A review of differing approaches used to estimate the cost of corrosion (and their relevance in the development of modern corrosion prevention and control strategies)

R. Bhaskaran, N. Palaniswamy and N.S. Rengaswamy
Corrosion Science and Engineering Division, Central Electrochemical Research Institute, Karaikudi, Tamilnadu, India

M. Jayachandran
Department of Commerce, H.H. The Rajah's College, Pudukottai, Tamilnadu, India

Abstract

Purpose – To analyze the different approaches used to estimate the cost of corrosion and understand the limitations so as to have proper appropriation in future appraisals.

Design/methodology/approach – Four well-known approaches to analysis of cost of corrosion viz., the Uhlig method, the Hoar method, NBS-BCL input/output method and net present value method have been considered in great detail and the impact of these approaches on corrosion economy in different countries has been highlighted.

Findings – Uhlig method of estimating corrosion cost always gives a conservative estimate of the direct cost of corrosion. The direct cost of corrosion, as estimated by the Hoar method, is found to be somewhat higher than is the estimate made using the Uhlig method, as shown by Shibata of Japan. The NBS-BCL method of input/output analysis, though apparently more scientific, is subject ultimately to uncertainties in quantifying the capital cost and intermediate output. The net present value method appears to be more realistic than do other approaches as it enables a life cycle costing of each structure/facility to be made and arrives at the most cost-effective corrosion control method. Even though all the above four approaches enable an estimation of direct cost of corrosion, there is no standard approach to assess the indirect cost of corrosion.

Originality/value – In a developing economy, each and every industry has to go for systematic corrosion auditing in order to identify and adopt the most appropriate corrosion control measures and effect considerable savings. This paper would be of immense use in that regard.

Keywords Corrosion, Corrosion protection, Research methods

Paper type General review

1. Introduction

The earliest attempt to estimate the cost of corrosion was made by Hadfield (1922, p. 83). His approach was based only upon a speculative estimate of the annual rate of rusting of iron and steel in the whole world. Credit for first scientifically classifying and analysing the cost of corrosion should go to Prof. Herbert H. Uhlig (1950) in the USA. Uhlig's approach was quite conservative and the estimate of the cost of corrosion was likely to be something of an underestimate.

Whereas Uhlig's approach involved the collection of cost data from the manufacturer, the approach of UK Committee on the cost of corrosion formed under the Chairmanship of Dr T.P. Hoar in 1966 was based primarily upon direct interaction with industry. The Hoar approach also led to an estimation of the possible percentage contribution from each individual industrial sector within the corrosion economy of a country.

The input/output model applied in 1978 by NBS-BCL when estimating the cost of corrosion in USA had some inherent uncertainties in quantification. There was also a problem of how to obtain updated data from a single source. Perhaps a more systematic approach to the analysis of cost of corrosion is that based on life cycle costing, using the net present value method which was initially suggested by Dillon in 1966 but which was adopted in a comprehensive manner by the Hoar Committee.

Thus, different individuals and/or organisations in various countries have followed a variety of corrosion cost estimation methodologies. It was worthwhile to analyse the different approaches and understand their advantages and limitations in order that a more reliable appropriation might be made in future appraisals. Accordingly, several approaches to the estimation of cost of corrosion were considered during the preparation of this paper. Recent work in India has shown

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that the annual cost of corrosion computed over a period of 40 years (1950-1990), using the corrosion coefficients worked out in the NBS-BCL study of USA, revealed polynomial growth behaviour and demonstrated that the cost of corrosion in any year could be predicted by using a polynomial function of a type $Y = ax^2 + bx + c$.

2. The Uhlig approach

Uhlig classified the cost of corrosion into two components:

1. direct loss – due to use of special alloys and replacement of corroded equipments; and
2. indirect loss – due to shutdown, over design, loss of product and efficiency, explosion and contamination.

The basic philosophy employed by Uhlig with regard to direct loss stemmed from the following assumptions.

The ferrous metals, iron and steel, are by far the engineering materials most used in industry. If iron were completely resistant to corrosion, there would not be any need for alternate material. Since iron and steel obviously undergo dissolution under many environmental conditions, special alloys or protective coatings are used. Therefore, when non-ferrous metals or alloy steels are used, the increased cost over iron and steel of the same shape and size can be considered to be a direct loss due to corrosion.

With regard to protective coatings, Uhlig made an assumption that approximately 50 per cent of annual production of paints might be consumed in protecting metals against corrosion. This percentage would be likely to vary from country to country. In consequence, for example, the annual sales of phosphating solution were reported as a direct cost of corrosion, since phosphating is a primary protection before painting.

Uhlig applied an interesting approach to the estimation of direct cost of corrosion in the boiler industries. He multiplied the total horsepower capacity of the country by the unit cost of water conditioning plus labour and boiler tube replacement per unit of horsepower.

His data on domestic water heater replacements were based on a user survey. Nearly half-a-million domestic hot water tanks being used throughout the country were observed for 5 years and a figure of 25 per cent of all tanks in service, which required annual replacement, was arrived at. Surprisingly, only 10 per cent was included as a direct loss, indicating the conservative approach he adopted.

His data on internal combustion engines were based on laboratory experimental studies as well as service data. He concluded that, on an average, 60 per cent of automobile engine wear could be attributed to corrosion. Automobile mufflers need periodic replacement because of corrosion failures. He collected the data on total number of mufflers supplied by car dealers and independent repair shops and multiplied the figure by unit cost and labour cost. He himself admitted that these data did not include mufflers installed at gasoline filling stations, fleet shops or by individual car owners, and the total estimate therefore represented a conservative figure.

2.1 The United States of America

Uhlig's (1950, pp. 29-33) conservative estimate of USA $5,427 million as direct loss due to corrosion is summarised in Table I. With regard to indirect losses, Uhlig stated that indirect losses could not be estimated and did not offer even an educated guess as to what they might be and his approach was based primarily on cost data collected from product manufacturers.

2.2 India

Rajagopalan (1958, pp. 191-3) of Central Electrochemical research Institute followed Uhlig's method to estimate the annual cost of corrosion in India. He also projected a conservative figure of Rs. 1,538 million as annual cost of corrosion for the year 1960-1961, as shown in Table II.

By comparing Tables I and II, it is evident that the cost data for the following headings were not included, viz. boiler, underground pipe maintenance and replacement, oil refinery maintenance, domestic water heater replacement and mufflers. If the data on the above categories had been included, the estimated annual cost of corrosion in India would have been increased by a minimum of Rs. 350 million, yet still remain a conservative figure.

On a percentage basis, it was quite revealing that, in a developing country like India, copper and its alloys played a dominant role as corrosion resistant materials. Protective coatings also contributed significantly. Stainless steel occupied the third position.

2.3 Australia

Revie and Uhlig (1974, pp. 3-5, 11) made a detailed estimate on the cost of corrosion in Australia and projected a figure of $466.7 million as shown in Table III.

It was reported that in Australia, protective coatings, as a class, played a predominant role in controlling corrosion. Tin-plating also was reported to have contributed significantly. Under this approach, stainless steels contributed to control of corrosion as corrosion resistant alloys. It is also worth pointing out that considerable effort was made to control underground corrosion by proper maintenance.

2.4 Japan

In Japan (Shibata, 2002, pp. 97-102), Uhlig's method of estimating the corrosion cost was adopted in 1974 and the exercise was repeated again in 1997 after a gap of 23 years. The comparative data for 1974 and 1997 are summarised in Table IV.

It is interesting to note that, in Japan, the percentage cost of each item remained almost constant over a period of 23 years (1974-1997). Approximately 60 per cent of expenditure was attributed to the use of protective coatings. Next to protective coatings, the surface finishing industries (i.e. industrial metal finishing) featured significantly. It was reported that only a moderate percentage of expenditure (i.e. around 10 per cent) was utilised for corrosion resistant materials.

The Japanese findings identified that increasing industrialisation and developments in anticorrosion products and processes within the paint industry and metal finishing industries tended to support the continued rapid growth of those industries and therefore there should be a continued demand for the development of new corrosion resistant materials.

3. The Hoar approach

In March 1966, the UK Committee on Corrosion Protection was established by the UK Minister of Technology under the Chairmanship of Dr T.P. Hoar. The committee contacted

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Table I Annual US direct loss by corrosion including cost of corrosion control

S. no.	Particulars	Direct cost of corrosion (amounts in $ million)	Percentage in total cost
1	Paints	2,045	37.68
2	Phosphate coatings	20	0.37
3	Galvanized sheet, pipe and wire	136.5	2.52
4	Tin and terne plate	316	5.82
5	Cadmium electroplate	20.1	0.37
6	Nickel and nickel alloys	182	3.35
7	Copper and copper base alloys	50	0.92
8	Stainless chromium-iron and chromium-nickel-iron alloys	620.4	11.43
9	Boiler and other water conditioning	66	1.22
10	Underground pipe maintenance and replacement	600	11.06
11	Oil refinery maintenance	50	0.92
12	Domestic water heater replacement	225	4.15
13	Internal combustion engine corrosion	1,030	18.97
14	Mufflers	66	1.22
Grand total		5,427	100

Table II Cost of corrosion control in India

S. no.	Particulars	Direct cost of corrosion (amounts in rupees million)	Percentage in total cost
1	Paints, varnishes and lacquers	400	26.01
2	Zinc for galvanizing	57	3.71
3	Tin for tinplate	113	7.35
4	Electroplating	100	6.50
5	Nickel and its alloys	10	0.65
6	Copper and its alloys	508	33.03
7	Lead and its alloys	33	2.15
8	Stainless steel	224	14.56
9	Aluminium	83	5.40
10	Prevention of corrosion in internal combustion engines	10	0.65
Grand total		1,538	100

Table III Annual Australian direct loss by corrosion, including cost of corrosion control

	Estimated corrosion cost (Aus.$ million)	Percentage in total cost
Paints, varnishes and lacquers	181.200	38.82
Phosphate coatings	1.957	0.42
Galvanized steel production	15.870	3.40
Tin and terne plate production	60.590	12.98
Cadmium electroplate	1.609	0.34
Nickel and nickel alloys	30.387	6.51
Copper and copper alloys	21.400	4.59
Stainless steels	43.600	9.34
Boiler and other water conditioning	5.540	1.19
Underground pipe maintenance and replacement	71.920	15.41
Oil refinery maintenance	1.140	0.24
Domestic water heaters	16.500	3.54
Automobile muffler corrosion	15.000	3.21
Total	466.713	100

Table IV Cost of corrosion in the national economy of Japan

Preventive measures for corrosion	Corrosion cost in 1974 (billion yen)	Percentage in total cost	Corrosion cost in 1997 (billion yen)	Percentage in total cost
Painting	1595.48	62.5	2299.46	58.4
Surface finishing	647.62	25.4	1013.52	25.7
Corrosion resistant materials	238.82	9.4	443.24	11.3
Anticorrosion oil	15.65	0.6	63.68	1.6
Inhibitor	16.10	0.6	44.90	1.1
Cathodic protection	15.75	0.6	21.68	0.6
R&D for corrosion	21.51	0.8	41.65	1.1
Corrosion inspection	–	–	9.56	0.2
Total	2550.93	100	3937.69	100

800 industries and all government organisations and obtained confidential information on the economic effects of corrosion, including plant shutdowns, production losses and structural failures.

Information was gathered by interviewing corrosion experts who worked in companies and agencies and by surveys on expenditures for corrosion protection practices. Corrosion experts estimated corrosion costs and the potential savings based on their experiences with major economic sectors. Technical judgments and estimates of industry experts were used extensively.

Information on education and research in the corrosion field was obtained by means of a questionnaire which was distributed to universities and technical colleges. The inquiry into research and information dissemination was extended to research associations, development associations and government departments. Trade associations and professional bodies assisted in the information gathering. Information gathered for a specific industry was used to estimate costs in other similar industry sectors.

The cost of corrosion for each industry sector subsequently was added together to arrive at an estimate of total cost of corrosion for the whole UK economy. The report identified the sources for the cost of corrosion by sectors of the economy. It evaluated and summarised the direct expenditures in each economic sector. Indirect costs were not included in the study.

After adding the costs of items replaced and expenditure on corrosion protection to these, the committee arrived at an industry-wide estimate of the overall cost of corrosion.

The UK committee and industrial organisations listed 16 factors that could lower the cost of corrosion. The factors, in order of priority assigned by the combined judgment of experts, were as follows:

1. better dissemination of existing corrosion control information;
2. improved protective treatments;
3. closer control over the application of existing protective measures;
4. improved design with existing materials;
5. greater awareness of corrosion hazards by the users;
6. use of new materials;
7. cost-effectiveness analysis of materials and protective treatments leading to procurement based on total life costs;
8. previous feedback on service performance;
9. improved specifications for protective treatments;
10. more basic research on corrosion mechanisms;
11. improved communication between government departments;
12. improved storage facilities;
13. information on corrosion sensitivity of equipment;
14. better non-destructive testing techniques;
15. standardisation of components; and
16. more frequent or longer duration maintenance periods.

The single most important factor considered necessary to reduce the costs of corrosion in the UK was better dissemination of existing information on corrosion control.

The effect of taxation in the UK on the costs of corrosion also was considered. It was noted that the taxation system encouraged a low capital investment and a high maintenance approach within some industries. Maintenance costs effectively qualified for tax relief because these costs could be expensed in the year in which they were incurred. Thus, a company fully conscious of the consequences of corrosion might select inferior materials deliberately for plant construction, resulting in a reduced capital outlay but increased maintenance costs. The Hoar report concluded that such a tax system, in fact, increased the cost of corrosion.

The study noted that the UK corrosion costs were substantial; however, these costs were not higher than should have been expected, based on the consideration of annual expenditures for corrosion protection technologies. The annual expenditures in the UK on protective coatings, including the cost of application, were estimated to be £772 million. In addition, approximately £620 million was estimated for annual expenditure on corrosion resistance materials such as austenitic stainless steels and non-ferrous alloys. It was noted that these costs were not incurred solely for the purpose of corrosion resistance.

3.1 The United Kingdom

Hoar (1971) estimated conservatively the cost of corrosion for UK as £1,365 million per annum, which represented 3.5 per cent of the GNP of 1970. In addition, the committee estimated that better utilisation of current knowledge and techniques could enable approximately £310 million to be saved per annum.

The UK national costs of corrosion by major areas of industry are presented in Table V.

It can be seen from Table V, that the cost of corrosion was the highest in the transport sector, and accounted for 26 per cent of the total. The likely potential savings also were highest

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Table V Cost of corrosion by major areas of industry in UK

Sector	Corrosion costs (amount in £ million)	Percentage in total cost	Potential savings (amount in £ million)
Building and construction	250	18	50
Food	40	3	4
General engineering	110	8	35
Government departments and agencies	55	4	20
Marine	280	21	55
Metal refining and semi-fabrication	15	1	2
Oil and chemical	180	13	15
Power	60	4	25
Transport	350	26	100
Water	25	2	4
Total	1,365	100	310

for this sector. Marine corrosion accounted for a substantial part of the cost. It was followed closely by building and construction sector. Likely potential savings in these sectors were reported to be "quite appreciable". Surprisingly, the cost figure cited for the oil and chemical industries was just 13 per cent on the basis that cost-effective control systems were in practice in oil and chemical industry, though with hindsight this conclusion would appear to have been somewhat optimistic.

During 1998-2001, the Department of Trade and Industry (DTI) awarded a project to the Paint Research Association (PRA) to look at corrosion losses in a changing industrial landscape. Data relating to current corrosion problems and the measures being used to control them, together with estimates of the cost being incurred were solicited by means of questionnaires, interviews and a focus group meeting. Information was gathered primarily from five industry sectors and the total cost of corrosion in each industrial sector is as given in Table VI. Comparing Tables V and VI, it can be seen that there was estimated to have been tenfold increase in the cost of corrosion in two vital sectors viz. construction and chemicals. However, it was pointed out that only a few companies in each sector were able to provide detailed information on corrosion cost and the estimates provided varied widely. In consequence, the projected figures can at best be considered only to be a guestimate. This conclusion illustrates that it is very difficult to project the total cost of corrosion of an entire national economy by following the Hoar method.

3.2 Japan

In Japan (Shibata, 2002, pp. 97-102) along with Uhlig's method, the Hoar method also was adopted in 1974, and again the same approach was used to estimate the cost of corrosion in 1997, i.e. after a gap of 23 years. The objective was to compare the cost of corrosion computed by different approaches.

Table VI Cost of corrosion in UK

Sector	Total cost of corrosion (amount in £ million)	Avoidable cost (per cent)
Chemicals and petrochemicals	1,730	15
Offshore	250	15
Construction steel work	2,500	15-20
Food industry (one major company)	5	–
Automotive industry	160	–

The estimation was made by inquiries and important factories were visited by the Japanese Investigation committee. In the earlier 1974 survey, the Hoar method did not cover the concerned items extensively because of lack of data. On the other hand, by 1997, a more comprehensive estimation could be made. In addition, the cost estimated by the Hoar method included maintenance costs that were estimated in detail.

Table VII shows the cost of corrosion data for 1974 as well as 1997.

It can be seen that as a class, the mechanical engineering sector in Japan continued to contribute the highest costs components both in 1974 and 1997. In 1974, the contribution from the construction sector was around 17 per cent, whereas in 1997 the contribution had almost doubled, indicating the important role played by corrosion in this sector. The chemicals sector contributed to a moderate extent. In the overall estimate, the cost of corrosion, as per the Hoar method, had escalated by a factor of almost five over a period of 23 years. In one sense, this might be indicative of rapid industrialisation. However, there had been a significant decline in Japanese industrialisation during the period and in consequence it seems probable that the increase was due to the relative cost of engineered solutions.

4. Input/output approach

The input/output (IO) analysis was invented by Wassily Leontief, for which he received a Nobel Prize in 1973. IO is a general equilibrium model of an economy showing the extent to which each sector uses inputs from the other sectors to produce its output – and thus showing how much each sector sells to each other sector. The IO model shows the increase in economic activity in every other sector that would be required to increase net production of a sector, for example, if $1 million worth of paint were required for corrosion prevention, the IO model would show the total activity through all the sectors in order to produce this amount of paint.

Economic IO analysis accounts explicitly for all of the direct (within the sector) and indirect (within the rest of the economy) inputs to produce a product or service by using the IO matrices of a national economy. Each sector of the

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Table VII Cost of corrosion in the national economy of Japan

Industrial sectors	Corrosion cost in 1974 (billion yen)	Percentage in total cost	Corrosion cost in 1997 (billion yen)	Percentage in total cost
Energy	59.8	5.76	456.8	8.69
Transportation	194.5	18.74	544.7	10.36
Chemical	154.3	14.86	1070.0	20.35
Mechanical	427.8	41.21	1561.5	29.70
Metallurgical	26.5	2.55	27.6	0.52
Construction	175.2	16.88	1597.6	30.38
Total	1038.1	100	5258.2	100

economy is a row (or corresponding column) of the IO matrix. The rows and columns are normalised to add up to one. When selecting a column (industrial sector "A"), the coefficients in each row would tell how much input of each sector would be needed to produce $1 worth of output in industry "A". For example, the column of steel industry specifies the quantities of each input purchased by the steel industry to make a ton of steel. For example, an IO matrix might indicate that the producing $1 worth of steel requires $0.15 worth of coal, $0.10 of iron ore, etc. (the numbers 0.15, 0.10, etc. are called coefficients). A row of the matrix specifies to which sectors the steel industry sells its product. For example, steel might sell $0.13 to the automobile industry, $0.06 to the truck industry, etc. of every dollar of revenue.

In response to a congressional directive, a study of the Annual Cost of Metallic Corrosion in the USA was undertaken in 1978 by the National Bureau of Standards (NBS) and the Battelle Columbus Laboratories (BCL). The Battelle report essentially was sparked by attention drawn to the corrosion issue by the UK Hoar Report of 1971. However, it improved on the Hoar approach in that it was the first to combine the expertise of corrosion and economic experts to determine the economic impact of corrosion on a national economy (Bennett *et al.*, 1978). The study used a version of the Battelle National IO model to estimate the total corrosion cost. This model quantitatively identified corrosion-related changes in the resources (i.e. material, labour and energy), changes in capital equipment and facilities, and changes in the replacement lives of capital items for entire sectors of the economy. The IO model is able to account for both the direct effects of corrosion on individual sectors and the interactions among various sectors.

4.1 The United States of America

The USA economy was divided into 130 industrial sectors in the IO model For each industry sector, the investigators asked experts to estimate the costs of corrosion prevention and the cost of repair and replacement due to corrosion. Elements were identified within the various sectors that represented corrosion expenditures, e.g. coatings for steel pipelines. Since the only purpose of coating a steel pipeline was to prevent corrosion, the particular coefficients in the steel pipeline column were normalised to total one. This new matrix represented the world without corrosion. With the new matrix, the level of resources used to produce GNP in a world of corrosion would produce a higher GNP in a world without corrosion.

The following three worlds were developed for the analysis:

1. World I – real world of corrosion (year 1975 was modified to full employment level of economic activity)
2. World II – hypothetical world without corrosion (to establish a baseline); and
3. World III – hypothetical world in which the economically most efficient corrosion prevention practiced by everyone.

The total national cost of corrosion was the difference between GNP of the World I and the GNP of World II.

Avoidable cost of corrosion was the difference between the GNP of World I and the GNP of World III or "cost which is amenable to reduction by the most economically efficient use of recently available corrosion control technology".

Unavoidable cost of corrosion was defined to be the difference between GNP of World II and the GNP of World III or "those which are not amenable to reduction by presently available knowledge".

The following direct costs were included in this study.

1. replacement of equipment or buildings;
2. loss of product;
3. maintenance and repair;
4. excess capacity;
5. redundant equipment;
6. corrosion control (such as inhibitors, organic and metallic coatings);
7. engineering research and development testing;
8. design;
   - material of corrosion not for structural integrity;
   - material of corrosion for product purity;
   - corrosion allowance; and
   - special processing for corrosion resistance.
9. insurance; and
10. parts and equipment inventory.

However, indirect costs of the structures were not included in the study.

Ultimately, all of the information was reduced to industry indicators in the form of coefficients for each of the 130 sectors per dollar of production. The coefficients for direct cost varied from 0.0011 to 0.1008. By multiplying the dollar value of production by the respective coefficients, the direct and avoidable costs of corrosion for the year 1975 were obtained for each of the 130 sectors.

Based on the above IO approach, NBS-BCL worked out the cost of corrosion in the USA for 1975. The same exercise was repeated (though in far greater detail) after a gap of 20 years, i.e. in 1995 (Battelle, 1995). The comparative data are presented in Table VIII.

Table VIII Metallic corrosion in the United States

Sector	1975 Cost of corrosion (amounts in $ million)	1975 Avoidable cost (amounts in $ million)	1995 Cost of corrosion (amounts in $ million)	1995 Avoidable cost (amounts in $ million)
Motor vehicles	31.4	23.1	94	65
Aircraft	3	0.6	13	3
Other industries	47.6	9.3	189	36
Total	82	33	296	104

It should be recognised that NBS analysed the uncertainties in the estimate for the year 1975 and brought down the total cost of corrosion to $70 billion. However, Table VIII can be compared as it is. It can be seen that over a period of 20 years (1975-1995) the cost of corrosion escalated by a factor of 3.60. Avoidable cost also correspondingly increased by a factor of 3.15 thereby suggesting that the percentage of avoidable cost had remained almost unchanged over a period of 20 years.

4.2 Australia

In 1982, the Commonwealth Department of Science and Technology commissioned a study to determine the feasibility of the establishment in Australia for a National Centre for Corrosion Prevention and Control (Cherry and Skerry, 1983). The feasibility study included a determination of the Annual Cost of Corrosion to Australia.

The Australian study was patterned after the Battelle-NBS study. An IO model of the Australian national economy was constructed, first to represent the real world, and secondly, to represent the world of optimum corrosion mitigation technology. Differences between the two scenarios were used as estimates of the avoidable costs of corrosion and to indicate areas of potential savings. The study used statistical data from the Australian Bureau of Statistics and therefore did not perform any major data collection.

By applying the BCL methodology to the Australian economy, a figure for the potential economic savings to the Australian community was computed. As in the BCL model, it was calculated by forming a judgment of the extension of the useful life of capital assets by application of IO econometric analysis.

Two Australian economic world scenarios were constructed. World I was representative of the real world, and World III was representative of a world of optimum corrosion mitigation technology. Both scenarios thus constructed referred to the Australian economy during 1974-1975 because the most recent IO data for Australian economy that were available during 1982 from the Australian Bureau of Statistics referred to the fiscal year 1974-1975. Computed final demand and intermediate costs for 29 industry sectors are shown in Table IX. Computed (Australian) dollar values for the major components are shown in Table X.

The model results indicated that the potential economic savings by use of best practice corrosion mitigation technology in Australia during the year 1974-1975 totalled Aus.$992.8 million.

Portions contributing to the final demand cost savings included Aus.$339.6 million, attributed to private consumer expenditures, and Aus.$26.9 million attributed to government expenditure savings. Potential economic savings in private fixed capital formation were computed to be Aus.$541.4 million.

If the impact of applying best corrosion practice technology on going from the constructed World I scenario to the World III scenario led to a computed potential economic savings of Aus.$992.8 million at 1975 values, a consideration of the potential economic savings at 1982 values would be appropriate. A value for the GDP in Australia during 1981-1982 was obtained from the Australian Bureau of Statistics data. The quoted value of GDP in Australia for 1981-1982 thus would be Aus.$142,255 million, which represents a factor of increase of 2.07 over the 1974-1975 quoted value of Aus.$71,647 million. The same factor of increase would imply a potential economic savings of Aus.$2,055 million in 1982 values, if optimum best corrosion control practice had been applied throughout Australia.

4.2.1 Consideration of uncertainty: (Table XI)

The Australian model was based on Australian 1974-1975 IO inter-industry flow data and the respective coefficients may not have been the same in 1983 as they were in 1975. The level of uncertainty in this respect was not quantified. There were no alterative statistical data that could have been used as the Australian Bureau of Statistics 1974-1975 IO tables were the most recent ones available during 1982.

In order to generate the capital/output ratio coefficient matrix, data were calculated directly from the equivalent BCL matrix. This approach assumed that the capital structure of the relevant industries affected in the model was similar in the USA to those same industries in Australia. It was recognised that there were likely to be differences in the structure of equivalent industries in the two countries, though this was not quantified.

The concepts of best practice technology in 1983 could be different to those in 1975. Again, this uncertainty was not quantified.

4.3 India

Rajagopalan (1986, pp. 35-40) of India followed the model of NBS-BCL analysis for 22 core industrial sectors and arrived at a figure of Rs. 40,760 millions as direct cost of corrosion, of which, almost Rs. 18,040 millions was avoidable. The break-up details of the overall expenditures are shown in Table XII.

Interestingly the avoidable cost of corrosion was almost 44 per cent, indicating that proper corrosion control awareness would need to be created if that percentage of avoidable cost were to be brought down.

More recently, the authors have computed the direct annual cost of corrosion in Indian industries over a 40 year period (1950-1990) using the corrosion coefficients worked out in the NBS-BCL study of USA. Seventy nine industries were

Table IX Computed final demand and intermediate costs

Sector	Final demand cost ($ million) World I-World III: Personal consumption expenditure (PCE)	Private fixed capital formation (PFCF)	Federal, state and local government expenditure (F/S/LGE)	Intermediate costs ($ million) World I - World III
Agriculture	0	0	0	6.47
Forestry, finishing, hunting	0	0	0	0.65
Mining	0	0	0	12.01
Food manufacture – animal	0	0	0	0.22
Food manufacture – vegetable	0	0	0	0.77
Beverages/tobacco production	0	0	0	0.34
Textiles	0	0	0	0.22
Clothing and footwear	0	0.01	0	0.37
Wood, wood production/furniture	0	28.49	0	0.68
Paper, printing, publishing	0	0	0	0.48
Chemicals	0	0	0	0.67
Petroleum and coal products	0	0	0	0.47
Non-metallic mineral products	0	3.35	0	0.55
Basic metals	0	0	0	0.42
Fabricated metal products	0	50.13	1.1	3.23
Transport equipment	322.4	61.08	22.0	1.06
Other machinery and equipment	17.1	96.09	3.8	0.85
Other manufacturing n.e.c	0	0.87	0	0.89
Electricity, gas and water	0	0	0	5.40
Construction	0	182.51	0	3.22
Wholesale and retail trade	0	53.20	0	13.45
Repairs	0	0.01	0	0.38
Transport and communication	0.1	65.70	0	28.25
Finance, insurance, real estate	0	0	0	0.97
Ownership of dwellings	0	0	0	0.04
Public administration, defence	0	0	0	0.01
Health, education and welfare	0	0	0	1.03
Entertainment, personal service	0	0	0	1.79
Business expenses	0	0	0	0
Total	339.6	541.4	26.9	84.9

Table X Computed dollar values for the major components of potential cost savings to the Australian economy (Aus.$ million, 1974-1975 values)

Component	Computed potential cost savings
Total IO	84.9
PCE	339.6
PFCF	541.4
Exports	0
F/S/LGE	26.9
Net inventory change (NIC)	0
Total	992.8

covered. An exponential growth in the cost of corrosion was observed when the variation of costs with respect to time in years was plotted (Figure 1). When this variation was converted to a polynomial graph, correlation coefficients were closer to unity. It was concluded that a polynomial equation of the type $Y = ax^2 + bx + c$ could be used to predict the cost of corrosion for any year. The polynomial graph for direct cost of corrosion vs time in years is shown in Figure 2. The corresponding mathematical equation is $Y = 0.0005x^2 + 0.0265x + 2.2238$, where "$Y$" is the logarithmic value of the cost of corrosion for the relevant year and "x" is the number of years between the base year 1950 and the relevant year. The theoretical corrosion cost worked out, based on the polynomial equation, was compared with the values derived from the NBS-BCL model, summarised in Table XIII. It can be seen that values obtained by application of the polynomial function were more or less close to the predicted values for different years.

4.4 Japan

The Committee on Cost of Corrosion in Japan attempted to estimate the cost of corrosion by the IO method, as reported by Shibata (2002, pp. 97-102). The IO table consisted of 32 × 32 items, in which the direct cost of corrosion (obtained using the Uhlig method) were input to the concerned items table and the change in the total output was calculated. The difference in the output, when the direct cost was subtracted from the concerned items, yielded the cost of corrosion, including both direct and indirect costs. The result of the

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Table XI Summary of Australian results in relation to the consideration of uncertainty

Components	Model result	After uncertainty consideration	Possible range
Total IO	84.9	84.9 − *Y*	− *y* − 84.9
PCE	339.6	104.5	81.2–339.6
PFCF	541.4	268.0	129.8–828.3
F/S/LGE	26.9	26.9	13.5–40.4
Total	992.8	(484.3 − *Y*)	(224.5 − *Y*)–1293.2
(obtained by scaling by factor of × 2.07)			
Total at 1982	2055.1	1002.5 − *Y*	(464.7 − *Y*)–2676.9

Table XII Direct cost of corrosion and avoidable cost of corrosion for various sectors using production data and NBS-BCL corrosion co-efficients

Sector	Value of production for the year 1984-1985 (rupees in million)	NBS-BCL coefficients	Direct cost of corrosion (rupees in million)	NBS-BCL coefficients	Avoidable cost of corrosion (rupees in million)
Agriculture, livestock, forestry and fishery	8,25,000	0.0218	18,000	0.0133	11,000
Extraction of mineral resources, metallic minerals, coal, lignite, petroleum, gas, non-metallic minerals including fertilizer minerals	51,000	0.0165	840	0.0063	320
Manufacture of food leather and textile products	1,80,000	0.0033	600	0.0017	300
Wood and paper products	27,000	0.0156	420	0.0030	80
Petroleum refining and chemical products	1,50,000	0.0083	1,250	0.0017	250
Glass, refractors, cement products	18,000	0.0044	80	0.0017	30
Manufacture of ferrous and non-ferrous metals and coke	70,000	0.0200	1,400	0.0017	120
Fabricated metal products	10,000	0.0500	500	0.0020	20
General machinery and components	17,000	0.0324	550	0.0012	20
Specialised machinery	4,50,000	0.0009	400	0.0001	30
Transportation equipment	47,000	0.0200	940	0.0009	40
General and special electrical apparatus	82,000	0.0117	960	0.0004	30
Household appliances	7,000	0.0143	100	0.0000	Neg.
Scientific measuring devices	3,000	0.0067	20	0.0000	Neg.
Office equipment	2,900	0.0103	30	0.0000	Neg.
Miscellaneous manufacturers	20,000	0.0200	400	0.0010	20
Highway passenger traffic transport, motor freight	80,000	0.0313	2,500	0.0125	1,000
Public utilities	26,000	0.0923	2,400	0.0038	100
Construction	2,40,000	0.0125	3,000	0.0042	1,000
Trade and business	3,00,000	0.0200	6,000	0.0117	3,500
Other services	35,000	0.0086	300	0.0043	150
Post office	5,000	0.0140	70	0.0080	40
Total	22,40,900	–	40,760	–	18,040

preliminary estimation, using the IO method based on the data estimated by the Uhlig method, is shown in Table XIV. It can be seen from the table, that the corrosion cost estimated by the IO method was almost four times that estimated by Uhlig method. This is understandable because Uhlig's method normally projected a conservative (i.e. low) estimate.

5. Life cycle cost approach

Dillon (1966, pp. 47-49) of Union Carbide Corporation discussed the economic comparison of corrosion control measures with emphasis on calculation of net present value and equivalent uniform cost. Subsequently, NACE Standard RP-02-72 (1972) brought out a standard on "Direct

Figure 1 Direct annual cost of corrosion for Indian economy-based NBS-BCL model for the period 1950-1990

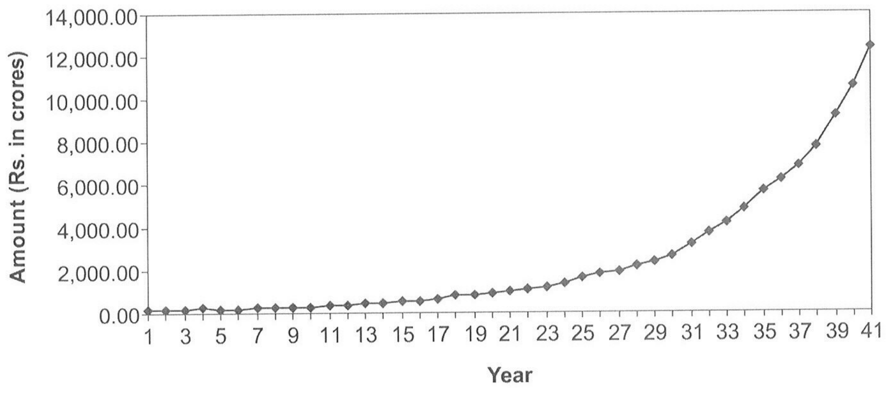
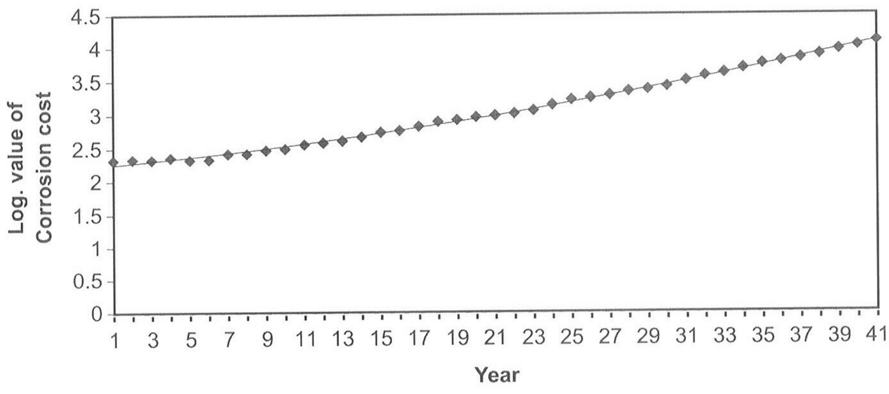


Figure 2 Polynomial graph for direct annual cost of corrosion for the period 1950-1990



Calculation of Economic Appraisals of Corrosion Control Measures". Verink, of the University of Florida, also elaborated on this method in the ASM Handbook (Verink, 1990). Watson (1984), dealt with economic evaluation of corrosion control by comparing three methods, viz. straight-line depreciation, sum of digits, and constant percentage of declining balance, for assessing the cost-effectiveness of alternative options. However, a comprehensive application of this latter method in the life cycle cost analysis has been attempted only recently.

When optimising both the direct and the indirect costs of corrosion, it is important that all benefits and costs of all the options are taken into account. This analysis determines the net present value of options and the highest net benefit to the society. In other words, life cycle costing is equivalent to a cost-effectiveness framework that seeks to minimise the cost of achieving the specified goal. The analysis can be used to evaluate different corrosion management options. It determines the annualised value (AV) of each option and the lowest cost option is the most cost-effective option. Therefore, the life cycle cost analysis is an appropriate method for comparing the cost of different options.

Life cycle costing consists of the following three steps:

1 determination of the cash flow of corrosion-related activities;
2 calculation of the present discounted value (PDV) of the cash flow; and
3 calculation of the annualised equivalent value.

5.1 Cash flow

The corrosion-related cash flow of a structure/facility includes all costs, direct and indirect, that are incurred due to corrosion throughout the whole life cycle of the structure/facility.

Direct cost includes the following:

- amount of additional or more expensive material used to prevent corrosion damage multiplied by the (additional) unit price of the material;
- number of labour hours attributed to corrosion management activities multiplied by the hourly wage;
- cost of the equipment required as a result of corrosion-related activities; and
- loss of revenue due to lower supply of a good.

Indirect costs include the following:

- increased costs for consumer of the product (lower product supply on the market result in higher cost to consumers) or lost time due to search for alternative goods/services;
- effect on local economy (loss of jobs); and
- effect on the natural environment by pollution.

5.2 PDV of the cash flow

The cash flow cycle of a structure/facility consists of the following:

- *Zero year* – the total initial investment including user cost (in case of old structured/facility the removal cost as well as user cost not included).

Table XIII Comparison of polynomial equation values with the actual values derived by NBS-BCL model

Year	Base year	Direct cost of corrosion obtained by NBS-BCL method	Polynomial equation
1950	0	209	167
1951	1	218	178
1952	2	213	190
1953	3	230	203
1954	4	211	218
1955	5	215	234
1956	6	266	252
1957	7	265	272
1958	8	300	294
1959	9	313	318
1960	10	365	346
1961	11	386	377
1962	12	412	411
1963	13	471	450
1964	14	552	493
1965	15	580	542
1966	16	672	597
1967	17	795	659
1968	18	841	729
1969	19	932	809
1970	20	984	899
1971	21	1,045	1,002
1972	22	1,156	1,119
1973	23	1,398	1,253
1974	24	1,652	1,405
1975	25	1,775	1,581
1976	26	1,934	1,782
1977	27	2,212	2,013
1978	28	2,371	2,279
1979	29	2,608	2,587
1980	30	3,190	2,943
1981	31	3,765	3,356
1982	32	4,161	3,835
1983	33	4,843	4,393
1984	34	5,603	5,044
1985	35	6,144	5,805
1986	36	6,829	6,696
1987	37	7,695	7,741
1988	38	9,172	8,970
1989	39	10,519	10,418
1990	40	12,343	12,128

- *Service period* – cost of maintenance, repair and rehabilitation.
- *Last year* – cost of removal of structure/facility including user cost. After removal, a new life cycle begins.

As stated previously, all direct and indirect costs should be included in the analysis.

5.2.1 Calculation of the present value of the cash flow

Initial investment (I). The initial investment occurs in the present; therefore no discounting is necessary.

Annual maintenance (AM). Annual maintenance is assumed to be constant throughout the life of the structure/facility.

Table XIV Cost of corrosion in the national economy of Japan as in 1997

	Corrosion cost estimated by the input/output method (billion yen)	Direct corrosion cost estimated by the Uhlig's method (billion yen)
Total cost	9694.72	2418.50
Per cent GNP	1.88	0.47

The present discounted annual value of AM is calculated as per the following formula:

$$\mathrm{PDV(AM)} = \mathrm{AM} \times [1 - (1+i)^{-N}]/I$$

where AM is the cost of AM; N the structure/facility service life in years; i the interest rate; and I the initial capital investment.

To obtain the present value of activities that grow annually at a constant rate (g), a modified interest rate needs to be calculated by using the following formula:

$$i_0 = (i-g)/(1+g) \quad \text{and} \quad i > g$$

where i_0 is the modified interest rate; i the interest rate; and g the constant annual growth rate.

If the first payment ($P1$) occurs in year 1, the present value of a cash flow that grows annually at a constant rate over "n" years is calculated by the following formula:

$$\mathrm{PV}(P) = [P1/(1+g)] \times [1 - (1+i_0)^{-N}]/i_0$$

PV(P), the present value of cash flow series that starts at $P1$ in year 1 and grows at a constant rate "g" for "n" years when interest rate is "i", is equivalent to the present value of annuity of [$P1/(1+g)$] for "n" years when interest rates i_0, where i_0 is given by the above equation.

The first payment for repair activities, however, usually does not occur in year 1, but rather, in year "t" therefore, the above formula calculates the value at year $(t-1)$ discounted back to year zero of the life cycle to determine the PDV of the repair.

$$\mathrm{PDV}(P) = \mathrm{PV}(P) \times (1+i)^{-(t-1)}$$

One-time expenditure. The PDV of one-time costs, such as one-time repairs or rehabilitation, is calculated as follows:

$$\mathrm{PDV}(R) = R \times (1+i)^{-tR}$$

5.3 AV of the cash flow

The irregular cash flow of the whole lifetime is transformed into an annuity (a constant annual value paid every year) for the same lifetime The annualised value (AV) is calculated as follows:

$$\mathrm{AV} = \mathrm{PDV} \times i/[1 - (1+i)^{-N}]$$

5.3.1 The United States of America

During the late 1990s, a need arose to carryout a systematic study to estimate the optimal asset management strategy for roads and bridges in the United States. In due course, the scope of the investigation was extended to address also the impact of metallic corrosion on the USA economy. Subsequently, Corrosion Control Technologies Laboratories Inc., conducted the systematic study during 1999-2001 in a cooperative agreement with the Federal Highway Administration (FHWA) and NACE International (Koch *et al.*, 2001) in what has become the most comprehensive such study to date. In this study, the total direct cost of corrosion was determined by analysing 26 industrial sectors in which corrosion was known to exist and extrapolating the results for a nationwide estimate. The total direct cost due to impact of corrosion for the analysed sectors was reported to be (US)$138 billion per year (equivalent to approximately 1.57 per cent of GDP). The distribution of expenditure is shown in Table XV.

Since not all economic sectors were examined, the sum of the estimated costs for the analysed sectors did not represent the total cost of corrosion for the entire US economy. By estimating the percentage of USA GDP for the sectors for which corrosion costs were determined and by extrapolating the figures to the entire US economy, a total direct cost of corrosion was estimated as some $276 billion (or 3.14 per cent of Nation's GDP). The indirect cost of corrosion was conservatively estimated to be equal to the direct cost; giving a total direct plus indirect cost of US$552 billion (i.e. 6 per cent of GDP).

5.3.2 India

Very recently, the authors have adopted the net present value method for estimating the cost of corrosion in three specific industries.

At first a personal visit was made to the particular factory and personal contact was established with the plant personnel

Table XV Direct cost of corrosion of 26 industrial sectors in USA

Industrial sectors	Cost of corrosion ($ billion)
Highway bridges	8.3
Gas and liquid transmission pipelines	7.0
Waterways and ports	0.3
Hazardous materials storage	7.0
Airports	ND
Railroads	ND
Gas distribution	5.0
Drinking water and sewer systems	36.0
Electrical utilities	6.9
Telecommunications	ND
Motor vehicles	23.4
Ships	2.7
Aircraft	2.2
Railroad cars	0.5
Hazardous materials transport	0.9
Oil & gas exploration and production	1.4
Mining	0.1
Petroleum refining	3.7
Chemical, petrochemical and pharmaceutical	1.7
Pulp and paper	6.0
Agricultural	1.1
Food processing	2.1
Electronics	ND
Home appliances	1.5
Defence	20.0
Nuclear waste storage	0.1
Total	137.9

(production, maintenance, purchase, inspection and accounts). Each unit in the plant was visited and the conditions were noted. Data of cash flow for corrosion related activities were collected. By using present value method, the total direct annual cost of corrosion was worked out. The corrosion coefficient for the particular industry was arrived at by dividing the annual corrosion cost by the annual production value as obtained in that plant. Subsequently the total product value for the whole industry was multiplied by the coefficients to arrive at the corrosion cost.

The direct annual cost of corrosion data for three industries is shown in Table XVI. It can be seen that the corrosion coefficients arrived at by NPV method are less than that of NBS-BCL method.

It was further shown that in a typical sugar factory, if the mild steel parts are replaced by 409 mm SS (12 per cent Cr stainless steel) every year Rs. 2.10 lakhs could be saved in replacement schedule. A direct extrapolation of Rs. 2.10 lakhs to all the 506 sugar industries in India will yield a figure of Rs. 106 million as annual savings to the sugar industries, i.e. 15 per cent of the direct annual cost of corrosion (Bhaskaran *et al.*, 2003).

Similarly, in paper and pulp industry by opting for an alternate corrosion resistant material such as duplex stainless steel in bleaching unit alone can lead to annual savings of Rs. 10 million for a single unit alone (Bhaskaran *et al.*, 2004a, b).

6. Conclusions

The following conclusions can be drawn from the comparison of different approaches:

1 The Uhlig method of estimating corrosion cost always gives a conservative estimate of the direct cost of corrosion. Since it is a customary practice to consider indirect cost as equivalent to direct cost, the total cost of corrosion, as estimated by the Uhlig method, will tend to below. Another limitation of Uhlig's method is that data are generated from the particulars gathered at the point of manufacturer. Industry-wide distribution of the costs of corrosion, and the likely potential savings of each industrial sector, will not be obtained.
2 The Hoar method is based mainly on direct interaction with industries and corrosion experts. It involves lot of effort and utmost cooperation from industries. The direct cost of corrosion, as estimated by the Hoar method, is found to be somewhat higher than is the estimate made using the Uhlig method, as shown by Shibata of Japan.
3 The NBS-BCL method of IO analysis, though apparently more scientific, is subject ultimately to uncertainties in quantifying the capital cost and intermediate output. This method relies on the development of coefficients for each industrial sector and therefore is quite laborious. However, adoption of this coefficient to the Indian economy revealed an interesting correlation between cost of corrosion and year. By using a polynomial equation of type $Y = ax^2 + bx + c$, the cost of corrosion in any year can be estimated.
4 The net present value method appears to be more realistic than do other approaches as it enables a life cycle costing of each structure/facility to be made and arrives at the most cost-effective corrosion control

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Table XVI Comparison of corrosion coefficients of NPV model with NBS-BCL model for Indian economy

Name of the industry	Direct cost of corrosion (rupees in million)	Value of output (rupees in million)	Corrosion coefficients of NPV model	Corrosion coefficients of NBS-BCL model
Sugar	670	200,000	0.00335	0.0037
Pulp and paper	120	306,000	0.00039	0.0181
Refinery and petrochemical	6,240	1,514,563	0.00412	0.0165

method. Recent studies in India have shown that the corrosion coefficients arrived at by this method invariably are less, compared to NBS-BCL coefficients.

5 All of the four approaches enabled an estimation of direct cost of corrosion. However, the indirect cost of corrosion invariably is worked out on a speculative basis.

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