A-16, where we also show results for the Navy and the Civil Works Division of the Army. We will now describe how we obtained the figures for these last two services.

Overall figures for operations and maintenance of Navy facilities are contained in Reference 9. These figures indicate that the Navy expended $255 M for this purpose in 1975. However, consultation with individuals at Port Hueneme[10] indicate that this is only about half the amount expended for real property maintenance. The other half is recovered by an overhead charge carried out on repair work done at depots, etc. As a result, the overall maintenance expenditures for the Navy were taken as $500 M for FY 1975. This is exclusive of family housing, of which the Navy has 107 M square feet.

The estimate of the corrosion expenses was then made in two different ways. In one way, 15% of this overall total was attributed to corrosion. This fraction is 25% higher than that used for the Army, and was used because of the proximity to the ocean of Navy installations. This figure is consistent with the judgment of Navy personnel[10]. In another way, each of the specific systems costs listed in Reference 9 was analyzed according to the figures given by Hahin[8] for specific systems, and in addition includes a cost of $0.03/sq ft year for family housing (see below, GSA). Both sets of estimates are given in the table and are seen to be quite consistent.

TABLE A-16. DOD REAL PROPERTY CORROSION COSTS

	M & R ($M)	% Corrosion	Corrosion Cost ($M)
Army, Military	1000 US	12	120
	1630 World		196
Navy	510(1)	15	80(2) 74-87(3)
AF	600	10	60
Army, Civil	380		20
TOTAL			280

(1) Does not include family housing

(2) Includes 3M for 107M sq ft family housing.

(3) By larger calculation from NAVFACNOTE 11%.

The figures for the Civil Works Division of the Army were arrived at from the maintenance expenses for each type of facility. With the help of Mr. Hahin, a fraction was attributed for corrosion for each of these expenses. Because of the nature of these facilities, the fraction is generally quite small. The error in the total estimate is probably substantial, but fortunately the final figure is only a small percentage of the total.

6.3 The Coast Guard

The Coast Guard provided accurate figures for total maintenance and repair expenses for their shore units. These are divided into routine maintenance and repair and major maintenance and repair. To estimate the fraction of these expenses that are attributable to corrosion, the same reasoning as above for the Navy real property was used, and a figure of 15% was assigned. The figures are shown in Table A-17. Here, because of figures provided, a breakdown between materials and labor was possible. This checks very well with data provided by GSA presented below.

TABLE A-17. CG, SHORE UNITS

	Total $K	% Corr.	Corr. $K
Routine			
Labor	12,292	15	1,844
Parts	5,766		665
Major			
Labor	6,983	15	1,047
U.S. parts	1,144		172
TOTAL			3,728.

6.4 NASA

Figures for real property maintenance costs and associated corrosion costs were obtained from discussions with NASA representatives.

In NASA's budget structure, the appropriate costs come in two categories: Capital Rehabilitation, and Operation and Maintenance. In each category, funds are appropriate in two sub-categories: Institutional, and R&D. The corrosion costs for each of these categories are given in Table A-18. It is to be noted that this is an estimate that is completely independent of the DOD study.[8]. This is important, for it will be used in the final estimate made for the Federal Government below.

6.5 GSA

The General Services Administration has custody of a large amount of real property in the form of office buildings. In Reference 1, they are shown as housing custody of 36% of the office buildings space, and 39.4% of the book value of office building inventory in the Federal Government. While this is a substantial amount of real property, in terms of the total Federal Government it amounts to only 2.5%.

TABLE A-18. NASA CORROSION COSTS; REAL PROPERTY MAINTENANCE

Category	Total M$	Labor M$	Materials M$
Capital Rehabilitation			
Institutional	0.9	0.45	0.45
R & D	0.44	0.22	0.22
Operation and Maintenance			
Institutional	3.5 - 5	1.9 - 2.2	1.6 - 2.3
R & D	3.5 - 5	1.9 - 2.2	1.6 - 2.3
Inhibitors	0.1		
TOTAL	8.5 - 11.5		

Accurate figures were provided by GSA on operations and maintenance expenses for the last quarter of 1976 and the first quarter of 1977. A rough calculation from the data of Hahir[8] shows that approximately 13% of these operations and maintenance costs are attributable to corrosion. The corrosion maintenance costs for Navy buildings is estimated to be approximately 8% of operations and maintenance. When it is considered that the GSA buildings are self contained, i.e., contain their own heating and air conditioning plants, etc., whereas the Navy buildings generally involve separate heating and air conditioning, the agreement is satisfactory.

The GSA provided other information that is of importance to our study. This has to do with the lifetime of building systems. Besides operations and maintenance, the GSA has a program called Alteration and Repair. This includes ''Basic Work to Correct Deterioration and Malfunction'', ''Improvement of Space to Promote Utilization, and Special Fire Safety, Life Safety and Property Protection'', ''Special Aids for the Handicapped'', ''Special Environmental Protection Measures'' and ''Special Energy Conservation Measures''. Approximately 60% of the expenses in FY 1977 are for ''Basic Work...'', and clearly some of these are corrosion related.

Figure A-1 shows the expenses in this program as a function of building age. It will be seen that the cost per unit area of building space rises dramatically when the building age reaches 30 years. This corresponds to the average lifetime of major building systems, and is the age when replacement is required.

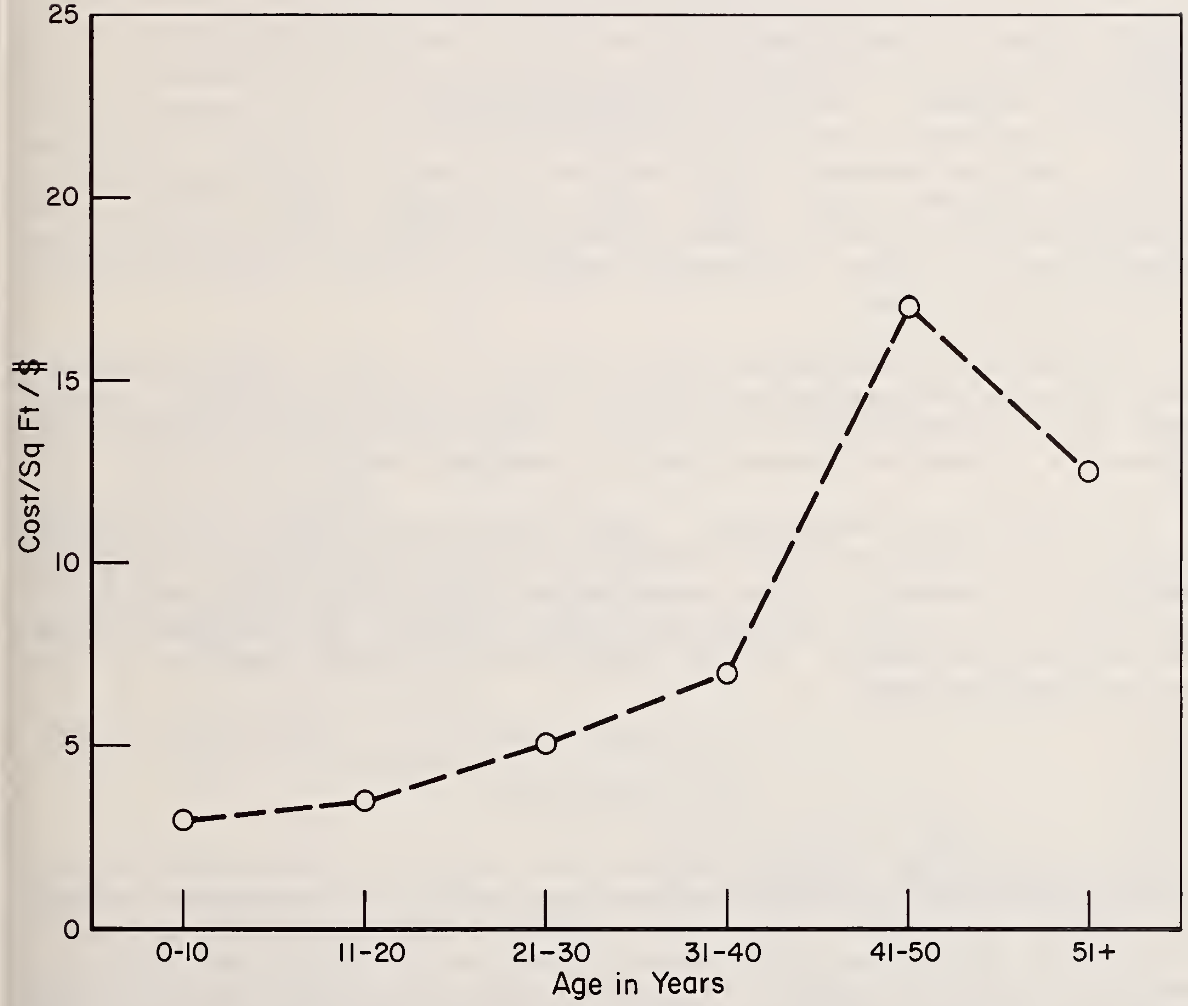

FIGURE A-1. COST OF BUILDING REPAIR AND ALTERATION AS A FUNCTION OF AGE

It should not be assumed that the costs shown in Figure A-1 are the actual expenses of the GSA for this purpose. In fact, only about 10% of the estimated amount necessary is appropriated per year. The remaining amount is the backlog.

6.6 National Bureau of Standards

An intensive and detailed study of corrosion costs at the Gaithersburg site of NBS was also carried out. An itemized list of corrosion expenses incurred in corrosion protection, generally for 1975, is provided in Table A-19. Where costs do not occur on an annual basis, the time between operations was estimated, and the costs distributed uniformly over this time. The largest such item was the replacement of a reactor heat exchanger, which is very likely comparable to the type of cost included by NASA in their capital rehabilitation budget.

The building maintenance costs incurred by NBS are $0.53/sq ft/year. This is comparable to the GSA costs of $0.60/sq ft/year and the Navy of an estimated $0.46/sq ft/year. Additional NBS costs due to the extensive grounds maintenance are not included here.

The corrosion maintenance costs for NBS amount to $0.036/sq ft/year. This is very comparable to the costs of $0.029/sq ft/year at Battelle[11]. Indeed, if the extraordinary heat exchanger expense is subtracted, the cost becomes $0.0284/sq ft/year, an agreement which can only be fortuitous. It is anticipated that these costs will rise as the facility ages.

6.7 Post Office

On the surface it would appear that the Post Office owns a considerable amount of property which is subject to corrosion, namely collection and distribution mail boxes located throughout cities in the United States and real property such as buildings and vehicles. However, a detailed study of the area indicates that corrosion related maintenance costs are minimal. The Post Office Department leases most of its buildings. It also turns out that only a small amount of the maintenance painting of the mail boxes can be attributed to corrosion. The boxes need repainting because of noncorrosion related damage, long before the protective quality of the paint has been compromised.

6.8 Federal Government Summary

Before we discuss the overall summary for the Federal Government we present a table of some unit costs. In Table A-20 we present the yearly corrosion maintenance costs for the agencies we have studied,

TABLE A-19. NBS CORROSION MAINTENANCE COSTS

Water treatment, steam and chilled water: chemicals	$ 20,560
technician salary (50%)	8,746
Calgon consulting	1,150
Cooling tower, deck plate repair, $1,487, est. 5 yr. cycle	300
Electrical failure near cooling tower, $880, est. 4 yrs.	220
Tower fan repair	200
Hood systems, fans and ducts, GP	5,200
Air conditioner buffles, $6,000 over 2 yrs.	3,000
Lab sink drain leaders	2,551
Hot water valve repairs, est. per year	250
Chilled water nipple replacements per year	300
Hot water vertical header lines, $97,684, est. 5 year period	20,000
Exterior metal painting, loading docks, $10,531, est. 7 year period	1,500
Reactor heat exchanger replacement, $326,000, est. 20 year period	16,300
corrosion costs, total, for 1 year, est. about 1975	$ 80,277

NBS total maintenance costs, 1975, $1,200,000 (excluding grounds maintenance)

Corrosion % = 6.7 of maintenance

NBS bulding floor area = 2.25×10^6 ft^2

Corrosion costs 1 ft^2 = $0.036 ft^{-2}

NBS facility cost (initial) = $104,000,000

Corrosion cost/initial value = 0.0008

TABLE A-20. RATIO, YEARLY CORROSION COST TO BOOK VALUE, REAL PROPERTY

	Book Value M$	Corrosion Cost, M$	C/B, $/$ Year
Army Military, U.S.	11,700	120	0.010
Army, Civil	10,100	20	0.002
Navy	9,900	80	0.008
AF	14,300	60	0.0042
TOTAL DEFENSE	46,000	280	0.0061
NASA	2,617	8.5 - 11.5	0.0032 - 0.0044
CG	523	3.73	0.0071
NBS	90	.080	0.0008

and the ratio of these costs to the inventory book value of the property as obtained from Reference 1. This ratio is sensitive to the type of facility, but perhaps more importantly to the age of the facility. Age influences this ratio in two ways. First, since the value of the property is carried as the original acquisition cost, this ratio will be higher for older facilities. Second, as we have seen above in the GSA actual costs are a very strong function of building age, being much higher for older buildings.

The ratio shown in the table varies by a factor of approximately ten from a low 0.0008 for the Gaithersburg site of NBS to a high of 0.010 for the Army. Now, NBS has the newest facilities; NASA had the next newest. Among the DOD facilities, the Army facilities are known to be much older than the Air Force[8] and it is estimated that the Air Force is somewhat older than NASA. Hence, in at least a qualitative way the ratio seems to correlate with building age. A more thorough analysis would require the age distribution of the facilities. We have not done this.

Finally, in Table A-21 we show the final figures for yearly corrosion maintenance costs for real property in the continental U.S. for the total Federal Government. The total was estimated in two different ways. First, the costs developed for the DOD were divided by 0.70 to obtain an estimate from this source. Second, the NASA costs, which are a completely independent estimate were scaled upward to the rest of the non-Defense part of the Government. This scaling assumes (among other things) that building structures and facilities mix for NASA is the same as for the rest of the non-Defense part of the government. In fact, the ratio of inventory value of structures and facilities to inventory value of building for NASA is 1.45:1. Whereas from Tables A-14 and A-15 the ratio is seen to be approximately 1:1 for the non-DOD part of the Government (including NASA). Hence there will be some error in this extrapolation, whose magnitude is hard to assess, but will probably not be too large. In fact, considering the nature of the assumptions, the agreement between the two methods is quite satisfactory. The total was taken as the approximate mean of the two results.

The breakdown into materials and labor is the average of figures for this breakdown provided by GSA and the Coast Guard. The total figure is undoubtedly too low for two reasons: First, it does not include expenses outside the continental U.S. These were obtained for the Army ($76 M, see Table A-16) but could not be obtained for the other services. Second, it does not include that portion of minor construction which is directed to replacement of corroded systems. It is felt that this is small for Defense agencies, but may be substantial for other agencies (see above under GSA).

TABLE A-21. TOTAL REAL PROPERTY CORROSION MAINTENANCE COSTS

	M$
DOD	280
Remainder Federal: (Estimated)	
Scaled from DOD Costs	120
Scaled from NASA	66-92
Selected Value	95
TOTAL	375

REFERENCES

(1) Real Property owned by the U.S. throughout the World, Summary Report, 1975, GSA. Real Property Leased by the U.S. throughout the World, 1975, GSA.

(2) Real and Personal Property of the DOD as of June 30, 1975, and June 30, 1976. By OASD (Comptroller).

(3) Highway Statistics, for 1975 by FHWA, in four volumes.

(4) Statistical Abstracts of the U.S. Department of Commerce, 1975.

(5) FY-76 USAF Maintenance Costs, Provided by Dr. C. T. Lynch, AFML.

(6) USAF Corrosion Data, Manhours Expended for Corrosion Inspection and Treatment, Robert L. Lough, July-September, 1975.

(7) M. Peterson, et. al., ''Feasibility Study for a Diesel Engine Condition Monitoring System for 1179 Class LST's'', 1975.

(8) ''Construction of a Joint Service Facility System Corrosion-Cost Prediction Model'', Christopher Hahin, U.S. Army—CERL, February, 1977.

(9) NAVFACNOTE 11010, ''Facilities Management Statistics'', FY 1975.

(10) Personal Communications, R. T. Weldon, Port Hueneme, California.

(11) Personal Communication, W. Boyd.

(12) Personal Communication, Cmdr. Pearson.

(13) Department of Defense Appropriations for 1977, Hearings before a Subcommittee of the Committee on Appropriations, House of Representatives.

APPENDIX B

CORROSION COSTS IN THE ELECTRIC POWER INDUSTRY

1 INTRODUCTION

This section discusses the special problem areas that impact on the cost of corrosion in the electric power industry. Two broad areas are considered, electric power generation and electric power transmission and distribution. Corrosion problems and corrosion costs are the same in the latter area regardless of the means of generating electricity. However, in the generating field, the problems and the costs vary widely depending on the type of generating plant. Particular emphasis is placed on nuclear generating stations where outages can be costly because of the added cost of buying replacement power generated from higher priced fossil fuels.

The information for this section was obtained from several sources and included a visit to the Electric Power Research Institute where discussions were held with four specialists in the nuclear and fossil fuel fields, some ten telephone calls to well-known corrosion experts in major utility companies (who, in turn, often consulted with economists in their company), and a review of the literature in the overall project reference source plus additional references suggested by those people who were contacted.

2 BACKGROUND

Electricity is generated by several means. Regardless of the means of generating electricity, all systems experience the same type of corrosion problems in the transmission and distribution of electricity, namely atmospheric corrosion of above ground structures and soil-ground water corrosion of buried structures. The major differences in corrosion problems exist in the area of power generation because of the variety of generating systems.

There are five generic types of power plants as indicated below:

- Fossil Fuel
  - Coal
  - Gas
  - Oil
  - Wastes
- Hydroelectric
- Nuclear
- Geothermal
- Solar

The classifications depend on the energy source employed.

Note that there are sub-breakdowns for the fossil plant category and there are even further breakdowns within these categories such as gas turbines and gas-fired boiler. The latter is being drastically reduced due to restrictions imposed on firing boilers with gas because of the natural gas shortage.

Electric power generation from solid wastes, geothermal steam, or solar sources is so small at this time that these sources are not tabulated in the Electrical World 1977 Annual Statistical Report[1]. The present geothermal capacity is about 600 Mw. The Electrical World report projects additional geothermal capacity of 161 Mw in 1978 rising to 245 Mw in 1979 and 1094 Mw for 1980 and beyond. Projections for solid waste are 32 Mw in 1978. The 1977 Statistical Report lists the following generating capacity breakdown for 1976:

Fuel Type	Mw	Percent
Fossil-Steam	366,533	69.5
Combustion turbine	45,661	8.7
Internal combustion	5,287	1.0
Nuclear	42,412	8.0
Conventional hydro	57,636	10.9
Pumped storage	10,161	1.9
Total	527,690	100.0

Combustion turbine represents oil and gas fired direct turbines, internal combustion is power from internal combustion engines, while pumped storage is hydroelectric power that is stored by pumping water to higher elevations during low demand periods for later use during peak demands.

The electrical World 1977 report breaks down actual electricity generated in 1976 as follows:

Type of Fuel	Billions kwhr	Percent
Coal	942.4	53.8
Oil	319.4	18.2
Gas	294.4	16.8
Nuclear	190.7	10.9
Total	1750.5	

The total above includes production from geothermal, wood, and waste but does not address hydroelectric.

3 TRANSMISSION AND DISTRIBUTION CORROSION COSTS

Major corrosion areas in the transmission and distribution portion of the power industry involve the following:

- Atmospheric corrosion—above ground
- Aqueous corrosion—underground
- Aqueous corrosion—underwater

Transmission towers, lines, and hardware; underground cables and equipment; substation equipment; and electric watt-hour meters are the principal items exposed to atmopheric attack. Industry experts assert that electric meters are well sealed and corrosion plays little or no role in their operation or service life. Approximately 98 percent of the transmission towers in use are constructed of galvanized steel[2]. In 1970 the estimated inventory was $1,165,000,000[2]. Towers in rural areas last 25 to 40 years before rusting which is within design life. However, towers in polluted areas rust within 5 to 15 years. These towers represent 12.5% of the total. Painting galvanized steel extends tower life by about 8 years in polluted air. Based on 1970 data of 194,000 towers, a cost of $375 to $1000 to paint a tower, and 12.5% of the towers in polluted areas, an annual corrosion loss of $1,480,000 was calculated[2]. Based on the average inflation rate since 1970 this figure projects to $2,380,000 in 1975 dollars.

Corrosion underground or underwater is mostly controlled by coatings plus cathodic protection with the major difference being heavier coatings for underwater service. Costs of the cathodic protection-coating system are assumed to be about the same as in the gas industry, where estimates were available, namely, 0.05 percent of the total installed cost.

Increasing attention is being given to corrosion of bare copper concentric neutrals on buried cable. The extent of the problem has not yet been defined. Part of the difficulty lies in the fact that cables with corroded concentric neutrals can continue to function via earth or adjacent conductors. Thus, they do not provide the intended low impedance path for load and short circuit currents and can pose a safety hazard during dig-ins or other operations involving personnel.

A survey prepared by Harco for EPRI[3] reveals a reported incident rate of 0.006 per cable mile, which extrapolates to $60,000,000 replacement based on the incident rate of 0.006 per mile, although Harco feels the problem is more widespread than most believe. Some 200,000 miles of this type of cable are now in service. Estimated replacement cost is $50,000 per cable mile which extrapolates to $60,000,000 replacement based on the incident rate of 0.006 per mile although complete replacement may not be necessary to effect repair.

4 MAJOR SPECIFIC CORROSION PROBLEM AREAS

4.1 Coal Fired Units

Coal-fuel power plant performance is boiler dominated. Total unit outage time for coal plants is about 1.25 times the boiler outage while the total time spent in all outages is about 2.5 times the boiler outage according to the Edison Electric Institute data base. According to an industry expert, most outages in today's coal plants are due to corrosion and many trace to variable fuel supplies which require plants to operate on coals of different quality from that specified in original designs.

Boiler failures occur on the water-steam side of boiler tubes as well as on the fire side. A survey made in 1970 of 640 high-pressure boilers operating over the period 1955 to 1970[4] revealed 20% of the units experienced forced shutdown because of internal water-steam side corrosion. Sixty-two percent of these failures were the result of corrosion gouging associated with high alkalinity while the remainder were brittle hydrogen damage associated with contamination and low pH conditions.

The second major cause of outages in coal plants is turbine failure. Stress-corrosion cracking and corrosion fatigue of blades and deposits on the blades are principal causes of outages. Forced outage from turbine malfunction representes about 20% of total downtime compared to 67% for the boilers[5] .

Coal plants have planned outages of 700 to 1000 hours/year to maintain turbines and boilers. Some of this planned outage can be accomplished in the shadow of major forced outages so that not all downtime in a forced outage due to corrosion can be debited to corrosion.

4.2 Gas Fired Units

Gas-fired boilers are being phased out because of the critical natural gas shortage. Thus, principal corrosion failures in gas fired units will now be in the gas turbine units. High-temperature corrosion is reported by some experts to represent 25 to 33 percent of maintenance costs on blades where total maintenance costs run 5 to 6 mils/kwhr. Thus, based on the 294.4 billions of kwhr generated by gas in 1976 as reported in Electrical World, a potential corrosion loss of $5,000,000/year can be projected for gas turbines.

4.3 Oil-Fired Units

Oil-fired steam plants experience the same steam-side corrosion as coal-fired units. On the fireside, corrosion problems come from two sources: vanadium-sodium and sulfur-sodium. The vanadium problem is related to vanadium oxide present in some sources of oil that combines with sodium salts (usually NaCl) to form sodium vanadates. The latter possess low melting points and upon depositng on boiler tubes serve to flux the normally protective oxide film thereby causing increased oxidation. The sulfur problem is somewhat similar. During combustion, sulfur in the fuel oil combines with sodium salts (NaCl) to produce low melting sodium sulfate salts. Increased oxidation plus sulfidation results from this fluxing action which is popularly termed ''hot corrosion''.

Hard data are scarce on the costs of corrosion in oil-fired units. The overall cost is accounted for in maintenance costs which will be discussed later.

4.4 Hydroelectric Units

Principal corrosion problems in hydroelectric power plants are related to the turbine, piping, and pumps. Because of the low-temperature aspect of hydroelectric power, the corrosion-erosion is not greatly accelerated and is of the order of that experienced in the water and sanitary services industry sector 18.04.

4.5 Geothermal Units

Corrosion is a serious problem in geothermal power production. Piping, valves, pumps, and turbines all are attacked by the high-temperature acidic sulfide brines characteristic of this power source. Corrosion probably accounts for at least 80% of the outages in this segment of the industry, but total power output is so small that the input to the overall cost in the entire industry is not significant.

4.6 Solar Units

Electric power generation by solar units is still in the embryonic stage. Depending on which concepts are used, the potential corrosion problems will be marine corrosion (and fouling) of Ocean Thermal Energy Corrosion (OTEC) units, atmospheric deterioration of solar collectors, corrosion and erosion of wind generators, chemical attack of bio-mass units, aqueous corrosion of water storage units, and high-temperature water and steam corrosion of central station solar thermal units.

4.7 Nuclear Power Plants

The Electric Power Research Institute (EPRI) has conducted extensive studies on costs in the nuclear power industry. Lapides and Zebroski[6,7] relate the costs to outage duration rather than to the maintenance costs during the outage. Their reasoning is based on the large price differential between power generated by nuclear plants as compared with replacement power which must be purchased from fossil fuel plants. For a 1000 Mw nuclear plant, this cost differential can run as much as $500,000/day. Actual costs for power generated from coal and oil are reported by industry experts to be some 30% greater than that produced by nuclear. In rare cases, where the replacement power must be obtained from peaking units fueled with emergency gas, the cost difference can be as great as 700%. The incremental direct cost—mostly fuel—is about 100% higher for coal replacing nuclear, and 300 to 900% for oil or gas replacing nuclear. The cost-differential approach to costs appears valid since corrosion-related shutdowns require extra reserve capacity (capital cost), the replacement power is generated by a more costly fuel, and the replacement power is probably generated by a less-efficient system (older plants).

Lapides and Zebroski [6,7] have summarized the details of nuclear power plant shutdowns. Their data are summarized in Tables B-1 and B-2. Industry expert estimates of the percent of each outage cause due to corrosion are included in Table B-1. Note that when each outage percentage is adjusted for corrosion that the total outage due to corrosion is about 48 percent. This figure agrees well with the 50 percent figure due to corrosion that is often quoted for outages by experts in the power industry.

Several items in Table B-1 require additional mention. Note the high percentage attributed to corrosion for turbines, steam generators, and condensers. The latter two will be discussed in more detail later. The turbine problem is related to corrosion-erosion by the relatively low temperature wet steam that is generated by nuclear plants.

Although refueling represents the major outage percentage, corrosion problems are estimated to extend refueling outages by 50 percent. Similarly, downtime due to regulatory requirements also is about 50 percent corrosion related.

TABLE B-1. REPRESENTATIVE AVERAGE OUTAGE DURATION AND PARTIAL POWER REDUCTION IN NUCLEAR UNITS THROUGH JANUARY 1, 1976[6]

A. ITEM	DURATION (HOURS)	PERCENT TOTAL	CORROSION RELATED PERCENT OF, OUTAGE[a]	TOTAL
Forced Outage (Equipment Malfunction)				
Turbine/Generator	140	5.1	80	4.0
Condenser	105	3.8	60	2.3
Steam Generator	120	4.3	60-100	3.0
Pumps	75	2.7	25	0.7
Valves	122	4.4	30-40	1.4
Vessel and Core	60	2.2	25	0.5
Plant Electrical Distribution	90	3.2	-	-
All Other	281	10.1	50	5.0
SUBTOTAL	993	35.8		
Scheduled Outage				
Maintenance	288	10.4	50	5.2
'Refueling'	1350	48.7	50	24.3
Training and Administration	30	1.1	-	-
SUBTOTAL	1668	60.2		
Regulatory	112	4.0	50	2.0
TOTAL	2773	100.0		48.4

- Availability Factor (Based on One Year Operation Between Refueling)

$$1 - \frac{2773}{8760 + 1350} = 72.5\%$$

B. Partial Power Reductions (Approximate)

Fuel Defect Related
Equipment Failure Related
Regulatory Issues
Load-Following
Time to Come to Full Power
All Other and Unaccounted

OUTPUT FACTOR
(PRODUCT)

- Capacity Factor = Availability x Output Factor

$$72.5\% \times .84 \cong 61\%$$

(a) Estimated by industry expert

TABLE B-2. MALFUNCTION RATE AND MEAN-TIME-TO-REPAIR (MTTR) DATA FOR NUCLEAR PLANT AVAILABILITY ESTIMATION*(7)

COMPONENT OR SUBSYSTEM	λ INCIDENT/YEAR	MTTR (HOURS)	C_{90} INCIDENT/YEAR
A) Derived From This Study			
Turbine	1.74	44	-
Generator	.07	60	.14
Condenser	.68	12	.90
Steam Generator	.43	90	.67
Reactor Vessel and Core	.25	20	.36
Pumps			
Condensate and Booster (BWR)	.012	17	.027
(PWR)	.025	21	.041
Recirculation (BWR)	.30	90	.42
(PWR)	.13	178	.19
Condenser Coolant	.0065	6	.022
Make-up/Charging (BWR)	NF	NF	-
(PWR)	.01	50	.04
Heater/Drain	NF	NF	-
Main Feedwater (BWR)	.040	62	.12
(PWR)	.19	19	.30
Component Closed Cooling Water	NF	-	-
Service Water (BWR)	.012	30	.04
(PWR)	NF	-	-
All Pumps (BWR)	.036	-	-
(PWR)	.050	-	-
Valves			
Stop/Isolation	.003	85	.0035
Safety/Relief	.022	62	.024
Main Steam Isolation	.063	61	.067
Bypass	.007	42	.012
Control/Regulation	.030	37	.042
Check	.009	53	.016
Governor	.011	34	.016
Discharge	.004	17	.006
Intercept	.006	24	.013
All Valves			
B) Derived from EEI Data Sources			
Plant Piping	.00113	20	-
Feedwater Heaters	.11	54	-
Switchgear and Electrical	.140	18	-
Operator Error	1.2	7	-

*Notes:

1) These data are for events causing full power outage - or mandating full isolation of the component in the case of a multi-loop system. Condensers in particular frequently undergo repair with partial power outage only.

2) λ = Observed Malfunction Rate/Active Operating Year

MTTR = Mean-Time-To-Repair (Hours)

C_{90} = Malfunction Rate at 90 Percent Confidence Level

3) Note that data for supporting systems (e.g., radwaste) and safety equipments are not included.

4) Conversion of availability to inherent capacity factor data requires empiric assessment of scheduled outage, refueling and factors which decrease output factor. See Reference 1, pages C10-11.

5 SPECIAL PROBLEMS

Several special corrosion related problems have beset the nuclear power industry. The first of these is associated with boiling-water reactors (BWR's). To date, stress-corrosion cracks have been detected in heat affected zones of some 80 welds in small diameter (<2 in.) piping out of some 17,000 welds in service. Major costs have been associated with downtime to replace affected components, determine cause, and justify replacements.

A second problem is associated with steam generator tubes in pressurized-water reactor plants (PWR's). Chronologically, outages have occurred as the result of caustic stress-corrosion cracking of the tubes, phosphate (water treatment chemical) attack of the tubes, and runaway corrosion (denting) of the steel support plates surrounding tubes.

Denting attack in steam generators in several plants has progressed to the point that replacement is being considered. Estimated replacement costs vary from $30 to 50 million[7] per plant depending on whether the steam generators can be introduced through existing hatchways or whether openings must be made in the containment vessel. Estimated downtime will be 6 months to 2 years depending on the same entry problems. In addition to these costs, a group of utilities plans to spend some $40 million to attack the problem and EPRI has committed another $3 to 4 million[8].

Many utilities are retrofitting condensate polishers to further reduce the possibility of chloride intrusion which is believed to be the major contributor to denting. According to utility experts, the total cost for these units will be about $7 million per plant. If condensers are replaced with improved designs consisting of double wall tube sheet construction and titanium tubes, the cost would be an additional $10 million/plant.

Also in the generating part of the industry, a common problem in all steam plants is corrosion of the condenser. After initial problems with leaking tubes because of unrolled tubes (in tube sheet) and vibrations and steam impingement, most condenser problems are corrosion related. Because of the potential for leaking condensers, additional costs are required for ion exchange equipment and boiler water chemicals to prevent corrosion and fouling. Marked improvement in condenser performance is a major consideration for World III best practice efforts.

6 GENERAL CONSIDERATIONS

Maintenance represents a major cost in the electric power industry. According to the Electric World 1977 Annual Statistical Report, maintenance costs in the power industry were 3.7 billion in 1976 and will be 4 billion in 1977. Percentage breakdowns for 1976 were:

Category	Percent	Amount, millions
Generation	53	1,900
Transmission	8	320
Distribution	34	1,300
Miscellaneous	5	177

Applying an estimate of 10 percent corrosion factor to the last three items and the industry-acknowledged 50 percent factor to the generation portion results in an average $1.1 billion as the annual maintenance cost due to corrosion in the power industry.

Excess capacity in the power industry is generally agreed by experts to be about 20 percent. As stated by one expert, ''with 30 percent excess capacity a company is in good shape, with 20 percent excess capacity a company can get by with good management, while with only 10 percent excess capacity a company is in trouble''. Almost all the excess capacity is in generating plants. Since the cost of corrosion in generating plants is about 50 percent, the excess capacity required because of corrosion is estimated to be 10 percent of the total capital investment.

A sizeable item in the cost of doing business in the power industry are expenditures for research. Electric Power Research Institute expects to fund $180,000,000 for research in 1977. This plus the industry's $25,000,000 annual contribution to the Clinch River Breeder Demonstration Plant and an estimated $200,000,000 total research sponsored by individual utilities in 1977 brings the total expenditure for research to about $400,000,000. According to the 1977 Electric Power Research Institute Digest, of the 3,000 utility research projects listed with a total funding of $250,000,000, some $11,800,000 or 4.75 percent was corrosion related. Thus, the total, annual cost of corrosion related research is estimated to be 4.75 percent of $400,000,000 or approximately $10,000,000 for 1977. The percentage for 1977 is up somewhat over that tabulated in the data base for all prior research funding which was 4 percent ($30,000,000 for corrosion research compared to $754,000,000 for all research).

7 CONCLUSIONS

The major corrosion cost in the electric power industry appears to be associated with generating power. As much as 50 percent of the outages (downtime) have been attributed to corrosion. Downtime affects costs in three areas: maintenance costs, lost revenue plus higher costs for replacement power, and capital to maintain excess capacity (reserve). The cost of replacement power is greatest for nuclear plants where the price of fossil fuel is much higher than that of nuclear fuel. Corrosion problems have been dealt with in fossil and other non-nuclear generating plants for many years and reasonably good economical fixes have been developed. Thus, further application of good corrosion practice is not expected to have a major effect in reducing costs in these plants. However, solutions to the corrosion problems in nuclear plants should effect a major reduction in costs.

It appears that some, but no major, reduction in costs can be realized with further application of good corrosion practice in the areas of transmission and distribution of electrical power, since considerable experience also has been gained over the years in dealing with corrosion problems in these areas and reasonable economical fixes have been developed. Solutions are needed for the corrosion problems with bare copper concentric neutrals on buried cables. However, the extent of the problem has not yet been ascertained so that the economic benefits to be gained by such a solution cannot be predicted at this time.

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APPENDIX C

CORROSION COSTS FOR PERSONALLY OWNED AUTOMOBILES

1 INTRODUCTION

The automobile industry was one of the industrial sectors selected for more detailed analysis. The scope of the study did not provide for surveys or analysis to generate new data, but rather the approach was to collect available imformation from the literature and interviews with technical experts. In this section of the report results of previous studies on various aspects of corrosion costs associated with automobiles are presented with a discussion of factors affecting corrosion of automobiles. The costs of corrosion for providing corrosion protection to automobiles during manufacture is then discussed, followed by a discussion of operating corrosion costs for maintenance, repair, and corrosion control for automobiles. The information presented here was used as a basis for estimates of corrosion effects associated with automobiles in the Input/Output analysis.

The automobile industry is aware of corrosion and its detrimental effects on their products. These companies employ materials and corrosion specialists to conduct and monitor programs aimed at controlling or preventing corrosion. Special facilities exist in the laboratories and at proving grounds specifically oriented towards corrosion evaluation and prevention. In addition, exposure tests in the field are often conducted to correlate the R&D findings with real world situations. At the present time many forms of corrosion prevention measures are employed, including

(1) Metallic paints and coatings offering galvanic protection

(2) Organic coatings, with or without metallic components

(3) Inorganic coatings

(4) Metallic (electroplated) coatings

(5) Corrosion inhibitors

(6) Physical separation of dissimilar metals

(7) Substitution of materials

(8) Improved design

(9) Improved fabrication techniques.

Many of these measures are discussed below by comparing costs in a World III scenario (best corrosion control practices used) with the World I (existing technology) and World II (no corrosion) scenarios.

2 PREVIOUS ESTIMATES OF CORROSION COSTS

To place the results of the present study in perspective, it is desirable to know what estimates exist in the contemporary literature for automobile related corrosion costs in the U.S. Both the original equipment and the replacement (maintenance and repair) markets have been included in Table C-1 where data are available. The products manufactured by the automobile industry are subject to corrosion attack, and this attack can decrease the aesthetic value of the product; or the properties of some structural members; or specific components can be degraded. (For example, perforation of mufflers and tail pipes can occur.)

Early data[1-3] were concerned largely with the replacement costs of mufflers and tail pipes, and based on prior estimates made by Uhlig. In 1960, for example, Reference 2 reported that corrosion damage to automobile exhaust systems cost the owners \$500,000,000. This total was broken into \$375,000,000 for mufflers (30×10^6 units sold) and \$125,000,000 for tail pipes (35×10^6 units sold). More recent estimates[4-7] attribute a cost of \$700,000,000 to the corrosion related replacement of mufflers and tail pipes, while total automobile and truck corrosion-related costs have been set at about \$5,000,000,000 to \$7,000,000,000. Note that these dollar values given have not been translated into 1975 constant dollars. However, from the data presented it would appear that in 1975, the reference time frame, the average automobile owner incurred a cost of at least \$40 per annum, primarily as a result of body corrosion and corrosion of the exhaust system. This value is in close agreement with similar estimates[9] made for automobile owners in the U.K., although driving habits and environmental conditions vary somewhat from those found in parts of the U.S.

Another point made in the literature is that in the ''snow-belt'' regions, where salt used on highways and bridges for deicing purposes increases the rate of corrosion attack, preventative ''rustproofing'' or ''undercoating'' can lessen the amount of attack, hence lower the depreciation rate and improve the resale value of an automobile. Estimates of savings vary widely. For example, Reference 1 gives an estimated resale value of a 3-year-old, rust-proofed vehicle some \$200 to \$300 more than an untreated vehicle. More recently, the National Assocation of Corrosion Engineers tried to obtain quantitative data, but with limited success, and an estimate of \$100 to \$150 was considered to be more realistic.[29]

TABLE C-1. AUTOMOBILE RELATED CORROSION COSTS FOUND IN THE LITERATURE

Year	No. of Cars Registered (Millions)	Corrosion Cost, $ x 10^6 Mufflers and Tailpipes	Total	Cost+ per Car, $	Reference
1956	∿52	66	1,030	∿20	1
1960	61.4	500	-	-	2
1967	80.0	500	∿5,000	∿62	3,19
1975*	106.7	-	>2,000++	>19	4
1976	∿135**	-	5,000**	∿37	5
1976	∿135**	-	5,500**	∿41	6,22
1976	∿135**	700	6-7,000**	∿44-52	7

* Reference year for the present study.

** Estimate for cars and trucks.

\+ Obtained by dividing the estimated "total" cost (column 4) by the number of cars registered in that year (column 2).

++ $2,000 x 10^6 only due to highway deicing salt usage.

3 FACTORS AFFECTING CORROSION

Today a much better appreciation exists[20] of the many factors which affect corrosion of automobiles, either directly, such as the influence of design or choice of materials of construction, or indirectly, such as changing or different patterns in driving habits. Steps taken to apply this knowledge to build a more corrosion resistant automobile, or to educate the driving public in proper care and maintenance and driving habits, all contribute to the costs of corrosion. Specific examples of some of these costs are detailed in subsequent paragraphs.

For the purposes of this present study, in 1975, the reference years, although there was an understanding of the factors affecting corrosion, the implementation of the necessary technology to prevent or minimize corrosion was not fully applied for a variety of reasons. Other requirements placed upon the automobile industry also necessitated considerable expenditure of time and money, notably the need to reduce pollutant levels in exhaust, and to reduce weight in order to improve gas mileage, so as to conserve petroleum supplies. These other requirements may themselves indirectly affect the cost of corrosion. For example, reducing weight by using thinner gage materials further increases the need to minimize corrosion attack, particularly of the localized type.

Between 1977 and 1980, however, there is a consensus that adequate materials and corrosion control methods will be implemented to give a product acceptable to the consumer in terms of its rate of degradation (corrosion) and initial cost premium resulting from the corrosion control methods implemented. Table C-2 lists some of the possible approaches to controlling automobile corrosion under the categories of modifying the environment, design, and materials. Factors such as proper and adequate maintenance and care are discussed in Section 5.

Of the three types of possible approaches listed in Table C-2, modifying the environment is likely to be the least effective technically and economically. Reported efforts to modify the environment have met with only limited success. The addition of corrosion inhibitors to road (deicing) salts has been shown to be ineffective.[13] The use of plastic film-forming materials[14] to replace road salt is in the experimental stage, but the indication is that this approach will not be cost effective. Similarly, heating large stretches of road surfaces to melt ice is impractical. Because it is not practical to modify the environment, recourse must be made to other approaches such as the careful selection of corrosion-resistant materials and coatings, and the implementation of good corrosion design practices. In marine areas where salt deposits can form on automobiles, in rural and industrial areas where dust and chemicals can settle or be present in rainfall, and in the ''snow-belt'' region where deicing salts are used extensively, frequent car washing to remove these soils can

TABLE C-2. POSSIBLE APPROACHES TO CONTROLLING AUTOMOBILE CORROSION

Item	Approach
Modify Environment	• Reduce salt usage • Use alternative road deicers • Reduce pollution levels
Modify Design	• Minimize number of traps for moisture, mud • Provide good drainage • Use preferred joining techniques
Modify Materials	• Specify new alloys • Use inorganic coating • Use organic coatings • Add inhibitors • Use protective shields and other non-metallic materials • Use metallic coatings

This table is given to illustrate some of the approaches which might be possible under each category: each approach has to be analyzed for technical and economic feasibility before being specifically considered for use in conjunction with automobile corrosion control.

reduce the incidence of corrosion. These car washings may be considered as indirectly modifying the environment, and in a detailed analysis would constitute one of the costs of corrosion.

Assessing a cost for modifying automobile design to improve corrosion resistance has not been attempted because it could be considered as part of the engineering development of a new product. There is some controversy[15] over whether design costs should be allocated in this manner; however, there is no doubt that improved designs can significantly reduce the occurrence and extent of corrosion. Reference 16 is an excellent review of current practice and thinking in this area.

Modifying the materials of construction, that is selecting alternative materials which are more corrosion resistant; applying corrosion resistant coatings; adding inhibitors to fluids such as coolants, oils and waxes, or to sound-deadening materials; and using plastic inserts or coatings in wheel arches or on lower body panels to resist chipping (exposing bare metal which can subsequently corrode) are all examples of modifying materials which can substantially reduce the incidence of corrosion attack. This is the other area where much attention has been placed in recent years, and which affects the cost of the automobile. Thus, in the following discussion emphasis will be placed on materials technology, and how changes over the last few years have impacted the cost of an automobile. This increased cost for corrosion control represents a major component of the cost of corrosion attributable to automobiles.

4 CORROSION CONTROL AND COSTS IN NEW AUTOMOBILES

Because measures and materials being incorporated into automobiles in 1977 reflect good corrosion control practices, and it is anticipated that improvements incorporated between 1977 and the near future will only add a relatively small increment in manufacturing cost, it is convenient to use 1977 cost data for assessing best available technology relevant to the 1975 reference year for the Input/Output Model.

Table C-3 lists the principal materials to be found in a 4000 lb, six-passenger vehicle which comprised over 70 percent of the vehicles registered and used in 1971.[17] Both original usage (new automobiles) and replacements averaged over an assumed 10 year life are presented. It is obvious that over 80 percent of the automobile's weight results from the iron and steel present, materials which require protection from corrosion attack. The majority of the other metals which are listed are used as alloying additions, or as electroplated decorative and corrosion-resistant coatings. Some lead is used in bearings and solder, but the majority is associated with the automotive battery in which corrosion is small and will be neglected for the purposes of this study. Copper is a more corrosion resistant material, and does

TABLE C-3. MATERIALS BREAKDOWN FOR AN AVERAGE 4000 lb, SIX-PASSENGER AUTOMOBILE

Material	Original Equipment Materials Requirements (lb/car)	Aftermarket Materials Requirements (lb/Car-Year)	Percentage AM to OEM Materials Over a Ten Year Span
Iron (including that in steels)	3440	49.6	14.4
Aluminum	65	1.77	28.3
Lead	28	9.93	355.0
Copper	30	0.79	26.3
Zinc	65	1.22	18.0
Nickel	4.5	0.04	8.9
Chromium	8	0.02	2.5
Molybdenum	0.5	--	--
Manganese	12	0.35	29.2
Silicon	18	0.25	13.9
Tin	2.0	0.004	2.0
Synthetic Rubber	122	23.25	190.0
Plastics	100	2.55	25.5
Ethylene Glycol (antifreeze)	19	4.4	230.0
Petroleum Lubricants	18.2	25.8	1420.0
Electrolyte (battery grade acid)	11	3.26	296.0
Insulation	5.2	0.70	134.5
Glass and Ceramic	90	2.14	23.8
Paper	5	1.05	210.0

1971 data taken from Reference (17).

not rapidly deteriorate when incorporated into the automobile wiring circuits. The corrosion of radiators will be discussed later. Aluminum finds use as decorative trim for example, and as a corrosion resistant material. In later automobile models, where weight savings are important, the percentage of aluminum is likely to be higher because of applications such as bumpers, even hoods. In 1975, for example, the usage of aluminum had risen to about 87 lb per automobile. The nonmetallic materials listed in Table C-3 will not be subject to corrosion in the sense adopted for this study (degradation of metals). Ferrous materials are therefore those of greatest concern to the present study, and Table C-4 shows a breakdown of automotive steel consumption in the U.S.[18] for both 1971 (the baseline used in Table C-3) and 1975 (the baseline for the Input/Output Model).

Various techniques may be used for protecting the large amounts of iron and steels used in automobiles where surface appearance is important, or where structural integrity must be maintained. As Table C-2 shows, metallic, inorganic and organic coatings, or combinations of these, may be used. Alternatively, in critical areas (subject to relatively more wear, impingement, or corrosive environments) materials may be substituted. A brief discussion of these coatings and materials follows. Different manufacturers use different amounts or combinations of these materials.

Figure C-1 shows the trends in the use of galvanized sheet and strip and ''Zincrometal'' in passenger automobiles. Zincrometal is a proprietary inorganic coating containing zinc placed on specially treated coil steel.[5] In 1969, when this two-coat system was introduced a total of only 150 tons were used. By 1975, this total had risen to about 250,000 tons, or approximately 75 lb per automobile produced. In 1977 production is expected to be about 1,000,000 tons, or the equivalent of about 200 to 250 lb per automobile. It is currently being used on exterior parts such as doors, fenders, quarter panels, rear decks and tail gates, as well as for some underbody structural parts. Reference 5 describes the use of Zincrometal on Ford Motor Company and General Motors Corporation products.

The use of galvanized steel in the automobile industry has remained fairly constant over the last 5 or so years. There was a temporary drop in average usage* in 1975, but there is some indication now that the usage is increasing[29] as shown by the projections in Figure C-1. At the same time it is expected that the use of Zincrometal will level off; however, the total use of zinc (including the use of zinc-rich paints as discussed below) is expected to show a continued upward trend.

*Computed by dividing the total tonnage used in the automobile industry by the new car production figure for that year.

TABLE C-4. BREAKDOWN OF AUTOMOTIVE STEEL CONSUMPTION IN THE USA

Type of Steel	Consumption (net tons) 1975	1971
Ingots, blooms, slabs, billets, sheet, bar	266,703	444,363
Wire rods	60,029	59,679
Structural shapes	33,972	188,268
Plates	187,495	252,678
Hot rolled bars	2,012,485	2,360,046
Cold finished bars	167,315	205,499
Pipe and tubing	179,950	167,839
Wire	87,502	144,576
Black plate	9,699	12,944
Tin plate	73,129	63,061
Tin free steel	2,170	1,155
Tin mill products	30,638	38,370
Hot rolled sheet	4,490,058	4,654,795
Cold rolled sheet	6,088,857	6,935,083
Galvanized sheet and strip	656,769	857,390
Metallic coated sheet and strip	331,227	355,914
Electrical sheet and strip	6,365	7,371
Hot rolled strip	401,567	561,279
Cold rolled strip	128,302	172,559
Net total steel product	15,214,232	17,482,869
Percentage of shipments	19.0	20.1

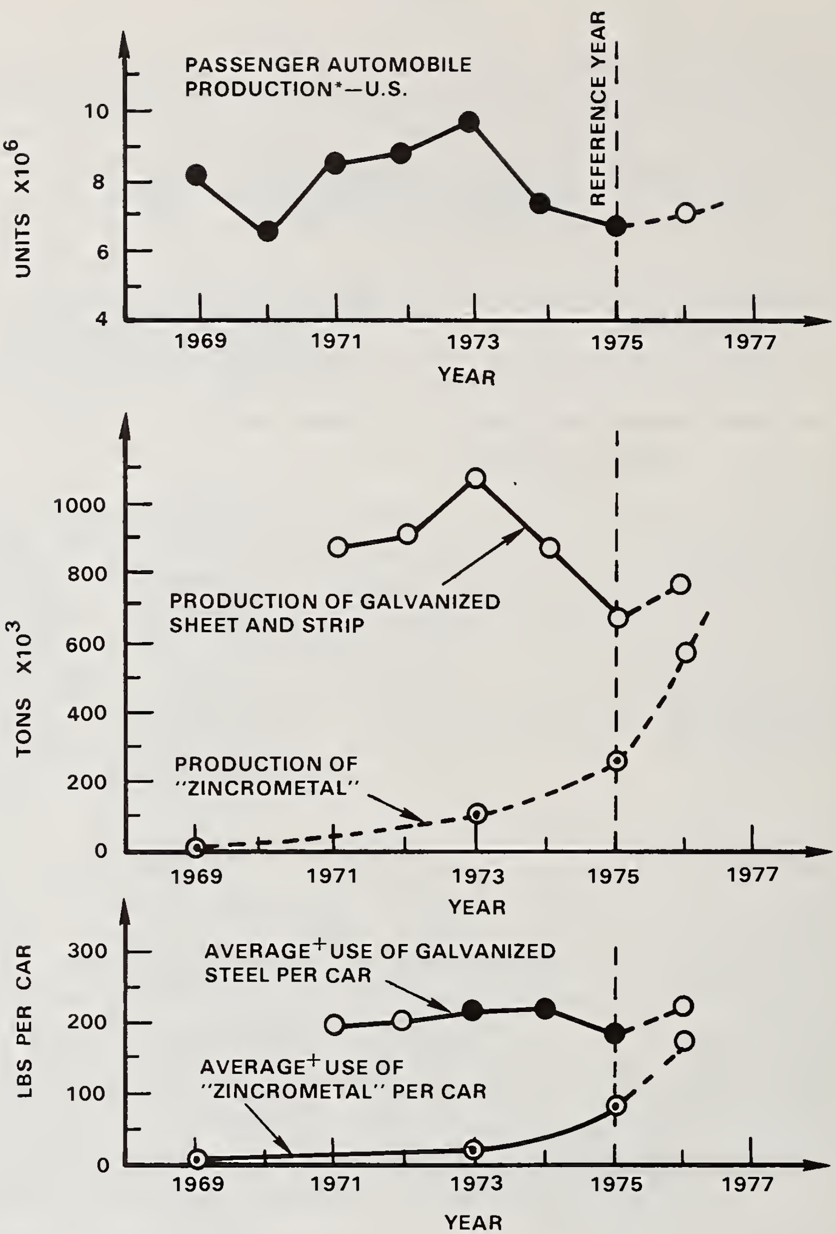

FIGURE C-1. SOME TRENDS IN USE OF ZINC FOR CORROSION PREVENTION IN PASSENGER AUTOMOBILES

* Open circles and dashed lines represent estimated values.

\+ Average weight is computed by dividing total tonnage used in the automobile industry by the new car production figure for that year.

What might be the cost of incorporating these more corrosion resistant materials in new automobiles? In 1975, the 75 lb of Zincrometal used per car would have cost approximately $2.00 to the manufacturer. New car production in 1975 is given[21] as 6,717,043 units, thus the total cost to the manufacturer in the 1975 World I scenario was about $\$13.5 \times 10^6$. In 1977, the cost of cold-rolled steel for the automotive industry was $375/ton compared with $429/ton for Zincrometal, thus a premium of $54/ton (about $2 per car) is being paid for the corrosion resistance imparted as opposed to the World II scenario, where, if no corrosion existed, the unprotected cold-rolled steel would be used. The additional cost of using Zincrometal to manufacture a car in 1977 (taken as being representative of the World III scenario) is estimated to be $\$45.6 \times 10^6$, based on a value of about $6.00 per car and an estimated new car production figure of 7,500,000 units.

The use of galvanized steel has remained fairly constant over the last few years (Figure C-1) in terms of weight. Part of this trend is the use of thinner hot-dipped coatings, the use of one-side galvanized, electrogalvanized, and other specialty forms which use less zinc per square foot of steel covered. For exterior surfaces the use of Zincrometal became more prevalent because of the better paint finish obtained. In 1975, about 195 lb of galvanized steel was used on each new automobile.[18] A ''paintable'' galvanized steel costs $440/ton in 1977, while a high quality temper-rolled or electrogalvanized steel costs about $560/ton. Taking the lower value, the premium for using galvanized steel in a World I compared with a World II scenario is 440-375 or $65/ton, or about $6.35 per automobile. The total cost amounts to $6.35 \times 6{,}717{,}043$, namely $\$42.6 \times 10^6$ per annum for the 1975 production.

The use of galvanized steel in the automobile industry increased by about 15 percent in 1976 according to Reference 30. Assuming the use increases by another 10 percent in 1977, followed by a levelling off in usage, the cost of corrosion in the World III scenario is estimated to be about $\$53.9 \times 10^6$.

Zinc dust is used in zinc-rich paints which are sprayed on surfaces needing additional protection, or in areas which are relatively inaccessible or not suited to other corrosion protection treatments, e.g., in the fenders, on frames, or in quarter panels. In 1975, an average of about 2.5 lb of zinc dust (just over 3 lb of zinc-rich paint, 80 percent solids content) was used per automobile at a cost of 49.¢/lb. In 1977, the cost of zinc dust was lower at about 49.5¢/lb but the usage was in the range of 4 to 18.5 lb per car, with an average of approximately 8.5 lb (10.6 lb zinc-rich paint). With 6,717,043 cars produced in 1975, and an estimate of 7,500,000 in 1977, the added cost of using zinc-rich paints becomes $8,312,341 for 1975 (World I) and $30,281,250 in 1977 (World III).

Metallo-organic, petroleum-based (MOPB) waxes, either as dip or spray coatings are used for some frame members[26], and wax coatings are also used around windows, wheel arches and in the bottom of doors. Vinyl-based sealers are also used in wheel housing, fenders, on door edges and inside some body panels. The vinyl-based coatings are resistant to chipping by flying stones, etc., which could expose bare metal and promote corrosion. Some automobiles now being manufactured have chip-resistant coatings on lower body panels.[26] All sound-deadening materials of the spray-on type now incorporate corrosion inhibitors. As an example of these costs, consider the use of MOPB or aluminum-filled waxes. These currently cost about $2 per gallon, and each gallon can cover about 240 ft^2 (0.002 inch thick dry coating). In World III probably the frames, rear control arms, doors, fenders, trunk and wheel arches would be coated, at least in part. The total cost for this coverage, in terms of materials alone, would amount to approximately $8.00 per automobile. If all the automobiles produced in 1977 were to receive this treatment, because it represents best available practice, then the total cost would be of the order of $60 x 10^6.

It should be pointed out that it is common practice in the automobile industry to use multiple protective coatings for corrosion protection. Thus, even though galvanized steel, or other coated steels are specified, additional corrosion protection coatings such as the MOPB waxes or zinc-rich paints will be applied in critical areas where moisture can collect or poultices form, or where abrasion or impingement is severe. Also additional coatings can cover scratches, nicks and flaws in the as-supplied coated material. Aftermarket ''rust proofing'' or coating (''undersealing'') are often applied, and will have a beneficial effect if performed shortly after manufacture.

Other examples of corrosion preventative measures are the use of zinc- or aluminum-coated steel for mufflers[28], and the use of greases to prevent corrosion fatigue of torsion bars. Some manufacturers use galvanized steel while others use aluminum-coated steel or combinations of both for mufflers and tail pipes, although for some high-performance engines which run hotter (or in catalytic converters) stainless steel components have to be incorporated. The zinc or aluminum coatings extend service life[2] by a factor of two or more, but a cost penalty is incurred of $60 per ton over uncoated cold-rolled steel at about $375 per ton. In comparison, a 400 series stainless steel costs about $2500 per ton. Assuming 3,750,000 automobiles had coated mufflers and/or tail pipes in 1975, but that 7,500,000 automobiles were manufactured with these more corrosion-resistant components in 1977, the total costs would be of the order of $7,875,000 and $15,750,000, respectively, assuming 70 lb of coated steel are used in 1975, and also 70 lb in 1977, based on data given in Table C-4. In Europe, one manufacturer[23] is using a sprayed coating of atomized zinc covered with a synthetic rubber sleeve for protecting its torsion bars. In the U.S. one manufacturer uses a corrosion resistant enamel coating on its torsion bars (estimated at less then $1 per unit) thus the contribution to the cost of corrosion is thought to be $1 x 10^6 or less.

In terms of metal trim, two developments are of interest. The first is that adhesives are being used to affix the trim to the body work. Before, holes were drilled and fasteners used, however, the bare edges of the drilled holes could be sites for the initiation of corrosion (''cosmetic'' corrosion) and staining. The second is the use of stainless steel clad aluminum trim[24]. The cladding protects the base steel by forming galvanic couples which reduces the corrosion attack on the body work under the trim. Other trim such as grilles, headlamp and tail-light bezels, and bumpers are often electroplated both for corrosion protection and for decorative purposes. A copper-nickel-chromium system is usually employed on ferrous and zinc-base components. About 86 percent of the total electroplating cost is considered to be attributable to corrosion[25], namely about $1.30 out of every $1.50 on a square footage basis (1977 data), or $1.13 out of $1.30 per ft^2 (1975 data). In 1975, 2 x 6,717,043 = 13,434,086 bumpers were fitted on new automobiles. Assuming 10 ft^2 per bumper and a corrosion related cost of $1.13/$ft^2$ the total cost in 1975 is $151,000,000, to which should be added an additional 20 percent for the other plated trim, making the grand total of $182,000,000. Similarly the estimated World III grand total (1977) is $234,000,000. Because of the need to reduce weight, the use of aluminum bumpers may become prevalent, although for aesthetic reasons such bumpers may also be chromium plated. Thus, the near future technology for electroplated bumpers and trim is somewhat uncertain.

It is estimated that between two-thirds and three-quarters of the cost of preparing and painting an automobile is related to corrosion protection and control.* Taking a value of 67 percent the input/output model gives a value of about $25 for the corrosion related fraction in 1975. With best available technology, e.g., better surface preparation, improved primers, especially electrophoretic primers, and better topcoats[7,26] this corrosion cost is likely to double to $50 per car. Considering the number of automobiles produced in 1975 and estimated for 1977, the corresponding corrosion costs for the industry are $167,000,000 and $335,000,000, respectively.

Whereas, up to now only materials related costs for corrosion control have been discussed and quantified, it is obvious that many other miscellaneous costs should be taken account in an ideal model. For example, the cost of new equipment needed to produce, coat, and fabricate new materials; the development of new techniques to handle and join some of these new materials (especially zinc-coated steel); the cost of retraining personnel; the redesign of components and sections; drawing up new specifications; the cost of performing corrosion tests and maintaining a research laboratory and proving ground; and so on. Under the scope of the present study it was not possible to assign

*In the original disaggregation for the input/output model, described in the main body of the text, the division between corrosion and non-corrosion related costs was 50:50 for the use of all organic materials. This includes coatings on non-exposed parts as well as exposed parts.

individual values to the above; therefore, a rough estimate was made that the total miscellaneous costs are approximately equal to materials-related costs given in Table C-5. Thus, in Table C-5, which summarizes the important production-related corrosion costs discussed above for new automobiles, the totals become $\$937 \times 10^6$ and $\$1577 \times 10^6$, respectively, for the World I (1975) and III (1977+) scenarios. These costs are equivalent to about $140 and $210 per new automobile. To these costs must be added the corrosion costs to the owner for maintaining, servicing, and repairing automobiles already on the road.

5 CORROSION CONTROL AND COSTS FOR USED AUTOMOBILES

Whereas the above discussion dealt with new car production, the following discussion centers primarily on maintenance and repair costs incurred by owners. The principal items to be considered are

(1) Body corrosion (rusting)

(2) Aftermarket rustproofing and undercoating

(3) Mufflers and tail pipes (replacements)

(4) Radiator repairs and coolants (inhibitors).

The cost estimates given will be based on the total number of automobiles registered, and include fleets which represent about 9 percent of the total. Table C-6 shows the total numbers of automobiles registered in the U.S. over the time frame of interest, but excluding new car production for the year in question. Corrosion related costs believed to be of minor significance include

(1) Added gasoline consumption due to weight of undercoating and rustproofing

(2) Rust inhibitors added to the cooling system other than in antifreeze

(3) Car washing and waxing for rust prevention

(4) Interior engine parts

(5) Damage due to overheating caused by corrosion products clogging cooling systems

(6) Increased insurance rates because of added repair costs due to corrosion occurring before accidents.

With respect to the corrosion-related wear of interior engine parts such as cylinders, pistons and valves, Reference 8 states that approximately 30 percent of the total wear may be attributable to corrosion in 1950. However, this is only an estimate, and improved materials of construction, and the use of inhibitors in coolants, oils and fuels, can affect a 50 to 95 percent reduction in corrosion, hence its related cost.

TABLE C-5. ESTIMATED COSTS OF CORROSION FOR NEW AUTOMOBILE PRODUCTION

Item	Corrosion Cost*, \$ x 10^6	
	Total+	Unavoidable++
Coated Steel ("Zincrometal")	13.5	45.6
Coated Steel (Galvanized)	42.6	53.9
Paint, Zinc-rich; MOPB Waxes	23.3	91.8
Paint, Finish Coats	167.9	335.9
Trim, Electroplated; Bumpers	182.2	234.0
Mufflers, Tailpipes, Coated	7.9	15.8
Subtotals	437.4	777.0
Miscellaneous**	500.0	800.0
Totals	937.4	1577.0

* Cost to manufacturer.
** Includes other materials, plant maintenance and services, etc., as described in this Appendix.

\+ Estimate of cost of corrosion protection for new automobiles in 1975.

++ Estimate of cost of corrosion protection if best corrosion control practice were used.

TABLE C-6. TOTAL NUMBERS OF AUTOMOBILES REGISTERED IN THE USA

Year	New Car Production*	Total Number of Cars Registered*	
		Privately Owned	Privately and Publicly Owned
1971	8,584,592	92,244,448	92,741,552
1972	8,823,938	96,567,175	97,096,162
1973	9,657,697	101,188,735	101,762,477
1974	7,324,504	104,272,566	104,901,066
1975**	6,717,043	106,680,000	107,371,000
1976***	7,000,000	108,900,000	109,600,000
1977***	7,500,000	110,900,000	111,700,000

* Data from the Motor Vehicle Manufacturers Association of the U.S., Inc.
** Estimates by the Motor Vehicles Manufacturers Association of the U.S., Inc.
*** Estimates by extrapolation.

A corrosion expert with one of the larger automobile companies roughly estimates on the basis of a recent survey that the average 3 year old car has $20 of corrosion damage, and the average 5 year old car $60 to $80 of corrosion damage. Assuming that 6 years was the average age of a car in 1977, and that the amount of damage after 5 years was $15 less than after 6 years, the automobile population by year enables an estimated corrosion cost of $2,945,000,000 to be calculated. In Reference 4 the damage to bodywork by deicing salts in 1974-1975 was estimated to be $1,400,000,000, and if this is considered to represent only one half of the total body corrosion damage[27] resulting from other causes, the total is $2,800,000,000. Thus, for 1975 the total cost due to body corrosion is estimated to be about $2,872.5 x 10^6, as shown in Table C-7. It is expected that more frequent car washings and waxings, because of increasing consumer awareness, and the rapidly increasing attention being paid to corrosion prevention and control in new cars being manufactured, will lead to a decrease in total costs for body corrosion in the World III scenario compared with the World I scenario. Assuming that 1977 technology had been available in 1975, and using the same guidelines as described above, a total corrosion cost to the owner of $1,284,-000,000 is calculated for World III.

Little quantitative information exists for aftermarket rustproofing and undersealing. An estimate indicated that between 5 and 20 percent of new cars in 1975 received some form of rustproofing treatment at an estimated cost of $90 per car. Up to 40 percent of new cars received a dealer-applied undersealing treatment at an estimated cost of $35 per car. Taking a value of 15 percent for the proportion of cars receiving a rustproofing treatment in 1975, and a figure of 6,717,043 for the number of units produced, the World I scenario cost for rustproofing and undersealing is estimated to be $184.7 x 10^6. If best available corrosion control technology had been used in 1975 on

TABLE C-7. ESTIMATED COSTS OF CORROSION TO OWNERS FOR USED AUTOMOBILES

	Corrosion Cost, \$ x 10^6	
Item	Total*	Unavoidable**
Body corrosion	2,872.5	1,284.2
Rustproofing/undersealing	184.7	90.7
Muffler/tailpipe replacement	1,160.0	600.0
Radiator repair/coolants	750.1	149.9
Totals	4,967.3	2,124.8

* Estimate of cost of corrosion in 1975.

** Estimate of cost of corrosion if best corrosion control practice were used.

all new cars manufactured, there would be less incentive to use aftermarket coatings and treatments; however, multilayer corrosion control coatings have been described as being beneficial. In the absence of any firm data, it is estimated that the dealer applied coating would not be requested in the World III scenario, and the owner-related corrosion cost would be only about $\$90.7 \times 10^6$.

According to the 1972 Census of Manufacturers, 32,000,000 replacement mufflers and 42,300,000 replacement tail pipes were sold in 1972. Between 1972 and 1975 there was an increase in registered vehicles of 11 percent (Table C-6); therefore, for 1975 it is assumed that 36,075,000 and 46,953,000 units were sold. However, only 78 percent of these totals represent automobiles (as opposed to trucks, buses, etc.) thus the 1975 totals become 28,138,500 for mufflers, and 36,623,340 for tail pipes. The average retail and installation prices for these items in 1977 were $28 and $17 (quotes from a department store automobile service chain and a muffler replacement franchise store). Using a factor of 1.2243 to prorate the costs to 1975 the corrosion related costs became $647,185,500 and $512,726,760 for a total of $\$1,160 \times 10^6$, assuming a negligible replacement rate (cost) because of accidents. In World III, a continuing increase in the use of aluminum or zinc-coated exhaust components would extend their life, making the frequency of replacement less. Ceramic-coated components, and the use of stainless steels could reduce the frequency of replacement even further. As a conservative estimate, if their life is doubled, the associated cost would be halved, making a total of about $600,000,000 as shown in Table C-7.

According to a trade journal representing the industry, a survey made of radiator shops in 1976 showed total receipts of about $700,000,000, of which two-thirds could be attributed to corrosion-related failures or malfunctions. Making allowance for the fraction fitted in trucks and other vehicles, the total for automobiles becomes $546,000,000, which when adjusted to represent just corrosion costs decreases to $364,000,000. With proper selection of materials, coolant, and proper maintenance, the majority of this cost item could be eliminated. A value of a 80 percent reduction was selected for Table C-7, pending more accurate data.

Trade journals and chemical manufacturing companies state that approximately 200,000,000 gallons of coolant are sold per year. In 1975, the volume was 217,000,000 gallons, and the cost was about $3.50 per gallon. Making allowance for the fact that only 78 percent of this total represents automobiles, and of this adjusted value 80 percent represents replacements, the total volume is then 135,408,000 gallons. At $3.50 per gallon the equivalent cost is $473,928,000. Of this cost about 80 percent can be attributed to the need for corrosion prevention, thus the World I scenario cost becomes $379,142,400. In World III, improved inhibitors and the use of controlled (closed) coolant systems (possibly with in-line filters) would probably reduce this figure by 80 percent, making the total, for the purposes of Table C-7, $75,828,480.

The total costs to the owner for the maintenance and repair of used automobiles is the sum of the various items listed in Table C-7, to a first approximation. In the World I scenario these items total $4,967.3 x 10^6; while in World III the total is $2,124.8 x 10^6, a reduction of 57 percent through using best available corrosion control technology.

6 TOTAL COSTS OF CORROSION

The total costs of corrosion for automobiles is obtained by adding the data presented in Tables C-5 and C-7, as shown in Table C-8. Thus, in 1975, the World I scenario, the total cost of corrosion resulting from both new and used cars registered and operated is estimated to be approximately $6,000 x 10^6. Similarly the estimate for the unavoidable costs in the World III scenario, represented by technology available in the 1977 to 1980 time frame, is approximately $3,700 x 10^6. The detailed estimate for World I is very similar to the prior rough estimates shown in Table C-1.

It may be concluded that for reference year 1975 the cost of corrosion in the U.S. attributable to automobiles is of the order of $6,000 x 10^6. When averaged, this cost is equivalent to $56 per automobile per year, a significant figure, especially when the current trend is to own a car for a longer period, and the likelihood that some corrosion related repair or replacement being encountered is greater. Technology currently available could reduce the total corrosion cost by up to 40 percent which would result in a reduced per automobile expenditure of approximately $33 per year. These calculations use the privately owned automobile population data given in Table C-6.

TABLE C-8. SUMMARY OF TOTAL COSTS OF CORROSION FOR PRIVATELY OWNED AUTOMOBILES

Item	Corrosion Cost, $ x 10^6 Total*	Unavoidable**
New Automobiles, Materials[(a)]	437.4	777.0
New Automobiles, Miscellaneous[(b)]	500.0	800.0
Used Automobiles[(c)]	4,967.3	2,124.8
TOTALS	5,904.7	3,701.8

Data from Tables C-6 and C-7

(a) Cost to the manufacturer; labor, plant etc. not included.
(b) Estimates for labor, plant, etc. included.
(c) Cost to the owner; includes cost of materials and labor for replacement items.

* Estimate of total cost of corrosion in 1975.
** Estimate of cost of corrosion if best corrosion control practice were used.

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APPENDIX D

SECTOR TITLES AND CORRESPONDING STANDARD INDUSTRIAL CLASSIFICATIONS

		SIC's*
1. AGRICULTURE, FORESTRY & FISHERY		
1.01	Livestock and Livestock Products	013, 0193; parts of 014, 0729 and 02
1.02	Field and Orchard Crops	011, 012, 0192; parts of 014 and 02
1.03	Forestry and Fishery Products	08, 09, 074
1.04	Services to Agriculture, Forestry & Fishery	07 (except part of 0729, 074) 085, 098
2. EXTRACTION OF MINERAL RESOURCES		
2.01	Iron and Ferroalloys Ores	101, 106
2.02	Copper Ores	102
2.03	Nonferrous Ores, Except Copper	103, 104, 105, 108, 109
2A04	Underground Coal Mining	parts of 11 and 12
2B04	Strip Coal Mining	parts of 11 and 12
2C04	Other Coal Mining	parts of 11 and 12
2A05	Crude Petroleum	parts of 13
2B05	Natural Gas	parts of 13
2.06	Stone and Clays	14 (excl. 147)
2.07	Chemical and Fertilizer Minerals	147

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* Standard Industrial Classification Manual, prepared by Office of Statistical Standards, Bureau of Budget, 1967.

		SIC's
3. MANUFACTURE OF FOOD, LEATHER & TEXTILE PRODUCTS		
3X01	Food and Kindred Products, Tobacco	20, 21
3.03	Leather Tanning & Industrial Leather Products	311, 312
3X04	Misc. Leather & Fabricated Textile Products	23, 225, 227, 313-19
3.05	Fabrics, Yarns and Threads	221-4, 226, 228
3.07	Tire Cord & Misc. Textile Goods	227
4. WOOD AND PAPER PRODUCTS		
4X01	Lumber Mills, Plywood, Wooden Containers	242, 2432, 244
4.03	Lumber & Wood Products, Except Containers	241, 243 (excl 2432), 249
4X05	Furniture and Fixtures	251, 252-4, 259
4.07	Pulp, Paper and Paper Products, Except Containers	26 (excl 265)
4.08	Paperboard Containers and Boxes	265
5. PETROLEUM AND CHEMICAL PRODUCTS		
5.01	Petroleum Refining and Related Products	291, 299
5.02	Paving Mixtures and Asphalt Products	295
5.03	Industrial Inorganic and Organic Chemicals	281
5.04	Fertilizers	287 (excl 2879)
5.05	Agricultural Chemicals, Except Fertilizers	2879
5.06	Miscellaneous Chemical Products	286, 289
5X07	Plastics Materials & Organic Man-made	2821, 2822, 2823, 2824
5.09	Drugs	283
5X10	Cleaning & Toilet Preparations	284
5A12	Paints and Allied Products, Corr.	part of 285
5B12	Paints and Allied Products, N-Corr.	part of 285

		SIC's
5. PETROLEUM AND CHEMICAL PRODUCTS (Continued)		
5.13	Tires and Inner Tubes	301
5.14	All Other Rubber Products	302, 303, 306
5.15	Manufactured Plastics Products	307
6. STONE, CLAY AND GLASS PRODUCTS		
6.01	Glass and Glass Products	321-3
6.02	Hydraulic Cement, Lime & Gypsum Products	324, 3274-5
6.03	Clay and Cement Products & Refractories	325, 326, 3271-3, 3297
6.04	All Other Stone & Nonmetallic Mineral Products	328, 329 (excl 3297)
7. PRIMARY METALS AND MANUFACTURES		
7A01	Mild Steel - Carbon Steel	
7B01	Low Alloy Steel	
7C01	Alloy Steel	
7D01	Stainless Steel	
7E01	Coke	
7.02	Primary Copper	
7.03	Primary Aluminum	
7A04	Ni, Ni Alloys, CO	
7B04	Zinc	
7C04	Magnesium	
7D04	Lead	
7E04	Ti, Ta, Zr	
7F04	Au, Ag, Pt, Pd	
7G04	All Others	

		SIC's
8. FABRICATED METAL PRODUCTS		
8.01	Metal Cans	341
8.02	Metal Barrels, Drums and Pails	3491
8.03	Metal Sanitary Ware & Plumbing Fittings	3431, 3432
8.04	Nonelectric Heating Equipment	3433
8.05	Fabricated Structural Metal Products	344
8.06	Screw Machine Products, etc., & Stampings	345, 346
8A07	Coating and Plating, Corr.	part of 347
8B07	Coating and Plating, N-Corr.	part of 347
8C07	All Other	342, 348, 349
9. GENERAL MACHINERY AND COMPONENTS		
9.01	Engines and Turbines	351
9.02	General Industrial Machinery & Equipment	356
9.03	Machine Shop Products	359
10. SPECIALIZED MACHINERY		
10.01	Farm Machinery	352
10.02	Construction Machinery	3531
10.03	Mining Machinery	3532
10.04	Oil Field Machinery	3533
10.05	Materials Handling Machinery, Except Trucks	3534, 3535, 3536
10.06	Industrial Trucks and Tractors	3537
10.07	Metalworking Machinery	354
10.08	Special Industry Machinery	355

		SIC's
11. TRANSPORTATION EQUIPMENT		
11A01	Automobiles	part of 3714
11B01	Trucks, Buses, etc.	part of 3714, 3715
11.02	Aircraft and Parts	372
11.03	Ship and Boat Building & Repair	373
11.04	Locomotives & Rail and Streetcars	374
11.05	Motorcycles, Bicycles, Trailer Coaches, etc.	375, 379
12. GENERAL ELECTRICAL APPARATUS		
12.01	Electrical Measuring Instruments	3611
12.02	Electric Motors and Generators	3621
12.03	Industrial Controls, Transformers, etc.	361 (excl 3611), 362 (excl 3621)
12X04	Electric Lamps and Fixtures	364
12.06	Electronic Components and Accessories	367
12.07	Miscellaneous Electrical Machinery	369
13. SPECIAL ELECTRICAL APPARATUS		
13.01	Service Industry Machinery	358
13.02	Household Appliances	363
13.03	Radio, T.V., and Communication Equipment	365, 366
14. SCIENTIFIC AND MEASURING DEVICES		
14.01	Scientific Instruments, Measures and Controls	381, 382
14.02	Medical, Surgical, Dental Instruments and Supplies	384
14.03	Watches, Clocks and Parts	387
14.04	Optical and Ophthalmic Goods	383, 385
14.05	Photographic Equipment and Supplies	386

		SIC's
15. BUSINESS MACHINES AND SUPPLIES		
15.01	Computing and Related Machines	3573, 3574
15.02	All Other Office and Business Machines	357 (excl 3573-4)
15.03	Office Supplies	Dummy Industry
16. MISCELLANEOUS MANUFACTURES		
16.01	Ordnance and Accessories	19
16.02	Other Miscellaneous Products	39 (excl 3992)
17. TRANSPORTATION		
17.01	Railroads and Related Services	40, 474
17.02	Local and Other Highway Passenger Transport	41
17.03	Motor Freight and Warehousing	42, 473
17.04	Water Transportation	44
17.05	Air Transport	45
17.06	Pipelines	46
17.07	Transportation Services	471, 478, 472
18. PUBLIC UTILITIES		
18.01	Telecommunication	48 (excl 483)
18.02	Electric Power	491, part 493
18.03	Gas	492, part 493
18.04	Water and Sanitary Services	494, 495, 496, 497, part 493
19. CONSTRUCTION		
19.01	New Construction, Nonfarm Residence	part 15, part 16, part 17, 6561
19.02	New Construction, Nonresidential Buildings	part 15, part 17

		SIC's
19. CONSTRUCTION (Continued)		
19.03	New Construction, Public Utility	part 15, part 16, part 17
19.04	New Construction, Highway and Other	part 15, part 16, part 17, 138
19A05	Maintenance & Repair Construction, Corr.	part 15, part 16, part 17
19B05	Maintenance & Repair Construction, N-Corr.	part 15, part 16, part 17
20. TRADE AND BUSINESS SERVICES		
20.01	Wholesale and Retail Trade	50 (excl manufacturers' sales offices) 52-59, 7396
20X02	Finance, Insurance, Real Estate, Advertising	60, 61, 67, 62, 63, 64, 65, 66 (excl 656) 731
20.05	Other Business & Professional Services	73 (excl 731, 7396), 7694, part 7699, 81, 89 (excl 892)
20.06	Business Travel, Entertainment & Gifts	Dummy Industry
21. OTHER SERVICES		
21.01	Printing and Publishing	27
21.02	Radio and Television Broadcasting	483
21.03	Hotels and Lodging Places	70
21.04	Personal & Repair Services, Except Auto	72, 76 (excl 7694 & 1/2 7699)
21.05	Automobile Repair and Services	75
21.06	Amusements	78,79
21.07	Medical and Health Services	80
21.08	Educational Services and Nonprofit Organizations	82, 84, 86, 892

SIC's

22. GOVERNMENT ENTERPRISES

22.01 Post Office

23. OTHER SPECIAL SECTORS

23.01 Imports of Noncompetitive Products (Nonsubstitute)

23.0A Domestic Noncompetitive Imports

23.02 Scrap and Secondhand Goods

23.03 Government Industry

23.04 Rest-of-the-World Industry

23.05 Household Industry

OTHER ROW SECTORS

24.00 Total Intermediate Input

25.00 Value Added

25.0A Social Savings

26.00 Total Input

OTHER COLUMN SECTORS

24.00 Total Intermediate Output

25.00 Total Final Demand

25.10 Fixed Private Capital

25.20 Imports of Competitive (Substitute) Products

25.30 Gross Exports

25.40 Personal Consumption Expenditures

25.50 Federal Government Expenditures

25.60 State and Local Government Expenditures

25.70 Net Inventory Change

26.00 Total Output

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16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

The purpose of this study was to determine the economic effect of corrosion in the United States. The results provide a basis for development of technological, legislative, and other initiatives to promote effective economic savings. The study was confined to corrosion of metals.

For 1975 as the base year, total costs of corrosion were estimated as follows:

Total Costs to U.S.	$82 Billion	1.9% GHP
Avoidable Costs	$33 Billion	2.9% GHP
Unavoidable Costs	$49 Billion	2.0% GHP

Input/Output analysis, which provided the methodological framework for this study, permitted detailed and comprehensive treatment of all elements of the costs of corrosion. Production costs, capital costs, changes in replacement lives, etc. were treated in a coordinated and systematic manner. The corrosion I/O Model can be used to assess proposed means to reduce costs.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*
Capital; corrosion; costs; dollar flow; economics; input/output; interindustry; replacement; resources; transactions

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NATIONAL BUREAU OF STANDARDS

The National Bureau of Standards[1] was established by an act of Congress March 3, 1901. The Bureau's overall goal is to strengthen and advance the Nation's science and technology and facilitate their effective application for public benefit. To this end, the Bureau conducts research and provides: (1) a basis for the Nation's physical measurement system, (2) scientific and technological services for industry and government, (3) a technical basis for equity in trade, and (4) technical services to promote public safety. The Bureau's technical work is performed by the National Measurement Laboratory, the National Engineering Laboratory, and the Institute for Computer Sciences and Technology.

THE NATIONAL MEASUREMENT LABORATORY provides the national system of physical and chemical and materials measurement; coordinates the system with measurement systems of other nations and furnishes essential services leading to accurate and uniform physical and chemical measurement throughout the Nation's scientific community, industry, and commerce; conducts materials research leading to improved methods of measurement, standards, and data on the properties of materials needed by industry, commerce, educational institutions, and Government; provides advisory and research services to other Government Agencies; develops, produces, and distributes Standard Reference Materials; and provides calibration services. The Laboratory consists of the following centers:

Absolute Physical Quantities[2] — Radiation Research — Thermodynamics and Molecular Science — Analytical Chemistry — Materials Science.

THE NATIONAL ENGINEERING LABORATORY provides technology and technical services to users in the public and private sectors to address national needs and to solve national problems in the public interest; conducts research in engineering and applied science in support of objectives in these efforts; builds and maintains competence in the necessary disciplines required to carry out this research and technical service; develops engineering data and measurement capabilities; provides engineering measurement traceability services; develops test methods and proposes engineering standards and code changes; develops and proposes new engineering practices; and develops and improves mechanisms to transfer results of its research to the utlimate user. The Laboratory consists of the following centers:

Applied Mathematics — Electronics and Electrical Engineering[2] — Mechanical Engineering and Process Technology[2] — Building Technology — Fire Research — Consumer Product Technology — Field Methods.

THE INSTITUTE FOR COMPUTER SCIENCES AND TECHNOLOGY conducts research and provides scientific and technical services to aid Federal Agencies in the selection, acquisition, application, and use of computer technology to improve effectiveness and economy in Government operations in accordance with Public Law 89-306 (40 U.S.C. 759), relevant Executive Orders, and other directives; carries out this mission by managing the Federal Information Processing Standards Program, developing Federal ADP standards guidelines, and managing Federal participation in ADP voluntary standardization activities; provides scientific and technological advisory services and assistance to Federal Agencies; and provides the technical foundation for computer-related policies of the Federal Government. The Institute consists of the following divisions:

Systems and Software — Computer Systems Engineering — Information Technology.

[1]Headquarters and Laboratories at Gaithersburg, Maryland, unless otherwise noted; mailing address Washington,D.C. 20234.
[2]Some divisions within the center are located at Boulder, Colorado, 80303.

The National Bureau of Standards was reorganized, effective April 9, 1978.

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