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ECONOMIC EFFECTS OF METALLIC CORROSION IN THE UNITED STATES

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

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ECONOMIC EFFECTS OF METALLIC CORROSION IN THE UNITED STATES

Part I

*Special Publication

A Report to the Congress by the National Bureau of Standards

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Executive Summary

Metallic corrosion is the degradation that results from interaction of metals with various environments, such as air, water, chemical products, and pollutants. This process has a significant effect on many sectors of the American economy, since corrosion and its prevention results in the utilization of materials, energy, labor, and technical expertise which would otherwise be available for alternative uses. However, until the present study, no comprehensive investigation of the full extent of this economic impact had been undertaken.

As a result of corrosion, users of metal products incur a wide range of costs, including painting and other methods of corrosion control, more expensive, corrosion-resistant materials, premature replacement of capital goods, larger spare parts inventories, and increased maintenance. Some of these expenses (the avoidable costs) could be reduced through the economical best practice application of available corrosion control technology, but lessening the remaining costs (the presently unavoidable costs) would require advances in technology.

In response to a Congressional directive, this study of the cost of metallic corrosion to the United States was undertaken by the National Bureau of Standards (NBS). The analysis required in this study was placed under contract to the Battelle Columbus Laboratories (BCL). The overall study was conducted jointly by BCL and NBS. The study was designed to provide a reference to allow the economic impact of corrosion to be compared with other factors affecting the economy.

In 1975, corrosion cost the United States an estimated $70 billion. This was 4.2 percent of the estimated Gross National Product for that year. Of this total, about 15 percent or $10 billion was avoidable. An uncertainty of about ±30 percent for the total corrosion cost figure results from inadequate data in some areas and unsure technical and economic judgments. The uncertainty in the avoidable costs is considerably greater.

This study used a modified version of the BCL National Input/Output Model. The model quantitatively identifies corrosion-related changes in resources (material, labor, energy, value added), changes in capital stock, and changes in replacement lives of capital stock for all sectors of the economy. The use of this model is well suited for estimating the total direct and indirect costs of corrosion.

To quantify corrosion costs, three scenarios were developed and applied using the input/output model. They were: (1) the "real world" economy in 1975, (2) a "corrosion-free world," and (3) a world in which "best corrosion prevention practices" are used. Cost differences between these three "worlds" provided estimates of total and avoidable corrosion costs. The model placed industrial corrosion costs on a common scale to allow better comparison of existing and future data. The total cost was determined for final demand groups and intermediate producers and was also allocated among the various producing sectors of the economy via a series of "industry indicators." These indicators identified both avoidable and unavoidable, direct and indirect costs that each sector experienced in the production of goods and services and in capital acquisition.

Four aspects of the U.S. economy received especially detailed analysis for corrosion costs. These were the Federal Government, personally owned automobiles, electric power industry, and loss to the nation of energy and materials due to corrosion. The total corrosion costs in the Federal Government sector amounted to about $8 billion, or approximately 2 percent of the Federal budget. Personally-owned automobiles accounted for $6 to $14 billion. The uncertainty in this cost resulted primarily from uncertainties in estimating ranges of useful lifetimes of cars. Corrosion costs to the electric power industry were estimated to be about $4 billion. Further, the loss to the nation of energy and materials due to metallic degradation was analyzed. About 3.4 percent of this country's present energy demand was generated by such corrosion; of this, one-sixth (about 0.6 percent of energy demand) was estimated to be avoidable. About 17 percent of our present demand for metallic ores resulted from metallic corrosion, about one-eigth of this (2.1 percent of metallic ore demand) was avoidable.

Due to the emphasis in this report on the U.S. economy in 1975, the important issue of corrosion costs associated with new and developing technologies was addressed only in general terms. New corrosion problems will arise in the areas of energy, environment, materials conservation, and food production. As an example, new energy technologies will utilize materials under high temperatures and pressures in highly corrosive environments. Thus, future costs of corrosion may rise substantially in some sectors.

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I. Introduction

The Congress, in Senate Report 94-328 (PL 94-121), directed the National Bureau of Standards "to embark upon a study of the economic effect of corrosion." Initially, NBS concluded that the essential elements of such a study were to:

- Review previous attempts to assess metallic corrosion costs;
- Develop a detailed plan including definitions and methods for acquiring, analyzing and reporting data;
- Expose the study plan to criticism by experts in corrosion and economics from industry and Government; and
- Elicit cooperation from industries and Government agencies which use corrodible equipment, including vehicles and structures.

NBS, a technical organization with extensive expertise in corrosion control technology, conducts research on prevention of metallic degradation and develops methods for testing metals and alloys for corrosion resistance. This program has made major contributions to corrosion control technology since the establishment of NBS in 1901 by direct special funding by the Congress. However, the NBS corrosion group had not conducted economic analyses in the past. For this reason, the analysis required in this study was placed under contract to Battelle Columbus Laboratories. BCL personnel have expertise in both economic analysis and corrosion control practices. The overall study was conducted jointly by BCL and NBS. Its goals included the development of a definition of the economic effect of corrosion from the standpoint of both a monetary loss to the economy and a consumption of materials that would not otherwise be required and the determination of both materials and dollar savings that could be realized by more effective control of corrosion. Upon completion of the review of previous work and formulation of a study plan, an advisory panel was formed to review the plans and to suggest methods for acquiring the necessary data. The advisory panel consisted of corrosion experts from industry, Government, and universities. The panel members, who are listed in the Acknowledgments section of this report, met at all-day review sessions with the BCL/NBS study team on four separate occasions.

Like any broad interdisciplinary study, determination of the economic effects of corrosion in the United States is a complex task requiring the assistance of skilled professionals from many different scientific, engineering, and economic fields. It is also subject to uncertainties, especially in those quantities which are difficult to separate from other degradative phenomena such as wear or fracture. For this reason, the National Bureau of Standards has proceeded cautiously and sought a broad base of input, advice, and support for its approach. In this final report we transmit not only cost data but also a detailed description of how these data were obtained and analyzed. In this way, we hope to provide information which will be useful both to Congress and to our colleagues in the scientific and technical community.

I.A. Previous Studies

A number of assessments of national corrosion costs have been carried out in several industrial nations. In some instances, corrosion losses in a country are merely asserted by an author with no reference as to how the costs were computed. In other cases, major data gathering and interpretation efforts were made. In some cases, a single authority has attempted to analyze corrosion costs in terms of his knowledge of corrosion minimization policies and industrial practices in a specific country. A brief review of the previous studies follows.

Union of Soviet Socialist Republics

In 1969, losses were stated to be six billion rubles ($6.7 billion, 1969 basis) or about 2 percent of the Gross National Product (GNP) for the entire USSR [1].* No indication as to what this figure includes or how it was computed was provided.

German Federal Republic

For the period 1968-69, total losses were asserted to be 19 billion DM ($6 billion, 1969 basis), while avoidable costs were asserted to be 4.3 billion DM ($1.5 billion, 1969 basis) [2]. No indication as to what these figures include or how they were computed was provided. Total costs are about 3 percent of the West German GNP for 1969, and avoidable losses are roughly 25 percent of total costs. These figures, with respect to GNP and percentage of avoidable cost, are in good agreement with figures from other nations.

Finland and Sweden

Costs to Finland for the year 1965 have been estimated at 150 to 200 million Markaa ($47 million to 62 million, 1965 basis) [3]. Linderborg referred to these losses in an article describing factors which must be taken into account in assessing corrosion costs to the Finnish nation [4].

In his paper, Linderborg recognizes the issues raised by variable lifetimes for a variety of items. The specific example of the automobile is used to illustrate this point. Linderborg also quotes a partial study of corrosion costs in Sweden in which painting expenditures to combat corrosion were analyzed for the year 1964. These costs were found to be 300 to 400 million Crowns ($58 million to 77 million, 1964 basis) of which between 25 and 35 percent were found to be avoidable [5].

* Figures in brackets indicate literature references, p. 33.

United Kingdom

A 25-member committee headed by a corrosion expert was constituted by the Minister of Technology in the United Kingdom in 1969 to determine the cost of corrosion. This committee comprised a large number of subpanels and apparently was authorized to make detailed inquiries and to obtain confidential information.

The committee contacted 800 industries in the country and all government departments, in addition to holding discussions with corrosion protection companies and corrosion consultants. The industries gave confidential information from their records on the effects of corrosion, including the amount of shut-downs, rejection of canned foodstuffs, other product losses, structural failures, and the loss to industries from these. The committee took a weighted mean of each loss for a number of units and multiplied this by the total number of units in the country. To this, the committee added the costs of items replaced because of corrosion, expenditures on corrosion protection, and information services, research, and development in the various industries. Thus, it arrived at industry-wide cost of corrosion estimate [6].

The results, shown in Table 1, indicate losses to the U.K. of £1.365 billion ($3.2 billion) for 1969-70. This amounts to about 3.5 percent of the GNP of the U.K. for that period. In addition, the committee found that some £310 million or 23 percent of this total figure was potentially avoidable. Table 2 shows the committee's view of the estimated potential savings and suggested avenues to achieve these.

The committee did not provide quantitative estimates on the uncertainty of its findings. However, its report heightened awareness of corrosion problems throughout the nation. Indeed, an informal conference was held in 1971 to discuss the report. Six sessions were held, one for each section of the report [7]. These discussions are an invaluable supplement to the committee report.

The work of the committee led directly to the establishment of a National Corrosion Service which provides "hot line" information to those with corrosion problems. In addition, in response to the committee report, a Corrosion and Protection Centre for Industrial Services (CAPCIS) was founded. CAPCIS acts as a central supplemental source for industrial corrosion research. At present, CAPCIS carries out ten to twenty tasks per month; the job "gestation period" is about one month.

The government of the United Kingdom also established a Corrosion Research Center at the University of Manchester to provide a place where industrial clients could turn for aid in solving specific corrosion related problems. The Center carries out research and tests for corrosion on a reimbursable basis. The government provides funds for some of the Center's expenses.

TABLE 1. *National Cost of Corrosion and Corrosion Protection in the U.K.**

Industry or Agency	Estimated Cost, £M
Building and construction	250
Food	40
General engineering	110
Government departments and agencies	55
Marine	280
Metal refining and semi-fabrication	15
Oil and chemical	180
Power	60
Transport	350
Water	25
Total	1365

*After Ref. [6].

TABLE 2. *Potential Savings in the U.K. through the Use of Better Corrosion Protection Technology**

Industry or Agency	Estimated Potential Saving £M	%	Changes Required to Achieve Savings
Building and construction	50	20	More awareness in selection, specification and control of application of protectives.
Food	4	10	More awareness in selection of equipment and protection methods.
General engineering	35	32	Greater awareness of corrosion hazards at design stage and throughout manufacture.
Government departments	20	36	Mainly on defense side by better design and procedures.
Marine	55	20	Improved design, awareness and application.
Metal refining and semi-fabrication	2	13	Improved awareness in plant and product protection.
Oil and chemical	15	8	Improved effectiveness in selection of materials and protection.
Power	25	42	Greater use of cathodic protection and improved awareness at design stage of operating conditions.
Transport	100	3	Change of exhaust system material and improved awareness at design stage.
Water	4	16	Improved awareness of corrosion and protection.
Total	310	22.7	

*After Ref. [6].

India

For the period 1960-61, the cost of corrosion to India was estimated at 1.54 billion rupees ($320 million, 1961 basis) [8]. This was based on calculations of expenditures for certain measures to prevent or control corrosion including direct material and labor expenses for protection, additional costs for increased corrosion resistance or redundancy, costs of information transfer, and funds spent on research and development. Table 3 shows the results. No quantitative estimate of uncertainty was attempted nor were avoidable and unavoidable costs broken down.

Australia

For 1973, the direct costs of corrosion were estimated at A$470 million ($550 million, 1973 basis) [9]. Table 4 shows the factors used in developing this figure. The authors comment that these costs are "probably too low." Some additional direct costs—mostly labor—for the mining, transportation and communications industries were unavailable. Only muffler corrosion was considered as contributing to automobile losses. Lifetimes were not taken into account quantitatively. The cited figure of A$470 million was 1.5 percent of Australia's GNP for 1973. However, since indirect costs may equal or exceed this figure, total corrosion costs to Australia are estimated to be about 3 percent of GNP. No quantitative effort was made to assess uncertainties nor to separate these costs into avoidable and unavoidable components.

TABLE 3. *Cost of Corrosion Control in India (1960-61)*[a]

Industry	Cost, Rupees
Paints, varnishes and lacquers[b]	40.0×10^{7}
Zinc for galvanizing[c]	5.7
Tin for tin plate[c]	11.3
Electroplating	10.0
Nickel and its alloys[c]	1.0
Copper and its alloys[c]	50.8
Lead and its alloys[c]	3.3
Stainless steel[c]	22.4
Aluminum[c]	8.3
Prevention of corrosion in Internal Combustion Engines	1.0
Total	153.8×10^{7}

[a]K. S. Rajagopalan, *Journal of Scientific and Industrial Research*, 17, No. 5 (1958), 191-93.
[b]Including labor cost (descaling, preparation of metal surface and application).
[c]Including cost of fabrication.

TABLE 4. *Annual Australian Direct Loss by Corrosion, Including Cost of Corrosion Control**

Industry		Loss, A$
Paints, varnishes and lacquers for protecting metals, based on 0.35		
total consumption (year ended June 1970)	$ 45,300,000	
Labour costs of application	135,900,000	
		$181,200,000
Phosphate coatings: materials and application:		
Automotive industry	1,415,000	
Appliance industry	542,000	
		1,957,000
Galvanised steel production		
537,400 tonnes (1972) at $29.53/tonne differential		15,870,000
Tin and terne plate production		
322,000 tonnes tin plate (1972) at $187/tonne differential	60,230,000	
6100 tonnes terne plate (1972) at $59/tonne differential	360,000	
		60,590,000
Cadmium electroplate		
119,800 kg produced (1972), 50% for electroplating:		
59,900 kg at $6.39/kg	383,000	
Application cost (based on Ni application cost): $20.46/kg	1,226,000	
		1,609,000
Nickel and nickel alloys		
Electroplate: 862,900 kg (1972) at $2.48/kg	2,140,000	
Application cost: $20.46/kg	17,600,000	
Nickel and nickel alloy consumption other than electroplate and stainless steels (year ended June 1972)	10,647,000	
		30,387,000
Copper and copper alloys		
21,600,000 kg of copper and alloy pipe and tube (year ended June 1972) at $0.99/kg differential		21,400,000
Stainless Steels		
36,033,000 kg (year ended June 1970) at $1.21/kg differential		43,600,000
Boiler and other water conditioning:		
Chemicals	4,000,000	
De-aerators	840,000	
Salaries and wages	700,000	
		5,540,000
Underground pipe maintenance and replacement:		
Water	63,900,000	
Gas	8,020,000	
		71,920,000
Oil refinery maintenance		1,140,000
Domestic water heaters		
111,000 replacements (1972) at $150 each		16,500,000
Automobile muffler corrosion		
600,000 mufflers per year replaced at $25 each (incl. materials and labour)		15,000,000
Grand Total		$466,713,000

From: The Journal of The Institution of Engineers, Australia, March-April 1974

*After Ref. [9].

Japan

A survey [10] of the "direct" costs of corrosion in Japan, enumerated in Table 5, was conducted in 1976-1977. The annual cost of corrosion was found to be 2500 billion yen ($9.2 billion, 1974 basis), which amounts to 1.8 percent of the Japanese Gross National Product. The "indirect" costs might increase the total by several times.

Previous U.S. Studies

Uhlig [11] carried out the first detailed assessment of the costs of corrosion in the U.S. He obtained a value for the total direct corrosion losses of $5.5 billion for the late 1940's. Using an approach similar to Uhlig's, NBS did a preliminary in-house survey in 1968 to develop data on corrosion costs in the U.S. The results, while widely quoted and misquoted, were never published.

The most recent study was carried out by the National Association of Corrosion Engineers (NACE) [12]. The results led to estimates of the cost of direct expenditures to NACE members of $9.67 billion for 1975. Table 6 shows the breakdown for these costs. The results are based on replies of 1006 persons to a questionnaire developed by NACE. No uncertainty estimate was made for these data and no critical review of the responses to the questionnaire was carried out.

In summary, the fact that so many countries have attempted to assess their national corrosion costs points up the worldwide awareness that corrosion can be a serious economic concern. These studies, however, were incomplete and made no effort to assess the uncertainties associated with their reported results. Rather than being a criticism, this highlights the attempt by the present study to look at the entire economy of the nation as well as to estimate the uncertainties in the reported numbers.

TABLE 5. *Estimate of Cost of Corrosion Prevention in Japan in 1976 Based on Production and Manufacturing Sectors**

	Percentage of 2500 Billion Yen Total
Surface Coating	62.55
Surface Treatment	25.39
Corrosion-Resistant Materials	9.36
Anti-Corrosion Greases	0.61
Inhibitors	0.63
Electrolytic Protection	0.62
Research	0.84
	100.00

*After Ref. [10].

TABLE 6. *Total Corrosion Expenditures According to NACE Survey for All Industry Classifications and All Regions of the United States**

	Actual $ Provided by Respondent ($1000)	$ Extrapolated to Entire "User" NACE Membership ($1000)
PROTECTIVE COATINGS		
Coating Application Services (Including Surface Preparation Service)	174,425	805,510
External Pipeline Coatings, Underground	58,764	310,060
Internal Pipeline Coatings	46,650	245,947
Marine Coatings, Sea Water Exposure	94,084	502,925
Atmospheric Coatings, Plant & Industrial Exposure	101,111	531,117
Linings, Internal Surfaces of Tanks & Vessels	38,475	203,004
Coating Instrumentation (Film Thickness Gages, Holiday Detectors, Surface Profile Gages, etc.)	2,935	15,375
Coating Testing Service	1,343	6,920
Coating Consulting Services	7,343	7,162
Surface Preparation Equipment (Sandblasting, Water Blasting, Shot and Grit)	15,837	83,532
Galvanizing and Metallizing Services	30,549	195,881
TOTAL	565,511	2,907,433
CORROSION INHIBITORS		
Oil Soluble Types	16,236	93,919
Water Soluble Types	35,721	185,751
Vapor Phase Types	2,347	12,389
Inhibitor Instrumentation (Oxygen Meters, Galvanic Cells, Instantaneous Corrosion Rate Measurements, etc.)	4,660	28,983
Inhibitor Consulting Services	2,872	15,244
Inhibitor Testing Services	842	4,548
TOTAL	62,678	340,834
CATHODIC PROTECTION		
Anodes	4,615	24,352
Backfill	28,065	144,606
Galvanic	15,963	82,679
Rectifiers	5,862	30,790
CP Installation Services	23,432	123,608
CP Instrumentation (Pipe Locators, Reference Electrodes, Voltmeters, Ammeters, Current Interrupters)	1,848	13,900
CP Consulting Services	5,276	27,870
TOTAL	85,061	447,805
FIBERGLASS & PLASTIC MATERIALS (Piping, Tanks, Pumps, Valves, etc.)	85,879	453,196
CORROSION RESISTANT METALLIC EQUIPMENT (Valves, Pumps, Tanks, Vessels, Scrubbers, Ducts, etc.)	1,049,629	5,424,198
METALS TESTING & ANALYSES		
Metal Nondestructive Testing Services	8,899	47,216
Tubing & Casting Testing Services	5,853	31,021
Metal X-ray Analysis	4,021	21,235
TOTAL	18,773	99,472
TOTAL EXPENDITURES	1,867,533	9,672,529

*After Ref. [11].

I.B. Legislative History

On July 15, 1974, Senator John V. Tunney of California wrote [13] the following letter to Senator John O. Pastore, Chairman of the Subcommittee on State, Justice, Commerce and Judiciary:

Dear Mr. Chairman:

I know of your deep concern about the rapid depletion of this nation's vital materials resources. Your Subcommittee could take an important step to help ameliorate this problem in the area of corrosion prevention.

According to recent estimates by The National Commission on Materials Policy, the United States loses about $15 billion annually due to the cost of corrosion. This loss to our economy is more than the entire cost of floods and fires in the United States. In fact, it has been estimated that 40% of the U.S. steel production goes to the replacement of corroded parts and products and our oil industries are spending over a million dollars a day due to corrosion of underground structures.

The United States government alone sustains 10% of this enormous corrosion bill. This means over $1.5 billion annually or more than 20 times the entire budget for The National Bureau of Standards is currently being lost by the government due to corrosion.

The National Commission on Materials Policy states that an estimated 5 billion dollars of this nation's 15 billion dollar annual corrosion bill could be saved with the application of existing knowledge and technology.

Furthermore, corrosion prevention is not only a matter of monetary savings but has a significant impact on safety and health. Corrosion has felled bridges, sunk ships, caused pipelines to explode and even caused airplane crashes. It also in conjunction with pollutants has aided in causing health hazards.

Although corrosion is not a problem with a 100% cure, it is an indisputable fact that by using present knowledge more effectively we can diminish its damaging effects and help save our resources while in the process recovering billions of dollars presently being lost.

Unfortunately, despite these opportunities this problem has not been systematically and thoroughly analyzed in the United States.

Informal discussions with members of the National Bureau of Standards and specialist groups in the field indicate that such a study would be extremely useful.

Therefore, I strongly urge your Subcommittee to appropriate $250,000 for use by the National Bureau of Standards to enable a study to be conducted on the economic costs and benefits of corrosion prevention and to make recommendations to the Congress on the measures to be taken to decrease the loss of materials through corrosion. This figure has been suggested by a number of specialists as adequate to carry out such a study. The study in my view should be composed of an interdisciplinary team such as experts from the fields of metallurgy, chemistry, and economics and should be submitted in approximately eight to twelve months.

A mere 5 to 10% increase in materials effectiveness in this field means savings to the country of immense proportions and the potential impact on our vital resources makes it mandatory that we take action now.

I look forward to hearing from you on this matter.

Sincerely,

(Signed)

JOHN V. TUNNEY
United States Senator

Subsequently, the National Association of Corrosion Engineers (NACE) and the Federation of Materials Societies wrote a joint letter to Senator Tunney thanking him, affirming their support, and stating that the proposed study would provide a major step toward a national program to reduce "wastage of materials."

The fiscal year 1976 Appropriation Act for NBS, Senate Report 94-328 (PL 94-121), directed that "The National Bureau of Standards shall embark upon a study of the economic effects of corrosion." This report is the response to this Congressional mandate.

I.C. Corrosion Costs: Concepts and Definitions

Costs associated with corrosion include items such as material and labor expenditures associated with painting, applying cathodic protection, coatings, and use of inhibitors. Replacement costs and lost production may be partially assessed as losses due to corrosion. Extra material and labor for prevention are also expenses to be included. In addition, corrosion costs include funds spent on information and technology transfer as well as on research, development and demonstration of methods to minimize the deleterious effects of metallic degradation. A key factor in assessing macrocorrosion costs in a sector of any economy is the lifetime and replacement value of a given component subject to damage by corrosion. A complete list of the elements of the costs of corrosion and their treatment in the I/O model is given in Table I of the BCL Report. A simplified version of this table is given in Table 7 here.

TABLE 7. *Some Elements of the Costs of Corrosion**

Capital Costs
– Replacement of equipment and buildings
– Excess capacity
– Redundant equipment
Control Costs
– Maintenance and repair
– Corrosion control
Design Costs
– Materials of construction
– Corrosion allowance
– Special processing
Associated Costs
– Loss of product
– Technical support
– Insurance
– Parts and equipment inventory

*A more complete list is given in Appendix B, Table I.

For an individual industry or sector of the economy, knowledgeable design engineers will usually select the cheapest material which will withstand the expected corrosive conditions for a preselected "lifetime of the product." This procedure, involving the use of discounted cash flow (DCF) analysis, is rather straightforward and is invaluable for equipment selection. However, in the case of many items manufactured for mass retailing such as automobiles or housing, application of the DCF procedure may not optimize the economic benefits of corrosion over the whole system consisting of manufacturer, wholesaler, retailer, and consumer.

A more subtle example of corrosion costs is possible delay or other difficulty in obtaining the optimum material. Under pressure of construction and/or installation deadlines, a more corrosion prone material may have to be substituted. If the latter fails prior to design lifetime, a production system may be shut down. The failure of the market to provide the optimum material thus can lead to direct and indirect corrosion costs through all sectors of the economy affected by this productivity decrease.

Public policy may impose extra corrosion costs as a trade-off against property damage or loss of life. The case of heavily salted roads in winter in certain areas serves as one instance. Automobile purchasers in such areas may opt for additional corrosion protection for the bodies of their cars. As a second example, use of the environment as a dumping ground for effluent contributes to extra maintenance or shortened lifetimes for structures such as bridges, rails, cables and buildings.

The total national cost of corrosion as used in this study is defined as the difference in Gross National Product between two worlds, a modified real world of corrosion (World I) and a hypothetical world in which corrosion does not exist (World II). The year 1975, modified by raising it to a hypothetical full employment level of economic activity, was used for World I.[1]

To estimate the avoidable costs of corrosion, another construct, World III, was formulated. World III is a hypothetical world in which the economically best corrosion prevention practice is used by everyone. The difference in Gross National Product between World I and II, the total national cost of corrosion, represents resources that could be useful for other goods and services if there were no corrosion. Similarly, the difference in GNP of Worlds I and III signifies resources which would be available if economically best preventive practices were used throughout the economy and represents the total national avoidable costs of corrosion. The GNP difference between Worlds II and III measures presently unavoidable costs.

Worlds II and III are, of course, not worlds of full employment, but they do represent the year 1975, as does World I. All three worlds were evaluated under an assumption of a steady rate of growth which varied from sector to sector.

In World III, best practice corrosion technology was defined, not as that practice which reduced corrosion, but as that which minimized its lifetime capital and operating costs, with an appropriate discount rate. The cost of acquiring capital funds is not the same for larger and smaller firms in the same industry, so that best corrosion practice is not necessarily the same from firm to firm.

In all three worlds, the same level of usefulness of goods and services to the public was assumed. Thus, for example, fewer end items were delivered to consumers in Worlds II and III. Because those delivered spent less time in maintenance or lasted longer than in World I, fewer items were needed to provide the same level of services to their users as the larger number delivered in World I.

The input/output approach used in the present study has the advantage of capturing all direct and indirect costs of corrosion through the creation of a total economic model for each of the three worlds. Direct costs include all reductions in the requirements for inputs for production which would become possible if there were no corrosion as in World II or best practice corrosion as in World III. These include flow inputs (e.g., pig iron into steel), capital inputs for expansion and replacement of capacity (e.g., blast furnaces for steel), and value added. The direct flow effects include reduced maintenance costs and the use of less expensive materials for embodiment in outputs. Among the direct capital effects are the reduced need for equipment due to less time down for maintenance and the lower replacement cost because of increased equipment life. The value-added effects include reduced costs of labor and lower depreciation allowances for the smaller capital requirements. The indirect effects include two elements: (1) in addition to the reduced input requirements, the inputs also cost less, because of savings in their own and earlier production processes and (2) the general interactive effects of reductions in production levels on one another.

[1] The full employment modification was used in order to account for all possible corrosion costs. Full employment was defined in terms of an extrapolated trend fitted to peak values of real GNP per person of age 18 through 64.

Value added is the additional value accruing to a product's ingredients as they are fashioned into the product itself. It includes 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 those purchased from other industries.

I.D. Input-Output (I/O) Model

A number of characteristics make input-output analysis, pioneered by W. W. Leontief, and the modified Battelle model well suited for use in estimating the total direct and indirect costs of corrosion. The model is quite detailed. In this study, it has 130 economic sectors and each is represented by a production function consisting of the respective inputs from that sector plus value added. As a result, relatively detailed industry corrosion cost data may be incorporated into the model for simulation purposes. The complex structure serves as a guide for the precise analysis of corrosion costs and a means for integrating the results.

The model is comprehensive. It has sufficient components to allow all the contributions to corrosion costs (production expenses, capital cost, reductions in replacement, and excess capital capacity, for example) to be considered in the analysis. Because of the model's structure, all of these aspects, and their interactions, may be evaluated in a coordinated and systematic manner.

The model is simultaneous and, therefore, able to account for both direct and indirect effects of certain changes in the economy. This is critical to estimating the total costs of corrosion to society.

Because the model simultaneously determines equilibrium values, comparative static analysis (i.e., comparison of alternate growth scenarios at the same moment in time) is an obvious application. For example, the costs of corrosion in the existing world (World I) are compared to those in each of the two hypothetical worlds mentioned previously—World II in which no corrosion exists and, thus, the costs are zero, and World III in which "best practice" corrosion control methods are employed.

Finally, since the model consists of the process sectors described in terms of "ex ante"[2] parameters, it is well suited to "ex ante" changes describing Worlds II and III. The process orientation 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.

Input-output is weakest where the coefficients (i.e., the input requirements per unit of output) change as a result of model solutions. For some purposes, such as modeling the adjustment to a disruption in supply, process alternatives must be offered under the control of a pricing system or through linear programming or another kind of optimizing model. For the purposes of the corrosion study, no such need exists. Each of the three worlds for which the input-output model was established represents a stable condition of steady growth at full employment—stability within each world, but not among them. Under these conditions, the stable coefficients required for an input-output model are reasonably assumed.

I.E. Operation of the Data Survey

The use of the I/O model to determine the cost of corrosion required the collection of the following data:

(a) For the "A" or flow matrix—inputs to make a product.

(b) For the "B" or capital/output matrix—capital equipment needed to produce a product.

(c) For the replacement rate matrix—replacement lives of the capital equipment.

(d) For the final demand vector—final demands for the product.

[2] The "ex ante" procedure for estimation 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.

These data were collected by grouping like industries (usually viewed as a producer but sometimes as a user of goods) and assigning the groups to an individual data gatherer. The results of the data collection are assembled in Appendix C.

The U.S. economy as represented by the SIC classification [14] and by the 130 sectors of the I/O model was divided into about 20 areas as listed on pages 67-107 of the BCL report. An area or sector leader was responsible for gathering data in his sector. These are shown in the Acknowledgments (Part V of this report). For example, a typical sector was wood and paper products, which included lumber mills, plywood, wood containers, lumber and wood products, furniture and fixtures, pulp, paper and paper products, and paper board containers and boxes.

Because all industries could not be studied with equal attention, priorities were assigned based on the extent of the effect of corrosion on products or production processes.

After identifying for each sector the World I coefficients in the matrices expected to be affected significantly by corrosion, the data gatherers interviewed knowledgeable individuals in a sector, reviewed the literature, and consulted technical experts. They determined the extent of changes that should be made in the World I coefficients identified as corrosion sensitive to change them to World II and World III conditions. These collected data were reviewed and adapted by BCL economists.

When the data were not available in a broken down form (sector by sector) but only as a total cost, technical judgments based on knowledge of corrosion processes were used to distribute the costs to the various sectors involved. All data were then reviewed and adapted for the I/O model. The final coefficient adjustments were made jointly by corrosion and economics experts.

II. Results

II.A. National Costs

The study separates the total costs of corrosion into avoidable and presently unavoidable losses. Avoidable costs were defined as those amenable to reduction by the most economically effective use of presently available corrosion technology. For the base year 1975, total costs of metallic corrosion (materials, labor, energy, and technical capabilities) were estimated by BCL to be $82 billion, 4.9 percent of the $1677 billion Gross National Product (GNP). Approximately 40 percent of this ($33 billion, 2.0 percent of GNP), was estimated to be avoidable. NBS has analyzed the uncertainties in these estimates (Appendix A). Based on the BCL results and the NBS uncertainty analysis, the total national yearly cost of metallic corrosion is about $70 billion (4.2 percent of GNP), with an uncertainty of about ± 30 percent.[3] The currently avoidable cost of corrosion was found to be roughly 15 percent of the total, but could run from 10 to 45 percent. The error in the avoidable cost is greater than that in the total.

As BCL noted in their report, the treatment of useful lives contains the greatest uncertainties in their results. We concur in this judgment, noting that, in particular, the choice of lifetimes for the automobile leads to a large effect on the total corrosion costs. NBS has estimated the magnitude of this effect under different assumptions of automobile lifetimes. The complete analysis, including other effects, leads to the values above as reasonable estimates.

In the BCL study, the total costs were allocated to the various sectors of the economy. A series of industry indicators provided by BCL (Table 8) expressed corrosion losses on a dollar basis and as cost per unit of sales for the total and avoidable costs of both direct and direct plus indirect costs. The largest 25 values in each column in Table 8 are numbered in order of decreasing magnitude.

[3] The indirect effects of systematic errors specified in Appendix A on intermediate output and capital costs of corrosion have been ignored. The downward effect this would have had on corrosion cost estimates is assumed to be compensated for by the various upward effects noted in the BCL report, Section 5.3.4. (See Section 4.3 in Appendix A.)

Table 8. Industry Indicators of Metallic Corrosion (from BCL)*

	Total Costs of Corrosion (World I Minus World II)				Avoidable Costs of Corrosion (World I Minus World III)			
	Direct		Direct and Indirect		Direct		Direct and Indirect	
	Per Unit ($)	Total (M $)	Per Unit ($)	Total (M $)	Per Unit ($)	Total (M $)	Per Unit ($)	Total (M $)
1.01 Livestk+Livestk Prod	0.0258	1086.10 (8)	0.0644	2710.74 (11)	0.0159 (4)	671.35 (3)	0.0347 (4)	1460.26 (4)
1.02 Field+Orchard Crop	0.0215	1377.67 (5)	0.0523	3349.98 (8)	0.0130 (9)	833.85 (2)	0.0276 (10)	1771.53 (2)
1.03 Forestry+Fishery P	0.0191	96.29	0.0448	226.28	0.0103 (20)	52.0	0.02 3 (19)	1 2.51
1.04 Agri,Forst+Fish S	0.0290	141.48	0.0739	360.59	0.0125 (13)	61.13	0.0239 (15)	116.62
2.01 Iron+Ferroalloys O	0.0334	164.90	0.0762	376.71	0.0159 (5)	78.72	0.0315 (6)	155.84
2.02 Copper Ores	0.0566 (8)	84.66	0.1251 (7)	187.09	0.0237 (1)	35.45	0.0478 (1)	71.45
2.03 Nonferrous Ores, Exp	0.0361 (21)	78.15	0.0812	175.87	0.0186 (2)	40.36	0.0378 (2)	81.82
2A04 Underground Coal Min	0.0284	177.43	0.0662	413.78	0.0121 (15)	75.54	0.0245 (14)	153.03
2804 Strip Coal Mining	0.0151	89.58	0.0433	256.18	0.0062	36.75	0.0134	79.43
2C04 Other Coal Mining	0.0184	4.36	0.0477	11.28	0.0098 (21)	2.31	0.020 (20)	4.73
2A05 Crude Petroleum	0.0142	329.60	0.0272	630.74	0.0040	92.43 (25)	0.0068	158.19
2805 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	103.11	0.0502	277.77	0.0079 (23)	43.54	0.0160 (23)	88.81
2.07 Chem+Fertlzr Miner	0.0195	34.24	0.0416	72.94	0.0072 (25)	12.69	0.0138 (24)	24.30
3X01 Food+Kindrd Prod, TOB	0.0037	701.58 (19)	0.0191	3619.69 (6)	0.0020	374.82 (6)	0.0052	986.00
3.03 Lethr Tan+Ind Lethr	0.0028	8.20	0.0158	46.25	0.0003	0.96	0.0020	5.80
3X04 Misc.Leath+Fab Text	0.0011	79.29	0.0104	734.37	0.0004	31.21	0.0019	135.08
3.05 Fabrics, Yarns+Thr	0.0017	41.80	0.0165	415.76	0.0009	21.81	0.0030	75.96
3.07 Tire Cord+Misc Text	0.0009	3.99	0.0141	60.23	0.0005	2.55	0.0024	10.41
4X01 Lumber Mill,Plywd,Wd	0.0043	59.98	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	60.59
4X04 Furniture+Fixtures	0.0400	622.90 (24)	0.0858(22)	1335.08	0.0006	8.94	0.0027	41.81
4.07 Pulp+Papr Prd Ex Con	0.0181	561.47	0.0440	1369.06	0.0033	102.35 (20)	0.0073	227.50 (22)
4.08 Paperbrd Containers	0.0015	17.11	0.0236	274.23	0.0008	8.96	0.0037	43.02
5.01 Petrol Refng+Reltd	0.0165	1053.67 (9)	0.0382	2440.12 (13)	0.0013	80.79	0.0033	207.67 (24)
5.02 Paving Mix+Asphalt P	0.0048	23.09	0.0236	113.71	0.0028	13.46	0.0059	28.53
5.03 Industrl Inorg+Org C	0.0216	691.70 (20)	0.0432	1382.38	0.0028	90.73	0.0058	184.87
5.04 Fertilizers	0.0072	28.88	0.0211	84.66	0.0008	3.34	0.0025	10.15
5.05 Agri Chem Ex Fertlzr	0.0071	10.16	0.0212	30.32	0.0010	1.43	0.0026	3.69
5.06 Misc Chem Prd	0.0212	127.01	0.0477	285.42	0.0038	22.77	0.0079	47.51
5X07 Plas Matls+Org Manma	0.0067	96.14	0.0342	493.48	0.0036	52.35	0.0068	97.42
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	123.01	0.0281	370.07	0.0014	17.92	0.0035	46.22
5A12 Paints+Allied Prd. Co	0.0214	40.98	0.0390	74.80	0.0033	6.37	0.0073	13.90
5812 Paints+Allied Prod, Nc	0.0206	75.33	0.0347	126.80	0.0031	11.25	0.0066	24.30
5.13 Tires+Innertubes	0.0023	15.35	0.0147	97.45	0.0005	3.23	0.0020	13.38
5.14 Othr Rubber Prd	0.0036	23.03	0.0186	120.10	0.0011	6.77	0.0030	19.38
5.15 Manufac Plastics Prd	0.0031	33.83	0.0162	179.93	0.0014	16.05	0.0033	36.78
6.01 Glass+Glass Prd	0.0052	33.23	0.0219	139.90	0.0011	7.30	0.0034	21.85
6.02 Cement+Lime+Gypsum P	0.0030	9.52	0.0200	63.80	0.0016	5.05	0.0050	15.83
6.03 Clay+Cement Prd+Refr	0.0071	92.64	0.0318	415.73	0.0034	44.29	0.0079	103.29
6.04 Othr Nonmet Mineral	0.0046	23.02	0.0216	108.95	0.0018	9.18	0.0045	22.69
7A01 Mild Steel-Carbon St	0.0223	916.66 (10)	0.0469	1923.58 (22)	0.0018	73.57	0.0052	212.37 (23)
7801 Low Alloy Steel	0.0130	23.57	0.0301	54.45	0.0019	3.40	0.0048	8.75

*From Appendix 8.

Table 8. Continued

	Total Costs of Corrosion (World I Minus World II)				Avoidable Costs of Corrosion (World I Minus World III)			
	Direct		Direct and Indirect		Direct		Direct and Indirect	
	Per Unit ($)	Total (M $)	Per Unit ($)	Total (M $)	Per Unit ($)	Total (M $)	Per Unit ($)	Total (M $)
7C01 Alloy Steel	0.0120	53.70	0.0275	123.70	0.0019	8.31	0.0047	21.28
7D01 Stainless Steel	0.0202	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	0.0062	21.50	0.0144	50.00	0.0004	1.27	0.0020	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	5.81
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(17)	194.44	0.1036 (15)	485.07	0.0003	1.62	0.0020	9.45
8.02 Metal Barrels, Drum+P	0.0559(10)	43.03	0.1284 (6)	98.88	0.0003	0.20	0.0020	1.54
8.03 Met Sanit+Plumbing P	0.0701 (5)	83.16	0.1961 (2)	232.68	0.0003	0.34	0.0019	2.25
8.04 Nonelec Heating Equi	0.0477(13)	113.84	0.1213 (8)	289.84	0.0014	3.27	0.0039	9.22
8.05 Fab Structural Metal	0.0568(7)	1153.10 (7)	0.1314 (5)	2668.79 (12)	0.0005	9.24	0.0020	41.02
8.06 Screw Mach Prd+Stamp	0.0721 (4)	855.60 (11)	0.1714 (4)	2032.98 (18)	0.0004	4.18	0.0018	21.50
8A07 Coating+Plating, Cor	0.0619 (6)	281.44	0.0782	355.70	0.0033	14.91	0.0068	31.14
8B07 Coating+Plating, Ncor	0.0389(20)	150.40	0.0841 (24)	324.81	0.0034	13.16	0.0070	27.22
8C07 Misc. Fabr. Metal Prod	0.0738 (3)	683.37 (21)	0.1820 (3)	1684.15 (25)	0.0005	4.23	0.0020	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(15)	784.23 (17)	0.1127(12)	2056.50 (16)	0.0014	25.38	0.0035	63.12
9.03 Machine Shop Prd	0.0059	32.12	0.0205	112.31	0.0008	4.13	0.0021	11.28
10.01 Farm Machinery	0.0160	109.59	0.0607	416.28	0.0004	2.57	0.0020	13.96
10.02 Construction Machine	0.0292	192.64	0.0819	539.63	0.0003	2.30	0.0018	12.09
10.03 Mining Machinery	0.0412 (19)	31.94	0.1003 (17)	77.69	0.0003	0.27	0.0018	1.39
10.04 Oil Field Machinery	0.0278	18.66	0.0689	46.18	0.0004	0.24	0.0014	0.93
10.05 Mtrl-Hndlng Mach Fx	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	0.52	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(14)	586.04 (25)	0.1061(14)	1329.97	0.0004	4.43	0.0015	18.74
11A01 Automobiles	0.0221	2206.38 (3)	0.0885(19)	8819.28 (2)	0.0010	98.29 (23)	0.0033	325.56 (18)
11B01 Trucks, Buses, etc.	0.0175	576.59	0.0582	1913.13 (23)	0.0009	30.77	0.0026	85.96
11.02 Aircraft+Parts	0.0080	336.84	0.0357	1501.85	0.0003	13.04	0.0014	58.85
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	0.0342(24)	149.25	0.0972 (18)	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	0.0016	7.68
12.02 Elec Motors+Genera	0.0142	63.56	0.0452	202.80	0.0003	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	0.0533	384.85	0.0003	1.94	0.0017	12.10
12.06 Electrnc Compnts+Acc	0.0341(25)	341.76	0.0871 (21)	872.96	0.0004	4.41	0.0022	21.86
12.07 Misc Electrical Mach	0.0037	20.85	0.0253	142.82	0.0003	1.79	0.0017	9.71

Table 8. Concluded

	Total Costs of Corrosion (World I Minus World II)				Avoidable Costs of Corrosion (World I Minus World III)			
	Direct		Direct and Indirect		Direct		Direct and Indirect	
	Per Unit ($)	Total (M $)	Per Unit ($)	Total (M $)	Per Unit ($)	Total (M $)	Per Unit ($)	Total (M $)
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	0.0565 (9)	463.73	0.1307 (6)	1073.55	0.0005	4.28	0.0025	20.91
13.03 Radio, TV+Commun Equi	0.0094	294.19	0.0381	1188.42	0.0003	9.94	0.0014	44.08
14.01 Scientific Instrumnts	0.0255	176.70	0.0735	508.55	0.0003	2.05	0.0018	12.40
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	0.0010	0.93
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	0.0530	253.57	0.0005	2.19	0.0016	7.57
15.03 Office Supplies	.0000	.00	0.0246	173.16	.0000	.00	0.0022	15.39
16.01 Ordnance+Accessori	0.0171	307.75	0.0438	790.11	0.0014	24.55	0.0030	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	576.81	0.0824(25)	1685.38 (24)	0.0111 (19)	226.86 (15)	0.0224 (17)	457.85 (16)
17.02 Local+Highway Passng	0.0310	540.09	0.0763	1328.57	0.0162 (3)	282.00 (13)	0.0370 (3)	643.66 (13)
17.03 Motor Freight+Wareho	0.0300	808.08 (15)	0.0764	2056.18 (17)	0.0118 (17)	318.48 (10)	0.0270 (12)	725.89 (11)
17.04 Water Transportation	0.0352(23)	266.19	0.0851 (23)	644.13	0.0125 (12)	94.39 (24)	0.0233 (16)	176.55
17.05 Air Transport	0.0352(22)	380.18	0.0874 (20)	942.85	0.0054	58.24	0.0129	139.74
17.06 Pipe Lines	0.0429(16)	59.50	0.1142 (10)	158.24	0.0127 (10)	17.63	0.0264 (13)	36.56
17.07 Transportation Servi	0.0160	18.56	0.0407	47.37	0.0078 (24)	9.09	0.0179 (22)	26.84
18.01 Telecommunication	0.0133	447.00	0.0600	2011.79 (19)	0.0014	45.59	0.0037	123.21
18.02 Electric Power	0.1008(1)	4106.01	0.1130(11)	4603.12 (4)	0.0030	120.30 (18)	0.0066	267.41 (19)
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(11)	411.04	0.1009(16)	843.06	0.0119 (16)	99.30 (22)	0.0220 (18)	184.01
19.01 New Const, Nonfarm Re	0.0111	571.22 (22)	0.0452	2743.51 (10)	0.0051	308.76 (12)	0.0125	760.79 (9)
19.02 New Const, Nonresid B	0.0139	796.04 (16)	0.0610	3502.67 (7)	0.0036	206.26 (16)	0.0086	496.63 (15)
19.03 New Const, Public Uti	0.0779(2)	1976.62 (4)	0.2208 (1)	5606.32 (3)	0.0124 (14)	315.38 (11)	0.0271 (11)	688.47 (12)
19.04 New Const, Highway+Ot	0.0255	652.50 (23)	0.0756	1935.22 (21)	0.0131 (8)	335.12 (8)	0.0285 (9)	728.81 (10)
19A05 Maint+Repr Const, Cor	0.0483(12)	269.50	0.1168 (9)	652.40	0.0059	32.98	0.0135	75.22
19B05 Maint+Repr Const, Nco	0.0139	846.98 (12)	0.0457	2784.85 (9)	0.0059	358.50 (7)	0.0134	815.02 (7)
20.01 Wholesale+Retail Tra	0.0211	5441.38 (1)	0.0567	14620.20 (1)	0.0126 (11)	3250.67 (1)	0.0289 (8)	7438.91 (1)
20X02 Financ, Ins, Real E, Ad	0.0051	1257.47 (6)	0.0165	4061.97 (5)	0.0027	668.64 (4)	0.0065	1604.33 (3)
20.05 Othr Bus+Prof Servic	0.0122	702.69 (18)	0.0345	1960.60	0.0056	320.82 (9)	0.0136 (25)	781.48 (8)
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	0.21	0.0039	.56
21.03 Hotels+Lodging Pla	0.0275	415.49	0.0703	1063.65	0.0133 (7)	201.46 (17)	0.0292 (7)	441.52 (17)
21.04 Persnl+Repar Serv, Ex	0.0226	831.08 (13)	0.0646	2375.85 (14)	0.0111 (18)	408.50 (5)	0.0252 (14)	928.48 (6)
21.05 Automobile Repair+Se	0.0413(18)	826.10 (14)	0.1102(13)	2202.42 (15)	0.0141 (6)	281.34 (14)	0.0317 (5)	634.47 (14)
21.06 Amusements	0.0033	49.28	0.0171	252.40	0.0016	24.21	0.0046	68.01
21.07 Medical+Health Ser	0.0045	198.89	0.0186	816.76	0.0024	105.69 (19)	0.0056	248.25 (21)
21.08 Educat Servc+Nonprof	0.0030	184.27	0.0153	943.43	0.0016	100.56 (21)	0.0040	248.37 (20)
22.01 Post Office	0.0147	157.81	0.0435	465.81	0.0080 (22)	85.75	0.0187 (21)	199.84 (25)
TOTAL		45266.33		126019.49		11895.04		27717.99

A summary of differences in final transactions in dollars (social savings) provided by BCL is given in Table 9 for both the total and avoidable costs of corrosion along with the percentage of corrosion that is avoidable. The industry sectors that produce the final demand items are listed in Table 10. This table also contains a listing of intermediate costs (intermediate output social savings). When these costs are subtracted from the direct industry indicators (Table 8), the residual is approximately the capital costs of corrosion to the various sectors. We believe that values for those industries showing the highest capital costs of corrosion have been overestimated.

TABLE 9. *Major Components of Metallic Corrosion Costs**

	Total Costs of Corrosion (M $)	Avoidable Costs of Corrosion (M $)	Avoidable/Total %
Cost of Corrosion	82,264.3	32,942.6	
Total Intermediate Output	24,447.0	2,043.1	8
Total Final Demand	57,817.3	30,899.5	53
Personal Consumption Expenditures (PCE)	22,759.7	15,880.2	70
Private Fixed Capital Formation (PFCF)	24,089.2	12,457.0	52
Exports	0	0	
Federal Government Expenditures (FGE)	8,062.2	1,655.9	21
State and Local Government Expenditures (S/LGE)	2,906.2	906.4	31
Net Inventory Change	0	0	

*Data from Appendix B. See Appendix A for NBS estimate of uncertainties and reestimation of these values.

Table 10. Final Demand and Intermediate Corrosion Costs (from 8CL)

Sector	World I minus World II (M $) PCE	PFCF	FGE	S/LGE	World I minus World III (M $) PCE	PFCF	FGE	S/LGE	Intermediate Costs (M$) World I minus World II	World I minus World III
1.01 Livestk & Livestk Prod	0	0	0	0	0	0	0	0	43.7	14.8
1.02 Field & Orchard Crop	0	0	0	0	0	0	0	0	96.8	33.5
1.03 Forestry & Fishery P	0	0	0	0	0	0	0	0	13.4	4.7
1.04 Agri. Forst & Fish S	0	0	0	0	0	0	0	0	101.9	35.9
2.01 Iron & Ferroalloys O	0	0	0	0	0	0	0	0	57.8	16.6
2.02 Copper Ores	0	0	0	0	0	0	0	0	21.7	9.0
2.03 Nonferrous Ores, Exp	0	0	0	0	0	0	0	0	17.0	4.9
2A04 Underground Coal Min	0	0	0	0	0	0	0	0	96.1	27.5
2B04 Strip Coal Mining	0	0	0	0	0	0	0	0	30.3	9.7
2C04 Other Coal Mining	0	0	0	0	0	0	0	0	1.4	0.5
2A05 Crude Petroleum	0	0	0	0	0	0	0	0	199.6	13.6
2B05 Natural Gas	0	0	0	0	0	0	0	0	57.7	4.2
2.06 Stone & Clay Mining	0	0	0	0	0	0	0	0	60.3	14.6
2.07 Chem & Fertlzr Miner	0	0	0	0	0	0	0	0	18.1	3.3
3X01 Food & Kindrd Prod, TOB	0	0	0	0	0	0	0	0	165.4	40.2
3.03 Lethr Tan & Ind Lethr	0	0	0	0	0	0	0	0	4.5	0.5
3X04 Misc. Leath & Fab Text	0	3.0	0	0	0	1.0	0	0	29.4	12.9
3.05 Fabrics, Yarns & Thr	0	0	0	0	0	0	0	0	15.6	7.2
3.07 Tire Cord & Misc Text	0	0.3	0	0	0	0.1	0	0	1.7	0.8
4X01 Lumber Mill, Plywd, WD	0	19.0	0	0	0	8.7	0	0	31.2	14.4
4.03 Lmbr & Wood Prd Ex Con	0	5.9	0	0	0	2.5	0	0	23.1	10.8
4X05 Furniture & Fixtures	0	76.7	0	0	0	24.0	0	0	607.9	3.3
4.07 Pulp & Papr Prd Ex Con	0	0	0	0	0	0	0	0	456.1	54.8
4.08 Paperbrd Containers +	0	0	0	0	0	0	0	0	10.4	4.9
5.01 Petrol Refng & Re Ltd	0	0	0	0	0	0	0	0	881.9	29.0
5.02 Paving Mix + Asphalt P	0	0	0	0	0	0	0	0	11.4	5.8
5.03 Industrl Inorg & Org C	0	0	0	0	0	0	0	0	489.1	23.7
5.04 Fertilizers	0	0	0	0	0	0	0	0	22.8	0.8
5.05 Agri Chem Ex Fertlzr	0	0	0	0	0	0	0	0	7.4	0.3
5.06 Misc Chem Prd	159.0	0	17.5	9.2	0	0	0	0	75.4	4.1
5X07 Plas. Matls & Org. Nanma	0	0	0	0	0	0	0	0	34.5	12.4
5.09 Drugs	0	0	0	0	0	0	0	0	35.5	4.8
5X10 Cleaning & Toilet Prep	0	0	0	0	0	0	0	0	95.6	10.8
5A12 Paints & Allied Pro, Co	0	0	3.1	3.7	0	0	0	0	0.4	4.6
5B12 Paints & Allied Pro, Nc	0	0	0	0	0	0	0	0	63.5	8.5
5.13 Tires & Innertubes	0	0	0	0	0	0	0	0	8.2	1.7
5.14 Othr Rubber Prd	0	6.0	0	0	0	1.4	0	0	12.6	3.5
5.15 Manufac Plastics Prd	0	9.0	0	0	0	2.1	0	0	22.3	8.1
6.01 Glass & Glass Prd	0	0	0	0	0	0	0	0	19.6	3.2
6.02 Cement & Lime & Gypsum P	0	0	0	0	0	0	0	0	2.3	1.0
6.03 Clay & Cement Prd & Refr	0	6.6	0	0	0	2.7	0	0	42.7	16.5
6.04 Othr Nonmet Mineral	0	0	0	0	0	0	0	0	7.7	3.0
7A01 Mild Steel-Carbon St	0	0	45.1	0.4	0	0	0	0	694.0	10.2
7B01 Low Alloy Steel	0	0	2.0	0.2	0	0	0	0	4.5	0.6
7C01 Alloy Steel	0	0	4.7	0.5	0	0	0	0	15.3	1.4
7D01 Stainless Steel	0	0	7.6	0.7	0	0	0	0	13.3	1.1
7E01 Coke	0	0	0	0	0	0	0	0	28.4	1.6
7.02 Primary Copper	0	0	202.9	0.1	0	0	0	0	91.5	2.0

Table 10. Continued.

Sector	World I minus World II (M $)				World I minus World III (M $)				Intermediate Costs (M$)	
	PCE	PFCF	FGE	S/LGE	PCE	PFCF	FGE	S/LGE	World I minus World II	World I minus World III
7.03 Primary Aluminum	0	0	29.2	0.1	0	0	0	0	39.1	3.4
7A04 Ni, Ni Alloys, Co	0	0	0	0	0	0	0	0	7.9	0.3
7B04 Zinc	0	0	0	0	0	0	0	0	1.0	0.4
7C04 Magnesium	0	0	0	0	0	0	0	0	3.1	0.2
7D04 Lead	0	0	0	0	0	0	0	0	1.8	0.5
7E04 Ti, Ta, Zr	0	0	0	0	0	0	0	0	6.1	1.0
7F04 Au, Ag, Pt Pd	0	0	0	0	0	0	0	0	20.6	1.1
7G04 All Others	0	0	0	0	0	0	0	0	2.7	0.5
8.01 Metal Cans	0	0	0	0	0	0	0	0	190.7	0.8
8.02 Metal Barrels, Drum + P	0	4.0	1.3	0	0	0.3	0	0	37.3	0.1
8.03 Met Sanit & Plumbing P	0	0	0	0	0	0	0	0	78.6	0.1
8.04 Nonelec & Heating Equi	0	2.3	7.2	0.6	0	1.5	0.2	0	108.2	2.7
8.05 Fab Structural Metal	0	1044.0	19.2	0	0	692.2	15.1	0	1045.7	5.6
8.06 Screw Mach Prd & Stamp	0	0	0	0	0	0	0	0	680.9	1.9
BA07 Coating + Plating, Cor	0	0	6.9	0	0	0	0	0	7.0	12.9
8B07 Coating + Plating, Ncor	0	0	0	0	0	0	0	0	119.0	10.8
8C07 Misc. Fabr. Metal Prod	0	282.2	49.9	0	0	145.1	0	0	589.4	2.6
9.01 Engines & Turbines	0	334.3	38.9	0	0	92.4	30.4	0	156.1	4.0
9.02 Gen Indus Mach + Equip	0	851.4	144.5	36.0	0	441.9	103.3	24.8	667.8	20.3
9.03 Machine Shop Prd	0	0	0	0	0	0	0	0	24.0	2.5
10.01 Farm Machinery	6.9	1221.0	5.2	16.1	3.2	815.0	2.4	7.5	86.6	1.0
10.02 Construction Machine	0	1415.3	56.6	61.2	0	878.2	38.3	40.9	138.8	0.8
10.03 Mining Machinery	0	81.1	0.3	0	0	34.2	0.1	0	22.8	0.1
10.04 Oil Field Machinery	0	112.0	0.4	0	0	54.5	0.2	0	14.3	0.1
10.05 Mtrl-Hndlng Mach Ex	0	343.0	3.2	0	0	162.0	2.6	0	118.3	1.1
10.06 Indust Trucks + Trac	0	56.2	0	0	0	17.8	0	0	17.4	0.3
10.07 Metal Working Machin	0	654.5	0	0	0	338.2	0	0	139.1	1.5
10.08 Specl Industry Machin	20.0	670.3	7.4	7.4	13.2	306.9	5.1	5.0	532.4	1.2
11A01 Automobiles	15429.1	8641.1	208.3	400.8	13754.9	5347.8	187.5	358.0	1348.7	22.3
11B01 Trucks, Buses, etc.	2088.9	2005.7	309.3	543.2	1646.8	1076.9	244.6	428.4	441.4	7.5
11.02 Aircraft & Parts	45.5	226.9	2465.8	0	21.3	10.3	556.9	0	298.8	5.6
11.03 Ship + Boat Bldg. + Rep	142.7	91.1	904.6	13.3	82.7	49.1	407.7	5.0	94.7	1.7
11.04 Locomtv + Rail + St Car	0	266.6	2.4	5.8	0	107.1	1.7	4.3	133.6	5.0
11.05 Cycles, Trailers, etc.	0	23.8	0	0	0	5.6	0	0	85.8	1.3
12.01 Elec Measuring Instr	0	268.1	30.6	0	0	51.9	0	0	28.5	0.8
12.02 Elec Motors + Genera	0	75.5	0	0	0	23.9	0	0	56.1	0.3
12.03 Industrl Controls, Et	0	339.8	0	0	0	100.3	0	0	88.5	0.9
12X04 Elec. Lamps + Fixtures	23.1	6.5	1.5	7.6	12.1	1.3	0.8	4.0	114.8	1.0
12.06 Electrnc Compnts + Acc	0	0.5	0	0	0	0.2	0	0	322.6	1.9
12.07 Misc Electrical Mach	0	19.9	0	0	0	4.2	0	0	17.6	0.7
13.01 Serc Industry Machi	3.1	567.7	7.2	10.0	1.6	308.9	3.5	5.1	154.2	6.2
13.02 Household Appliances	847.5	91.5	4.2	7.1	344.2	43.6	1.7	2.9	404.7	2.4
13.03 Radio, TV, + Commun. Equi.	661.7	163.1	1032.7	42.4	0	27.5	0	0	265.8	5.0
14.01 Scientific Instrmnts	0.3	146.2	102.8	40.6	0.2	25.3	53.5	20.6	156.5	1.3
14.02 Med, Surgcl, Oental In	0	0.3	0	0	0	0.1	0	0	13.8	0.1
14.03 Watches, Clocks, + Par	0	0	0	0	0	0	0	0	7.4	0.0
14.04 Optical + Opthalmic Go	0	0.1	0	0	0	0	0	0	2.1	0.1
14.05 Photo Equip + Suppli	0	21.0	0	0	0	5.9	0	0	47.4	0.6
15.01 Computing + Relat Mach	0	128.6	0	0	0	37.9	0	0	86.4	1.2
15.02 Othr Office + Busin Ma	0	50.5	0	0	0	17.5	0	0	139.2	1.1

Table 10. Concluded.

Sector	World I minus World II (M $) PCE	PFCF	FGE	S/LGE	World I minus World III (M $) PCE	PFCF	FGE	S/LGE	Intermediate Costs (M$) World I minus World II	World I minus World III
15.03 Office Supplies	0	0	0	0	0	0	0	0	.0	.0
16.01 Ordnance + Accessori	-0.0	0.0	224.1	0.5	0	0.0	0	0	296.9	17.9
16.02 Othr Misc Prd	0	69.0	0	0	0	16.1	0	C	338.1	2.8
17.01 Railroads + Relatd Ser	0	26.8	0	0	0	10.7	0	0	202.8	54.4
17.02 Local + Highway Passng	0	0	0	0	0	0	0	0	225.5	52.5
17.03 Motor Freight + Wareho	0	39.5	0	0	0	15.6	0	0	446.8	110.0
17.04 Water Transportation	0	4.8	0	0	0	0.8	0	0	180.0	46.9
17.05 Air Transport	0	1.2	0	0	0	0.5	0	0	70.2	10.6
17.06 Pipe Lines	0	0	0	0	0	0	0	0	28.1	3.7
17.07 Transportation Servi	0	3.6	0	0	0	1.6	0	0	5.3	1.3
18.C1 Telecommunication	0	0	0	0	0	0	0	0	326.9	19.1
18.02 Electric Power	0	0	0	0	0	0	0	0	2689.7	55.7
18.03 Gas	0	0	0	0	0	0	0	0	191.9	29.8
18.04 Water + Sanitary Ser	0	0	0	0	0	0	0	0	391.8	94.3
19.01 New Const, Nonfarm Re	0	0	0	0	0	0	0	0	273.7	31.9
19.02 New Const, Nonresid B	0	2338.5	0	0	0	908.4	0	0	495.0	14.3
19.03 New Const, Public Utl	0	1045.3	0	0	0	171.6	0	0	1485.1	31.6
19.04 New Const, Highway + OT	0	49:4	0	0	0	15.9	0	0	172.6	4.9
19A05 Maint + Repr Const, COR	925.3	0	592.6	1587.3	0	0	0	0	6.9	2.4
19B05 Maint + Repr Const, NCO	0	0	0	0	0	0	0	0	361.1	27.8
20.01 Wholesale + Retail Tra	0	178.8	0	0	0	48.0	0	0	606.4	272.5
20X02 Finance, Ins, Real E, Ad	0	0	0	0	0	0	0	0	617.5	280.2
20.05 Othr Bus + Prof Serv	0	0	14.5	0.4	0	0	0	0	222.6	31.8
20.06 Bus Travel, Enter + GIF	0	0	0	0	0	0	0	0	.0	.0
21.01 Printing + Publishin	0	0	0	0	0	0	0	0	9.9	3.1
21.02 Radio + TB Broadcast	0	0	0	0	0	0	0	0	0.1	0.1
21.03 Hotels + Lodging Pla	0	0	0	0	0	0	0	0	157.3	56.1
21.04 Persnl + Repar Serv, Ex	331.0	0	0	0	0	0	0	0	176.2	30.7
21.05 Automobile Repair + Se	2075.2	0	14.6	111.7	0	0	0	0	272.5	15.0
21.06 Amusements	0	0	0	0	0	0	0	0	22.2	8.0
21.07 Medical + Health Ser	0	0	0	0	0	0	0	0	98.1	45.0
21.08 Educat Servc + NCNPROF	0	0	0	0	0	0	0	0	76.4	36.2
22.01 Post Office	0	0	0	0	0	0	0	0	22.9	6.3
23.02 Government + Industry	0	0	1494.2	0	0	0	0	0	0.0	0.0

II.B. Special Area Costs

II.B.1. Federal Government

The Federal Government owns a large amount of capital equipment that is subject to corrosion. Maintenance, repair and replacement expenses resulting from corrosion of that equipment represent a significant proportion of the total U.S. cost of corrosion. However, since each agency has custody of its own equipment, maintenance and other costs would have had to be obtained from each. Many agencies are well aware of corrosion problems, and some important studies of corrosion have been performed, but no overall investigation or careful government-wide estimate was uncovered in this study. Given the time and resource limitations of the present analysis, we decided to examine those agencies that owned the largest amounts of capital equipment. A government-wide result was obtained by scaling these data.

Data were obtained from the three services of the Department of Defense (DOD), National Aeronautics and Space Administration (NASA), Coast Guard, Government Services Administration (GSA), the Legislative Branch, and National Bureau of Standards (NBS). Maintenance and repair costs for these agencies came from various sources. In a few cases, corrosion costs were found, but generally, careful estimates of the fraction of losses due to corrosion were required. The total capital items considered here were estimated by BCL to represent $650 billion (97.6 percent of those owned by the Federal Government). They include real capital (buildings and structures, for example) and "personal" capital (aircraft, ships, and ordnance, for instance). Corrosion cost information was determined in our study for 83.4 percent of the total capital owned by the Government. Costs for the remainder were then estimated.

Information on aircraft was obtained from the Air Force, Navy and Coast Guard. The total Federal capital in aircraft was estimated by BCL to be $195 billion. The annual corrosion maintenance costs of these was estimated to be $990 million. Lifetime in service was judged to be unaffected by corrosion, but rather determined by obsolescence. However, a redundant excess of aircraft of 5 to 8 percent results from the influence of corrosion on aircraft downtime.

Detailed maintenance records were available for ships in both the Navy and Coast Guard fleet; however, corrosion-specific actions were not identified. Certain assumptions regarding the proportion of corrosion-related work at the fleet, tender and shipyard repair levels were made. In summary, the Coast Guard annual corrosion cost was $7.5 million and the estimated Navy cost was $392 million for a total cost of about $400 million for ships, which is 0.7 percent of the estimated Federal capital in ships of $56 billion.

Real property (buildings, structures) comprises 36 percent of the total Federal capital. The inventory is quite variable, with ten types of buildings and sixteen types of structures. Because it was not possible to examine the corrosion costs in all cases data from DOD, which owns about 70 percent of the Federal buildings and structures, was used to deduce total losses. A thorough study of corrosion-related maintenance at seven Army and Air Force installations had been previously conducted by Hahin [15], and the results were used here. The corrosion fraction of maintenance found in that study was used together with published maintenance costs for the DOD groups. The annual DOD corrosion maintenance costs were calculated to be $280 million. Data were also gathered from the Coast Guard, NASA, GSA, and NBS, and total Federal real property corrosion maintenance costs were determined to be $375 million annually.

Combining the expenses for aircraft, ships and real property leads to an annual maintenance corrosion cost estimate of $1.775 billion on 84 percent of all Federally owned capital. Based on that, a total cost of corrosion maintenance in the Federal sector is estimated to be about $2 billion annually.

To determine the full effect of corrosion in the Federal sector, costs caused by the need for redundant capital and by shortening of equipment lifetimes due to corrosion must also be included. For example, in the case of Federally-owned aircraft, there is no estimated change in lifetime, but there is an estimated 6 percent capital redundancy. This causes a yearly capital redundancy cost due to corrosion of $2.4 billion, as compared to a yearly maintenance cost of

$986 million. In other cases, such as automobiles, there is little redundant equipment, but the lifetime is shortened. When these considerations are applied to all the capital equipment of the Federal Government, a capital cost of $6 billion is determined, in addition to the $2 billion in maintenance expenses. These corrosion costs together amount to about 2 percent of the Federal budget. Of the $8 billion total costs of corrosion to the Federal Government, about 20 percent is estimated to be avoidable.

II.B.2. Personally Owned Automobiles

The principal expenses of corrosion in the ownership of an automobile are associated with the degradation of components made of the iron and steel which comprise approximately 80 percent of the weight of an auto. These costs may be separated into three parts:

(1) Costs of built-in protection against corrosion included in the purchase price. These include payment for a wide range of features such as more expensive materials, special designs and coatings, and corrosion inhibitors.

(2) Those portions of maintenance and operating costs attributable to corrosion. This includes replacement of components such as mufflers, tailpipes and radiators, repair and painting of corroded parts, and replacement of coolants.

(3) Costs of premature replacement of autos. Since corrosion reduces the market value of a car, autos are generally discarded and replaced more frequently than would occur in the absence of corrosion. Often, the decision to scrap an auto is made when the potential costs of engine repairs, parts replacements, or repair of damage incurred in an accident are too large compared to the current market value of the auto to justify such expenditure.

Among the expenses incurred in accident-free auto ownership, some, such as muffler replacement, would not occur to any significant degree in the absence of corrosion. For other costs, like painting, protection against corrosion is only a part of the overall expense. In such cases, attribution of expenses to corrosion can usually be made by experts with reasonable accuracy.

Finally, some costs are undoubtedly larger because of corrosion, but attribution of these to corrosion is, of necessity, largely a matter of subjective judgment. For example, the average lifetime of autos does not depend solely upon auto condition, but is a complex function of rates of deterioration, accident frequency, maintenance costs, new car prices, used car demand, styling and new features, and general economic conditions. Though corrosion may be a significant factor in rates of deterioration, it is not fully separable, in the economic sense, from other forms of deterioration. Nor can deterioration itself be given an exact quantitative significance relative to the other variables involved in lifetime.

Estimates of the cost of corrosion for personally owned autos appear in two parts of the BCL report: in the input/output model and in Appendix C of that report. The latter summarizes available data and conclusions of some previous studies. As with the overall study, the sections on the auto rely upon available data and estimates made by technical experts.

The major differences between the two treatments of the auto in the BCL report are in the treatment of useful lifetimes and in the discussion of approaches to reducing corrosion costs. In the input/output model, useful automobile lifetime is treated explicitly in the form of input data and assumptions on replacement rates in the three worlds defined in the study. In particular, data for the current practice World I, provided by IRS Bulletin F,[4] are given as a lifetime range of 2 to 20 years for personally-owned autos. The ranges used for the best practice World III, 8 to 20 years, and for the no corrosion World II, 10 to 20 years, represent assumptions on how lifetime ranges would shift under best practice and no corrosion, respectively.

[4] IRS Bulletin F gives other lifetime ranges for fleet or industrial uses.

In Appendix C of the BCL Report, auto lifetime is not treated explicitly, but estimates are given of body corrosion damage. Such damage, a key factor in auto deterioration, contributes to shortening of useful lifetimes, but cannot be regarded as an economic measure of shortened useful lifetime.

The discussion of approaches to reducing corrosion costs (Appendix C of the BCL Report) in the BCL appendix includes a variety of options: to alter the environment that contributes to auto corrosion; to modify auto design; and to modify the materials of construction. In addition, there are owner options—such as, washing, waxing, and undersealing—which may also reduce corrosion costs. Modification of the environment, primarily by reducing the use of deicing salts, is not considered feasible at this time in view of the needs for highway safety and open roads during winter. Moreover, poor results have been obtained in tests of alternative methods for removing snow and ice from roads. The BCL report concludes that modifications in design and materials offer the best prospect for minimizing corrosion damage to autos. It also suggests that improved owner care of autos could also reduce corrosion costs. While the potential effectiveness of options considered feasible was not discussed, the meaning of best practice implicit in the options mentioned includes both the manufacturing practices of the auto makers and the maintenance procedures of car owners.

The BCL results obtained from the input/output model give the overall cost of auto corrosion (see Table 8, sectors 11A01 and 21.05 in PCE column) as about $17.5 billion of which an estimated $13.8 billion is avoidable using best practice. The analysis of the personally owned auto in Appendix C to the BCL Report gives the total cost of auto corrosion as about $5.9 billion of which about 2.2 billion is avoidable.

In the input/output treatment of auto corrosion, premature replacement of autos accounts for $15.4 billion, or about 90 percent of the total. The remaining $2.1 billion represents replacement of auto parts, coolants, and auto repairs. The latter generally agrees with corresponding costs given in the BCL Report's Appendix C. However, premature replacement ($15.4 billion) is much larger than the most nearly corresponding term—body corrosion damage ($2.9 billion)—given in their appendix. Thus, the major difference between the two estimates resides in the treatment of useful lifetimes.

As indicated above, the calculation of replacement rates requires input data representing ranges of useful lifetimes for each of the three worlds. As shown in Appendix A of this report, the replacement rate is sensitive to changes in lifetime particularly for very short lifetimes. Thus, corrosion loss estimates are most sensitive to assumptions regarding ranges of lifetimes under current practice. For example, if this range were assumed to be about 4 or 5 to 20 years rather than 2 to 20 years, the replacement cost estimate would be reduced to about $8 billion.[5] Based upon this analysis and given the uncertainties surrounding the estimation of lifetimes, a replacement cost of $4 to $12 billion is probably a more reasonable estimate than the $15.4 billion discussed above. This revised estimate of replacement cost reduces the total cost of corrosion derived from the input/output analysis to the range $6 to $14 billion, and the avoidable losses to between $2 and $8 billion.

Even after revision, the input/output estimates of total and avoidable corrosion costs are greater than those given in the appendix to the BCL report. As the latter analysis does not include costs of premature replacement per se but does include estimates of the costs of body damage, one factor in premature replacement, we conclude that the $6 billion total cost given in the appendix of the BCL report should be considered a lower limit. The upper limit, as derived from input/output analysis and modified in the error analysis carried out by NBS is estimated to be about $14 billion.

[5] Other approaches to estimating replacement rates, for example, emphasizing the affect of corrosion on the longer rather than the shorter lifetimes in assumed lifetime distribution curves, yield similar results.

II.B.3. Electric Power

The electric power industry consists of two main segments: generation of electricity and transmission and distribution of electricity. Corrosion problems for the latter segment, which are the same regardless of the type of generating plant, consist of atmospheric corrosion of structures above ground and underground corrosion of buried structures.

There are five types of electric power generating plants: fossil fuel (coal, gas, oil, or waste-fired), hydroelectric, nuclear, geothermal, and solar. The corrosion problems vary considerably depending on the type. Corrosion failure of boiler tubes and turbine blades are prominent problems in coal-fired plants. Gas-fired boilers are being phased out, but gas turbine plants suffer high temperature blade corrosion. Oil-fired units have the same steam-side boiler corrosion problems as coal-fired units, but their fire-side problems relate to vanadium and sulfur in the oil. Hydroelectric corrosion is similar to that found in the water and sewer sector. Geothermal corrosion is serious, but total power output is small. Solar units are very small in total output. Nuclear corrosion costs are large, in part due to the large price differential of replacement power generated by fossil plants when the nuclear plant is down.

Direct corrosion costs are given by the I/O Model as $4.1 billion, with avoidable expenditures of only $120 million or about 3 percent of total costs. This may be compared with the Hoar report [6] estimates of £60 million total and £25 million avoidable, or 42 percent for the power industry. (Note that these U.K. figures do not include loss of plant revenues during shutdowns.) The difference in these percentages is related in part to inclusion in the Hoar Power Industry Sector of not only electrical power generation, transmission, and distribution, but also the generation, transmission, and distribution of gas and the mining of coal. An example given in the Hoar report of an avoidable cost in gas distribution is the estimate of £8 million avoidable expenses due to corrosion of gas service pipes to dwellings. This is nearly one-third of the avoidable costs given.

Maintenance expenditures in the electric power industry due to corrosion are estimated to be about 10 percent of all maintenance costs in the areas of transmission, distribution, and miscellaneous and about 50 percent of all maintenance costs in the area of generation of power. From these estimates, and from others by the industry of maintenance costs in the electric power industry, the total annual corrosion maintenance costs are considered to be about $1.1 billion. Corrosion-related excess capacity is estimated to be 10 percent of total capital investment. Corrosion research costs are approximately $10 million.

Best practice is not expected to change non-nuclear generation corrosion costs significantly. In nuclear plants, solutions to corrosion problems should result in major cost reductions. Some, but not major, reduction in cost by best practice in transmission and distribution can be expected.

For further detail, see the BCL report (Appendix B of the present report). The likely effects on corrosion costs of future developments in electric power technology are discussed further in Section III.B. of the present report.

II.B.4. Energy and Materials

The outputs of the BCL input-output analyses of Worlds I, II, and III were used to estimate the costs of additional energy and materials required because of metallic corrosion. Total national energy and materials costs of metallic corrosion were estimated from differences in total outputs between World I and World II for the energy and materials sectors. Avoidable national energy and materials costs of metallic corrosion were estimated from differences in total outputs between World I and World III for the energy and materials sectors.

To capture the corrosion impact effects on energy and materials as resources, the total outputs of the primary extractive sectors for non-renewable energy and materials resources were used. Renewable resources, such as hydro-electric power, and agricultural, forestry, and fishery products, were excluded from the analysis.

The energy and material costs of metallic corrosion were calculated in the form of dollar differences and percentage changes relative to World I. The costs of corrosion in energy and materials, both total and avoidable, are always positive.

In order to fit these costs into a meaningful context, the percentage changes for energy and materials have been compared to the percentage changes in Gross National Product, the latter as a measure of the national average impact of metallic corrosion. In general, in percentage change the costs of corrosion in energy have proved to be slightly less than the overall average costs to the economy, but the costs to coal sectors were slightly higher and the costs to the petroleum sector were slightly lower. The costs of metallic corrosion on the metallic ore sectors were found to be several times higher than the national average, in percentage change.

The following sectors identified by BCL nomenclature were selected:

To Represent Energy:

2A04: Underground Coal Mining
2B04: Strip Coal Mining
2C04: Other Coal Mining
2A05: Crude Petroleum
2B05: Natural Gas.

These sectors are not a perfect representation of non-renewable primary energy. Thus, uranium is omitted, whereas metallurgical coal and petrochemicals, which should be excluded, are included. These imperfections in classification have a negligible effect on the analytical conclusions.

To Represent Materials:

2.01 Iron and Ferroalloy Ores
2.02 Copper Ores
2.03 Non-ferrous Ores, Except Copper
2.06 Stone and Clay Mining
2.07 Chemical and Fertilizer Mining.

Table 11 summarizes the results of the analysis of the national impacts of corrosion, total and avoidable on primary energy sectors. Table 12 summarizes the results of the analysis of these impacts on non-renewable raw materials sectors.

It is noteworthy that Table 11 shows the overall energy cost of corrosion to be relatively low, 3.4 percent, which is a smaller proportion than the 4.2 percent of the Gross National Product estimated as the total cost of corrosion. The overall avoidable energy impact of corrosion, at 0.6 percent, is almost the same as the percentage change of GNP for that case. Within the energy sectors, there is more impact on coal than petroleum or natural gas. These results stem from the strong capital focus of corrosion, in contrast to the strong demand for energy products, and particularly petroleum products, as consumables.

Table 12 shows the materials impacts of metallic corrosion to be relatively high. The overall total impact of 10.7 percent for materials is two and a half times the percentage impact on Gross National Product. The overall avoidable materials impact of metallic corrosion, at 1.3 percent, is more than double the percentage impact on Gross National Product. Within the materials sectors, the metallic corrosion effects are concentrated mainly on the metallic ores, sectors 2.01, 2.02, and 2.03. For those sectors, the impacts are 16.7 percent for total corrosion and 2.1 percent for avoidable corrosion. For the non-metallic minerals sectors, sectors 2.06 and 2.07, the impacts of metallic corrosion are smaller, in percent, than the impacts of these sectors on Gross National Product.

The strong impact on metallic resources represents two factors:

° The substitution from more expensive metals to less expensive metals.

° The strong link of metal products with the capital sectors.

TABLE 11. *National Impacts of Metallic Corrosion on Primary Energy Sectors**

Selected Sectors		Total Output Levels in Million Dollars			Differences in Million Dollars		Percentage Change From World I	
		World I	World II	World III	Total: World I - II	Avoidable: World I - III	Total	Avoidable
2A04:	Underground Coal Mining	6254.5	5876.3	6016.3	378.2	238.2	6.0	3.8
2B04:	Strip Coal Mining	5917.0	5568.3	5697.1	348.7	219.8	5.9	3.7
2C04:	Other Coal Mining	236.5	217.0	224.1	19.5	12.3	8.2	5.2
2A05:	Crude Petroleum	23,147.5	22,507.6	22,935.8	639.9	211.7	2.8	0.9
2B05:	Natural Gas	6154.7	5901.0	6055.7	253.7	99.0	4.1	1.6
Total		41,710.2	40,070.2	40,929.2	1640.0	781.0	3.9	1.9
Recalculated Total					1400.0	248.5	3.4	0.6

*Data from Appendix C, except recalculated line, which is scaled from these in accordance with the results of Appendix A.

TABLE 12. *National Impacts of Metallic Corrosion on Non-Renewable Raw Materials Sectors**

Selected Sectors		Total Output Levels In Million Dollars			Differences In Million Dollars		Percentage Change From World I	
		World I	World II	World III	Total: World I - II	Avoidable: World I - III	Total	Avoidable
2.01:	Iron and Ferroalloy Ores	4941.0	4351.4	4498.8	589.6	442.2	11.9	8.9
2.02:	Copper Ores	1495.1	774.2	1443.2	720.9	51.9	48.2	3.5
2.03:	Non-ferrous Ores Except Copper	2164.8	1795.6	2086.1	369.2	78.7	17.0	3.6
2.06:	Stone and Clay Mining	5538.0	5269.5	5457.6	268.4	80.4	4.9	1.5
2.07:	Chemical and Fertilizer Mining	1754.5	1705.1	1738.5	49.4	16.0	2.8	0.9
Total		15,893.4	13,895.8	15,224.2	1997.5	669.2	12.6	4.2
Recalculated Total					1705.2	212.9	10.7	1.3
Metallic Ore Sectors only (Sectors 2.01, 2.02, and 2.03)		8600.9	6921.2	8028.1	1679.7	572.8	19.5	6.7
Recalculated Metallic Ore Sectors					1433.9	182.3	16.7	2.1

*Data from Appendix C, except recalculated lines, which are scaled from these in accordance with the results of Appendix A.

From a long-run resource point of view, a breakthrough in corrosion of metals technology might have the effect of conserving national resources of metallic ore, but would have less effect on non-metallic ores and national coal resources, and would have the least effect on national resources of petroleum and natural gas.

III. Discussion

The present study differs from previous ones because it attempts to assess all costs of corrosion, direct and indirect, over the entire economy and to evaluate the uncertainties in these cost estimates. Thus, this is an important advance over earlier attempts to determine the national economic effects of corrosion.

The results of this NBS-BCL analysis agree qualitatively with those found in previous studies. Because of efforts to be more complete, however, it is not surprising that the higher total costs of corrosion were found.

III.A. Reliability of Results

In assessing the reliability of results we must consider the soundness of both the I/O methodology and the data that the I/O model uses. The validity and reliability of the I/O model are discussed in detail in Section 3 of the BCL report. Some comments should be made, however, on the particular classification system of the present corrosion study. There is no classification system that cannot be improved, particularly since:

- The data gathering must await the classification system.
- Defects in the classification system will be discovered during the data gathering.

In the present study, many cases were uncovered in which the corrosion cost needed to be assigned to a supporting industry, but yet the corrosion effect was lost in a large aggregate coefficient in the supporting industry. This is the product mix problem.

The product mix problem is a significant generator of error of estimation in an input-output model. This problem arises because the economy produces more types of items than the approximately 130 sectors of the I/O model. Hence, many different products must be grouped into composite sectors. No error arises as long as either (1) the different products in a sector have quite similar input requirements, or (2) the different products in a sector always move together (i.e., always maintain the same proportion of the sectoral output).

The construction sector is a significant one for concern about product mix. The construction coefficients tend to be among the largest coefficients in the capital matrix. As for the differing input requirements, our concern is not so much within the three worlds of corrosion analysis, but with the significant differentiation in moving from world to world. The data from the large, amorphous construction sectors are ill-suited to the purposes of corrosion analysis. This is a case where, with more time and resources for analysis, other techniques might have been explored.

If a new corrosion study were to be initiated or the present one significantly extended, two alternative ways for reducing the product mix error in the construction sector would be considered:

1. Break the sector into a finer level of detail, or
2. Pass-through of information so that materials requirements coefficients would bypass the construction sector and be assigned directly to the using sectors.

Either method would be sufficient for the accurate treatment of corrosion data. The latter would give a slightly smaller matrix which would be somewhat less costly to handle. The former would permit a more accurate estimate of the cost of corrosion in the service of construction sectors.

The transportation sectors, although quite large and amorphous, are not sufficiently differentiated in input structure to generate a significant product mix problem.

In a future study, the use of less expensive materials in capital equipment, as in structures, and the use of thinner walls in tanks because the walls do not corrode might be included as direct capital effects.

No other classification system changes are recommended.

The comparison between World I and World III shows that roughly from 1/2 to 2 percent of Gross National Product is spent on avoidable corrosion costs. Much of this cost may occur in the smaller firms of an industry, perhaps too small to afford the expense of adequate corrosion engineering and maybe even unable to use the best practice of larger firms because of their higher costs of acquiring capital funds. These possibilities suggest that there may be value in a program to develop and maintain a data base on the economics of corrosion best practice for smaller firms and to transfer that information to those in the private sector needing it.

In conclusion, the input-output model appears to be an appropriate vehicle for a study of national and sectoral corrosion costs. The model offers the advantages of a comprehensive checklist of questions on corrosion and a vehicle for integrating the answers. The application of the model to the measurement of corrosion costs sidesteps the pitfalls of some other input-output applications.

Regarding the reliability of data for use in the I/O methodology, as the BCL Report notes, the most uncertain data are the useful lives and particularly the avoidable costs. We concur in this judgment. We also note that the final demand data, which drive the I/O model, must be obtained with much higher precision than the interindustry data.

In order to estimate the uncertainty in the corrosion costs due to errors in the input data, it is sufficient to examine some of the major contributions to the total cost. This examination is described in Appendix A to this report. The single product contributing most to corrosion costs is the automobile, and the largest contribution to the uncertainty in automobile corrosion expenses comes, as expected, from the useful life estimates. This leads to a large error in the overall costs of corrosion, clearly skewed to the high side, especially for the avoidable costs. That is, the best estimate of the error in the total cost of corrosion would be approximately +10 percent and –40 percent. The central value is, therefore, reduced to give equal uncertainties upward and downward. In the case of avoidable costs, we consider the BCL result to be an approximate upper limit. For more details on the estimates of uncertainty, see Appendix A.

In addition to the results obtained by BCL using the I/O model, three examples of detailed or limited scope studies appear in their report: Federal, Electric Power and Automobile. The reliability of such limited scope studies depends more directly on the soundness of the data obtained from interviews or the literature than in the I/O model. Consequently, limited studies can be helpful when examining a small segment of the U.S. economy in detail. In such an approach, a simple summation of costs taken over all components of equipment, production, and other similar factors within the sector may be sufficient. In some instances, determining costs per unit may be useful. For example, in non-residential construction, builders suggest that about 1 percent of the cost of an edifice is attributable to corrosion prevention devices. Hence, one percent of an estimate of the total of such building costs, as obtained from the Statistical Abstract of the U.S., for example, yields an approximate total corrosion cost.

For individual cases, a discounted cash flow computation may be used to assess the effects of corrosion costs. Thus, if capital expenses for corrosion prevention are ascertained via the data gathering process, costs due to corrosion for various equipment lifetimes can be computed.

Yet another method is to carry out empirical correlations of corrosion costs with the corrosion agent intensity. This has been performed by Hahin [15] for certain military installations. For example, costs for paint maintenance can be correlated with certain climatological factors and air pollution concentrations [15]. If such correlations can be carried out successfully, then the data may be used in a predictive fashion.

In sum, data gathering is basically the same whichever analysis scheme is to be employed. For the entire economy or large segments of industry, perhaps I/O is the optimum analytical tool. However, for other purposes, a more limited analysis leading to specifically required results, e.g., how often to repaint a structure in order to minimize costs, is more effective.

III.B. Corrosion Problems in Developing Technologies

An important issue not directly addressed by the BCL report is the corrosion costs associated with new technologies. This omission results from the NBS requirement that the report be concerned with the economy as it existed in 1975. Thus, while new technologies for coal mining and oil extraction under increasingly severe conditions (deeper mines and deeper offshore wells) may not be reflected in the 1975 results, they undoubtedly will have large impacts in the future. The report predicts as a result of interviews with oil industry experts that corrosion costs for oil extraction will "rise dramatically" in the future because of more use of offshore sites and increased oil production from fields containing higher amounts of corrosives.

As another example, in 1975 nuclear energy constituted only 10 percent of the energy generation total. This technology, which must cope with a number of difficult problems, will undoubtedly have larger impacts in the future. The BCL report indicates that solutions to corrosion problems can be expected to have a substantial effect on reducing costs of nuclear energy.

Of great importance, also, are corrosion costs in the area of new technologies whose commercialization is inhibited by the lack of solutions to the complex corrosion problems brought about by quite different sets of conditions. Thus, a number of new problems will have to be solved in order to cope with corrosion under the novel conditions expected under future technological, economic, political and sociological constraints. Good descriptions of some of these future problems can be found in committee or workshop reports concerned, for example, with the following:

1. Material problems in coal conversion technologies [16].
2. An overview of the material sciences [17].
3. Materials technology in the near-term energy program [18].
4. Research needs in energy conversion [19].

The main thrust in this section is to describe briefly the issues that will have impacts on corrosion-prevention practices needed for developing technologies. Four major areas will be briefly discussed: (1) energy, (2) environment, (3) materials conservation, and (4) food.

(1) *Energy*—The many developing technologies in the area of energy have several ramifications that will affect corrosion costs. First, there will be the increasing need to develop materials and protective measures to enable exploration of techniques that use highly corrosive conditions under high temperatures and pressures. Second, the continuing need to extract oil and coal from deeper and more inaccessible wells and mines will demand an extension of presently established corrosion prevention technologies. Finally, the utilization of polluting fuels will entail new corrosion prevention measures.

(2) *Environment*—Developing technologies to meet the requirements of environmental regulations will necessitate materials that can withstand highly corrosive operating conditions. For example, the requirement to control emissions from polluting fuels such as sulfur-bearing coals has created the need to cope with the corrosion problems of desulfurizing systems. Another concern is the development of non-polluting inhibitors for cooling water treatment that are inexpensive and as effective in preventing corrosion as the older inhibitors, such as chromates.

(3) *Materials Conservation*—In an economy where shortages of critical materials are a problem, developing technologies will require the ability to use substitute materials that are economical and corrosion resistant and contain no critically short components. Another approach to effect material conservation will be the use of coatings and special surface treatments, such as ion implantation, to enable the technology to achieve satisfactory corrosion protection while using small amounts of critically short materials. Finally, the use of recycled materials (a materials conservation measure) will require corrosion protection methods that are less sensitive to wide variations in alloy impurity contents.

(4) *Food Production*—A need to raise the rate of food production will require an increase in the extent and efficiency of irrigation and food storage systems. Inexpensive, corrosion resistant alloys will be needed for these applications.

While today's corrosion prevention measures will contribute towards making developing technologies economically viable, new corrosion technology will be also needed for future problems.

IV. Conclusions

An investigation of the economic effect of corrosion in the United States was carried out by the National Bureau of Standards. The economic analysis required was placed under contract to Battelle Columbus Laboratories. A significant feature of the study is that the method employed—input-output analysis—provides a methodological framework that permits comprehensive treatment of all elements of the costs of corrosion: production costs, capital costs, and changes in useful lives, for example. The input/output model allows analysis of interindustry relationships in the national economy and attribution of relative costs to specific segments of the economy. While there have been previous estimates of the costs of corrosion, none has provided a focused effort based upon a sound technical-economic method, and none included the indirect effects of corrosion.

The working definition of the cost of corrosion was the increment of total costs incurred because corrosion exists. This total was separated into avoidable and unavoidable costs. Avoidable costs are those amenable to reduction by the most economically effective use of presently available corrosion control technology. Reduction of presently unavoidable costs requires technological advance.

Using the results obtained in the input-output analysis as a basis, the total cost of corrosion in the United States (1975) is estimated to be $70 billion—about 4.2 percent of the Gross National Product. Of this amount, about 15 percent is estimated to be avoidable under criteria developed in the study. This means that a significant fraction, approximately $10 billion, of the total now expended for corrosion control and in the production of goods for replacement or repair because of corrosion, could be available for other uses through the economic use of presently available technology.

One important aspect of this study of the economic effect of corrosion is its placement of a full range of maintenance and replacement problems into an economic context that affords a measure of the severity of these problems and provides estimates of where and how the impacts of corrosion are felt. The methodology established in the study, moreover, gives a basis for placing industrial corrosion costs data on a common scale thus rendering existing data and future data more comparable and valuable.

The study also provides a bibliography of 418 references on corrosion economics which should serve as a resource for industry groups, Federal agencies, State and Local Governments, and others, in their efforts to enhance productivity and reduce maintenance and replacement expenditures. Another immediate value of the study is that it provides the Congress with a reference point for the impact of corrosion against which the relative effect of other factors affecting the economy can be compared. In addition, the procedures developed in this study provide a basis for technology assessments and the I/O model can possibly be used to assess economic effects of proposed means to reduce costs. This study does identify specific sectors of the economy where high avoidable and presently unavoidable corrosion costs are encountered and where corrosion reduction activities might have an impact.

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APPENDIX A

to

ECONOMIC EFFECTS OF METALLIC CORROSION IN THE UNITED STATES

Estimate of Uncertainty

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CONTENTS

CONTENTS—Continued

LIST OF TABLES

Estimate of Uncertainty

1. Introduction

In this Appendix, we will attempt to estimate the uncertainties in the final estimate of the cost of corrosion as determined by BCL, and the uncertainty in its elements. The method that will be followed in this analysis is similar to that which would be used in estimating the uncertainty in any measurement process, although the present situation is more complex in that it does not involve physical measurement and often involves personal judgment. In such an estimate, however, we will need to be concerned with systematic uncertainties and random uncertainties. Often, we do not know the range of values of the input data. In many cases, therefore, the analysis will be more in the sense of a sensitivity analysis, in which the sensitivity of the result for reasonable changes in the input data are calculated. In any case, we need to relate the final results to the data obtained by survey or otherwise. Hence, we begin with a description of the method used to determine the cost of corrosion.

2. Cost of Corrosion

It is important to recognize that BCL determined six costs of corrosion. These six costs are broken down into three categories each consisting of avoidable and unavoidable costs. The three categories are:

a) Overall costs to the economy.

b) The *direct* costs as expressed by industry indicators, and their sum. As will be seen, this is essentially a portion of the costs included in (a).

c) The *direct* plus *indirect* costs as expressed by industry indicators.

For each of these categories, both avoidable and unavoidable costs were estimated, giving the total of six costs as previously mentioned.

2.1 Overall Costs

The overall costs are given by the sum of the costs in individual sectors considered either as a row or a column. The equation that relates the total cost of corrosion to the original data is

$$
\begin{aligned}
cc^i &= \sum_k \Delta FD^i_k + \sum_k ss^i_k X^i_k \\
&+ \sum_k \sum_l [B^1G + B^1R^1]_{kl} X^1_l \\
&- \sum_k \sum_l [B^iG + B^iR^i]_{kl} X^i_l
\end{aligned} \tag{1}
$$

$$i = 2,3$$

The terms in this equation have the following meaning:

cc^i is the total cost of corrosion in World i, i=II, III,

ΔFD^i_k is the change in stipulated final demand in sector k between World I and World i, i=II, III.

The components of stipulated final demand that contribute to the cost of corrosion are Personal Consumption Expenditures (PCE), Federal Government Expenditures (FGE), and State and Local Government Expenditures (S/LGE).

ss^i_k is the social savings in World i (i=II,III) for sector k, per unit output.
X^I_k is the total output for sector k in World I.
X^i_k is the total output for sector k in World i (i=II,III).
G is the growth matrix.
B^I is the capital-output matrix in World I.
B^i is the capital-output matrix in World i (i=II,III).
R^I is the capital replacement matrix in World I.
R^i is the capital replacement matrix in World i (i=II, III).

In this equation, all the quantities on the right hand side are experimentally determined except the total outputs. These in turn are given by:

$$X^j_k = \sum_l [1 - A^j - (B^jG + B^jR^j)]^{-1}_{kl} \quad FD^j l \qquad j=I,II,III \tag{2}$$

where A^j is the matrix of direct technical coefficients (BCL Report, p. 17).

This equation, in combination with eq. (1), shows that stipulated final demand which is determined exogenously from the input-output analysis, enters all of the terms in the equation. From these two equations, we can see that an analysis of the uncertainty involves answers to the following questions.

a) What are the uncertainties in the estimates of final demand, or more precisely, the uncertainty in the difference in final demand between World I and World II or III?

b) What are the uncertainties in the A matrix?

c) What are the uncertainties in the three capital matrices, B, G, and R? How are the errors in the A and capital matrices propagated on inversion?

2.2 Direct Costs to Industries

The direct costs τ^i_k to industries are given by (BCL Report, p. 34ff):

$$\tau^i_k = ss^i_k X^i_k + [r^I c^I + \rho^I) - (r^i c^i + \rho^i)]_k X^i_k \qquad i=II,III \tag{3}$$

where

$$(r^j c^j + \rho^j)_k = \sum_l (B^jG + B^jR^j)_{lk} \qquad j=I,II,III \tag{4}$$

The terms have the same meaning as in eq. (1) and (2). It will be recognized that, with the exception of the total outputs used, the sum of eq. (3) is the same as the the second and third terms in the right hand side of eq. (1), but summed in a different order. Hence, in an estimate of the uncertainty in the sum, those terms of eq. (1) will be the same as the uncertainty in the *sum* of the direct costs to industries, although the individual terms will be different.

2.3 Direct Plus Indirect Costs

The equations for these costs are given in the BCL Report, p. 38. They were not investigated in detail. The overall uncertainty is not likely to be different from that in the direct costs.

2.4 Summary

Considering the above analysis, an estimate of the uncertainty for the overall costs in Worlds II and III will serve as an estimate of the uncertainty in the total of the other costs as well. Hence, we now proceed to the estimate of the uncertainty in the overall costs.

3. Uncertainties in Stipulated Final Demand

3.1 World II

The vectors of stipulated final demand for which corrosion costs were determined for both World II and World III were Personal Consumption Expenditures (PCE), Federal Government Expenditures (FGE), and State and Local Government Expenditures (S/LGE). The costs estimated by BCL for World II are:

PCE	\$22.8 B
FGE	8.1 B
S/LGE	2.9 B
Total	\$33.8 B

Treating the uncertainties in each of these estimates as standard errors and as independent, then the fractional standard error in the total is given by

$$f_{FD} = [(f^2\chi^2)_{PCE} + (f^2\chi^2)_{FGE} + (f^2\chi^2)_{S/LGE}]^{1/2} \tag{5}$$

where the f's are the fractional uncertainty for the specific vector, and the χ's are the fraction of the total final demand cost associated with that vector. For the BCL results, the values of the χ's are: $\chi_{PCE} = 0.675$; $\chi_{FGE} = 0.239$; $\chi_{S/LGE} = 0.086$. If all the f's are the same then the uncertainty in final demand is $f_{FD} = 0.721$ f.

The cost for each of the vectors in turn is made up of a sum of costs for a number of sectors. In analogy with eq. (5), the fractional uncertainty for each of the vectors is given by

$$f_k = [\sum_i f_{ki}^2 \chi_{ki}^2]^{1/2} \tag{6}$$

where the subscript *k* refers to the vector and *i* to the sector.

Hence, in order to carry out an accurate estimate we should estimate the uncertainties for each of the *sectors*, calculate the uncertainty for each of the *vectors* from eq. (6), and from these calculate the uncertainty in the total from eq. (5). Within the time constraints this was impossible. Moreover, it is not essential if all that is required is a reasonable estimate of the uncertainty. For this, it is necessary only to choose some of the largest contributors to the total cost. These, therefore, were the sectors that were analyzed:

a) Aircraft in the Federal Government. Aircraft corrosion expenditures represent approximately 40 percent of the total corrosion costs to the Federal Government.

b) Real Property Maintenance in Federal Government. While not a large fraction of the costs in the Federal Government, this is important because BCL did it by in-house estimation, and a survey was also carried out.

c) Automobiles in PCE.

We will now discuss the uncertainties in each of these.

3.1.1 Aircraft in the Federal Government

3.1.1.1 Maintenance Costs

Based on information developed by the survey of the Federal Government, we assign a minimum uncertainty of approximately ± 25 percent to these costs. This uncertainty arises principally from (1) the uncertainty as to the fraction of maintenance expenses that are attributable to corrosion, (2) the uncertainties of extrapolating depot costs to obtain field costs for the Air Force, and (3) uncertainties with respect to spare parts costs in the Air Force.

3.1.1.2 Capital Costs

Capital costs for corrosion come from two sources: premature replacement and expenses for redundant capital. As described in Section 3.4 of the BCL report, the calculation is done as follows. Consider that there is only one type of equipment, with a lifetime u^i in World i (i= I,II,III). Let the capital stock in World i be K^i, and let the growth rate be g, taken to be the same for all three worlds. Then the yearly capital replacement cost in World i is given by

$$C^i = K^i \left[\frac{g}{1+g} + \frac{g}{(1+g)^{u^i}-1} \right]. \tag{7}$$

The difference in this quantity for the two worlds in question (World I and II or I and III) gives the total cost for that world.

When the capital equipment produced by a sector has a range of lifetimes, BCL used the average value of the function in eq. (7), weighting all lives equally. This assumes that there is equal monetary value of stock at each lifetime. As will be seen later under Automobile, this emphasizes the short lives and can lead to very serious uncertainties. For aircraft, the lifetime range was estimated to be 10-40 years, with no change for corrosion.

To see the sources of uncertainty, consider eq. (7) for the case where there is no change in lifetime, but there is redundant capital. Under these conditions, eq. (7) gives for the cost of corrosion in World II

$$cc^{II} = \zeta^{II} K \frac{g(1+g)^u + g^2}{[(1+g)^u-1][1+g]} \tag{8}$$

where ζ^{II} is the fraction of capital equipment that is redundant in World II. The uncertainty is thus determined by the uncertainties in this fraction, in K, in g, and in u. From this equation, the fractional uncertainty in the total cost can be related to the fractional uncertainty in ζ, in K, in g, and in u. The resulting expression is unwieldy. However, evaluated for u=10 and g=0.1030 (the value used by BCL), we obtain

$$f_{cc} = [f_\zeta^2 + f_K^2 + (0.34\ f_g)^2 + (0.598\ f_u)^2]^{1/2}. \tag{9}$$

Our estimates in these uncertainties are as follows.

1) f_ζ. The value of ζ used by BCL was 6 percent. The actual estimate from the survey was 5-8 percent, and it is estimated that the range could be from 4-9 percent, but probably not greater. Hence, ζ has an estimated uncertainty of ± 40 percent.

2) f_K. This is the uncertainty in the capital stock. Considering that the capital stock was calculated by BCL (see pgs. 33 and 34 of the BCL report) from the trend year purchases and the growth rate, with assumptions of long term steady state, etc., an uncertainty of 10 percent is arbitrarily assigned. This is probably a minimum estimate.

3) f_g. This is the uncertainty in the growth rate. The growth rate was derived by BCL by a regression analysis for five years from 1947 to 1967 for which data are available. An uncertainty of ± 10 percent is arbitrarily assigned.

4) f_u. This is the uncertainty in the lifetime. This can be quite large. A value of ±25 percent is arbitrarily assigned.

These estimates of uncertainty give a total uncertainty of ±44 percent for the capital costs. If we also consider that there is uncertainty because of the method of calculation with a range of lifetimes, the uncertainty in this capital estimate is estimated to be ±50 percent.

3.1.1.3 Summary on Aircraft

The total annual capital costs for aircraft are about $2.2 B, and the maintenance costs are $1 B. From the ±25 percent uncertainty for maintenance and the ±50 percent uncertainty in capital expenses, an uncertainty of ±36 percent in the total corrosion costs for aircraft is calculated.

3.1.2 Maintenance and Repair Construction-Corrosion in Federal Government

This is an important element to analyze because it is one for which a survey was conducted, and which BCL also did by an in-house disaggregation. The survey estimate for this expense was $375 M, whereas BCL used a figure of $592 M. This suggests a high estimate of 58 percent based on $375 M as the correct figure.

3.1.3 Automobiles in Personal Consumption Expenditures

The BCL figures indicate that personal consumption expenditures related to corrosion ($22.8 B) account for 67.5 percent of the corrosion expenditures associated with stipulated final demand ($33.7 B) in World II. Automobiles, in turn, account for 76.7 percent of PCE corrosion costs, divided between 88 percent ($15.8 B) in capital replacement costs and 12 percent ($2.1 B) in maintenance and repair. Hence, personal automobile capital corrosion costs account for 45.5 percent of total stipulated final demand costs. It is, therefore, important to analyze this in detail.

3.1.3.1 Maintenance and Repair

Corrosion related maintenance and repair expenses for automobiles were carried out by a survey (see automobile chapter in BCL report) and were also estimated by BCL as a fraction of total expenses for automobile repair and maintenance (Sector 21.05 in the BCL listing). BCL took the maintenance and repair expenses for World II to be 25 percent less than those in World I. After considering the uncertainty in the case of aircraft, and upon consultation with a member of the survey team, an uncertainty ±40 percent is assigned to this estimate. This is equivalent to saying that corrosion-related maintenance and repair expenses range from 15 percent to 35 percent of all maintenance and repair expenses on automobiles.

3.1.3.2 Capital Costs

In this case, BCL assumed no difference in capital stock because of corrosion, but there is a difference of lifetime of equipment. This is a reasonable assumption. The method of calculation used was to calculate the average value of annual capital replacement, as in eq. (7), for World I for its range of lifetimes, and subtract from this the average value for World II for that range of lifetimes. Uncertainties are caused by:

(1) The range of lifetimes used.

(2) The method of averaging, which assumes equal capital stock for each lifetime. This is important since the function in eq. (7) rises very steeply as u decreases. The minimum value u can have is two, by the definition of a durable good, and a simple change from two to three can cause large changes in the estimate of corrosion costs.

(3) The value of the capital stock, K. This is not a survey estimate, but estimated from growth rates and purchases in the trend year (BCL Report, p. 33).

(4) Uncertainties caused by an error in the estimate of g.

We now discuss each of these.

3.1.3.2.1 Uncertainties Caused by Lifetime

The calculations for several cases are given in Table A–1. In all cases, g has the value 0.0607, which is what was used by BCL. Case 1 is the BCL case. In Case 2 all that was done was to change the minimum lifetime in World I from two years to three years. This decreased the corrosion cost from $15.4 B in World II and $13.8 B in World III to $10.7 B and $9.0 B, respectively.

TABLE A-1. *Corrosion Cost, PCE Automobiles*

Case 1: BCL Case

World	**Range of Lifetime**
I	2-20
II	10-20
III	8-20

Cost, World II = $15.4 B
World III = $13.8 B

Case 2: Change of life in World I from 2-20 to 3-20, no other change.

Cost, World II = $10.7 B
World III = $ 9.0 B

Case 3: Use of a distribution of capital stock (see text p. A-7).

Cost, World II = $10.4 B (Lifetime of mufflers 2 years)
$ 9.6 B (Lifetime of mufflers 3 years)

Case 3
Personally Owned Automobiles (see text, page A-7)

	World I		World II
Lifetime	Fraction of Stock	Lifetime	Fraction of Stock
2	0.0296	10	0.0387
3	0.0091	11	0.0395
4	0.0154	12	0.1176
5	0.0241	13	0.2192
6	0.0548	14	0.2496
7	0.0628	15	0.1647
8	0.0959	16	0.0815
9	0.1233	17	0.0431
10	0.1308	18	0.0161
11	0.1188	19	0.0124
12	0.0954	20	0.0076
13	0.0693		
14	0.0488		
15	0.0327		
16	0.0211		
17	0.0220		
18	0.0161		
19	0.0124		
20	0.0076		

Case 3 is more complicated. For this a more accurate distribution of capital stock with respect to lifetime was attempted. This distribution was arrived at in the following way: Two parts of a car—exhaust systems and water pumps[1]—were assumed to have lifetimes of 2 and 6 years, respectively, and to be replaced because of corrosion. Their fraction of the capital stock was calculated by taking their replacement value—$100 and $70, respectively—and dividing them by the total replacement value of the automobile, taken as $4000. The remainder of the distribution is made up from the known scrappage rates of automobiles, taking for the distribution the probability of scrappage at a given age for a given model year. (E. Passaglia, unpublished results) The whole distribution was then normalized. For World II, the distribution for World I was compressed to ten years, and distributed between the years 10 and 20 to be as consistent as possible with what BCL has done. These two distributions are given in Table A-1. (This computation still has deficiencies; see below.) The corrosion cost is $10.4 B for this distribution, which is significantly less than the Case I value of $15.4 B. If, in addition, the life of mufflers is raised to three years, the cost is decreased to $9.6 B.

The distributions given in Table A-1, while approximately correct, do not give the desired quantity, namely the fraction of capital stock of automobiles in each lifetime range. To obtain this quantity, what is needed is: (1) the fraction of automobiles in the population for each age of automobiles, and (2) the age-specific probability of scrappage; i.e., the conditional probability that having arrived at age τ, the automobile will be scrapped before age $\tau+1$. The product of these two quantities, when normalized to unity, gives the desired distribution. For World I, the data for such a computation are available [1], and the methods for their treatment are given by Gornick and Passaglia [2]. For World II, the data need to be constructed, and this can be done by the methods given by Gornick and Passaglia. The method is as follows:

(1) Construct a curve giving the a-priori probability at year zero that an automobile will last at least to age τ. The sum of these probabilities gives the average expected life of the automobile.

(2) From this curve, construct the age specific probabilities of scrappage. This can be done by the methods given in [2].

(3) From the age specific probabilities and the assumption of a steady state growing population, compute the age distribution of the population.

(4) From the product of (2) and (3) compute the desired distribution as in World I.

This calculation was carried out. The curves of the a-priori probability in year zero of lasting to year τ is given in figure A-1. The curve for World I is calculated from data given in reference 1. The expected life is 9.6 years. The curve for World II was constructed with the following criteria.

(1) The probability in the early years does not change. This seems reasonable in that scrappage in these early years is not affected by corrosion.

(2) The expected life should be four years longer than World I. This is done to be consistent with the BCL estimates. The curve shown in figure A-1 represents an expected life of 13.6 years.

(3) No car lasts longer than 20 years, again to be consistent with the BCL estimate.

These three constraints are quite restrictive. Curves were drawn by eye until they were met. Analytical calculation was not attempted.

From these curves, using the method described above, the distributions of the population with respect to lifetime were constructed. These are shown in figure A-2. For the World I case, we have added mufflers and water pumps as described above, with mufflers considered to have a lifetime of 2 years. The curve for World II shows a very definite peak in the later years, as necessitated by the constraints put on the distribution as discussed above.

[1] Water pumps are not replaced exclusively because of corrosions. Their use here represents all other items, such as radiators, that are sometimes replaced because of corrosion. An error here does not materially affect the results obtained in this Section.

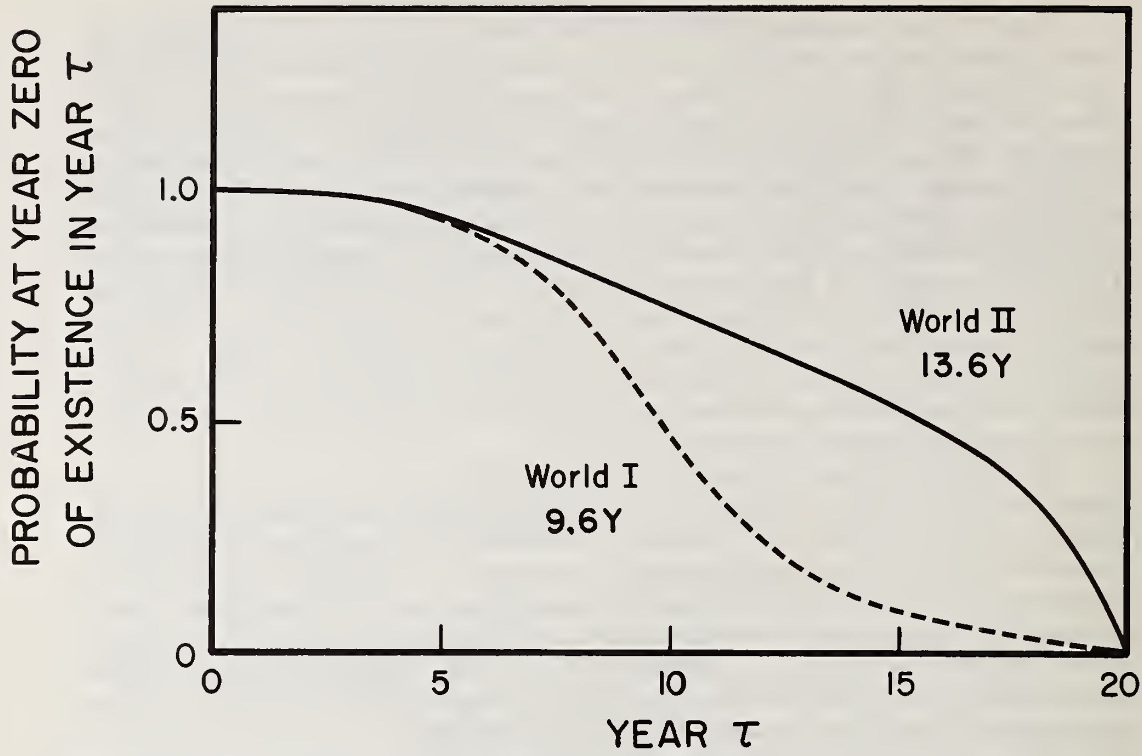

FIGURE A-1. *The probability, when new, that an automobile will be scrapped at age τ. The lower curve represents World I, and the upper curve represents World II. The numbers associated with the curves give the average expected life when new.*

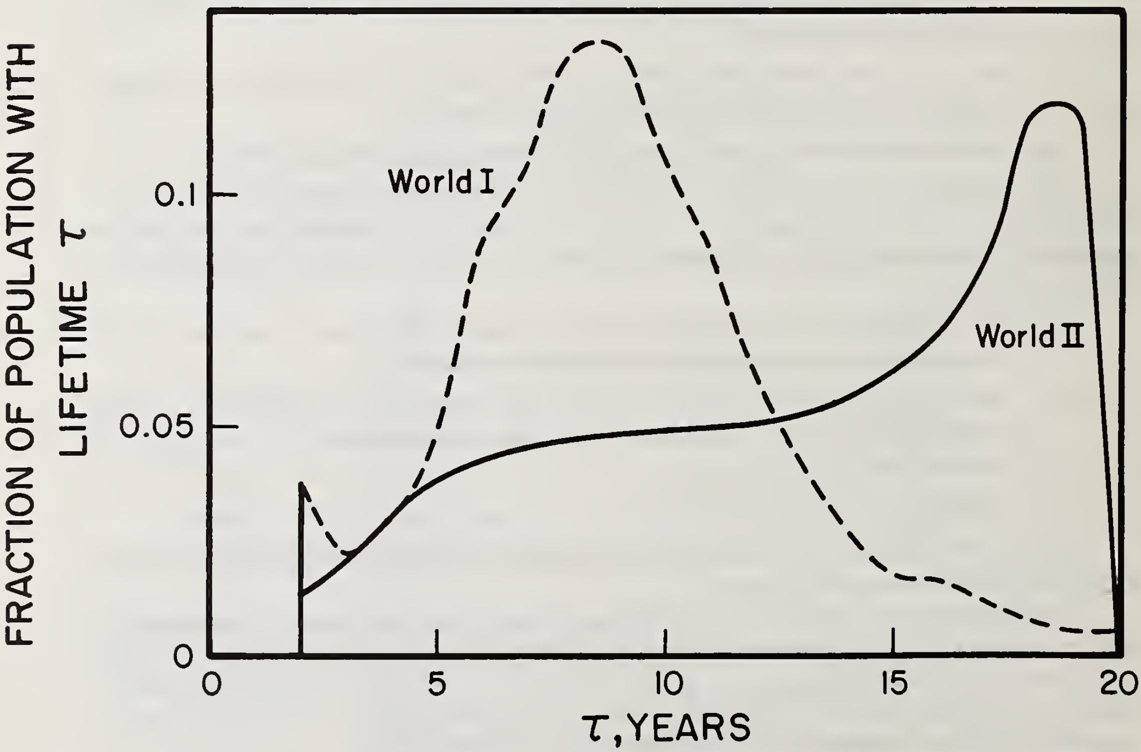

FIGURE A-2. *The fraction of the population of automobiles with lifetime τ. The dotted curve is for World I, and the solid curve is for World II. These curves are derived by the methods given on page A-7.*

The corrosion cost calculated from these distributions is \$7.9 B. If, in addition, the lifetime of mufflers is increased to 3 years, the cost is reduced to \$6.9 B.

The results obtained in this section demonstrate the sensitivity of the BCL calculation to the range of lifetimes and the distribution of capital stock with respect to lifetime. It should be noted that in the special chapter on the automobile, BCL derived at a total cost of about \$6 B—a number significantly different from the \$17.4 B obtained by the I/O method. The results obtained by the analysis presented here are closer to the special chapter results, although the two methods differ widely in methodology.

In addition to these factors associated with the lifetime distribution, there is an uncertainty caused by the range of lifetimes in World II. This range was taken by BCL to be 10-20 years, or an average of 15. No extensive calculations were made on the uncertainties caused by possible changes in this range. However, using the BCL distribution of lifetimes, it is calculated that if the average life in World II is changed by ± 1 year, an uncertainty in the corrosion cost of approximately ± 13 percent is introduced. If it is changed by ± 2 years, an uncertainty of approximately ± 27 percent is introduced.

3.1.3.2.2 Uncertainties Caused by Estimates of the Capital Stock

The stock of personally owned capital from the automobile sector was estimated by BCL to be \$228 B. The magnitude was calculated from the purchases in the trend year, the growth rate, and the range of lifetimes (BCL Report, p. 33). The actual equation used was

$$K = \frac{C(1+g)[(1+g^{u})-1]}{g[(1+g)^{u}+g]} \tag{10}$$

where C is the PCE in the automobile sector for the trend year. This function was averaged over the range of lifetimes (2-20 years). No detailed analysis of this expression was carried out. It is reasonably sensitive to the value of growth rate used, and considering the uncertainties in the fraction of capital stock in each lifetime, an uncertainty of ± 25 percent is arbitrarily assigned.

3.1.3.2.3 Uncertainties Caused by Estimates of the Growth Rate

Direct computation shows that uncertainties in the growth rate do not affect the cost of corrosion substantially for a given capital stock. For example, a growth rate of 0.035 (E. Passaglia, unpublished results) gives a cost of corrosion only a few hundred million dollars different from the value obtained by BCL. This is an insignificant difference, considering the magnitude of the other uncertainties.

3.1.3.3 Summary of Automobiles in PCE

The findings for automobiles in PCE are summarized as follows:

1) An uncertainty of ± 40 percent in maintenance and repair expenses for corrosion.
2) A likely overestimate of \$5-8 B in capital expenses, caused by the method of averaging the capital stock lifetimes and the particular choice of lifetimes.
3) An uncertainty of perhaps ± 25 percent because of the uncertainty of the estimate of capital stock.
4) An uncertainty of another ± 30 percent because of the uncertainty of lifetimes in World II.

The total effect of all of the considerations are difficult to estimate analytically. Probably, a reasonable estimate would be as follows:

1) A systematic overestimate of +\$7 B.
2) A random uncertainty of ± 50 percent.

3.1.4 Summary of World II Uncertainties

3.1.4.1 Federal Government Expenditures

3.1.4.1.1 Systematic Error

The one systematic overestimate found was \$0.2 B for Maintenance and Repair Construction corrosion.

3.1.4.1.2 Random Uncertainties

The total uncertainty for aircraft was ±36 percent, with the uncertainty in maintenance and repair being ±25 percent and that in capital costs being ±50 percent. Since these were some of the best known of all the costs, it is not unreasonable to assign an overall uncertainty to the remaining sectors of FGE expenditures of ±50 percent. When this is done, use of eq. (6) gives an overall uncertainty in FGE corrosion costs as ±21 percent.

3.1.4.2 Personal Consumption Expenditures

3.1.4.2.1 Systematic Error

As discussed above, there is a possible systematic overestimate of \$5-8 B in the automobile sector. No evidence of other systematic uncertainty was found, but the other sectors were not investigated extensively.

3.1.4.2.2 Random Uncertainty

In the BCL results, the corrosion costs in the automobile sector account for 76.7 percent of PCE corrosion costs. Practically all of the uncertainty in this vector comes, therefore, from the uncertainty in the automobile sector. This is estimated to be ±50 percent. Using this uncertainty for all the other sectors of PCE, we calculate an uncertainty of ±35 percent.

3.1.4.3 State and Local Governments

3.1.4.3.1 Systematic Error

The BCL results show that the largest expense in S/LGE is from Maintenance and Repair Construction. This is \$1.587 B out of a total of \$2.906 B. The figure of \$1.587 B was arrived at by BCL's disaggregation procedure, which led to a high estimate in the Federal Government of \$0.2 B. We, therefore, conclude that the figure of \$1.587 B may be high by \$0.5 B.

3.1.4.3.2 Random Uncertainty

This vector was the least studied of the stipulated final demand vectors. A consideration of the other vectors leads us to assign a probable uncertainty of ±40 percent in the results.

3.1.5 Summary of Systematic Error in Stipulated Final Demand—World II

Consideration of the various factors above leads to a possible total systematic error of \$5.7-8.7 B. The value taken as representative of this range is \$7 B.

3.1.6 Summary of Random Uncertainty in Stipulated Final Demand—World II

Recapitulating the above we have for the random uncertainties:

PCE:	±35%
PGE:	±21%
S/LGE:	±40%.

Using eq. (5) and the associated values of χ, we obtain for the total estimated uncertainty in stipulated final demand the value of 24.3 percent. Table A-2 gives the present estimates as compared to the BCL estimates. Considering the type of data available for this study, this uncertainty is not considered excessive.

3.2 World III

The estimates for World III were perforce largely subjective. As such, it is very difficult to estimate the uncertainty. In Table A-3, we show the actual and avoidable costs for all the vectors in which corrosion costs are incurred. For completeness, we have included Private Fixed Capital Formation and Intermediate Output Social Savings,[2] although these are not part of stipulated final demand.

The table shows some striking results. Thus, the BCL results indicate that approximately 70 percent of expenses made by consumers for corrosion are avoidable, and that approximately 52 percent of corrosion expenses associated with private fixed capital are avoidable. These are important results that warrant investigation.

TABLE A-2. *Stipulated Final Demand and Range of Uncertainty in World II*

	Billions of Dollars			
	BCL		NBS	
	Total	Range	Total	Range
PCE	22.8		15.8	10.3—21.3
FGE	8.1	--	7.9	6.2— 9.6
S/LGE	2.9	--	2.4	1.2— 3.6
Total	33.8		26.1	17.9—34.5

TABLE A-3. *Comparison of World II and World III BCL Estimates of Corrosion Cost*

	Billions of Dollars		
Vector	World I-World II Total Cost	World I-World III Avoidable Cost	Avoidable/Total %
PCE	22.76	15.88	69.8
FGE	8.06	1.66	20.6
S/LGE	2.91	0.90	30.9
PFCF*	24.09	12.46	51.7
Intermediate Output*	24.48	2.04	8.3
Total	82.30	32.94	40.0

*Not part of stipulated final demand, but added for completeness.

3.2.1 PCE—The Automobile

The BCL results show that $13.8 B of the capital corrosion expenses associated with the personally-owned automobiles are avoidable (World I minus World III). Since the total expenses (World I minus World II) were $15.4 B, BCL considers that approximately 90 percent of the

[2] The second term in eq. (1). See also BCL report, page 18.

capital expenses associated with automobiles are avoidable.[3] This is an extraordinarily high percentage. Moreover, capital expenses associated with the personally-owned automobile account for 13.8/15.9 or 87 percent of the avoidable costs in PCE, and 13.8/32.9 or 42 percent of total avoidable costs to the whole economy. Hence, it is important to examine the assumptions in this calculation in detail.

The principal reason for the BCL estimate for avoidable cost being so high is the assumption that the lifetime range of automobiles in World III (8-20 years) is very similar to that in World II (10-20 years). A simple calculation shows that a change in the World III lifetime from 8-20 years to 7-20 years, and 6-20 years, gives a change in avoidable costs from $13.8 B to $12.7 B and $11.4 B, respectively. In addition, no convincing reason is given for making the lifetime of equipment in World III closer to that in World II rather than that in World I. It is possible, therefore, to consider that the true estimate may be as low as zero (although this is unlikely), and is probably no higher (in percentage) than derived by BCL. Perhaps a reasonable estimate of the avoidable cost is 25 percent of the total cost.[4] If this is applied to the BCL estimate and the analysis presented in this Appendix in Section 3.1.3, the total range is $1.7 B to $3.9 B. This leads to the conclusion that the BCL estimate of $13.8 B may be $10 B to $12 B too high. Taking the other sectors of PCE as determined by BCL, we obtain a final estimate of avoidable costs for PCE of $4.9 B as compared to $15.9 B.

3.2.2 Other Vectors

The other vectors of stipulated final demand were not investigated in detail. They are sufficiently small as compared to the above that they do not warrant a great deal of analytical effort except to note that the actual value may be as low as zero, although this is unlikely. The values were, however, not changed from the BCL estimates, but an uncertainty of ±50 percent was arbitrarily assigned.

3.2.3 Summary of World III

The summary of our estimate of uncertainty is given in Table A-4. This table expresses the following:

1) There is a probable overestimate of about $11 B in PCE, arising from the method by which automobile capital costs are handled.
2) The range of uncertainty in the other costs is such that they are probably no higher than the BCL estimates.

TABLE A-4. *Summary of Uncertainties in World III, Stipulated Final Demand*

	Billions of Dollars			
	BCL Estimate of Avoidable Cost	NBS Estimated Systematic Error	NBS Total Range Estimate	NBS Revised Estimate
PCE	15.88	11	3.8 to 15.9	4.9
FGE	1.66	--	0.8 to 2.5	1.7
S/LGE	0.90		0.5 to 1.4	0.9
Total	18.44	11	5.1 to 19.8	7.5

[3] See, however, the automobile chapter in the BCL report and in the NBS Report.
[4] See BCL report, page C18, and reference 3.

4. Uncertainty in Intermediate Output Costs of Corrosion

Intermediate output costs of corrosion are represented by the second term in eq. (1), page A-1. Uncertainties in it come from two sources: uncertainties in the estimate of social savings, and uncertainties in the estimate of final demand components.

The sum of the costs represented by the second term in eq. (1) can be written

$$cc^i = \sum_k cc^i_k \tag{11}$$

where cc^i_k refers to the intermediate output corrosion costs for sector k and world i (i=II,III), and cc^i is the total cost for that world. From eq. (11), it follows that

$$\sigma_{cc^i} = \left(\sum_k \sigma^2_{cc^i_k}\right)^{1/2} \tag{12}$$

where σ denotes the uncertainty.

Because of the square terms in eq. (12), we need to look at those sectors that have the largest costs. Accordingly, in Table A-5, we show all the sectors that have costs greater than $200 M. There are 31 such sectors. Together they account for 77.6 percent of the intermediate output costs. These thirty-one sectors are still too many to analyze in detail. Hence, we inspect three of them: 11A01—Automobiles, 18.02 Electric Power, and 19.03, New Construction, Public Utilities. We will analyze each of these for coefficient uncertainties in the A matrix and uncertainties in total output.

4.1 Coefficient Changes in A Matrix

4.1.1 Sector 11A01—Automobiles

From the BCL results, the principal contributors to changes in the A matrix between World I and World II, and the percentage change of total change they account for are Alloy Steel (13.2 percent), Paints (13.2 percent), Primary Copper (9.9 percent), Primary Aluminum (15.7 percent), Corrosion Plating (26.3 percent), and Auto Repair and Service (21.8 percent).

These figures were investigated by the NBS corrosion staff. Qualitatively, it is felt that the results may be somewhat of an overestimate, particularly the changes in the alloy steel. However, no quantitative estimate was attempted. It is estimated that the uncertainty in the BCL results is ±20 percent.

4.1.2 New Construction, Public Utilities

From the BCL results, a full 82.2 percent of the social savings in this sector comes from assigning 90 percent of the copper to corrosion uses. The NBS corrosion staff feels this may be somewhat of an overestimate because of the use of copper for heat exchanger and esthetic purposes. However, no quantitative estimate was made. A random uncertainty of ±20 percent is assigned to the remainder.

4.1.3 Electric Power

The social savings in this sector comes from maintenance and repair construction, corrosion, and other business and professional services. No systematic error was found, and an estimated uncertainty of ±20 percent is assigned to the total.

4.2 Uncertainties in Total Output

Total output is calculated by eq. (2). It is thus subject to uncertainties in stipulated final demand, in the A matrix, and in the capital matrices. The only good way to get an estimate of what effect these uncertainties are likely to have is to carry out test calculations with selected changes. This was not done, and hence, we cannot say anything definitive about the uncertainties.

TABLE A-5. *Sectors with Largest Costs in Intermediate Output*

Sector	Intermediate Output Costs (Millions of Dollars)	% of Total
4X05	602.9	2.47
4.07	456.1	1.87
5.01	881.9	3.61
5.03	489.1	2.00
7A01	694.0	2.84
8.05	1045.7	4.28
8.06	680.9	2.79
8C07	589.4	2.41
9.02	662.8	2.71
10.08	532.4	2.18
11A01	1348.7	5.52
11B01	441.4	1.81
11.02	298.8	1.22
12.06	322.6	1.32
13.02	404.7	1.66
13.03	265.8	1.09
16.01	296.9	1.21
16.02	338.1	1.38
17.01	202.8	0.83
17.02	225.5	0.92
17.03	446.8	1.83
18.01	326.9	1.34
18.02	2689.7	11.00
18.04	391.8	1.60
19.02	495.0	2.02
19.03	1485.1	6.07
19B05	361.1	1.48
20.01	606.4	2.48
20.02	612.5	2.51
20.05	222.5	0.91
21.05	272.5	1.11
Total of 31 Largest Sectors	18,978.4	77.6

It seems clear that if the uncertainties are indeed random and apply to all sectors, then the process of matrix inversion and multiplication shown in eq. (2) will not cause a serious uncertainty in the *sum* of the sector total outputs. What happens to individual sector total outputs is unknown. Moreover, we have seen above that for some sectors (e.g., 11A01, automobiles) there is may be tendency for the estimates of corrosion costs to be systematically high. What effect this will have on total output in that and other sectors is unknown without model calculation.

For an estimate of the effect of Final Demand on Total Intermediate Output Costs, we can, however, reason as follows. A decrease in Final Demand of $57.8 B causes total output to change from $2917 B in World I to $2756 B in World II. This is a change of only 5.5 percent. Hence, it is reasonable to conclude that fractional changes in the decrease in final demand will not have a significant effect on total output and, hence, on those portions of the corrosion cost estimate that depend on total output. Hence, uncertainties caused by changes in total output resulting from changes in final demand appear to be quite small and will not be considered.

4.3 Summary of Uncertainties in Intermediate Output—World II

Not all sectors were investigated. Of the three that were, some evidence of overestimate on the results was uncovered. However, in other sectors (e.g., Pulp and Paper) evidence of an underestimate exists. In this respect, the comments in the BCL report, Section 5.3, should be considered. Hence, we conclude that there is no likely systematic error.

With this conclusion, the results for Intermediate Output are the most certain results obtained. Estimating the uncertainty for each sector as ±25 percent, use of eq. (6) leads to an estimate of uncertainty of about ±4 percent. This is negligible.

4.4 Intermediate Output—World III

For World III, Intermediate Output Social Savings are $2.04 B out of a total of $32.9 B in avoidable costs. The only changes BCL considered in going from World I to World III were changes in maintenance practices which, in a few cases, led to changes in value added. No changes in inputs such as more corrosion resistant metals, more zinc coatings, etc., were considered, as these changes in manufacturing inputs were considered second order effects (see page 63 of the BCL report). Thus, World I manufacturing technology is considered by BCL to be best practice, or so close to it that the difference, as far as costs is concerned, is negligible. Maintenance practices are, however, not considered by BCL to be best practice, for it is estimated that by going to best practice the producing and service sectors of the economy can save about $2 B in maintenance costs. The only changes considered by BCL in going to best practice are therefore in maintenance costs and equipment life. Maintenance costs are decreased and equipment life is increased in the BCL results!

The assumption of no change in input coefficients leads to an unusual (although not impossible) result. It implies that the cost of capital equipment would decrease, and yet the equipment would last longer. This comes about because the capital producing sectors would have lower costs (because of lowered maintenance in going to best practice) and, hence, could afford to charge less for their equipment. The users of the capital equipment, in turn, would also have lower maintenance costs, and in addition would pay less for their equipment. At the same time, they would be saving an estimated $12.5 B of costs caused by shortened equipment life in World I as compared to World III.[5] It is to be noted that in the BCL results *all* sectors would lower maintenance costs in going to best practice.

Both results, namely that best practice maintenance would lead to a decrease in maintenance costs in all sectors, and that best practice requires only a negligible change in A matrix input and value added coefficients, must be questioned, although the first result is more reasonable than the second. To investigate these questions in a quantitative manner would, unfortunately, involve a great deal of analysis. We can, however, reason, that the BCL result is very likely an upper estimate on the Intermediate Output avoidable costs, although as BCL assumed, the overestimate may not be significant. Certainly, it is hard to conceive that better corrosion practice manufacturing technology would decrease manufacturing costs, for this would imply that capital equipment manufacturing industries are, in most cases, incurring added costs to make equipment wear out sooner. Moreover, with respect to maintenance costs, the conventional wisdom is that more money spent on corrosion prevention maintenance will more than pay for itself in extended life. The BCL results, on the other hand, show that all the producing sectors of the economy could spend less for maintenance and still achieve extended life. While not impossible, this also has to be considered an upper limit on the possible savings. Hence, almost every alternative in the BCL results will tend to lower the estimate of avoidable costs in Intermediate Output. Indeed, it is not unlikely that the avoidable costs might be negative when manufacturing inputs are changed appropriately.

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[5] In this report, see also automobiles in PCE. There, 90 percent of lifetime costs of automobiles ($13.9 B out of $15.4 B) were estimated by BCL to be avoidable with no change in maintenance expenditures. That such a large saving could be accomplished with negligible changes in manufacturing input to the automobile sector, or in value added, is highly questionable.

Unfortunately, at this time we are unable to make even a rough estimate of the lower bound of the estimated avoidable costs in Intermediate Output. All that we can do is to label the lower bound Y, and let the estimate of the value of Y await further analysis.

5. Uncertainties in Capital Costs—PFCF

5.1 Introduction

The corrosion cost due to capital replacement is given by the second and third terms of eq. (1). Each of these terms is a sum of two matrices times a total output. However, each of the elements of the sum of these two matrices will be similar in form to eq. (7), with, however, the term $\bar{K}^i$ in that equation replaced by the capital/output coefficient, which, when multiplied by the total output vector will give the capital stock. Hence, the uncertainty will depend upon:

1) Uncertainties in total output. This is similar to the problem discussed previously in Section 4.2. The uncertainty of the total arising from this source is felt to be small, and will be neglected.
2) Uncertainties in the capital-output coefficient.
3) Uncertainties in the growth rate.
4) Uncertainties in the lifetime of equipment.

It is clear from this that the analysis is very similar to that given in Sections 3.1.1.2 and 3.1.3.2 with one important difference. In the BCL treatment of capital costs, they are driven by changes in stipulated final demand. This is taken care of appropriately by the use of the "dynamic inverse" (see page 22ff in the BCL report). The result of this treatment of PFCF is that even in the absence of redundancy (changes in the B matrix) and lifetimes (changes in the R matrix), there will still be a corrosion cost associated with PFCF because of the lower stipulated final demand in the absence of corrosion, or possibly, in best practice. This is a correct treatment of corrosion costs for capital, and represents a significant advance over previous studies. This point will, however, not be pursued, since it is not germane to the uncertainty problem.

In Table A-6, we show the BCL results for all the sectors listed in Table 2 of the BCL report. In Table A-7, we show the total cost contributed by this sector; the percentage of these costs of the total PFCF costs, for each sector; the avoidable costs; and the percentage of the total avoidable PFCF costs; the percentage of the total costs that are avoidable; and the BCL rating for each sector as to the Best Practice Impact. The sectors shown in this table represent 78 percent of the actual PFCF costs and 86 percent of the avoidable PFCF costs.

Two things are immediately evident from this table. First is the importance of the automotive sector. In the BCL results, this sector accounts for 35.8 percent of the PFCF total costs and 42.9 percent of the avoidable costs. The second is the disparity between the rating and the percentage of actual costs that are avoidable. Thus, the rating "minor" (14 entries) encompasses the range of 17 to 67 percent avoidable costs, with a relatively uniform distribution over this range. The rating "moderate" (4 entries) encompasses the range of 51 to 62 percent avoidable costs, and the rating "major" (5 entries) encompasses the range 40 to 65 percent avoidable costs. There seems to be little, if any, relationship between the rating and the percentage avoidable costs. Now, BCL meant to assign the terms "minor", "moderate", and "major" to the effect on lifetime. Hence, again the difficulty of relating lifetime estimates to corrosion costs becomes apparent, as discussed above in detail in Section 3.1.3, for the personally-owned automobile. Since the automobile is again the single largest source of costs, we begin by a discussion of the effect of lifetime on the costs caused by it in PFCF.

Table A-6. *PFCF Costs by Sector,* $M*

BCL Results

		Total Costs	% of Total	Avoidable Costs	% of Total	% Avoidable	Best Practice Input
8.02	Metal Bbls	4	.016	0.3	.002	7.5	minor
8.04	Heat Equip.	2.3	.01	1.5	.012	65	major
8.05	Fabr. Metal	1044	4.33	692	5.56	66	major
8C07	Gen. Hardware	282	1.17	145	1.16	51	moderate
9.01	Engines & Turbines	334	1.38	92	.74	27	minor
9.02	Gen. Machinery	851	3.53	442	3.55	52	major
10.01	Farm Machinery	1221	5.07	815	6.54	67	minor
10.02	Const. Machinery	1415	5.87	878	7.04	62	minor
10.03	Mining Machinery	81	.34	34	.27	42	minor
10.04	Oil Field Mach.	112	.46	55	.44	49	minor
10.05	Material Handling	343	1.42	162	1.30	47	minor
10.08	Special Machinery	670	2.78	307	2.46	46	major
11A01	Automobiles	8641	35.9	5348	42.91	62	moderate
11B01	Trucks, Buses	2006	8.3	1077	8.64	54	minor
11.02	Aircraft, etc.	227	0.9	10	.08	4	minor
11.03	Ships	91	.38	49	.39	54	moderate
11.04	Railroad	267	1.11	107	.86	40	major
12.03	Indust. Controls	340	1.40	100	.80	29	minor
12.04	Electric Lamps	6.5	.02	1.3	.01	20	minor
13.01	Service Machinery	568	1.35	309	2.48	54	moderate
13.02	Household Appl.	92	.38	44	.35	48	minor
13.03	Radio, TV, etc.	163	.67	28	.22	17	minor
14.01	Sci. Instruments	146	.60	25	.20	17	minor

*This table lists all the sectors for which BCL made replacement life adjustments.

Table A-7. *Effect on Corrosion Costs of Changes in Automobile Lifetime Assumptions**

Case	World I Life, Yrs.	World II Life, Yrs.	Corrosion Cost, % Change from Case 1	World III Life, Yrs.	Corrosion Cost, % Change from Case 1
1)	3–5⁺	6–8⁺	0	4–7⁺	0
2)	4–6	7–9	−32	5–8	−34
3)	3–5	6	−19	4–6	−22
4)	2–4	5–7	+65		
5)	3–5	3–7	−63		

*Calculated with $g=0.0607$.
⁺Case used by BCL.

5.2 Effect of Lifetime

5.2.1 Capital Costs for Automobiles

The equation used for this calculation is eq. (7), as already discussed. Now, this expression, as already noted in Section 3.1.3.1.1, is extremely sensitive to short lifetimes. Moreover, the cost is dependent on the actual value of the lives chosen not on only the difference between World I and the world in question.

We have carried out illustrative calculations to see what effect on corrosion cost small changes in estimated life can have. These are shown in Table A-7. Here we have shown three cases. Case 1 is the case used by BCL. For Case 2, the lifetimes in each world have been increased by one year, keeping the difference constant. In World II, the corrosion costs decrease by 32 percent, and in World III by 34 percent, as compared to the BCL case. In Case 3, World II, the lifetime has been set at 6 years, since a value higher than this seems unrealistic for a commercially used automobile.[6] The corrosion costs decrease by 19 percent as compared to the BCL case. In Case 3, World III, we have used a range of three years for the life, rather than four, as was done by BCL. The decrease in corrosion cost is 22 percent as compared to the BCL case. In Case 4, we have unrealistically lowered all the lifetimes by one year. There is an increase in corrosion costs of 65 percent, but this is unrealistic in that it could not be argued that a two-year-old car would be replaced because of corrosion.

Finally, in Case 5, we have calculated the case in which the lifetime goes from 3-5 years in World I to 3-7 years in World II. The reasoning here is that cars that are replaced after three years are not replaced because of corrosion, while those that are replaced after five years may be, and would have their lives extended to seven years in World II. This leads to a corrosion cost 63 percent below that estimated. It appears, therefore, that other and perhaps equally reasonable estimates can lead to the conclusion that the BCL results may represent an overestimate as large as $5 B in World II. This analysis again demonstrates the sensitivity of the results to estimates of the lifetimes.

5.2.2 Other Sectors

Without detailed analysis, no definite statement can be made about the other sectors. The most critical of them would, of course, be the ones with short lifetimes, since, as already noted, the analysis is very sensitive to even minor changes in the estimates when short lifetimes are changed to long. The sectors where this occurs (see Table 2, BCL report) are 8.05 (4.3 percent of PFCF costs), 10.02 (3.6 percent of PFCF costs) 10.04 (0.46 percent of PFCF costs), and 11B01 (8.3 percent of PFCF costs). These four sectors account for $4.7 B, or 19.2 percent of the total PFCF costs. While no specific calculations have been made, analogy to the automobile case suggests that the estimate for these sectors may be somewhat high.

In other cases, where the lifetime is long, the results are much less sensitive to uncertainties in the lifetime, and even more important, are not likely to lead to a systematic overestimate.

It is to be noted that the lifetimes used for World I were those obtained from Bulletin F of the IRS. These are lifetimes for depreciation. The actual useful life of equipment can be considerably longer. To the extent that the lifetime in World II is estimated as an increment on the Bulletin F lifetime, then the use of this lifetime will overestimate the cost, but the actual magnitude of the error is difficult without detailed study of individual sectors.

Except in rare cases, redundancy was not taken into account. This will, of course, underestimate the costs in those sectors where some redundancy exists.

It is well nigh impossible to take all these factors into account quantitatively with our stage of knowledge. Considering the model calculations done on the automobile, a reasonable estimate of the uncertainty is that the BCL estimate for PFCF other than the automobile, may be high by $1 to $2 B, with an uncertainty of ± 40 percent.

5.3 Uncertainties in Capital-Output Coefficients and Growth Rates

Both these quantities were obtained by regression analysis. The uncertainty in these is expected to be insignificant compared to that caused by uncertainty in lifetimes, and hence, are not considered.

[6] The median life of automobiles in the U.S. is approximately 9.6 years. Commercially-owned automobiles, which are used more intensively than personally-owned automobiles, are expected to have a shorter life.

5.4 World III

The costs estimated for World III are based on highly subjective judgments as necessitated by the lack of data. As a result, the data for World III for PFCF are some of the most questionable in the whole report. This is hardly surprising, since lifetime data of the type required are very difficult to obtain.

However, inspection of the results in Table A-6 leads to some important conclusions. The first is that generally speaking the percentage of avoidable costs is very high, particularly when compared to, for example, FGE, which BCL estimates to be 21 percent avoidable. Further, an analysis of the Industry Indicators shows that for even the least corrosion-aware industries, the non-capital parts of the costs are 35 percent or less avoidable, as compared to the capital costs, which go up to 67 percent avoidable.

The second observation is that, as already noted, there appears to be no relationship between the qualitative judgments of the effect of best practice ("minor", "moderate", and "major") and the percentage of avoidable cost, as already mentioned above.

Another attempt at obtaining the avoidable costs can, however, be made in the following way. Let us assume that the estimate "minor" means an avoidable cost of 10 to 30 percent (average 20 percent), and estimates of "moderate" means 30 to 45 percent (average 37.5 percent) and an estimate "major" means 45 to 60 percent (average 52.5 percent). These are, generally speaking, the judgment of BCL experts on the effects of corrosion in the various sectors. In Table A-8, we show a recalculation of the avoidable costs on this basis, using in each case the average percentage avoidable. Calculated in this way, the percent avoidable for PFCF is 32.4 percent, which seems more reasonable in view of the qualitative estimate. Hence, we obtain the following estimate for the PFCF avoidable costs. We subtract $5 B from the total costs of $24.1 B to account for the possible overestimate discussed in the preceding sections, and take 32.4 percent of the remainder as representing the avoidable costs. The result is $6.2 B, with a subjectively estimated range of $3.0 B to $19.1 B.

6. Summary and Conclusions

All the preceding results are summarized in Table A-9. In this table, we have given the BCL results, and the results derived in this appendix, along with the associated ranges. *No statistical significance must be associated with these ranges.* They are *not* 66 percent or 95 percent confidence levels. They are often subjective, and represent essentially the ranges that could be obtained with reasonable estimates other than those made by BCL. Hence, it follows that the lower and upper values of the estimate may be just as likely as the mid-value,

Some important differences arise. The first is in the total cost. The estimate in this Appendix is $69.7 B (rounded to $70 B), with a range of $52.7 B to $86.2 B, as compared to a BCL estimate of $82.4 B with no range given. The important point to note is that whether the actual cost is $52.7 B or $86.2 B, it is still very high.

Another important point is that most of the uncertainty in the costs arises from the uncertainties in the lifetime of equipment with and without corrosion. Since the automobile is the largest item of capital equipment in the economy, it is by far the largest influence. This is reflected in PCE and PFCF.

For the avoidable costs, our estimates are substantially different from those of BCL. Indeed, we have an unknown factor of "Y," as discussed above in Section 4.4. The range we have given is very large, since we have made it to include the whole range of estimates. Our estimate for the total is $15.4 B, to be reduced by "Y" when it becomes available.[7] The large difference between our estimate and that made by BCL is because of the difficulty of determining the effect of corrosion on equipment lifetimes, and incorporating the reasons for those changes in the accounting. The necessary data is, in most cases, not available, and even when available, the analytical methods of treatment are very sensitive to the actual values used, as we have shown. If

[7] A rough estimate for "Y" is given as a footnote to the table.

Table A-8. *Recalculation of Avoidable Costs, $M*
(Private Fixed Capital Formation)

Sector	BCL Total Cost	Rating	BCL Avoidable Cost	NBS Recalculated Avoidable Cost
8.02	4	minor	0.3	0.80
8.04	2.3	major	1.5	1.2
8.05	1044	major	692	548.1
8C07	282	moderate	145	105.8
9.01	334	minor	92	66.8
9.02	851	major	442	446.8
10.01	1221	minor	815	244.2
10.02	1415	minor	878	283.0
10.03	81	minor	34	16.2
10.04	112	minor	55	22.4
10.05	343	minor	162	68.6
10.08	670	major	307	351.8
11A01	3641*	moderate	2257**	1365
11B01	2006	minor	1077	401.2
11.02	227	minor	10	45.4
11.03	91	moderate	49	34.1
11.04	267	major	107	140.2
12.03	340	minor	100	68.0
12.04	6.5	minor	1.3	1.3
13.01	568	moderate	309	213.0
13.02	92	minor	44	18.4
13.03	163	minor	28	32.6
14.01	146	minor	25	29.2
Totals	13906.8		7631	4504.1

*Corrected from BCL results given in Table A-6 on the basis of discussion in Section 5.2.1.
**Calculated as 62 percent of total cost (Column 2), in accordance with BCL result (See Table A-6).

Table A-9. *Summary of Results*

	Total Costs ($B)				Avoidable Costs ($B)			
Sector	BCL	BCL Range	NBS	NBS Range	BCL	BCL Range	NBS	NBS Range
PCE	22.8	--	15.8	10.3–21.3	15.9	--	4.9	3.8–15.9
FGE	8.1	--	7.9	6.2– 9.6	1.7	--	1.7	0.8– 2.5
S/LGE	2.9	--	2.4	1.2– 3.6	0.9	--	0.9	0.5– 1.4
IO	24.5	--	24.5	23.5–25.0	2.0	--	2.0–Y	– Y– 2.0
PFCF	24.1	--	19.1	11.5–26.7	12.5	--	6.2	3.0–19.1
Total	82.4	--	69.7	52.7–86.2	33.0	--	(15.7–Y)*	(8.1–Y)–40.9

*The value of Y is a matter of speculation, but assuming it costs between 10 and 70 percent of the expected final demand gain for best practice (extra coatings, etc.), Y would be between $1.4 and $9.6 B, and the total avoidable costs would be between $6.1 and $14.3 B, or about 10 and 20 percent of the total cost. Note that these values of Y could make the avoidable IO contribution negative. This would mean an increased cost to manufacturers in a best practice world, to achieve a net savings to manufacturers plus final demand (life-cycle costs).

any further study were to be done, this is the area in which the main effort should be placed. At the present time, the estimate of avoidable cost has only marginal utility, with respect to the detailed accounting of how it arises.

This Appendix has concentrated heavily on the automobile sector, both for PCE and PFCF. This was not intentional, but was inevitable. In any estimate of uncertainty, the sector with the largest costs must be investigated in detail. Because in the BCL results the automobile represents by far the sector with the largest costs, we were inevitably led to consider it in greater detail than other sectors.

7. References to Appendix A

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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.)*

In response to a Congressional directive, this study of the cost of metallic corrosion to the United States was undertaken by the National Bureau of Standards (NBS). The analysis required in this study was placed under contract to the Battelle Columbus Laboratories (BCL). The overall study was conducted jointly by BCL and NBS. The study was designed to provide a reference to allow the economic impact of corrosion to be compared with other factors affecting the economy.

In 1975, corrosion cost the United States an estimated \$70 billion. This was 4.2 percent of the estimated Gross National Product for that year. Of this total, about 15 percent or \$10 billion was avoidable. An uncertainty of about ±30 percent for the total corrosion cost figure results from inadequate data in some areas and unsure technical and economic judgments. The uncertainty in the avoidable costs is considerably greater.

This study used a modified version of the BCL National Input/Output Model. The model quantitatively identifies corrosion-related changes in resources (material, labor, energy, value added), changes in capital stock, and changes in replacement lives of capital stock for all sectors of the economy. The use of this model is well suited for estimating the total direct and indirect costs of corrosion.

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)* Battelle Columbus Labs; Corrosion; Cost of Corrosion; Economic effects; I/O Model; Metallic corrosion.

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