Investment Analysis of Chemical Projects And Development of Standardised Mathematical Cor-relation for Cost Estimation of Pressure Vessels in Chemical Industry.

THESIS SUBMITTED TO THE UNIVERSITY OF COCHIN
(FACULTY OF SOCIAL SCIENCES)
IN PARTIAL FULFILLMENT OF THE DEGREE OF DOCTOR OF PHILOSOPHY.

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November 1, 1979.

CERTIFICATE

This is to certify that the thesis entitled INVESTMENT ANALYSIS OF CHEMICAL PROJECTS AND DEVELOPMENT OF STANDARDISED MATHEMATICAL CORRELATION FOR COST ESTIMATION OF PRESSURE VESSELS IN CHEMICAL INDUSTRY submitted by Mr. P.V.S. Namboothiripad is an original piece of work done by him under my guidance and this work has not been submitted to any other University for the award of any degree or diploma.

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Research Guide.

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PREFACE

The present study is intended to provide a new, scientific approach to the solution of one of the most important cost engineering problems encountered in the chemical industries in our nation. The problem is that of the cost estimation of equipments, especially of pressure vessels when setting up chemical industries. The present study attempts to develop a model for such cost estimation. This, in turn, it is hoped, would go a long way to solve this and related problems in forecasting the cost of setting up chemical plants.

The economic development of a nation would ultimately depend upon the development of industries along with the progress made on other fronts. Chemical industries are an important constituent of such industrial growth. In the development of chemical industries, design and consultancy companies have to play a vital role because they are the agencies which make available to the entrepreneur a reliable prediction of cost of the equipment or plant. Such a prediction, to be true, requires that it is based on sound principles of engineering design and economics. The state of the art in the area of cost estimation, especially in the case of chemical industries, leaves much to be desired. The estimated figures are, often, far from the actuals. In the present study an attempt has been made to identify the essential and more important parameters which influence the cost of a pressure vessel. These parameters are then brought under logical groupings. Based on such groupings, a mathematical correlation amongst themselves has been developed for the cost estimation of pressure vessels.

In the absence of proper and scientific standardization in the cost estimation of chemical industry equipments, especially of pressure vessels, it would be difficult to keep the time and cost of installation of chemical plants within estimates, except perhaps by chance. This has, to some extent, contributed to our failure in the achievement of targets set up for chemical industries under successive five year plans. Investment analysis of chemical projects that have been commissioned would show that the overrun of cost and time in all chemical and allied industries has become more or less a regular feature in our plan implementation. These overruns can be avoided or atleast reduced to the minimum by application of a standardised procedure for cost estimation. Though in the present study, such standardisation has been attempted for only pressure vessels, the principles evolved can be extended to other equipments also.

The preliminary cost estimates of most of the chemical projects are made based primarily on major equipment costs. Since pressure vessels form the major equipment, the correlation developed for estimating the cost of pressure vessels will also to a large extent help in the prediction of the total project cost.

The application of scientific cost estimation techniques would be of great value to the cost engineer, the consultant and the entrepreneur.

This study could have been, perhaps, done under the faculty of technology. At the time of registration for the Ph. D. degree of this University by the scholar the faculty of technology was not in existence. The only alternative for the scholar was to register himself under the faculty of Social Sciences to which the School of Management Studies of the University belongs. As the problems discussed in the study have relevance to the field of management studies also it was considered not too inappropriate to have the registration for research done under the faculty of social sciences. This is by way of explanation for bringing this study on a cost engineering problem under the scope of the faculty of social sciences.

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INTRODUCTION

The project cost for industrial investment is generally estimated by the finance required for its various constituents such as knowhow, land, plant and machinery, etc. Of the above, the different items of machinery and equipments constitute a major portion, especially in industries employing sophisticated technologies. In the case of chemical industries, this fact is particularly noteworthy. Among the several types of machinery and equipments needed for setting up a chemical industry, costwise, a lion's share is claimed by the cost for pressure vessels. For estimating the cost of pressure vessels, most of the vendors and fabricators use at present their own conventional estimating practices. The industry is forced to accept these estimates. There is no standardised procedure in the country as a whole to make this estimation, based on scientific methods of cost and investment analysis.

This study is concerned with developing a standardised procedure for the cost estimation of pressure vessels in chemical industries.

In the execution of chemical projects, it has been the experience that there is a great deal of divergence between the estimated project cost and the actual cost. This divergence is also seen in the achievement of outputs which are, almost invariably, different from what were originally estimated and planned for. The delay in the execution of the project, severe fluctuations in factor costs and other similar reasons may also be responsible for the cost overrun, but it could be easily seen on analysis that the original estimates themselves are not, in most cases, realistic. An important reason for such unrealistic estimates is the absence of a logical and scientific basis for the determination of equipment costs.

INTERPLAY OF INTERESTS

In the actual implementation of a project there is a close interplay of interests among the entrepreneur who promotes the project, the contractor who executes it and the cost engineer who has to estimate and control the project costs.

(a) Interest of the entrepreneur

To the entrepreneur, an estimate of cost is the basis for estimating the financial viability of the project and for organising its financial structure. A time bound cash budget based on such estimates is essential for the planning for resources and the scheduling of its availability over the project execution period. His basic objectives are, primarily, low project cost and high rate of return on investment.

A proper cost estimate, therefore, assumes paramount importance to the entrepreneur.

(b) Interest of the contractor

The contractor uses the cost estimate to make a competitive offer to the entrepreneur for the construction, fabrication and installation of the plant and machinery. He quotes for the equipments and work after conducting a survey of the cost of material and labour as well as unit equipment costs. To the actual labour and material cost estimates so obtained he may make some provisions for overhead costs, price escalation and expected returns. In making cost estimates, his own or other people's experience is his main guide. On account of the numerous possibilities for error in arriving at such cost estimates the contractor faces a high risk situation. To COUNTANANCE this he tries to raise the amount of the tender to as high a level as he thinks the market would bear. To the contractor too, better methods of estimation on a scientific footing are thus important.

(c) Interest of the cost engineer

The role of the cost engineer is pivotal in the translation of a project idea into reality. All projects are after all primarily economic propositions. The cost engineer estimates the project cost on the basis of his information of the cost of land, plant and equipment and construction. His estimates are to be vide in the minimum time. Accuracy of estimates is vital in his profession. Besides, the cost engineer is required to monitor the expenditure on the project with a view to keeping the costs within estimates. It is, therefore, in his interest also to have more reliable methods of cost estimation, scientifically arrived at.

COST OF CHEMICAL PLANT

A large portion of the cost for a manufacturing plant is incurred in the purchase and fabrication of equipment and machinery. Generally, such equipment costs may go up from 60 to 80 per cent of the total cost of the plant.

TABLE-1

BREAK UP OF THE TOTAL COST OF CONSTRUCTION OF A CHEMICAL PLANT(1)

Equipment, Machinery and support	-	61 per cent
Erection and installation labour	-	22 per cent
Building materials and labour	-	7 per cent
Engineering and supervision	-	10 per cent
Total	=	100 per cent

(1) Butler. P., "Cost Focus" in Chemical Engineering (New York 1974), Vol.81, No. , 136-137.

Equipment cost is the total cost of individual pieces of equipments called unit equipments. More than fifty per cent of such equipment cost is accounted for by pressure vessels.

TABLE-2

BREAK UP OF THE EQUIPMENT COST IN THE CONSTRUCTION OF A CHEMICAL PLANT[2]

Fabricated equipment	-	37 per cent
Process machinery	-	14 per cent
Pipe, valve, fitting	-	20 per cent
Process instrument and control	-	7 per cent
Electrical	-	5 per cent
Structural support and installation	-	10 per cent

Since more than 50 per cent of the total equipment cost is accounted for by pressure vessels, an attempt to standardise the procedure for a reliable

(2) *Ibid.*, 137.

estimation of the cost of pressure vessels will contribute to arriving at more reliable plant and equipment cost estimations and, therefore, of total project cost estimations.

As in the case of making cost estimates with regard to plant and equipments in general, no specific, scientific approach is available for cost estimation of chemical plant equipments, especially of pressure vessels. There are several instances of the variation of quotations of vendors for the same equipment varying sometimes by as much as 300 per cent.(3) Therefore, the unit prices collected from vendors' quotations do not necessarily provide any reliable pattern for cost estimation. Nor can a reliable basis of estimation be developed from the historical costs as the cost pattern does not indicate steady trends. This is why a scientific approach to the standardisation of methods of estimation of the cost of pressure vessels as well of other unit equipments assumes critical importance.

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(3) Based on the personal experience of the scholar in the course of his work as a chemical engineer.

THE EXISTING METHODS AND THEIR SHORTCOMINGS.

Several analytical studies on the standardisation of cost estimates have been made in developed countries. These have been mostly confined to the equipment parameters such as volume and capacity. Besides volume and capacity there are several other important parameters such as plate thickness, working pressure, density of the material used for construction of the pressure vessel and its accessories and fittings and elements of conversion cost such as machine hours and man hours. The equipments' length and diameter have already been taken into account in the derivation of volume. Any cost estimation based on the parameters of volume and capacity may not be a completely reliable guide to the estimation of the actual cost. This is because parameters other than volume and capacity would have considerable influence on the equipment cost. It is on account of this situation that the present study directs itself at the investment analysis of chemical projects and the development of standardised mathematical correlations for cost estimation of pressure vessels, taking into account all the major factors and their interrelationships.

In the chemical industry, unit equipments are integral components of total equipments. The term 'equipment' is a general one. It was feared that the study, if extended to cover all equipments, would have become too elaborate and unwieldy. Hence the study has been confined to the most important of the unit equipments, namely, pressure vessels.

The total equipment design of a chemical plant is related to the purpose for which the plant is erected, such as manufacture of petroleum products or paper or oil or some specific chemical. But the basic components of all chemical plants are the same, namely pressure vessels, heat exchangers, storage tanks and piping, etc. Among such unit equipments, pressure vessels are the most important as their average application varies from 37 to 53 per cent in any chemical plant as can be seen from the tables attached.[4] Therefore, the present study is

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(4) Kharbanda. O. P., <u>Process Plant and Equipment Estimation</u>, (Bombay, 1978), 51.

TABLE - FLUID PROCESS PLANT --- COST BREAK-UP

DIRECT	Process Equipment	46.61%	(53.7)	
	Utilities	8.19	(12.4)	
	Receiving, shipping and storage	1.12	(4.9)	
	General Services	1.5	(3.2)	
	Buildings	2.4	(2.8)	77.0
INDIRECT				23.0
		Total		100

TABLE - PROCESS PLANT --- CHEM.ENG. BREAK-UP

Equipment, Machinery & support	61
Erection and installation, Labour	22
Building, material and Labour	7
Engineering & Supervision	10
	100

TABLE - PROCESS EQUIPMENT --- TYPICAL BREAK-UP

Fabrication equipment	37
Process machinery	14
Pipe, valve, fitting	20
Process instrument and control	7
Pumps and compressor	7
Electrical equipment	5
Structural steel, insulation	10
	100

primarily directed at developing a mathematical correlation among the major factors responsible for the cost estimation of pressure vessels. The objective is, thus, to arrive at a proper estimation method which will have universal application. The need for the present study has arisen from the strongly felt inadequacies in the existing systems in the cost estimation of chemical equipments.

DIFFERENT METHODS OF COST ESTIMATION IN PRACTICE IN THE COUNTRY

Generally, in India, four types of equipment estimates are followed.[5]

(i) Man hour - Machine hour method

(ii) Pre-calculated rate per unit weight method

(iii) Ratio method

(iv) Pre-bill method.

(i) Man Hour - Machine Hour Method

From the drawing, the estimator assesses the quantity of sheet materials required for fabrication of

(5) Namboothiripad. P.V.S., Chemical Engineering World, (Bombay, July-August 1969), 30.

the equipment and its cost. He estimates the labour time and machine time required for the various processes such as cutting, machining, fitting, assembling and welding. The quantity and cost of indirect materials such as welding electrodes are also estimated.

The estimator arrives at a working cost figure, taking into account the following:

(i) Cost per machine hour, calculated on the basis of the profitable working of the machinery.

(ii) The quality of the material and its cost.

(iii) Cost of man hours to be spent for the fabrication.

These rates are computed and added on to the overhead charges and other shop burdens. With the help of the above data the estimator arrives at the final cost estimation of a particular equipment.

Among the several methods for cost estimation, prevalent at present this is perhaps the best and the most reliable. The main defect of the system is that at the time of the preparation of the initial cost estimate, details regarding machine hour and man hour are seldom available. This results in the estimates becoming rather unreliable in practice. This method may be more advantageous in the case of machine tools or other similar purely mechanical equipments where specific data relating to all parameters are more readily available. This method may not, however, lend itself to reliable application in the case of pressure vessels due to the complexities in the nature of fabrication and differences in the types of material and designs of units.

(ii) Pre-calculated rate per unit weight method

A number of fabricating concerns as well as designing and consulting companies in India follow this method. The estimator selects representative categories of equipments such as heat exchangers, pressure vessels and columns. Based on the data for different capacities of the equipment in a particular category, the machine hours and man hours are estimated. The machine hour rates and man hour costs are clubbed together with shop burdens and other overheads and the resultant cost figures are plotted against the weight of the unit on a graph. A review of the past performance of the shop is also made to check the validity of the graphical relationship. Using the relationship so obtained, the cost of any unit equipment is easily determined.(6)

This method is far simpler and quicker than other methods. But, it has the disadvantage that the rate so obtained cannot be uniformly applied to all equipments falling in the same category of unit equipments as such approximations may sometimes lead to figures which are far from reality. For example, the rate for a floating heat exchanger due to differences in design and fabrication characteristics, differ much higher than for an ordinary heat exchanger.

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(6) (i) Bluck. D., "Estimating Techniques - Market Factors and Capital Cost Estimation" in Processing, (New York, February 1976), 213.

(ii) Eggleston. J. C., "Price and Delivery Forecasts for Equipment and Materials", Chemical Engineering Progress, (London, 1975), 24, 29.

(iii) Popper. H., Modern Cost Engineering Techniques, (New York, 1970), 538.

(iii) Equipment Ratio Method

This method of estimation presupposes an exponential relationship between capacity and cost of unit equipment falling in the same category. The cost of an equipment of a particular capacity is arrived at by developing a proportional price in comparison with a similar equipment and multiplying the same by an exponent. Exponents are established in every country based on equipment indices by scientific methods. Usually 0.62 rule is applied for this purpose. For individual equipment this may vary from 0.4 to 0.9.(7)

The equipment ratio method can be used to advantage only when bare equipments are involved. But, in making cost estimates for equipments including internals and other accessories, the scope of application of this method becomes limited.

(iv) Prebill Method

As the name indicates, this method of cost estimation is based on previous bills of the same

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(7) Namboothiripad. P. V. S., Rapid Cost Estimation in Indian Chemical Journal, (Bombay, 1968), 27.

equipment or a similar one procured at an earlier stage. The method is advantageous for making quick estimates for budgetary purposes. In situations where there is no equipment cost index or the latest information on cost escalation is not available, this method may not provide realistic cost estimates.

A large portion of the cost of a manufacturing plant consists of purchased or fabricated equipment and machinery. Usually the methods presented above are for estimation of the plant as well as individual equipments.

MODERN TRENDS IN PROCESS EQUIPMENT ESTIMATION

A number of modern approaches based on the equipment criteria and mathematical principles have been evolved in recent years. In all such approaches certain equations have been developed to establish the relationship among the various criteria and to arrive at proper cost estimations. The following symbols have been used in these equations.

d = diameter of the vessel in feet

v = volume of vessel in cubic feet

ρ = density of the material

t = wall thickness of vessel

k = cost of vessel based on rupees per pound of construction material

S_1 = shape constant for inside surface of vessel (dimensionless)

S_2 = shape constant for volume of vessel (dimensionless)

The following expressions can be arrived at:

$S_1 d^2$ = inside surface of the vessel (1)

$tS_1 d^2$ = volume of the material inside (2)

$tS_1 d^2 \rho$ = weight of the material in the vessel (3)

$S_2 d^3$ = inside volume of vessel (4)

$d = S_2^{1/3} \; v^{1/3}$ (5)

By substitution of the value 'd' from the vessel equation, (5), in equation (3), weight of a material in vessel $tS_1 S_2^{2/3} \; \rho v^{2/3}$ (6)

This equation is multiplied by cost per lb. to obtain an expression of the cost of the vessel as $K \rho t S_1 S_2^{2/3} v^{2/3}$.

However, a more fundamental equation for pressure vessels can be derived from the commonly accepted design equation

$$t = \frac{P D_m}{2 SE} + C$$ where P = Pressure in Psi

D_m = Average of inside and outside diameters

E = Joint efficiency

S = Maximum allowable working stress

C = Corrosion allowance

If D_m, D and E are assumed as unity, the equation changes to $t = \frac{P D}{2S}$. Substitute the value for 't' and $S_2^{1/3} V^{1/3}$ for D in the earlier equation, the cost of vessel = $k \rho S_1 S_2 \{P/2S\} \times V$. Usually for a given process 'p' pressure remains constant and hence cost of the vessel is proportional to volume V.

Similarly, for a vessel subjected to wind load and stretching due to internal pressure as well as dead weight stress, with a few assumptions for a plain carbon steel vessel with length twice the diameter and maximum allowable working stress of 10,000 psi, the cost of the vessel = $\frac{k \rho \rho_w S_1 (S2/w)^{7/3}}{S} V^{3/\rho}$

where ρ_w = density of water

and S = Maximum allowable working stress.

By further synthesising and introducing the concept of weight range, the cost of tanks, vessels, etc. of different materials can be derived.

Factors Influencing Costs

The various parameters that are considered for the formation of an equation to estimate the cost of pressure vessels have been grouped under six categories.

Diameter Vs. Length (d/l)

The relation between diameter and length has a vital influence on the design and cost of pressure vessels. In design considerations, certain established relationships between diameter and length are available for reducing waste and minimising the cost. The use of such standardised relationships in designing pressure vessels in various chemical and petro chemical industries can cut costs substantially.

Machine Hour/Man Hour (M_c/M_m)

In the manufacture of pressure vessels, the utilisation of machines and workmen is interrelated. The ratio of machine hour to man hour has, therefore, significant relevance in the estimation of costs. There are certain optimum values for this ratio which, if achieved, would lead to the cost being within economic limits.

Pressure and Thickness

The quality of the material of construction and its thickness are governed by the pressure for which the equipment is designed.

For the same pressure, there could be different thicknesses for different materials. To optimise the cost, the thickness of the equipment can be altered in relation to the quality (and therefore cost) of material employed, without detriment to the strength of the unit.

Density

The density of the material of construction of the pressure vessel is another important parameter to be considered for cost estimation. The density represents the molecular structure and strength of the material. This strength is significant because it denotes the ability of the material to withstand pressure. The density has also an important bearing on the cost as the weight of the material is proportional to the density.

The factors of pressure, density and thickness are closely interlinked and the correct combination of these factors would lead to optimisation of the equipment cost.

Installation - Cost of Internals and Bought out Items

The internals of a pressure vessel are the agitators, baffles and coils which are fitted inside the vessel depending upon the process. These internals are items which are fabricated by the same agency which fabricates the vessel. The bought out items are those which are standardised and are readily available in the market. They are reduction gears, motors, level indicators and necessary fixtures. The ultimate cost of procurement and installation of bought out items is inclusive of the expenditure incurred for third party inspection, radiographic tests and stress relieving.

A disturbing feature of the behaviour of the cost of internals and bought out items is that it rises disproportionately with the increase in size of the vessel. Therefore, in estimating costs, the cost of internals and cost of bought out items become significant.

METHODOLOGY

The methodology adopted for the study is as follows:

A literature survey relating to cost estimation of pressure vessels in the past was done for identification of the problem and definition of the scope of the present study.

Primary data relating to the different parameters of cost estimation of pressure vessels were collected. These sources included main manufacturers, fabricators, designing and consulting firms, installation contractors and marketing agencies.

The data so collected were checked for their correctness and realibility.

The graphical method was employed to develop an equation to represent the cost for pressure vessels.

Dimensional analysis was employed to analyse the dimensionless groups formed from the primary data.

The fitness of the equation developed by dimensional analysis and the graphical method was tested by employing multiple linear regression analysis using a computer.

The equation that has been developed to obtain the estimated cost of pressure vessel is thus established to be reliable for all practical purposes.

Sources of Primary Data

The primary data for the study were collected from several sources. The different sources were selected on the basis of their direct involvement with the process of setting up chemical industry units and, especially of pressure vessels.

The first group of sources from where primary data was collected are the manufacturing concerns who are the main manufacturers of pressure vessels of various specifications in the country. They are thus an indispensable source to identify the defects in the existing methods of estimation.

The second group of sources are the fabricating concerns. Unlike the manufacturing concerns, they specialise themselves in the manufacture of only certain types of specialised equipments. Together, they thus supply all types of chemical equipments including pressure vessels. The difficulties experienced by them due to inaccurate estimation methods are more pronounced than in the case of even the manufacturers because of the specialised nature of their work and their greater constraints of finance.

The third group is constituted of the designing and consultancy firms. The problems encountered by them are at two levels. Due to pressure of time, they are forced to submit the quotations even before the detailed estimates are drawn up. This latter work is done usually only after the award of the contract. The problem here is of the possibility of major divergences between the quotations and the detailed estimates. The second level is when the work is executed. In this second phase the cost of execution may often go much beyond than what was computed in the detailed estimates.

A fourth group of sources of primary data are the installation contractors. The installation contractors are those who take up the work of the construction and installation of the plant. To control the cost of installation within the estimates is vital to them.

Another source of primary data is the marketing agencies. They are dependent on the main manufacturing concerns for taking up work of chemical plant erection. The basic estimates are mostly supplied by the main manufacturers to the marketing agencies to enable them to quote. The primary data collected from this source are relevant as the estimates are affected further by the interest of such agencies.

There are also then the several chemical factories in the country which, with the help of their own internal resources, estimate, plan and execute projects. These are mostly for expansion. The absence of proper estimation procedures, coupled with the limited experience of the personnel may often lead to heavy cost overruns. Often threatening the basic health of the enterprise itself.

EXPERIENCE OF THE SCHOLAR

The present scholar has been working in the field of cost estimation and control for chemical plants for the last two decades in several capacities. He has been exposed to almost all the types of organisations mentioned above. This background of work has enabled him to be directly exposed to the problem and to be conscious of its importance. This industrial experience has also helped him to collect and build up the primary data relevant to the study.

Methods of Analysis

Graphical analysis is done to establish relationships with a fair degree of accuracy. This is a scientific method and will be far superior than all existing methods to develop necessary correlations for the cost estimation of pressure vessels in chemical industries.

Various dimensionless groups were formed by combining and correlating the basic parameters. An equation has been developed. The method followed is dimensional analysis of dimensionless group.

To test the reliability of the equation obtained graphically, SRS WR is adopted to select a few random samples. 73 individual data have been selected to establish empirical relationships through multiple linear regression analysis employing an IBM 360 computer.

Practical Implications of the Study

The equation developed in this study to establish the relationship among the various parameters will help the cost engineer to ensure that the gap between the preproject estimates (on the basis of which offers for a contract are made) and the detailed design cost estimates (which is prepared after securing the contract) is minimal.

The method of estimation proposed in this study is also useful to the designing and consulting companies. During the first phase of the development of a project, the designing and consulting company issues a preproject survey report containing all the cost estimates such as for land, building, equipment, erection, trial run and other related services. The entrepreneur mobilises his resources on the basis of this preproject report. The designing and consulting company mostly employs the conventional methods of estimation which have been already described. The preproject cost estimate so calculated more often than not becomes much lower than the detailed design cost estimate which is, as mentioned earlier, worked out only after securing the contract. The gap so formed between the two estimates is bridged by finding more finances by the entrepreneur. This results in upsetting the plans of the entrepreneur and reduces the return on his investment.

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CHAPTER-II

TECHNIQUES FOR COST ESTIMATION OF PRESSURE VESSELS

Most of the work on cost estimation, with particular reference to unit equipment cost, has been done in the developed countries.[1] It is a serious lacuna in the planning for chemical projects in India that even though significant advances have been made in chemical plant technology and also in the availability of vast amounts of related information, knowledge and very little work has been done on the vital problem of cost prediction. The absence of this has, to a considerable extent, vitiated the planning process, both at the micro and macro levels, regarding the implementation of chemical projects.

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(1) Popper, H., Modern Cost Engineering Techniques, (New York, 1970), 513.

The methods illustrated in page Nos 32 and 33. given below presents some shortcut methods which have proved very popular and some of the best used for so-called quickie estimates.(2) By the first one, the total plant cost is arrived and using this, manufacturing cost is estimated in the second illustration.

Various methods have been developed by cost engineers/technologists for cost estimation of pressure vessels. The more important of these techniques are as follows:

1. Quantitative Method
2. Subassemblies Method
3. Ratio Method
4. Similar Method
5. Unit Method
6. Index Number Method
7. Formula Method
8. Cost Estimation based on Weight
9. Rapid Equipment Cost Estimate
10. Fundamental Approach

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(2) Howard. F. Rare and Barrow. M. H., Project Engineering of Process Plants, (New York, 1961), 51, 53.

1. ESTIMATE EQUIPMENT COST (Major items not including piping, instruments etc.)

"Quickie" Estimate — Lang (5)

Type of Process	Factor
Solid	3.10
Solid-Fluid	3.63
Fluid	4.74

→ 13. Total Plant Cos

Factor 1.15 — Chilton (1)

2. INSTALLED EQUIPMENT COST (These values can be obtained directly from curves of Chilton (1)

3. Process Piping

Type Plant	% of Item 2
Solid	7 - 10
Solid Fluid	10 - 30
Fluid	30 - 60

4. Instrumentation

Amount Automatic Controls	% of item 2
None	2 - 5
Some	5 - 10
Extensive	10 - 15

5. Buildings & Structure

Type Plant	% of Item 2
Outdoor	5 - 20
Outdoor & Indoor	20 - 60
Indoor	60 -100

6. Auxiliaries

Extent	% of item 2
Existing	0
Minor additions	0 - 5
Major additions	5 - 25
New Facilities	25 -100

7. Outside Lines

Average Length	% of Item 2
Short	0 - 5
Intermediate	5 - 15
Long	15 - 25

8. Sum of Items 2,3,4,5,6 & 7

9. ENGINEERING & CONSTRUCTION

Complexity	% of item 8
Simple	20 - 35
Difficult	35 - 50

10. Contingencies

Type process	% of Item 8
Firm	10 - 20
Subject to change	20 - 30
Speculative	30 - 50

11. Size Factor

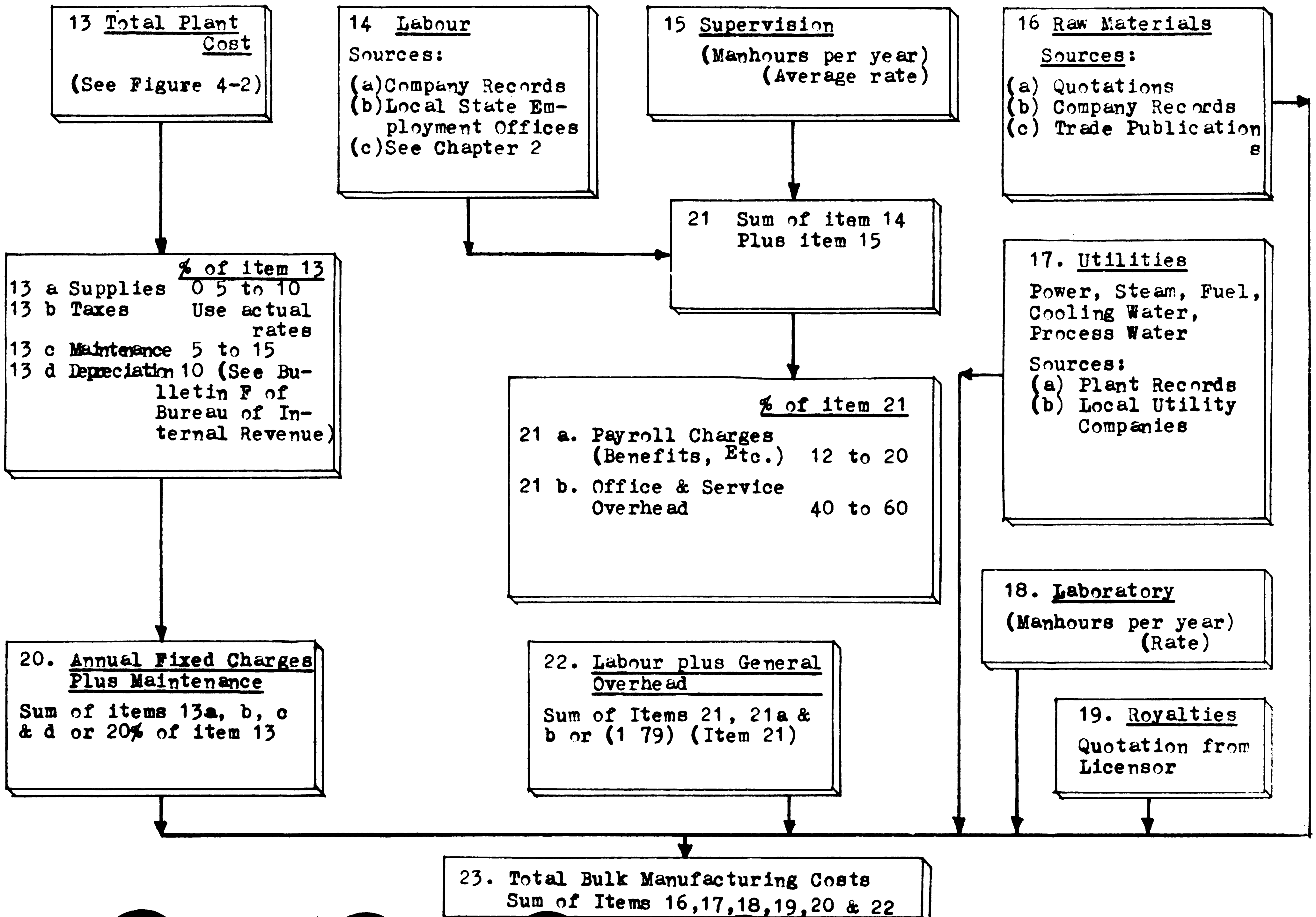
Size	% of Item 8
Large	0 - 5
Small	5 - 15
Pilot Plant	15 - 35

12. Sum of items 8,9,10&11

Basic of Equipment Cost Data	Multiply Item 12 by
Chilton's Data	Current ENR Inde: 400
Current	1.0
Other Data	Current Index ÷ Base Index

13. Total Plant Cost

FIG 4 - 2 (cont'


13 Total Plant Cost
(See Figure 4-2)
14 Labour
Sources:
(a)Company Records
(b)Local State Employment Offices
(c)See Chapter 2
15 Supervision
(Manhours per year)
(Average rate)
16 Raw Materials
Sources:
(a) Quotations
(b) Company Records
(c) Trade Publications
% of item 13
13 a Supplies 0 5 to 10
13 b Taxes Use actual rates
13 c Maintenance 5 to 15
13 d Depreciation 10 (See Bulletin F of Bureau of Internal Revenue)
21 Sum of item 14 Plus item 15
17. Utilities
Power, Steam, Fuel, Cooling Water, Process Water
Sources:
(a) Plant Records
(b) Local Utility Companies
% of item 21
21 a. Payroll Charges (Benefits, Etc.) 12 to 20
21 b. Office & Service Overhead 40 to 60
18. Laboratory
(Manhours per year)
(Rate)
20. Annual Fixed Charges Plus Maintenance
Sum of items 13a, b, c & d or 20% of item 13
22. Labour plus General Overhead
Sum of Items 21, 21a & b or (1 79) (Item 21)
19. Royalties
Quotation from Licensor
23. Total Bulk Manufacturing Costs
Sum of Items 16,17,18,19,20 & 22

Almost all these methods are useful to ensure economic balance of costs of individual units. They are of use in providing a rough and ready basis for preliminary cost estimation. They cannot, however, be used to measure the variance between the estimated cost and actual cost. They were also developed in the context of specific projects, and were not, therefore, intended for universal application in the cost estimation of pressure vessels.(3)

1. Quantitative Method

The quantitative method is based on statistical theory, particularly involving normal distributions. This method has been developed to provide a set of working equations, curves and worksheets, which can be used by the estimator to make computers of costs to desired levels of accuracy.

Cost estimation as per this method is based on the following.

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(3) Namboothiripad, P. V. S., "Mathematical Approach to Pressure Vessel Cost Estimation" in Chemical Engineering World, (Bombay, 1969), 34.

(i) Optimum ratio of length to diameter of the vessel

(ii) The problems of heat transfer in process plants

(iii) Expected rate of fluid flow

The important features of this method are as follows.

(i) Only the economic aspects of the project have been considered

(ii) A basis for estimating total plant cost, and not the unit equipment cost, is indicated

(iii) The general design and operational characteristic parameters have been ignored.

Due to absence of important parameters such as diameter length, machinehour, manhour, pressure density, cost of interior fittings, cost of boughtout items (d, l, M_c, M_m, P, ρ, C_i and C_f). This method does not appear to offer any scope for realistic estimates for unit equipment cost.

2. Subassemblies Method

Under this method, once the cost of parts, subassemblies or assemblies are known, the estimate of the total project cost can be computed. Obviously, this reduces the time required for arriving at the estimate. The accuracy of the estimate depends upon the accuracy of the component cost data. If the data relate to items that have a stable price level or show only slight price fluctuations, the total estimate becomes more reliable. If, however, the cost of materials has wide fluctuations, the estimate will tend to be less reliable. Estimates for projects requiring the assembly of fabricated parts can be prepared by this method with reasonable speed and accuracy, since the prices for such parts are easily obtainable.

3. Ratio Method

In this method estimation is done on the basis of cost data relating to earlier constructions. The data are so formulated as to contain summaries such as those illustrated in the case of Purdue House.(4) The ratio that the cost of each major part bears to the total plant cost is first estimated. By applying the ratio of this apportioned cost of the division to the total cost, it becomes possible to estimate the cost of

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(4) Purdue House . It is an estimating data developed by a Private Company.

other parts of the project or a similar part of another project, depending upon the extent of data available.

4. Similar Method

There are occasions when the project for which an estimate is to be made is very much similar to another project previously completed. An estimate of the cost of the new one may be derived from the cost of the previous one by making adjustments for the difference between the new and the old projects. This difference may be estimated by the machine hour/manhour method or by the ratio method. When the type of material used is changed, the Similar Method may be used to estimate the difference on the basis of the cost of material alone.

5. Unit Method

In the Unit Method, the cost is estimated per unit surface area or unit volume of the equipment. For auxilliary equipment like compressors, power plants and allied machinery and for pipe lines, the cost is reckoned on the basis of weight. This method has a limitation that it may not be reliable for estimating the cost of equipments operating with critical parameters.

6. Index Number Method

Index numbers of cost of construction are based on a selected list of commodities and services, costs for which are collated specifically for each construction. One of the most successful examples is of the Boeckh System sponsored by E. Boeckh and Associates Inc., Appraisal Engineers.(5) They have a manual containing index numbers for various types of construction in various parts of U. S. A. But these indices are basic and represent comparative average costs per cubic foot of equipment for the years 1926 to 1929, by making an analysis in accordance with the Boeckh routine. Multiplied by the cubic contents, this gives the cost as of the base year for any construction. The figure so obtained has to be corrected by applying an index of change in prices/costs as compared to the base

(5) Boeckh, E. H., Manual of Appraisals, (Indianapolis, 1945),

year. This change index is made up by Boeckh company on the basis of escalation of local prices of specific list of commodities and services. The firm mentioned above has a proprietory right on the method and the related information derived by them.

7. Formula Method

As per this method the cost of equipment is plotted against the capacity or size using uniform coordinates and loglog coordinates. Two formulae are available, one each for each of the methods of plotting. These formulae can be used as a means for quick estimation of the first cost of equipment. The publication titled Data and methods for Cost Estimation contains reliable methods for solution of the problem.(6) Of special interest in this context is an article entitled Six Tenths Factor Aids in Approximating Costs .(7) The Six Tenth Factor is a rule-of-the thumb to find the cost of a unit when the cost of a similar unit of different size is known.

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(6) Curtis, A. B., ed., Data and Methods for Cost Estimation, (New York, 1946), 52.

(7) Williams, R. J., "Six Tenths Factor Aids in Approximating Costs", Chemical Engineering (New York, 1947) 54.

8. Cost Estimation Based on Weight

This method attempts to develop a cost estimation based on the equipment weight, taking into consideration the cost per unit weight, wall thickness and volume.(8) This method appears inadequate as the fundamental parameters besides the thickness and volume have been ignored. One of the conclusions of the author of this method is that with the increase of volume of the vessel, the cost per unit weight decreases. While this conclusion can be accepted, there are many strong assumptions made by the author which are untenable. These assumptions are:

(i) The shape of the vessel remains constant regardless of capacity.

(ii) Volume is directly proportional to capacity.

(iii) Wall thickness will remain constant, over a small range of differences in capacity.

(iv) The cost of the vessel is related to its weight.

There are very serious reservations about accepting these assumptions. The shape of the vessel is

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(8) Private publication of E. I. du Pont de Nemours and Company, Plastic Department.

dependent upon the process that is employed and it may not, therefore, be constant. The volume of the vessel is largely dependent on the pressure and thickness of the material used and need not, therefore, be proportional to the capacity alone. Wall thickness is governed by the pressure level for which the vessel is designed and by the materials used and cannot, therefore, be assumed to be constant. The cost of the vessel is related not only to its weight but also to several other factors which have been described earlier.

9. Mathematical approach to cost estimation

Another approach for estimating the cost of equipment based on weight using fundamental considerations is also available. This approach relates cost of equipment to unit weight cost, wall thickness and volume. Using this approach, a method for estimating cost of special equipment has been derived but no published information about the application of this method is available.

Dr. O'Connel, F. P., a cost engineer, has attempted a further refinement of this method. He has exemplified this method by working it out in the case of a simple cylindrical vessel as shown below.(9)

Assumptions:

(i) The shape of the vessel remains constant regardless of capacity.

(ii) Volume is directly proportional to the capacity. This is on the premise that the holdup time for the fluid in the vessel is constant.

(iii) Wall thickness remains essentially constant, over a small range of capacity.

(iv) The cost of the vessel per pound of material remains constant, at least over a small range of capacity.

In order to derive the equation, the following parameters are used.

D = diameter of the vessel in inches

V = volume of the vessel in cubic inches

ρ = density of the material in the vessel in pounds per cubic inch

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(9) O'Connel, F. P., "An Approach to Process Equipment Estimation," Transactions of American Association of Cost Engineers, (Los Angeles, 1968), 1.

ρ_w = density of water in pounds per cubic inch.

t = wall thickness of vessel in inches

k = cost of vessel in rupees per pound of construction material

C_1 = shape constant for inside surface of vessel (dimensionless)

C_2 = shape constant for volume of vessel (dimensionless)

The expressions for the inside surface of the vessel, volume and weight of material will then be:

(1) Inside surface of vessel = C_1D^2

(2) Volume of material in vessel = tC_1d^2

(3) Weight of material in vessel = $tC_1D^2\rho$

Using the shape constant C_2, the corresponding expressions are:

(4) Inside volume of vessel = $V = C_2D^3$, or $\therefore D = \frac{V^{1/3}}{C_2^{1/3}}$

$$D = C_2^{-1/3} \cdot V^{1/3}$$

$$\therefore D^3 = \frac{V}{C_2}$$

(5) $\therefore D = C_2^{-1/3} \cdot V^{1/3}$

Substituting for 'D' in Equation (3),

(6) Weight of material in vessel = $tC_1C_2^{2/3}\rho V^{2/3}$

If the weight of material in equation (6) is multiplied by 'k', the cost per unit weight, the expression for the cost of the vessel will be:

(7) Cost of vessel = $k\rho tC_1C_2^{2/3}\ V^{2/3}$

Given the cost of material per pound, density of the material, wall thickness, shape of the vessel and its volume, the cost can be calculated by using equation (7). All parameters given in equation (7) are readily available except 'k' and 't'.

The above relationship is based on the concept that the surface of similar solid bodies varies with the 2/3 power of the volume, and this concept is probably the simplest explanation given for the Six Tenths Power Rule for the variation of cost with capacity.

More fundamental approach

However, on closer examination, one can realize that neither 'k' nor 't' is necessarily constant with varying volumes, and that the Six Tenths Power Rule does not always hold good. Sometimes this exponent will differ considerably from the value of 0.6.

For one thing, the cost per pound, 'k', would be expected to decrease as the vessel gets larger. If only because the fabrication expenses would not proportionately keep up with the increased amount of material, 'k' appears to be an index of the complexity of fabrication, and perhaps it could be called the complexity index. One might also expect 'k' to vary with pressure and temperature, since these affect the wall thickness and the intricacy of fabrication.

The wall thickness, 't', can be influenced by pressure and the need for the vessel to have a stiffness to hold its own weight and any other loads that may be imposed on it. At higher pressures, say over 50 to 100 psi, the pressure will tend to govern 't', and at pressures below this range stiffness requirements will tend to determine 't'. For the sake of simplicity, temperature is considered constant and not fluctuating.

Taking another case, that of pressure vessels, a commonly accepted design relationship is:

(8) $t = \frac{P D_m + C}{2 SE} + C.$

where P = pressure in psi

D_m = average of inside and outside vessel diameters in inches

E = joint efficiency (dimensionless fraction)

S = maximum allowable working stress in psi,

and C = corrosion allowance in inches.

For the sake of simplicity, it may be assumed that D_m is equal to D and that E is unity. The corrosion allowance for plain carbon steel may be 1/16 to 1/8 inch or more, but for many other materials it is not applicable.

This will give:

(9) $t = PD/2S$

substituting in equation (7) the value of 't' in equation (9) and value of 'D' in equation (5), the cost of the vessel will be

(10) Cost of vessel = $k \rho C_1 C_2 (P/2S)V$, and

(11) Weight of vessel = $\rho C_1 C_2$ (P/2S)V.

For any given process, if the pressure 'P' is taken to be a constant, the cost of the vessel becomes proportional to the volume, 'V', and, therefore, to capacity.

In the case of a vessel at lower pressures, there is a number of relationships which any be used to calculate 't'. A useful relationship for illustration is that of the stress at the bottom tangent of a vertical vessel subject to a wind load and to stretching due to internal pressure, as well as to dead weight stress.

(12) $t = 2P_w h/\pi DS - W/\pi D_m S + P D_m/4S$ for the windward side,

where P_w = equivalent pressure due to wind in pounds per square foot

h = height of vessel above bottom tangent in feet

D = outside exposed diameter of vessel in inches

S = maximum allowable working stress in psi.

W = weight of vessel filled with water in pounds.

If it is assumed that there is no wind load, the first term in equation (12) will vanish. If pressure near one atmosphere is taken into consideration the third term will drop out. There will then remain only the middle term in equation (12), which becomes

$$(13) \quad t = W/wDS$$

$$W = C_1 D^2 t \rho + C_1 D^2 \rho w$$

Substituting for W in equation (13), and simplifying, the expression for t will be as follows:

$$(14) \quad t = \frac{C_2 D^2 / \pi \rho_w}{S - \frac{C_1 D \rho}{\pi}}$$

The second term in the denominator can be neglected since, for a plain carbon steel vessel, with length twice the diameter, and with a maximum allowable working stress of 10,000 psi, it will introduce an error only of less than one per cent.

Substituting in equation (7) the value of t in equation (14) and value of D in equation (5), the cost of the vessel will be

$$(15)\ \text{Cost of vessel} = \frac{k \rho p w C_1 (C_2^{7/3}/w)\ V^{3/4}}{S},$$

$$(16)\ \text{Weight of vessel} = \frac{\rho p w C_1 (C_2^{7/3}/w)\ V^{4/3}}{S}$$

Test of Data

It then becomes evident from the examination of equations (10) and (15) that the exponent of 'V' for high pressures is lower than that for low pressures. Also, if 'k' can be shown to decrease with increasing value of 'V', the overall exponent of 'V' will be brought down and will remain closer to the traditional value of 0.6. This can be tested from cost data which is reported by weight rather than by the volumetric capacity of the vessel.

Bauman has published data on this.[10] For example, there is listed cost data under the title, Process Towers, Less Internals, Carbon Steel.[11] For the weight range of 6,000 to 20,000 pounds, the following relation for cost holds.

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(10) Bauman, H. C., "Fundamentals of Cost Engineering in the Chemical Industry," (New York, 1970), 62.

(11) Ibid, 67.

(17) $\text{Cost} = A_1 \cdot (\text{weight})^{0.790}$

where A_1 = a constant determined by the data

Dividing the above equation by the weight of the vessel, the cost per unit weight, or k will be:

(18) $k = \frac{(\text{Cost})}{(\text{Weight})} = A_1 (\text{weight})^{-0.210}$

In equation (11), representing all coefficients of V by B_1,

(19) $\text{Weight} = B_1 V$

Substituting this value for the weight in equation (18) we get

(20) $k = A_1 B_1^{-0.21} \; V^{-0.21}$ and

the cost of the vessel will equal the product of k and the weight, $B_1 V$, or

(21) $\text{Cost of Vessel} = A_1 B_1^{0.79} \; V^{0.79}$

In the case of low pressure the weight has been expressed according to equation (16) and representing the coefficient of $V^{4/3}$ by B_2,

(22) $\text{Weight} = B_2V^{4/3}$

Substituting this value for the weight in equation (18)

(23) $k = A_1B_2^{-0.21}\ V^{-0.28}$, and the

cost of the vessel will equal the product of k and the weight, $B_2V^{4/3}$, or

(24) $\text{Cost of vessel} = A_1B_2^{0.79}\ V^{1.05}$

Applying this concept to the second weight range, 20,000 to 300,000 pounds, for high pressures the following expressions are obtained.[12]

(25) $k = A_2B_1^{-0.29}\ V^{-0.29}$, and

(26) $\text{Cost of vessel} = A_2B_1^{0.71}\ V^{0.71}$, and for low pressures

(27) $k = A_2B_2^{0.29}\ V^{-0.386}$, and

(28) $\text{Cost of vessel} = A_2B_2^{0.71}\ V^{0.95}$,

where the subscript of A simply denotes the weight range used.

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(12) O'Connel, F. P., "An approach to Process Equipment Estimation" in Transactions American Association of Cost of Engineers, (Los Angeles, 1968), 6.

Applying the above relationships to the other cost data under the title, Tanks, Horizontal, Carbon Steel in the same publication, for a weight range of 3,000 - 7,000 pounds, the cost of vessel can be written as follows.[13]

For low pressure,

(29) Cost of vessel = $A_1B_2^{0.55} v^{0.733}$, $k = A_1B_2^{-0.45} v^{-0.60}$

For high pressure,

(30) Cost of vessel = $A_1B_1^{0.55} v^{0.55}$, $k = A\ B^{-0.45} v^{-0.45}$

For low pressure,

(31) Cost of vessel = $A_2B_2^{0.67} v^{0.89}$; $k = A_2B_2^{-0.33} v^{-0.44}$

For high pressure,

(32) Cost of vessel = $A_2B_1^{0.67} v^{0.67}$, $k = A_2B_1^{-0.33} v^{-0.33}$

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(13) Ibid, 7.

Under the title, <u>Pressure Vessels, Unfired, Carbon Steel</u>, it is assumed that only high pressures apply. Then, for a 3,000 - 6,000 pound range.[14]

(33) Cost of vessel $= A_1 B_1^{0.60} V^{0.60}$; $k = A_1 B_1^{-0.40} V^{-0.40}$

For the 6,000 - 30,000 pound range,

(34) Cost of vessel $= A_2 B_1^{0.68} V^{0.68}$, $k = A_3 B_1^{-0.32} V^{-0.32}$

For the 30,000 - 100,000 pound range,

(35) Cost of vessel $= A_3 B_1^{0.80} V^{0.80}$, $k = A_3 B_1^{-0.20} V^{-0.20}$

Finally, under the title, <u>Tanks, API Conical Roof, Carbon Steel</u>, it is assumed that only low pressures apply.[15]

Then, for a 10,000 - 30,000 pound range,

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(14) <u>Ibid</u>, 12.
(15) <u>Ibid</u>, 12.

(36) Cost of vessel = $A_1B_2^{0.63}\ V^{0.839}$, $k = A_1B_2^{-0.37}$
$V^{-0.494}$.

For 30,000 - 200,000 pound range,

(37) Cost of vessel = $A_2B_2^{0.72}\ V^{0.960}$, $k = A_2B_2^{-0.28}$
$V^{-0.373}$

10. Rapid Equipment Cost Estimate

The Rapid Equipment Cost Estimate provides quick cost estimates on the basis of which early technical and administrative decisions can be made.

Cost estimates present summations of the overall effects of many factors in terms of simple overall costs. The final comparison, in which all relevant factors are considered, provides the basis on which the most attractive alternative can be chosen from the economic point of view.

A complete list of equipments is included in the preliminary engineering flow sheets. It is important to price each unit of the process equipment in the estimates. The bulk of such equipments consists of tanks, vessels, agitators and other standard units for which prices may be readily available. If not, a rapid estimation has to be resorted to.

There are a number of methods to arrive at estimates of the total project costs. Almost all these methods are linked to major equipment costs. These different types of rapid methods are intended only to give a cost assessment which is somewhat more reliable than an outright guess. They can not be used in lieu of a preparation of a preliminary estimate.

A case of installing equipment in a chemical plant for the purpose of waste recovery may be considered. By following the conventional estimation methods directly linked with major equipments, the cost estimated may not include provisions for foundations, supports and insulation. Once the costs of major process equipment elements are known, the approximate figures for the total project cost can be arrived at without going into details of piping arrangement, building design and other aspects by using the various estimating methods which are available from published data. Sometimes, one may not have enough time or process data to estimate thus the cost of a plant. In such a case, on the basis of the actual costs of similar equipments installed earlier, the cost of the new equipment can be estimated by applying necessary correction factors.

Several rules of thumb have been developed over the years to aid in cost estimation. One of the most valuable among these aids is the Six Tenth Factor which is used in approximating the cost of a piece of equipment or a complete plant when the cost of a similar unit or plant of a different size is known. Restated in simple terms, this rule states that if the cost F of a given unit of a particular capacity G is known the cost of another unit of capacity H will be $(H/G \times F)^{0.6}$.[16] The validity of this rule has been extensively checked by statistical analysis and it has been found to be fairly reliable.

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(16) Namboothiripad, P. V. S., "Mathematical Approach to Pressure Vessel Cost Estimation", Chemical Engineering World, (Bombay, 1969), 34.

Another method of correlating the cost of equipment with capacity is to plot the cost against capacity on a graph using logarithmic scales. The advantage of this type of plotting is that it leads to linear relationships.

Perhaps, an example will clarify this still further. Let x_1 be the capacity of the first unit and x_2 be the capacity of the second unit. Let y_1 be the cost of the first unit and y_2 be the cost of the second unit. Then, $y_1 = mx_1^a$ and $y_2 = mx_2^a$ where m is the constant for the equipment and a is the exponent.

$$\therefore \; y_2/y_1 = \{(x_2)/(x_1)\}^a$$

$$y_2 = y_1 \{(x_2)^a/(x_1)\}^a$$ (17)

The latter equation becomes the sixth tenth factor expressed in formula a = 0.6.

Now, the effect of 0.6 on the cost, when the capacity is increased, may be examined. When the exponent is approximately 0.6, the size or capacity of an

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(17) Other things remaining same this may hold good. Fluctuations in prices will change the cost levels too.

equipment does not make a big difference in cost. The unit price will increase approximately by 50 per cent as can be seen from the following calculations.

If the cost of a 4 gpm pump is Rs.660 the cost of a 8 gpm pump, using the relationship $y_2 = y_1 \frac{(x_2)^a}{(x_1)}$ will be, $y_2 = 660 \frac{(8)^a}{(4)}$

$$y_2 = 660\ (2)^{0.6} = \text{Rs.1,000/- approximately.}$$

The difference in cost of the two pumps = Rs.1,000 - Rs.660
= Rs.340/-

The difference in cost of the two pumps is thus about 50 per cent of the cost of the first equipment.

Some of the more commonly used exponents in U. S. A. have been tabulated and published.[18] Corresponding figures for India, worked out by the scholar are also given below.[19]

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(18) Caplan, F., Heating, Piping and Air Conditioning, (New York, December 1967),

(19) Namboothiripad, P. V. S., "Rapid Cost Estimation", Indian Chemical Journal, (Bombay, 1968), 27.

TABLE-1

		U. S. A.	India
Centrifugal blower with motor 3 to 7.5HP	-	0.4	0.3
Package Boiler over 30 HP to 300 HP	-	0.52	0.504
Centrifugal blower with motor over 7.5 HP	-	0.9	0.71
Radient Exhaust Fans upto 5000 cfm	-	0.46	0.47
Air Compressor reciprocating	-	0.90	0.85
Carbon steel pressure vessels	-	0.66	0.601
Heat Exchangers	-	0.55	0.66
Columns	-	-	6.69
Cooling Towers	-	--	0.707
Storage Tanks	-	0.66	0.62

CONCLUSION

Examination of equations (20) through (37) takes one to certain definite conclusions. Firstly, the unit material cost decreases with increasing volume, which is what is to be expected. Secondly, on the basis of strong theoritical considerations as well as experimental data regarding unit cost of material, it is possible to derive a relationship between cost and capacity which approaches the six tenths power rule . In some instances, the exponent appears a little high, especially for vessels at low pressures. This may partly be due to the existence, as in some cases, of a corrosion allowance in the wall thickness, t, which would tend to lower the power of 'V', to which it is proportional.

The exponents of V in high pressure cases are consistently lower than the exponents of 'V' in low pressure cases. This may help to explain why the exponents for overall high pressure plants tend to be lower than 0.7, the usual range being 0.6 to 0.7.

Summarising the above, it can be stated that

(38) Cost of vessel $\propto ktV^{e}$

where k and t are held constant for a given capacity, or volume. Also for a given process

(39) $t \propto V^{g}$, and

(40) $k = FV^{f}$

where 'g' depends on the pressure and the material of the vessel, 'F' on the shape and material of the vessel and 'f' on the complexity of construction. The dependence of 'k' on pressure is not clearly brought out in the studies reviewed above. However, for a given process the pressure will be fixed for all capacities.

In the absence of definite data, this approach can be utilised with a fair degree of confidence for estimating the cost of any special item of equipment. While 't' and 'V' can be estimated by the application of fundamental engineering principles, 'k' can be worked out by matching this special piece of equipment with another type of equipment of the same degree of complexity, the value for the latter being known. This value of 'k' can be substituted in equations (7), (15) or (40) to arrive at an estimate of the cost of the equipment. Matching the degree of complexity requires a certain amount of engineering judgement based on length of weld, temperatures under cold and hot working, mechanical fitting and similar other quantifiable aspects.

A critical appraisal of the methods of cost estimation reviewed above indicates that in the development of the various methods only limited data have been made use of, leading to a number of assumptions relating to aspects which ordinarily merit more serious consideration. Also, the methods have been developed on limited number of parameters such as diameter, thickness, pressure and length. Though it cannot be denied that these basic parameters form the very foundation of any scientific approach to estimation of costs, there is a good number of other important parameters such as fabrication time expressed as machine hours and manhours, cost of internals and cost of bought out items, which, if considered, may lead to a more accurate result and thus enhance the credibility of such estimates.

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CHAPTER-III

INVESTMENT ANALYSIS OF CHEMICAL PROJECTS IN INDIA

INTRODUCTION

A proper and realistic cost estimate with built-in features of correction for passage of time will provide a fairly good basis of control of project costs. Without such control, it may not be possible to check cost overruns or to apply timely correction for lack of due returns. This is true of small or large projects. In the case of projects where delay in execution is experienced, it is quite common to compare the total cost with the original estimates (without applying the correction factor for escalation) and to arrive at disproportionately high figures of losses caused.

This problem can be exemplified by analysing the country's experience in making investments in chemical industries projects in the country over the five five year plan periods. Such an analysis would enable a proper appreciation of the dimensions of savings that could have been effected with proper estimating procedures and therefore, of the need for better management of investment costs.

This analysis has been done by looking at the total volume of investments made by the country during the twentyfive year period (1950-1975) in chemical industries and comparing these figures with corresponding figures for other countries using international rates developed through SRSWOR. This is followed by an examination of the total investment on all chemical projects and their rates of return. The differences between the actual returns and the estimated returns are computed. These differences are analysed by relating them to the cost overruns which is the difference of the actual cost from the estimated cost. The continuing nature of the problem is seen when the differences between the returns on investments based on the estimated production and the actual production are analysed.

The Industrial Policy Statement of 1948 and the first, second and third five year plans had laid great emphasis on the development of heavy industries in the country.[1] The rate of investment in chemical industries showed an upward trend during the first three plan periods, but showed a decline subsequently.[2] The volume of investments in chemical projects during several plan periods is shown below:

TABLE-1

GROWTH OF CHEMICAL INDUSTRIES: 1951-1970

Year	No. of Chemical Units: At the beginning of the plan period	No. of Chemical Units: At the end of the plan period	Plan period	Increase over
1951	37,667	127,544	1951-1964	89,877
1964	127,544	467,921	1964-1970	340,377
1970	467,921	527,965	1970-1975	669,044

(1) Eastern Economist (J) Annual issues, 1973, 1974 and 1975.

(2) Southern Economist (J) Annual issues, 1973, 1974, 1975 and 1976.

TABLE-2

INVESTMENT IN CHEMICAL INDUSTRIES AND RATE OF RETURN

Plan	Investment (Rs. in millions)	Net Return in Absolute terms (Rs. in millions)	Net Return (in percentage)
I	270	142.02	52.6
II	1,400	679.42	48.53
III	4,460	1,642.618	36.83
IV	6,750	3,504.0	51.92
V	7,900	4,017.15	50.85

It is also seen that in the setting up of chemical projects considerable variation was seen in the original estimated cost and the actual cost incurred subsequently. This is evident from the following table.

TABLE-3[3]

PERCENTAGE INCREASE IN ACTUAL EXPENDITURE OVER ORIGINAL ESTIMATES

Year	Increase (%)
I Plan	
1951	+28
1952	+36
1953	+42
1954	+40
1955	+50
II Plan	
1956	+31.5
1957	+37.7
1958	+46.5
1959	+45.75
1960	+51.51
III Plan	
1961	+32.5
1962	+38.1
1964	+44.7
1965	+45.0
IV Plan	
1966	+43
1967	+46.5
1968	+48.5
1969	+52.6
1970	+69.7
V Plan	
1971	+52
1972	+55
1973	+61
1974	+59
1975	+67

(3) Reserve Bank of India Bulletin, Various issues.

Such overruns are in consequence of several factors. While certainly such factors as abnormal price escalation contributes significantly to this variance it cannot be denied that unscientific estimating procedures are basic to the problem.

It is interesting to note that in all the five year plans the overruns in the first year of each plan is the minimum and in the last year the maximum. There is a steady increase in the intervening years.(4) This behaviour supports the earlier hypothesis that there is absence of close and proper estimation of project costs in India, especially in chemical industries.(5)

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(4) *Ibid*, (Table-3, page 67)

(5) It is clearly evident that [illegible] every year, 50 to 75 per cent of the industrial expenditure unanticipated and unexpected is appropriated by the Parliament of India and State Legislatures by [illegible] the passing of the Appropriation Bill. This is a common feature. (Social Science (J), Indian School of Social Science, Trivandrum, Vol.III, 1973 June, Flap Note.)

In the case of some major chemical and chemical based industries, the actual expenditure has been almost double of the amount estimated.(6)

This same variance is also evident in the case of the expected returns from these investments and the actuals. The return on investment in chemical industries in India fluctuated between 37 and 53 per cent during the 1950-1975 period. This 16 per cent spread is considerably higher than what the more developed countries experienced. For example, during the same period, the fluctuations in the return on investment was 10 per cent in G. D. R., 5 per cent in Japan and 1 per cent in U. S. A. The rate of return in the more developed countries was sometimes as high as 99 per cent. To some extent, this difference between the performance of chemical industries in India and in the developed countries is a reflection of our inadequacies in planning, estimation, execution and control of chemical industries products.

(6) The expenditure estimated for the fertilizer industry under the IV Plan was 45 per cent of the total volume of investment planned for chemical industries as a whole. But the net expenditure came upto 86 per cent of the estimation which was subsequently appropriated. (Asok Mehta - Plans in Perseptive, p.83, Asia Publishing House, New Delhi.)

VOLUME OF RATE OF RETURN IN CHEMICAL AND CHEMICAL BASED INDUSTRIES IN DIFFERENT COUNTRIES: 1950-1975

COUNTRY	1950-1955		1955-1960		1960-1965		1965-1970		1970-1975	
	Investment	Return	Investment	Return	Investment	Return	Investment	Return	Investment	Return
INDIA	36.5	52.61	46.5	48.53	52.5	36.83	51.6	51.92	48.5	50.85
G.D.R.	15.2	86.5	13.5	89.15	12.5	93.65	11.75	96.8	13.6	96.7
JAPAN	30.5	93.6	25.6	96.7	29.6	96.5	36.85	98.5	31.5	96.85
U. S. A.	14.7	98.5	13.1	98.4	15.0	98.5	21.55	99.0	20.17	98.65

Investment relates to the industrial investment Vs. chemical industrial investment.

Return relates to the actual Vs. estimated production.

Source: Industrial Economy in Developed Nations - A survey, edited by Dr. Nirondal P. Paking, published by Pennsylvania University.

An analysis of the percentage of actual to estimated returns for the major classes of chemical industries reveals that the actual return has been as low as 29.6 per cent of estimated and as high as 66.2 per cent. This does not compare favourably with that in other countries where the rate of return works out to as high as 99 per cent.

Among all the chemicals, Sulphuric Acid and Caustic Soda have the largest production and sales volumes as they are basic chemicals to feed several other chemical industries. Data relating to the growth of production of Sulphuric Acid and Caustic Soda are given below:

TABLE SHOWING THE PERCENTAGE OF INVESTMENT IN CHEMICAL INDUSTRIES IN FIVE YEAR PLANS

	I	II	III	IV	V
INORGANIC	35	20	35	20	20
H_2SO_4	13	8	8	6	6
Caustic Soda	12	4	10	6	7
C_1	10	8	7	8	7

	I	II	III	IV	V
ORGANIC	**13**	**10**	**10**	**15**	**15**
Acetone	1.5	1.5	1.0	2.0	1.5
D A A	1.5	1.5	1.0	2.0	1.5
Acetic Acid	2.0	1.5	1.0	1.5	2.0
M I B K	1.0	1.0	1.5	2.0	2.0
Plasticise	2.0	1.5	1.0	2.0	2.5
Alchbolic	1.5	1.0	1.5	1.5	2.0
Plasticesers	2.0	1.0	1.5	1.5	2.0
Ethylene	0.5	1.0	1.5	2.5	1.5
PETROCHEMICALS	**10.0**	**15.0**	**15.0**	**20.0**	**20.0**
Ethylene	2.5	2.5	2.5	3.5	3.5
Polymer	2.5	3.0	3.0	3.5	3.0
	1.5	3.5	4.0	6.5	8.0
Bulledue	2.5	2.5	2.0	3.5	3.0
Benzene	1.0	3.5	3.5	3.0	3.0
PLASTICIZERS	**43**	**55**	**50**	**45**	**45**
N	20	20	15	15	20
P_2O_5	10	20	10	15	20
K_2O	13	15	15	15	5

Source: 1. Sinha Chakradhar, Approach to the Fifth Plan: A Critique, Southern Economist, (Bangalore, May, 1973), 9-11.
2. Fifth Five Year Plan: A Summary, Southern Economist, (Bangalore, Jan. 1974), 9-16.

TABLE SHOWING THE PERCENTAGE RETURN TO THE ESTIMATE THROUGH FIVE YEAR PLANS

	I	II	III	IV	V
INORGANIC	**60**	**49**	**37**	**52.5**	**51**
H_2SO_4	58.5	48.25	35.1	54.2	50
Caustic Soda	62.5	50.5	35.2	60.0	52
C_1	61.0	49.5	60.5	43.5	49
ORGANIC	**50**	**48.1**	**35.0**	**56.5**	**56**
Aceton	49	46.6	36.2	51.6	50.2
D A A	48.1	47.25	37.5	58.5	51.5
Acetic Acid	51.5	49.75	34.25	29.6	53.6
M I B K	49.0	51.5	35.5	41.8	59.8
Plaslicise	47.5	48.75	33.6	36.8	49.5
Alcoholic	52.0	50.5	36.5	60.5	66.2
Plaslicezene	51.0	49.25	40.5	39.6	58.3
Ethylene	49.0	48.5	29.6	40.5	56.1
PETROCHEMICALS	**48.0**	**49.5**	**36.0**	**55.0**	**52.0**
Ethylene	49.5	50.1	36.5	56.7	50.0
Polymer	47.5	48.2	37.5	55.1	51.0
	51.6	51.6	40.5	54.2	55.0
Bulledus	40.5	47.6	32.5	55.2	49.0
Benzene	47.5	47.0	40.1	55.5	55.0
PLASTICIZERS	**40.0**	**46.5**	**36.0**	**43.0**	**41.5**
N	39.5	43.7	35.1	40.5	36.5
P_2O_5	41.6	48.5	36.8	45.5	45.6
K_2O	40.1	46.7	37.1	42.5	41.5

Sources: 1. Balasubramoniam, V., Plan in Perspective, Southern Economist, (Bangalore, 1976), 1213-1214.

2. Hayek, F. A., New Confusion about Planning, Eastern Economist, (Calcutta, Feb. 1976), 229-230.

3. Kantha Rao, M. L., and Narasimha Reddy, D., Southern Economist, (Bangalore, Aug. 1973), 5-12.

1. Sulphuric Acid

The last two decades have witnessed increase in the production of sulphuric acid by nearly ten times, from 0.104 million tonnes in 1950 to 1.010 million tonnes in 1971. Further expansion plans envisaged a production of 2.0 million tonnes at the end of IV plan and 3.3 million tonnes at the end of 1975. But, at the end of IV plan only 1.197 million tonnes had been produced and, at the end of 1974-1975, the production stood at 1.292 million tonnes. The expected production for 1978-1979 is 3.300 million tonnes.(7)

Though 24 per cent of the total investment in chemical sector has been allocated for production of sulphuric acid, the resultant production has not been able to cope up with even 75 per cent of the actual internal demand. This reality conflicts with the planners' estimates which included provisions for export after meeting the internal demand entirely. At present, though production at the rate of 2,600 tonnes per day has been estimated the actual production is only 1,500 tonnes

(7) Chemical Weekly, (Bombay, June 26, 1979), 68.

per day. The indigenous demand is 1,900 tonnes per day. The shortfall has not been met with the result that several H_2SO_4 based industries are facing acute raw material problems, and several others waiting to be commissioned are, perhaps, waiting for more favourable supply situation.

2. Caustic Soda

Next to sulphuric acid, caustic soda is the most important chemical in demand. The production of caustic soda has also had a tremendous increase, but not in step with the estimates. From 1951 to 1970, production increased from 12,000 tonnes to 354,000 tonnes. The total production in 1970, according to plans, should have been 420,000 tonnes. On account of the slow rate of growth in production of caustic soda, the Alkali Manufacturers' Association submitted a proposal before the Government of India for increase in production at an accelerated pace. This plan was accepted by the Government for implementation. The situation has not, however, shown any appreciable improvement in subsequent years also.

TABLE-1

PRODUCTION OF CAUSTIC SODA 1973-1978 (8)

Year	Production in '000 tonnes		Percentage Expenses	
	Estimated	Produced	Estimated	Actual
1973	500	391	6.5	8.9
1974	650	424	7.0	9.8
1975	720	428	8.0	10.1
1976	800	476	9.5	12.75
1977	880	N.A.	N.A.	N.A.
1978	980	N.A.	N.A.	N.A.

(8) Source: 1. Eastern, Southern Economist (Annual Volumes)
2. Industrial Labour Gazette.

INVESTMENT ANALYSIS

In all the major countries of the world standardised norms of investments and returns have been adopted. Such an approach naturally results in reducing the prices of chemicals. It is a fact that the existing Indian prices of almost all chemicals are considerably higher than the prices in other countries. At the same time, the rate of growth of chemical industries in India has been much higher than in many other developed countries.(9) In prices and availability of chemicals we are still lagging behind the more developed nations, indicating thereby the undeveloped nature of the industry in the country.(10)

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(9) AVERAGE ANNUAL GROWTH RATE (PERCENTAGE) 1963-1971

Country	Chemicals	All Countries	Ratios
Britain	6.1	3.4	1.8
France	10.2	6.8	1.5
West Germany	10.7	5.0	2.1
Holland	17.6	8.2	2.2
Japan	14.1	13.2	1.1
U.S.A.	8.1	4.3	1.9
India	12.3	7.0	1.8

(10) INVESTMENT BY CHEMICAL INDUSTRY - 1974

Country	Investment in $ B/year
Britain	3
France	2
Germany	4
Japan	10
U.S.A.	16
India	0.3

Never the actual return does justice to the estimation.

An important feature of industrial progress from 1965 has been that the growth in the production of machinery for chemical and pharmaceutical industries has been remarkable compared to the growth of the industries in general.[11]

In the execution of chemical projects, it is generally seen that the delay in completion seems to increase with the magnitude of the project. It is also seen that nearly two thirds of the number of projects

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(11)

INDEX OF PRODUCTION IN INDIA

(Base 1960 = 10)

Industry	1965	1970	1975
1. Chemical and Pharmaceutical machinery.	373	840	1,310
2. Engineering Industry.	213	226	260
3. All Industries	154	181	205
Total:	740	1,077	1,775

got delayed regularly. Consequently the project cost also tends to escalate far beyond the original estimates.(12)

Right from the first five year plan, India has been experiencing acute shortage of chemical products. The indigenous demand can be met only by adoption of a planned system of development of this industry. The rate of growth in indigenous and international demand is on the increase almost day by day. Growth of the chemical industry is vital for the economic development of the nation. It has great potential for exports also.

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(12)

INDIAN PROJECTS - TIME AND COST OVERRUNS

Project	Completion time (months) Estimated	Completion time (months) Actual	Project Cost (Rs. million) Estimated	Project Cost (Rs. million) Actual
Paper	54 + 66	120	75 + 77	152
Fertilizer (New)	48 + 48	96	383 +482	865
(Expansion)	48 + 72	120	295 +380	675
Refinery	72 + 28	100	460 +330	790
Steel Plant Expansion	24 + 42	62	1055 +537	1587
Iron Ore A	44 + 28	72	365 +269	634
B	20 + 20	40	158 +122	280
Heavy Electricals	67 + 75	142	674 +390	983

Source: Indian Economy; Arnold Publishing Co., Bombay.

As far back as 1962, it was estimated that through export of chemicals, India could earn one third of the total foreign exchange that she would need for development.(13)

The rate of increase in investments in chemical industries over the various plan periods has been as follows:

INVESTMENT DIFFERENCE IN INCREASED TO THE PLANS

(Rs. in millions)

Plans	I	II	III	IV
I 270	-	-	-	-
II 1400	1130	-	-	-
III 4460	4190	3040	-	-
IV 6750	6480	5350	2390	-
V 7900	7630	6500	3440	1150

Though thus there has been substantial increase in investments, there is no such improvement in the matter of returns. The total volume of returns

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(13) Pandit J. Nehru, Rate of Chemical Industry in Indian Economy (Speech), Hindu, Industrial Survey, 1962.

from investments in the chemical industry upto the end of V Plan has not reached even the neighbourhood of what was estimated for the II Plan.

RATE OF RETURN IN ABSOLUTE TERMS

(Rs. in millions)

Plan	Amount estimated	Return in estimation
I	270	142.020
II	1400	679.420
III	4460	1642.518
IV	6750	3504.600
V	7900	4017.150

The differences between the estimated returns and actuals under the various plans were as follows:

PLAN GAIN AND LOSS STATEMENT

(Rs. in millions)

Plan	Investment	Anticipated Plan Gain	Actual Plan Loss
I	270	127.980	142.020
II	1400	720.580	679.420
III	4460	2817.482	1642.518
IV	6750	3245.400	3504.600
V	7900	3882.850	4017.150
TOTAL	20780	10794.292	9985.708

The increase in expenditure for investments in chemical industries from the estimates to the actuals under the various plans has been about Rs.10,380 million, which is about 50 per cent of the total plan investment of Rs.20,780 million. Obviously, the estimation methods adopted by the planners leave much to be desired.

TABLE SHOWING THE DIFFERENCES BETWEEN ESTIMATES AND ACTUALS IN INVESTMENT IN CHEMICAL INDUSTRIES

Plan	Rs. in Million
I	95.84
II	596.288
III	1,788.014
IV	3,412.800
V	4,457.200
Total:	10,380.142

The two types of losses relating to loss of returns and estimate over-runs have been calculated on the basis that the projects proposed are completed within the scheduled time. But, completion of all projects are generally subjected to inordinate delay. The losses due to such time overruns during the previous plans have been estimated at Rs.13,936 million which is about 70 per cent of the plan investment itself. The plan-wise losses due to time overruns are given below:

ESTIMATED LOSS DUE TO TIME OVERRUNS

Plan	Rs. in Millions
I	48.6
II	490.0
III	2,798.0
IV	5,062.5
V	5,537.0
Total:	13,936.1

The total losses on account of the three types of causes discussed so far are, therefore, as follows:

STATEMENT OF INVESTMENT AND CONSOLIDATED LOSS

(Rs. in millions)

Plan	Investment	LOSSES DUE TO Under Rea-lisation of Returns	Estimate over-runs	Time over-runs	Total losses
I	270	142.020	95.840	48.6	286.46
II	1,400	679.420	596.288	490.0	1765.708
III	4,460	1,642.518	1,788.014	2798.0	6228.532
IV	6,750	3,504.600	3,412.800	5062.5	11979.9
V	7,900	4,017.157	4,487.2	5537.0	14041.35
TOTAL:	20,780	9,985.708	10,380.142	13936.1	34301.95

The above data indicate that the total losses as they relate to chemical industries have been of the order of Rs.34,300 million as against the planned investment of about Rs.20,800 million, which is roughly 170 per cent over the past five plan periods. This, in other words, means that the nation ended up spending 270 per cent of what was initially planned to achieve the same level of investment.

The 170 per cent overrun has been contributed by the three factors as follows:

i)	Loss due to under-realisation of returns	- 50 per cent
ii)	Loss due to under-estimation of expenditure (estimate overrun)	- 50 per cent
iii)	Loss due to delay (time overrun)	- 70 per cent
	TOTAL:	- 170 per cent

Of the above, items (i) and (ii) have resulted largely from rough and faulty financial and technical estimates. Part of the deviations in the financial estimates are due to price fluctuations in the economy. But there is no valid explanation for the technical estimates to go wrong, especially when the variations run upto as high as 50 per cent. Knowledge of engineering principles and the technology of chemical plant design is abundant in this country. This knowledge, applied with the principles of engineering economy should provide a sound basis of estimation so that deviations of the actuals from the estimates are contained within narrow limits. The results indicate that efforts in this direction have not been applied by the planners.

Many reasons can be attributed to the delay in execution of projects, leading to the third factor i.e. loss due to time overrun. Some of the reasons are:

(a) Political influence on the selection of project, its location, execution, manning and infra-structure leading to decisions which fail to provide expected results.

(b) Problems of knowhow, such as use of obsolete technology and selection of partially developed technology leading to delay in obtaining the plant and equipments.

(c) Problems of fixing contracts for supplies and erection - indigenous and foreign.

CHAPTER-IV

THE APPROACH TO THE STUDY AND METHODOLOGY

INTRODUCTION

A close and accurate cost estimation results from careful consideration of the behaviour of the various parameters. Standardisation of a cost estimation procedure in chemical industries is still a very complex problem. This applies equally in the case of pressure vessels too. Due to the severe complexity of various influencing factors, it becomes necessary to identity the parameters for standardisation of cost estimation of pressure vessels. The influence of the different parameters on the cost of pressure vessels has been clearly brought out in the nomogram below which also highlights the necessity for standardisation of cost estimation of pressure vessels in view of the complexity of correlation of the inherent factors.[1]

Factors of Cost Estimation

For standardisation of cost estimates of pressure vessels, four major factors viz. capacity factor, process factor, fabrication factor and purchase cost factor have to be considered.

(i) Capacity Factor

Capacity factor is influenced by the parameters of diameter and length of the vessel. These depend upon the working pressure, fluid flow and vacuum. These parameters are to a great extent the components of the capacity factor because the capacity of the pressure vessel is controlled to a great extent by the cumulative effect of these parameters.

(ii) Process Factor

In this factor the work pressure and the density and thickness of material of construction are

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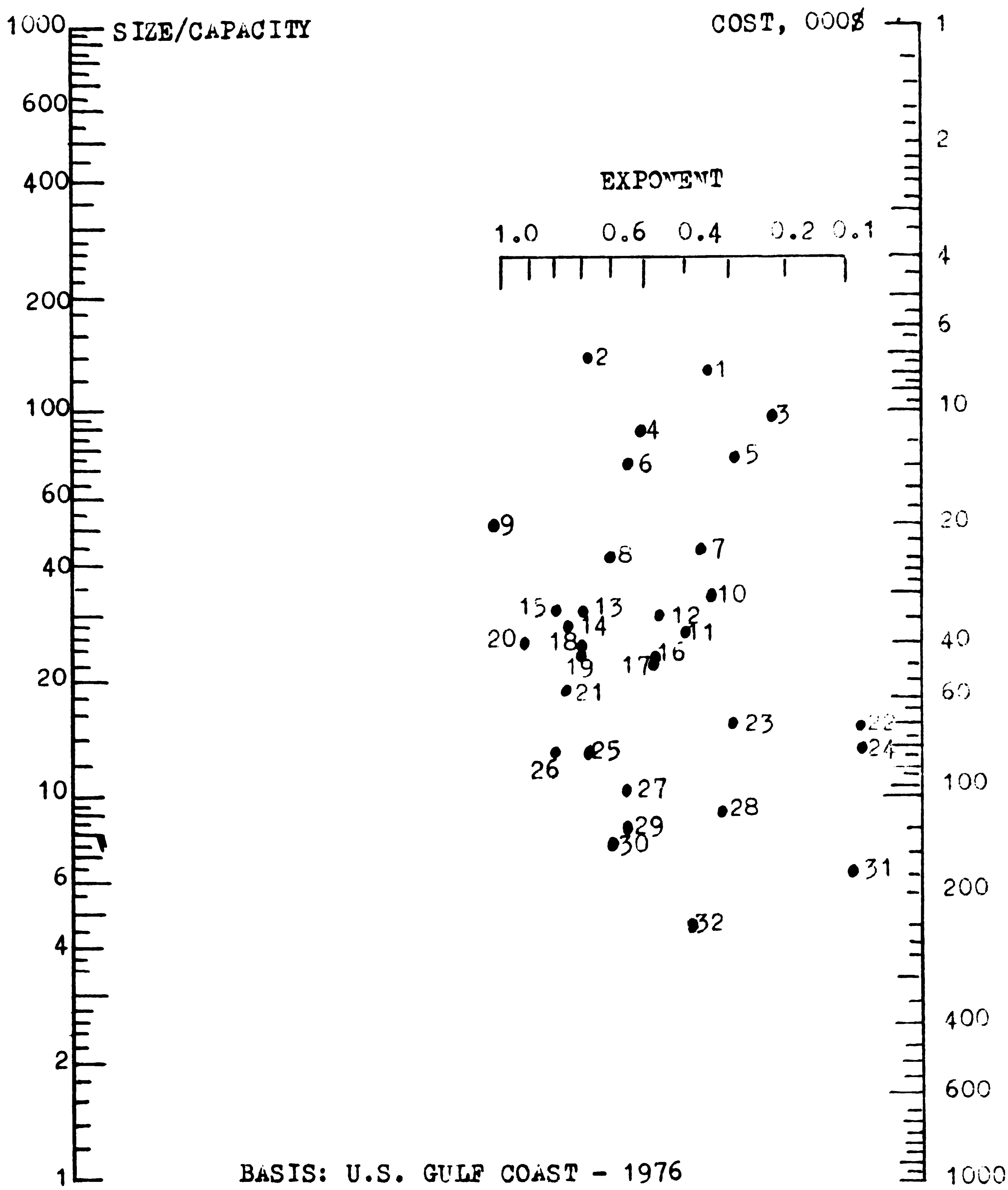
(1) Kharbanda, O. P., Process Plant and Equipment Cost Estimation,

NOMOGRAM 1. 1. PROCESS EQUIPMENT



Notes: 1. Other items: Process Vessel, Tank & Tray - Nomogram 1.2 Distn. Col., Glass-lined equip., LPG storage & spray dryer - Nomogram 1.6.

2. To obtain cost of fully installed "module" (inclusive of piping, instrument and electrical etc.), multiply cost from Nomogram by M.

involved. These are the main process parameters and hence this group is called the process factor. The working pressure of the process is a critical parameter. According to the variation of pressure, the thickness of the vessel may change. Depending on the material processed, the construction material is selected. Hence, these three parameters viz. working pressure, density of material of construction and thickness of the construction material have been clubbed together and called the process factor. This can be expressed as $P/\rho t$ where P is the working pressure, ρ the density and t the thickness.

(iii) Fabrication Factor

The capacity factor and the process factor are largely dependent on the process design aspects. This fabrication factor is very much influenced by the time spent in the application of mechanical effort and human effort expressed respectively in terms of machine hours and man hours. The contribution of these parameters to the fabrication factor can never be ignored.

(iv) Purchase Cost Factor

The purchase cost factor is constituted by the cost of internal fittings such as agitators, baffles, internal coil arrangements and allied accessories and the cost of bought out items such as motors, reduction gears and welding rods. In the cost of bought out items (C_f), the utility items, charges for services such as radiography, inspection and stress relieving have also been included.

All the parameters considered in the above major factors individually and collectively influence the standardisation of cost estimation of pressure vessels.

The four major factors viz. capacity factor, process factor, fabrication factor and purchase cost factor represent the four groups of critical parameters as was described above. These four groups have specifically been made dimensionless for arriving at a basis of standardisation of cost estimation. These groups have been made dimensionless in order that linear relationships of the various parameters can be established. In any other treatment, it would have yielded highly non-linear partial differential equations. Such differential equations are difficult to be solved making use of the current knowledge available.(2)

The problem is analysed by two methods as under:

1. Dimensional Analysis of dimensionless groups by the graphical method.

2. Analysis of dimensionless groups by multiple regression analysis using a computer.

The dimensional analysis yields useful correlation only when all the influencing parameters, both variable and nonvariable are taken into consideration.

THE DIMENSIONAL ANALYSIS METHOD

Dimensional analysis is a simple mathematical test. Generally, this reduces the number of experimental variables to be correlated and often points out the best experimental approach to the solution of the problem. It does not give quantitative information,

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(2) Namboothiripad, P. V. S., M. Tech. Thesis, p.47.

for which purpose, experiments must still be relied upon. When two variables are to be correlated, a simple plotting on a graph of one against the other results in a curve. When the number of variables is increased to three, the first curve plotted against corresponding values of the second for several constant values of the third produces a set of curves. The addition of the fourth or more variables greatly complicates both the exercise as well as graphical correlation. In cases where more variables, each with varying degrees of dimensional complexity, are present, they have to be formed into dimensionless groups. A single chart becomes sufficient for the general correlation of all these original parameters represented by dimensionless groups.

There are two methods of dimensional analysis of dimensionless groups.

(A) The Buckingham Pi Method:

Although this method was introduced in 1914, no rigorous proof was presented until Langhaar's contribution in 1951. He stated Pi Theorem as follows:

> If an equation is dimensionally homogeneous, it can be reduced to a relationship among a complete set of dimensionless products... A set of dimensionless products of given variables is complete of each production, the set is independent of others and every other dimensionless product of the variables is a product of powers of dimensionless products in the set. (3)

The dependence of 'n' quantities may be expressed in the form of $Q_1^{a_1}\ Q_2^{a_2}\ Q_3^{a_3}$ --- $Q_m^{a_m}$ ---

$$Q_n^{a_n} = \pi$$

$$i = 1, 2, 3 \text{ --- } P \quad (x)$$

The explanation of the significance of 'm' and 'P' are as follows. No dimensionless constant is introduced in equation (x). In the Raleigh method, which is explained later, the minimum number of dimensionless groups possible from 'n' quantities described by 'r' dimensions is (n-r). In the Buckingham method, it is necessary to know beforehand how many dimensionless groups will constitute a complete set. Consequently, the symbol 'm' is introduced

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(3) John H. Perry; Chemical Engineers Handbook.

and defined as the number of restrictions placed upon the equation by virtue of the requirement of dimensional homogeneity. Furthermore, 'm' will have as its maximum value the number of primary dimensions 'r'. If there are m restrictions on the values of a_1, a_2, a_3 --- in the equation, there will be n-m unrestricted exponents and consequently n-m dimensionless groups 'P' constituting a complete set for n quantities. This is given by the equation, P = n - m.

According to the Buckingham's theorem, the 'P' dimensionless groups π_1, π_2, π_3 --- π_p are then related by the general functional equation, $\phi(\pi_1, \pi_2, \pi_3 --- \pi_p) = 0$.

This equation helps to describe the phenomenon as accurately in terms of the complete set of 'P' dimensionless groups as it might be in terms of the n quantities.

The existence of 'm' in the equation has been the major obstacle in the use of the Buckingham Method. Van Driest stated that 'm' could be considered as the maximum number of quantities involved in the problem that could be combined without forming a dimensionless group.[4]

(B) Raleigh Method

Raleigh Method is based on the premise that if 'n' quantities, Q_1, Q_2, Q_3 ---- Q_n are involved in a certain physical phenomenon like diameter, length, thickness and type of material for fabrication for the purpose of the dimensional analysis, their mutual dependence may be expressed as a power product of the following type

$$Q = k\ (d/l)^a\ \ (M_e/M_m)^b\ \ (P/\rho t)^c\ \ (C_1/C_f)^d$$

where k is a dimensionless constant.[5] In this equation Q must be construed to be quantity which is of the principal interest, (to make it more clear, Q_1 in the original formula is converted into a dimensionless group Q) although such an interpretation is not essential to the method.[6] But, for maximum precision, the interpretation followed here is that except for 'k', all the

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(4) Ibid.,(3).

(5) John H. Perry, Chemical Engineers Handbook, (Fourth Edition),

(6) Ibid. (5).

components on the right hand side of the equation are dimensional variables involved in the phenomenon or included in the equation due the demand of the dimensional system. The requirement of dimensional homogenuity places some restrictions upon the values that (n - 1) constants a_1, a_2, a_3 --- a_n may have. If the n variables and dimensional constants consist of 'r' primary dimensions, there exists a maximum number of r conditions which the constant exponents of the equation must satisfy. The final result of analysis by the Raleigh Method is an arrangement of 'n' quantities into such a form that dimensionless products of groups containing Q is equated to the product of the components on the right hand side. Each one of the other dimensionless groups is raised to the power represented by n - 1 - r unrestricted exponents. As a consequence, there results an arrangement of the 'n' quantities into minimum of n - 1 - r + 1 = n - r dimensionless groups.

A close examination and analysis is possible only by following this method. Hence, in attaining maximum possible accuracy, dimensionless groups are formed on both sides of the equation and analysed.

All the influencing parameters are, therefore, selected and formed into dimensionless groups for the dimensional analysis, in order to correlate them.

After proper groupings are made, the exponents are to be thought of. The exponents, as such, are the result of the quantitative influence of dimensionless groups, analysed using dimensional analysis techniques. Exponents can be found out by using empirical equation. A great number of formulae and equations used in all fields today are derived from experimental data or statistics. Such equations are known as empirical equations.

The empirical equations can be adopted in three types, viz:

(1) the linear type, i.e. $Y = mx + b$,
(2) the exponential type, $Y = bm^x$ and
(3) the power type, $Y = bx^m$

where x and y are variables; and b and m are constants to be determined from the given data. The slope, m, is numerically equal to the tangent of the angle, x, which the line makes with the x axis. The slope may be determined by dividing the difference between the two values of Y on the curve by the difference between the two corresponding values of u. If the exponential equation $Y = bm^x$ is written in logarithmic form, it assumes properties similar to linear equation.

To find out the exponents in the equation,

$$C = k \left[(d/l)^a \; (M_c/M_m)^b \; (P/\rho t)^c \; (C_l/C_f)^d \right],$$ the

empirical method is adopted. As per this method, several curves are drawn using log log scale, plotting the values obtained from primary data of one dimensionless group on the x axis against the various costs on the y axis, keeping the values of each of the other dimensionless groups constant or close to it. Thus a host of curves for various ranges of values for each dimensionless group is obtained, indicating their influence on the cost, from which the exponents are derived.

For the primary stage, each dimensionless group has to be taken individually and independently. That is $(d/l)^a$ is taken as a unit and (d/l) has to be plotted on the x axis of the log log graph keeping cost on the y axis. The slope of the straight line graph in the log log graph plotted as specified above will be the exponent for that particular dimensionless group. Experimental programme has to be followed by plotting various data, collected for the particular dimensionless group. The slopes of all curves for different ranges for a particular dimensionless group have to be taken and the average of the slopes so obtained is taken as the exponent for that dimensionless group. Thus the average of various different data plotted in log log graph is the exponent of that particular dimensionless group.

After finding out the exponent of a dimensionless group, the value of that group has to be raised to the value of the exponent, and so on for all the groups. When the products of all such groups are plotted on the x axis of the log log graph against various costs on the y axis, the intercept of the resultant curve on the y axis gives the value of the constant k.

To explain further, at the primary stage, each dimensionless group has to be taken individually and independently, i.e. $(d/l)^a$ is taken as a unit and (d/l) is to be plotted on the x axis against the estimated cost on the y axis of a log log graph. This process is repeated for (d/l) ratio of different ranges and the pattern of the curves is examined. The average of the slopes of curves so attained is considered as exponent a for the dimensionless group (d/l).

In the same manner each dimensionless group is plotted and the average slope of the graph is taken to obtain the exponent of each dimensionless group. After finding out the exponent of all the dimensionless groups, the product on the right hand side of the equation is found out by raising the values to the respective exponents. This product is again plotted on the x axis against the estimated cost on y axis in a log log graph. The straight line so obtained on the y axis and the value of this intercept is the value of k. Thus

$$Q = k \{ (d/l)^a \ (M_e/M_m)^b \ (P/\rho t)^e \ (C_l/C_r)^d \}.$$

COST NUMBER

The cost number is a concept which has been developed in this study to establish the relationship between the estimated cost of the equipment and the material cost. The Cost Number, Q, is the ratio of the estimated cost in rupees to the material cost in rupees.

That is, $Q = \frac{\text{Estimated Cost in rupees}}{\text{Material Cost in rupees}}$

The cost number, Q, is dimensionless and can be expressed as an absolute number for a given set of parameters. When the value of the parameters is changed, Q will also change.

In the equation given earlier showing the relationship of Q to the various parameters, the groups on the right hand side have been made dimensionless by converting each group into a ratio of entities expressed in the same units. To keep the balance of the equation, it is necessary to treat the term on the left hand side of the equation, Q, also as dimensionless. Hence the expression of Q as a relationship of estimated cost to the material cost, both reckoned in the same unit, viz. rupees.

The method of development of Q as a Cost Number is analogous to the method employed to derive Nustle's Number and Prandal Number which are extensively applied in Chemical Engineering practice.

In the present study, the Cost Number Q has been developed for pressure vessels. Using the same concept, it may be possible to develop cost numbers for other chemical equipment, e.g., heat exchangers, distillation columns, vertical tanks, etc.

MULTIPLE LINEAR REGRESSION ANALYSIS BY COMPUTER IBM 360

The relationships obtained by the graphical method described above have been tested by applying regression analysis with the aid of an IBM 360 Computer. The initial results of the regression analysis were found to be more reliable than those obtained by the graphical method and hence further work was done by using only the multiple linear regression analysis on the computer to refine the results and arrive at the final correlation. The following procedure has been adopted for this exercise:

Firstly, from the 2,067 primary data, the respective ratios of the dimensionless groups were collected. The l_n values of these data were tabulated from which 74 results obtained from SRSWOR were selected for being tested on the computer. These 74 data were fed into the computer as per the standard programme package for multiple linear regression analysis method. The multiple linear regression analysis can be carried out either by Matrix Method or by the Gauss's Elimination of Least Square Method. Under both these methods, the presentation of the problem and the mode of solution are given as under:

MULTIPLE LINEAR REGRESSION

Problem: To correlate 74 sample observations from 2,067 population data to the following equation:

$$Q = k \left[(d/l)^a \ (M_e/M_n)^b \ C_1/C_f)^c \ (P/\rho t)^d \right] \quad .. \quad (1)$$

where, a, b, c and d are coefficients of regression and k is the intercept.

Taking logarithm on both sides of Eq(1) in its linear form as $l_n Q = a \, l_n (d/l) + b \, l_n (M_e/M_n) + c \, l_n (C_1/C_f) + d \, l_n (P/\rho t)$

OR

$$Y = a \, x_1 + b \, x_2 + c \, x_3 + d \, x_4 \quad .. \quad (2)$$

where,

$Y = l_n Q$

$x_1 = l_n (d/l)$

$$x_2 = l_n (M_c/M_n)$$

$$x_3 = l_n (C_i/C_f)$$

$$x_4 = l_n (P/\rho t)$$

Sample data in terms of Y, x_1, x_2, x_3 and x_4 is supplied.

Linear Regression

a, b, c, and d are unknown. The estimates of a, b, c and d are found using the information provided by the 74 sample data. Thus we can write

$$Y_{cal} = a\,x_1 + b\,x_2 + c\,x_3 + d\,x_4 \qquad .. \quad (3)$$

where, Y_{cal} is the predicted or calculated value of Y for given x_1, x_2, x_3 and x_4 when a, b, c, and d are determined.

Estimation of Parameters

The parameters a, b, c and d are estimated by minimising the sum of squares of deviations from the true line, i.e.

$$S = \sum_{i=1}^{n} (Y_i - Y_{cal})^2 = \sum_{i=1}^{n} (Y_i - a\,x_{1i} - b\,x_{2i} - c\,x_{3i} - d\,x_{4i})^2 \qquad .. \quad (4)$$

where, S = sum of squares of deviations

n = number of observations.

The values of a, b, c and d are obtained by differentiating Equation (4) with the respective parameters.

$$
\left.
\begin{aligned}
dS/da &= -2\sum_{i=1}^{n} (Y_i - Y_{cal})^2 = \sum_{i=1}^{n} (Y_i - a\, x_{1i} - b\, x_{2i} \\
&\qquad - c\, x_{3i} - d\, x_{4i})^2\, x_1 = 0 \\
dS/db &= -2\sum_{i=1}^{n} (Y_i - a\, x_{1i} - b\, x_{2i} - c\, x_{3i} - d\, x_{4i})\, x_{2i} = 0 \\
dS/dc &= -2\sum_{i=1}^{n} (Y_i - a\, x_{1i} - b\, x_{2i} - c\, x_{3i} - d\, x_{4i})\, x_{3i} = 0 \\
dS/dd &= -2\sum_{i=1}^{n} (Y_i - a\, x_{1i} - b\, x_{2i} - c\, x_{3i} - d\, x_{4i})\, x_{4i} = 0
\end{aligned}
\right\} \quad (5)
$$

After simplification, we get

$$
\left.
\begin{aligned}
&\sum_{i=1}^{n} Y_i\, x_{1i} - a\sum_{i=1}^{n} x_{1i}^2 - b\sum_{i=1}^{n} x_{1i}x_2 - c\sum_{i=1}^{n} x_{1i}x_3 - d\sum_{i=1}^{n} x_{1i}x_4 = 0 \\
&\sum_{i=1}^{n} Y_i x_{2i} - a\sum_{i=1}^{n} x_{1i}x_{2i} - b\sum_{i=1}^{n} x_{2i}^2 - c\sum_{i=1}^{n} x_{2i}x_{3i} - d\sum_{i=1}^{n} x_{2i}\, x_{4i} = 0 \\
&\sum_{i=1}^{n} Y_i x_{3i} - a\sum_{i=1}^{n} x_{1i}x_{3i} - b\sum_{i=1}^{n} x_{2i}x_{3i} - c\sum_{i=1}^{n} x_{3i}^2 - d\sum_{i=1}^{n} x_{4i}x_{3i} \\
&\qquad = 0 \\
&\sum_{i=1}^{n} Y_i x_{4i} - a\sum_{i=1}^{n} x_{1i}x_{4i} - b\sum_{i=1}^{n} x_{2i}x_{4i} - c\sum_{i=1}^{n} x_{3i}x_{4i} - d\sum_{i=1}^{n} x_{4i}^2 = 0
\end{aligned}
\right\} \quad (6)
$$

These are normal equations and can be solved for a, b, c and d by the matrix method or by any numerical method. Normal equation (6) can also be solved by Gausses Elimination method.

a) MATRIX METHOD

Given data

Variables

Observations

	A	B	C	D	E
1					
2					
3					
. . .					
73					

(1) Compute the averages, $\bar{A}$, $\bar{B}$, $\bar{C}$, $\bar{D}$ and $\bar{E}$,

(2) Compute for the pairs

(A, B), (A, C), (A, D)

(B, C), (B, D), (C, D)

$$C_{AB} = \frac{\Sigma(A_i-\bar{A})\ (B_i-\bar{B})}{\sqrt{\Sigma(A_i-\bar{A})^2\ \Sigma(B_i-\bar{B})^2}}$$

And similarly for other pairs.

(3) From the Matrix

		A	B	C	D
M =	A	1	C_{AB}	C_{AC}	C_{AD}
	B	C_{AB}			
	C	C_{AC}			
	D	C_{AD}			

(4) Solve (M) x (Q) = $\underline{b}$

$$\text{where } \underline{b} \text{ is } \begin{Bmatrix} C_{AE} \\ C_{BE} \\ C_{CE} \\ C_{DE} \end{Bmatrix} \text{ as per definition (2)}$$

Q is the required solution.

<u>GAUSES ELIMINATION METHOD</u>

A computer programme has been written for Gause's elimination method and it is used as a subroutine to the main programme. The given sample data in terms of Y, x_1, x_2, x_3 and x_4 can be obtained. The absolute values of Y, x_1, x_2, x_3 and x_4 as defined in equation (1) represents the experimental Q (Q_{exp}) and (Q_{cal}) represents the equation by using the regression respectively in the columns when we run the computer processing.

$$Q_{cal} = k \{ (d/l)^a \quad (M_c/M_m)^b \quad (C_1/C_f)^c \quad (P/\rho t)^d \}$$

where, a, b, c, d are the exponents and the best values of a, b, c, d and k are found out, where k is the intercept.

The sum of squares of the fractional residues can be calculated as $\sum_{i=1}^{n} \left[\frac{(Q_{exp} - Q_{cal})}{(Q_{exp})} \right]^2$

$\therefore$ The standard deviation $= \sum_{i=1}^{n} \left[\frac{(Q_{exp} - Q_{cal})}{(Q_{exp})} \right]^2 \times$ Total number of observations.

Thus the standard deviation also can be found out.

<u>Goodness of the fit:</u>

The standard deviation is one of the measures, whether the fit is good or bad. So also the correlating coefficient of Q with respect of the independent variables.

Further, the significance of a, b, c and d in the equation have been tested. All the standard methods of multiple regression analysis have been employed which includes the following procedure:

(a) Significance of the coefficients has been tested. Since all the coefficients were significant, no new regression equation has been set up with the remaining variables.

(b) The analysis for the new set of variables was repeated. The co-variance table for the regression equation has also been analysed. In addition, matrix observations were collected for obtaining the inverse A^{-1} for the original variables. The details of the programming and other data received from the computer are appended.

In brief, all possibilities of standardisation of cost estimation of pressure vessels have been explored by using these new correlation tests. Further details are elaborated in Chapter V.

CONCLUSION

It was stated earlier that it is very difficult to solve the highly nonlinear partial differential equation with a high degree of accuracy with the knowledge available at present. The numerical techniques for solving partial differential equations have been evolved from finite difference approximations for the partial derivatives. In these methods, to estimate the accuracy of the results becomes extremely difficult for most of the cases. If the numerical procedure satisfies two criteria, viz. convergence and stability, the degree of accuracy is determined by the number of increments used. Better accuracy can be obtained only at the cost of great effort. The convergence criterion is concerned with the approach of the approximate numerical solution to the exact solution, as the number of increments rises indefinitely. Unless the numerical solution converges to exact solution the limits of the numerical method are unsatisfactory. The stability criterion deals with the growth of errors in the calculation. Because any partial solution deals with a finite number of increments and finite number of significant figures, errors are introduced into the calculation. These errors are not serious unless they increase during the progress of solution of the problem.

Due to the limitations explained above, it was decided to adopt dimensional analysis to solve the present problem. The methodology of dimensional analysis has been discussed earlier in this chapter. After using dimensional analysis, the graphical approach was selected to find out the exponents and the constant. Later, due to the unavoidable errors in the graphical method, multiple linear regression analysis was employed as a suitable method to solve the problem. The equation which is developed here is a power type of equation which is very similar to that evolved for production functions in economics, where multiple regression techniques are used for deriving the value of the exponents.

The method of regression analysis is highly useful and beneficial, especially in the evaluation of process data. In such applications, process having as many as 50 variables which are continuously changing can be evaluated. Further, daily log records of even 150 to 500 data points can be analysed by this method to determine the relative dependence of any variable on any other or all the variables. The analysis in many situations has led to the quantitative determination of the hidden effect of individual variables less known or unknown on the key operating variables.

As indicated above, the problem dealt in this study is to determine the effect of the individual variables, under simultaneously changing conditions on the key operating variables. Hence, though the problem was initially solved graphically, using values obtained through dimensional analysis and the fitness of the correlation proved by multiple linear regression analysis, the correlation has been further refined through a series of regression analyses and the improved values so obtained have been used to establish the correlation and to arrive at conclusions.

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CHAPTER-V

C O R R E L A T I O N

INTRODUCTION

Basis of correlation

To discover the correlation of the cost number with critical parameters is the core of this study. For formulating this correlation, the method of multiple linear regression analysis was employed.

The correlation has been expressed as

$$Q = k \{ (d/l)^a \cdot (N_c/N_n)^b \cdot (P/\rho t)^c \cdot (C_1/C_r)^d \}$$

In analysing the physical nature and content of the various parameters of the dimensionless groups given in the above equation, each group has been individually considered.

Taking the group (d/l), the two parameters more or less reflect the shape of the pressure vessel which is cylindrical. From the design point of view, d and l govern thickness at a given pressure and capacity for a cylindrical vessel. This group takes care of physical aspects such as size, shape, capacity, space for installation and dimension of supporting structures, in addition to the installation and the fabrication costs. Hence, by properly defining this group (d/l), the accuracy of estimates of the unit equipment cost and consequently of the total project cost can be ensured to a large extent.

For this particular study, values of diameters and lengths over a wide range have been taken. The range of diameter is from 0.25 meters to 9.98 meters i.e., the maximum is 40 times the minimum. The range of lengths is from 0.60 meters to 17.4 meters, where the maximum is 29 times the minimum. The resulting values for the group (d/l) have been 0.030 to 1.070, the maximum being 36 times the minimum.

In the group of (M_c/M_m), the man hours and machine hours are the parameters having importance next only to diameter and length. They bear a direct relationship to the cost of pressure vessels. This group is influenced by many factors like diameter, length, capacity, type of construction and availability of skilled personnel and machines. In this study, the (H_e/H_m) ratio varies from 0.0346 to 2.7. This means that the maximum is about 82 times the minimum.

The group $(P/\rho t)$ is the third dimensionless group which has significant relationship with the process design aspects. Given the process conditions, once the pressure is fixed by the design equations and the material of construction chosen, the thickness is automatically obtained. Thus this factor $(P/\rho t)$ has a wide impact on cost estimation of pressure vessels. Using the primary data, the value of the group $(P/\rho t)$ varies from 160.3 to 4678 considering pressures from 1 kg./Cm.^{2} to 135kg./Cm.^{2} and thicknesses from 5mm to 37mm.

In the group (C_i/C_r), the numerator C_i covers the cost of internal fittings such as agitators, internal coils, baffles and other accessories. The factor C_r, represented as the denominator, represents the cost of bought out items such as reduction gears, electric motors and welding rods. The C_f value carries the cost involved for radiography stress relieving, code inspection and other services. The range of ratio of C_i/C_f varies from 0.0359 to 9.609%. It can be seen that the range covered is very wide to include all types of internal fittings and bought out items.

In the equation $Q = k \{ (d/l)^a .(M_c/M_m)^b .(P/\rho t)^c .(C_i/C_f)^d \}$

for the various values of the different groups described earlier, applying the values of a, b, c and d and the constant k obtained through multiple linear regression analysis, the range of variation in Cost Number Q is found to be from 1.8101 to 19.91. That is, the maximum is 10 times the minimum.

<u>Multiple Linear Regression Analysis</u>

In most research problems where regression analysis is applied, more than one independent variable is needed in the regression model. The complexity of most scientific mechanisms is such that, in order to be able to predict an important response, a multiple regression model is needed. When this model is linear in the coefficient, it is called a multiple linear regression model.

A normal equation can be put in the matrix from $Ab = g$. If the matrix A is nonsingular, the solution for the regression coefficients can be expressed as $b = A^{-1}g$.

Estimating the Error Variance

The error and the regression sums of squares take on the same meaning that they did in the case of a single independent variable. The error variance indicates how adequate the model is. Without making a distributional assumption on the errors, no form of testing of hypothesis or estimate of confidence intervals is possible.

The standard error of estimation and sum of squares at the regression of the present study can be observed from the working sheets of the computer appended.(1)

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(1) Appendix III.

Knowledge of the distributions of individual coefficient estimations enable the experimenter to construct confidence intervals for the coefficient to test hypotheses about them.

In many regression situations individual coefficients are important. In general economic applications confidence interval and tests of hypothesis on parameters are of interest. In most of the chemical industrial problems the interest is not likely to be in the individual parameters but rather in the ability of the entire function to predict the true response in the range of the variables considered.

Further, while doing regression analysis, deletion of factors is necessary, when the situation so dictates, for arriving at a workable prediction equation. This is also to find out the best regression involving only those variables that are useful and significant.

One criterion that is commonly used to illustrate the adequacy of a fitted regression model is the coefficient of multiple determination. This quantity merely indicates what proportion of the total variation in the response is accounted for by the model. Often this is expressed in percentage and the result interpreted as percentage variation, explained by the model. The square root of this percentage variation is called multiple correlation coefficient. It can be seen from the computer data appended that the multiple correlation coefficient obtained is upto 0.967. That is, upto 96.7 per cent of variation has been explained by the linear regression model.

The regression sum of squares is generally used to give indication whether or not the model is an adequate explanation of the true situation.

One can test the significance of regression with respect to initial point of the distribution for the particular degrees of freedom. While the result does indicate that the regression explained by the model is significant, the possibility that the model might have excluded certain critical variables cannot be ruled out.

As stated earlier, the correlation was attempted to be established using the graphical method using dimensionless groups and by application of multiple linear regression analysis. A comparison of the values of the exponents and also the constant 'k' as derived by the graphical method and by the regression analysis are given below:

VALUE OF EXPONENTS OF DIMENSIONLESS GROUPS AND VALUE OF INTERCEPTS

	Carbon Steel	Stainless Steel	C_i/C_f range below 1.0	C_i/C_f range between 1.0 and 2.0	C_i/C_f between range 2.0 and 6.0
d/L: Graphical	-0.3863	-0.0087	-0.2241	-0.1825	0.1215
Regression Analysis	-0.2398	-0.00274	-0.2016	-0.16339	0.1009
M_e/M_s					
Graphical	0.0349	0.0349	0.0069	0.2816	0.0314
Regression Analysis	0.0251	0.00769	0.0078	0.36311	0.48
C_i/C_f					
Graphical	-0.4663	-0.0524	-0.4824	0.5031	-0.0483
Regression Analysis	-0.3464	-0.04059	-0.5784	0.54241	-0.0578
$P/\rho t$					
Graphical	-0.1405	0.0175	-0.0018	0.3216	0.2987
Regression Analysis	0.1828	0.00[illegible]9	-0.0011	0.34692	0.3165
Value of intercept k using					
Graphical	0.9	1.121	1.8412	0.2861	0.2312
Regression Analysis	0.70	1.1507	1.9713	0.2321	0.2997

It can be seen that the values obtained for the exponents and the constant 'k' are more reliable using the multiple linear regression analysis than those obtained through graphical application. It was, therefore, decided at this stage to pursue the former method only for further analysis and refinement of the model.

Further Exercises

As stated in the previous chapter, 74 items of data were selected from the 2,067 items in the primary data using SRSWOR. These 74 data related to carbon steel and stainless steel as materials of construction.

In the first attempt at correlation using the multiple linear regression analysis, the multiple correlation coefficient obtained was 0.72. This is indicative of a confidence level of 0.52 which cannot be considered as quite reliable for the present study.

As a second step, 72 items of data relating to carbon steel only were isolated and these were used for regression analysis. The resulting correlation coefficient was 0.78 which indicated a confidence level of 0.61.

Similarly, items of data relating to stainless steel were analysed, leading to a correlation coefficient of 0.667, indicating a confidence level of 0.433. This disturbing result has been traced to the fact that the primary data relating to stainless steel has inherent weaknesses due to the wide flustuations in the price of stainless steel in the open market vis-a-vis the controlled price. The reliability of the primary data relating to stainless steel prices has thus been very much vitiated because its price flustuations in the open market.

Out of the 72 items of data for stainless steel used for regression analysis referred to in the earlier paragraph, 11 items of data were found to be outside the normal limits of standard deviation and they were removed. The balance of 61 items of data were put through the regression analysis to obtain a multiple correlation coefficient of 0.87 leading to a confidence level of 0.76 which appears satisfactory.

Similarly abnormal points outside the normal limits have been removed from stainless steel data and run through the regression analysis. The multiple correlation coefficient is 0.968 leading to a confidence level of 93.7 which is a quite good result.

Presuming that in the basic equation, the purchase cost factor represented by the dimensionless group (C_1/C_f) did not have much influence, that group was deleted and the regression analysis was carried out using the other three groups representing the capacity factor, fabrication factor and the process factor. In this regression the correlation coefficient was 0.23 indicating a confidence level of 0.05. This proved beyond doubt that the purchase cost factor in the group (C_1/C_f) is highly significant.

Having established the significance of the group (C_1/C_f) for the correlation, further regression analysis were carried out using three ranges of values for this group viz., 0.0 to 1.0, 1.1 to 2.0 and 2.1 to 6.0. The results are given below:

Range of (C_1/C_f)	Multiple correlation coefficient	Confidence level
0.0 to 1.0	0.958	0.918
1.1 to 2.0	0.610	0.372
2.1 to 6.0	0.894	0.799

In the above regression analysis, the results for the ranges of values of (C_1/C_2) from 0.0 to 1.0 and 2.1 to 6.0 are seen to be quite satisfactory. The results of the range of values from 1.1 to 2.0 indicate a lower correlation coefficient and consequently lower confidence level due to the basic reason that the relevant items in the primary data relating to (C_1) and (C_2) values for this range are very few. In these causes too, the likelihood of variations in costs experienced by the basic manufacturers being wide cannot be ruled out.

Here also abnormal points outside normal limits have been removed from this range of (C_1/C_2) 1.1 to 2.0 and put through the regression analysis. The multiple correlation coefficiencies obtained is 89.6 leading to a confidence level of 80.28 which is quite satisfactory.

From the analysis carried out under different conditions as described in the earlier paragraphs, the following values for the exponents a, b, c and d and the constant k for the following five cases have been finally chosen.

Case I - Carbon Steel

Particulars	Value
Exponent of group (d/l)	-0.2398
Exponent of group (M_e/M_n)	0.0251
Exponent of group ($P/\rho t$)	0.1828
Exponent of group (C_l/C_r)	-0.3464
Constant k	0.70

The resulting equation is

$$Q = 0.70 \{ (d/l)^{-0.2398} \cdot (M_e/M_n)^{0.0251} \cdot (P/\rho t)^{0.1828} \cdot (C_l/C_r)^{-0.3464} \}$$

Case II - Stainless Steel (S.S)

Particulars	Value
Exponent of group (d/l)	0.00274
Exponent of group (M_e/M_n)	0.00769
Exponent of group ($P/\rho t$)	0.00659
Exponent of group (C_l/C_r)	0.04059
Constant k	1.1507

The resulting equation is

$$Q = 1.1507 \{ (d/l)^{-0.00274} (M_e/M_n)^{0.00769} (P/\rho t)^{0.00659} (C_l/C_r)^{0.04059} \}.$$

Case III - C_1/C_f Range below 1.0

Particulars	Value
Exponent of group (d/l)	-0.2016
Exponent of group (M_e/M_n)	0.0078
Exponent of group $(P/\rho t)$	-0.0011
Exponent of group (C_1/C_f)	-0.5784
Constant k	1.9713

The resulting equation is

$$Q = 1.9713 \{ (d/l)^{-0.2016} (M_e/M_n)^{0.0078} (P/\rho t)^{-0.0011} (C_1/C_f)^{-0.5784} \}.$$

Case IV - C_1/C_f Range between 1.1 and 2

Particulars	Value
Exponent of the group (d/l)	-0.16339
Exponent of the group (M_e/M_n)	0.36311
Exponent of the group $(P/\rho t)$	0.34692
Exponent of the group (C_1/C_f)	0.54241
Constant k	0.2321

The resulting equation is

$$Q = 0.2321 \{ (d/l)^{-0.16339} (M_e/M_n)^{0.36311} (P/\rho t)^{0.34692} (C_1/C_f)^{0.5421} \}.$$

Case V - (C_i/C_r) Range between 2 and 6

Particulars	Value
Exponent of group (d/l)	0.1009
Exponent of group (M_e/M_n)	0.0348
Exponent of group ($P/\rho t$)	0.3165
Exponent of group (C_i/C_r)	0.0578
Constant k	0.2997

The resulting equation is

$$Q = 0.2997 \left\{ (d/l)^{0.1009} \; (M_e/M_n)^{0.0348} \; (P/\rho t)^{0.0348} \; (C_i/C_r)^{0.0578} \right\}.$$

Versatility of the correlation

It was noted earlier that, at present, there is no equation available which is derived from sound mathematical principles. The confidence level of the equation developed through regression analysis has been discussed in the earlier part of this chapter.

Some of the main features of this correlation are given below:

1. Generally for most of the estimation procedures so far developed, a shape factor is introduced. As a result of the present correlation analysis, it is seen that there is no necessity to consider the shape factor due to the following reasons.

a) The effect of shape on cost is very much reflected in the weight of the material used for construction, and consequently, in the material cost.

b) The changes in machine hours and man hours have already been taken care of in the correlation by adopting an appropriate dimensionless group M_e/M_n.

2. This correlation is applicable to any material of construction except rubber lining, lead lining and F.R.P. lining. The change in material of construction is taken care of in the correlation by the material cost as well as by the parameter of density.

3. By incorporating C_1/C_2 factor as explained earlier, costs of the internals and of the boughtout items have been covered.

Further details and review of the correlation analyses are discussed in the next chapter.

CONCLUSION

The present study attempts to develop a model for cost estimation in chemical industry, taking into consideration all major parameters influencing cost. It goes a step beyond earlier attempts in that all major parameters have been taken into consideration. It is, of course, possible that certain factors have been altogether omitted or should have been included in the model. Even if this is done the validity of the present study would continue. This is because, even if any other parameter is either added the result would be that such parameters would only influence the constant k, without in any way altering the basic relationship of C, the cost number, to the major parameters considered. The present model, thus, provides the basis for a standardised approach to cost estimation of chemical plants and equipments.

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CHAPTER-VI

RESULTS AND CONCLUSIONS

The correlation between the cost number and its different parameters for estimation of the cost of pressure vessels have been derived in this study as:

1) $$Q = 0.70 \left\{ (d/l)^{-0.2398} \cdot (M_c/M_n)^{0.0251} \cdot (P/\rho t)^{0.1828} \cdot (C_l/C_f)^{-0.3464} \right\}.$$

2) $$Q = 1.1507 \left\{ (d/l)^{-0.00274} \; (M_c/M_n)^{0.00769} \; (P/\rho t)^{0.00659} \; (C_l/C_f)^{0.04059} \right\}.$$

3) $$Q = 1.9713 \{ (d/l)^{-0.2016} (M_e/M_n)^{0.0078} (P/\rho t)^{-0.0011} (C_l/C_r)^{-0.5784} \}.$$

4) $$Q = 0.2321 \{ (d/l)^{-0.16339} (M_e/M_n)^{0.36311} (P/\rho t)^{0.34692} (C_l/C_r)^{0.5421} \}.$$

5) $$Q = 0.2997 \{ (d/l)^{0.1009} (M_e/M_n)^{0.0348} (P/\rho t)^{0.3165} (C_l/C_r)^{0.0578} \}.$$

where Q = Cost Number

d = diameter of the vessel in mm.

l = length of the vessel in mm.

M_e = Machine Hours employed for fabrication of the vessel

M_n = Man hours employed for fabrication of the vessel

P = Working pressure of the vessel in Kg/cm^2

ρ = Density of material of construction in Kg/cm^3

t = Thickness of the vessel in mm.

C_i = Cost of internals in rupees

C_f = Cost of bought out items in rupees.

The Cost Number Q is expressed as the ratio of estimated cost of equipment to the actual cost of the material

$$\text{i.e. } Q = \frac{\text{Estimated cost of equipment in rupees}}{\text{Total cost of material in rupees}}$$

Hence, using the cost number as derived from the above equation, if the total quantity of material and its unit price are known, the cost of the equipment can be estimated. The above relationships can be used for all types of pressure vessels at any point of time.

Review of the Results

An evaluation of the study and its results and the relevance of the various influencing factors on the equipment cost estimate would show that the major contributions of the study can be described as follows.

a) Probable Variation in cost estimates at different values of influencing parameters

The ranges of values of the various influencing parameters in the primary data have been referred to in Chapter V. An attempt has been made to determine the probable variation in the cost estimates at the minima and maxima of these parameters. It has already been stated that the range of values of each parameter is sufficiently wide. But, despite these wide variations in the range, variations in cost estimates calculated by the developed equation and the actual estimate collected from vendors are within reasonable limits as can be seen from the following table:

Particulars	Minimum	Maximum	Max./Min. i.e. No. of times	Variation of cost estimates ± at Minimum percent	Variation of cost estimates ± at Maximum percent
Diameter m.m.	250	9988	40	-8	+16
Length m.m.	600	17400	29	+1.06	+2.89
Pressure, kg/cm^2	1	135	135	+2.1	+7.96
Thickness m.m.	5	37	7	-0.8	+7.87
(M_c/M_n)	0.0346	2.70	..	-15.23	-20.17
(C_1/C_r)	0.0359	9.6094	+6.85	+ 6.85	+20.98
$(P/_1ot)$	160	4678	+3.45	+3.45	+7.67
Cost Number C	1.8101	19.92	..	-8.89	+15.49

It is also observed that the variation in the estimated cost calculated by the developed equation against the actual estimated cost obtained from different vendors is quite encouraging. The variations for the five different cases are given in the following table:

Percentage of Variation	Percentage of Number of Data falling within				
	Case No. 1 (Carbon Steel	Case No. 2(Stainless Steel	Case No. 3(C_1/C_f range below 1.0	Case No. 4 (C_1/C_f between 1.0 and 2.0	Case No. 5 (C_1/C_f between 2.0 and 6.0
± 5	15	100 (± 4)	11	13	29
± 10	33	Nil	42	50	50
± 15	42	Nil	58	63	64
± 20	57	Nil	74	80	79
± 25	70	Nil	80	Nil	100

Similarly, the validity of the correlation has been examined with reference to the different aspects of practical application. It has been concluded that the correlation holds good irrespective of changes in the organisational or other extraneous factors affecting cost estimation.

The correlation also holds good irrespective of changes in the value of different variables, such as

a) final cost to the vendor;

b) classes of vessels (e.g., A, B or C);

c) additional costs of inspection and radiography;

d) variation of thickness of vessel wall and dished ends;

e) material of construction;

f) occasional rejection and rework due to faulty workmanship; and

g) inflation in the economy.

This can be substantiated as follows:

Generally the estimates made by different vendors vary to a considerable extent. Cost can be regarded as the actual amount of money spent to produce the item and price as the amount that is paid to buy the item in the market. The final cost may differ to a certain extent from vendor to vendor. For the present study, the primary data has been collected from vendors of the same status, fabricating capacity and overheads in order to avoid abnormal divergence in the data.

Another question which can be easily raised is whether this equation is suitable for all pressure vessels irrespective of class differences such as Class A, Class B and Class C. A special feature of the model is that it is applicable to all classes of pressure vessels, Class A, B or C. This is because the material and its cost change according to the class of vessel. The relevance of this change is already accounted for in the model. The class of vessel also has a bearing in the costs of inspection and radiographic tests which have also been taken care of by the factor C_r. The variation due to the class of vessel has thus been accommodated in the equation.

In pressure vessels, the shell and dished ends thicknesses may vary in certain cases. In more than 90 per cent of the primary data this phenomenon does not appear. However, in order to build in the variation in the correlation, the average thickness has been taken.

The correlation does hold good for any material of construction as the density of material ρ has already been taken as an important parameter governing the cost number in the equation developed.

It is worthwhile examining as to how inflation in the economy affects the correlation. As a matter of fact, due to inflation, the factors such as d, l, ρ, P, t, M_c, M_n are not at all affected as they are either design factors or factors beyond the influence of inflation. M_c and M_n are expressed in hours and not in monetary terms. Inflation may result in the escalation of material costs. Similarly, the costs of bought out items and internal fittings may also increase.

For the cost engineer, the equation may not appear to have solved all his problems. It may be pointed that adequate and fairly reliable data of machine hours and manhours of fabrication are not always available. But, it may be noted that almost all the established fabricators have well equipped shops with facilities for recording data relating to machine time and skilled manhours spent on fabrication. It may, therefore, be assumed that there may not be any insuperable problems to obtain data relating to M_c or M_n.

The important features of the multiple linear regression analysis which led to the development of the equations for each case can be seen from the computer-Printouts appended.(1)

A question may be asked as to how the estimated cost is affected when a pressure vessel is rejected due to bad welding or poor workmanship. This can happen but occurs very rarely. No equation can take care of such odd occurrences and no correction factor can be envisaged for such cases.

Since inflation may affect the cost of internals (C_1) and the cost of bought out items (C_2) more or less equally or within definite limits, the ratio of (C_1/C_2) in the correlation may not get affected appreciably. As for the effect of inflation on material cost, it is to be stated that the estimated cost at any time is the product of the cost number derived in the equation and the prevailing material cost at that point of time. Hence the estimated cost is factual and it takes into account the effect of inflation on the material cost at any time.

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(1) Appendix III.

CONCLUSION

A standardised procedure for the estimation of cost of pressure vessels based on sound engineering and mathematical principles has been developed. The following relationships can be used for cost estimation of pressure vessels:

i) $$Q = 0.70 \{(d/l)^{-0.2398} (M_e/M_n)^{0.0251} (P/\rho t)^{0.1828} (C_l/C_f)^{-0.3464}\}.$$

ii) $$Q = 1.1507 \{(d/l)^{-0.00274} (M_e/M_n)^{0.00769} (P/\rho t)^{0.0089} (C_l/C_f)^{0.04059}\}.$$

iii) $$Q = 1.9713 \{(d/l)^{-0.2016} (M_e/M_n)^{0.0078} (P/\rho t)^{-0.0011} (C_l/C_f)^{-0.5784}\}.$$

iv) $$Q = 0.2321 \{(d/l)^{-0.16339} (M_e/M_n)^{0.36311} (P/\rho t)^{0.34692} (C_l/C_f)^{0.5421}\}.$$

v) $Q = 0.2997 \{(d/l)^{0.1009} (M_e/M_n)^{0.0348}$

$(P/\rho t)^{0.3165} (C_l/C_r)^{0.0978}\}.$

and (ii) $Q = \dfrac{\text{Estimated cost of equipment in rupees}}{\text{Total cost of material in rupees}}$

The above relationships have been developed for cost estimation of pressure vessels. It may not be difficult to develop similar relationships for other major chemical equipments such as heat exchangers, distallation columns, vertical tanks and others. It is hoped that the approach developed in the present study may lead to the development of equations defining the relationships for cost estimation of other equipments.

Much more work is yet to be done in the field of cost estimation of chemical equipments. The main problems encountered in this area are lack of primary data and increasing and disproportionate trends in costs. Most of the fabricators and vendors are reluctant to make available their data for any study or research, even when the requisite data is available with them. It is hoped that some effort is made by the industry to collect this data so that further studies can be conducted in this important area.

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APPENDIX-I

GRAPHICAL SOLUTION OF EXPONENTS OF DIMENSIONLESS GROUPS

1. (d/l) - Carbon Steel
2. (M_e/M_n) - Carbon Steel
3. (C_1/C_2) - Carbon Steel
4. (P/ρt) - Carbon Steel
5. (d/l) - Stainless Steel
6. (M_e/M_n) - Stainless Steel
7. (C_1/C_2) - Stainless Steel
8. (P/ρt) - Stainless Steel

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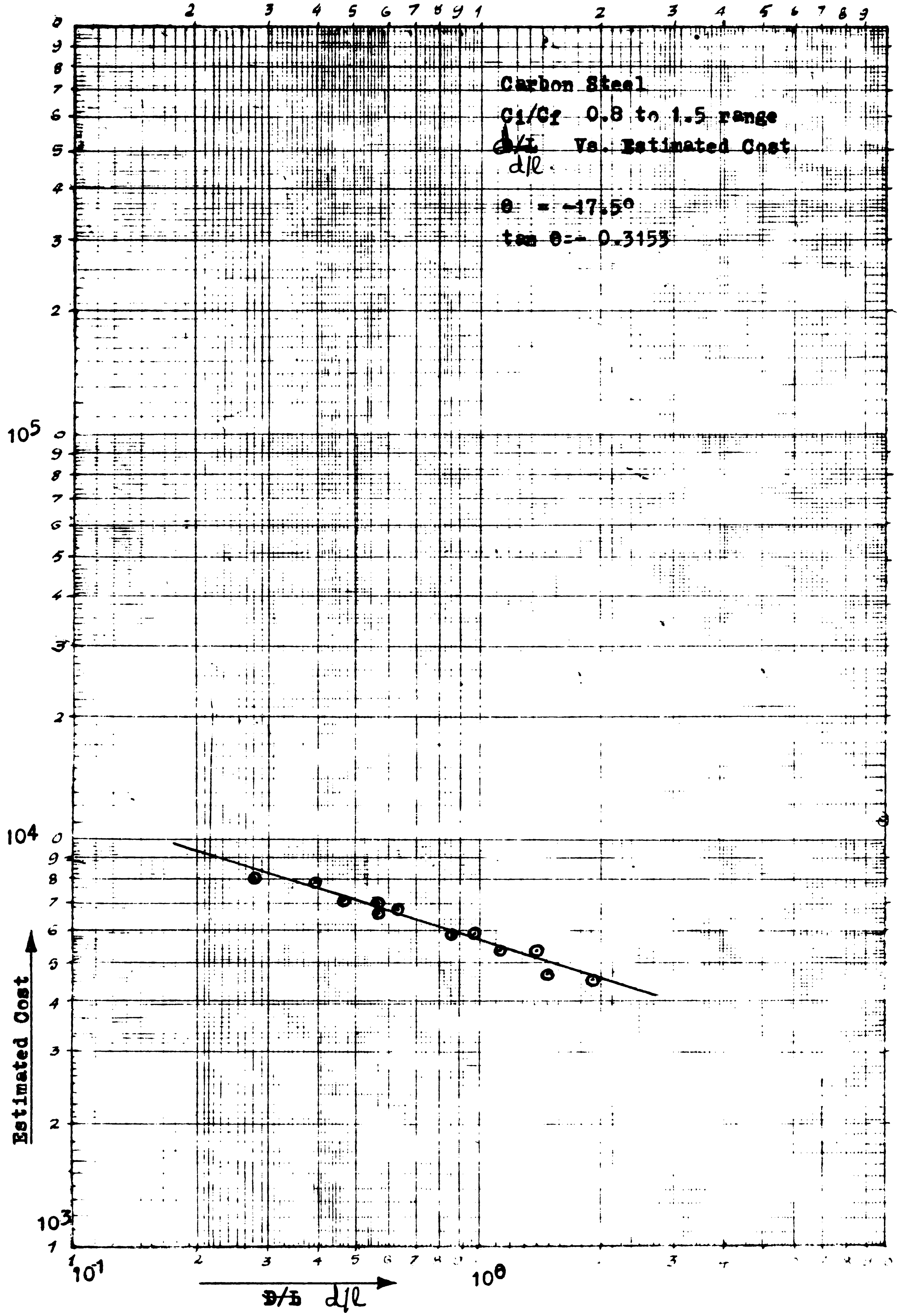
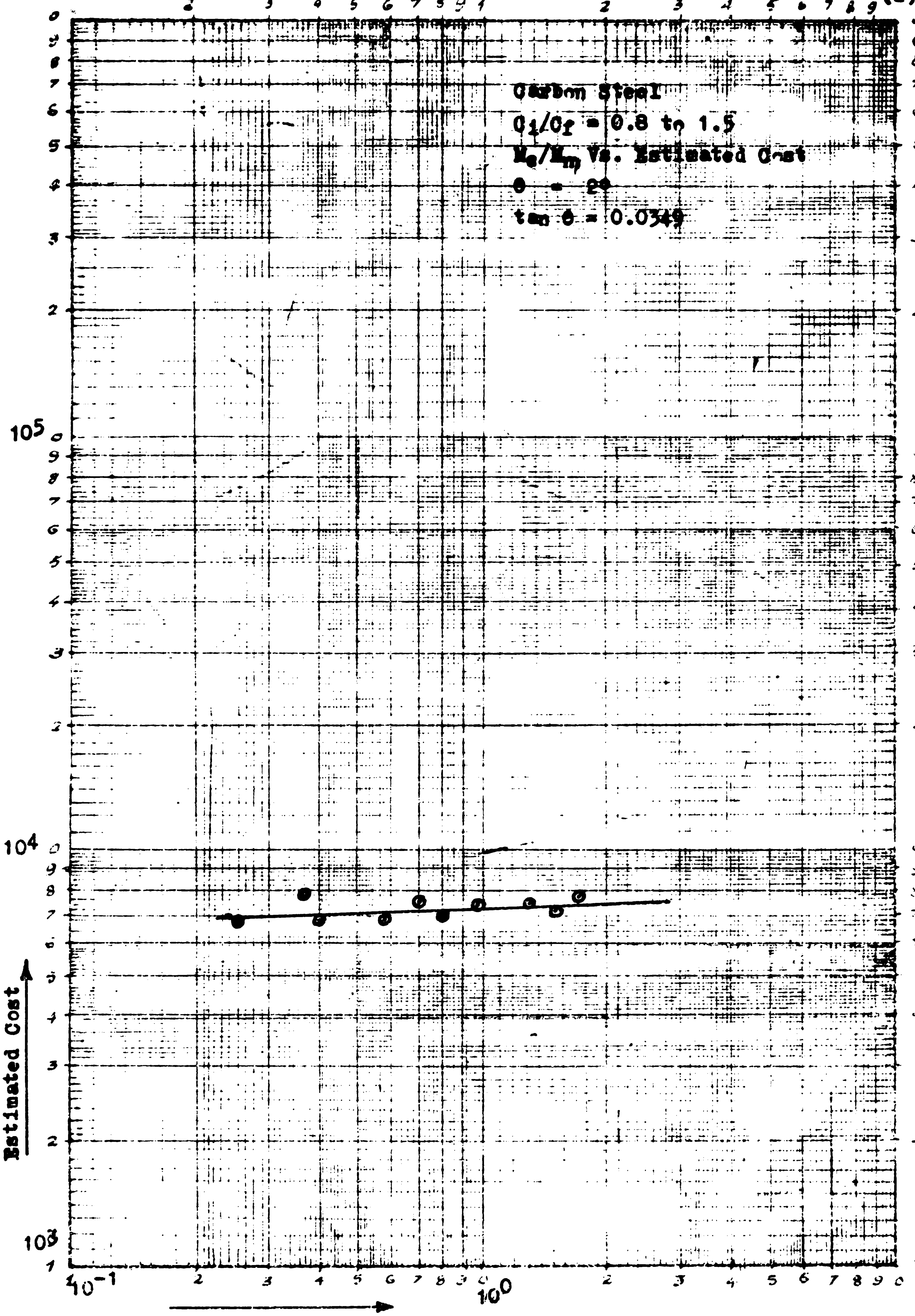
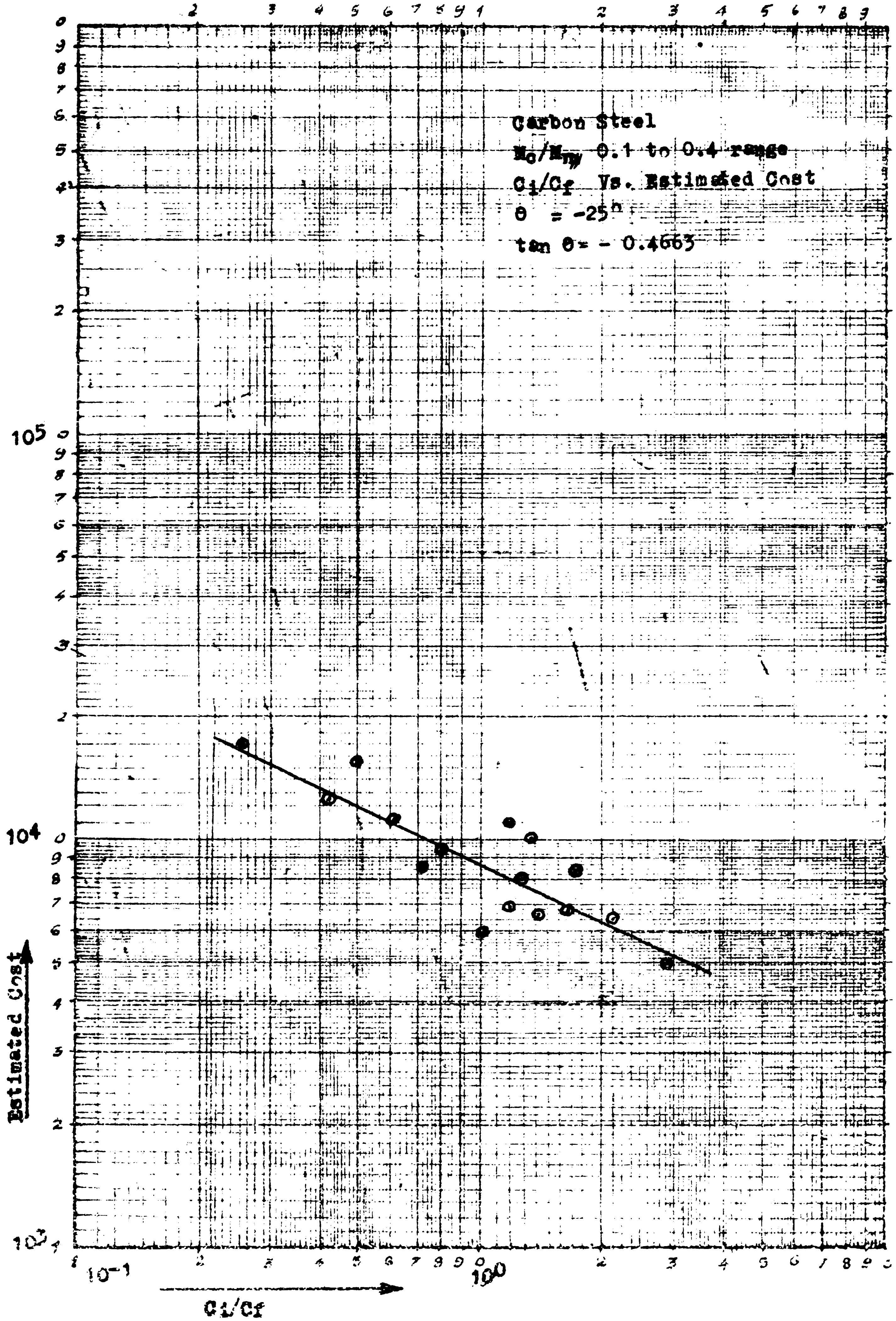
(1)

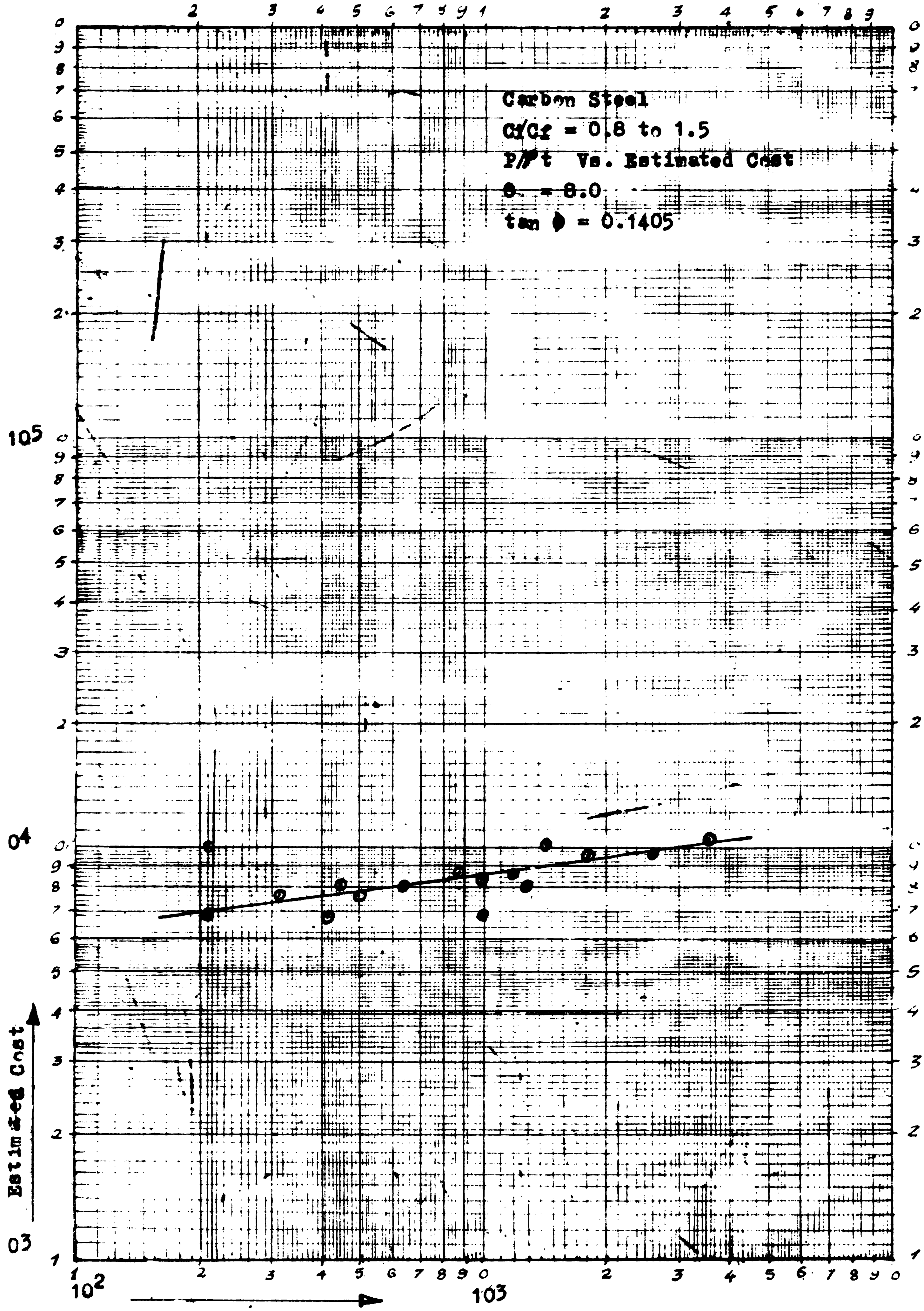

Carbon Steel
Ci/Cf 0.8 to 1.5 range
D/L Vs. Estimated Cost
d/l
θ = -17.5°
tan θ = - 0.3153
Estimated Cost
D/L d/l
10^5
10^4
10^3
10^{-1}
10^0

(2)

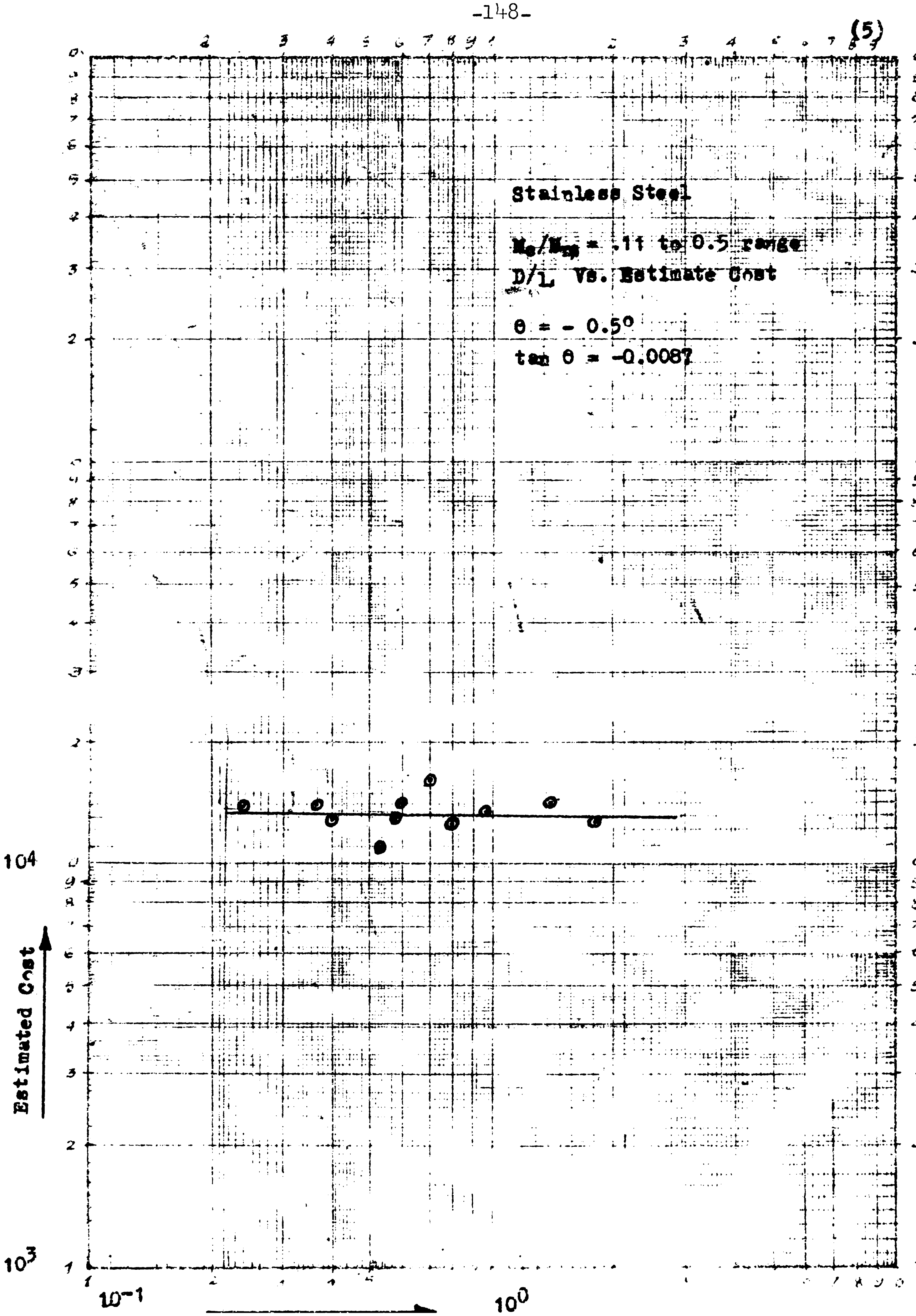

Carbon Steel
Ci/Cf = 0.8 to 1.5
Me/Mm Vs. Estimated Cost
θ = 2°
tan θ = 0.0349
Estimated Cost
10^5
10^4
10^3
10^{-1}
10^0



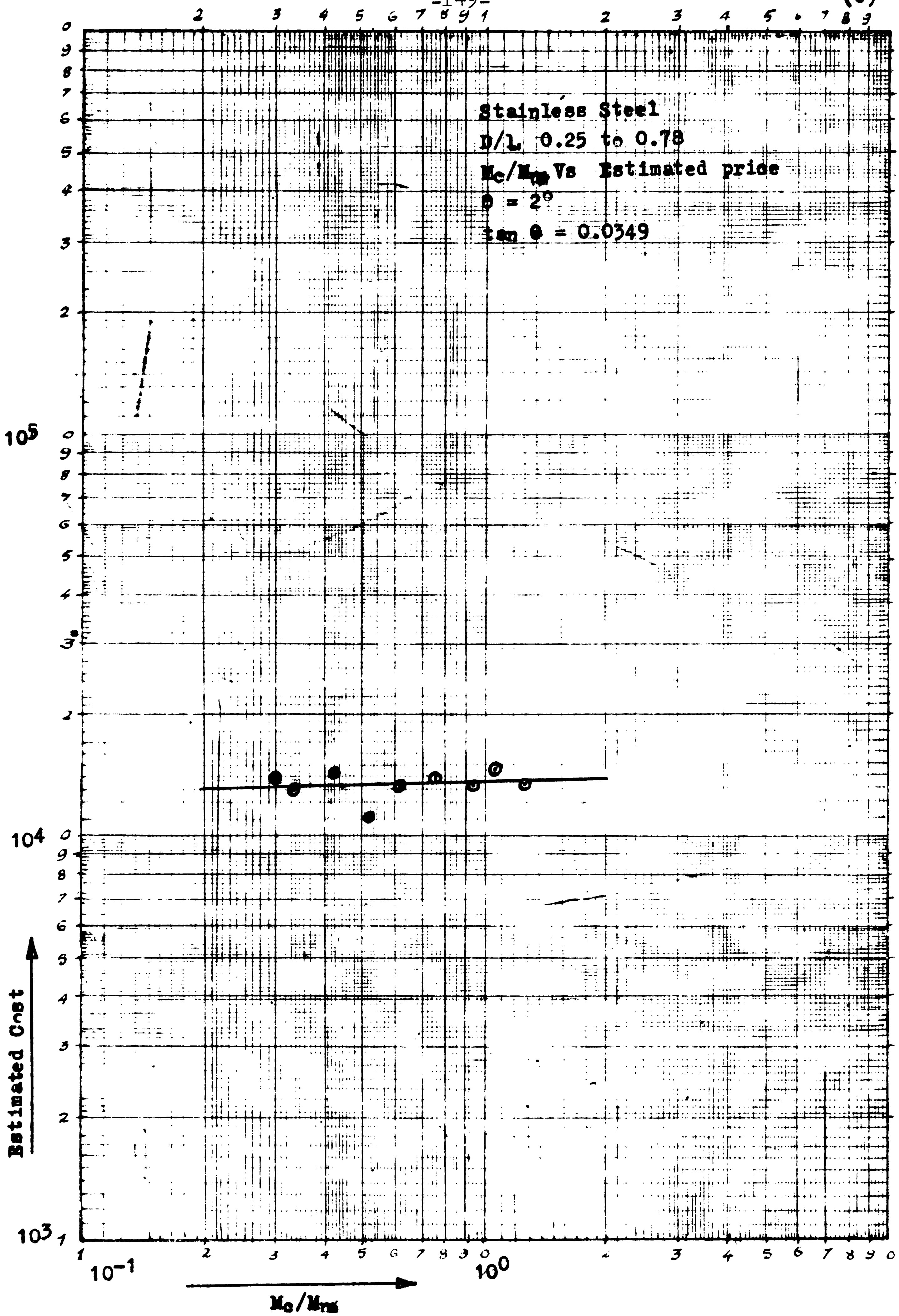
Carbon Steel
M_c/M_m 0.1 to 0.4 range
C_i/C_f Vs. Estimated Cost
θ = -25°
tan θ = - 0.4663
Estimated Cost
C_i/C_f
10^5
10^4
10^3
10^{-1}
10^0

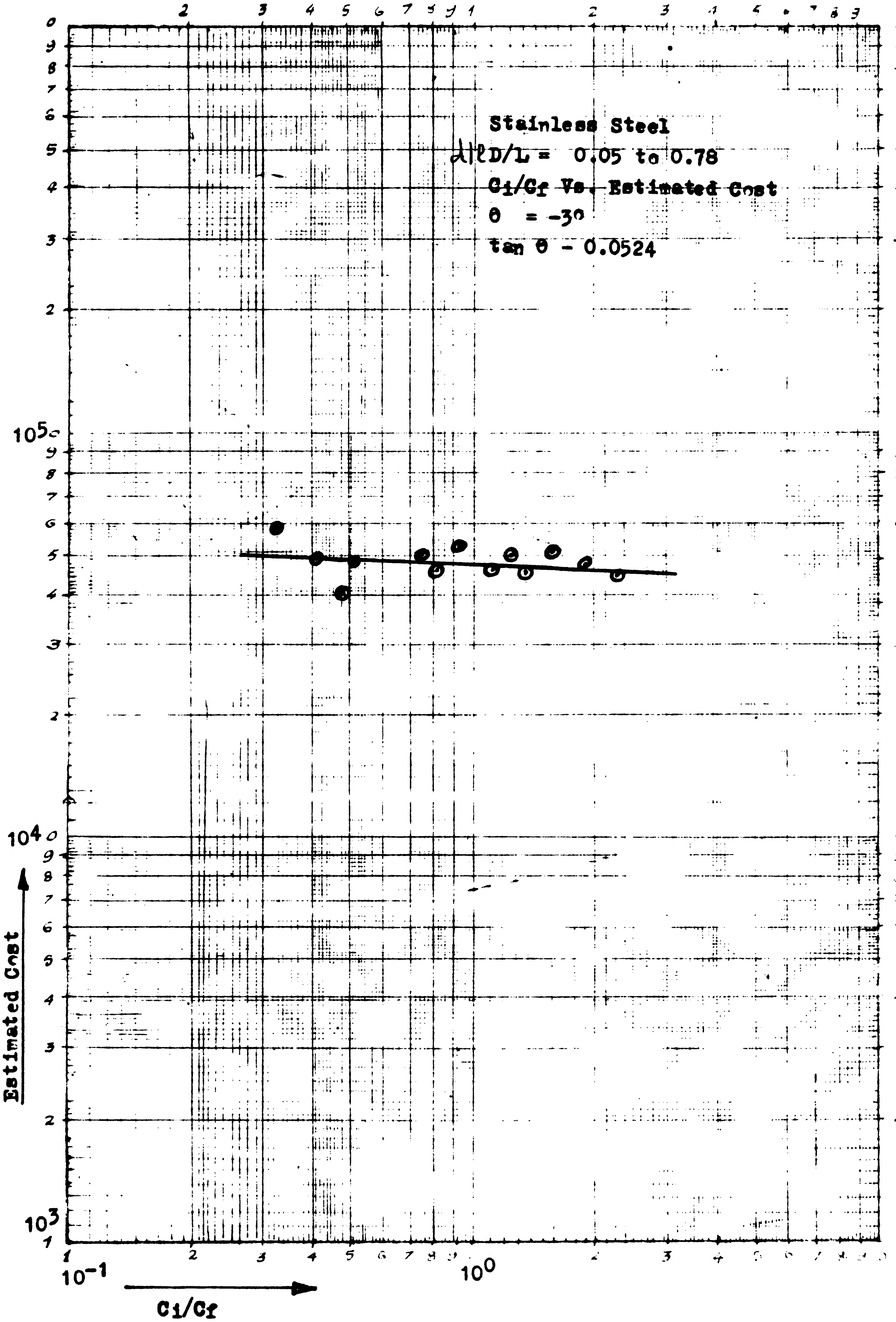


Carbon Steel
Ci/Cf = 0.8 to 1.5
P/Pt Vs. Estimated Cost
θ = 8.0
tan ϕ = 0.1405
Estimated Cost
10^5
10^4
10^3
10^2
10^3

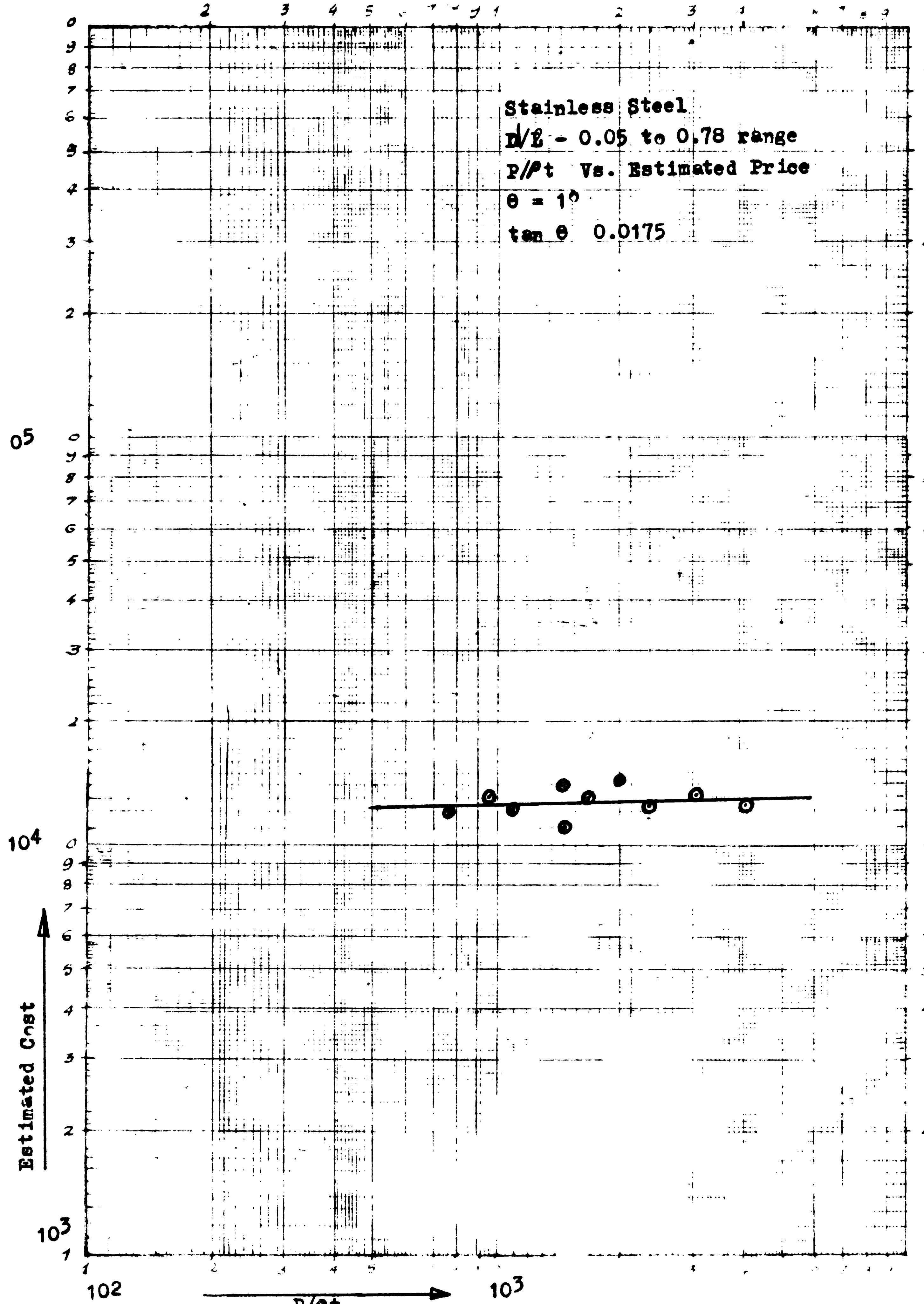

(5)
Stainless Steel
Ms/Mm = .11 to 0.5 range
D/L Vs. Estimate Cost
θ = - 0.5°
tan θ = -0.0087
Estimated Cost
10⁴
10³
10⁻¹
10⁰

(6)


Stainless Steel
D/L 0.25 to 0.78
Mc/Mm Vs Estimated price
θ = 2°
tan θ = 0.0349
Estimated Cost
Mc/Mm
10^5
10^4
10^3
10^{-1}
10^0



Stainless Steel
D/L = 0.05 to 0.78
Ci/Cf Vs. Estimated Cost
θ = -3°
tan θ - 0.0524
Estimated Cost
Ci/Cf
10^5
10^4
10^3
10^-1
10^0


Stainless Steel
D/L - 0.05 to 0.78 range
P/ρt Vs. Estimated Price
θ = 1°
tan θ 0.0175
Estimated Cost
10^5
10^4
10^3
10^2
10^3
P/ρt

APPENDIX-II

RANDOM SELECTED PRIMARY DATA

LIST OF TABLES

XI. - Value of each Dimensionless Group with respective Exponents for the range C_l/C_f between 1.0 and 2.0.

XII - Calculated Cost Number, Material Cost, Estimated Cost by Correlation developed, Actual Estimated Cost and deviation as per Correlation for the range C_l/C_f between 1.0. and 2.0.

XIII - Value of each Dimensionless Group for the range C_l/C_f between 2.0 and 6.0.

XIV - Value of each Dimensionless Group with respective Exponents for the range C_l/C_f between 2.0 and 6.0.

XV - Calculated Cost Number, Material Cost, Estimated Cost by Correlation developed, Actual Estimated Cost and deviation as per Correlation for the range C_l/C_f between 2.0 and 6.0.

TABLE-I

CARBON STEEL ITEMS

VALUE OF EACH DIMENSIONLESS GROUP

Sl.No.	(d/l)	(M_e/M_n)	(C_1/C_2)	$(P/\rho t)$
1.	0.5773	0.2597	1.8564	427.6
2.	0.3333	0.1389	3.2226	427
3.	0.7833	0.4839	1.1081	641
4.	0.5000	0.2083	1.9397	427
5.	1.0444	0.0769	0.5931	427
6.	1.0404	0.1558	3.0729	961.5
7.	0.8276	0.20	1.0369	427
8.	0.4348	2.0588	1.9880	1389
9.	0.5161	1.7143	3.6429	513
10.	0.3333	0.40	0.42	1282
11.	0.4186	0.1667	0.4935	1282
12.	0.0509	0.40	0.1628	961.5
13.	0.2532	0.3750	0.5017	641
14.	0.1250	0.3852	0.0359	854.7
15.	1.0728	0.450	1.2334	961.5
16.	0.6400	0.40	1.0909	1025.6
17.	0.7727	0.50	0.9066	1282
18.	0.8261	0.0346	1.7376	1025.6
19.	0.7843	0.44	0.7164	1282
20.	0.3636	0.3667	1.9187	961.5
21.	1.0000	0.625	1.0385	1282
22.	1.0000	0.4706	2.0745	1282

Sl.No.	(d/l)	(M_e/M_s)	(C_i/C_f)	(P/pt)
6				
23.	0.48	0.50	0.5556	1282
24.	0.5454	0.6667	0.405	1282
25.	0.2800	0.2222	0.29	1773
26.	0.25	0.1184	3.7261	1025.6
27.	0.9504	0.375	1.1230	1282
28.	0.1404	0.2340	0.2676	1282
29.	1.0012	0.4739	0.6421	1282
30.	1.0000	0.4444	0.6944	1282
31.	0.575	0.3236	1.9081	2484
32.	0.7333	0.2143	1.4167	1229
33.	0.3469	0.2222	3.20	910
34.	0.7272	0.2660	0.0908	2564
35.	0.4210	0.2800	0.8362	2484
36.	0.1687	0.3853	1.8605	2564
37.	0.31818	0.3235	2.2109	4678
38.	0.2611	0.3251	2.4272	2003
39.	0.2800	0.2727	1.3274	641
40.	0.2414	0.2553	2.1843	1931
41.	0.4757	0.4060	9.4094	1819
42.	0.5833	0.4903	0.5167	1683
43.	0.4782	0.5257	0.8686	1779
44.	0.3826	0.4977	1.1234	1819
45.	0.6385	0.5079	1.0612	1931
46.	0.0300	0.3377	2.3793	213.7
47.	0.0800	0.8000	1.0417	213.7
48.	0.3600	0.4889	2.4337	160.3
49.	0.5600	0.8000	1.6670	213.7
50.	0.63 64	0.6700	1.5000	213.7

Sl.No.	(d/l)	(N_e/N_n)	(C_1/C_2)	(P/pt)
51.	0.6667	1.9189	0.7609	213.7
52.	0.7000	0.4133	1.4063	213.7
53.	0.7778	0.99	0.5048	213.7
54.	0.80	0.32	1.6670	213.7
55.	0.8333	0.5982	1.9500	160.3
56.	0.8462	0.614	2.8478	160.3
57.	0.8462	0.6857	2.8472	213.7
58.	0.8667	1.0707	1.2647	213.7
59.	1.0000	0.47	2.1430	213.7
60.	1.0625	2.70	0.3086	213.7
61.	0.8261	0.3636	0.9956	1282

TABLE-II

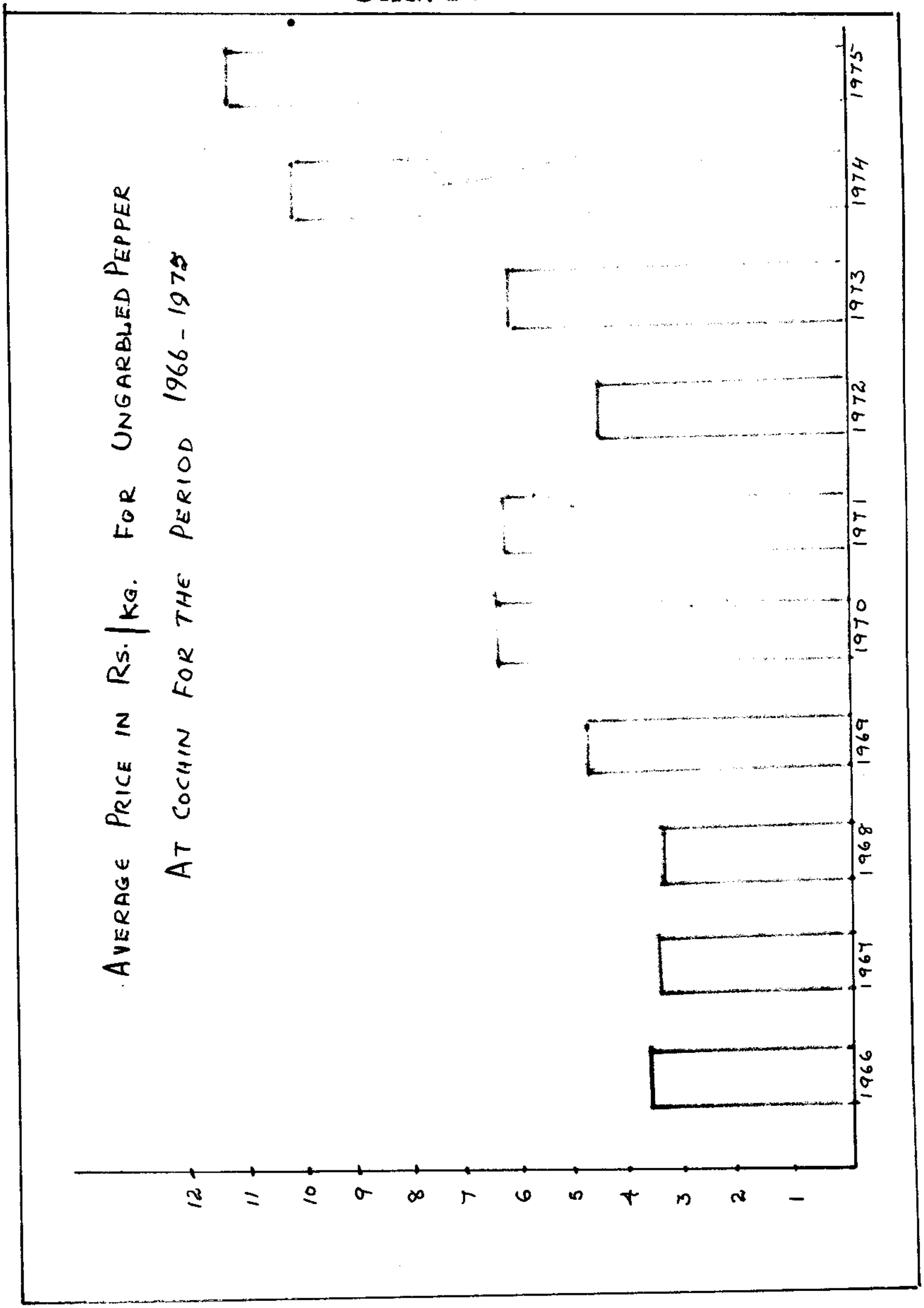
VALUE OF EACH DIMENSIONLESS GROUP WITH ITS RESPECTIVE EXPONENTS

Sl. No.	-0.2398 (d/l)	0.0251 (M_e/M_m)	-0.3464 (C_l/C_f)	0.1828 $(P/\rho d)$
1.	1.1408	0.9667	0.8071	3.0258
2.	1.3014	0.9517	0.6667	3.0258
3.	1.0603	0.9819	0.9651	3.2591
4.	1.1808	0.9614	0.7949	3.0258
5.	0.9896	0.9376	1.1984	3.0258
6.	0.9905	0.9544	0.6778	3.5098
7.	1.0464	0.9604	0.9875	3.0258
8.	1.2211	1.0183	0.7882	3.7539
9.	1.1719	1.0136	0.6390	3.1290
10.	1.3014	0.9773	1.3505	3.6993
11.	1.2322	0.9560	1.2772	3.6993
12.	3.0944	0.9773	1.8754	3.5098
13.	1.3901	0.9797	1.2699	3.2591
14.	1.6465	0.9763	3.1660	3.4351
15.	0.9833	0.9802	0.9299	3.5098
16.	1.1123	0.9773	0.9703	3.5515
17.	1.0638	0.9828	1.0345	3.6993
18.	1.0469	0.9190	0.8258	3.5515
19.	1.0599	0.9796	1.1225	3.6993
20.	1.2746	0.9751	0.7979	3.5098
21.	1.0000	0.9883	0.9870	3.6993
22.	1.0000	0.9813	0.7766	3.6993
23.	1.1924	0.9828	1.2258	3.6993

Sl. No.	-0.2398 (d/l)	0.0251 (N_o/N_m)	-0.3464 (C_1/C_2)	0.1828 (P/pB)
24.	1.1565	0.9899	1.3676	3.6993
25.	1.3570	0.9629	1.5354	3.9252
26.	1.3944	0.9479	0.6340	3.5514
27.	1.0123	0.9757	0.9606	3.6993
28.	1.6013	0.9642	1.5788	3.6993
29.	0.9997	0.9814	1.1658	3.6993
30.	1.0000	0.9798	1.1346	3.6993
31.	1.1419	0.9721	0.7995	4.1748
32.	1.0772	0.9621	0.8863	3.6709
33.	1.2890	0.9629	0.6684	3.4747
34.	1.0794	0.9673	2.2957	4.1990
35.	1.2305	0.9686	1.0639	4.1748
36.	1.5322	0.9763	0.8065	4.1990
37.	1.3160	0.9722	0.7597	4.6869
38.	1.3799	0.9722	0.7355	4.0137
39.	1.3569	0.9679	0.9066	3.2591
40.	1.4061	0.9663	0.7629	3.9869
41.	1.1950	0.9776	0.4567	3.9436
42.	1.1380	0.9823	1.2570	3.8880
43.	1.1935	0.9840	1.0500	3.9276
44.	1.2591	0.9827	0.9605	3.9436
45.	1.1136	0.9831	0.9796	3.9869
46.	2.3184	0.9729	0.8946	2.6662
47.	1.8325	0.9944	0.9859	2.6662
48.	1.2776	0.9822	0.7348	2.5297
49.	1.1492	0.9944	0.8378	2.6662
50.	1.1145	0.9899	0.8690	2.6662

Sl. No.	-0.2398 (A/L)	0.0251 (M_e/M_w)	-0.3464 (C_1/C_2)	0.2828 (P/pA)
51.	1.1021	1.0165	1.0993	2.6662
52.	1.089	0.9781	0.8887	2.6662
53.	1.0621	0.9975	1.2672	2.6662
54.	1.0550	0.9718	0.8378	2.6662
55.	1.0447	0.9872	0.7935	2.5297
56.	1.0409	0.9878	0.6959	2.5297
57.	1.0409	0.9906	0.6959	2.6662
58.	1.0349	1.0017	0.9219	2.6662
59.	1.0000	0.9812	0.7679	2.6662
60.	0.9856	1.0252	1.503	2.6662
61.	1.0469	0.9749	1.0015	3.6993

Chart No.IV



AVERAGE PRICE IN Rs./KG. FOR UNGARBLED PEPPER
AT COCHIN FOR THE PERIOD 1966 - 1975
1966
1967
1968
1969
1970
1971
1972
1973
1974
1975
1
2
3
4
5
6
7
8
9
10
11
12

TABLE-III

CALCULATED COST NUMBER, MATERIAL COST, ESTIMATED COST BY THE CORRELATION DEVELOPED, ACTUAL ESTIMATED COST AND DEVIATION AS PER CORRELATION FOR CARBON STEEL

$$Q = k\,(d/l)^{a}\,(M_e/M_m)^{b}\,(C_l/C_r)^{c}\,(P/pt)^{d}$$

$$Q = 0.70\,(d/l)^{-0.2398}\,(M_e/M_m)^{0.0251}\,(C_l/C_r)^{-0.3464}\,(P/pt)^{0.1828}$$

Sl. No.	Cost No.	Material Cost	Calculated Estimated Cost	Actual Estimated Cost	Deviation in percent
1	2	3	4	5	6
1.	2.6932	3,125	5,891	6,835	-13.81
2.	2.4985	6,875	12,024	14,440	-16.73
3.	3.2747	18,200	41,720	50,034	-16.62
4.	2.7304	1,875	3,584	2,840	+26.19
5.	3.3645	18,950	44,630	44,770	- 0.313
6.	2.2489	73,750	116,100	110,400	+ 5.16
7.	3.0028	1,500	3,152	2,560	+23.12
8.	3.6791	1,375	3,552	3,752	- 5.33
9.	2.3750	3,400	5,652	5,416	+ 4.36
10.	6.3541	600	2,668	2,640	+ 1.06
11.	5.5657	1,135	4,422	4,800	- 7.87
12.	19.9100	1,750	24,389	9,600	+154.05
13.	5.613	5,000	19,647	15,680	+25.29
14.	17.48	28,015	342,791	264,000	+29.85
15.	3.1457	5,900	12,992	11,200	+16.0

1	2	3	4	5	6
16.	3.7483	3,200	8,396	6,880	+22.03
17.	4.0011	2,387.5	6,687	5,200	+28.60
18.	2.8217	6,225	12,098	14,272	-15.23
19.	4.3114	3,892.5	11,748	8,526	+37.79
20.	3.4806	9,050	22,049	16,800	+31.24
21.	3.6085	450	1,137	1,536	-25.97
22.	2.8192	1,625	3,206	3,984	-19.52
23.	5.3141	500	1,850	1,680	+10.11
24.	5.7913	405	1,642	1,600	+ 2.62
25.	7.8749	14,375	79,241	96,000	-17.45
26.	2.9760	48,625	101,296	191,420	-47.08
27.	3.5098	3,575	8,783	7,960	+10.33
28.	9.0175	4,135	26,101	17,200	+51.75
29.	4.2312	15,925	47,167	28,000	+68.45
30.	4.1124	18,750	53,975	32,960	+63.76
31.	3.705	9,000	23,342	18,400	+26.86
32.	3.314	4,250	9,859	9,600	+ 2.69
33.	2.8826	8,000	16,143	16,000	+ 0.89
34.	10.0648	1,250	8,807	8,000	+10.09
35.	5.2937	4,000	14,822	9,600	+54.39
36.	5.066	80,000	283,696	224,000	+26.65
37.	4.5555	162,500	518,188	480,000	+ 7.96
38.	3.9603	112,500	311,874	360,000	-13.37
39.	3.8809	3,750	10,186	8,000	+27.32
40.	4.1327	216,250	625,587	608,000	+ 2.89
41.	2.104	153,750	226,443	212,000	+ 6.81
42.	5.4632	4,650	17,783	16,000	+11.14
43.	4.8432	12,450	42,209	36,000	+17.25

TABLE-IV

STAINLESS STEEL ITEMS

VALUE OF EACH DIMENSIONLESS GROUP

Sl.No.	(d/l)	(M_e/M_n)	(C_l/C_r)	(P/pt)
1.	0.5856	0.625	0.1003	763.36
2.	0.625	0.1667	0.4893	2035.6
3.	0.50	0.1429	0.3356	2261.8
4.	0.375	0.2963	0.4162	1272.26
5.	0.3333	0.4074	0.2611	1526.7
6.	0.375	0.1563	0.1135	1590.3
7.	0.333	0.4118	0.5134	1696.35
8.	0.40	0.25	0.1796	1526.7
9.	0.30	0.3636	2.8626	1272.3
10.	0.25	0.4444	0.0942	2035.6
11.	0.35	0.4167	0.2045	2035.6
12.	0.40	0.3333	0.29575	1696.35
13.	0.5454	0.5333	0.1871	1526.0
14.	0.0534	0.04	0.1205	1908.4
15.	0.1275	0.11	0.09375	1908.4
16.	0.7784	0.35	0.1256	1272.30
17.	0.60	0.2963	0.1390	1526.7
18.	0.4130	0.2222	0.5033	1526.7

TABLE-I

STAINLESS STEEL ITEMS

VALUE OF EACH DIMENSIONLESS GROUP WITH RESPECTIVE EXPONENTS

Sl. No.	-0.00274 (d/l)	0.00769 (M_e/M_n)	-0.04059 (C_1/C_r)	0.00659 (P/pt)
1.	1.0015	0.9964	1.0978	1.0447
2.	1.0013	0.9863	1.0294	1.0515
3.	1.0019	0.9851	1.0453	1.0522
4.	1.0027	0.9907	1.0362	1.048
5.	1.0030	0.9931	1.0560	1.0495
6.	1.0027	0.9858	1.0923	1.0498
7.	1.0030	0.9932	1.0274	1.0502
8.	1.0025	0.9894	1.0722	1.0495
9.	1.0033	0.9922	0.9582	1.048
10.	1.0038	0.9938	1.1006	1.0515
11.	1.0029	0.9933	1.0665	1.0515
12.	1.0025	0.9916	1.0507	1.0502
13.	1.0017	0.9952	1.0704	1.0495
14.	1.0081	0.9756	1.0897	1.0510
15.	1.0097	0.9832	1.1008	1.0510
16.	1.0007	0.9920	1.0879	1.048
17.	1.0014	0.9907	1.08340	1.0495
18.	1.0024	0.9885	1.0283	1.0495

TABLE-VI
S.S.ITEMS

CALCULATED COST NUMBER, MATERIAL COST, ESTIMATED COST BY THE CORRELATION DEVELOPED, ACTUAL ESTIMATED COST AND DEVIATION AS PER CORRELATION.

$$C = 1.1507 \ (d/l)^{-0.00274} \ (M_c/M_n)^{0.00769} \ (C_l/C_r)^{-0.04059} \ (P/pt)^{0.00659}$$

Sl. No.	Cost No.	Material Cost	Calculated Estimated Price	Actual Estimated Price	Deviation
1.	1.1444	9,913	13,054	12,963	+0.702
2.	1.0690	33,079	40,690	40,712	-0.053
3.	1.0855	47,413	59,223	58,354	+1.49
4.	1.0787	40,583	50,374	49,948	+0.853
5.	1.1039	6,788	8,623	8,877	-2.87
6.	1.1335	29,405	38,353	38,452	-0.256
7.	1.0749	39,153	48,428	48,188	+0.498
8.	1.1161	21,407	27,493	27,994	-1.79
9.	0.9996	69,465	79,901	80,152	-0.31
10.	1.1545	111,105	14,753	14,521	+1.60
11.	1.1171	16,128	20,732	21,090	-1.70
12.	1.0969	9,996	12,617	13,072	-3.48
13.	1.1199	8,515	10,973	11,135	-1.45
14.	1.1264	26,000	33,700	34,000	-0.88
15.	1.1440	5,200	6,845	6,800	+0.67
16.	1.1318	17,550	22,856	22,950	-0.41
17.	1.1280	10,725	13,921	14,025	-0.74
18.	1.0694	62,400	76,787	76,800	-0.017

TABLE-VII

C_1/C_2 BELOW 1.0

VALUE OF EACH DIMENSIONLESS GROUP

Sl.No.	(a/l)	(N_e/N_n)	(C_1/C_2)	(P/pt)
1.	0.3333	0.40	0.42	128.2
2.	0.4186	0.1667	0.4935	128.2
3.	0.0509	0.40	0.1628	961.5
4.	0.2532	0.3750	0.5017	641
5.	0.1250	0.3852	0.0358	854.7
6.	0.7727	0.50	0.9066	1282
7.	0.7843	0.44	0.7164	1282
8.	0.48	0.50	0.5556	1282
9.	0.5484	0.6667	0.405	1282
10.	0.2800	0.2222	0.2900	1773
11.	0.1404	0.2340	0.2676	1282
12.	0.7272	0.2660	0.0908	2564
13.	0.4210	0.28	0.8362	2484
14.	0.5833	0.4903	0.5167	1683
15.	0.4782	0.5257	0.8686	1779
16.	0.6667	1.9189	0.7609	213.7
17.	0.7778	0.99	0.5048	213.7
18.	1.0625	2.70	0.3086	213.7
19.	0.8261	0.3636	0.9956	1282.0

TABLE-VIII

C_1/C_2 BELOW 1.0

VALUE OF EACH DIMENSIONLESS GROUP WITH ITS RESPECTIVE EXPONENTS

Sl. No.	-0.2016 (d/l)	0.0078 (M_e/M_n)	-0.5784 (C_1/C_2)	-0.0011 ($P/\rho t$)
1.	1.2479	0.9929	1.6516	0.9922
2.	1.1919	0.9861	1.5045	0.9922
3.	1.8227	0.9929	2.8575	0.9925
4.	1.3191	0.9924	1.4903	0.9929
5.	1.5208	0.9926	6.8617	0.9926
6.	1.0534	0.9946	1.0584	0.9922
7.	1.0502	0.9936	1.2128	0.9922
8.	1.1595	0.9946	1.4048	0.9922
9.	1.130	0.9968	1.6867	0.9922
10.	1.2926	0.9883	3.055	0.9918
11.	1.4856	0.9887	2.1436	0.9922
12.	1.0663	0.9897	4.0054	0.9914
13.	1.1905	0.9901	1.1090	0.9914
14.	1.1148	0.9945	1.4651	0.9919
15.	1.1608	0.9950	1.0849	0.9918
16.	1.0851	1.0051	1.1712	0.9941
17.	1.0520	0.9999	1.4850	0.9941
18.	0.9879	1.0078	1.9739	0.9941
19.	1.0392	0.9921	1.0026	0.9922

TABLE-IX

CALCULATED COST NUMBER, MATERIAL COST BY CORRELATION DEVELOPED, ESTIMATED COST, ACTUAL ESTIMATED COST AND DEVIATION AS PER CORRELATION.

$$Q = k \; (d/l)^{a} \; (M_e/M_n)^{b} \; (C_i/C_r)^{c} \; (P/pt)^{d}$$

Q = 1.9713 $(d/l)^{-0.2016}$ $(M_e/M_n)^{0.}$[illegible]078 $(C_i/C_r)^{-0.5784}$ $(P/P_t)^{0.0}$

Sl. No.	Cost No.	Material Cost	Calculated Estimated Price	Actual Estimated Price	Deviation in percent
1.	2.0304	600	2,402	2,640	- 9.01
2.	1.7545	1,135	3,926	4,800	-18.20
3.	5.1326	1,750	17,706	9,600	+84.43
4.	1.9306	5,000	19,029	15,680	+21.35
5.	10.28	28,015	567,723	264,000	+115
6.	1.1002	2,387.5	5,178	5,200	- 0.42
7.	1.2557	3,892.5	9,635	8,520	+13.08
8.	1.6074	500	1,584	1,680	- 5.71
9.	1.3851	405	1,505	1,600	- 5.93
10.	3.8707	14,375	109,685	96,000	+14.26
11.	3.1240	4,135	25,465	17,200	+48.05
12.	4.1906	1,250	10,326	8,000	+29.07
13.	1.2960	4,000	10,219	9,600	+ 6.44
14.	1.6111	4,650	14,768	16,000	+ 7.70
15.	1.2424	12,450	30,492	36,000	-15.30
16.	1.2698	2,722	6,814	5,818	+17.11
17.	1.5523	5,025	15,382	13,760	+11.78
18.	1.9536	4,060	15,636	14,416	+ 8.46
19.	1.0256	2,812.5	5,686	5,840	- 2.63

TABLE-X

VALUE OF EACH DIMENSIONLESS GROUP
FOR THE RANGE C_1/C_r BETWEEN 1.0 & 2.0

Sl.No.	(d/l)	(M_e/M_n)	(C_1/C_r)	(P/pt)
1.	0.8276	0.20	1.0369	427
2.	0.4348	2.0588	1.9880	1389
3.	0.4762	1.5556	1.54	961.5
4.	1.0728	0.450	1.2334	961.5
5.	0.6400	0.40	1.0909	1025.6
6.	0.3636	0.3667	1.9187	961.5
7.	0.9504	0.375	1.1230	1282
8.	0.575	0.3236	1.9081	2484
9.	0.7333	0.2143	1.4167	1229
10.	0.2800	0.2727	1.3274	641
11.	0.3826	0.4977	1.1234	1819
12.	0.0300	0.3357	1.3793	273.7
13.	0.5600	0.80	1.667	213.7
14.	0.6364	0.67	1.50	213.7
15.	0.8333	0.5982	1.95	160.3
16.	0.8667	1.0707	1.2647	213.7

TABLE-XI

VALUE OF EACH DIMENSIONLESS GROUP WITH RESPECTIVE EXPONENTS FOR THE RANGE C_1/C_2 BETWEEN 1.0 AND 2.0

Sl. No.	$(d/l)^{-0.16339}$	$(N_c/N_B)^{0.36311}$	$(C_1/C_2)^{0.54241}$	$(P/\rho t)^{0.[illegible]}$
1.	1.0314	0.5974	1.0198	8.1761
2.	1.1458	1.2998	1.4517	12.31
3.	1.1289	1.1740	1.2639	10.84
4.	0.9886	0.7483	1.1205	10.84
5.	1.0756	0.7170	1.0483	11.08
6.	1.1797	0.6947	1.4240	10.84
7.	1.0083	0.7004	1.0650	11.97
8.	1.0946	0.6639	1.4197	15.06
9.	1.0520	0.5716	1.2080	11.80
10.	1.2312	0.6239	1.1660	9.41
11.	1.1700	0.7762	1.0651	13.52
12.	1.7735	0.6728	1.1906	6.43
13.	1.0994	0.9222	1.3194	6.43
14.	1.0766	0.8647	1.2460	6.43
15.	1.0302	0.8278	1.4365	5.82
16.	1.0237	1.0251	1.1358	6.43

TABLE-XII

CALCULATED COST NUMBER, MATERIAL COST, ESTIMATED COST BY THE CORRELATION DEVELOPED, ACTUAL ESTIMATED COST AND DEVIATION AS PER CORRELATION FOR THE RANGE C_1/C_2 BETWEEN 1.0 AND 2.0

$$Q = 0.2321\ (d/1)^{-0.16339}\ (N_c/N_n)^{0.36311}\ (C_1/C_2)^{.54241}\ (P/pt)^{0.34692}$$

Sl. No.	Cost No.	Material cost	Calculated Estimated Cost	Actual Price	Deviation in percent
1.	4.7936	1,500	1,669	2,560	- 34.81
2.	26.61	1,375	8,493	3,752	+126.34
3.	18.16	3,850	16,228	17,264	- 6.00
4.	8.99	5,900	12,311	11,200	+ 9.92
5.	8.9577	3,200	6,653	6,880	- 3.30
6.	12.65	9,050	26,571	16,800	+ 58.17
7.	9.003	3,575	7,470	7,960	- 6.16
8.	15.53	9,000	32,441	18,400	+ 76.31
9.	8.57	4,250	8,454	9,600	- 11.94
10.	8.43	3,750	7,337	8,000	- 8.28
11.	13.08	9,000	27,323	24,240	+ 12.72
12.	9.13	5,050	10,701	10,440	+ 2.50
13.	8.60	4,140	8,264	7,040	+ 17.38
14.	7.46	1,100	1,905	2,248	- 15.28
15.	7.13	1,500	2,482	2,688	- 7.66
16.	7.66	3,100	5,511	5,926	- 7.00

TABLE-XIII

VALUE OF EACH DIMENSIONLESS GROUP FOR THE RANGE C_1/C_r BETWEEN 2.0 AND 6.0

Sl.No.	(d/l)	(M_c/M_n)	(C_1/C_r)	(P/pt)
1.	0.3333	0.1389	3.2226	427
2.	0.7833	0.4839	1.1080	641
3.	0.5161	1.7143	3.6429	513
4.	1.0000	0.4706	2.0745	1282
5.	0.3469	0.2222	3.2000	910
6.	0.1687	0.3853	1.8604	2564
7.	0.31818	0.3235	2.2109	4678
8.	0.3611	0.3251	2.4272	2003
9.	0.2414	0.2553	2.1843	1931
10.	0.6385	0.5079	1.0612	1931
11.	0.3600	0.4880	2.4337	160.3
12.	0.8462	0.614	2.8478	160.3
13.	0.8462	0.6897	2.8472	213.7
14.	1.0000	0.47	2.143	213.7

TABLE-XIV

VALUE OF EACH DIMENSIONLESS GROUP WITH RESPECTIVE EXPONENTS FOR THE RANGE C_1/C_2 BETWEEN 2.4 AND 6.0

Sl. No.	$(d/L)^{0.1009}$	$(N_c/N_m)^{0.0348}$	$(C_1/C_2)^{-0.0978}$	$(P/\rho t)^{0.3165}$
1.	0.8951	0.9336	0.9346	6.8003
2.	0.9757	0.9721	0.9942	7.7333
3.	0.9354	1.0189	0.9280	7.2070
4.	1.0000	0.9741	0.9587	9.630
5.	0.8987	0.9490	0.9350	8.6404
6.	0.8356	0.9674	0.9647	11.99
7.	0.8909	0.9615	0.9552	14.5069
8.	0.8733	0.9617	0.9500	11.0913
9.	0.8664	0.9536	0.9558	10.8635
10.	0.9597	0.9787	0.9966	10.9635
11.	0.9021	0.9753	0.9499	4.9873
12.	0.9833	0.9832	0.9413	4.9873
13.	0.9833	0.9870	0.9413	5.4624
14.	1.0000	0.9741	0.9569	5.4624

TABLE-XV

CALCULATED COST NUMBER, MATERIAL COST, ESTIMATED COST BY THE CORRELATION DEVELOPED, ACTUAL ESTIMATED COST AND DEVIATION BY CORRELATION FOR THE RANGE W_i/C_r BETWEEN 2.0 AND 6.0

$$Q = 0.2997\ (A/\lambda)^{.1009}\ (M_e/M_n)^{0.0348}\ (C_i/C_r)^{.0578}\ (P/pt)^{0.3165}$$

Sl. No.	Cost No.	Material Cost	Calculated Estimated Price	Actual Estimated Price	Deviation in percent
1.	5.3111	6,875	10,943	14,440	-24.22
2.	7.3141	18,200	39,895	50,034	-20.70
3.	6.3743	3,400	6,495	5,416	+19.92
4.	8.9932	1,625	4,380	3,984	+ 9.94
5.	6.8901	8,000	16,520	16,000	+ 3.25
6.	9.35	80,000	224,176	224,000	+ 0.078
7.	11.4039	162,500	578,084	480,000	+20.43
8.	8.5019	112,500	298,389	360,000	-17.11
9.	8.3180	216,250	561,256	608,000	- 7.688
10.	9.7977	65,000	198,701	181,600	+ 9.42
11.	4.0044	18,700	23,359	23,920	- 2.34
12.	4.5386	12,120	16,486	16,856	- 2.19
13.	4.9902	10,200	15,255	13,680	+11.51
14.	5.0916	1,250	1,907	2,248	-15.17

1	2	3	4	5	6
44.	4.6867	9,000	29,526	24,240	+21.81
45.	4.2777	65,000	194,944	181,600	+ 7.12
46.	5.3799	5,050	19,018	10,440	+82.16
47.	4.7099	1,400	4,694	3,960	+18.54
48.	2.3326	18,700	30,534	23,920	+27.65
49.	2.552	4,140	7,396	7,040	+ 5.06
50.	2.5561	1,100	1, 968	2,248	-12.46
51.	3.2835	2,722	6,256	5,818	+ 7.53
52.	2.5238	16,800	29,680	10,264	+189.17
53.	3.5774	5,025	12,590	13,760	- 8.50
54.	2.2901	11,950	19,157	15,920	+20.33
55.	2.0702	1,500	2,174	2,688	-19.12
56.	1.8101	12,120	15,357	16,856	- 8.89
57.	1.9132	10,200	13 ,459	13,680	- 0.35
58.	2.5481	3,100	5,529	5,926	- 6.70
59.	2.0089	1,250	1,758	2,248	-21.79
60.	4.0492	4,060	11,508	14,426	-20.27
61.	3.7813	2,812.5	7,444	5,840	+27.46

APPENDIX.III

COMPUTER PRINTOUTS

1. Solution for Exponents and Constants using computer by Multiple Linear Regression Analysis - Carbon Steel.

2. Solution for Exponents and Constant using computer by Multiple Linear Regression Analysis - Stainless Steel.

3. Solution for Exponents and Constant using computer by Multiple Linear Regression Analysis - C_1/C_f range below 1.0.

4. Solution for Exponents and Constant using computer by Multiple Linear Regression Analysis - C_1/C_f range 1.0 to 2.

5. Solution for Exponents and Constant using computer by Multiple Linear Regression Analysis - C_1/C_f range 2.0 to 6.

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(1) Carbon Steel

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
-.24424	-.72588	.79575	6.46303	1.01128
-.69315	-1.56878	.66253	6.05678	.41520
.04344	-2.56525	.17075	6.05678	.85973
.03961	-1.85918	1.81574	6.86849	.40343
-.18923	-1.60944	.03624	6.05678	.53454
-.83287	.72212	.68713	7.23633	1.00383
-.66145	.53900	1.29278	6.24027	.46558
-1.09871	-.91629	-.86755	7.15617	1.48160
-.87084	-1.79156	-.70623	7.15617	1.44198
-2.97789	-.91629	-4.11782	6.86849	4.00473
-1.37358	-.98083	-.68975	6.46303	1.14295
-2.07944	-.95399	-2.63387	6.75075	2.24321
.07027	-.79851	.20977	6.86849	.64096
-.44629	-.91629	.08700	6.93303	.76547
-.25786	-.69315	-.09805	7.15617	.77841
-.19104	-3.36390	.55250	6.93303	.84592
-.24296	-.82098	-.33352	7.15617	.78336
-1.01170	-1.00321	.65165	6.86849	.61861
.00000	-.47000	.03778	7.16617	1.22769
.00000	-.75375	.72972	7.15617	.89678
-.73397	-.69315	-.58771	7.15617	1.21194
-.60624	-.40542	-.90387	7.15617	1.37387
-1.27297	-1.50418	-1.23788	7.48043	1.89886
-1.38630	-2.13369	2.00850	6.93303	1.37033
-.05087	-.98083	.11600	7.15617	.80046
-1.96326	-1.45243	-1.31826	7.15617	1.42542
.00120	-.74676	.25021	7.15617	.56431
.00000	-.81103	.32851	7.15617	.56410
-.55339	-1.12825	.09358	7.81762	.71513
-.31020	-1.54038	.34833	7.11395	.81484
-1.05872	-1.50418	1.16315	6.81344	.69315
-.31855	-1.32426	-2.39910	7.84932	1.85630
-.86512	-1.27297	-.17889	7.81762	.87547
-1.77963	-.95373	1.31397	7.84932	1.02962
-1.14514	-1.12856	1.48655	8.45254	1.08311
-1.34285	-1.12362	1.57989	7.60240	1.16315
-1.27297	-1.29938	.28322	6.46303	.75769
-1.42130	-1.36532	1.47446	7.56579	1.03374
-.74297	-.90140	2.95595	7.50604	.32126
-.53905	-.71274	-.66029	7.42833	1.23572
-.73773	-.64302	-.14087	7.48380	1.06180
-.96077	-.69375	.11636	7.50604	1.21392
-.44863	-.67747	.75255	7.56579	1.02742
-3.50656	-1.09154	.32158	5.36457	.72626
-2.52573	-.22315	.04085	5.36457	1.03977
-1.02165	-.71744	1.58256	5.07704	.24619
-.57982	-.22314	.51103	5.36457	.53091
-.45193	-.40048	.40546	5.36457	.71473
-.40542	.65165	-.27325	5.36457	.75959
-.35667	-.88358	.34075	5.36457	.08355
-.25129	-.01005	-.60359	5.36457	1.42784
-.22314	-1.13943	.51085	5.36457	.28684
-.18236	-.51383	.64783	5.07704	.58333
-.16700	-.48776	1.04655	5.07704	.32985
-.16700	-.37732	1.04634	5.36457	.29355
-.14386	.06831	.13483	5.36457	.64693
.00000	-.75502	.76216	5.36457	.58690
.06062	.99325	-1.17571	5.36457	1.26716
-.19104	-1.01170	-.10441	7.15617	.73066

SUMS OF SQUARES AND CROSS PRODUCTS

65.57907	63.91235	3.15964	-297.33663	-54.04413
63.91235	83.04662	-16.27062	-382.37177	-52.48075
3.15964	-16.27062	78.34178	76.48796	-18.75595
-297.33663	-382.37177	76.48796	2732.96400	388.35021
-54.04413	-52.48075	-18.75595	388.35021	73.66497

VARIANCE COVARIANCE MATRIX

.54795	.05471	.19759	-.05807	-.20909
.05471	.52205	-.08275	-.19072	-.00620
.19759	-.08275	1.24397	-.07825	-.49469
-.05807	-.19072	-.07825	.79542	.18169
-.20909	-.00620	-.49469	.18169	.33843

CORRELATION MATRIX

1.000000	.102299	.239328	-.087953	-.485548
.102299	1.000000	-.102690	-.295970	-.014739
.239328	-.102690	1.000000	-.078661	-.762419
-.087953	-.295970	-.078661	1.000000	.350186
-.485548	-.014739	-.762419	.350186	1.000000

ARITHMETIC MEANS	STANDARD DEVIATIONS
-.7260	.7402
-.9162	.7225
.2008	1.1153
6.6338	.8919
.9323	.5818

-REGR. COEFFS.	S.DS OF REG. COEFS	T-VALUES
-.23981	.05434	-4.41308
.02516	.05695	.44191
-.34640	.03624	-9.55857
.18287	.04575	3.99716

INTERCEPT	-.36233
MULTIPLE CORREL. COEFNT.	.86731
STANDARD ERROR OF ESTIMATE	.30223

ANALYSIS OF VARIANCE TABLE

SOURCE OF VARIATION	D.F.	SUM OF SQUARES	MEAN SQUARE	F-VALUE
REGRESSION	4	15.52924	3.88231	42.50204
ERROR	56	5.11527	.09134	
TOTAL	60	20.64451		

-.535143	-.470004	-2.299302	6.637726	.268213
-.470004	-1.791760	-.714724	7.618554	.207624
-.693147	-1.945911	-1.091754	7.723914	.207652
-.980829	-1.216396	-.376509	7.148657	.207633
-.980829	-1.856298	-2.176189	7.371694	.268248
-1.098612	-.837303	-.566766	7.436232	.207633
-1.203973	-1.011601	1.051717	7.148551	.143102
-1.386296	-.810930	-2.362196	7.618554	.268200
-1.049822	-.875469	-1.587214	7.618554	.268242
-.606136	-.628609	-1.575884	7.330871	.268264
-2.929059	-3.216877	-2.116257	7.554014	.268264
-2.060024	-2.207275	-2.367124	7.554014	.268264
-.250475	-1.049822	-2.067019	7.148551	.268264
-.510826	-1.216396	-1.372959	7.336872	.268264
-.884358	-1.504078	-.582676	7.330871	.207639

NUMBER OF OBSERVATIONS= 15

SUMS OF SQUARES AND CROSS PRODUCTS

22.888479	26.263065	23.944659	-116.217230	-3.794468
26.263065	35.850409	31.111467	-153.910690	-4.978504
23.944659	31.111467	43.565101	-159.386190	-5.682628
-116.217230	-153.910690	-159.386190	816.230640	26.509249
-3.794468	-4.978504	-5.682628	26.509249	.883649

VARIANCE COVARIANCE MATRIX

.438809	.312677	.094577	-.061671	-.003045
.312677	.437331	.037340	-.092127	-.001262
.094577	.037340	.336473	-.007906	-.033596
-.061671	-.092127	-.007906	.071350	.000252
-.003045	-.001262	-.033596	.000252	.001454

CORRELATION MATRIX

1.000000	.676155	.156107	-.348536	-.120544
.676155	1.000000	.136796	-.494057	-.047415
.156107	.136796	1.000000	-.032362	-.963430
-.348536	-.494057	-.032362	1.000000	.024709
-.120544	-.047415	-.963430	.024709	1.000000

ARITHMETIC MEANS	STANDARD DEVIATIONS
-1.0426	.6624
-1.3794	.6981
-1.4403	.9146
7.3718	.2671
.2397	.0381

REGR. COEFFS.	S.DS OF REG. COEFS	T-VALUES
-.00274	.00616	-.44544
.00769	.00629	1.22359
-.04059	.00332	-12.22794
.00659	.01291	.51054

INTERCEPT	.14041
MULTIPLE CORREL. COEFNT.	.96869
STANDARD ERROR OF ESTIMATE	.01159

ANALYSIS OF VARIANCE TABLE

SOURCE OF VARIATION	D.F.	SUM OF SQUARES	MEAN SQUARE	F-VALUE
REGRESSION	4	.02046	.00512	38.056
ERROR	10	.00134	.00013	
TOTAL	14	.02181		

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SP	R2	R3	R4	R
000566	000407	056046	164000	160
R7	MQ	SC	SLR	F
027534	000017	000360	000400	000

(3) C_i/C_f range below 1.

-1.09871	-.91629	-.86755	7.15617	1.48160
-.87084	-1.79156	-.70623	7.15617	1.44198
-2.97789	-.91629	-4.11782	6.86849	4.00473
-1.37358	-.98083	-.68975	6.46303	1.14295
-2.07944	-.95399	-2.63387	6.75075	2.24321
-.25786	-.69315	-.09805	7.15617	.77841
-.24296	-.82098	-.33352	7.15617	.78336
-.73397	-.69315	-.58771	7.15617	1.21194
-.60624	-.40542	-.90387	7.15617	1.37387
-1.27297	-1.50418	-1.23788	7.48043	1.89886
-1.96326	-1.45243	-1.31826	7.15617	1.42542
-.31855	-1.32426	-2.39910	7.84932	1.85630
-.86512	-1.22207	-.17889	7.81762	.87547
-.53905	-.71274	-.66029	7.42833	1.23572
-.73773	-.64302	-.14087	7.48380	1.06180
-.40542	.65165	-.27325	5.36457	.75959
-.25129	-.01005	-.68359	5.36457	1.42784
.06062	.99325	-1.17571	5.36457	1.26716
-.19104	-1.01170	-.00441	7.15617	.73066

SUMS OF SQUARES AND CROSS PRODUCTS

25.50315	16.89906	27.09550	-117.56362	-31.90060
16.89906	19.66279	16.54621	-107.71583	-22.51393
27.09550	16.54621	38.34200	-131.90064	-40.26470
-117.56362	-107.71583	-131.90064	920.41257	187.34545
-31.90060	-22.51393	-40.26470	187.34545	48.48596

VARIANCE COVARIANCE MATRIX

.56738	.21957	.54531	-.09580	-.42802
.21957	.45583	.10947	-.40326	-.10356
.54531	.10947	1.01688	-.01801	-.69730
-.09580	-.40326	-.01801	.55285	.02593
[illegible]	-.10356	-.69730	.02593	.53237

CORRELATION MATRIX

1.000000	.431756	.717909	-.171056	-.778781
.431756	1.000000	.160795	-.803309	-.210213
.717909	.160795	1.000000	-.024021	-.947714
-.171056	-.803309	-.024021	1.000000	.047793
-.778781	-.210213	-.947714	.047793	1.000000

ARITHMETIC MEANS	STANDARD DEVIATIONS
-.8803	.7532
-.7610	.6752
-1.0006	1.0084
6.9203	.7435
1.4211	.7296

REGR. COEFFS.	S.DS OF REG. COEFS	T-VALUES
-.20167	.12528	-1.60972
.00786	.16403	.04795
-.57845	.08214	-7.04234
-.00115	.13385	-.00863

INTERCEPT	.67878
MULTIPLE CORREL. COEFNT.	.95823
STANDARD ERROR OF ESTIMATE	.24311

ANALYSIS OF VARIANCE TABLE

SOURCE OF VARIATION	D.F.	SUM OF SQUARES	MEAN SQUARE	F-VALUE
REGRESSION	4	9.28768	2.32192	39.28691
ERROR	14	.82742	.05910	

(4) C_i/C_f range 1.1 to 2.0

-.741917	.441861	.431782	6.868490	1.500530
.070272	-.798508	.209774	6.868490	.640961
-.446287	-.916291	.087003	6.933029	.765467
-.050872	-.980829	.116004	7.156174	.800463
-.553385	-1.128247	.093581	7.817620	.715126
-.310200	-1.540379	.148330	7.113954	.814844
-1.272966	-1.299383	.283221	6.463028	.757685
-.960765	-.693747	.116360	7.506038	1.213923
-3.506558	-1.091537	.321576	5.364571	.726256
-.579819	-.223144	.511025	5.364571	.530912
-.143062	.058313	.234835	5.364571	.646934

NUMBER OF OBSERVATIONS= 11

SUMS OF SQUARES AND CROSS PRODUCTS

16.355719	7.444817	-2.440022	-52.732173	-7.176918
7.444817	9.695773	-1.710101	-55.891165	-6.090994
-2.440022	-1.710101	.395018	17.479649	2.305193
-52.732173	-55.891165	17.479649	489.800640	61.354785
-7.176918	-6.090994	2.305193	61.354785	8.340008

VARIANCE COVARIANCE MATRIX

.890399	.103745	-.028494	.318988	-.012605
.103745	.330884	.030269	-.169003	.060985
-.028494	.030269	.018706	-.068054	.002184
.318988	-.169003	-.068054	.702293	.093239
-.012605	.060985	.002184	.093239	.071831

CORRELATION MATRIX

1.000000	.191133	-.220784	.403388	-.049842
.191133	1.000000	.384741	-.350588	.395577
-.220784	.384741	1.000000	-.593742	.059586
.403388	-.350588	-.593742	1.000000	.415130
-.049842	.395577	.059586	.415130	1.000000

ARITHMETIC MEANS	STANDARD DEVIATIONS
-.7723	.9436
-.7420	.5752
.2503	.1368
6.6200	.8380
.8285	.2680

REGR. COEFFS.	S.DS OF REG. COEFS	T-VALUES
-.16339	.06107	-2.67539
.36311	.10065	3.60752
.54241	.45424	1.19411
.34692	.08043	4.31328

INTERCEPT	-1.46070
MULTIPLE CORREL. COEFNT.	.89653
STANDARD ERROR OF ESTIMATE	.16075

ANALYSIS OF VARIANCE TABLE

SOURCE OF VARIATION	D.F.	SUM OF SQUARES	MEAN SQUARE	F-VALUE
REGRESSION	4	.63509	.15877	6.14408
ERROR	6	.15505	.02584	
TOTAL	10	.79014		

(5) C_i/C_f range 2 to 6.

-1.09871	-1.97400	1.17019	6.05678	.17697
-.24424	-.72588	.79575	6.46303	1.01128
-.66145	.53900	1.29278	6.24027	.46558
.00000	-.75375	.72972	7.15617	.89678
-1.05872	-1.50418	1.16315	6.81344	.69315
-1.77963	-.95373	1.31397	7.84932	1.02962
-1.14514	-1.12856	1.48655	8.45254	1.08311
-1.34285	-1.12362	1.57989	7.60240	1.16315
-1.42130	-1.36532	1.47446	7.56579	1.03374
-.44863	-.67747	.75255	7.56579	1.02742
-1.02165	-.71744	1.58256	5.07704	.24619
-.16700	-.48776	1.04655	5.07704	.32985
-.16700	-.37732	1.04634	5.36457	.29355
.00000	-.75502	.76216	5.36457	.58690

SUMS OF SQUARES AND CROSS PRODUCTS

12.42783	11.20253	-14.12845	-74.50978	-8.40366
11.20253	14.77867	-14.33542	-82.14273	-9.06112
-14.12845	-14.33542	20.00742	108.23355	11.66162
-74.50978	-82.14273	108.23355	629.47609	70.97501
-8.40366	-9.06112	11.66162	70.97501	8.86583

VARIANCE COVARIANCE MATRIX

.31915	.15360	-.13685	-.33217	-.05966
.15360	.32031	-.03191	-.19258	-.03244
-.13685	-.03191	.09069	.07488	.00354
-.33217	-.19258	.07488	1.16772	.32504
-.05966	-.03244	.00354	.32504	.11926

CORRELATION MATRIX

1.000000	.480416	-.804383	-.544120	-.305829
.480416	1.000000	-.187255	-.314896	-.165966
-.804383	-.187255	1.000000	.230102	.033998
-.544120	-.314896	.230102	1.000000	.871023
-.305829	-.165966	.033998	.871023	1.000000

ARITHMETIC MEANS	STANDARD DEVIATIONS
-.7540	.5649
-.8575	.5660
1.1569	.3011
6.6178	1.0806
.7169	.3453

REGR. COEFFS.	S.DS OF REG. COEFS	T-VALUES
.10090	.22803	.44248
.03489	.11255	.31001
-.05763	.34255	-.16682
.31652	.06263	5.05401

INTERCEPT	-1.20482
MULTIPLE CORREL. COEFNT.	.89499
STANDARD ERROR OF ESTIMATE	.19213

ANALYSIS OF VARIANCE TABLE

SOURCE OF VARIATION	D.F.	SUM OF SQUARES	MEAN SQUARE	F-VALUE
REGRESSION	4	1.33739	.33435	9.05739
ERROR	9	.33223	.03691	
TOTAL	13	1.66961		

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