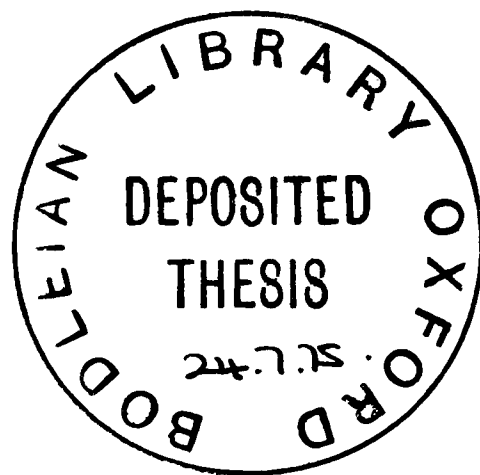


Production Planning and Design in the
Pressure Vessel Industry

by

MAHDI M. ASWED

Exeter College, Oxford



Thesis submitted for the degree of Doctor of Philosophy
at the University of Oxford.

Feb. 1975

Department of Engineering Science
University of Oxford
Parks Road
Oxford

SYNOPSIS

The Pressure Vessel Industry is quite unique in having a number of rigid Codes introduced and accepted in order to safeguard the integrity of the product rather than the efficient use of the fabrication facilities. Such Codes facilitate the task of designers and thus result in an economy of time and effort during the design stage. On the other hand their intrinsic lack of flexibility demands, for example, expensive inspection procedures which, sometimes, can not be substantiated by sound scientific reasoning. Also peculiar to this situation is the existence of licencing or insuring authorities, making radical departures from the Codes virtually impossible in many cases and unjustified by the possible saving in materials in most. This being so, it follows that any cost reduction must be made within the framework of the Design Codes.

This thesis summarises an investigation whose purpose was to evaluate the time and cost involved in design, fabrication and inspection depending on the codes.

It is concluded that the only significant savings can be achieved through careful planning of production and that the only advantage that a design code can offer is a reduction of weight by allowing a higher design stress.

ACKNOWLEDGEMENTS

The author wishes to express his grateful thanks to:

Dr. C. Ruiz Lecturer in Engineering Science, University of
Oxford, the author's supervisor, for his continued guidance and encouragement.

Professor D. W. Holder for placing the facilities of the Department
at the author's disposal.

The author also wishes to thank all the firms for their help, in
particular

K. Birch	Ralph M. Parsons Co. Ltd.
G. Lorraine and J. Round	Clarke-Chapman and John Thompson
H. Butler	International Combustion Ltd.,
J. Bullock	Robert Jenkins & Co. Ltd.
M. J. Kemper	A.P.V. Co. Ltd.
R. Thompson	Power-gas Ltd.
H. Heward	British Engine Co.
S. Menicatti	Snam Progetti Co.
J. Russell	Motherwell Bridge Ltd.
R. D. Kerr	Babcock & Wilcox Ltd.
P. Bramhill	British Steel Corporation
S. Nicholson	Whessoe Ltd.

The support provided by the National Oil Company of Libya and the
University of Tripoli is gratefully acknowledged.

The author also wishes to express his thanks to Mrs. Suzanne
Motyka for the typing of the thesis.

Finally, the author wishes to express his gratitude to his family
for their continuous encouragement.

CONTENTS

Chapter 1: General Introduction

- 1.1 Characteristics of the pressure vessel industry
- 1.2 Pressure vessel categories
- 1.3 Scope of present investigation and description of thesis

Chapter 2: General description of the production process

- 2.1 Introduction
- 2.2 The production process
- 2.3 The fabrication process
- 2.4 Conclusions

Chapter 3: Design codes and their effect on the P.V. industry

- 3.1 Introduction
- 3.2 Design of main shell
 - 3.2.1 Design stresses
 - 3.2.2 Shell thickness
- 3.3 Design of opening reinforcements
- 3.4 Vessel tolerances
- 3.5 Standardized pressure vessel steels
- 3.6 Conclusions

Chapter 4: Production cost analysis

- 4.1 Introduction
- 4.2 Breakdown of production time
- 4.3 Determination of the cost
 - 4.3.1 Approximate determination of the cost
 - 4.3.2 Effect of material cost
 - 4.3.3 Effect of capacity
- 4.4 Combined effect of material and design code on the cost

Chapter 5: Fabrication and workshop layout

- 5.1 Introduction
- 5.2 Analysis of fabrication time
- 5.3 Breakdown of fabrication time into unit operations
- 5.4 Percent utilisation of work centres
- 5.5 Plant equipment and layout
 - 5.5.1 Plant equipment
 - 5.5.2 Plant layout
 - 5.5.3 Workshop areas
- 5.6 The determination of the shop maximum output through vessel - machine occupation time
- 5.7 Selection of vessel from the point of view of fabrication
- 5.8 Site erection
- 5.9 Conclusions

Chapter 6: Production planning

- 6.1 Introduction
- 6.2 Classification of vessel parts
- 6.3 Planning for production
- 6.4 Conclusions

Chapter 7: General conclusions and further work

CHAPTER 1

CHAPTER 1INTRODUCTION

The pressure vessel industry is quite unique in having a number of rigid codes introduced and accepted in order to safeguard the integrity of the product rather than the efficient use of the fabrication facilities. Such codes facilitate the task of designers and thus result in an economy of time and effort during the design stage. On the other hand, their intrinsic lack of flexibility demands for example, expensive inspection procedures which, sometimes cannot be substantiated by sound scientific reasoning. Also peculiar to this situation is the existence of licencing or insuring authorities, making radical departures from the codes virtually impossible in many cases and unjustified by the possible savings in materials in most. This being so, it follows that any cost reduction must be made within the framework of the design codes. The pressure vessel designer may be free to choose the code that he considers to be most suitable for a given application and to minimize the cost of the finished product, but, once this choice has been made, no departure from the code rules is possible. A strength evaluation, based on stress analysis and the application of the general principles of materials science may be necessary to supplement those rules that are clearly inadequate but in most cases the purpose of such detailed study is to ensure the safety of the vessel rather than to reduce its cost. It is in fact doubtful whether any significant cost reduction would be achieved if vessels were to be designed from first principles only, without the practical

experience embodied in design codes.

Another aspect peculiar to the industry is the fragmentation of the production cycle. The main pressure vessel dimensions and design conditions are often fixed by engineering consultants, on the basis of specifications agreed with customers. Detailed drawings are then prepared by fabricators and submitted for approval to the consultants who are ultimately responsible for the whole plant. Even when vessels are entirely shop-fabricated, a not insignificant effort will be required at site by those responsible for the assembly of the plant. Throughout the whole process, independent assessors are called to ensure the integrity of the completed product by performing the inspections and tests specified by customers, consultants, fabricators and erectors, often operating in different countries. Given this division of responsibilities, the design code fulfills an essential unifying function between them and with the suppliers of materials. Although the volume of the pressure vessel industry in this respect, is small compared with structural and heavy engineering as a whole, the wide range of operating conditions, e.g. temperature, pressure, fluid contained, demands a correspondingly extensive range of materials. These in turn, are standardised as far as possible in design codes.

Finally, in common with other heavy engineering activities, pressure vessels are usually treated as unique, both in design and in construction. Details, such as supporting brackets, columns, penetrations, reinforcements, etc. are seldom standardised, though to do so would probably result in a saving in cost and design effort. An exception to this remark is the use of standard pipe fittings in some applications.

To a newcomer, be it an engineer who has had no experience of the pressure vessel industry or a nation whose interests have previously

been confined to the selling of raw materials, the aspects thus described are most bewildering. It is however important to acquaint oneself with them if, as is the case of Libya, technological development based on the petrochemical industry is deemed desirable, since pressure vessels constitute an essential part of any process plant as well as the main capital investment.

1.1 Characteristics of the pressure vessel industry

As mentioned before, the vessel industry is constituted by a variety of organizations practicing many different skills, and including customers, contractors, fabricators and erection teams, while inspection authorities will finally approve and stamp the product quality and safety.

Fluctuation in the selling market of the pressure vessel, diversity of vessel materials, dimensions and working conditions makes it virtually impossible to forecast its future progress. Working plans and networks from the order of material to the erection would be no more than "one-off" production conditions. New production control techniques, efficient management, new machines and up to date design will certainly result in better product quality, but may be unprofitable due to the small volume of orders processed. This is the reason why the outlook and organisation of this industry is more traditional than forward-looking.

1.2 Pressure vessel categories

Pressure vessels in general are classified into four categories (1).

- i. Class I, severe-duty vessels which are to contain flammable substances at temperatures above their ignition temperature.
- ii. Class II, medium duty vessels, which are not covered in Class I and III.

- iii. Class III, light duty vessels, for unfired purposes, plate thicknesses not exceeding 16 mm.
- iv. Vessels for service at sub-atmospheric pressure and liable to embrittlement at temperature below 0 °C. These are subject to impact testing at their lowest operating temperature

Construction and design thickness of above classes will depend on the combination of the following loading factors acting on the vessel;

- a. External and internal operating pressures.
- b. Shock loads, including rapid pressure fluctuations and surge loads due to the rapid movement of the vessel contents.
- c. The weight of the vessel and its contents at operating temperatures and pressures.
- d. Bending moments which may be caused by the eccentricity of the centre of the working pressure relative to the central axis of the vessel.
- e. Superimposed loads.
- f. Wind loads.
- g. Local stresses due to supporting lugs, internals or connecting piping.
- h. Additional pressure due to static head of contained fluid.

1.3 Scope of present investigation and description of thesis

The object of this investigation is to study the effect of Design Codes in the industry as a whole and to identify areas where further study would result in significant savings. In the past, most investigations have been limited to stress analysis and strength evaluation problems, in order to assess more accurately the safety of a vessel rather than to minimize its cost. These aspects are of interest to specialists, be they consultants, designers or fabricators, usually

working in highly industrialised countries. Technologists in the oil producing countries are more interested in acquiring a general understanding of industrial problems in order to select the best solutions to keep cost to a minimum and usefulness to a maximum.

Following this general introduction, chapter two describes the production process and the various production stages of the pressure vessel, starting from the moment when the order is placed to the final testing, inspection and despatch. In chapter three, the main features of Design Codes are reviewed, as regards the relationship between design stress and material behaviour, calculation of vessel thickness, design of opening reinforcements, manufacturing tolerances and standard steels. The investigation considers mainly steel vessels, as they are the most commonly used. Chapter four discusses in detail the determination of vessel cost, the effect of breakdown of the various stages of production, i.e. ordering, fabrication and inspection and the effect of code selection, material thickness and grade and labour effort on the final cost of the vessel. Chapter five studies the actual organisation of fabrication, considering the work centres within the vessel shop, the flow of materials, centre utilisation and the correlation between production volume, vessel size and workshop facilities. By describing the complete production process, those areas where detailed study might conceivably result in a reduction of cost or improvement of quality for a given cost, will become more apparent. Conclusions and discussion of results are presented at the end of each chapter, while a general conclusion and suggestions for further work are at the end of the thesis.

CHAPTER 2

CHAPTER 2

General Description of the Production Process

2.1 Introduction

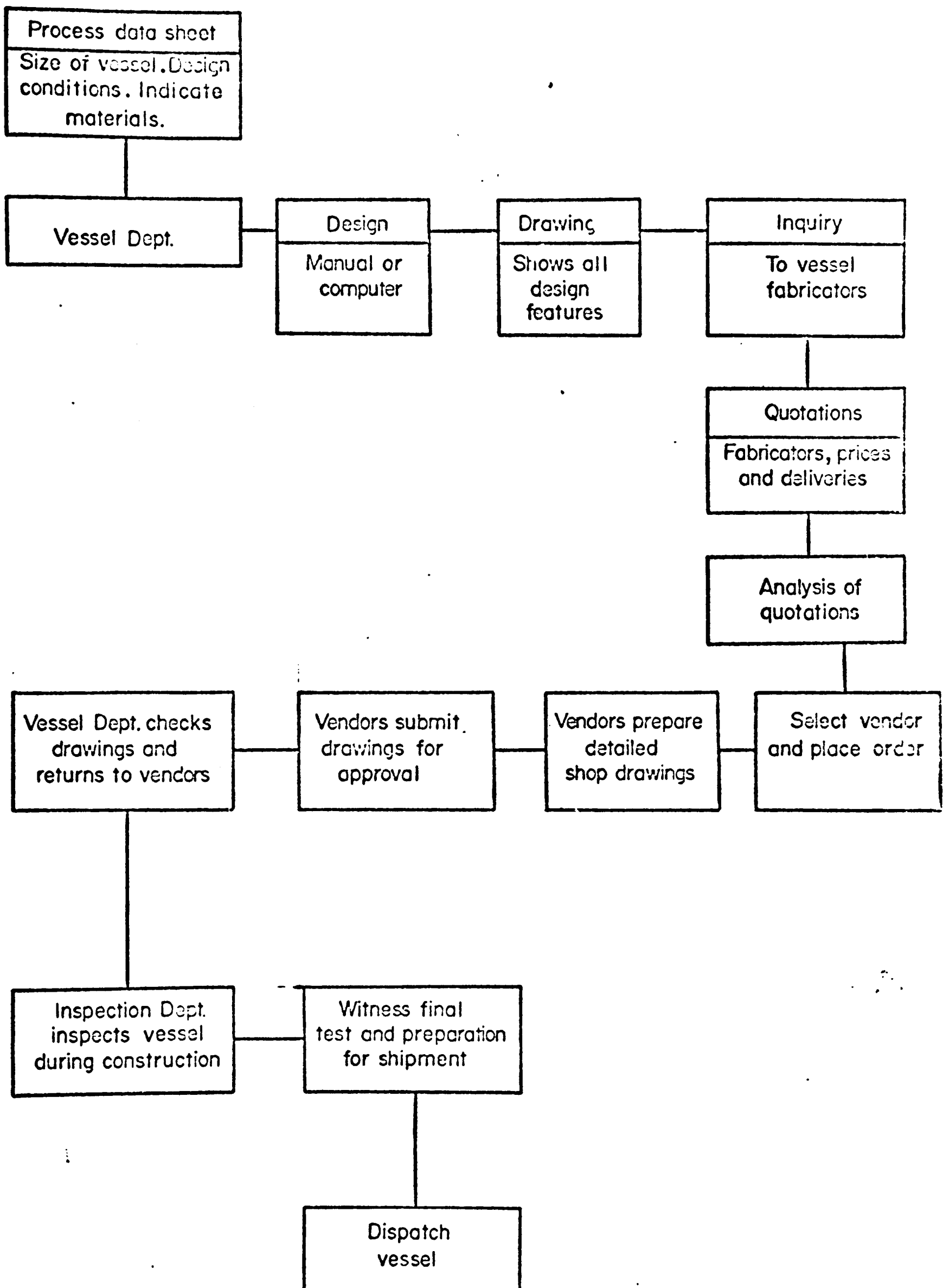
Production in this work is taken to represent the complete process, from the preparation of the specification, design, fabrication, inspection and testing, to the final commissioning, i.e. the process of production starts when plant designers define their requirements for a vessel, and finishes when the vessel is ready to commence operation. In this chapter, the production process is described with a view to studying the effect of design codes on the various stages of the process and to provide a framework for the analysis of costs.

2.2 The production process

The complete process of production, including the preliminary stages of preparation of specification and design, is illustrated by the diagram of Fig.2.1. The first stage consists in the preparation of a preliminary drawing and a detailed specification, which are submitted to the fabricators. These in turn submit quotations and, once a quotation has been accepted, detailed drawings for approval by the main contractors.

A more detailed planning chart is shown in Fig.2.2 in which the sequence of events is marked. The total time spent for the completion of the vessel is of the order of 40 to 50 weeks, irrespective of Code specified.

Throughout the course of production, the vessel documents inclu-

Fig. 2.1

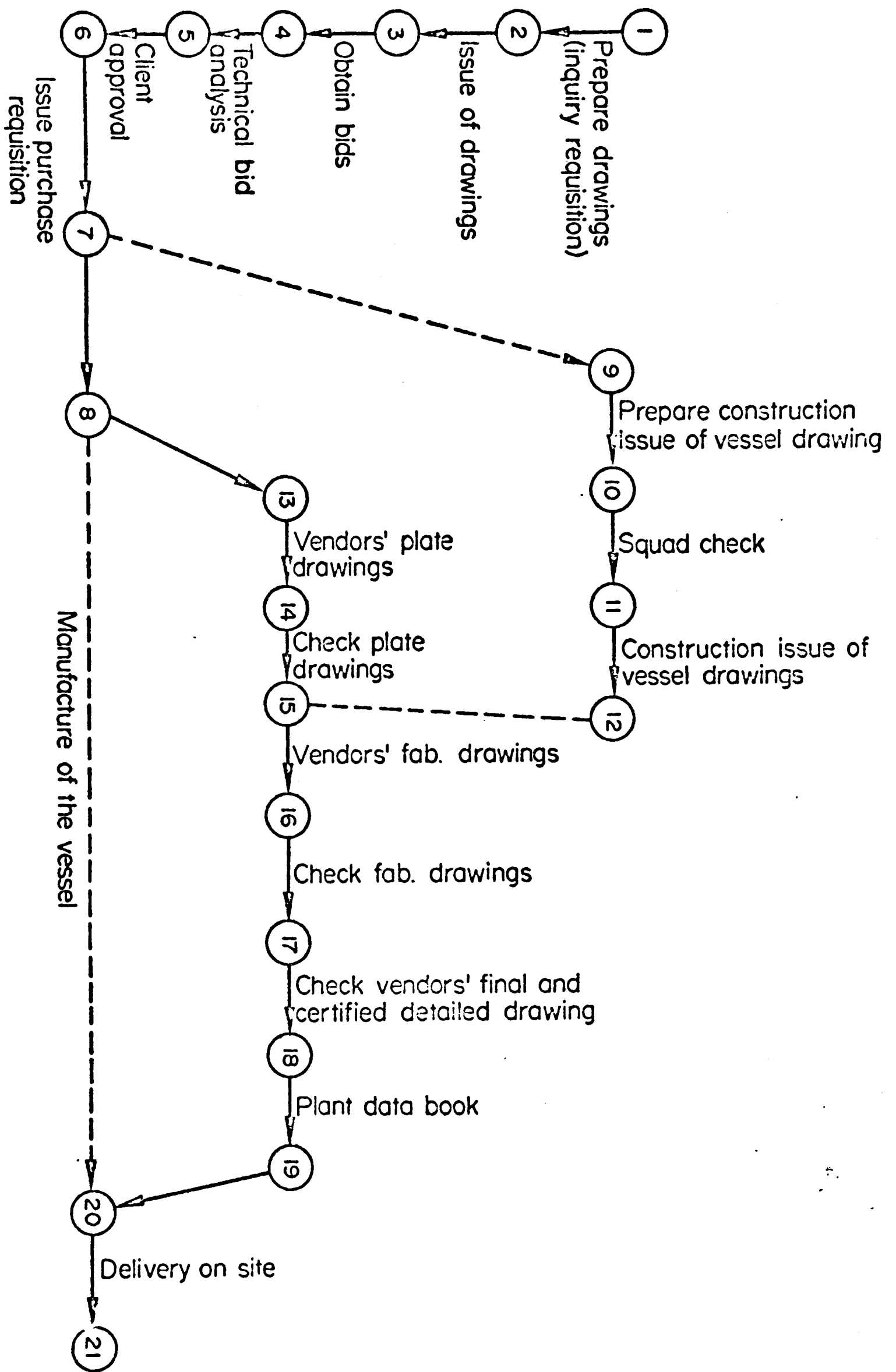


Fig. 2.2

sive of preliminary drawings of the vessel size, design conditions and materials to be used, is forwarded to vessel fabricators through the clients consultants. Fabricators then submit their bids containing estimated delivery dates, overall costs, schedule of production and inspection procedures. A technical bid analysis has to be carried out by the consultants and their clients, resulting in an approval of the purchase, which will be forwarded to the fabricators as "purchase-requisition". Fabricators then prepare the detailed vessel drawings and submit them for the consultants and/or clients approval, the fabricators also submit vessel plating drawings which has to be approved by the clients as well. During the fabrication, inspectors of consultants or clients have to check progress and quality and issue to the vendors acceptance certificates; at completion, the fabricators submit vessel or complete plant data book to the clients, with the transportation procedures. Recommendations for erection procedures are always expected to be supplied by fabricators, specially for large vessels when site assembly is required.

2.3 The fabrication process

The fabrication process is only a part of the whole vessel production cycle, but, as will be shown later, its importance is such that it has to be considered separately from the rest. The vessel fabrication chart is shown in Fig.2.3, while the sequence of operation and actual shop layout are shown in Fig.2.4. Prior to assembly, the fabrication of the shell is the decisive factor in establishing the duration of the process since both heads and attachments require

a shorter time or are purchased as finished products. The total fabrication time varies a great deal depending on the type of vessel. Time would be saved by using standard components but to do so requires the storage of stocks which would increase the capital investment. At present most vessels are designed and made as "one-off" units and no serious attempt to standardize details is made. This situation is a result of the lack of feedback of information from the fabricator to the designer. Lacking this information, designers often have no basis for the selection of preferred sizes of openings, mode of compensation, position, type and dimensions of supports, brackets, lugs or skirts, etc., thus creating an unnecessary variety of solutions when only a few would be sufficient.

Fig.2.3, describes the fabrication processes required by a conventional pressure vessel; materials in the form of plates, after being identified and marked, are allocated to machines and cut to required sizes, the edges of these plates are then prepared to the required weld profile. After this operation, plates are rolled to the correct diameters. Welding is the last stage of fabrication and post-weld heat treatment may be required for fairly thick vessels. Fabricated courses are always subjected to inspection and repair is preferred to be done in this stage. Assembly of the vessel body will be the next process, stress relief and hydraulic tests are then performed, bringing the vessel to its final stage.

The fabrication processes, shown in Fig.2.4, illustrate the three alternative ways of vessel body fabrication; at the top of the figure, the fabrication process shown is to be carried out on solid wall vessels. Lower route in the diagram, shows processes required to

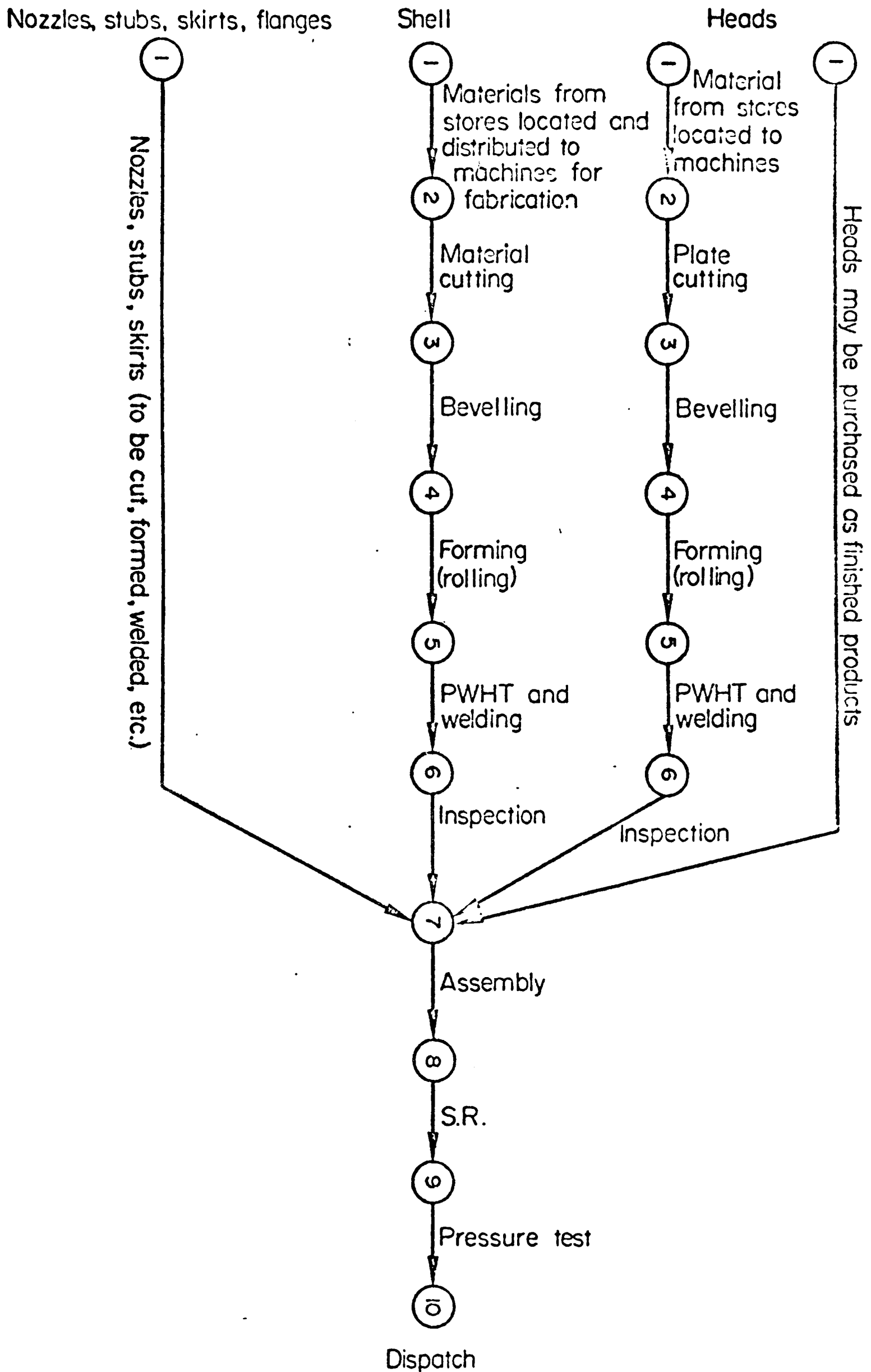
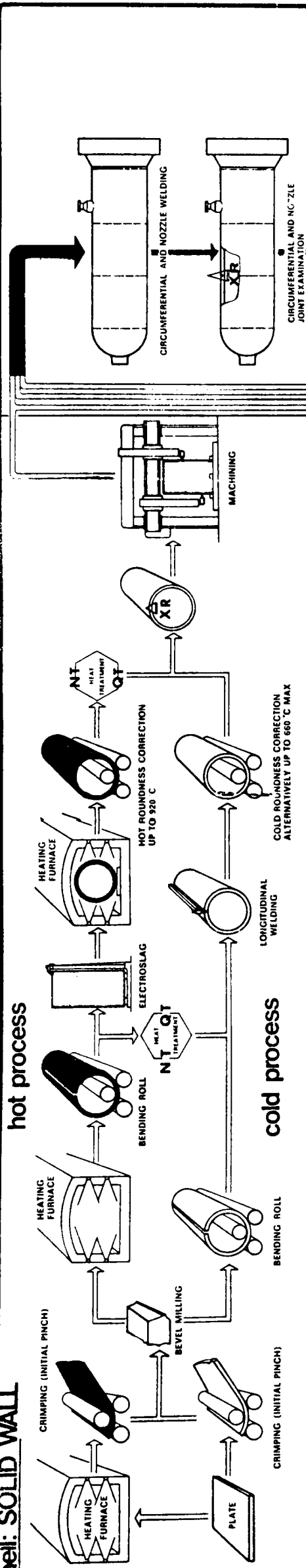
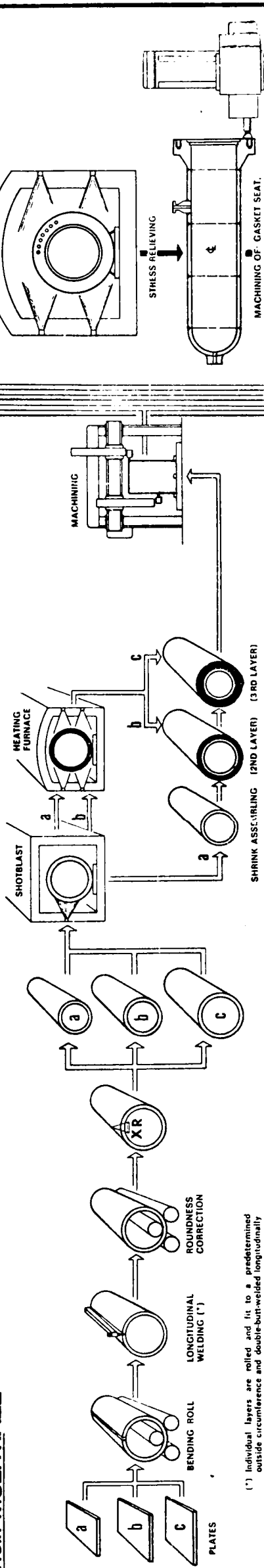


Fig. 2.3

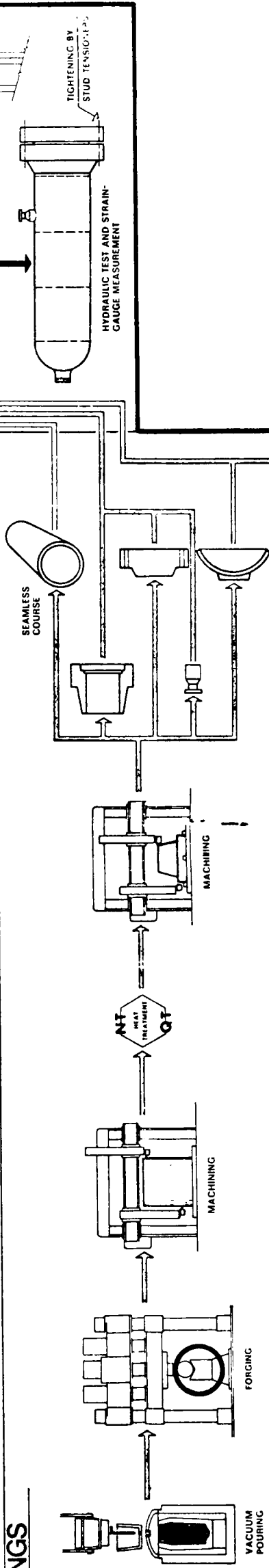
Shell: SOLID WALL



Shell: MULTIWALL



FORGINGS



HEADS

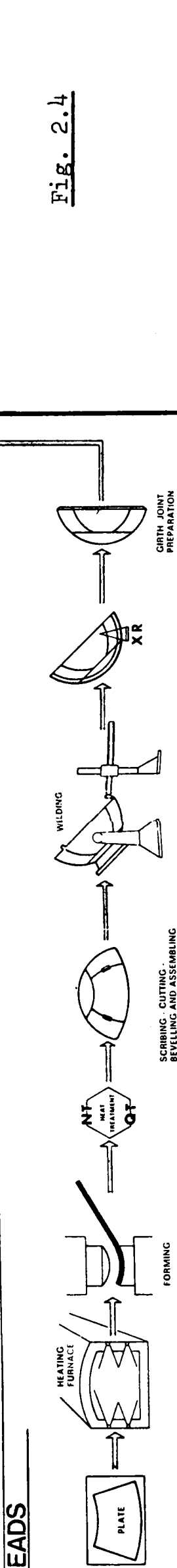


Fig. 2.4

fabricate thin vessels with thicknesses ranging from $\frac{1}{2}$ to 3 inches using cold rolling, while the top route, refers to processes requiring heating when forming, for thicknesses of 3 to 6 inches. For very high pressure vessels, when the vessel thickness would prevent manufacture as a solid wall unit, multi-layer shell fabrication may be used as shown in the middle-diagram; layers of shell courses rolled to close-fit diameters are fabricated, heated, shrunk inside each other. Another method of vessel fabrication that may be used, is the forging process; vessel courses are forged to required diameters and assembled together to form the body. The advantage of this method is that there are no longitudinal joints. The fabrication process for heads or shells of double curvature is also shown in the bottom of the diagram. The basic operations are cutting, forming, bevelling and welding. At the last stages shown in the inside of the diagram, vessel attachments and nozzles will be assembled to form the complete vessel body. Finally, the completed vessel is then stress relieved, hydraulically tested and despatched.

The vessel fabrication shop may consist of the following areas:

Component preparation shop,
Assembly and finishing shop,
Outdoor stock yard and
Maintenance shop.

Machinery usually available in a well equipped shop may be;

a. Associated with fabrication and welding:-

plate edge flame cutter, circular and profile flame cutter, plate edge planner, rolls, bending equipment, pressing equipment, welding equipment, rotators and moving beds, plate heating furnace, annealing furnace for the complete vessel.

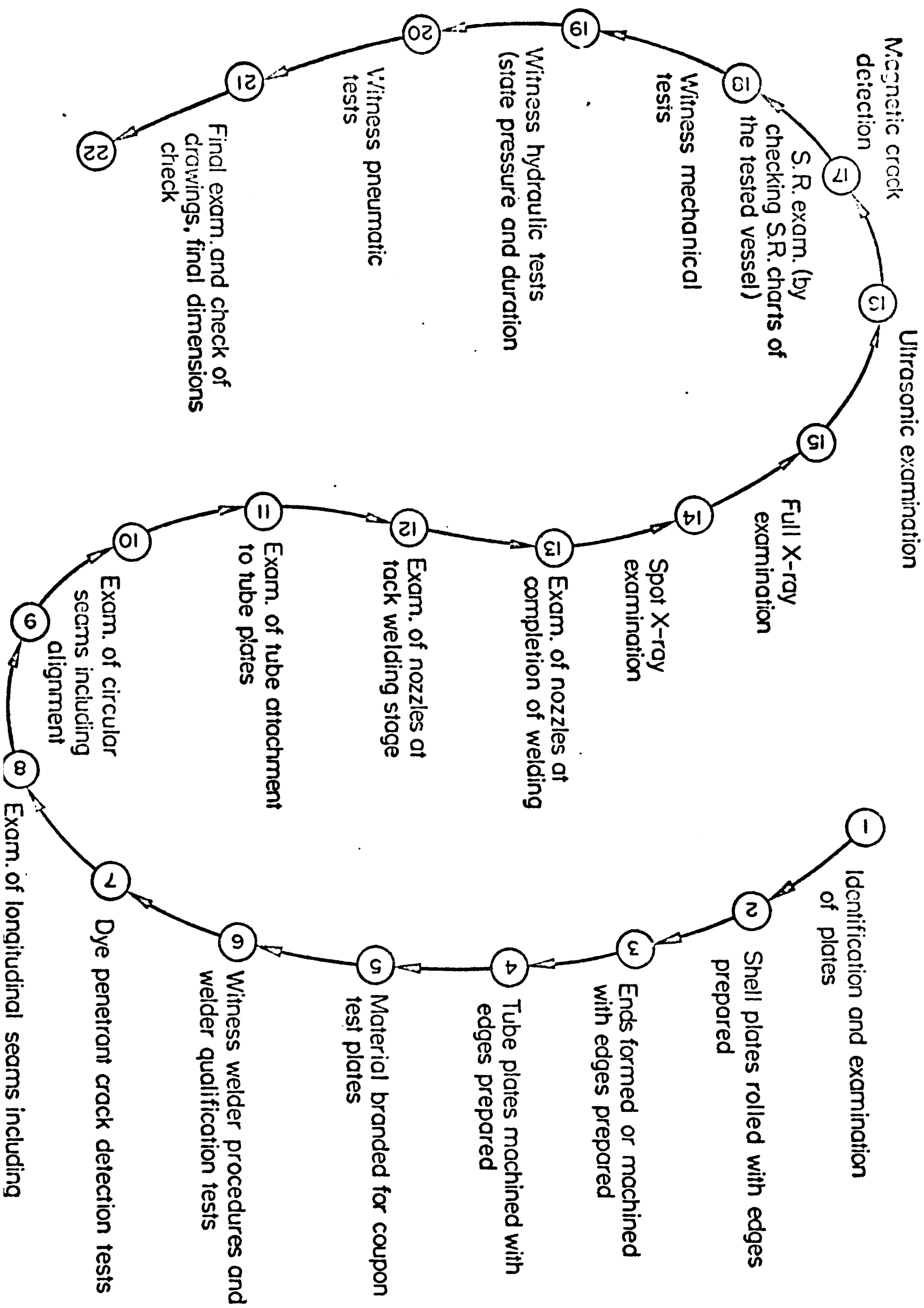


Fig. 2.5

- b. Machine tools; lathes, vertical and horizontal boring and drilling machines, milling machines.
- c. General equipment:-
 shot blasting equipment, Inspection equipment;
 including X-ray machines, magnetic particle testing
 equipment and dye penetrant testing.

Inspection as described in Fig.2.5, is carried out during fabrication and hydraulic test usually marks the completion of the vessel, when it is then despatched to site or connected to the rest of the plant.

The sequence illustrated in Fig.2.5 need not be the same in all practical cases, some of the tests may be dispensed with and others may be replaced or occur at alternative times, for instance, a pneumatic test has been shown as an alternative to a hydraulic test and no provision has been made for instrumented proof tests, with strain gauges or brittle lacquers, although such tests are becoming more frequent as vessels of complex geometry are replacing conventional designs.

2.4 Conclusions

The complexity of the complete production process is apparent from Fig.2.2, particularly when it is considered that the fabrication (Fig.2.3) and the inspection (Fig.2.5) also involve a complex sequence of inter-connected operations, in the hands of different organizations. This being so, it is essential to ensure the collaboration of the various organizations participating in the production of a vessel and this may be done by the drafting at some early stage of a contractual document assigning responsibility in unequivocal

cal terms and defining standards of fabrication, design and inspection. This is precisely the function of the Design Codes that will be studied in some detail in the next chapter.

CHAPTER 3

CHAPTER 3Design Codes Used In The Pressure Vessel Industry3.1 Introduction

Design codes were originally developed to safeguard the integrity of the vessel by means of rules for the dimensioning and detailed design of its components. In the course of the years, they have developed, and they now include rules representative of what is considered to be sound engineering practice for fabrication, site erection, inspection and testing. In addition to their original purpose, they now serve another function which is equally important. As has been mentioned in the last chapter, it is essential to establish a basis for the collaboration of the various parties involved in the production process. Such a basis is provided by the design codes; supplemented by rules set up by customers, fabricators or inspecting authorities.

There is a wide diversity of codes and their recommendations are by no means consistent. Wide discrepancies are found in the limits assigned to the allowable stresses, the rules for the acceptance of material, fabrication, inspection and testing. This results in production delays, particularly when a vessel is designed in one country, fabricated in a second and erected in a third. Apart from the mentioned difficulty, there exists another form of production delay when dealing with specialised customers who in most cases depend on their specifications, such as material equivalence, level of acceptance and testing procedures. There is clearly a need for a unified code, and the International Standards Organization is now attempting to produce one. In so doing, a reduction in the time required for ordering may

be achieved as well as a better interpretation of inspection and testing procedures.

Rigidity in the code - once selected - does not allow any departure that might result in saving. Cost does not come into consideration of codes, it is therefore important to know what will be the effect on cost of code selected before starting detailed design.

In this chapter, main vessel codes will be described, minimum recommended vessel thicknesses and overall tolerances applied by main vessel users is also given, standardised vessel steels and equivalent materials is studied.

3.2 Design of main shell

3.2.1 Design stress

The process of design has been described by Bickell and Ruiz (2 and 3) who also included a comparison between the main design codes in common use. A more recent comparative study between the rules set up by the various design codes was published by Poynor (4), while a detailed description of the criteria for the selection of stresses and of the rules for the dimensioning of the pressure vessel components is found in (Ref.5 and 6). Tables listing equivalent materials have been included in the national standards and are commonly used in industry, (Ref.7, 8, 9 and 10).

Codes define the design stress by applying a factor of safety to the strength properties of the material. This factor is applied to ultimate tensile strength or yield point of the material below its creep range. Where the material is to operate at a temperature where creep is of concern, the stress to cause rupture in 10^5 hours, or stress to produce 1% creep in 10^5 hours - whichever the least - is utilized.

Criteria followed by some codes are shown in Table 3.1 and the approximate variation of design stress with temperature in Fig.3.1.

Table 3.1
Design Stress Factors

Code	Yield stress, 0.2% Proof stress σ_Y	Tensile strength σ_R	Stress to rupture after 100,000h σ'_R	Stress to produce 1% strain after 100,000 h σ'_Y
BS 1500	-	4.0	-	-
BS 1515	1.5	2.35	1.5	1.0
ASME viii-1	1.6	4.0	1.67	1.0
ASME viii-2	1.5	3.0	-	-
AD Merkblatt	1.5	2.4	1.5	-
ANC (France)	-	3.0	-	-
ISO	1.4-1.5	2.4	1.5	-

3.2.2 Shell thickness

The most important decision when dimensioning a vessel for a given application consists in the determination of the shell thickness, since this in turn fixes the vessel weight which, as will be seen is often the only consideration when assessing its total cost.

Thicknesses permitted by the design codes, in equations shown in appendix (1) are minimum, in addition, other minimum values are often stipulated by the users or consultants in view of the possible overloads to which vessels may be subjected during transport and erection or assembly to the rest of the plant. Recommended minimum thicknesses are given in Table 3.2, - (Ref.11).

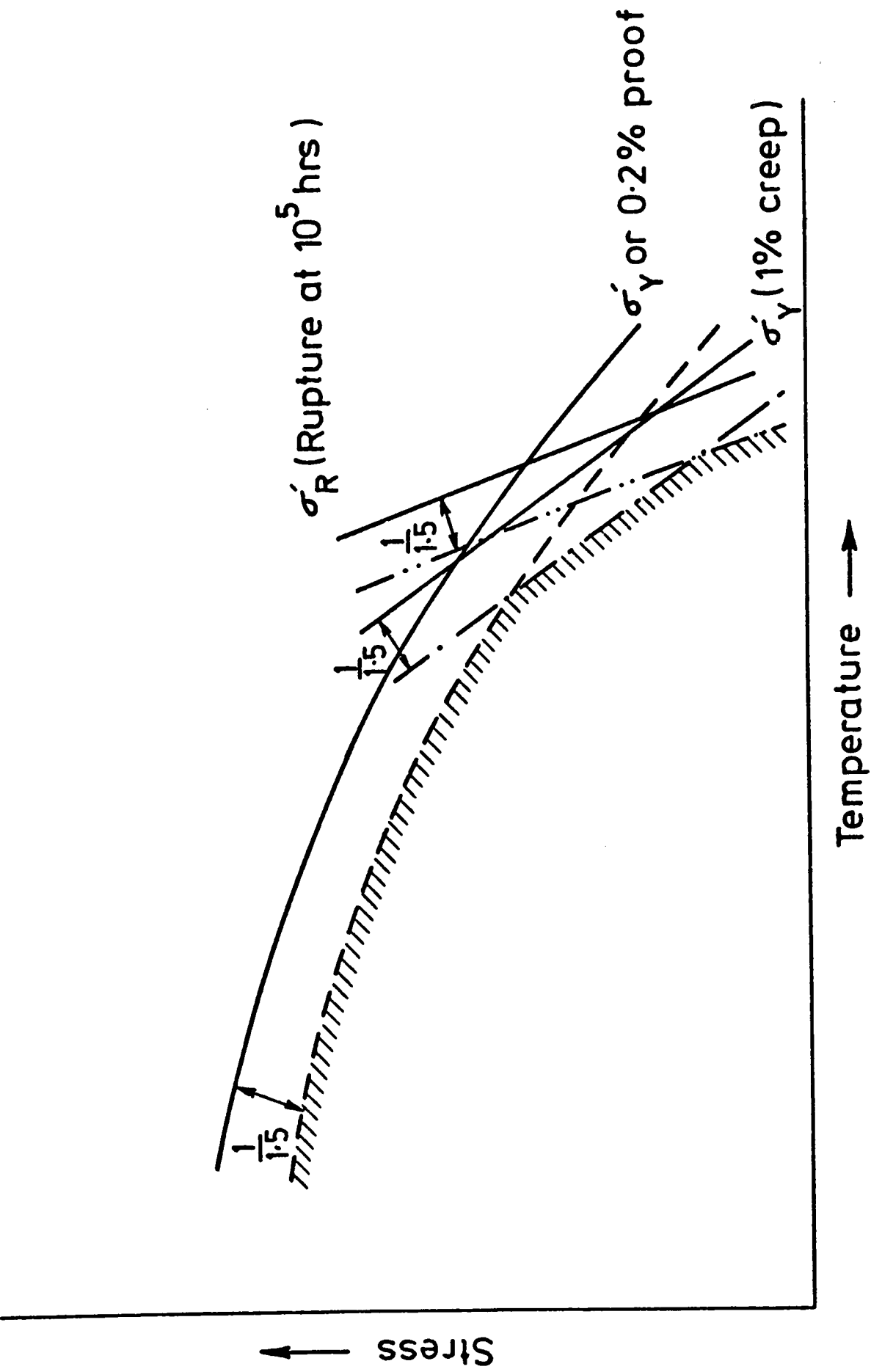


Fig. 3.1
Design stress curve.

Table 3.2Recommended Minimum Vessel Thickness

Diameter up to and including (ft. mm)	Length up to and including	Corroded Thickness (in., mm)
4 ft. (1200)	$L_1 = 20 \text{ ft. (6000)}$	1/8 in. (3)
	$L_2 = 50 \text{ ft. (15000)}$	3/16 in. (5)
	$L_3 = \text{over } 50 \text{ ft.}$	1/4 in. (6)
6 ft. (1800)	L_1	3/16 in. (5)
	L_2	1/4 in. (6)
	L_3	5/16 in. (8)
8 ft. (2400)	L_1	1/4 in. (6)
	L_2	5/16 in. (8)
	L_3	3/8 in. (10)
10 ft. (3000)	L_1	5/16 in. (8)
	L_2	3/8 in. (10)
	L_3	7/16 in. (11)
12 ft. (3600)	L_1	3/16 in. (10)
	over L_2	7/16 in. (11)

Length L is measured from base for vertical vessels and tan/tan for horizontal vessels.

Minimum thickness of skirt support shall not be less than $\frac{1}{4}$ in. (6).

3.3 Design of opening reinforcements

Apart from the main shell thickness, the other aspect in which Design Codes may influence the overall weight of the vessel is in the determination of the amount of reinforcement of openings and of connections between nozzles and vessels. Reference is made to the discussion of the design rules in (Ref.5) and to the comparison between the rules of BS 1500 (area replacement) and AD Merkblatt (weakening factor) in (Ref.3), while a more complete study was reported by Chukwujekwu (12) and Porter (5) of the E/-/3 committee who revised British and other codes concerning amount of compensation around nozzles and openings, Appendix (2).

Rules only differ in essence for isolated openings and branches while they all are virtually identical when dealing with groups of openings in close proximity. This means that the relative reduction of the total weight, and hence of the cost of the vessel of a Design Code demanding less compensation for isolated openings than another, is seldom as important as it would appear at first sight. It should be noted that the requirements of the BS 1515 and AD Merkblatt are similar and less demanding than those of the ASME viii and BS 1500 Codes.

There are situations where the judicious departure from a code is beneficial. For instance, a significant saving in weight with respect to the conventional ASME viii flanges may be achieved by using self sealing flangeless closures, as shown in (Ref.13) and illustrated in Fig.3.2 (Ref.14). Even when designing within the scope of the ASME rules, some freedom is available for the optimization of a given configuration. One must however recognise a natural reluctance on the part of the users and of insurance organisations to accept radical departures from a widely accepted code and to demand considerable supporting evi-

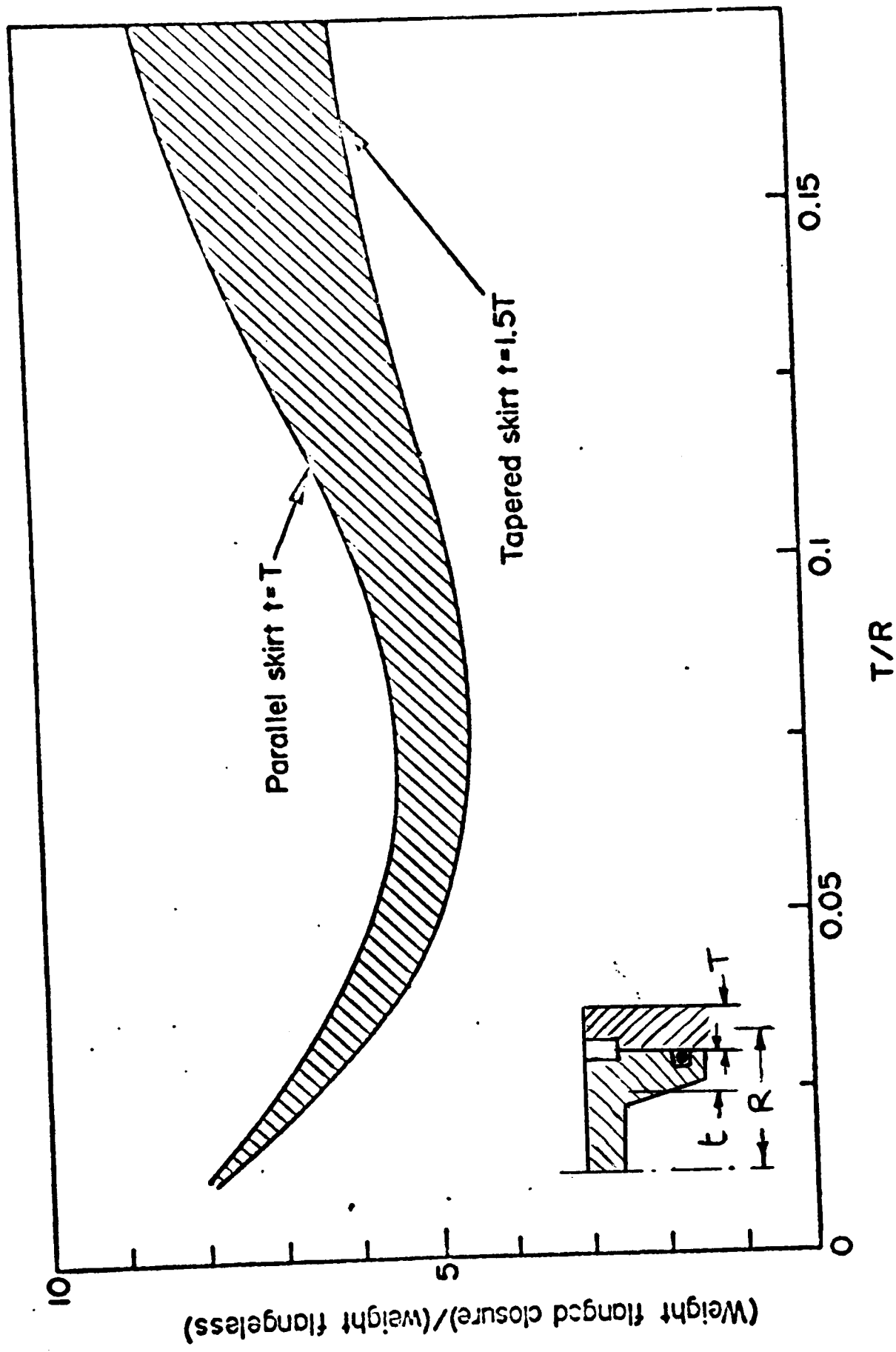


Fig. 3.2

dence whenever such departures are suggested by designers or fabricators. The costs involved can only be estimated for each particular problem.

3.4 Vessel Tolerances

The reason why geometrical tolerances are specified for pressure vessels is twofold:-

- (a) to limit stresses due to out-of-roundness, joint misalignment, and
- (b) to allow the free play between moving parts such as control rods in nuclear reactor vessels, stirrers in chemical reactors, etc.

Tight tolerances also characterise the quality and workmanship of the manufacturer, who is more likely to exercise equal care in observing a high general standard of quality for all other aspects of construction.

Besides the manufacturing tolerances presented in the design codes, such as ovality of cylinders, deviations from straight lines along cylinder generators, deviations between measured and nominal outside diameters, ratios of wall thickness to diameter - see Appendix (3) - contractors and buyers often specify limits considerably more demanding than the tolerances specified by the codes. The following limits, illustrated by reference to Fig.3.3 are typical of commercial practice. Numbers in brackets are dimensions in mm.

1. In addition to ASME code tolerances, tolerance from nominal inside shell diameter is measured by external strapping shall be given as; $\pm 1/8$ in. (3) for internal diameters < 4 ft. (1200), $\pm 3/16$ in. (5) for diameters > 4 ft. to 7 ft. (1200 to 2100), $\pm 1/4$ in. (6)

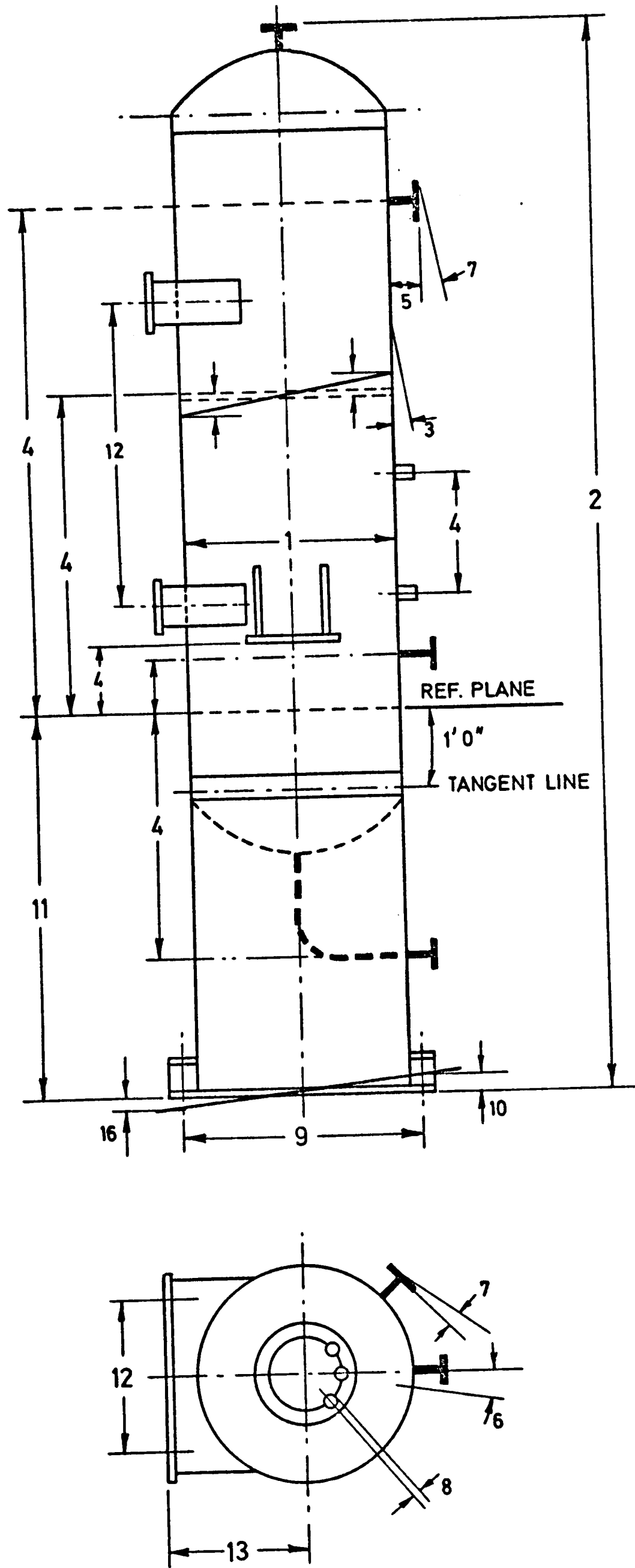


Fig. 3.3.

for diameters > 7 ft. to 16 ft. (2100 to 4800) and $\pm 5/16$ (8)
for diameters $\pm 16'$ (4800).

2. Length may vary $\pm 1/64$ in. (0.5) per 1 ft. (300) but not more than $\pm 1/2$ in. (13) whichever is smaller.
3. Outside surface of cylinder may be out of alignment not more than $1/4$ in. (6) at any point along a straight line 20 ft. (6000) long, but not more than $3/4$ in. (19) for any length.
4. Elevations may vary $\pm 1/2$ in. (13) for manholes, $\pm 1/4$ in. (6) For nozzles and $\pm 1/8$ in. (3) for tray and other internal supports, except that manholes and nozzles at trays may not vary more than $\pm 1/8$ in. (3) from adjoining tray locations. The distance between instrument connections shall not vary by more than $\pm 1/8$ in. (3) centre to centre.
5. Projection of flange face from shell may vary $3/16$ in. (5) for nozzles and $1/2$ in. (13) for manholes.
6. Circumferential deviation from true orientation of nozzles, manholes and supports shall not exceed $1/8$ in. (3) measured along perimeter of shell.
7. Horizontal and vertical deflection of nozzle flanges faces or supports from planes normal to nozzle centre lines or parallel to vessel centre line shall not be more than $\pm 1/2$ degree.
8. Bolt hole orientation of nozzles may vary $\pm 1/16$ (2) at bolt circle.
9. The base ring bolt circle diameter may vary $3/16$ in. (5) for any diameter measured at points 90° apart, $3/16$ in. (5) between holes. Or, $\pm 1/8$ in. (3) for inside diameter < 4 ft. to 7 ft. and $\pm 1/4$ in. (6) for inside diameters of 7 ft. or more.

10. Base or support lugs may not be out of level by more than $\pm 1/8$ in. (3) for diameters < 4 ft., $3/16$ in. (5) for > 4 ft. to 7 ft. and $\pm 1/4$ in. (6) for diameters > 7 ft.
11. Distance from base to reference plane may vary $\pm 1/4$ in. (6).
12. Distance between centre line to centre line of bolt holes in supports for horizontal vessels may vary $\pm 1/8$ in. (3).
13. Distance between centre line of horizontal vessel and bottom of support may vary $\pm 1/4$ in. (6).

3.5 Standardized pressure vessel steels

Classification of the pressure vessel and the vessel material depend in most cases - as shown above - on the service conditions and the contained liquid, i.e. liquid temperature and its corrosive effect at service temperature.

Ferrous materials which are usually used in the construction of a conventional pressure vessel, are mainly as follows (3);

- a. Carbon steel, the tensile strength of carbon steel depends on the amount of carbon which must be limited to maintain good weldability and good toughness. Carbon steels are the cheapest and most commonly used materials. Their properties may be improved by the addition of elements which act as deoxidizers such as manganese and silicon, or as grain refiners such as aluminium and boron. A further improvement may be achieved by the process of fabrication, e.g. by using the electric arc process which allows controlled environment.
- b. Low alloy steels. When the tensile strength is to be increased by increasing the carbon content, the steel ductility diminishes. In order to improve the strength of the material whilst maintaining

Table 3.3

Material specifications	ASME specification	German equivalent	British equivalent
<u>Carbon steel</u> (Low and intermediate strength carbon steel)	SA - 285 - A) SA - 285 - B) SA - 285 - C SA - 515 - 55 SA - 516 - 55	HI - DIN 17155 HII - DIN 17155 HII - DIN 17155 Ast.41 17135	1501 - 151 gr. 23 A, B 1501 - 151 gr. 26 A, B 1501 - 151 gr. 26 A, B 1501 - 224 26 A, B
Carbon steel plates for inter-mediate and higher temperature service	SA - 515 - 60 SA - 516 - 60 SA - 515 - 65 SA - 516 - 65 SA - 515 - 70 SA - 516 - 70	HIII - DIN 17155 Ast.45 17135 HIV DIN 17155 Ast.45 DIN 17135 19Mn5 DIN 17155 Ast.52 DIN 17135	1501 - 161 28 A, B 1501 - 224 26 A, B 1501 - 221 30 A, B 1501 - 224 30 A, B 1501 - 221 32 A, B 1501 - 224 32 A, B
<u>Low alloy steels</u>	SA - 204 - A SA - 204 - B SA - 204 - C	15 Mo 3 DIN 17155 16 Mo 5 DIN 17155	1501 - 240
C $\frac{1}{2}$ Mo	SA - 302 - A SA - 302 - B SA - 302 - C	20 Mn Mo 45	- - -
Mn $\frac{1}{2}$ Mo, Mn Mo N; steel plates	SA - 387 - B (A) - 387 - C (ANT) - 387 - D (ANT) - 387 - E (ANT)	13 Cr Mo 44 DIN 17155 - - - - 10 Cr Mo 910 -	1501 - 620 27A 1501 - 621 A 1501 - 622 31A - - -
Cr Mo steel plates; 1 Cr $\frac{1}{2}$ Mo 1 $\frac{1}{4}$ Cr $\frac{1}{2}$ Mo Si 2 $\frac{1}{4}$ Cr $\frac{1}{2}$ Mo Si 3 Cr 1 Mo			

Table 3.3

Material specifications	ASME specifications	German equivalent	British equivalent
High alloyed steel plates	SA - 240 - 405	X 7 Cr AL 13 (A) DIN 17440	BS 1501 - 405 S17
	SA - 240 - 304		
	SA - 240 - 304L	X 5 Cr Ni 189 (Q)	BS 1501 - 304 S15
	SA - 240 - 317	X 5 Cr Ni Mo 1810 DIN 17440	BS 1501 - 316 S16
	SA - 240 - 321	X 10 Cr Ni Ti 189 DIN 17440 (Q)	BS 1501 - 321 S49
	SA - 240 - 347	X 10 Cr Ni Nb 189 DIN 17440	BS 1501 - 347 S49
	SA - 240 - 405	X 7 Cr 13	BS 1501 - 403 S17
	SA - 240 - 410	X 10 Cr 13	BS 1501 - 403 S17
	SA - 240 - 430 B	X 8 Cr 17	
Low temperature steels			
		X 2 Cr Ni 189	BS 1501 - 304 S12
		X 2 Cr Ni Mo 1810	BS 1501 - 316 S12
		X 10 Cr Ni Mo Ti 1810	BS 1501 - 312 S17
	SA - 203 - D	10 Ni 14	
	SA - 203 - E	16 Ni 14	BS 1501 - 503
	SA - 353	Dukten 900	
	SA - 514 - A	N - A - XTIRA	
	SA - 517 - A		
	SA - 543 - A	HY 80	
	SA - 543 - 2	HY 100	
	SA - 508 - 2	22 Ni Mo Cr 37	

good ductility, it is possible to replace the carbon by other elements such as chromium, nickel or molybdenum. The range of low alloy steels commercially available covers materials for low temperature service, impact tested, creep-resistant material, usually chromium-molybdenum steels, steels with increased resistance to hydrogen.

c. High alloy steels, (stainless steels, 18 Cr - 8 Ni). For severe conditions, i.e. - 200 °C or above 500 °C. Refractory steels (25 Cr - 20 Ni), can be used for high temperature conditions above 550 °C.

The selection of material also depends to a certain extent on the size of the vessel. Large vessels as well as high towers and columns will clearly demand the use of high quality materials while small simple vessels may not need to be as demanding. Thick vessels, complex geometries, and the nature of the fluid contained would all have some effect on the likelihood of an accident and on its severity. Vessels can be classified as follows:

- (i) Conventional small size vessels with one or two nozzles and manholes. These are usually thin vessels (15 - 35 mm). used in handling and storing petrochemical products.
- (ii) Thick vessels, medium or large size vessels containing large number of nozzles and openings, boiler and steam drums.
- (iii) Thick or sometimes thin vessels containing large items of internals and externals, such as dryers, petrochemical reactors.
- (iv) Very thick high pressure vessels for the use in power generation, nuclear reactors etc.
- (v) Nuclear power presents some special characteristics, given the seriousness of a possible failure, and the design of nuclear vessels

is therefore subjected to very strict regulations compared with conventional vessels. The methods of design and the codes used for such vessels put them in a class of their own in which the paramount consideration is safety.

Selection of material and quality assurance are facilitated by using standardized materials, and most national design codes contain references to such standards. Like the design rules themselves, materials standards differ quite significantly from one country to another and even, within the same country, from one fabricator or user to another. It is therefore important to prepare equivalence tables based on similarities between the chemical composition, heat treatment, structure, mechanical properties and resistance to corrosive agents. In the following Tables 3.3 and 3.4, a correlation between American, German and British steels is given, based on chemical composition.

Figures 3.4 to 3.12, illustrate the variation of design stress with temperature for a number of materials in accordance with British, American and German specifications, it is clear that, from the viewpoint of weight alone, the design code which allows the highest stress for a specified material and temperature is to be preferred. Most widely used vessel steels as given in above codes are presented in Appendix (4), with their chemical composition, Refs. (15 to 24).

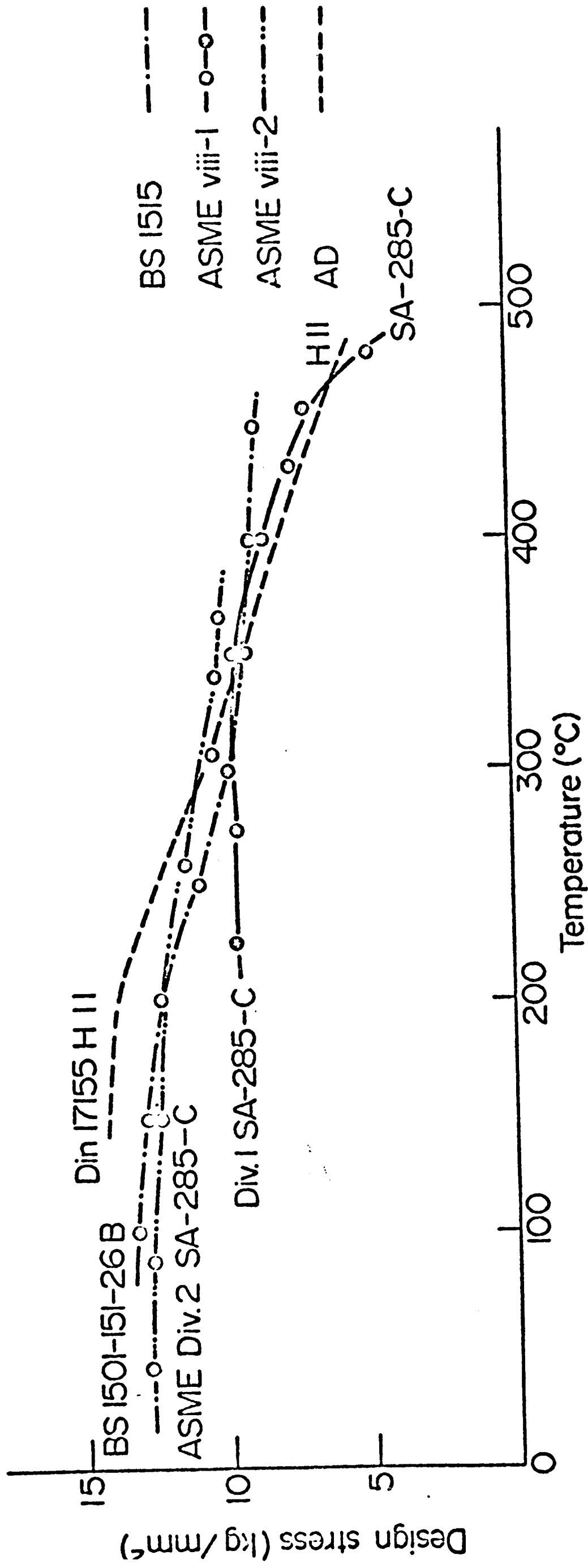


Fig. 3.4 Design stress against temperature in accordance with ASME viii Div.1 and Div.2, AD Merkblätt, and BS 1515 for carbon steel plates.

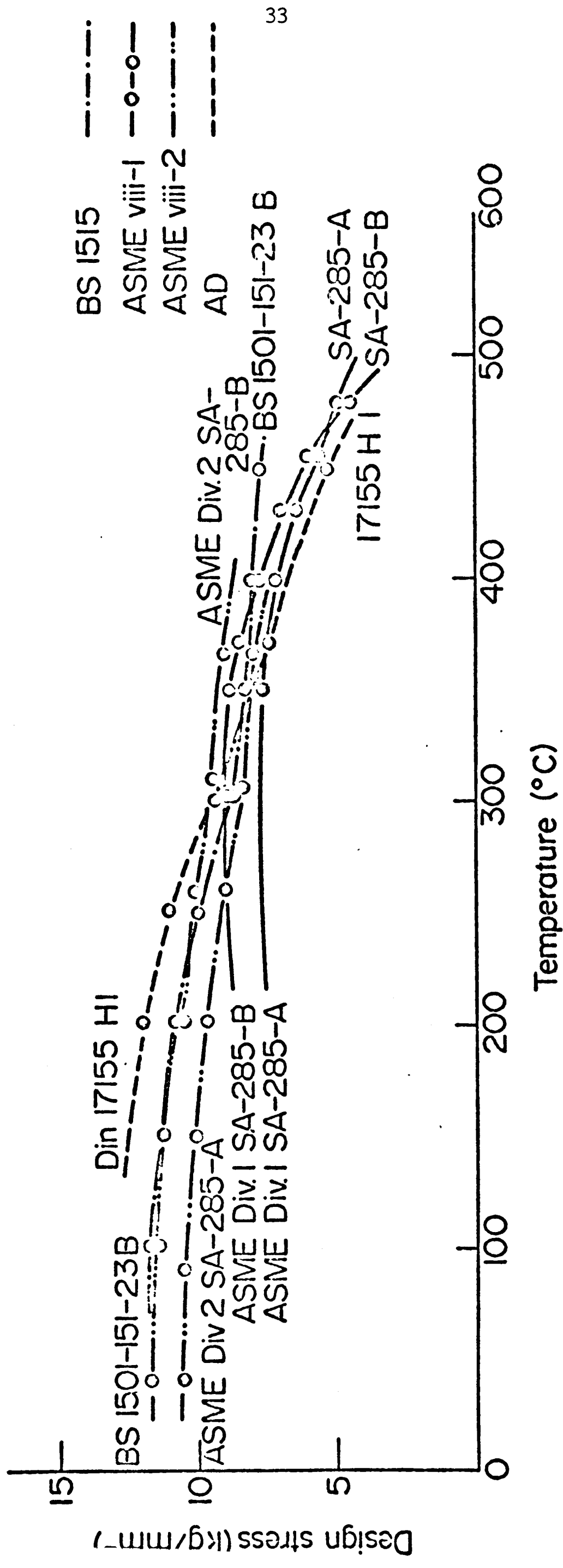


Fig. 3.5 Design stress against temperature in accordance with ASME viii Div.1 and Div.2, AD Merkblätt, and BS 1515 for carbon steel plates.

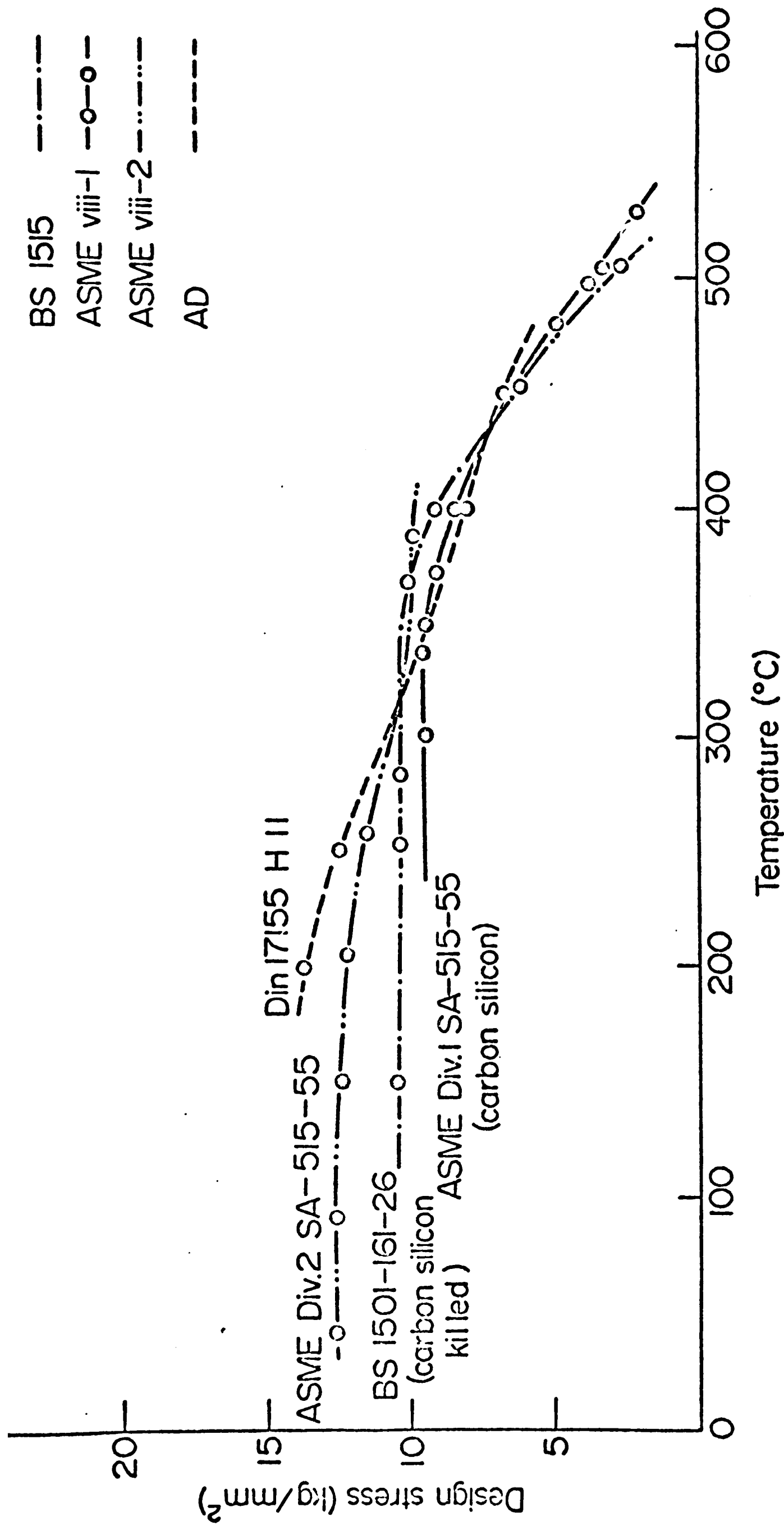


Fig. 3.6 Design stress against temperature in accordance with ASME VIII Div.1 and Div.2, AD Merkbblatt, and BS 1515 for carbon silicon killed steel plates.

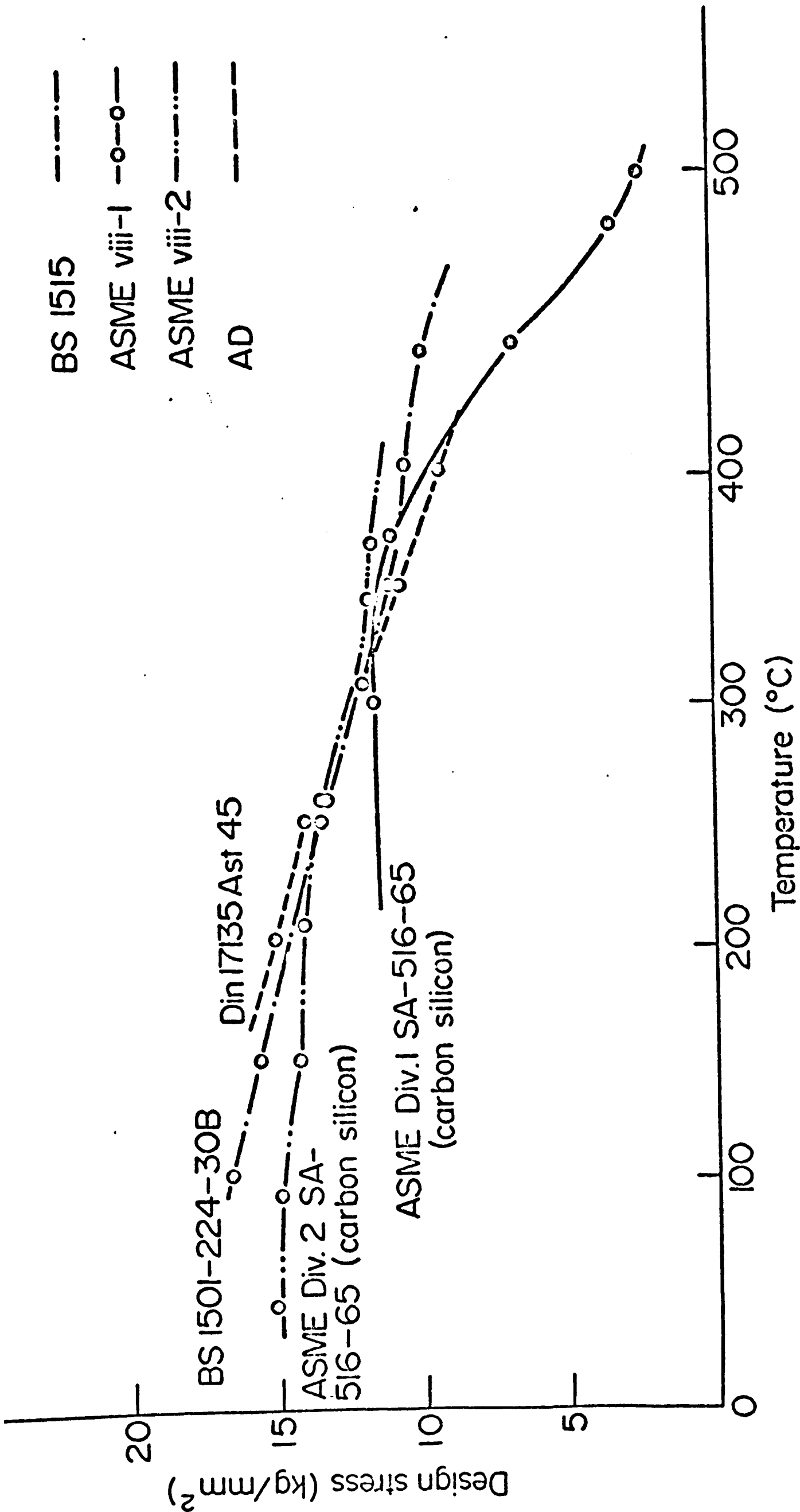


Fig. 3.7 Design stress against temperature in accordance with ASME viii Div.1 and Div.2, AD Merkblätt, and BS 1515 for carbon silicon killed steel plates.

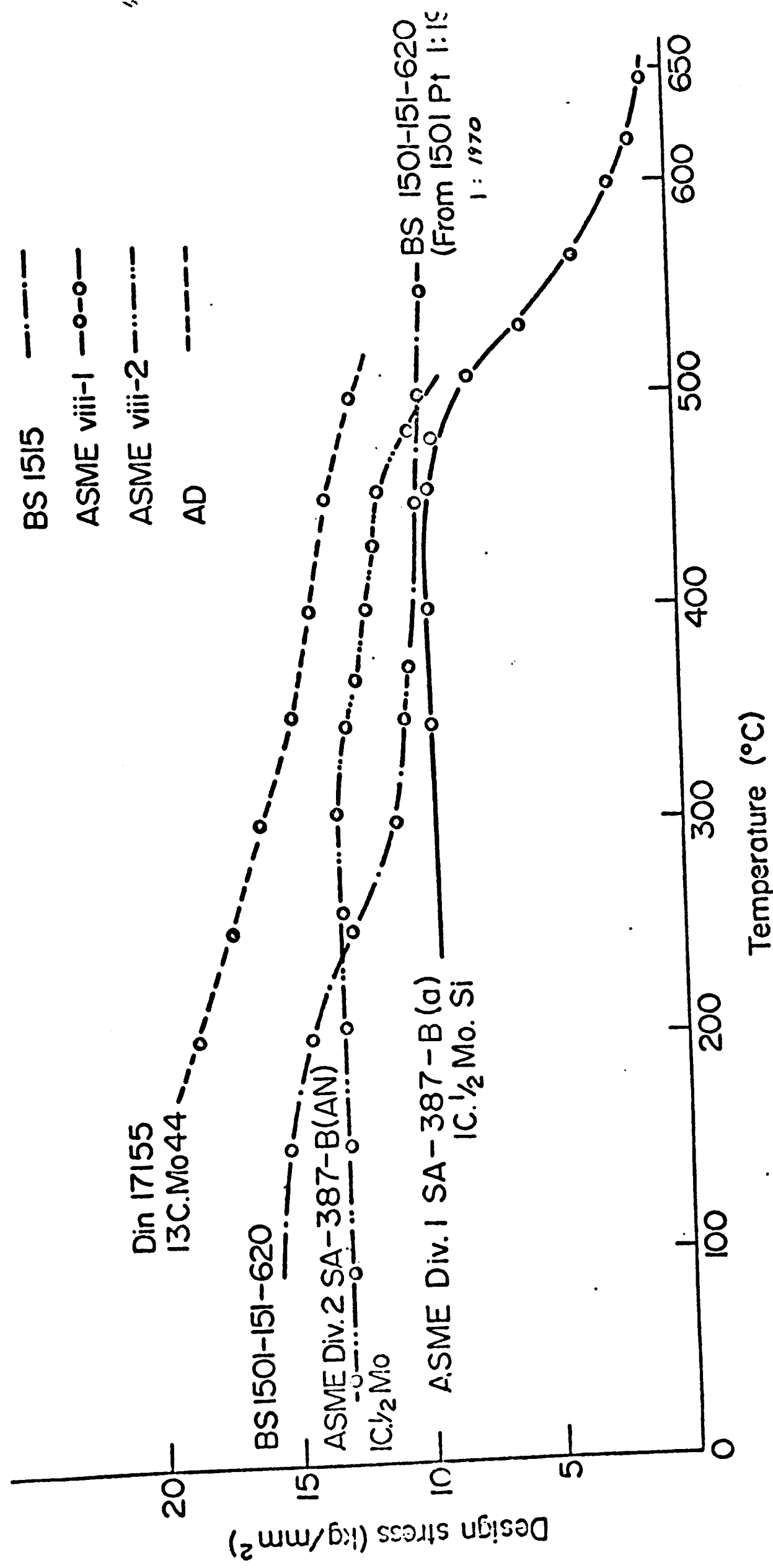


Fig. 3.8 Design stress against temperature in accordance with ASME viii Div.1 and Div.2, AD Merkblätt, and BS 1515 for Cr Mo steel plates.

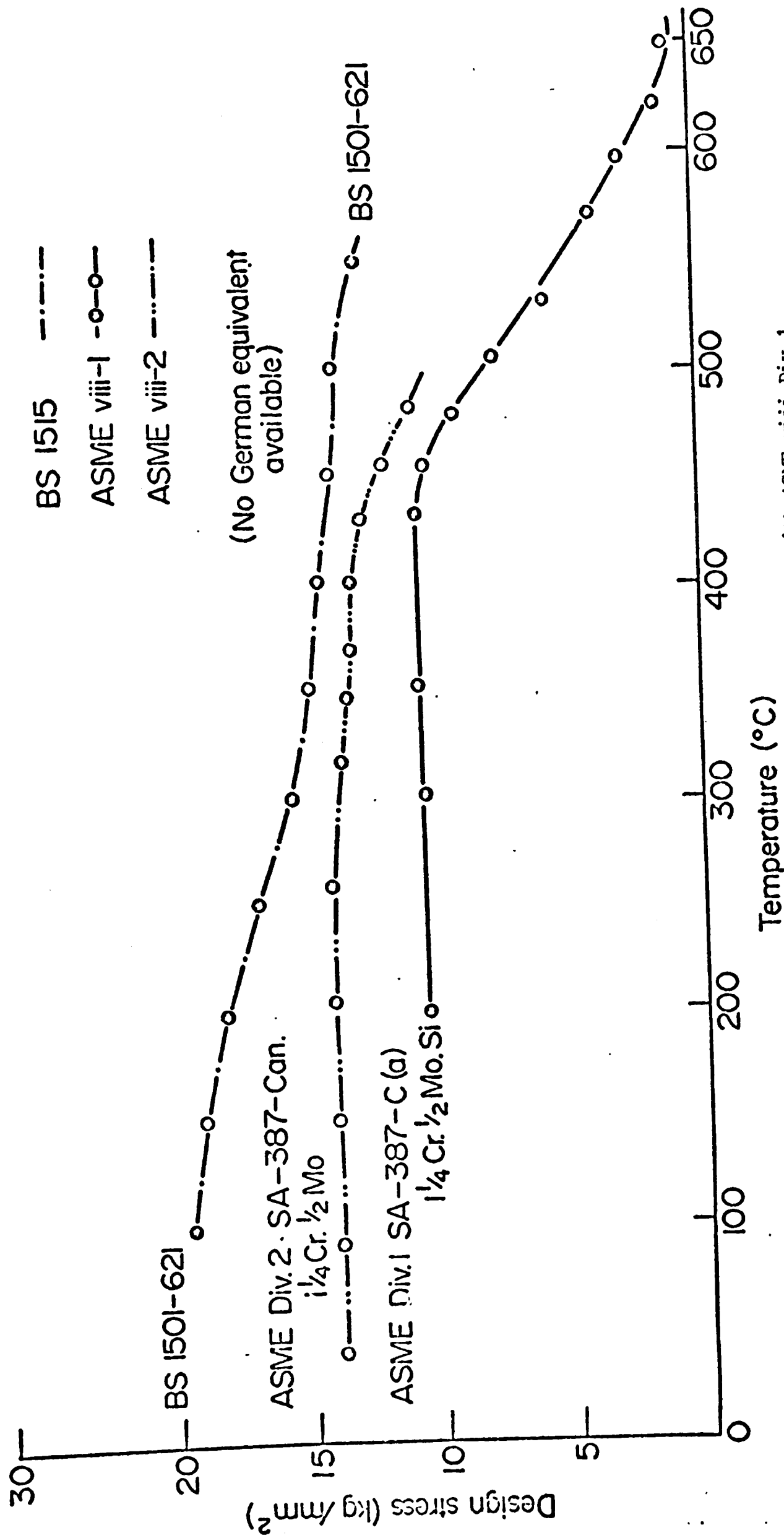


Fig. 3.9 Design stress against temperature in accordance with ASME VIII Div.1 and Div.2, AD Merkblätt, and BS 1515 for Cr Mo steel plates.

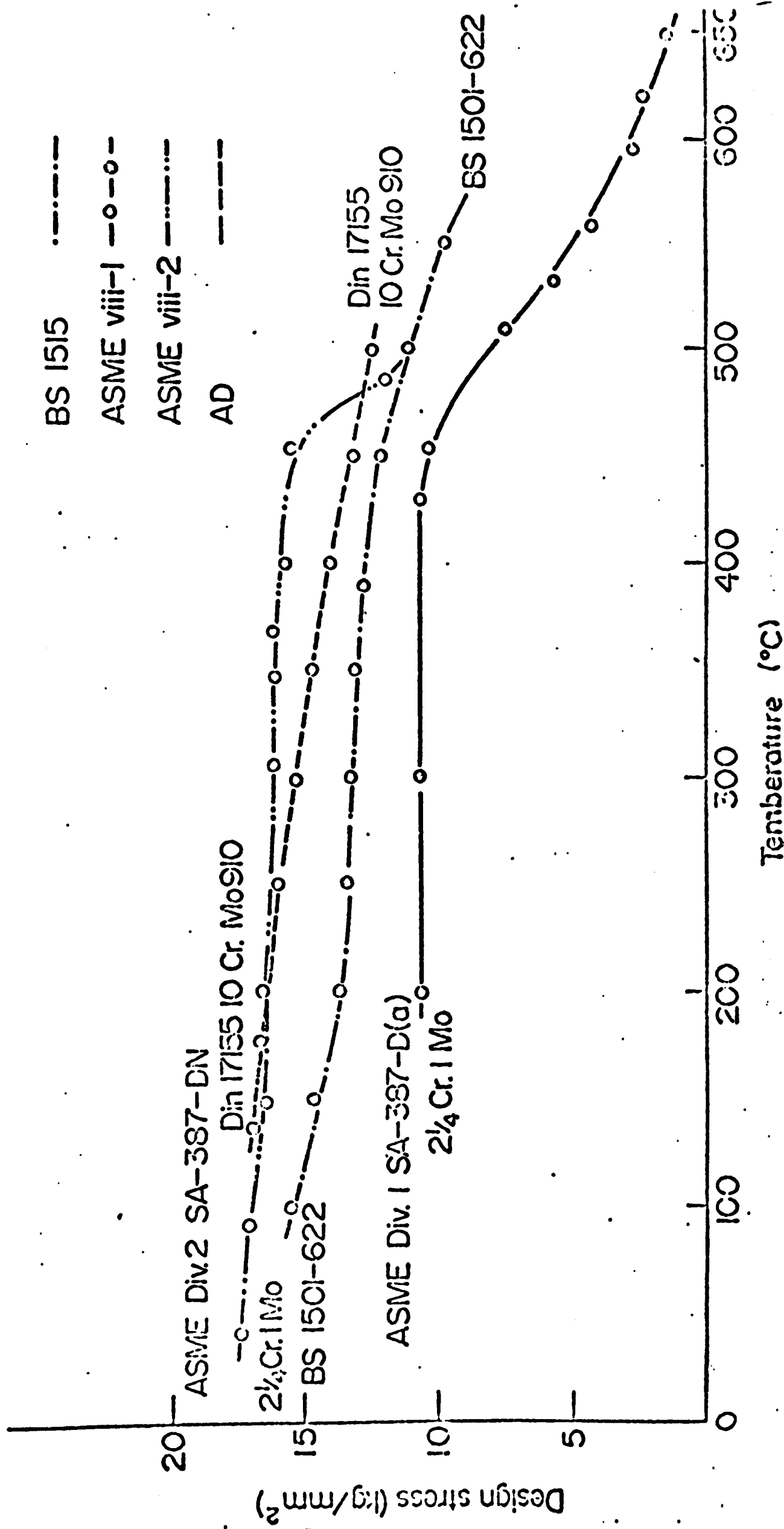


Fig. 3.10. Design stress against temperature in accordance with ASME VIII Div. 1 and Div. 2, AD Merkblätt, and BS 1515 for Cr Mo steel plates.

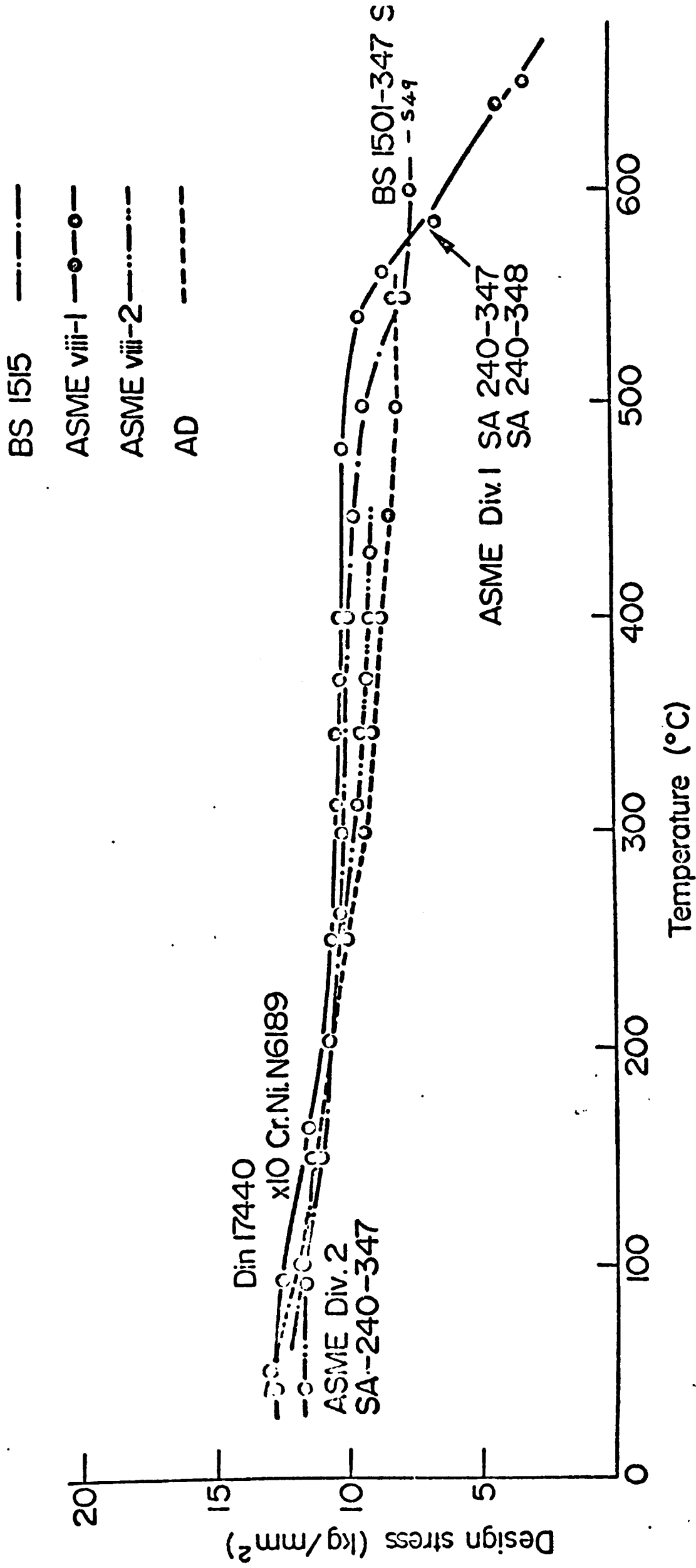


Fig. 3.11 Design stress against temperature in accordance with ASME viii Div.1 and Div.2, AD Merkblätt, and BS 1515 for austenitic chromium-nickel (niobium stabilised) steel plates. (18 Cr-10 Ni-Mn-Nb (8-10 x C%))

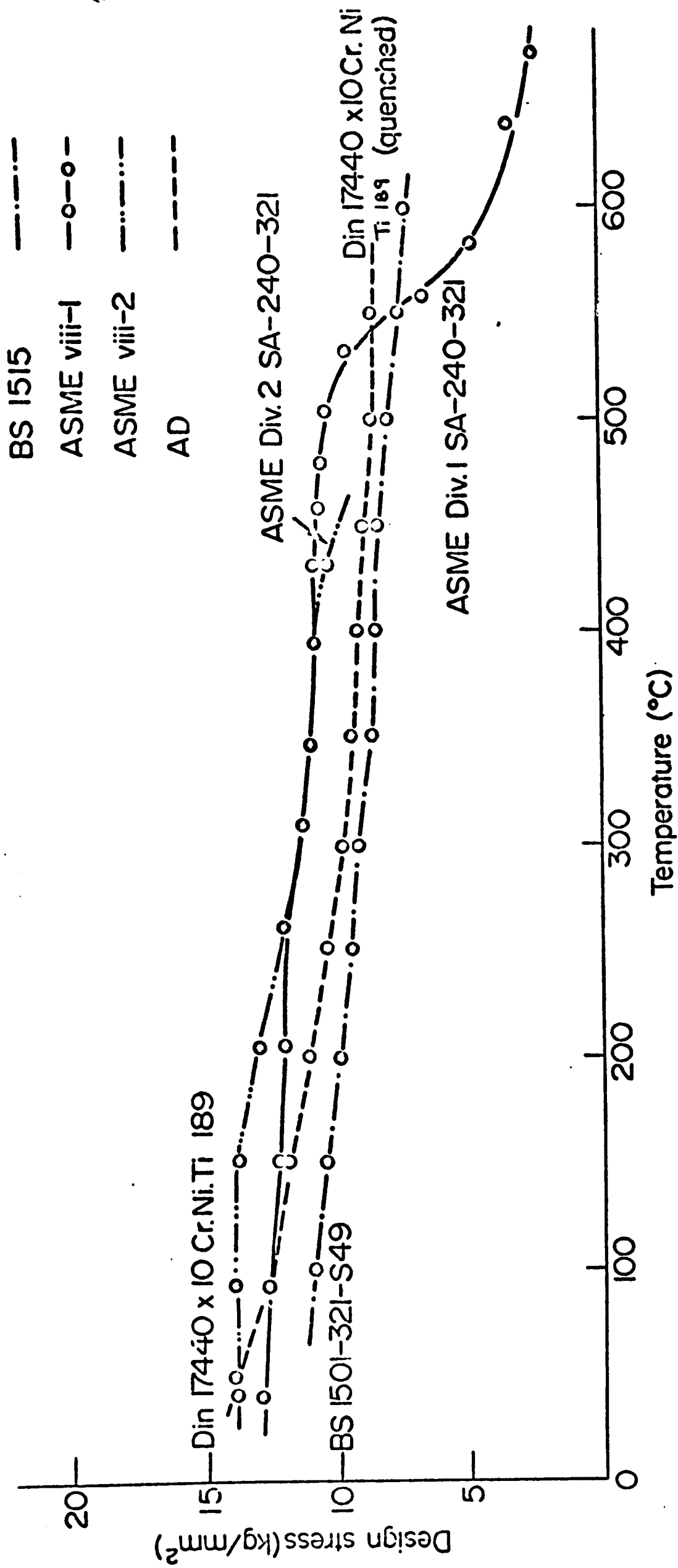


Fig. 3.12 Design stress against temperature in accordance with ASME VIII Div.1 and Div.2, AD Merkblätt, and BS 1515. For stabilised austenitic chromium - nickel steel (titanium stabilised) (18 Cr-10Ni-2Mo-Ti (5-10 x C%)).

3.6 Conclusions

For an efficient use of the material to be possible, a low safety factor which would result in a thin wall vessel, with a high nominal stress, is essential. This is only possible, if safe operation is to be ensured, when it is coupled with a high standard of quality, backed by adequate inspection techniques and design. In the recent years the general trend has been to increase the allowable design stress, provided that suitable care is taken in design details and inspection, in the assessment of the most probable service loading and in ensuring that the maximum loads for which the vessel is designed are not in fact exceeded, backing the design when necessary by means of stress analysis and strength evaluation. This trend is clearly represented in the existence, side by side, of codes such as BS 1500, BS 1515 in Britain and ASME section viii, Division 1 and 2 in U.S.A. A penalty is to be paid when using more advanced codes is that the design effort increases, accompanied by a corresponding tightening up of the quality control.

Codes which base allowable stresses on material yield strength result in reduced vessel weight and hence cost, since thinner plates require less welding than thicker plates and hence, apart from the reduction of weld metal, chipping costs are also kept to a minimum. Reduced weight also results in lower transport and erection costs.

Referring to Fig.3.4 to 3.12 it will be seen that:-

(a) BS 1515, produce economical advantage in vessel weight reduction, below 250 °C, at higher temperatures ASME viii-1, starts to result in thinner vessels.

(b) At temperatures of 350/400 °C, where the possibility of failure by creep starts to limit the design stress, the ASME code is less conservative than the rest of the codes, and at about 480 °C it permits a working stress about twice that allowed by the German code.

Thus, when designing vessel to AD Merkblatt, it becomes economic to use alloy plates at temperatures substantially below the permitted limit for carbon steel, i.e. at about 500 °C, whereas for ASME code the reverse is the case.

Most codes are generally the same in inspection and testing procedures, the only differences that lead to select one code than another, may be, that low design factor codes require steel mills to guarantee the hot steel properties - steels that do not have guaranteed properties cannot be used on stamped coded vessels. BS 1500, BS 1515 and A-D Merkblatt, insist that coupon tests be witnessed by their inspector, while ASME accepts test certificates only. European code inspectors sometimes insist on witnessing mill tests before starting vessel fabrication, and to perform some stage tests while production is in progress. This in most cases delays production. Cost of inspection at steel mills usually increase material prices by up to 20%.

ASME codes give boundaries of acceptance, i.e. what welds to accept and what not to accept by using porosity charts, differing from European codes which have no acceptance limits. Present thinking on the revision of the British codes - BS 1515 and ISO, which are either in operation or in draft - tends towards the "fitness - for - purpose" approach. This philosophy may result in relaxations on cer-

tain types of defects (25).

In chapters 4 and 5 codes' differences on design, material thickness, inspection and testing will be shown in terms of vessel cost.

CHAPTER 4

CHAPTER 4Production Cost Analysis4.1 Introduction

In this chapter, the production process described in Figs. 2.2, 2.3 and 2.5 of Chapter 2 is analysed in greater detail, the time taken by each operation is found from the information provided by several manufacturers and the effect on overall cost of the times required is considered. The effects of material, Design Code and labour costs on the total cost are also studied.

It must be noted that the information on which this chapter is based was obtained by studying vessels manufactured within the last 3 or 4 years and, given the current high level of inflation, the cost of materials in particular is considerably in excess of the one that has been considered here. Rather than introducing an arbitrary correction factor, subjected to periodic review, it has been preferred to leave the costs as they were when the vessels were being made. To a lesser extent, the same is true of labour costs which, again, have not been corrected for inflation. All vessels whose main dimensions, material, capacity and weight are listed in Table 4.1 have been included in this study, although only about 20 vessels were sufficiently well documented to provide the detailed information required in some cases.

The present trend towards increasing material costs does not in fact conflict with the findings of this investigation, it merely emphasises the need for more efficient use of materials while the corresponding increase in labour costs implies a parallel importance in the planning of production.

Table 4.1
Vessel fabrication costs*

Vessel No	Material	Length (L) Metres	Diameter (D) Metres	Thickness (T) (mm)	Capacity (C) M ³	Weight (W) kg	Vessel cost (S) £	Cost/capacity £/M ³	Cost/wt. (£/kg) £ x 10 ⁻³
1	CS-A-212-B	6	3.6	36.5	66	33200	6348	96.5	191
2	" " "	7.8	3.3	31.7	70	38800	10087	110.9	260
3	" " "	7.8	3	31.7	59	34400	9022	153	262
4	" " "	6	2.4	30	28.5	18200	3524	124	194
5	" " "	4.8	2.4	28.6	23	12900	2298	100	178
6	CS-A-285-C	2.55	1.5	28.8	4.57	4700	1395	305	297
7	CS-A-212-B	3.6	3.45	31.7	35	21900	4502	128	205
8	" " "	5.1	3.3	33	45	28900	7551	168	261
9	CS-A-285-C	2.4	1.35	19	3.47	3000	487	140	163
10	"-A-201-B	2.7	1.35	12.7	3.97	2200	629	158	286
11	CS-A-516-65	12	3.6	54.5	129	82700	13366	103	162
12	" " "	5.7	2.4	34.3	27.5	22400	3031	111	135
13	" " "	10.5	3	36.3	75.8	41000	5255	69.2	128
14	CS-A-285-C	9.9	2.7	19	58	18100	2912	50.5	161
15	" " "	9	3.9	14.3	111.3	20300	4410	40	217
16	" " "	2.4	0.9	9.75	1.56	1200	490	325	408
17	CS-516-65	6	2.85	42.6	39	29900	5001	130	168
18	" " "	8.7	2.55	38	41.5	29700	3948	95	133

* Costs based on the feedback information after the completion of each vessel

Table 4.1 (continued)

Vessel No	Material	Length (L) metres	Diameter (D) metres	Thickness (T) (mm)	Capacity (C) M ³	Weight (W) kg	Vessel cost (£)	Cost/capacity £/M ³	Cost/wt. (£/kg) £ x 10 ⁻³
19	CS-A516-65	6	2.7	41	34.5	27200	4048	111.7	149
20	BS-1505-151-26A	10.3	2.4	11	47.7	9400	2700	57	288
21	" " "	10.3	2.4	11	47.7	9400	2830	60	300
22	" " "	18.3	1.68	12	40.8	11600	5820	143	500
23	BS-1501-151-28A	2.17	1.13	6.3	2.27	1000	830	367	830
24	" " "	3.75	1.13	6.3	3.94	1340	1110	280	888
25	" " 26A	4.95	1.35	6.3	7.53	1500	869	111.6	580
26	" " "	2.17	1.05	6.3	2.03	1000	776	387	776
27	STE-36 Improved	12.4	1.95	75	38.5	51000	26750	70	525
28	BS-1501-151-28A	3.45	0.975	27	2.87	2680	1631	57	610
29	BS-1501-224-28A	5.7	2.2	60	23	21400	13280	58	635
30	" " "	17.1	2.7	73	101.5	94500	40300	39.5	427
31	STE (Improved)	24	2.87	66.5	163	12700	33700	20.8	265
32	Carbon steel vessel	2.7	0.9	19	1.82		250	137	
33		5.4	2.7	38	32.5		2510	77.3	
34		8.1	2.7	38	49.5		3550	71.6	
35		2.7	0.9	31.6	1.82		400	228	
36		5.4	2.4	31.6	25.6		1890	74	
37		8.1	3	31.6	60.05		3410	57	
38		2.7	1.8	9.5	4.2		390	94	
39		13.5	3	38	100		5930	59.3	
40		29.7	3	25.4	222		9770	44	
41		24.3	2.7	31.6	146.5		7140	49	

4.2 Breakdown of production times

The following example provides an indication of the time and effort required for the completion of a typical medium sized vessel 4 m diameter, 33 m long and 16 mm thickness.

(a) Referring to the chart of Fig.2.2

<u>Operations</u>	<u>Man hours</u>	<u>Man hours as percent of total</u>
1 - 2	35	29.2
2 - 3	5	4
4 - 7	8	6.7
9 - 10	20	16.7
11 - 12	4	3.3
13 - 14	5	4.2
14 - 16	3-4	3.3
16 - 17	20	16.7
17 - 18	2-3	2.5
18 - 19	8	6.7
20 - 21	8	6.7
Total	<u>118-120</u>	<u>100%</u>

(b) Referring to the chart of Fig.2.3

<u>Operations</u>	<u>Man hours</u>	<u>Man hours as percent of total</u>
1 - 2	6	1
2 - 3	48	6
3 - 6	320	41
6 - 7	130	15
7 - 8	80	10
8 - 9	48	6
Part total	<u>632</u>	
Add design analysis and drawings	150	20
	<u>782</u>	<u>100%</u>

(c) Referring to the chart of Fig.2.5

<u>Operations</u>	<u>Man hours</u>	<u>Man hours as percent of total</u>
1 - 2	4	3
2 - 3	2	1.5
3 - 4	4	3
4 - 5	8	6
5 - 6	1	0.8
6 - 7	16	12
7 - 8	8	6
8 - 9	4	3
9 - 10	4	3
10 - 11	8	6
11 - 12	4	3
12 - 13	4	3
13 - 14	4	3
14 - 15	8	6
15 - 16	16	12
16 - 17	8	6
17 - 18	1	0.8
18 - 19	8	6
19 - 20	2	1.5
20 - 21	not applied	
21 - 22	16	12
<u>Total</u>	<u>140</u>	<u>100%</u>

From (a), (b) and (c),

Contractors' engineering analysis represents about 12% of total

Fabrication and detailed drawing	"	"	75%	"	"
----------------------------------	---	---	-----	---	---

Inspection	"	"	13%	"	"
------------	---	---	-----	---	---

The time actually spent in design, (1 - 2, 9 - 12, 14 - 18 in chart Fig.2.2 and detailed drawing by fabricators) is about 20% of the total time.

Most inspectors allow one day inspection per week of vessel fabrication, roughly in agreement with the information above.

4.3 Determination of the cost

An accurate estimation of the cost is only possible after detailed drawings have been produced and fabrication and inspection charts have been drafted. It is, however essential to obtain an approximate estimate at an earlier stage and this may be done by noting that costs depend on the weight of the vessel and on its capacity.

4.3.1 Approximate determination of the cost

Intuitively, it would seem reasonable to expect that the cost of a given vessel is approximately proportional to its weight, since the material cost is likely to remain a fixed proportion of the total cost, within some limits, except for exceptional vessels, either with very thick walls, as in some chemical reactor vessels or with very thin walls as in large oil tanks. For such vessels, the capacity might also be considered to affect the cost. Thus,

in cylindrical atmospheric oil tanks, the actual bulk of the plates that make up each course rather than their weight is likely to cause difficulties. Handling, at site, will increase labour costs and as a result, the cost per unit weight of such a vessel is likely to be higher than for a more compact vessel. Assuming that,

$$\text{Cost} = Aw \quad (\text{£}) \quad (4.1)$$

and

$$\text{Cost} = Bc^n \quad (\text{£}) \quad (4.2)$$

where A, B and n are constants and w and c are respectively the weight in kg and the capacity in m^3 gives some rough guidance for the interpretation of available data.

For the vessels listed in Table 4.1 it is possible to draw the diagrams of Figs. 4.1 and 4.2 giving the cost against weight and capacity respectively. For these vessels, it was found, that the best fit to the data available was provided by taking $A = 0.2$ and $B = 300$ with $M = 0.632$. Histograms of vessel occurrence against cost of vessel per kilogram and per cubic meter are shown in Figs. 4.3 and 4.4 respectively. The largest deviations between the data and the predicted cost from these equations could be accounted for, and were equivalent to $\pm 50\%$. Most of the data - about 70% - fell within a $\pm 20\%$ band of the predicted results. Excessive costs were sometimes due to lack of coordination between the various organisations involved, difficulties in obtaining materials, delivery to site, complicated shapes, inspection delays, etc. It must be mentioned that the information was collected from vessels completed or under completion between (1970-73) and has not been corrected to take inflation into consideration.

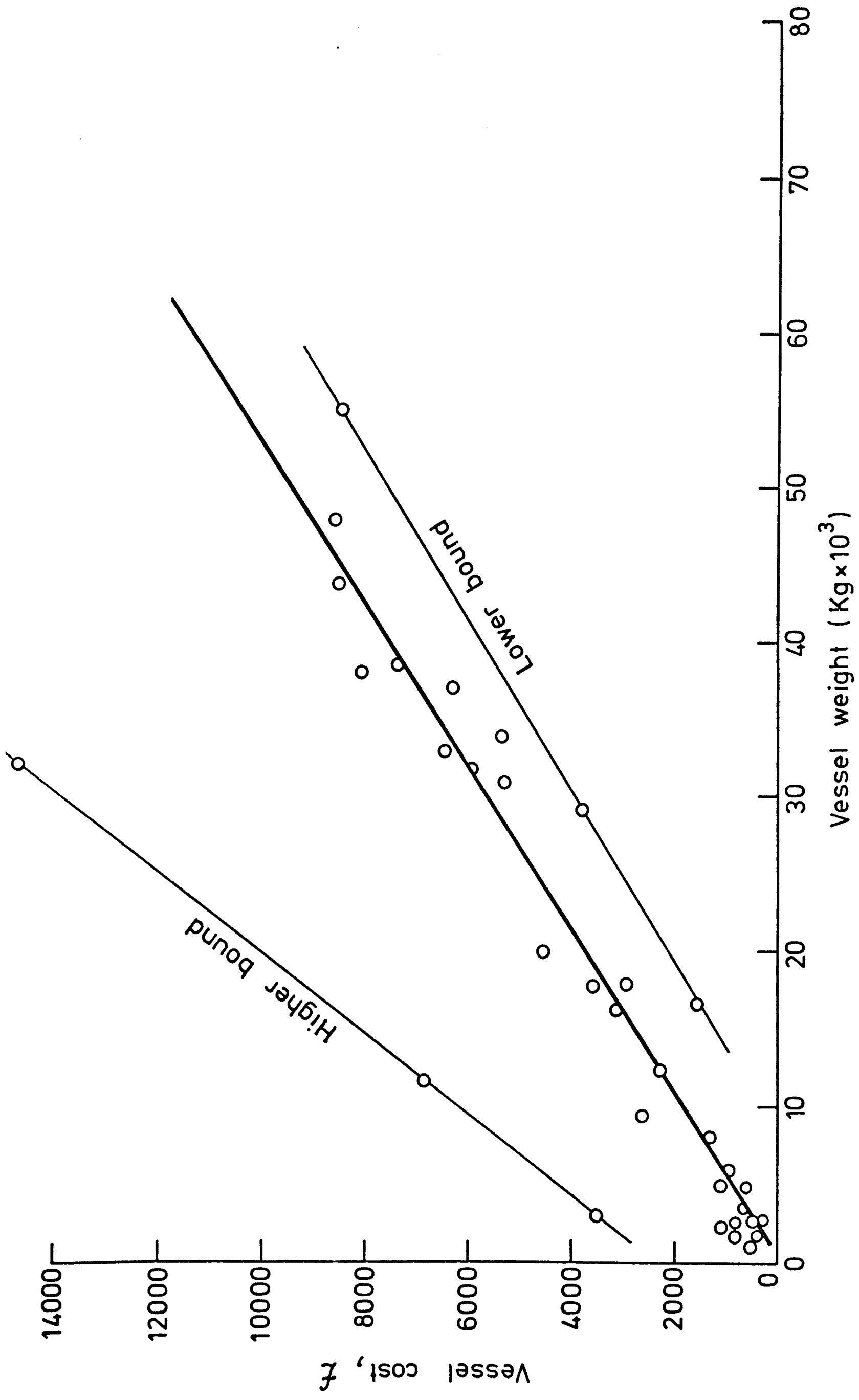


Fig. 4.1

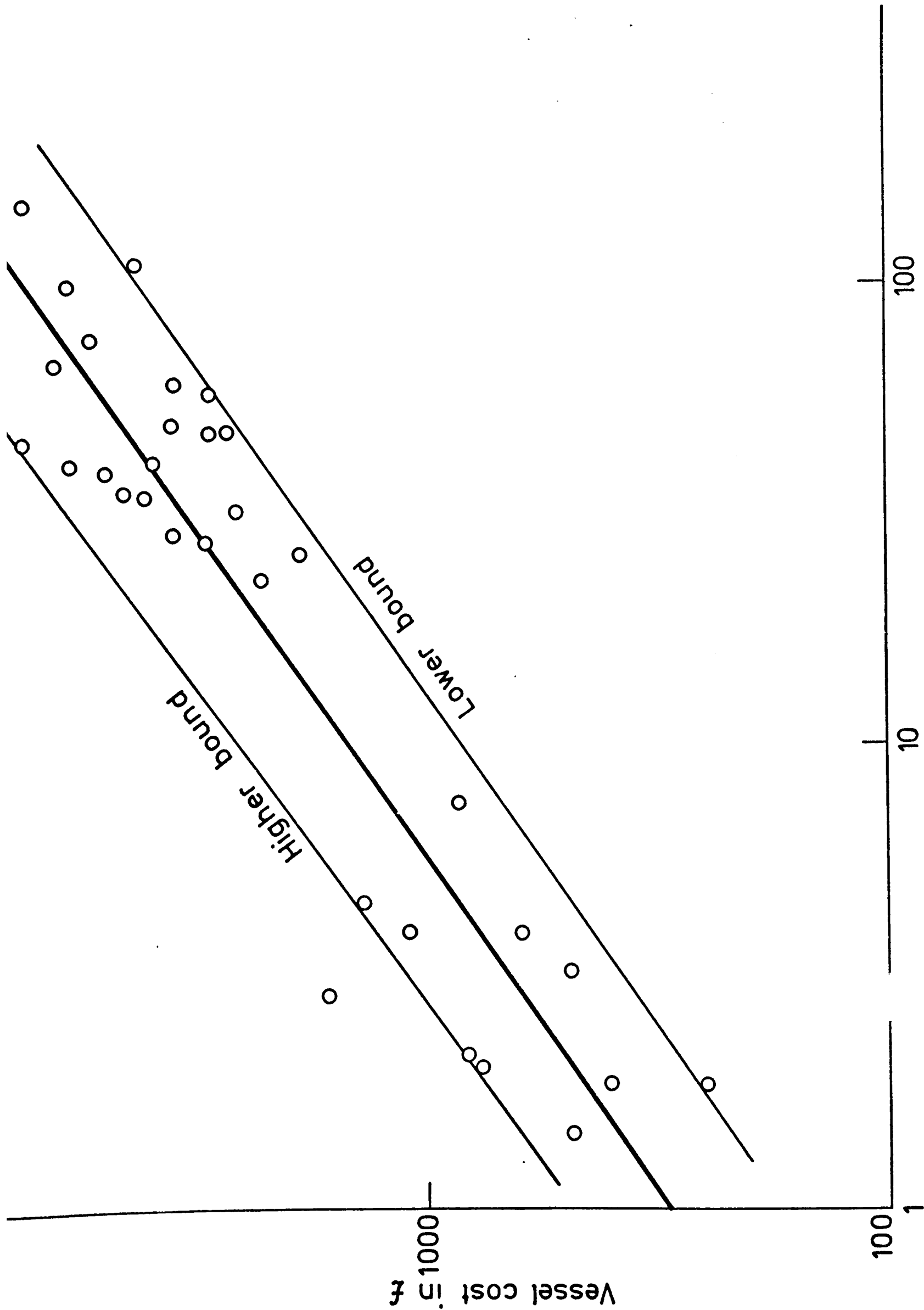


Fig. 4.2 Capacity (cubic meters)

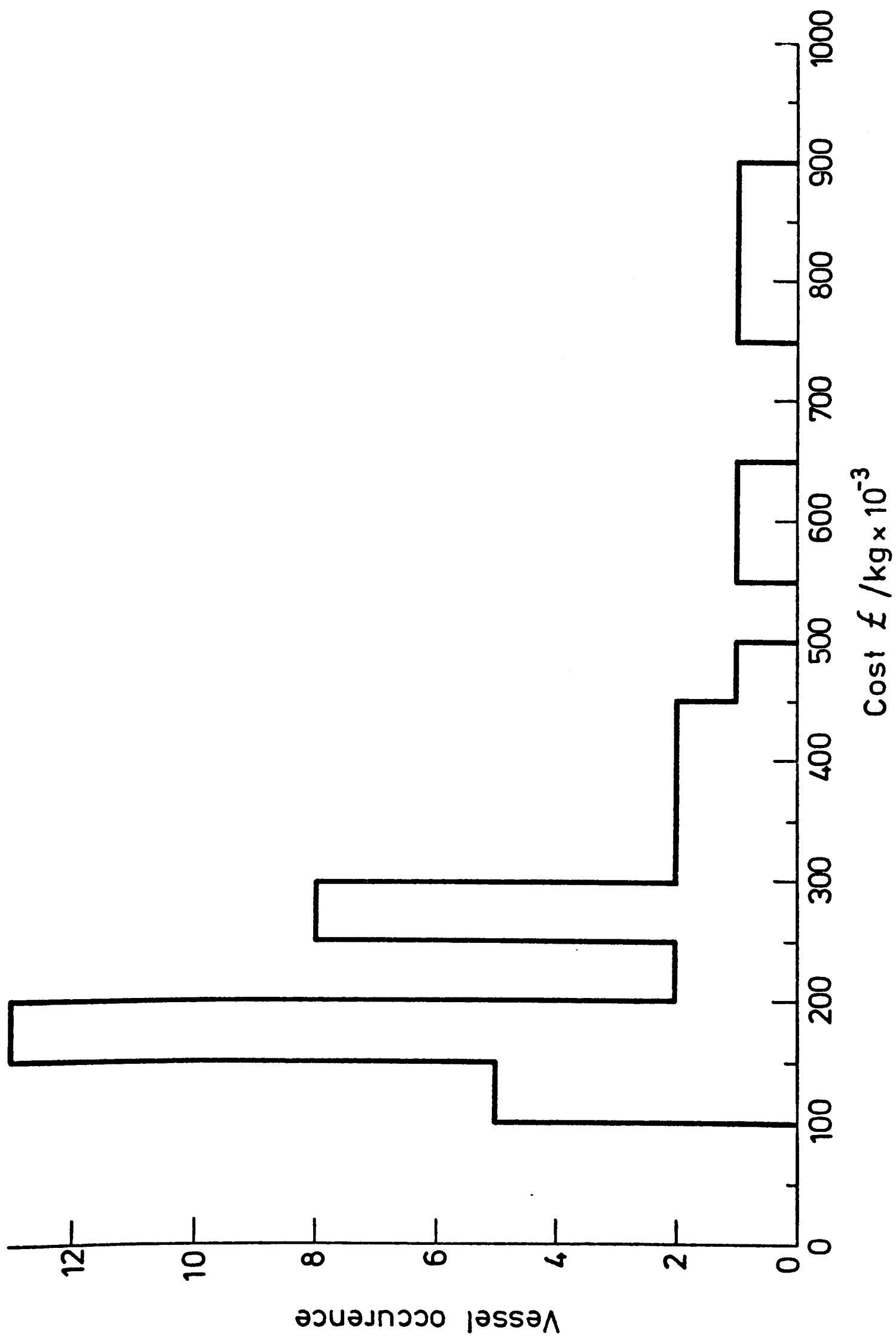


Fig. 4.3

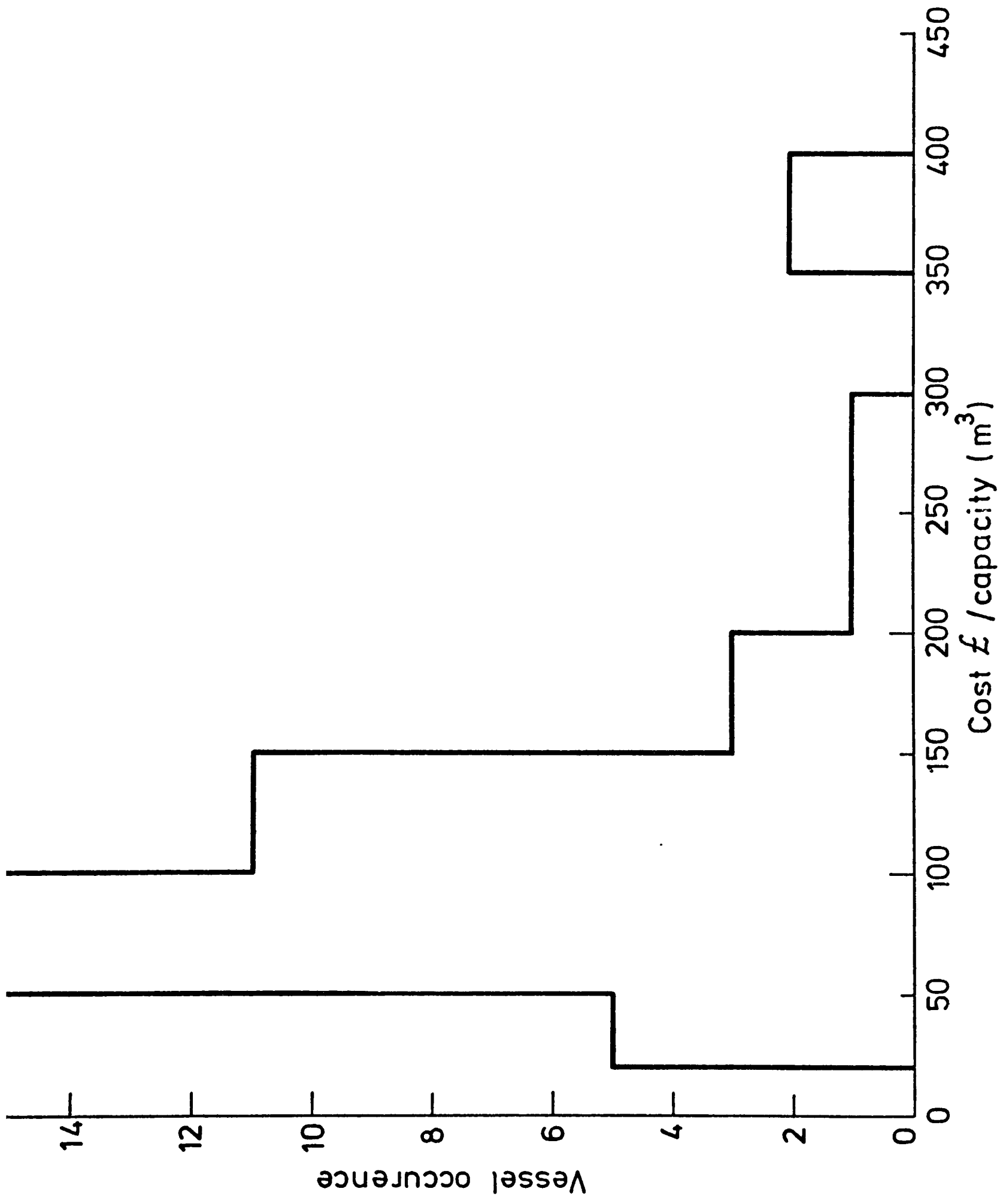


Fig. 4.4

4.3.2 Effect of material cost

While in the preceding paragraph it has been shown that the initial hypothesis of proportionality between vessel weight and cost provides a fair idea of what the total cost is most likely to be, there is a discrepancy between predicted and actual cost sufficiently large to require some further analysis. One important fact is that the diagrams of Figs.4.1, 4.2, 4.3 and 4.4 are mainly based on vessels made of conventional mild steel, to standard specifications.

Effect of material quality on vessel cost

The cost of material is increased when special precautions are required to ensure the adequacy for a given service. These special requirements may take the form of additional tests for the determination of mechanical properties, low temperature impact tests, stricter control of chemical composition than is normally the case, etc.

Taking,

W = material weight (kg)

M_c = material cost (£)

$M_{c(\text{standard})}$ = material cost, when plates are within dimensional limits, and no guaranteed properties required.

$M_{c(\text{non standard})}$ = if one or more of the qualities below required

a = notch ductility cost (£/kg)

b = certified elevated temperature property cost (£/kg).

c = PWHT (tests) cost (£/kg)

d = chemical properties cost (£/kg)

e = grain size test (McQuaid test) cost (£/kg)

f = material processing, i.e. electric furnace....
etc. cost (£/kg)

g = ultrasonic inspection cost (£), 30% of the
vessel invoice price

h = edge testing for plates say $\frac{1}{2}$ "-6" cost (£/kg)

i = carbon equivalent (CE) = 0.45 cost (£/kg)

j = non standard plate width cost, (about 5% increase
on the standard dimensions cost)

Then $M_{c(\text{non standard})} = M_{c(\text{stand.})} + \text{cost of mechanical and chemical}$
properties + non standard width cost (j)

$$M_{c(\text{non stand.})} = M_{c(\text{stand.})} + M_{c(\text{Stand.})} \times g + M_{c(\text{stand.})} \times j \\ + (a + b + c + d + e + f + h + i) \times \text{vessel wt. (w)}.$$

material increase with all above requirements:

$$M_{c(\text{non stand.})} = M_{c(\text{stand.})} + 30\% M_{c(\text{stand.})} + 5\% M_{c(\text{stand.})} + \\ (3.85 + 3.85 + 2.3 + 2.0 + 7.3 + 2.3 + 3.8 + 3.85 \\ + 4.4) \text{ £/kg} \cdot 10^{-3} \times \text{total wt. (kg)}$$

$$M_{c(\text{non stand.})} = M_{c(\text{stand})} + 35\% M_{c(\text{stand.})} + 29.8 \text{ £/kg} \cdot 10^{-3} \times \text{wt(kg)}.$$

$$M_{c(\text{non stand})} = 1.35 M_{c(\text{stand.})} + 30 \times 10^{-3} \times w. \quad (4.3)$$

Besides the additional cost incurred when it becomes necessary to supply material to some special requirement, it is always possible to use alternative materials. Thus, a cryogenic vessel may be made using stainless steel or impact tested low alloy steel, while at high temperature it may be cheaper to use a creep-resistant high alloy steel, operating at a high stress than a low alloy steel at a lower stress level.

Materials with high cost per weight are not necessarily considered as expensive, but in most cases they are cheaper for their high tensile properties, than those with low cost and tensile strength. A comparison can be made using, as a figure of merit, the ratio (26):

$$\frac{\text{Cost per unit weight of material}}{\text{design stress}}$$

The usefulness of this parameter may be shown by comparing two cylindrical belts of diameter D, length L and thickness T. If w is the specific weight,

$$W = w\pi DTL$$

and taking the vessel design pressure to be P and the nominal design stress σ ,

$$W = w\pi DL \frac{PD}{2\sigma}$$

with S = cost per unit weight of material, the vessel cost is,

$$\text{Cost} \propto SW = \frac{w\pi D^2 LP}{2} \times \frac{S}{\sigma}$$

For two identical vessels, one made of conventional carbon steel, the other of high tensile steel,

$$\frac{\text{HT cost}}{\text{CS cost}} = \frac{(S/\sigma)_{\text{HT}}}{(S/\sigma)_{\text{CS}}} \quad (4.4)$$

4.3.3 Effect of capacity

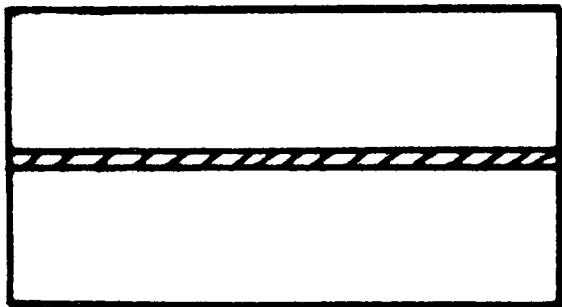
As shown in section 4.3.1

$$\text{Cost} = BC^n$$

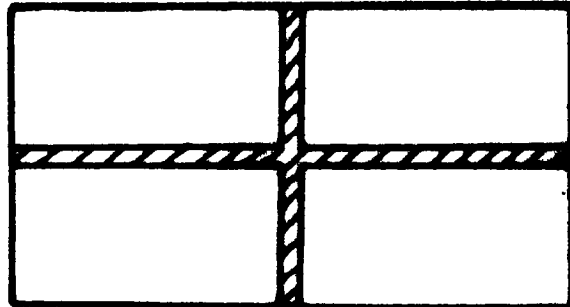
or, expressed in another form,

$$\frac{\text{Cost of vessel 1}}{\text{Cost of vessel 2}} = \left(\frac{\text{Capacity of vessel 1}}{\text{Capacity of vessel 2}} \right)^n \quad (4.5)$$

This expression was proposed by (Ref.27), where n was taken to be equal to 0.6. Although no account was taken of the costs of labour, overheads and material, it was shown that the fair measure of agreement between predicted values and actual costs may be quite surprising. Capacity does of course affect important cost factors, such as welding, e.g. when welding is performed on 10 ft. (3000) diameter, 20 ft. (6000) length vessel, manufactured from one plate, welding, assembly, dressing, grinding and tests are performed only on a 20 ft. length of the joint. If however two plates are used 10 ft. wide by 31.4 ft. circumference, an additional joint round the circumference is required, increasing the cost of operation by 157% between 20 and 51.4 ft. joint. Fig.4.5.



(a)



(b)

Fig. 4.5

Amount of weld and operation when using,
 a - one plate
 b - two plates

Equation (4.2) may be improved by considering other cost parameters: assume a vessel with a capacity c , then, capacity of the vessel \propto vessel volume (L^3), welded seams (welded material) \approx the area of weld (L^2), Fabrication (Bending of plates, manipulators....) \approx the length (L), material of vessel, weight, \approx (Diameter, length, thickness) \approx (L^3).

Assume cost elements of the vessel are,

Welding (x)

Fabrication (y)

Material (z)

Assume total vessel cost in terms of ϕ

welding costs = ϕ_x

Fabrication costs = ϕ_y

Material costs = ϕ_z

Cost of vessel 1 = $\phi_x + \phi_y + \phi_z$

By changing from a vessel of capacity C_1 to capacity of C_2 , and applying the exponential ratio:

$$\begin{aligned} \text{Cost}_2 &= \left(\frac{\text{Cap.}_2}{\text{Cap.}_1} \right)^n \times \text{Cost}_1 \\ &= \phi_x \left(\frac{C_2}{C_1} \right)^{\frac{2}{3}} + \phi_y \left(\frac{C_2}{C_1} \right)^{\frac{1}{3}} + \phi_z \left(\frac{C_2}{C_1} \right) \end{aligned}$$

Assume cost ratios in terms of z ; $x = 0.3 z$, $y = 0.2 z$

$$\begin{aligned} \text{Cost of vessel 1} &= 1.5 \phi_z \\ \text{and cost of vessel 2} &= \left[1.3 \phi \left(\frac{C_2}{C_1} \right)^{\frac{2}{3}} + 1.2 \phi \left(\frac{C_2}{C_1} \right)^{\frac{1}{3}} + \phi \left(\frac{C_2}{C_1} \right) \right] z \end{aligned}$$

$$\begin{aligned}
\text{Cost 2} &= 1.5 \phi z \left[0.87 \left(\frac{C_2}{C_1} \right)^{0.66} + 0.8 \left(\frac{C_2}{C_1} \right)^{-0.33} + 0.67 \left(\frac{C_2}{C_1} \right) \right] \\
&= \text{Cost 1} \left(\frac{C_2}{C_1} \right)^{0.6} \left[0.87 \left(\frac{C_2}{C_1} \right)^{0.06} + 0.8 \left(\frac{C_2}{C_1} \right)^{-0.27} + 0.67 \left(\frac{C_2}{C_1} \right)^{0.4} \right] \\
\text{Cost 2} &= \text{Cost 1} \left(\frac{C_2}{C_1} \right)^{0.6} \left[0.87 \left(\frac{C_2}{C_1} \right)^{0.06} + 0.8 \left(\frac{C_2}{C_1} \right)^{-0.27} + 0.67 \left(\frac{C_2}{C_1} \right)^{0.4} \right] \quad (4.6)
\end{aligned}$$

Equation (4.6), shows that vessel cost is affected by other cost elements when included. This does justify equation (4.5) reached by Corker (27). He stated that indirect costs were not included in his investigation, such costs do not vary in the same way with capacity as shown in equation (4.6). Changing to large capacity vessels, material required, welding procedures and preparation, production control and Inspection will change, such change will not be linear with capacity ratio, in most cases depends - beside above mentioned requirements - on material properties required, temperatures and pressures asked for.

4.4 Combined effect of material and Design Code on the cost

Mild steel vessels, made to a simple code such as BS 1500 and having a thickness of less than 1 in. naturally requires less inspection than those vessels made to more exacting specifications and employing more expensive materials or materials more difficult to fabricate or weld. Table 4.2, gives an indication of how the inspection time or effort varies with material, thickness and Design Code.

Table 4.2

Variation of inspection time or effort
with vessel thickness, material and Design Code

Reference: 1" thick, mild steel vessel to BS 1500 (Index)

Parameter change	Index
Thickness (2")	1.5 - 2.0
Stainless steel	1.5
High yield steel	2.0
Change of Code: ASME viii-1	1.3
BS 1515	1.5
ASME viii-2	1.8
AD Merkblatt	1.5 - 2.0

Selection of a more advanced code such as ASME viii-2 will be followed by an increase in design details and analysis, and results in an increase in design costs. Thus, by comparison with BS 1500, the times required for the completion of design in accordance with other codes are as follows:

Table 4.3Design Time

BS 1500	BS 1515	ASME viii-1	ASME viii-2	AD Merkblatt
1.0	1.5	1.5	2**	1.8*

*shorter time, similar to BS 1515 or ASME viii-1 depending on familiarity with Code.

**minimum time. May increase to 3 or 4 when a detailed stress analysis becomes necessary.

Total vessel cost is affected also by vessel material, whether a conventional carbon steel or an alloyed steel is to be used, material thickness and code selected, effort and time taken for the fabrication of the different vessel thicknesses as well as different materials is also varied. In the following tables ratios of increase in mentioned parameters are shown in Tables 4.4 to 4.11.

Table 4.4

Relative steel costs

Material	Relative market cost
Carbon steel (reference)	1.0
Low alloy steel	2.0
18/8 Tp - 304	6.0
18/8/1 (Ti) Tp-321	7.0
18/8/3 (Mo) Tp-316	8.0

The relative increase in the total cost of the vessel made of alloy steel, when material, direct labour and inspection and overheads are considered, will be as follows:

Relative increase of alloy steel vessel cost = Material weight x
 increase in material cost x design stress ratio + direct
 labour and inspection x ratio of effort increase due to
 alloying + overhead cost x ratio of increase + transport
 cost.

If say, 18/8 Tp 304 is to be used, then ratio of cost increase will be; 18/8 Tp 304 cost = vessel wt._{cs} x 6 x $\frac{\sigma_{cs}}{\sigma_{18/8}}$ + labour cost on carbon steel vessel x 2 + overhead cost_{cs} x 10-25% increase + Transport cost.

$$18/8 \text{ cost} = \text{wt.} \times 6 \times \frac{\sigma_{cs}}{\sigma_{18/8}} + 20\% \text{ vessel cost}_{cs} \times 2 + 20\% \text{ vessel cost}_{cs} \times 1.2 + 5\% \times \text{vessel cost}_{cs}.$$

Table 4.5

Relative labour and inspection and overhead costs increase

	D. Labour and Insp.	Overheads*
Carbon steel (ref.)	1.0	
Low alloy		
18/8 Tp 304	2.0	10-25% (increase)
18/8/1 T _i Tp-321		
18/8/3 Mo Tp-316	3.0	

*Overhead costs increase are not expected to change too much, this is mainly due to more careful welding.

Other factors that may affect the cost is the vessel thickness which increases labour effort spent in handling and welding of thicker vessels, inspection procedures and overheads, Tables 4.6 and 4.7.

Table 4.6

Relative increase in labour effort of carbon
steel vessels in terms of thickness

Material thickness (m.m.)	Labour effort
1-3 (ref.)	100%
4	110
5	120
6	135
8	150
10	170
15	250
20	350
25	450

Table 4.7

Variation of inspection and overheads with thickness
for stainless steel vessels

vessel thickness (mm)	Inspection increase 20%/5 mm	overhead increase 35-40%/5 mm
5 (ref.)	100%	100%
10	120	135
15	140	180
20	160	220
25	180	260
30	200	300

Table 4.8

Relative material cost increase for alloy steel vessels

code of construction	Temp. °c.	18/8 Tp-304	18/8/1(Ti)-321	18/8/3 (Mo)-316
BS 1500	50	2.66	3.1	3.16
	200	2.81	2.95	3.42
BS 1515 Pt.1	50	2.02	2.32	2.33
	200	2.10	2.18	2.47
ASMEviii - 1	50	2.67	2.68	2.96
	200	2.79	2.62	2.86
ASMEviii - 2	50	2.64	2.66	2.74
	200	2.54	2.54	2.69
AD-Merkblatt	DIN 17440	- x 4 CrNi189	10CrNiTi189	5 CrNiMo1810
	50	2.18	2.23	2.42
	200	2.59	2.50	2.83

Tables 4.9 to 4.11, summarize the previous information and show the effect of code familiarity on design, labour effort and Inspection.

Taking the BS 1500 Code as reference, a cost breakdown for a conventional carbon steel vessel for operation at ambient temperature would be as follows:

Table 4.9

Cost breakdown of Carbon steel Vessel depending on Design Code

Code	Materials	Direct Labour & Inspection	Overheads	Design	Transport	Total
BS 1500	0.4	0.15	0.2	0.2	0.05	1.0
BS 1515	0.24	0.23	0.2	0.3	0.05	1.02
ASME viii-Div.1	0.4	0.2	0.2	0.3	0.05	1.15
ASME viii-Div.2	0.3	0.27	0.2	0.4	0.05	1.22
AD Merkblatt	0.24	0.3	0.2	0.36	0.05	1.15

Table 4.10

Familiarity effect on Carbon steel Vessel Cost

Code	Materials	Direct Labour & Inspection	Overheads	Design	Transport	Total
BS 1500	not affected	0.15	not affected	0.2	not affected	1.0
BS 1515		0.20		0.2		0.89
ASME viii-Div.1		0.15		0.2		1.0
ASME viii-Div.2		0.22		0.3		1.07
AD Merkblatt		0.20		0.2		0.89

Table 4.11

Relative carbon steel to stainless steel total vessel cost

Code	carbon steel cost	stainless steel cost	Familiarity effect
BS 1500	1.0	3.45	3.45
BS 1515	1.02	2.81	2.68
ASME viii - 1	1.15	3.47	3.32
ASME viii - 2	1.22	3.44	3.29
AD-Merkblatt	1.15	2.98	2.72

4.5 Conclusions

It has been shown that the cost of a vessel is a function of weight and capacity (equations 4.1 and 4.2). The best fit to the data available in Table 4.1 was provided by taking $A = 0.2$ and $B = 300$ with $n = 0.632$. The largest deviation between the data and the predicted cost from equations (4.1 and 4.2) could be accounted for, and were equivalent to $\pm 50\%$. Most of the data - about 70% - fell within a $\pm 20\%$ band of the predicted results.

From the analysis of the production charts it has been shown that the time taken by engineering analysis is 12%, fabrication and drawings 75% and inspection 15%.

Design codes affect cost in two ways; by specifying a design stress and hence the thickness of main shell, and by specifying inspection procedures and standards of workmanship

Accepting that the cost is proportional to the vessel weight, would indicate that the code to be preferred in all circumstances, is the one which allows the maximum value of design stress. This may not be so when a detailed analysis of the cost is performed, since, as has been shown, the inspection and fabrication costs are also dependent on the code selected. Design represents a small proportion of the total effort, and an increase in the design time may well be worthwhile if it can justify a saving in material, since this constitutes a considerably more important factor in the total costs.

Fabrication is the most important area when considering costs, since it covers about 80% of the time and between 47 and 60% of the total costs excluding overheads. If overhead costs are included, the total fabrication cost becomes equal to about 75-80% of the cost of

the vessel. Savings in this area, therefore, are more significant in terms of cost reduction than in any other.

From the analysis it has been found that the most expensive code (ASME viii-2) is about 1.22 x BS 1500 (index), i.e. selection of code will affect vessel total cost by about $\pm 10\%$.

Familiarity in using the code has shown its effect on direct labour, inspection and design, it has been also shown that by excluding ASME viii-2 which actually requires more analysis and effort, familiarity could reduce the differences.

CHAPTER 5

CHAPTER 5

Fabrication and Workshop Layout

5.1 Introduction

In the previous chapters, the relationship between design, production and cost in the pressure vessel industry was considered. It was shown that, for a given vessel capacity, the weight depended on the stress level considered to be acceptable by the specified Design Code for the main shell. Once the weight had been fixed, it was concluded that the final cost was primarily dependent on the method of fabrication and, only to a very small extent, on the rules given by the Code for the detailed design, inspection and testing. It follows that an improvement in the planning of production will be more effective in reducing the final cost than a revision of the Design Codes. This chapter presents a more detailed description of the production process, and identifies those areas where careful planning can result in a reduction of the final cost.

A typical example of the fabrication process is illustrated in the diagram of Fig.5.1, referring to an ammonia separator, whose general dimensions are as indicated in the figure. For each operation, the numbers inside triangular frames refer to the actual time (in hours) taken to complete that operation. The numbers circled indicate the operation and do not necessarily refer to the sequence. In this case the totality of the vessel was shop fabricated and delivered to site when finished. Production is first subdivided into three main streams, converging simultaneously to one. End 1 is equal to End 2, with the exception of the fittings, which are small, standard nozzles, bought ready to be welded on and fabricated

nozzles respectively. In both cases, the hemispherical ends consist of a central cap and petal plates. While the ends are being assembled, the main body of the vessel, subdivided into two courses or belts, is under construction. Normally, the timing of each operation will be determined by estimating the time required and the need to reach the points or nodes where two or more streams converge simultaneously. Normal planning techniques are used. It will be noted that before fabrication starts, delays or queues may arise as a result of poor coordination in the delivery of end plates, main body plates, finished fittings, materials for fabricated fittings and the preparation of final workshop drawings. Throughout the production process, inspection, especially by outside Authorities may also cause delays. The possibility of minor repairs must also be considered. How much margin is allowed here is a matter of judgment.

An entirely different situation arises when most of the operations take place on site, as is the case for large capacity vessels and thin-walled tanks. A typical example, illustrated in Fig.5.2, is a 9% Ni steel spherical tank, 14.0 m diameter and 9.2 mm thick, supported on a cylindrical skirt which, in turn, is welded through an equatorial ring to the main shell. The production sequence also consists of three main streams converging into one. In this case, plates, supporting ring and fittings are all delivered ready to be assembled to site and only the site erection procedure is described in the diagram. The first operation is to assemble the supporting ring and to build up the first course of the skirt. While this is in progress, the bottom hemisphere is assembled in an inverted posi-

tion, i.e. with the lower cap facing upwards. Once this is completed, it is welded to the skirt/ring assembly and turned round prior to completing the assembly of the skirt. The top hemisphere is then welded to the equatorial ring after levelling and finishing the supporting skirt.

The similarity between the two sequences is quite obvious. Similar work planning diagrams may be prepared for the majority of vessels, regardless of their capacity, wall thickness, shape and material of construction. The estimated times for the completion of a given operation are, again, a matter of conjecture, although some guidance may be sought by considering elementary operations such as welding, radiography of welded joints, etc., it is inevitable that a large proportion of the time is spent in setting up, repairing, etc. It is therefore necessary to estimate upper and lower bounds for the time required

5.2 Analysis of fabrication time

In order to estimate the fabrication time and to decide at what instant it is necessary to start a given operation, one must know what proportion of the total time taken by a unit operation must be allowed for preparation, transport, finishing, etc. From a total of about 50 vessels, 25 were selected as being representative of common practice. These were analysed in detail and it was found that the fabrication time could be broken down as shown in Table 5.1.

<u>Operation set</u>	<u>% of total fabrication time</u>
Workshop drawing and work plan	8-9
Assembly and welding of main body	35-40
Assembly and welding of fittings (nozzles, brackets, other attachments)	30-35
Testing	8-10
Clean and finish	5-6

Table 5.1General Breakdown of Fabrication Time

An "operation set" is a group of operations of diverse nature but with a clearly defined common aim. Thus, under "Assembly and welding of main body", are included the bending of plates to form the cylindrical main shell, pressing of ends, positioning of ends, welding of longitudinal and circumferential seams, heat treatment and stress relieving. Similar unit operations are included under "Assembly and welding of fittings", as well as, possibly, machining of main body to receive nozzles and other attachments such as skirt supports.

The total time taken for the completion of all the operations listed in Table 5.1 is approximately 70% of the total time taken from ordering the vessel until it is in service. It must be noted that the actual relative time spent in a given operation set varies from one vessel to another, depending on the size, shape and number of fittings but, as shown in Table 5.1, this departure from the mean value is fairly small. As the analysis becomes more detailed, the operation sets being broken down into their unit operations, the

scatter of results becomes progressively larger, making it impossible to draw any valid conclusions.

The operation sets of Table 5.1 have been based on the subdivision of the production sequence into streams, as in Figs.5.1 and 5.2. Thus, the assembly and welding of the main body, followed by testing, cleaning and finishing constitutes the central stream, the assembly and welding of fittings is a lateral stream that joins the central one at a certain stage and the preparation of workshop drawings and work plans is the basis of the production process. Another way in which operation sets can be formed is by grouping together unit operations of similar nature, regardless of whether or not they belong to the same set. This has been done in Table 5.2, for a typical vessel.

<u>Unit operation</u>		<u>% of total fabrication time</u>
<u>Number</u>	<u>Description</u>	
1	Plate identification and marking	7.8
2	Edge preparation	5.4
3	Pressing, rolling (incl. heating)	2.5
4	Welding	26.5
5	Stress relief	2.8
6	Hand grinding	7.6
7	Machining	28.4
8	Inspection	8.8
9	Repair	3.2
10	Shot blast, clean, paint, finish	4.7
11	Hydraulic test	1.3

Table 5.2

Breakdown of fabrication time into unit operations

In table 5.2 the values quoted for the proportion of the fabrication time taken by each unit operation are average, and large variations are possible for a particular vessel. Thus, some vessels may require little machining, except for the preparation of edges for welding and boring of penetrations. Others may incorporate tube plates, flanges of complex profile, etc., and thus a significant proportion of the time spent in their fabrication will be taken by machining. An even utilisation of the machining facilities will be achieved by having a sufficiently large number of vessels of different types under construction at any time. Alternatively, it is also possible to specialise into a single type of vessel and to plan the machining facilities accordingly. To have a number of vessels of a given type followed by another group of a different type would result in uneven utilisation of some facilities.

While some facilities such as machining may be under-utilized, others are virtually always required to very similar extent, regardless of the nature of the vessel. Plate identification and marking, welding, pressing and rolling are some examples. It is important to distinguish between these two entirely different types of operations when planning for production. This can be done by grouping together those operations that take place in the same work centre, either because the same equipment and skills are involved or for reason of the sequence in which they occur during fabrication. Thus, the unit operations listed in Table 5.2 fall into the following work centres:-

- (a) Edge preparation, forming and heat treatment - Operations 1, 2, 3, 5.
- (b) Welding - Operations 4, 6, 9.
- (c) Machining - Operations 2, 7, 9
- (d) Inspection, repair and finish - Operations 1, 6, 8, 9, 10, 11.

Some unit operations - edge preparation, hand grinding, repair - appear in several work centres since they are closely related and complement the main unit operations performed in that particular centre. The relative time distribution between the various work centres may vary with each vessel. In an optimum situation, all centres would be utilised to their full capacity. In practice, some centres will be under-utilised while, in order to complete the vessel by a specified time, other centres will have to work overtime. In a flow diagram such as those illustrated in Figs.5.1 and 5.2, dates have to be fixed for the completion of each stage, so that the correct sequence can be observed without any waiting or delays. From the flow diagram the total time available for each one of the unit operations listed in Table 5.2 is then estimated. Grouping the unit operations into work centres, the relative centre utilisation is defined as the ratio between the time actually spent in each work centre and the time available if the completion dates specified in the flow diagram are to be met. A centre may be fully utilised, when it is active during all the available time, under-utilised if it is idle for some of the time or over-utilised if, in order to comply with the fixed dates it is necessary to work overtime, thus increasing the cost. There is

little difficulty in achieving the full utilisation when the work centre is only active in events that take place along a single stream, unrelated to any other e.g., between stages 7 and 13 in Fig.5.1. Additional resources, when available, may be brought in to reduce the time spent or the final delivery date may be put forward or delayed when this is permissible. The problem is more difficult when events are on parallel interacting streams

<u>Work Centre</u>	<u>Relative centre utilisation (%)</u>		
	<u>Average</u>	<u>Maximum</u>	<u>Minimum</u>
(a) Edge preparation, forming heat treatment	63	83	43
(b) Welding	59	77	38
(c) Machining	138	243	8
(d) Inspection, repair, finish	75	135	46

Table 5.3

5.4 Percent utilisation of work centres

It will be observed from Table 5.3 that work centres (a) and (b) are generally working at about 60% of their full capacity although, occasionally, in the production of some vessels it has reached a maximum of about 80% while in others it has dropped to about 40%. For the vessel to which Table 5.2 refers, about 50% of the fabrication time is spent in centres (a) and (b), or about 35% of the total time from the order being placed to the delivery of the vessel. Full utilisation of work centres (a) and (b) would therefore result in a saving of between 7% and 20% in the total order-to-delivery time, although in general the saving would be

about 14%. To achieve this saving it would be necessary to reduce the time during which a semi-finished vessel is waiting for a machining, inspection or repair operation to be performed. In theory, it should be a simple matter to increase the resources allocated to these latter operations in order to speed up the progress through the corresponding centres or to reduce the resources of work centres (a) and (b). We shall see later that this is not always practicable.

By comparison with the fairly even under-utilisation of work centres (a) and (b), work centre (d) - Inspection, repair and finish - is more utilised but with greater irregularity. The large average utilisation - 75% for (d) against 60% for (a) and (b) - is explained by the fact that the majority of the operations in this work centre occur towards the end of the production process and are therefore unaffected by other operations. On the other hand, the incidence of repairs can not be predicted, which explains why this centre is sometimes under-utilised while in other cases, it may be over-utilised by as much as 35% when a large number of repairs arise as a result of poor workmanship, of inadequate manufacturing techniques or of an unusually high standard of quality being required. When the centre is over-utilised, a delay in the completion date is unavoidable unless steps are taken to increase the allocation of resources. This may be done, for this type of operation, by working overtime without investing in more equipment that would stand idle most of the time. Another point worth noting is that the actual time taken by the repair itself may be very small compared to the fabrication, as shown, for a typical vessel, in

Table 5.2, but the disturbance caused by the repair can cause significant delays by interfering with the correct sequence of production.

The wide variation between maximum and minimum utilisation of work centre (c) - Machining - is even more striking and can not be explained by the unpredictability of the operations involved. It is clear that the total machining time for any given vessel, excluding repairs, can be estimated as accurately if not more than the time it takes to do the welding. Yet, welding centres are consistently slightly under-utilised, occasionally reaching full utilisation, while machining centres may be virtually unused or work at up to $2\frac{1}{2}$ times their normal capacity. The reason for this apparent anomaly is that the amount of welding is roughly proportional to the weight of the vessel while machining does vary considerably from one vessel to another and bears little correlation with the size or weight of the vessel. Just as it is a matter of conjecture how much repair work will be entailed in the construction of a given vessel, it is impossible to predict how much machining will be required by vessels not yet ordered. Given this uncertainty and the cost of the capital equipment, manufacturers tend to plan their machine shop to cope only with simple vessels that require little machining and to accept delays in other work centres, i.e., under-utilisation, while the machining centres are fully utilised or over-utilised in other cases. This situation can not be improved solely by increasing the resources allocated to the machining centre since this will reduce the over-utilisation but will also result in the centre being virtually idle in many

cases. There are several ways in which this problem can be tackled:-

(a) Specialise production, either simple vessels that require no machining or complicated vessels, e.g., heat exchangers, that need considerable machining, planning the machine shop accordingly.

(b) Diversify production, evening out differences in machining requirements by increasing the number and variety of vessels under construction.

(c) Plan the factory for the most complicated vessel envisaged and seek full utilisation of machining facilities through contract work.

5.5 PLANT EQUIPMENT AND LAYOUT

5.5.1 Plant Equipment

Table 5.4 lists the main, basic equipment used in the manufacture of pressure vessels against the unit operations for which it is used. The approximate proportion of the total plant investment is also listed. Although the actual cost of the equipment may vary a great deal, the values shown may be considered to be roughly representative of modern practice.

Cost of resources employed in the mentioned shop is shown in Table 5.5, the analysis show that the cost of employing the existing resources (machines + labour), is approximately £116/hr. This cost will involve only the use of one machine per Centre. i.e. one centre lathe, one boring machine, one edge planner, etc.

Table 5.4Basic equipment for manufacture of
pressure vessels

<u>Unit operations</u>	<u>Equipment</u>	<u>% of total investment</u>
1	Cranes, metrology	<5
2	Shears, gas cutting machine	10-15
3+5	Bending rolls, press heat treatment ovens	35-45
4+6	Automatic and manual welding	10-15
7	Machine tools (centre lathe, planing M/c, drilling M/cs, boring M/cs, milling)	20-30
8	X-ray, ultrasonic, magnetic crack detection	5-10
10+11	Shot blast equipment, pumps, etc.	<5

The largest investment corresponds to the bending rolls, press and heat treatment ovens. Welding, which takes a large proportion of the total fabrication time only needs a relatively small investment. Comparing Tables 5.2 and 5.4, it can be seen that unit operations 3 and 5 take about 5% of the total fabrication time and at least 35% of the total investment while welding takes about 25% of the time and only 15% of the investment at the most. It is also interesting to note that welding equipment consists of relatively low-cost items and can be augmented gradually as the need arises without spending a large sum at a time. On the other hand, bending, pressing and heat treatment all need large, expensive items of equipment whose capacity limits the maximum

size or wall thickness of vessel that can be handled. Once acquired, further improvement by building on to the existing equipment is not feasible. Machining once again presents a different problem: each machine tool may well represent a large proportion of the total investment and, unlike the previously mentioned equipment, which is essential to the fabrication of any vessel, it may only be used occasionally, while the planner has little choice in the selection of equipment for bending, pressing and heat treatment once the maximum size of vessel has been decided, there are many alternatives for the equipment in the machine tool shop, bearing in mind the three possible ways of solving the problem of full utilisation mentioned in the previous section.

The vessel industry is highly capital intensive, a fact that can only be deduced when actual costs of equipment, labour, overheads, etc. are assigned to the various items listed in table 5.4. Although incomplete, table 5.5 shows typical values of such costs which may be used as an indication of the order of the magnitude of each one. The price of machines ranges from £190,000 for a bending roll, down to a few hundred pounds for a single welding set. The depreciation value is defined on the basis of a purely arbitrary criterion. Large investment items such as the bending rolls are more likely to be kept in production for 20 years or more than for 10. Labour costs only include those directly involved when operating the machine. Normally, in a workshop of the type described, there will be several flame cutting machines, hand welding equipments, welding manipulators, ultra-sonic equipments and centre lathes, bringing the total labour force, on the shop floor, to about 100 men. This would also include

Table 5.5

Cost of Resources Employed in the Shop

Equipment used in Vessel Shop	Price of Machines used £	Depreciated value * £/hr	Cost of operating the M/C with-out labour £/h	Labour costs		
				Number employed	Rate £/hr	Total labour cost £/hr
• Flame cutting equipment	22,000	0.92	2.40	2	0.80	1.60
• Edge planner	30,000	1.25	2.55	1	0.85	0.85
• Heating furnace	65,000	2.71	2.40	4	0.80	3.20
• Bending rolls	190,000	7.92	2.40	3	0.80	2.40
• Electro slag welding equipment	7,000	0.29	2.40	2	"	1.60
• Submerged arc welding equipment	5,000	0.21	2.40	2	"	1.60
• Hand welding equipment	-	-	2.40	1	"	0.80
• Welding manipulators	3,000	0.13	2.40	1	"	0.80
NDT Equipments						
• X-ray equipment	25,000	1.04	1.65	2	1.10	2.20
• Ultrasonic equipment	7,500	0.31	1.65	1	1.10	1.10
• Magnetic particle testing equipment	2,000	0.08	1.65	1	1.10	1.10
• Dye penetrant	2,000	0.08	1.65	1	1.10	1.10
• Laboratory for testing X-ray films	-	-	1.65	2	0.85	1.70
• H ₁ Drilling M/C	4,500	0.19	2.55	1	"	0.85
• V ₁ " "	4,500	0.19	2.55	1	"	0.85
• V ₁ Boring " "	80,000	3.75	2.55	2	"	1.70
• H ₁ " "	22,000	0.92	2.55	2	"	1.70
• Centre Lathe	8,000	0.33	2.55	1	0.80	0.80
• Presses	30,000	1.25	2.40	6	"	4.80
• V ₁ Plate bending M/C + furnace	11,000	0.46	2.40	3	0.80	2.40
• Planning M/C	15,000	0.63	2.55	1	0.85	0.85
• Shot blast equipment	12,000	0.50	2.40	1	0.80	0.80

* Depreciation period was taken as 10 years, at 300 days per year and 8h/day shift work

auxiliary, unskilled staff and maintenance men. The average cost of utilising to their full capacity the workshop facilities would be, for the tabulated items, about £175/hr., including the auxiliary staff but excluding cost of administration, transport, etc.

5.5.2 Plant layout

The plant layout has to be considered together with the work area and the equipment. Planning the layout may be done in accordance with three different methods of approach:-

(a) Considering the sequence of fabrication, as illustrated in Figs. 5.1 and 5.2, so that all work proceeds along the lines shown, always progressing forwards.

(b) Subdividing the production process into unit operations so that equipment and personnel can be allocated to each operation and responsibility for its satisfactory completion assigned.

(c) Reducing the fragmentation that may result from the subdivision above by grouping unit operations into work centres.

At first sight, the first approach would seem to be the best of the three, since both (b) and (c) would require a certain amount of backwards as well as forward flow with the consequent flow interruptions, time wasted in unnecessary transport, the possibility of bottlenecks, the need to leave free space available while waiting for a component to return, etc. On the other hand, (a) is only possible when resources can be duplicated, making it difficult to achieve their full utilisation and increasing the investment unnecessarily. Also, (c) which avoids the fragmentation of (b), has the advantage of

organising the production by means of relatively small, interconnected work centres. Personnel can become identified with the operations performed, all of which require similar skills, and quality control will be facilitated. For these reasons, a compromise solution, including both (a) and (c) is preferred. Figs.5.3, 5.4 and 5.5 show the schematic layout and flow diagram of three typical workshops. In workshop A, forward flow is achieved only at the beginning of the production process, machining requires a cross-over flow, returning to the main line afterwards. One reason why the machine is kept separate from the rest in this layout is that in this way it may operate independently and accept contract work to improve its utilisation. In layout B, following the edge preparation, plates come into the pressing and bending area, separated from the heat treatment oven by the assembly and welding bay. It would seem preferable to reposition the oven at the side, between "assembly and welding" and "bending and pressing", with access from both sections. Cross-over of flow is apparent in the diagram. No provision is made for machining, which is done in an entirely different workshop. In C, forward flow is achieved without cross-over but the machine shop, being central to the whole layout, can not be readily used for outside contract work without interruption to the normal flow pattern, estimated forward to backward times of vessel parts in the working centres, for the three layouts, are shown in Table 5.6. A forward time is defined as the time taken by a part moving in the general direction of the work flow, while backward time represents the time taken when moving against the flow. From Table 5.6, it can be seen that on average, the forward-to-backward time ratio is about 3:1,

with layout A requiring the least backward time and layout B the most. The differences are however small. It must be noted that layout B requires the transport of large items, and even of the completed vessel for hydraulic test. This may increase the total production costs. Comparing the three layouts it is easy to understand their differences and their relative advantages for the production of general vessels requiring machining in some proportion of other - Layout A - ; for the production of simple, large capacity vessels that require very little machining - Layout B - and for boiler drums, very similar in design and all requiring the same amount of machining. Neither of these layouts can be said to be better than the others: all three probably are equally effective for the type of vessel for which they are planned.

Table 5.6

Estimated percentage in forward and backward times occurred
on vessel part flow through layouts A, B and C

Work centre	%age time taken in forward flow			%age time taken in backward flow		
	workshop A	workshop B	workshop C	workshop A	workshop B	workshop C
Edge preparation	90	90	90	10	10	10
Rolling or pressing & H.T.	70	70	70	30	30	30
Welding & assembly	70	65	70	30	35	30
Dressing	95	80	90	5	20	10
X-ray	65	70	80	35	30	20
Repair	70	60	70	30	40	30
S/R	80	80	70	20	20	30
Hyd. test	90	70	65	10	30	35
Boring	50	60	60	50	40	40
Final clean & finish	90	90	90	10	10	10

AMMONIA SEPARATOR

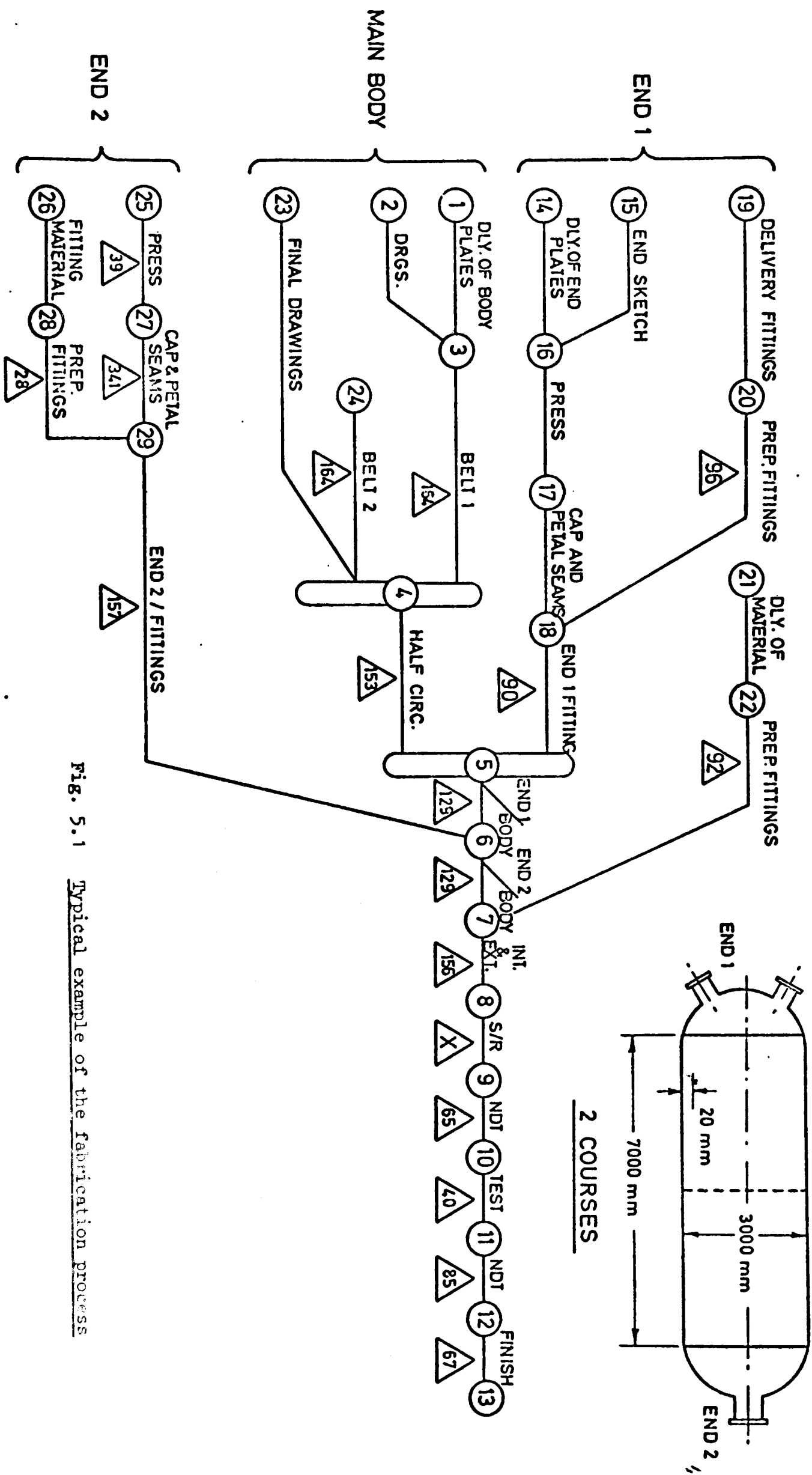


Fig. 5.1 Typical example of the fabrication process

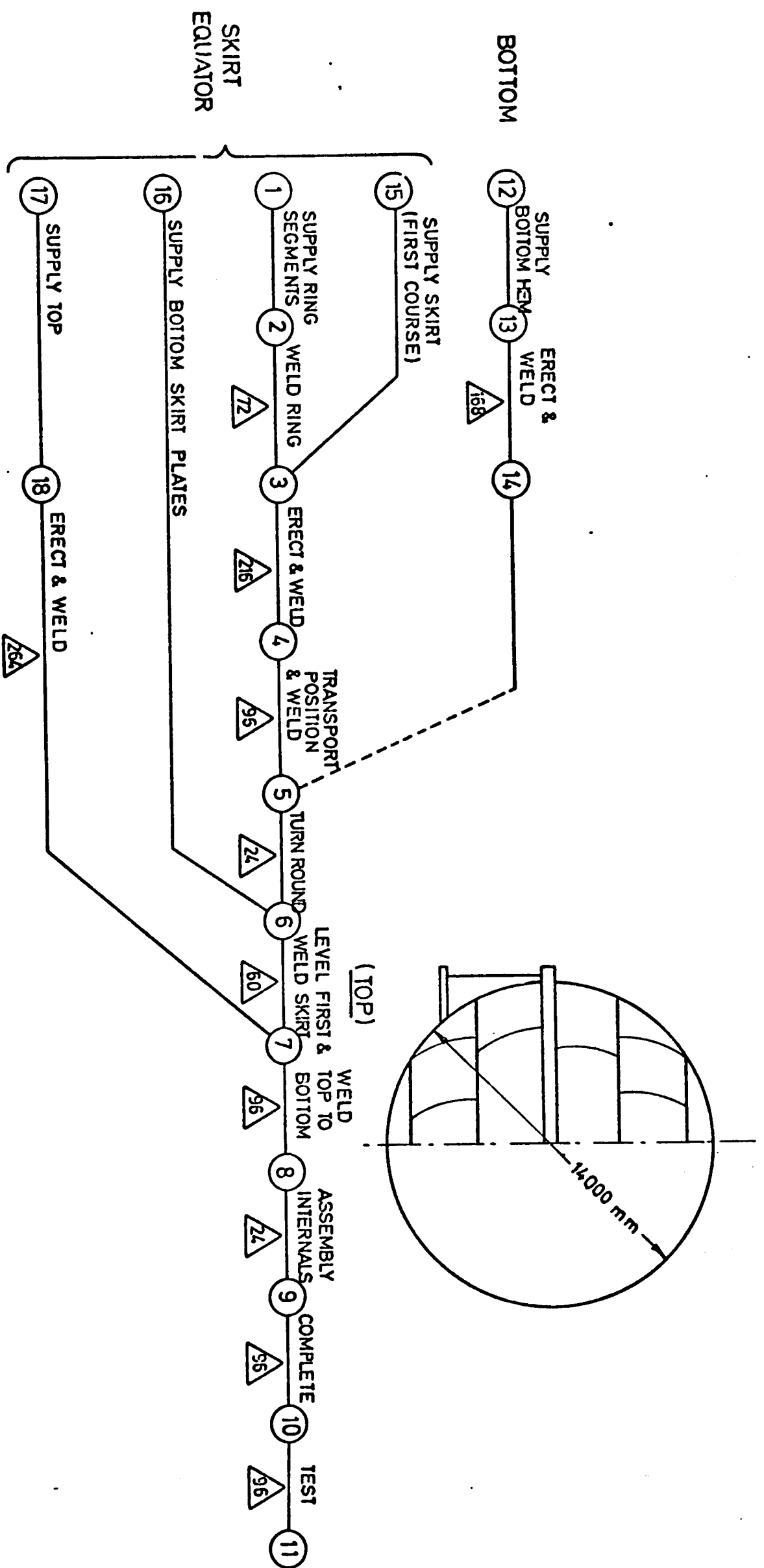


Fig. 5.2 Typical site fabricated vessels

PLATE FORMING &	= 30%
SHOP ASSEMBLY	
ERECTOR & WELDING	= 49%
ASSEMBLY & FINISH	= 14%
TEST & CLEAN	= 7%

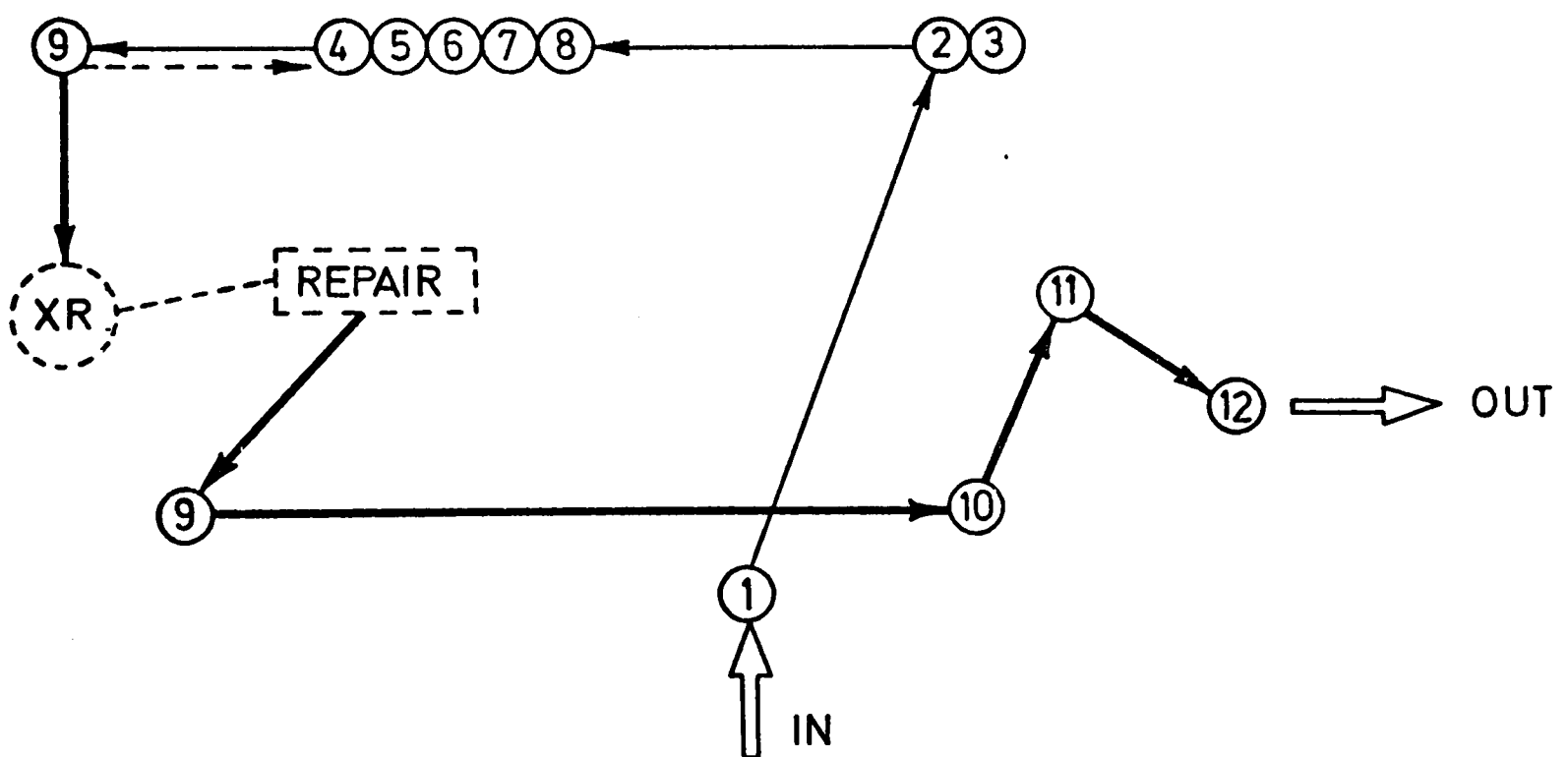
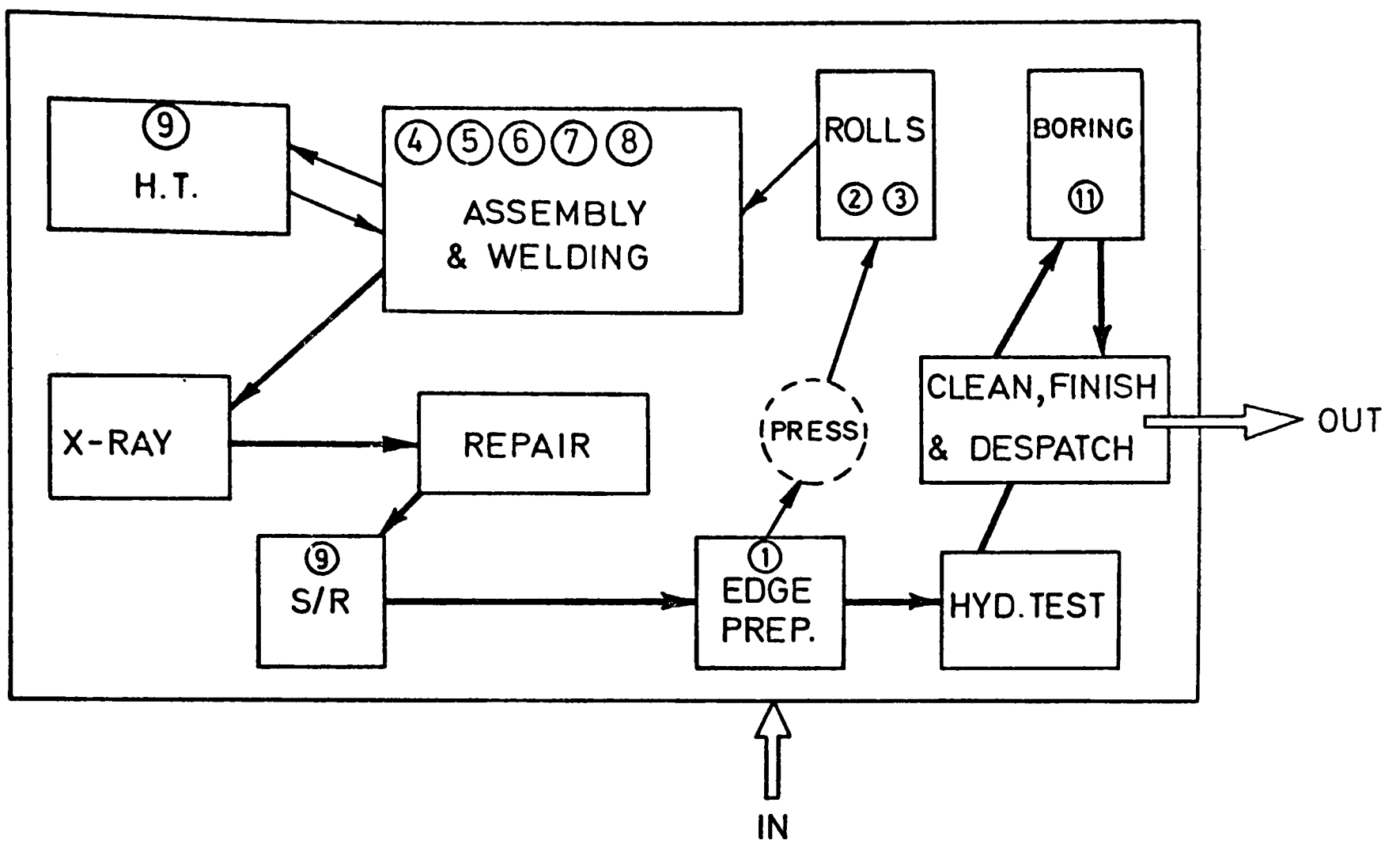


Fig. 5.4 Layout and flow diagrams: workshop B

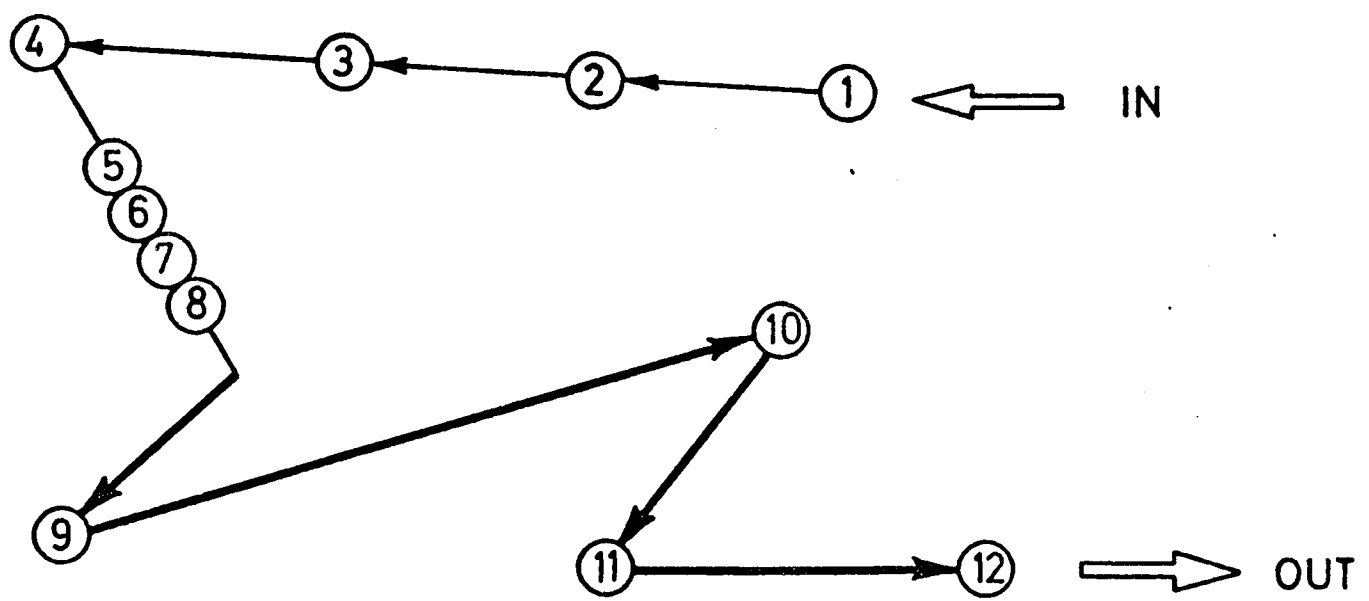
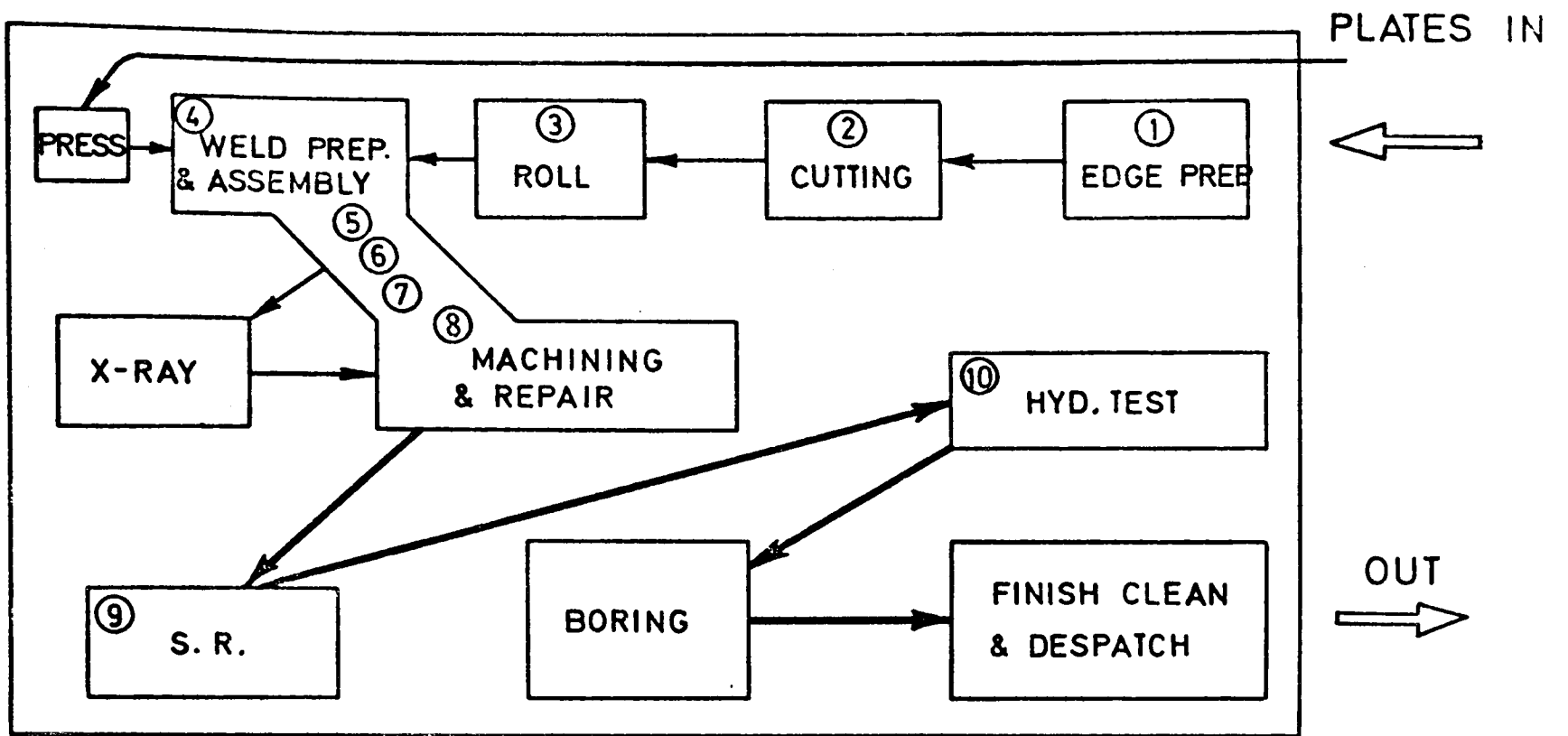


Fig. 5.5 Layout and flow diagrams: workshop C

5.5.3 Workshop area

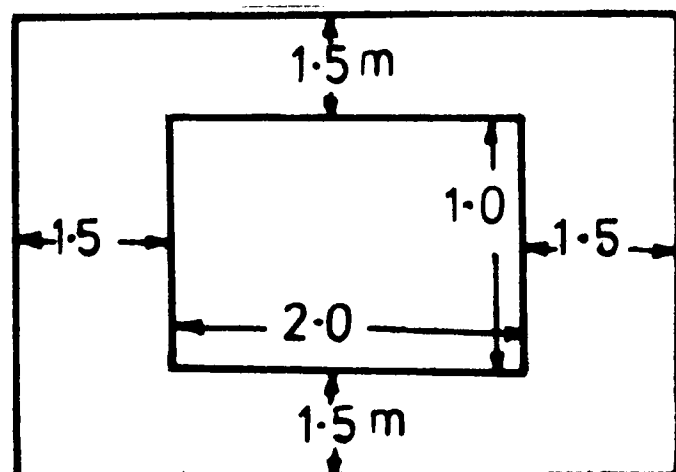
The work area is a facility that can be considered together with the equipment. Assume that over a certain period T , say five years, it is planned to make n_a vessels type A, of size A_a and taking a time t_a to complete, n_b of type B.... n_i of type I... etc. The total workshop area used by each type of vessel during the period T is $\left(A_a n_a \frac{t_a}{T} \right)$, etc. and thus, the workshop area required is

$$\text{Total area} = \sum A_i n_i \frac{t_i}{T}$$

and the area utilisation is the ratio between the area required and the actual area. Forecasting the production programme to such detail, is unlikely to be feasible and the normal problem will be the inverse of the one considered, i.e. given the work area whether or not there will be enough space available to undertake the manufacture of a vessel, knowing the vessel size and the estimated fabrication time.

5.6 The determination of the shop maximum output through vessel-machine occupation time

The areas which the various parts of the vessel and completed vessels occupy during manufacture, have been brought to a common basis known as "space-day". One space day is defined as the area occupied by one rolled course of an average size vessel, with 1.5 m walk way all around for one day. Physically this area is 20 m^2 per day and includes the machine tool area and a walk way, as illustrated in



the figure. A machine centre is said to be fully occupied when available area is entirely used. The centre is overloaded when additional area is required. The space availability for production round each facility in a year is obtained by multiplying the available space units by the number of working day per annum, (248 day), the viability of a contract depends on the ratio of the sales value to the total number of space days. The larger this ratio, the more viable the contract. In a sense, viability is synonymous with profitability and is a measure of the efficient use of the workshop facilities.

Assume that a factory is planned for a total output of N vessels/year, tonnage $N W$ tons/year, volume NV m^3 /year, equivalent area NA m^2 /year, then:

Total occupation days of one vessel

$$= \sum_{i=1}^n A_i t_i / 20$$

and for N vessels;

$$= \sum_{j=1}^N \left(\sum_{i=1}^n A_i t_i \right)_j / 20$$

If all vessels were identical, each one would occupy $\frac{A}{20}$ occupation days, N vessels will occupy $\frac{NA}{20}$ occupation days. If the workshop area is A_w , in one year, the number of occupation days is; $248 A_w$,

$$248 A_w > \frac{NA}{20}, \quad A_w > N \frac{A}{4960}$$

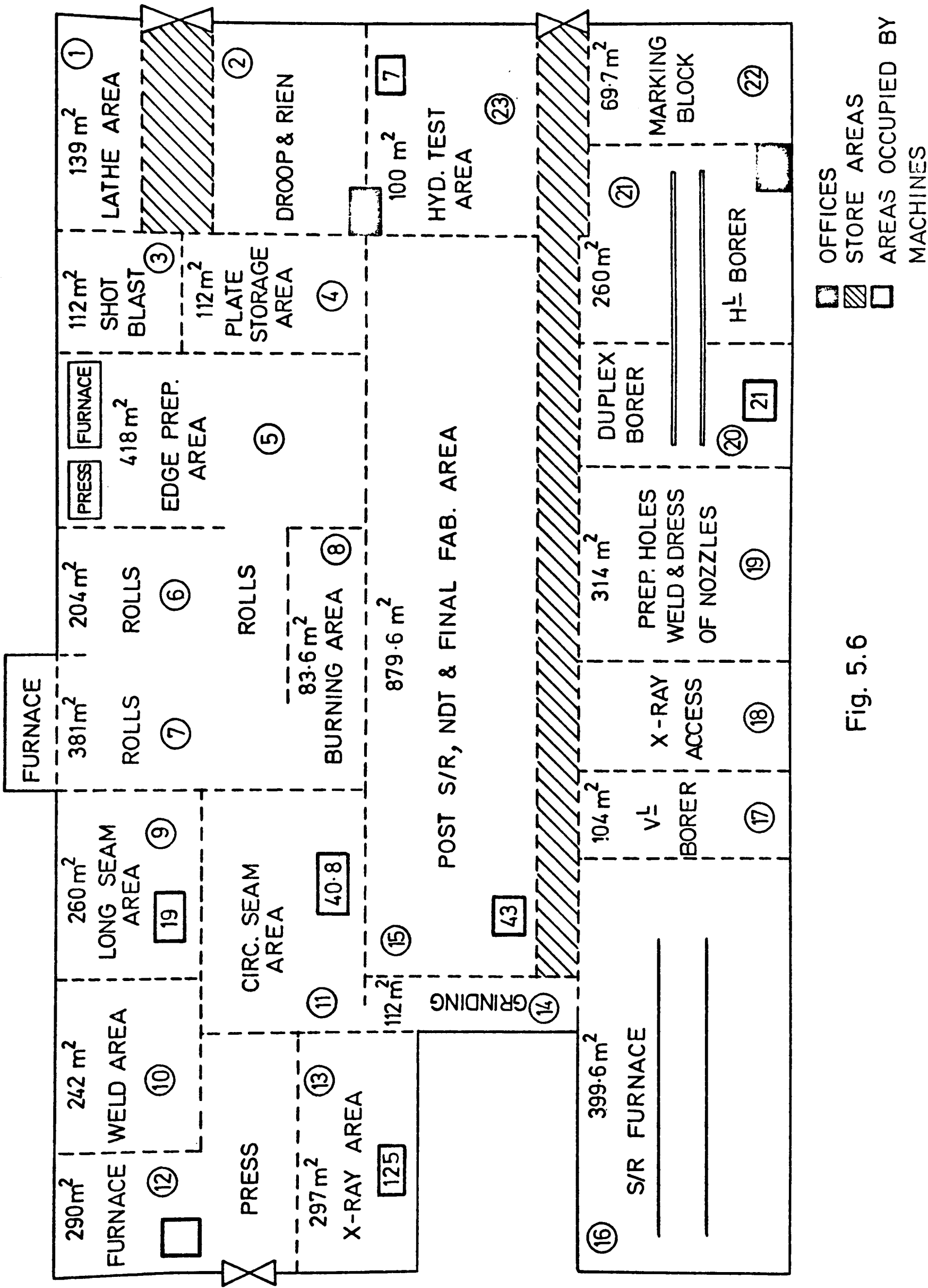


Fig. 5.6

Data presented below is obtained from one of the vessel producing firms:

Table 5.7

Workshop annual available areas

Centre	Activity	Available area (m ²) (Actual-tackle)	Space area units	Annual area space area x248
1	Lathes area	121	6	1488
2	Droop & Rein area (Edge prep. M/c)	153	7	1736
3	Shot blasting area	112	6	1488
4	Plate storage area	112	6	1488
5	Edge prep. area	418	21	5208
6	Rolls group (1) area	204	10	2480
7	Rolls group (2) area	381	19	4712
8	Burning area	84	4	992
9	Long seam assembly area	242	12	2975
10	Fab. welding area	242	12	2975
11	Circ. seam weld area	465	23	5704
12	Press area	290	15	3720
13	X-ray area	373	19	4712
14	Grinding area	112	6	1488
15	Post S/R, NDT + final fab. area	836	42	10416
16	S/R furnace	399	20	4960
17	Furnace storage area	104	5	1240
18	<u>V</u> l Borers	104	5	1240
19	Nozzle weld area	314	16	3968
20	Duplex borer	83	4	992
21	<u>H</u> l Borer	260	14	3472
22	Marking blocks	70	3	744
23	Hyd. test area	93	4	992

Table 5.8
Maximum workshop annual output

Working centre	Avail- able annual area	Vessel No (1)		Vessel No (2)		Vessel No (3)		Vessel No (4)		Vessel No (5)		Vessel No (6)		Vessel No (7)	
		Part area reqmt	No of parts fab. per annum	Part area reqmt	No of parts fab. per annum	Part area reqmt	No of parts fab. per annum	Part area reqmt	No of parts fab. per annum	Part area reqmt	No of parts fab. per annum	Part area reqmt	No of parts fab. per annum	Part area reqmt	No of parts fab. per annum
1 Lathe	1488	66.5	22.4	46	33	12	124	14.3	103	13	114	78	19	..	..
2 Droop & Rein	1736	..	..	..	..	..	..	..	..	..	..	10	181	..	..
3 Shot plasting area	1488	..	..	7.7	192.5	..	..	..	..	..	..	..	..	..	..
4 Plate storage area	1488	..	..	..	..	..	..	..	..	..	..	..	..	..	..
5 Edge prep. area	5208	..	..	15.3	340	3.8	1356	4.3	1083	..	..	9.0	567	0.36	145
6 Rolls group 1	2480	..	..	..	..	..	..	..	..	..	..	58	43	5	544
7 Rolls group 2	992	28.6	34.6	26	38	4.0	247	4.7	208	7	152	..	..	..	..
8 Burning area	4712	12.5	377.6	..	..	3.2	1482	6	805	..	..	11	436	..	..
9 Long sea area	3224	248	12.9	121	27	61.4	53	63	51	58	56	196	17	37	94.3
10 Fab. & welding area	3224	..	..	..	..	..	..	..	..	..	..	..	..	..	..
11 Circ. seam area	5704	254	22.4	260	22	109	52	65	88	41	139	239	624	17	335
12 Press area	3720	..	..	7.8	475	1.7	2175	2.7	1368	2.0	1771	..	..	..	..
13 X-ray area	4712	50.8	92.6	60	80	21	222	33	141	10	470	60	78	11	436
14 Grinding area	1418	17	85	6.0	230	..	..	..	..	..	..	..	..	..	..
15 S/R, NDT & Final Fab.	10416	1727	6	730	14	33	321	73	143	45	232	163	64	14	731
16 S/R Furnace	4960	39.7	125	21.6	230	9.0	559	14	347	10	478	4	1269	..	..
17 Furnace storage area	1240	42	30	..	..	..	..	..	..	..	..	..	..	..	..
18 VI Borer	1240	..	..	..	..	..	..	..	..	..	..	..	..	..	..
19 Nozzle weld. area	3968	666	5.9	475	8.0	38.5	103	..	21	37	109	23	55	..	..
20 Duplex borer	992	106.8	9.28	52	19	65	15.2	86	12	96	10.3	257	15.5	..	..
21 H1 borer	3472	..	..	..	..	..	..	..	..	..	..	4	153	..	..
22 Marking blocks	744	..	..	31	24	7.0	108	11	68	8	89	30	117	..	..
23 Hyd. test area	992	..	..	3.8	260	12	84	..	..	7	149	5.2	190	..	..
* max. output/annum/part		5.9		8.0		15.2			12	10.3			15.5		94.3
Centres requiring larger areas to increase production		nozzle weld area		nozzle weld area		boring area		boring area		boring area		nozzle weld area		long seam area	

Normally, A_w is fixed, then occupation has to be compared with available areas.

Above method is shown in detail in the analysis of the following vessels.

5.7 Selection of vessel from the point view of fabrication

From the previous definition of viability, it is inferred that the most profitable vessel is the one requiring the smallest number of space days, for a given sales value. In table 5.9 the number of space days and the sales value have been shown for seventeen vessels ranked in order of decreasing viability or preference. The large difference between vessel 1 with a ratio of sales value to space days of 89 to vessel 17 with a ratio of 17 should be noted. On this basis alone vessel 1 is obviously preferable to vessel 17 from the fabrication point of view. The area occupied is not the only criteria for the selection of the most profitable vessel. A vessel may be left for a long period occupying area that may be not valuable which low cost operations are being undertaken. Alternatively expensive operations with high labour costs may have to be completed within a short time in a small part of the vessel. Therefore, when assigning a preference, the ratio of labour costs to space days should also be considered. This ratio is tabulated in Table 5.10, for the same 17 vessels. It is now clear that if only Table 5.10 is considered vessel 11 is to be preferred to all others, vessel 4 comes a close second and vessel 16 comes last. If area used is entirely ignored and only the labour costs are considered Table 5.11 is obtained. The order of preference is almost reversed.

Vessel 16 comes now first, vessel 11 last by a very wide gap.

The criterion for the establishment of preference will depend on the relative importance of shop area and turn over-time against labour costs. No general conclusions can be established.

Table 5.10Viability based on ratio of labour value to space days

Vessel No	Total space days	Labour value £	Ratio of labour value to space days	% degree of viability
1	510	4,261	8.4	87.4
2	1862	12,329	6.6	68.6
3	53	452	8.5	88.6
4	63	587	9.33	97
5	785	4,000	5.0	52
6	344	2,945	8.5	88
7	286	2,363	8.3	86
8	3259	20,966	6.4	66.5
9	528	4,149	7.85	81
10	200	1,224	6.4	66.6
11	527	5,362	9.6	100
12	380	2,563	6.75	70
13	1206	3,690	3.0	31
14	1148	4,264	3.7	38
15	175	300	1.7	17.7
16	166	225	1.35	14.
17	81	293	3.6	37

Table 5.9Viability based on ratio of sales value to space days

<u>Vessel No</u>	<u>Total space days</u>	<u>Sales value £</u>	<u>Ratio sales value to space days</u>	<u>% Viability (preference)</u>
1	510	45,600	89	100
2	1862	160,000	86	94.6
3	53	4,000	75	82.5
4	63	4,750	76	83.6
5	785	53,000	68	75
6	344	22,000	64	70
7	286	18,000	63	69
8	3259	200,000	61	67
9	528	30,000	57	63
10	200	11,000	55	60.5
11	527	3,000	54	59
12	380	19,000	50	55
13	1206	50,000	41	45
14	1148	33,800	31	34
15	175	4,000	23	25
16	166	3,500	21	23
17	81	1,385	17	18.7

Table 5.11Viability based on ratio of sales value to labour value

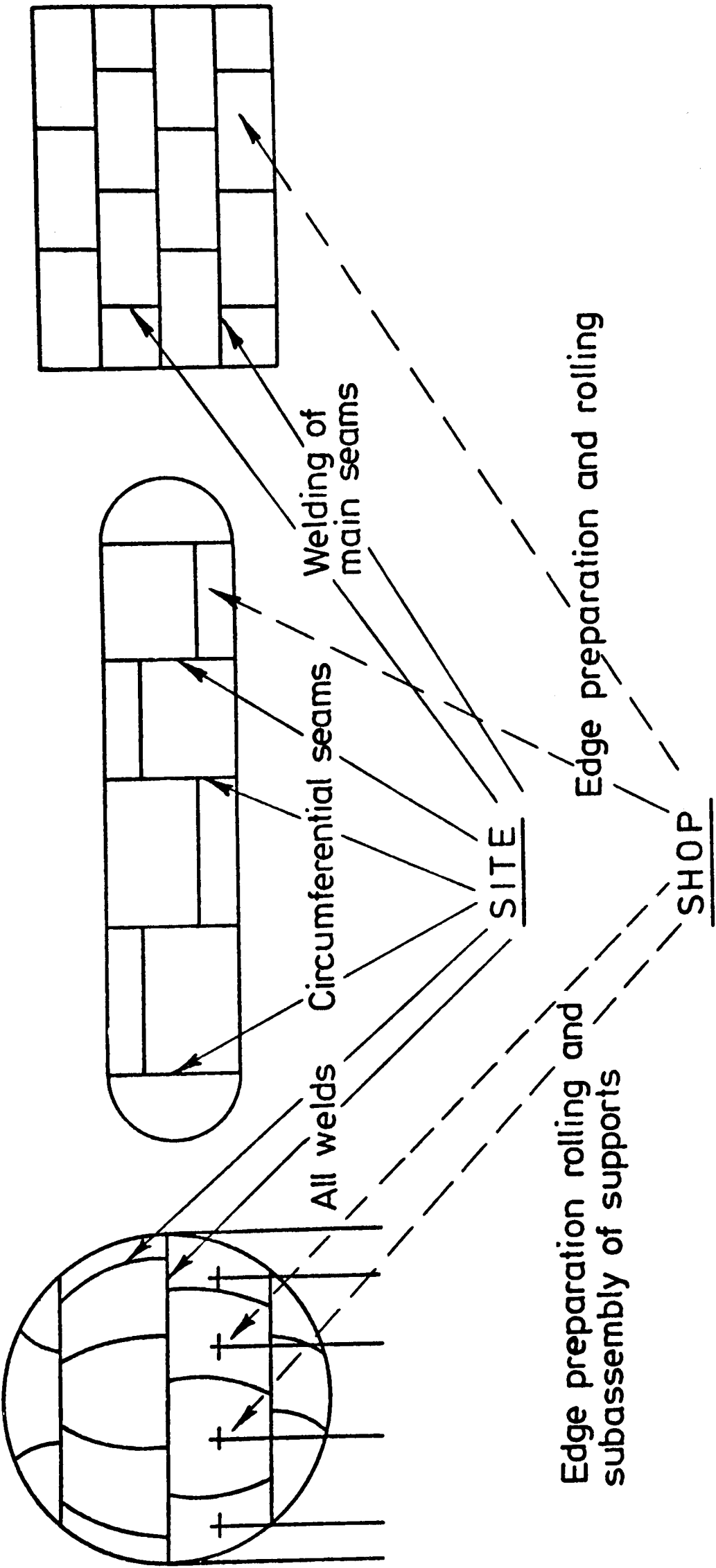
Vessel No	Sales value £	Labour value £	Ratio of S.V./L.V.	% preference viability
1	45,600	4,261	10.7	68.5
2	160,000	12,329	12.9	83
3	4,000	452	8.8	56
4	4,750	587	8.0	51
5	53,000	4,000	13.2	84.8
6	22,000	2,945	7.5	48
7	18,000	2,363	7.6	49
8	200,000	20,966	9.5	60
9	30,000	4,149	7.3	46
10	11,000	1,284	8.6	55
11	3,000	5,362	0.6	3.8
12	19,000	2,568	7.4	47
13	50,000	3,690	13.6	87
14	35,800	4,264	8.4	54
15	4,000	300	13.3	85
16	3,500	225	15.6	100
17	1,385	293	4.7	30

5.8 Site erection

When vessel sizes are excessive, vessel components, after their preparation are usually fitted in the works, dismantled and shipped to site. Volume of site works and equipment, depends on size and shape of vessel. Edge preparation and rolling may be the main operations to be performed in the shop, while main seams, assembly of supports and internals will be in site. Ratio of work required for each kind may be as shown in Fig.5.7.

In site fabrication, a number of uncontrollable variables may exist, such as, variety of vessel shape, vessel size, weight, type of welding required heat treatment and site conditions, which make it a very difficult task to draw out concrete conclusions and assessments on fabrication costs. Flexibility in site erection is therefore a requirement to cover all outcomes. For this reason, utilisation of site facilities becomes difficult.

Site progress of production and utilisation of facilities usually measured by how much weight of material has been put to site. This gives a rough estimation of completion dates as well as erection expenses. Fig.5.8 shows the rate of production per person, during the erection of the tank farm, of one of the Libyan refineries, whether conditions were acceptable, availability of materials as well as site handling facilities were fine. The average rate of erection was about 27 kg/man/hour. This was mainly concerned with the erection and welding of tanks and spheres without pumping units or electrical and civil works.



	Spheres	Drums	Tanks
Percentage of site work	30%	10%	90%
Percentage of shop work	70%	90%	10%

Fig. 5.7

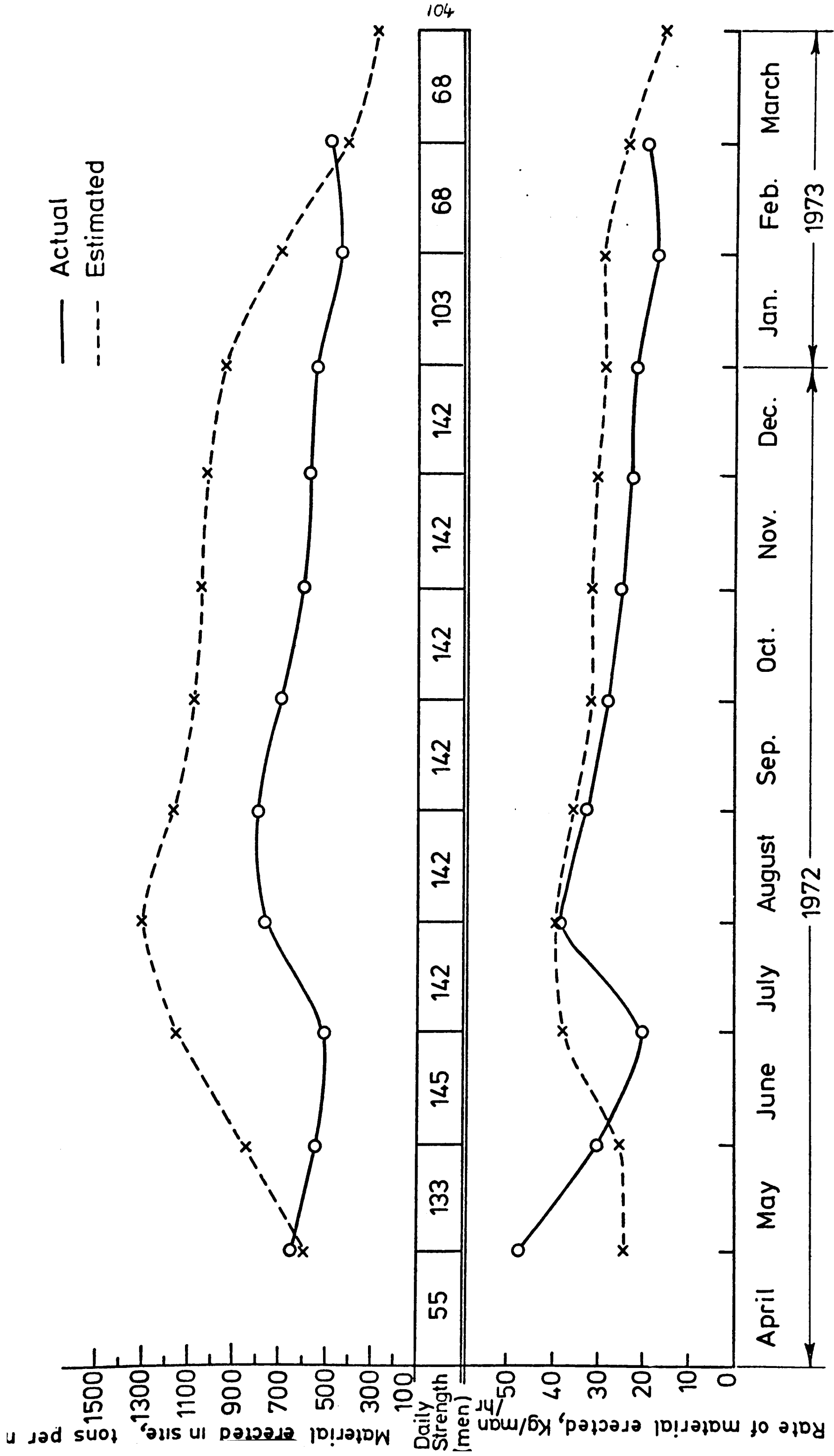


Fig. 5.8

5.9 CONCLUSION

Full utilisation of the production resources demands a minimum of repairs and the planning of inspection so as to interfere as little as possible with the production process. Since it is not possible to forecast with any accuracy the potential market demand for a given vessel, specialisation in production is not as good a policy as the diversification and increase in plant capacity or number of items in production. Flexibility in the plant is then essential. This can be achieved by investing in bending, pressing and heat treatment equipment of large capacity, which can be extended by smaller machines when required; by setting up a virtually independent machine tool workshop, capable of taking external contract work when not fully utilised for pressure vessels; by improving the welders' skills through adequate training programmes to reduce the occurrence of repairs and by using automatic welding equipment whenever possible. The plant layout must again be planned for flexibility and the minimum amount of back - and cross - flow.

In the pressure vessel industry, the type of vessels under construction by a given manufacturer at any given time affect the utilisation of the plant. Therefore, the true cost of a new order depends a great deal on the work already undertaken as well as on the nature of the new vessel. The price, on the other hand, does not seem to bear any relationship to the actual shape or type of vessel, as was shown in the previous chapters. This is an important fact, since it means that by carefully selecting the nature of the vessels ordered, a manufacturer could either obtain a high return for his investment or be unable to show any profits. It also implies that

customers may persuade manufacturers to reduce the prices quoted when the nature of the order is such as to provide full utilisation to otherwise under-utilised work centres.

From Table 5.8, it can be shown that the maximum workshop output can be controlled by the small areas containing essential operations, which in fact represents a bottleneck in the flow, and require increased facilities if production is to be increased. For the vessels considered it can be seen that nozzle welding area has to be increased if vessels 1, 2 and 6 were to be produced while boring area has to be increased if vessels 3, 4 and 5 were to be produced. This system will help in the two ways; first, suitable vessels for a given shop can be selected and second a more even utilisation of centres can be reached. The system in fact leads to more workshop specialisation, which improves production as mentioned in previous chapters.

CHAPTER 6

CHAPTER 6

PRODUCTION PLANNING IN THE PRESSURE VESSEL INDUSTRY

6.1 Introduction

In previous chapters it has been shown that a reduction of costs can best be achieved through the planning of production and that pressure vessels are usually treated as 'one-off' jobs. Whilst large pressure vessels can be considered as structures and are as such essentially unique, they nevertheless include a number of basic elements similar in nature, that could be easily standardized or grouped to simplify the task of planning. The industry has to operate on a batch production basis and the techniques of group technology devised to cope with the problems arising in these activities, would appear to be eminently suitable.

In group technology, components that require similar manufacturing operations are identified and grouped together following some pre-defined system. Several such systems have been proposed and some have been implemented in factories. Haworth (28), tested the Opitz system in the Rank Taylor Hobson, in Leicester, using the system to classify 12000 machined components. The information concerning actual dimensions, material used and factory locations was stored in punched cards. Ruiz and Koenigsberger (29), have discussed the standardization system from the point of view of preference; basic standardization of the product, i.e. sizes, scales, weight, dimensional standardization of engineering components - screws, nuts, etc., or material standardization - types, qualities, sizes and shapes. They also discuss the use of the Opitz

system in the classification and location of the workpiece.

Durie (30), in his survey of the use of group technology and its application, has reviewed the classification system and concluded that planning using group technology, will reduce fabrication expenses by up to 50%. Burbidge (31), has shown that the requirements and aims, when applying group technology, are as follows;

- (i) Route card for every component produced, or purchased.
- (ii) Each route card must show all operations from material issue to completion.
- (iii) Machine type should be shown in each card.
- (iv) The route should be an actual and accurate record of the methods in use.
- (v) Operation time to be shown opposite each operation.

With the following aims:-

- (i) As far as possible, each components should be fully processed in one department (centre).
- (ii) As far as possible each type of machine has to be grouped in one centre.
- (iii) In each centre, minimum drawings, number of destinations and resources have to be utilised.

Thornley (32), has tested the use of group technology, at Ferodo company, by using the technique for a period of 3 months. He concludes that, through-put times were reduced to about one tenth and the work-in-progress was cut to one eighth. Knight (33), has compared manufacturing costs, design costs and overall costs of a batched production shop, before and after the use of group technology, and found

that a reduction of 30-40% in overall manufacturing costs may be obtained.

The previous authors have obviously been concerned with industries in which the final product consists of a large number of components or requires a large variety of operations due to the complex shape of the product. Pressure vessels are simple structures and their basic elements of construction are not dissimilar in shape or in the operations they require. Closer examples showing the application of group technology may be sought in ship building.

The use of group technology in the ship building industry has been discussed by Gallagher et al. (34). In his work Gallagher stated that, "ship building is essentially a one-off or small batch manufacturing situation which involves the manufacture and assembly of a wide variety of items, many of which at the same time have a number of features in common". He showed that, the areas where group technology could be relevant are:

- (a) In the cutting, preparation and assembly of steel work for ship building.
- (b) In the use of a descriptive coding system for components and sub-assemblies to aid production organization.
- (c) In the field of purchased items, where reduction can be achieved with the use of a descriptive coding system.
- (d) In pipe work and pipe fitting, and assembly, during the ship-fitting-out process.

From his investigation, Gallagher, did not draw any specific conclusions, but he concluded that, the basic coding system, should

prove of value in the design rationalization and in the drafting of sound production planning systems by examining component sizes, shapes, variety, and production methods. An improvement of shopfloor organization and layout, based on the analysis of the types of components which pass through the area, and of the types of machining required was also possible.

In this chapter the feasibility of applying the group technology technique to the pressure vessel industry will be investigated.

6.2 Classification of vessel parts

The basis of group technology is the classification of items, not according to their function but to their shape and operations required. The first step in the application of group technology is therefore to establish a systematic classification of the vessel components. This is done by starting from the most general classification into plates, sections and forgings, as they come into the manufacturers workshop and by considering the detailed operations required to transform the initial shapes into finished products. In table 6.1, a class number has been assigned depending on the original form, typical operations are shown in the table. After the receiving of the plates, sections or forgings the next operation is to prepare them for forming. This may involve cutting to required shape in case of plates, and additional digits as shown in Table 6.2 can be used to describe such shapes. In the case of sections and forgings the variety of shapes requires the use of a second digit in addition to the one given in Table 6.2. Plates and sections, once they have been cut to size and to the right shape may require forming. The basic forming operations tabu-

Table 1 General Classification

Original form		Application	Class Number
Plates	All edges straight	Cylindrical course plates Brackets, internal baffles fabricated supports	0
	At least one edge curved	Petals for domed shells, conical transitions, fabricated bends Baffles, condenser tube plates	1
	Circular	Flat covers, trays, tube plates, Loose flanges Torispherical ends, spherical caps	2
Sections	Standard sections	Leg supports, internal structure ladders, stiffeners Pipes and tubes, attachments, opening reinforcements	3
	Solid bars	Support rings, stiffeners	4
Forgings		Integral neck flanges, forged rings for reinforcement of openings	5
		Forged flat covers	6

Table 2 Shape before forming

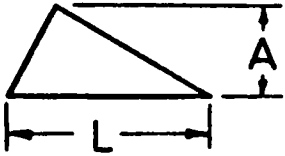
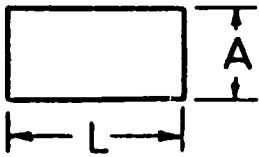
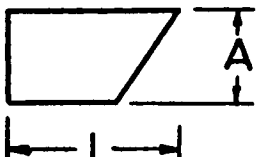
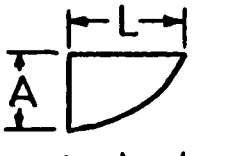
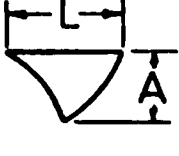
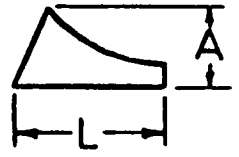
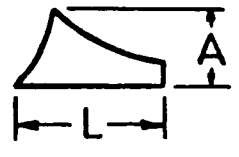

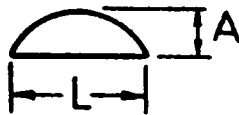
General Class Number	Shape before forming			2nd. Digit
0	3 sided		$L > A$ thickness=T	0
	4 sided rectangle			1
	combined			2
	irregular			3
	more than 4 sided			4
1	3 sided one curved edge, two flat			0
	two curved edges, one flat			1
	4 sided one curved edge, three flat			2
	two curved edges, two flat			3
	more than two curved edges			4
	more than 4 sided			5
2	Fully circular			0
	One straight edge			1

Table 2 continued

3	Rectangular cross section		0
	Angle		1
	Channel		2
	I		3
	Square tube		4
	Pipes and tubes		5
4	Circular cross section		0
	Other cross section		1
5	Flanges		0
	Forged rings		1
	Reinforcement rings (radial)		2
	Reinforcement rings (oblique)		3

Table 2 Continued

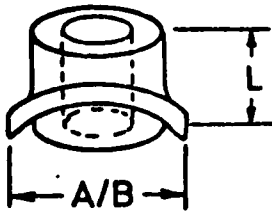
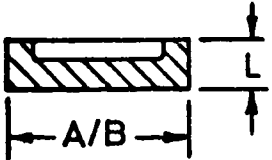
	Reinforcement: cylinder to cylinder (radial)		4
	" " (oblique)		5
	Forged rings ends not square, without flange		6
	" " " " " with "		7
6	Forged flat covers, raised lips		0

Table 3 Forming (General class 0 - 4 only)






General Class Number	Forming operation	3rd Digit
0 - 2	No forming	0
	Flange - Single 	1
	Flange - Multiple 	2
	Bending - Single generator (Cylindrical surface) 	3
	Bending - Non-parallel generators (Conical surface) 	4
	Bending - Double curvature (i.e. spherical cap, torispherical head, dome)	5
	Bending - Torispherical transition 	6
3 - 4	No forming	0
	Bend - plane	1
	Bend - out-of-plane	2

Table 4 Holes

Type	4th Digit
None	0
Flame cut	1
Drilled, no drilling pattern	2
" drilling pattern	3
Thread cutting, no drilling pattern	4
" drilling pattern	5
Combination of 1 and 2, 3	6
" 1 and 4, 5	7

Table 5 Weld preparation

Edge preparation	5th Digit
No preparation	0
Square	1
Y and V	2
X	3
U	4
χ	5
Square + Y or V	6
Square, Y or V and X	7
Square, Y or V and U	8
Square, Y, V or X and χ	9

Table 6 Material

Type of material	6th Digit
Standard carbon steel	0
Improved carbon steel	1
Low alloy steel	2
High alloy steel	3
Stainless steel	4
Clad steel	5
Ni Alloy	6
Al Alloy	7
Cu Alloy	8

Table 7 Finish

Type of finish	7th Digit
Non stated	0
Degrease, clean, shot blast, grind welds	1
Paint	2
Machined surfaces, other than edge preparation and drilling and thread cutting	3
Combination 1 + 2	4
" 1 or 2 and 3	5

Table 8 Inspection

Type of inspection	8th Digit
Non stated	0
Dimensional and visual	1
N.D.T. Magnetic crack detection, dye penetrant	2
" Ultrasonic, radiography	3
D.T. Tensile, impact, hardness	4
Chemical analysis	5
Combination 1 + 2 + 3	6
" 1 + 2 + 3 + 4	7
" 1 + 2 + 3 + 4 + 5	8

Table 9 Dimensions

Thickness-plates Breadth-sec- tions, forgings	9th Digit	Width-plates Depth-sections, forgings	10th Digit	Length-plates, sections Height-forgings	11th Digit
T, B <12.5mm	0	A < 100 mm	0	L < 100 mm	0
12.5 < <25	1	100 < < 500	1	100 < < 500	1
25 < <37.5	2	500 < <1000	2	500 < <1000	2
37.5 < <50	3	1000 < <1500	3	1000 < <1500	3
50 < <75	4	1500 < <2000	4	1500 < <2000	4
75 < <100	5	2000 < <2500	5	2000 < <2500	5
100 < <150	6	2500 < <3000	6	2500 < <3000	6
150 < <200	7	3000 < <3500	7	3000 < <3500	7
200 < <300	8	3500 < <4000	8	3500 < <4000	8
300 <	9	4000 <	9	4000 <	9

Digits 12 - 15 (0000 to 9999) number of identical parts
Digits 16 - 19 (0000 to 9999) T or B (incl.dec.)
Digits 20 - 23 (0000 to 9999) A
Digits 24 - 27 (0000 to 9999) L
Digits 28, 29 not allocated

Table 10 Subassemblies

Shape	Application	Class number
Cylinder/ Cone	Main shell courses, skirt supports, fabricated ducts, incl. branches, openings, etc.	0
Sphere/ Ellipsoid	Spherical shells, domed ends, incl. torispherical ends, incl. branches, openings, etc.	1
Junction (Two shells of similar overall dimensions)	Cylinder/Cylinder, radial	2
	Cylinder/Cylinder, oblique and stepped	3
	Cylinder/Sphere, radial	4
	Cylinder/Sphere, oblique	5
	Cylinder/Cone	6
	Cylinder/Plate	7

Table 11 Welding of main seams

Weld		Type	Digit
Longitudinal or Meridional	Second Digit	None	0
		Automatic	1
		Manual	2
Circumferential or along parallel circle	Third Digit	None	0
		Automatic	1
		Manual	2

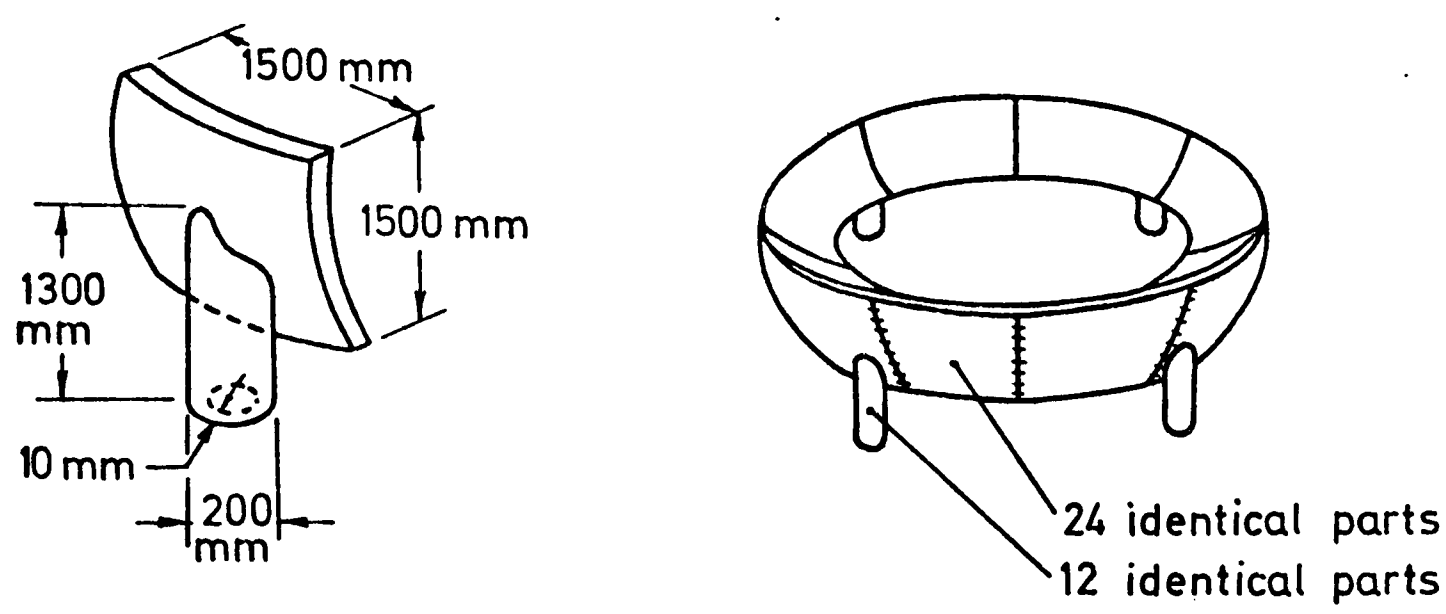
lated in Table 6.3 provide a third identification digit. Holes may have to be flame cut, drilled and threaded. They may be isolated or arranged in some pattern in which case they should be obviously all drilled with minimum setting-up time. The type of holes provides the fourth identification digit of Table 6.4. Table 6.5, describes the edge preparation for welding. To complete the identification of an item that will eventually form a part a sub-assembly, information has to be given on material (Table 6.6), the finish (Table 6.7), the inspection (Table 6.8) and the dimensions (Table 6.9). These tables are self explanatory. The complete information takes 27 digits and includes the exact dimensions of the item. Digits 28 and 29 are not allocated but may be used, for example, to give the weight in tons.

The basic items are assembled into the sub-assemblies of Table 6.10. To define a sub-assembly completely, the first consideration is its overall shape. We can have cylindrical or conical shells constituting the main pressure vessel course, spherical shells or part spherical, junctions between two shells with a common diameter, etc. as shown in Table 6.10. The sub-assemblies will be made by welding together some of the basic elements previously described, a classification of welding providing a second and third digits to form the identification of the sub-assembly is given in Table 6.11. The remaining digits are allocated as follows;

4th Digit - Weld deposited cladding:-	None	0
	Yes	1
5th Digit - Heat treatment:-	None	0
	Preheat	1
	Stress relief	2
	1 + 2	3
	Final stress relief	4
	2 + 4	5
	1 + 2 + 4	6
6th Digit - Welded branches:-	None	0
	Isolated	1
	Regular pattern	2
7th Digit - Welded brackets:-	None	0
	Yes	1
8th Digit - Finish, machining:-	None specified	0
	Bore	1
	Edge preparation	2
	Drilling, isolated holes	3
	" pattern	4
	1 + 2	5
	1 + 3 or 4	6
	2 + 3 or 4	7
	Other	8
9th Digit - Finish other than machining:-	None specified	0
	Degrease, grind	1
	Paint	2
	Combination 1 + 2	3

10th Digit - Type of inspection - See Table 8

11th Digit - Not allocated



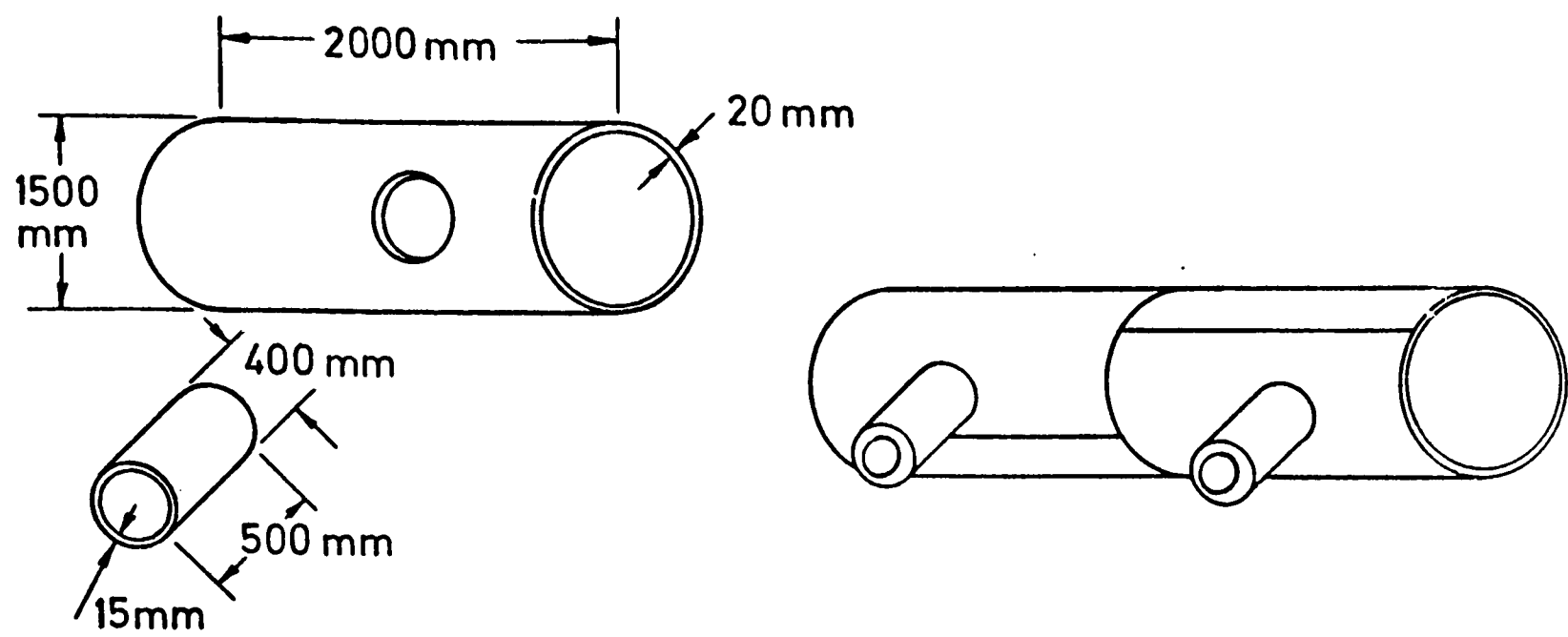
Forming information

Plate oper ^S No.	1	4	5	0	3	1	1	2	1	4	4	0	0	2	4	0	0	2	5	1	5	0	0	1	5	0	0
Support oper ^S No.	3	5	0	0	2	1	1	1	0	1	3	0	0	1	2	0	0	1	0	0	2	0	0	1	3	0	0
Digit number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
Forming information												no. of identical parts		T & B		A		L									

Sub-assembly information

Operation No.	1	2	0	0	2	1	0	0	3	1
Digit number	1	2	3	4	5	6	7	8	9	10

Fig .6.1



Forming information

Course oper ^S No.	0	1	3	1	3	0	1	2	1	4	5	0	0	0	2	0	0	2	0	1	5	0	0	2	0	0	0
Nozzle oper ^S No.	0	1	3	0	3	0	1	2	1	1	2	0	0	0	2	0	0	1	5	0	4	0	0	0	5	0	0
Digit number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27

Sub-assembly information

Operation No.	2	2	2	0	2	2	0	0	3	2
Digit number	1	2	3	4	5	6	7	8	9	10

Fig . 6.2

Figs. 6.1 and 6.2 illustrate the use of the classification of basic items and sub-assemblies by means of some examples.

6.3 Planning for production

The classification of previous section may be used to define the various component parts of a vessel and to follow them through the whole sequence of fabrication. This has been done in Table 6.12, in which it will be observed that the matrix work-centre/group class number is almost complete with the exception of the rows corresponding to cutting, rolling, turning, where two elements are missing from each; pressing and boring have four elements missing; forming has five. It must be emphasized that this table does not give any indication of the probability for a given vessel part to require a given operation only whether or not that particular operation will ever be essential to the fabrication of the part.

Given that the same operations are required for the manufacture of most of the parts of a vessel, the advantages that group technology has been shown to offer in other industries will not be as obvious in this particular problem. However, one fact, that emerges is that the traditional view to identify certain areas of the workshop with given vessel components is mistaken. For example, it is common practice to allocate the drilling of tube plates to a given work centre, whilst flanges are always done elsewhere, this can lead to uneven loading of work centres. Another conclusion that may be drawn from Table 6.12, is that the whole flow goes through the first three stages which could be grouped together, it then sub-divides into a number of lines going through at least one of the next six stages, becoming again a single flow in the last two stages, this is shown in fig.6.3, in which backward movement of parts are also indicated.

Work centre	Group class number	Sub-assembly
Identification & mark	<div>0123456</div>	<div>Yes</div>
Cutting	<div>01234</div> <div>56</div>	No
Edge prep.	<div>0123456</div>	<div>Yes</div>
Rolling	<div>01234</div> <div>56</div>	No
Pressing	<div>012</div> <div>3456</div>	No
Forging	<div>01234</div> <div>56</div>	No
Turning	<div>01</div> <div>23456</div>	<div>Yes</div>
Boring	<div>0</div> <div>12</div> <div>3</div> <div>4</div> <div>5</div> <div>6</div>	<div>Yes</div>
Drilling	<div>01234</div> <div>5</div> <div>6</div>	<div>Yes</div>
Welding	<div>0123456</div>	<div>Yes</div>
Grinding	<div>0123456</div>	<div>Yes</div>

Table. 6.12

The flow of vessel parts through work centres.

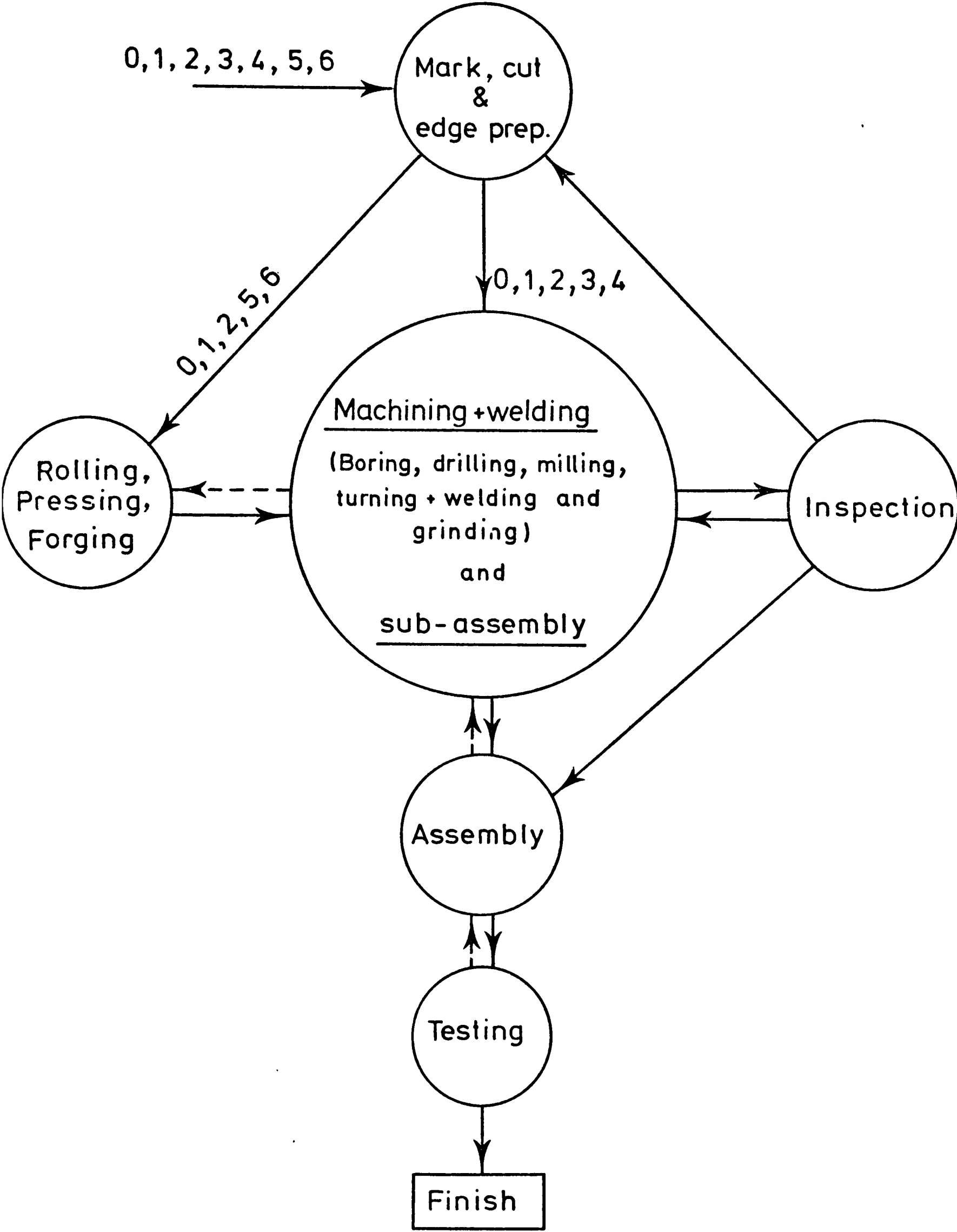


Fig. 6.3

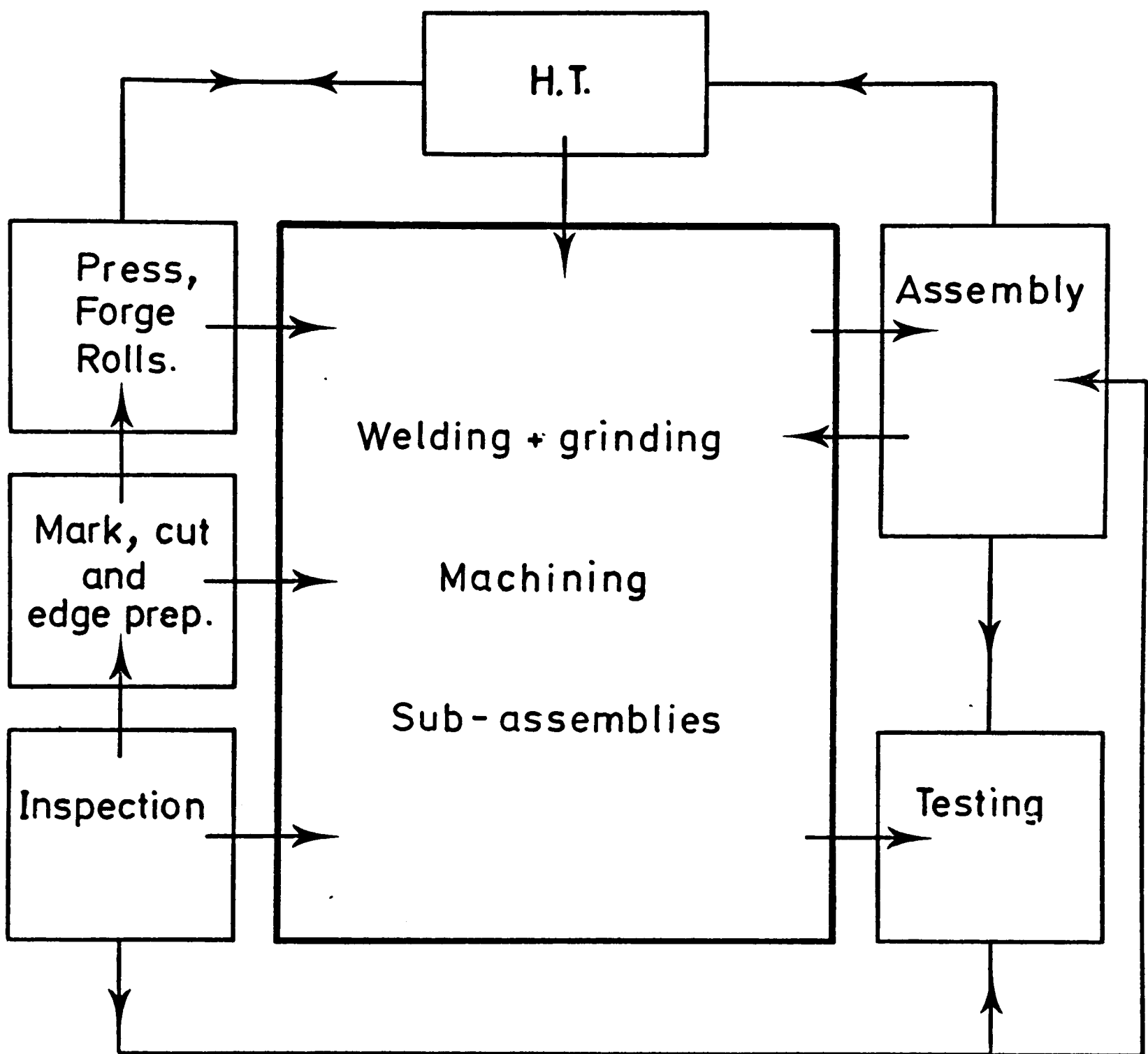


Fig. 6.4

At first sight it would appear that the ideal workshop layout would be one in which specific areas are allocated to the groups of operations of Table 6.12. Each area would be in such a position as to allow forward flow. There is however, backward flow of parts and what is more important sub-assemblies and assemblies have not been considered yet. Referring to sub-assemblies it is even more important to ensure the continuity of flow than for parts since they are larger, heavier items and therefore more difficult to move. It will be seen from Table 6.12, that most of the operations on sub-assemblies take part towards the end. It is possible that a sub-assembly will require some identification and marking, but this will not need any transport; edge preparation, if required will usually be done in the area reserved for machining. It is then clear from Table 6.12 that the production should be arranged in such a way as to feed a central area in which machining and welding of sub-assemblies take place. Sub-assemblies would leave that area to the final assembly shop and to be tested as completed vessel. A workshop layout such as the one shown in fig.6.4 would achieve this aim. Inspection requires mobile equipment and can be located at any point. Taking into account the probability of each item receiving a certain operation, the areas of the various sections will be in approximately the following ratios:

	<u>Ratio</u>	<u>% of total area</u>
Marking, cutting and edge preparing area	0.8	12%
Pressing, rolling and forging area	1.0	15%
Welding, machining and sub-assembly area	2.0	30%
Heat treatment area	0.6	9%
Assembly area (Index)	1.0	15%
Test area	0.6	9%
Inspection areas	0.6	9%

6.4 Conclusions

The classifications of shape and operations enables considerably greater flexibility in the planning of production than the traditional approach in which components are classified in accordance with their function. One direct conclusion from the preceding considerations is that it is advantageous to plan a workshop layout in which a central area including welding and machining facilities will be used for the fabrication of sub-assemblies. This area will receive formed components and services such as inspection, marking and heat treatment. Machined or welded components may have to be returned to the press, rolling or forging shops before they are joined to others to form a sub-assembly. Sub-assemblies will leave the central area to be finally assembled into a complete vessel which will then be tested. To return a large assembly to the central welding and machining shop would be very expensive and it is therefore important to ensure that the design is such that this is not required. The essential philosophy is to design in such a way that machining can be done in small parts or sub-assemblies and that the final assembly only needs welding using portable equipment.

The classification system and the use of group technology shown in the chapter for the fabrication of vessels, provide a basis for a detailed schedule of facilities required, starting and completion times of the different operations on facility, volume of work-in-progress available in the workshop at any fabrication stage and expected overall utilisation of the shop. It is not possible to give any detailed recommendations or to establish in a clear manner what benefits should come out of this technique, since this can only be done when implementing

it in an industrial environment.

Difficulty in applying the group technology in the vessel industry is likely to be experienced as a result of the following factors:

- (i) vessels are usually designed to perform satisfactorily in service. Little or no attention is paid to the fact that they have to be made in an economical manner.
- (ii) fabrication, design and inspection are split between several organizations and lack of co-ordination often results.
- (iii) the market conditions are such that an excess production capacity prevents manufacturers from specializing in given lines.
- (iv) vessels are designed as "one-off" items.

The application of group technology would be advantageous in that it would enable a better control of the production, the movement of the items in the shopfloor and a better utilization of the facilities.

CHAPTER 7

CHAPTER 7GENERAL CONCLUSIONS AND FURTHER WORK

The peculiar characteristics of the pressure vessel industry have been shown to result from the existence of the pressure vessel codes which fulfill a number of functions:

(i) They provide rules for the dimensioning of the vessel and the design of details, based on consideration of strength.

(ii) They form the basis for the contractual document between customers and suppliers

(iii) They are used to assign responsibility to the various organizations involved in the production and specification of the vessel.

(iv) They provide guidance on fabrication as well as criteria for the quality control of materials and workmanship, and thus influence the final cost.

The main effect of the design code is on the vessel thickness and therefore the weight, the selection of the code can therefore be of great importance, particularly in the case of large vessels where the cost of the material may be the primary consideration. The saving in weight is achieved by accepting a high design stress. At first sight it would appear that to do so implies the acceptance of correspondingly greater risk of failure. This would, indeed, be the case if steps were not taken to improve the design of details, the quality and reliability of the materials used and standard of workmanship. Given these safeguards the cheapest code is found to

be the one that gives the minimum shell thickness regardless of the expenses involved in implementing the safety measures just mentioned.

Given the coordinating function of the code it is important to gain some familiarity with the one that is selected. It has also been shown that, at the design stage, costs can be cut if the designer uses a code with which he is familiar, however, bearing in mind the design costs represent a fairly small part of the total costs, saving at that stage are not too important and it is advantageous to use a code which may require considerable design time provided it allows a reduction in weight. Another point of interest is that the current fashion to use computerized design procedures, although it may cut down the design time and perhaps cost, will not result in a substantial overall saving.

Referring to the function of the code as a means to assign responsibility and to provide a contractual basis, it is essential to accept its recommendations in full or to make it quite clear at the earliest stage that some recommendations should be replaced by others or ignored altogether. Familiarity with the code will quite clearly simplify the relationship between the various organizations involved.

It has been shown that the requirements for inspection procedure do not result in any significant variations in the total cost, at least in the case of conventional carbon steel vessels. In the case of complex vessels, with a large number of openings and for severe working conditions, codes may require additional material tests and qualifications of design procedures. This will obviously result in an increase in the cost per unit weight.

Whenever possible standardized materials should be used.

In the case of most vessels, with a few isolated openings, there is little advantage in choosing one code rather than another since the total weight is dictated by the weight of the shell. All codes coincide in the rules given for the reinforcement of multiple openings.

Two formulae have been proposed for the determination of the total cost of a vessel. In one, the cost is shown to be proportional to the weight, in the other it is proportional to a given power of the capacity. It would be possible to optimize the vessel size and the number of vessels for any specified total capacity. It is in this optimization process, which would require the repetitive computation of very simple formulae where digital computer techniques would prove useful. The parameters to be handled would be:

- (i) Code main shell thickness formula
- (ii) Code design stress formula
- (iii) Material properties.
- (iv) Capacity
- (v) Number of vessels
- (vi) Cost of material
- (vii) Additional constraints such as delivery time may also be added

Design codes have little or no bearing on the actual cost per unit weight, this depends entirely on the efficient use of the available facilities in design, fabrication, inspection, etc. Of the various production stages, fabrication is the most important

and the one in which the most significant savings can be achieved. Vessels are normally made in a "one-off" basis; they are designed for strength, not for production. It is therefore not surprising to find that the fabrication facilities are very unevenly utilized. Some vessels require machining, others do not require it at all. Sometimes machining has to be carried out in the completed vessel which necessitates either the transport of the vessel against the natural forward flow in the production process or the setting-up of large, expensive and under-utilized machining facilities in the assembly area. There are two ways in which full, even, utilisation of fabrication facilities can be achieved. One is by planning the factory for specialisation, the other by diversifying production as far as possible. In the present conditions in the industrialized countries, the first alternative is not feasible because there is an excess production capacity. The second alternative is therefore to be preferred.

Having chosen to diversify production it becomes essential to attempt some form of grouping of the products or components in order to rationalize planning. Modern production planning techniques have been developed to improve the control of the workshop in industries producing batches of similar products. Such techniques, in particular group technology, should be applied to the pressure vessel industry. However, it has been shown that their benefits will be less marked in this field since the operations involved in the production of the various component elements are very similar. A classification system, based on component shape rather than the

more traditional one based on function is likely to result in improved planning. Whether or not the advantages offered by such a system are really worthwhile can only be decided by its use in industry.

As it is proposed, such a system provides a convenient frame of reference for the determination of the shop layout, the areas to be allocated to the various work centres and for determination of the production flow.

Further work in stress analysis and design is unlikely to result in a reduction of cost. It is only required when it is essential to estimate the strength of a vessel or to justify changes in design stresses. Given the importance of the materials cost, the development of cheap materials of adequate mechanical characteristics is clearly an important area of study when considering reduction of cost. So are welding, fabricating and machining techniques.

Inspection by itself is not very expensive. What can be expensive is the rejection of products which though perfectly satisfactory in most respects, fail to comply with the, sometimes, arbitrary quality standards that are set up. The fitness-for-purpose philosophy is therefore of interest. A quantitative assessment of the savings that may be achieved should be undertaken. This work is particularly timely at present since new recommendations for dimensional tolerances and defect sizes are being considered by several code writing organizations.

The classification presented in chapter six only gives a broad

picture of the vessel components and sub-assemblies. A more detailed study, in collaboration with industry should be undertaken to ascertain the benefits to be gained.

From the point of view of the oil producing non-industrialized countries, there is little to be gained by setting up a pressure vessel industry which is highly capital intensive, given the excess capacity already available in the industrialized countries. It is likely that technologists from non-industrialized countries will play a more important part than they have done until now, in the selection, specification and inspection of plant and in the coordination of construction. The fitness-for-purpose approach should be presented in the form of rules as clear and unequivocal as those given in today's codes. Recommendations for material selection and fabrication techniques should also be included.

As customers, a knowledge of the industry and of the benefits to be gained by the standardization of components would be of use in reducing the total costs.

REFERENCES

1. British Standards Institution,
"Fusion welded pressure vessels for general purposes",
BS 1500: Part 1: 1958.
2. M. Bickell and C. Ruiz,
"Recent trends in pressure vessel design", Second
Commonwealth Welding Conference, London 1965
(I. Welding, 1966), 294-313.
3. M. Bickell and C. Ruiz,
"Pressure vessel design and analysis", Macmillan, 1967.
4. J. Poynor,
"The design of conventional pressure vessels", in
R. W. Nichols, ed. "Pressure Vessel Engineering
Technology", Elsevier Co. Ltd., 1971.
5. BS - PD 6437,
"A review of design methods given in present standards
and codes and design proposals for nozzles and openings
in pressure vessels", BS. PD-UDC 66.023: 621-225, 1969.
6. W. Chipperfield et al.
"Design criteria of boilers and pressure vessels",
Proc. 1st Inter. Conf. P.V. Technology, ASME/KIVI (Delft,
1969).
7. J. Lancaster,
"A comparison of British, European and U.S. pressure
vessel steels", ASME paper 64 - PET - 33. July 1966.
8. M. S. Northupp and A. R. Cluffreda,
"European V.S. U.S. steel specification", The petroleum
refiner, Oct. 1959.
9. ESSO,
"Permissible substitutes for USA specification materials,
ESSO Basic practice, Sept. 1966.

10. Kellogg International Corporation,
"British, French, German, Italian, Spanish and Swedish
equivalents of ASTM specifications", Eng. Stds.,
Jan. 1965.
11. Ralph Parsons, (UK) Ltd.,
"Code of practice".
12. S. E. Chukwujekwu,
"Reinforcement method for flush nozzles in pressure
vessels", Loc.cit. Ref.6.
13. C. Ruiz and I. El Magrissy,
"Flangeless closure joints: Experimental validation of
an unconventional design", Proc. 2nd. Int. Conf. PV
Technology, ASME, San Antonio, U.S.A. 1973.
14. C. Ruiz and I. El Magrissy,
"Flangeless closure joints for pressure vessels",
Chemical Process Engineering, Nov. 1971.
15. The British Standards Institution,
"Specifications for steels for pressure vessels",
Alloy steels, 1501: Part 2. 1970.
16. The British Standards Institution,
"Steels for fired and unfired pressure vessels, plates,
corrosion and heat resisting steels", BS 1501:
Part 3: 1973.
17. The British Standards Institution,
"Specifications for fusion welded pressure vessels,
carbon and ferritic alloy steels", British standards,
BS 1515: Part 1: 1965.
18. The American Society of Mechanical Engineers,
"ASME boiler and pressure vessel code", ASME viii-Div.1,
1971.
19. The American Society of Mechanical Engineers,
"ASME boiler and pressure vessel code", ASME viii-Div.2,
1971.

20. The American Society of Mechanical Engineers,
"Material specifications", ASME Section II, Part A
Ferrous, 1971.
21. DIN, Pocket book 4,
"Steels and Iron standards on quality", Pocket book 4,
1970.
22. Colvills Ltd., Glasgow, (Scotland),
"Boilers and pressure vessel steels", Dec. 1964.
23. Samual Fox & Co. Ltd. Sheffield, (England),
"General data sheets", 1966 and 1967.
24. Thyssen Niederrhein AG, FDR,
"Company publications and comments on German steels",
Oct. 1973.
25. R. B. Gibbon and J. A. Cameron,
"Inspection testing and acceptance", Pressure Vessel
Standards, Impact of change Conference, The Welding
Institute, London, Nov. 1972.
26. S. Nicholson and R. Blenkin,
"Influence of design criteria on material costs",
Welding Institute Conference, on Improving welding
design, Nov. 1971.
27. J. Corker,
"Pressure vessel costs", Chemical and Processing
Engineering, July 1966.
28. E. A. Haworth,
"Group technology using the Optiz system", The production
engineer, Jan. 1968.
29. C. Ruiz and F. Koenigsberger,
"Design for strength and production", MacMillan, 1970.
30. F. R. E. Durie,
"A survey of group technology and its potential for user
application in the UK". The Production Engineer, Feb. 1970.

31. J. L. Burbidge,
"Production flow analysis", The Production Engineer,
April/May 1971.
32. R. Thornley,
"Group technology - a complete manufacturing system",
CME, Jan. 1972.
33. A. W. Knight,
"The economic benefits of group technology", The
Production Engineer, May 1974.
34. C. C. Gallagher, S. K. Banerjee and G. Southern,
"Group technology in the shipbuilding industry",
Int. J. Prod. Res., Vol.12, No.1, 1974.

Private communications from pressure vessel firms have not been included in this list of references. The main communications are acknowledged at the beginning of the thesis.

APPENDICES

APPENDIX 1Standard Vessel ThicknessI BS 1500 and BS 1515 part 1

Cylindrical shells; the thickness of the shell shall be determined by;

$$t = \frac{PD_i}{2fj - P} + c \quad \text{or} \quad p = \frac{2fj (t-c)}{D_i + (t-c)} \quad (1)$$

or using the outside diameter;

$$t = \frac{P D_o}{2fj + P} + c \quad \text{or} \quad p = \frac{2fj (t-c)}{D_o - t+c} \quad (2)$$

Spherical shell;

$$t = \frac{PD_i}{4fj - P} + c \quad \text{or} \quad p = \frac{4fj (t-c)}{D_i + (t-c)} \quad (3)$$

or by using outside diameter;

$$t = \frac{P D_o}{4fj + P} + c \quad \text{or} \quad p = \frac{4fj (t-c)}{D_o - t+c} \quad (4)$$

t = minimum thickness of shell plate (inches)

P = design pressure lb/in^2

D_o and D_i = external and internal diameters in inches without corrosion allowance

f = allowable design stress

j = joint factor

c = corrosion allowance (inches)

II ASME viii;1. Cylindrical shells:

- a. For circumferential stress, longitudinal joints, and when thickness does not exceed $\frac{1}{2} R_i$ or P not exceed 0.385 SE. The minimum thickness, or maximum allowable working pressure of cylindrical shell is:

$$\text{use of } D_i; \quad t = \frac{PR_i}{SE-0.6P} \quad \text{or} \quad P = \frac{SEt}{R_i+0.6t} \quad (5)$$

- b. For longitudinal stress, circumferential joints, for t not exceeding $\frac{1}{2}R_i$ and P not exceeding 1.25 SE

$$t = \frac{PR_i}{2SE+0.4P} \quad \text{or} \quad P = \frac{2 SEt}{R_i-0.4t} \quad (6)$$

2. Spherical shells: when t not exceeding $0.356 R_i$
or P not exceeding 0.665 SE

$$t = \frac{PR_i}{2SE-0.2P} \quad \text{or} \quad P = \frac{2 SEt}{R_i+0.2t} \quad (7)$$

3. Thickness of cylindrical and spherical shells:

Use of D_o ;

$$\text{cylindrical shells; } t = \frac{PR_o}{SE+0.4P} \quad \text{or} \quad P = \frac{SEt}{R_o-0.4t} \quad (8)$$

$$\text{spherical shells; } t = \frac{PR_o}{2SE+0.8P} \quad \text{or} \quad P = \frac{2 SEt}{R_o-0.8t} \quad (9)$$

4. Thick cylindrical shells:

- a. circumferential stress, longitudinal joints. When thickness of cylinder under internal pressure exceeds $\frac{1}{2}R_i$ or when P exceeds $0.385 SE$.

when, P is known, t desired,
 then; $t = R_i (Z^{\frac{1}{2}} - 1) = R_o \left(\frac{Z^{\frac{1}{2}} - 1}{Z^{\frac{1}{2}}} \right)$ (10)

where $Z = \frac{SE + P}{SE - P}$

when, t is known and p desired,
 then; $P = SE \left(\frac{Z - 1}{Z + 1} \right)$ (11)

where; $Z = \left(\frac{R_i + t}{R_i} \right)^2 = \left(\frac{R_o}{R_i} \right)^2 = \left(\frac{R_o}{R_o - t} \right)^2$

- b. Longitudinal stress, circumferential joints, when thickness of shell under internal pressure. t exceeds $\frac{1}{2}R_i$ and P exceeds $1.25 SE$.

$t = R_i (Z^{\frac{1}{2}} - 1) = R_o \left(\frac{Z^{\frac{1}{2}} - 1}{Z^{\frac{1}{2}}} \right) \dots\dots(12)$, where $Z = \left(\frac{P}{SE} + 1 \right)$.

OR $P = SE (Z - 1)$, where, $Z = \left(\frac{R_i + t}{R_i} \right)^2 = \left(\frac{R_o}{R_i} \right)^2 = \left(\frac{R_o}{R_o - t} \right)^2$

5. Thick spherical shells:

when t of the spherical shell under internal pressure exceed $0.356 R_i$ or P exceeds $0.665 SE$

$$t = R_i(Y^{1/3}-1) = R_o \left(\frac{Y^{1/3}-1}{Y^{1/3}} \right) \dots (13), \text{ where } Y = \frac{2(SE+P)}{(2SE-P)}$$

P

$$P = 2 SE \left(\frac{Y-1}{Y+2} \right) \dots (14), \text{ where, } Y = \left(\frac{R_i+t}{R_i} \right)^3 = \left(\frac{R_o}{R_o-t} \right)^3$$

t = thickness (inches)

P = max. allowable stress $16/\text{in}^2$

R_i = inside radius without lining

S = max. allowable stress. $16/\text{in}^2$

E = joint efficiency

D_i = inside diameter

D_o = outside diameter

III German A-D Merkblätter:

a. Wall temperature not exceeding $<120^\circ\text{C}$, the minimum wall thickness is;

i. cylindrical vessels;

$$t = t_{th} + C_1 + C_2 = \frac{D_o P}{200 \cdot \frac{K}{S} \cdot V} + C_1 + C_2 \quad (15)$$

ii. spherical vessels;

$$t = t_{th} + C_1 + C_2 = \frac{D_o P}{400 \cdot \frac{K}{S} \cdot V} + C_1 + C_2 \quad (16)$$

b. Wall temperature $> 120^{\circ}\text{C}$, the minimum thickness;

i. cylindrical shells;

$$t = t_{th} + C_1 + C_2 = \frac{D_o P}{200 \cdot \frac{K}{S} \cdot V+P} + C_1 + C_2 \quad \text{or,}$$

$$= \frac{D_i P}{200 \cdot \frac{K}{S} \cdot V-P} + C_1 + C_2 \quad (17)$$

ii. for spherical vessels;

$$t = t_{th} + C_1 + C_2 = \frac{D_o P}{400 \cdot \frac{K}{S} \cdot V+P} + C_1 + C_2 \quad \text{or}$$

$$= \frac{D_i P}{400 \cdot \frac{K}{S} \cdot V-P} + C_1 + C_2 \quad (18)$$

P = max. permissible working pressure (Kg/cm^2)

t_{th} = theoretical wall thickness (mm)

t = actual wall thickness = $t_{th} + C_1 + C_2$ (mm)

D = diameter (mm)

C_1 = allowance on wall thickness to take care of reduced thickness due to abnormal tolerance in plate thickness (mm)

C_2 = corrosion allowance (mm)

V = weld joint factor

K = the strength characteristic factor used in design, (Kg/mm^2)

S = safety factor

APPENDIX 2Design methods presented in Codes, for the amount of
compensation around nozzles and openings

The basis of design as regards compensation for openings may be divided into the following (ref.3 and 5):

- i. Equal area methods
- ii. Experimental yield or bursting methods
- iii. Elastic stress analysis
- iv. Limit analysis methods
- v. Experimental stress methods

- i. Equal area method; The principle of the method is to provide material local to a vessel opening equal in cross-sectional area to that which would be removed by the hole in a shell of the required unpierced thickness.
- ii. Experimental yield or bursting method; An alternative form of reinforcement, based on experimental results obtained for yield and bursting strengths of various branch/pipe configurations.

A-D Merkblatt B9, as well as ISO/R831 have tested a series of openings and nozzles of various dimensions. Pressure to produce 0.2% strain at the nozzle/shell junctions were used to obtain the 'weakening factor' which could be used in the basic shell thickness formula. These factors are displayed in the

specification by curves plotted for nozzle thickening ratios and vessel geometry. For nozzles which protrude into the shell, an arbitrary reduction of 20% is allowed on the indicated nozzle thickness. For multiple openings equal area method is used.

- iii. Elastic strength analysis; The method is to gather a range of results from nozzle/vessel geometries curves, to provide shell or/ ranch thickening which is required to reduce the maximum elastic stress concentration (scf) to a value of 2.25. When used with vessel designed for the nominal code stress of $\frac{2}{3}$ x proof stress this scf implies.

- iv. Limit analysis method; Experimental analysis to determine plastic collapse strengths of both spheres and cylinders with welded-in nozzles. Limit analysis predicts the safe values of internal pressures. The proposals give design curves which show the design thickening required on shell or nozzle to produce a design which has a safety factor of 1.5 against plastic collapse.

- v. Experimental stress methods; A C.E.G.B. proposal for nozzle in cylindrical vessels is that a correlation of experimental results for max. scf, with vessel geometry will be used or a measure until theoretical analysis become available.

A design curve for nozzle thickness is proposed which uses these results to obtain a max. scf of 2.5 to ensure shake down in arrangements of small branch/vessel diameter ratio.

Rules in standards and codes on effective replacement material

Standards and codes specifying 'equal area' methods of reinforcement as the basic or alternative compensation rule, specify distances along shell or branch in which excess material may be considered effective.

Standard Code

BS 1500	(d_i) from Branch ϕ .	$\sqrt{d_i t_a}$ from outside of shell
BS 1515	AS BS 3915	As BS 3915
ASME I	Greater of (d_i) or $\left(\frac{d_i}{2} + t_a + T_a\right)$ from ϕ of Branch.	Lesser of $2.5 t_a$ or $2.5 T_a$ from outside of shell.
ASME viii	As ASME I	As ASME I
ASME III	As ASME I but 2/3 of material to be within distance $\left(\frac{d_i}{2} + 0.5\sqrt{RT}\right)$	$\frac{1}{2}\sqrt{rm t_a}$ from outside of shell
ISO pressure vessel code	$(D_i + T_a) T_a$ from outside of Branch. For $T_a/D_i \leq 0.02$. 2/3 of area within $0.35 (D_i + T_a) T_a$ from inside of Branch.	$0.8\sqrt{(d_i + t_a)} t_a$ from outside of shell
ISO/R 831	Greater of $\left(\frac{d_i}{2}\right)$ or $(T_a + 3 \text{ in.})$ From outside of membrane thick Branch.	Lesser of $2.5 t_a$ or $2.5 T_a$ from outside of shell.
BS 3915	Smaller of $\left(\frac{dm}{2}\right)$ or $\sqrt{DT_a}$ from outside of Branch.	$\sqrt{d_m t_a}$ from outside of shell.

d_i = inside diameter of Branch. T_a = actual thickness of shell.
 t_a = actual thickness of Branch. R = mean Radius of shell.
 dm = mean diameter of Branch. rm = mean Radius of Branch.
 d_i = inside diameter of shell.

Survey of standards and codes

. BS 1500 'fusion welded pressure vessels for general purposes. pt.1. 'Carbon and low alloy steels'	Design stress Method Limitations and applicability	UTS/4 Equal area. Branches up to 3 m diam. uncompensated. max. Branch/shell diam. Ratio: 0.5 for spheres. 0.33 for cylinders For external pressure use 1.5 x design pressure
BS 1515, fusion welded pressure vessels for use in petrochemicals pt.1. Carbon and ferritic alloys.	Design stress Method Limitations and applicability	UTS/2.35 or 0.2% PS/1.5 Based on elastic stress analysis Max. vessel scf limited to 2.25. Equal area for multiple openings. As in BS 1500
BS 1515, pt.2. Austenitic stainless steels	Design stress Method Limitations and applicability	UTS/2.5 or 1% PS/1.5 at RT. or 1% PS/1.35 at design temp. As BS 1515 pt.1.
ASME, Boiler and pressure vessel Sec.I, power Boilers.	Design stress Method Limitations and applicability	UTS/4 or 62.5% of 0.2% PS Equal area max. size hole without reinforcements up to max. of 8 ins. (200 mm) max. branch/shell diam. Ratio: up to 60 ins. (1500 mm), 0.5 vessel diam. but <20 ins. (500 mm); over 60 ins. (1500 mm) 0.33 vessel diam. <40 ins. (1000 mm) larger openings permitted but recommended that 0.66 of compensation within distance 0.25 of nozzle diam.

ASME viii	Design stress Method	UTS/4 or 62.5% of 0.2% PS Equal area up to 3 ins. diam. uncompensated.
	Limitations	Branch/shell diam. Ratio unrestricted but recommends reverse curve reducer for cylinder and openings $> \frac{1}{2}$ vessel diam.
ASME sec. III nuclear vessels	Design stress Method	As viii-2 UTS/3 or 0.66 x 0.2% PS Equal area, with 0.66 of compensation to be within $0.5 \sqrt{RT}$ from inside of opening.
	Limitations	Requires fatigue analysis including external load stress unless limiting conditions met.
ISO pressure vessel proposal	Design stress Method	UTS/2.4 or 0.2% PS/1.5 Equal area, but alternative method allowed. opening with- out reinforcement allowed up to $d = 0.14 \sqrt{D_m Tr}$
	Limitations	Max. opening/vessel diameter Ratio 0.33 for cylinders, spheres, cones. Branch/vessel angle limited to 15° from nor- mal.
ISO R831, Rules for construction of stationary boilers	Design stress Method	UTS/2.7 or 0.2% PS/1.6 Based on experimental yield and bursting test results. Pipe thickness = $PD/2fex + P$ where: $x = 1 - \beta(1 - 0.7 \sin \gamma)$ β = Branch/main ratio γ = angle Bet. main and branch e = weld joint factor $x = 1$ when $\beta \leq \frac{\gamma}{\gamma + 90}$
	Limitations	Pipe to branch angle 90° to 60° allowed.

AD Merkblatt B 9.
openings under Internal
pressure

Design stress
Method

By table, otherwise Yield/1.5
Based on experimental strain
methods. Weakening factor
plotted from results for pres-
sure to produce 0.2% strain.
Equal area for multiple
openings. 20% reduction are
required thickness of pro-
truding nozzles.

Limitations

Applicable to pad reinforced
holes. External pressure
rules not specified.

BS 3915
Carbon and low alloy
steel. pv. for primary
circuits of nuclear
reactors

Design stress
Method

UTS/2.7 or 0.2% PS/1.5
Based on elastic stress analy-
sis. Max. vessel scf limited
to 2.25. Equal area methods
for multiple openings.

Limitations

Max. branch/shell diam.
Ratio 0.5 for spheres, 0.33
for cylinders and cones.
nozzle/shell angles 50° from
normal. Pad reinforcement not
permissible on some vessels.
External pressure rules not
specified.

American welding
research council
proposal

Design stress
Method

As ASME III
Based on limit design with
opening design to provide s.f.
of 1.5 on collapse pressure,
and on elastic analysis for a
max. scf. of 3.0. Equal area
for multiple openings.

Limitations

No restriction on branch/vessel
diam. ratio.

C.E.G.B. cylinder
proposals

Method

Based on experimental results.
Design curve based on elastic
scf of 2.5 with recommendation
for limits on shell and branch
thickening flush nozzles only.

APPENDIX 3
Vessel Tolerances

German Tolerances:

German tolerances regarding pressure vessel fabrication may be summarized in the following points:
Deviations between measured and nominal outside diameters are $\pm 1.5\%$
Ovality for cylinders under internal pressure,

$$\frac{D_{\max} - D_{\min}}{D_{\text{mean}}} = 1.0 - 2.0\% < 30 \text{ mm}$$

where: D_{\max} = max. measured internal Diam.
 D_{\min} = min. " " "
 $D_{\text{mean}} = \frac{1}{2} (D_{\max} - D_{\min})$

For cylindrical vessels under external pressure, the above value of the ovality is taken to be 1.5%.

Buckled parts must be smooth and their depth must not exceed 1% of the length or width of the buckled area. The normal circumference or the shell generator is taken as a reference.

Deviation from straight line - e.g. along cylinder generators - must be less than 0.5% of the total cylindrical length.

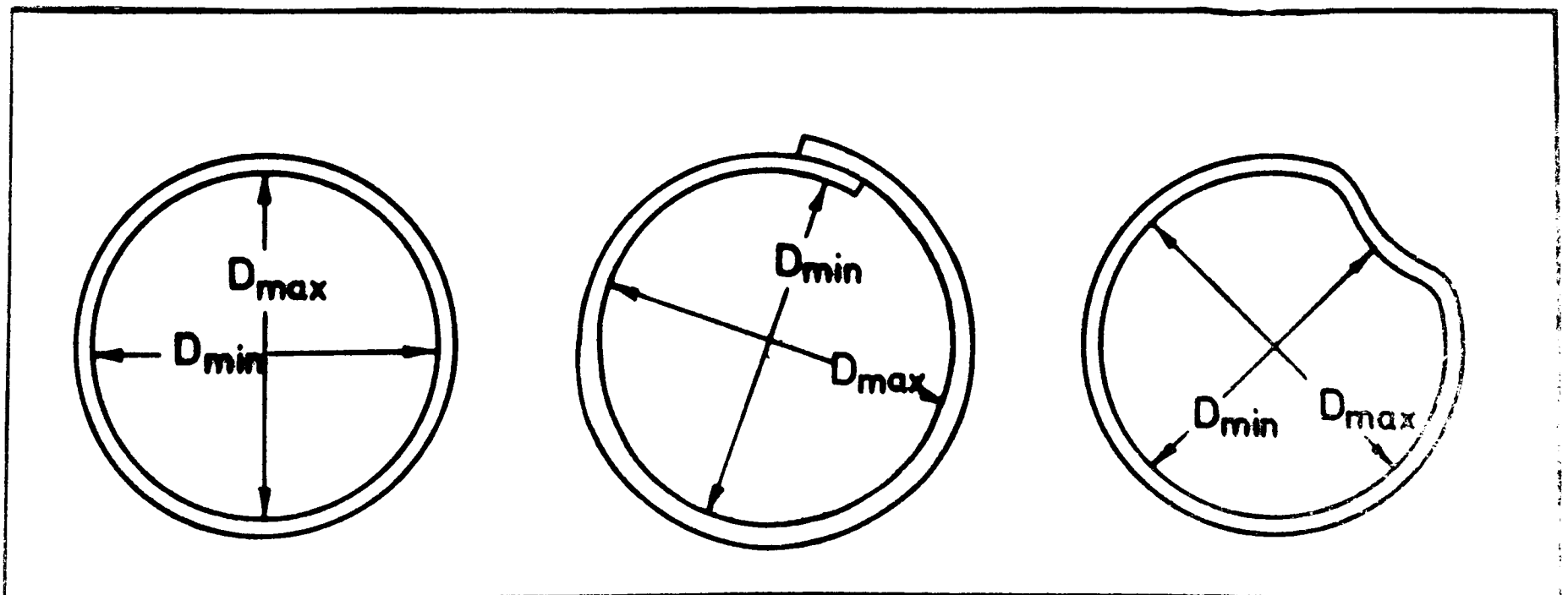
For vessels under internal pressure;

Ratio (R) = $\frac{\text{wall thickness}}{\text{Diam.}}$	not heat treated	SR or (N) (normalized)
Ratio (R) < 0.01 D	1.5%	2.0%
R > 0.01 D	1.0%	1.5%

In cylindrical vessels the offset at butt joints must not exceed 5% of the plate thickness for longitudinal seams, and 10% for circumferential seams.

It is interesting to note that the A-D Merkblätt B6, for cylinders under external pressure, does not specify a tolerance for local flats, leaving complete freedom to the designer. In this way, a substantial saving in thickness may be achieved when working to close manufacturing limits.

The American manufacturing tolerances are detailed in the ASME code. For cylinders under internal pressure, the allowable ovality is reduced to 1.0%. The difference between D_{\max} and D_{\min} (inside diameters) shall not exceed 1.0% of the nominal diameter at the cross-section under consideration.



Differences between max. and min. diameters in
cylindrical shells

For vessels with longitudinal lap joints the permissible difference in inside diameters may be increased by the nominal plate thickness.

The inner surface of a head shall not deviate from the specified shape by more than 1.25% of the inside diameter of the head skirt. Such deviation shall not consist of abrupt changes, shall not be outside the theoretical shape, and shall be measured perpendicular to the specified shape.

When a skirt of any unstayed formed head is machined to make a close fit into or over the shell, the thickness shall not be reduced to less than 90% of that required for a blank head. When so machined, transition machined thickness to original thickness of the head shall not be abrupt but shall be tapered for a distance of at least 4 x the difference between the thicknesses.

In Britain BS 1500 pt 1. and BS 1515 pt 1. specify a circumferential tolerance of $\pm 0.25\%$ for cylindrical shells over 2 ft. diam. (600), compared with 1.5% accepted in Germany. The ovality for cylinders under internal pressure varies from 1.0 to 0.4% depending on internal diameter, the lower limit corresponding to vessels between 6-75 inches (153-1905) internal diameters, 0.75 inches (19) is allowed as a difference between max. and min. diameters for vessels with internal diameters between (75 ins.-108 ins.) (1905-2743), while 0.4% is allowable for vessels with internal diameters between 108-120 inches (2743-3048).

For formed heads, the departure from the specified shape must be less than 1.0% of the skirt diam. or 0.75 inch (19).

For joint alignment British standards allow a maximum offset of 0.03-0.13 inches, (1-4 mm) for longitudinal seams and 0.06-0.19 inches, (1.5-5 mm) for circumferential seams in cylindrical vessels, depending on plate thickness.

APPENDIX 4

Pressure Vessel Steels

I - AMERICAN steels

ASME - Materials

Material Number	Material	chemical composition in % (by wt.).												
		C	Mn	P	S	Si	Cr	Ni	Mo	Ti	Cu	AL	V	others
<u>Carbon steels</u>														
SA-285-A	CS	0.17	0.9	0.035	0.045	.	.	.	.	.	.	.	.	.
SA-285-B		0.22	0.9	0.35	0.045	.	.	.	.	.	.	.	.	.
SA-285-C	CS	0.28	0.9	0.035	0.045	.	.	.	.	.	.	.	.	.
SA-515-55		0.24	"	"	"	0.3	.	.	.	.	.	.	.	.
SA-516-55		0.22	1.0	"	"	"	.	.	.	.	.	.	.	.
SA-515-60	CSi	0.29	0.9	0.035	0.04	0.3	.	.	.	.	.	.	.	.
SA-516-60		0.25	1.0	0.035	0.04	"	.	.	.	.	.	.	.	.
SA-515-65		0.33	0.9	"	"	"	.	.	.	.	.	.	.	.
SA-516-65		0.28	1.0	"	"	"	.	.	.	.	.	.	.	.
SA-515-70		0.35	0.9	"	"	"	.	.	.	.	.	.	.	.
SA-516-70		0.3	1.0	"	"	"	.	.	.	.	.	.	.	.
SA-299 (25-50mm)		0.3	1.4m	"	"	"	.	.	.	.	.	.	.	.
<u>Low Alloy Steels</u>														
SA-204-A	C ½ Mo	0.23	0.9	0.035	0.035	0.3	.	.	0.64m.	.	.	.	.	.
SA-204-B		0.25	"	"	"	"	"	.	"	.	.	.	.	.
SA-204-C	Mn½Mo	0.28	"	"	"	"	.	"	"	.	.	.	.	.
SA-302-A		0.23	1.0	"	0.04	0.3	.	.	0.4/0.6	.	.	.	.	.
SA-302-B		"	1.2	"	"	"	.	.	"	.	.	.	.	.
(m=max).														

Material Number	Material	chemical composition in % (by wt.)												
		C	Mn	P	S	Si	Cr	Ni	Mo	Ti	Cu	AL	V	Other
SA-302-C & D SA-410 SA-203-A SA-203-D SA-387-AN	Mn Mo Ni	0.23	1.2	0.035	0.04	0.3 m.	.	0.7/1.0	0.4/0.6	.	.	.	.	.
	Cr Cu Ni AL	0.12	0.5/1.0	0.04	0.04	0.1/0.35	0.5/0.95	.	.	.	0.7	0.3	.	.
		0.2	0.8	0.035	0.04	0.3 m.	.	2.0/2.5	.	.	.	.	.	.
		"	"	"	"	"	.	3.2/3.7	.	.	.	.	.	.
		0.21	0.5/0.8	"	"	"	0.5/0.8	.	0.4/0.6	.	.	.	.	.
High Alloy Steels:														
SA-387-B (AN)	1 Cr. ½ Mo	0.17	0.36	"	"	.	0.7/1.2	.	0.4/0.6	.	.	.	.	.
SA-387-C (AN)	1¼Cr. ½ Mo	"	0.69	"	"	.	0.9/1.5	.	0.4/0.7	.	.	.	.	.
SA-387-C (N)	" "	"	"	"	"	.	"	.	"	.	.	.	.	.
SA-387-D (AN)	2¼Cr. 1 Mo	0.15	0.27/0.6	"	0.035	.	1.8/2.6	.	0.8/1.1	.	.	.	.	.
SA-387-D (N)	" "	"	"	"	"	.	"	.	"	.	.	.	.	.
SA-387-E (AN)	3Cr. 1 Mo	"	"	"	"	.	2.6/3.4	.	0.8/1.1	.	.	.	.	.
SA-357-	5Cr. ½ Mo	"	0.3/0.6	0.04	0.03	0.5	4.0/6.0	.	0.45/0.6	.	.	0.1/0.3	.	.
SA-240-405	13Cr. AL	0.08	1.0	0.04	0.03	1.0	11.5/14.5	0.75	.	.	.	.	.	.
SA-240-410	13Cr.	0.15	1.0	"	"	"	11.5/13.5	0.75m.	.	.	.	.	.	.
SA-240-430A	15Cr.	0.12	1.0	"	"	"	14/16	8/12	.	.	.	.	.	.
SA-240-304L	18Cr. 18Ni	0.03	2.0	"	"	"	18/20	8/10	.	.	.	.	.	.
SA-240-302	"	0.15	"	"	"	"	17/19	8/12	.	.	.	.	.	.
SA-240-304	"	0.08	"	"	"	"	18/20	8/12	.	.	.	.	.	.
SA-240-316L	16Cr12Ni2Mo	0.03	"	"	"	"	16/18	10/14	2/3	.	.	.	.	.
SA-240-317														

		chemical composition in % (by wt.)													
Material Number	Material	C	Mn	P	S	Si	Cr	Ni	Mo	Ti	Cu	AL	V	Zr	Boron
SA-240-321	18 Cr.10Ni. Ti.	0.08	2.0	0.04	0.03	1.0	17/19	9/12	.	5xc%	.	.	.	.	.
SA-240-309 S	23 Cr.12Ni.	"	"	"	"	"	22/24	12/15	.	.	.	.	.	.	.
SA-240-310 S	23 Cr.20Ni.	"	"	"	"	1.5	24/26	19/22	.	.	.	.	.	.	.
SA-240-310 S	25 Cr.20Ni.														
Quenched Tempered Steels															
SA-517-A	Cr. Mo. Zr.	0.15	1.0	0.03	0.04	0.86	0.8	.	0.31	.	.	.	.	0.16	0.0025
SA-517-B	Cr. Mo. V.	"	"	"	"	0.37	0.7	.	0.28	.	.	.	0.09	.	.
SA-517-D	Cr. Mo. Ti. Cu.	0.11	0.36	"	"	"	1.2	.	0.64	0.1	0.4	.	.	.	.
SA-517-E	Cr. Mo. Ti. Cu.	0.1	0.7	"	"	0.37	2.0	.	0.64	0.1	0.4	.	.	.	.
SA-517-F	Cr. Mo. Ni. V.	0.08	1.0	"	"	"	0.69	1.0	0.69	.	0.4	.	0.09	.	.
SA-517-J		0.2	0.7	"	"	0.37	0.86	.	0.68	.	.	.	.	.	0.005

II British steels

Material Number	Material	chemical composition in % (by wt)												
		C	Mn	P	S	Si	Cr	Ni	Mo	Ti	CU	AL	V	other
<u>Carbon steels: (semi- killed)</u>														
BS-1501-151-23B -26B (up to 32mm)-28B		0.18	0.4/1.2	0.05	0.05	0.1	0.25	0.3	0.1	.	0.2	.	.	
		0.22	0.5/1.2	"	"	"	"	"	"	.	"	.	.	
		0.25	0.55/1.2	"	"	"	"	"	"	.	"	.	.	
<u>Carbon-manganese (semi-killed)</u>														
BS1501-161-26B (over 32-64mm) -28B		0.22	0.65/1.2	"	"	0.1/0.3	"	"	"	.	"	.	.	
		0.25	" "	"	"	0.1/0.35	"	"	"	.	"	.	.	
BS-1501-224-26B " " -28B " " -30B " " -32B		0.15	0.55	0.05	0.05	0.1	0.25	0.3	0.1	.	0.2	.	.	
		0.17	"	"	"	"	"	"	"	.	"	.	.	
		0.2	"	"	"	"	"	"	"	.	"	.	.	
		0.22	"	"	"	"	"	"	"	.	"	.	.	
BS-1501-620-27 " " -621-31 (76mm) -621-31 (>76mm) -622- (152mm)	1Cr. $\frac{1}{2}$ Mo. 1 $\frac{1}{4}$ Cr. $\frac{1}{2}$ Mo. " " 2 $\frac{1}{4}$ Cr. 1 Mo.	0.09/0.15	0.4/0.17	0.04	0.04	0.1/0.35	0.7/1.5	"	0.4/0.6	0.03	0.3	.	.	
		"	"	"	"	"	"	"	"	"	"	.	.	
		"	"	"	"	"	"	"	"	"	"	.	.	
		0.1/0.15	0.4/0.8	"	"	0.2/0.52	"	"	0.9/1.2	"	0.3	.	.	
<u>Corrosion and heat Resistance</u>														
BS-1501-403 S17 -405 S17	13 Cr	0.08	1.0	0.04	0.03	0.8	12/14	0.5	.	.	.	0.1/0.3	.	
		"	"	"	"	"	"	"	"	

Material Number	Material	chemical composition in %(by wt.)												
		C	Mn	P	S	Si	Cr	Ni	Mo	Ti	CU	AL	V	others
Un stabilized Cr.Ni. steel	18Cr.10Ni.1Mn.	0.03	2.0	"	"	1.0	17/19	9/12	.	.	.	.	.	.
		0.06	2.0	"	"	"	"	8/11	.	.	.	.	.	0.05
		0.09	"	"	"	"	"	"	.	.	.	.	.	Niobiu
Stabilized Cr-Ni steel	18Cr.8Ni.1Mn. "	0.08	2.0	0.04	0.03	1.0	17/19	9/12	.	5xc%	.	.	.	162
		0.09	"	"	"	"	"	"	.	5xc%	.	.	.	.
Stabilized steel (Niob.)	18Cr.10Ni.1Mn "	0.08	"	"	"	"	"	"	.	.	.	.	.	10xc% (Niob
		0.09	"	"	"	"	"	"	.	.	.	.	.	"
Aust.Cr.Ni.steels	17Cr.13Ni.2½Mo. "	0.03	"	"	"	"	16/18	11/14	2.2/3.0	.	.	.	.	boron/Ni
		0.07	"	"	"	"	"	10/13	"	.	.	.	.	0.05/0.03
	"	0.03	"	"	"	"	"	13/15	"	.	.	.	.
		0.09	"	"	"	"	"	10/13	"	.	.	.	.

Material Number	Material	chemical composition in % (by wt.)												
		C	Mn	P	S	Si	Cr	Ni	Mo	Ti	Cu	Al	V	others
<u>Stab.Aust.Cr.Ni.steel</u>	17Cr.13Ni.2½Mo 25Cr.20Ni.1 Mn	0.08	2.0	0.4	0.03	1.0	16/18	11/14	2.2/3.0	4xC%	.	.	.	
		0.15	"	"	"	"	23/26	19/22	.	.	.	.	.
<u>Nickel iron.Cr.steel</u>	21Cr.32Ni (A) 22Cr.42Ni.3Mo.2Cu	0.1	1.5	"	0.01	1.0	19/23	30/25	.	0.6	0.7	0.6	.	
		0.05	1.0	"	0.03	0.5	19/23	38/46	2/3.5	1.2	3.0	0.2	.	
high proof stress corrosion and heat resisting steels	14Cr, 5.5Ni, 1.5Mo, 1.5Cu 18Cr, 11Ni, 0.2Nitrogen " 18Cr, 10Ni 1Mn 18Cr, 10Ni 1Mn 0.2 N2 17Cr 13Ni 2½Mo.0.2N2	0.07	1.0	0.04	0.03	0.7	13/15	0.6	1.2/2	.	1.2/2	.	.	Niob
		0.03	2.0	"	"	1.0	17/19	9/12	.	.	.	.	.	0.2/0.7
BS1501-460 S52 "-304 S62 "-304 S65 "-321 S87 "-347 S67 "-316 S62 "-316 S66 "-316 S82		0.06	"	"	"	"	"	8/11	.	.	.	.	.	0.2 Nitrogen
		0.08	"	"	"	"	"	9/12	.	5xC%	.	.	.	"
		"	"	"	"	"	"	"
		0.03	"	"	"	"	16/19	11/14	2/3	.	.	.	.	0.25N2, 1.0 Niob.
		0.07	"	"	"	"	"	10/13	"	.	.	.	.	0.25N2
		0.03	"	"	"	"	16/18	12/14	"	.	.	.	.	"

British branded steels

Material Number	Material	chemical composition in % (by wt.)												
		C	Mn	P	S	Si	Cr	Ni	Mo	Ti	Cu	AL	V	others
<u>Creep resisting steels</u> COLMO 900 gr.29 " " " 31 COLMO 950 " 1000		0.18	0.15/0.9	0.05	0.05	0.1/0.3	:	:	0.45/0.65	.	.	.	.
		0.2	"	"	"	"		.	"	.	.	.	.
		0.17	0.4/0.7	"	"	"	0.7/1.1	.	"	.	.	.	.
		0.13	"	"	"	"	0.25/0.5	.	0.5/0.7	.	.	.	0.2/0.3	
High strength weldable steels														
DUCOL W30 (25mm) BS1501-271-281(25-76mm) (76-152")		0.17	1.3	0.05	0.05	0.3	0.7	0.3	0.28	.	0.2	.	0.12	
		"	"	"	"	"	"	"	"	.	"	.	"	
		"	"	"	"	"	"	"	"	.	"	.	"	164
<u>Notch tough steels</u> CULTUF 26 28 32		0.15	0.9/1.2	0.05	0.05	0.1/0.55	.	.	.	.	.	.	.
		0.16	0.9/1.5	"	"	"	.	.	.	.	.	.	.
		0.22	0.9/1.6	"	"	"	.	.	.	.	.	.	.
<u>Weathering quality steels</u> COR TEN A B C		0.12	0.2/0.5	0.05	0.07/0.15	0.25/0.75	0.3/1.25	.	.	.	.	.	.
		0.1/0.19	0.9/1.25	"	0.04	0.13/0.3	0.4/0.65	.	.	0.25/0.4	.	0.02/0.1	.	
		"	"	"	"	"	0.4/0.7	.	.	"	.	0.04/0.1	.	

Material Number	Material	chemical compositions in % (by wt.)												
		C	Mn	P	S	Si	Cr	Ni	Mo	Ti	CU	AL	V	others
High temp.steels														
Esshetf CRM9	9Cr.1Mo	0.15	0.3/0.6	0.03	0.03	0.25/1.0	8/10		0.9/1.1	.	.			
Esshetf 316	18Cr,12Ni,2.5 Mo	0.04/0.09	1/2	0.04	"	0.8	16/18	11/14	2/2.75	.	.			boron add
Esshetf 347	18Cr,12Ni -Nb	"	0.5/2.0	"	"	"	17/19	9/13		.	.		(Nb	10xC%)
Quenched Tempered Steels														
DUCOL QT122-A		0.18	1.4	0.05	0.05	0.5	.	.	.	.	.			165
" QT122-B		"	"	"	"	0.1/0.5	.	.	.	.	.			.
" QT131-A		0.2	1.6	"	"	0.5	.	.	.	.	.			.
" QT131-B		0.2	1.6	"	"	0.1/0.5	.	0.5	.	.	.			.
DUCOL QT342-A		0.17	1.5	"	"	0.5	0.7	0.3	0.28	.	.		0.1	.
QT342-B		0.18	1.3	"	0.4	0.1/0.5	1.1	1.3	0.55	.	.		0.12	.
DUCOL. QT 445		0.21	1.3	0.035	0.04	0.9	1.0	.	0.6	0.05	(Zr 0.15)		(boron 0.005)	

III - German steels

DIN-Materials

Material number	Material	chemical composition in % (by wt.)												
		C	Mn	P	S	Si	Cr	Ni	Mo	Ti	Cu	Al	V	others
<u>Unalloyed steels:</u>														
HI HII HIII HIV	DIN 17155	≤0.6	≥0.4	0.05	0.05m	0.35	0.3m	.	.	.	.	.	.	.
		≤0.2	0.5	"	"	"	"	.	.	.	.	.	.	.
		0.22	0.55	"	"	"	"	.	.	.	.	.	.	.
		0.26	0.6	"	"	"	"	.	.	.	.	.	.	.
<u>Alloyed steels</u>														
17 Mn 4 19 MN 5 15 Mo 3 13 Cr Mo44	DIN 17155	0.14/0.2	0.9/1.2	0.05	0.05	0.2/0.4	0.3	.	.	.	.	.	.	.
		0.17/0.23	1.0/1.3	"	"	0.4/0.6	"	.	.	.	.	.	.	.
		0.12/0.2	0.5/0.7	0.04	0.04	0.15/0.35	.	.	.	.	.	.	.	.
		0.1/0.18	0.4/0.7	"	"	0.15/0.35	0.7/10	.	0.4/0.5	.	.	.	.	.
Ast 41 Ast 45 Ast 52	DIN 17135	0.2	0.45	0.045	0.045	0.35	.	.	.	.	.	.	.	.
		0.22	"	"	"	"	.	.	.	.	.	.	.	.
		0.2	1.5	"	"	0.55	.	.	.	.	.	.	.	.
DIN 17175	10Cr Mo 910	0.15	0.4/0.6	"	"	0.1/0.5	2/2.5	.	0.9/1.1	.	.	.	.
<u>High alloyed steels</u>														
X 7Cr 13 (A) X 7Cr AL13 (A) X 10Cr 13 (A&T)	DIN 17440	≤0.08	1.0	0.04	0.04	1.0	12/14	.	.	.	0.1/0.3	.	.	.
		≤0.08	1.0	"	"	1.0	12/14	.	.	.	.	.	.	.
		≤0.08-0.12	1.0	"	"	1.0	12/14	.	.	.	.	.	.	.

Material Number	Material	chemical composition in % (by wt.)												
		C	Mn	P	S	Si	Cr	Ni	Mo	Ti	CU	AL	V	others
X5CrNi189 (Q) X2CrNi189 (Q) X10CrNiTi189(Q) X10CrNiN6189(Q)	DIN 17440	0.07	2.0	0.045	0.040	1.0	17/20	9/11.5	.	.	.	.	.	.
		≤0.03	2.0	"	"	1.0	17/20	"	.	≥5%C	.	.	.	.
		≤0.10	2.0	"	"	1.0	17/19	"	.	.	.	.	.	.
		≤0.10	2.0	"	"	1.0	17/19	9/11.5	.	.	.	.	.	Nb8%C
X2CrNiMo1810 (Q) X10CrNiMoTi1810 (Q) X5CrNiMo1810 (Q)		0.03	2.0	0.045	0.03	1.0	16.5/18.5	11/14	2/2.5	.	.	.	.	.
		0.10	2.0	"	"	1.0	"	10.5/13.5	"	≥5x%C	.	.	.	.
		≤0.07	2.0	"	"	1.0	"	"	"	.	.	.	.	.
High Alloy steels (guaranteed properties at RT)		16#												
X 7 Cr 14 (A) X15 Cr 13 (T) X20 Cr 13 (T) X40 Cr 13 X8 Cr Ti 17 X6 Cr Nb17 X6 Cr Mo17 X12 Cr Mol7 22 Cr Ni 17 (T) 12 Cr Ni 188 10 Cr Ni Mo Nb 1810	17440 (Ferritic steels)	≤0.08	1.0	"	"	1.0	13/15	.	.	.	.	.	.	.
		0.12/0.17	1.0	"	"	1.0	12/14	.	.	.	.	.	.	.
		0.12/0.22	1.0	"	"	1.0	"	.	.	.	.	.	.	.
		0.4/0.5	1.0	"	"	1.0	"	.	.	.	.	.	.	.
		≤0.10	1.0	"	"	1.0	16/18	.	.	.	.	.	.	.
		0.10	1.0	"	"	1.0	"	.	.	.	.	.	.	.
		≤0.07	1.0	"	0.15/0.25	1.0	16/17.5	.	0.9/1.2	7x%C	.	.	.	(Nb≥12%C)
		0.1/0.17	1.5	"	0.03	1.0	15.5/17.5	.	0.2/0.3	.	.	.	.	.
		0.17/0.25	1.0	"	"	1.0	16/18	1.5/2.5	.	.	.	.	.	.
		0.12	2.0	"	"	1.0	17/19	8/10	.	.	.	.	.	.
		0.1	2.0	"	"	1.0	16.5/18.5	1.05/13.5	2/2.5	.	.	.	(Nb≥ 8x%C)	.

Material number	Material	chemical composition in % (by wt.)											
		C	Mn	P	S	Si	Cr	Ni	Mo	Ti	CU	AlV	others
X5Cr Ni Mo 1812 (Q)	1740 (Aust. steels)	≤0.07	2.0	0.045	0.03	1.0	16.53/18.5	12/14.5	2.5/3.0	.	.	.	.
X2Cr Ni Mo 1812 (Q)		≤0.03	2.0	"	"	1.0	16.5/18.5	12.5/15	"	.	.	.	.
X10 Cr Ni Mo Nb 1812 (Q)		0.10	2.0	"	"	1.0	"	12/14.5	"	"	.	.	(Nb>8X%C)
Quenched & Tempered steels (for temps.bet.20-350°C)													
High grade steels													
CM 35	168	0.32/0.39	0.5/0.8	0.035	0.02/0.035	0.15/0.35	.	.	.	.	.	.	.
CM 45		0.4/0.5	"	"	"	"	.	.	.	.	.	.	.
CM 55		0.5/0.6	0.6/0.9	"	"	"	.	.	.	.	.	.	.
CM 60		0.57/0.65	"	"	"	"	.	.	.	.	.	.	.
34 Cr S 4		0.3/0.37	0.6/0.9	"	"	0.15/0.4	0.9/1.2	.	.	.	.	.	.
37 Cr S 4		0.34/0.41	"	"	"	"	"	"	.	.	.	.	.
41 Cr S 4		0.38/0.45	0.5/0.8	"	"	"	"	"	.	.	.	.	.
34 Cr Mo 54		0.3/0.7	"	"	"	"	"	.	0.15/0.30	.	.	.	.
42 Cr Mo 54		0.38/0.45	"	"	"	"	"	"	.	.	.	.	.

Material number	material	chemical composition in % (by wt.)												
		C	Mn	P	S	Si	Cr	Ni	Mo	Ti	CU	AL	V	others
<u>Branded steels</u> DUKTEN 900 N-A-Extra 55 Tough steels - 60 Used for Temps. - 65 (-40,400°C) -70		0.08	0.3/0.8	0.035	0.035	0.1/0.35	.	8.5/10	.	.	.	.	.	.
		0.2m	0.6/1.0	"	"	0.4/0.8	0.5/0.9	.	0.2/0.6	.	.	.	.	(Zr0.04/0.1)
		"	"	"	"	"	"	"	"	10
		0.2m	0.7/1.1	"	"	0.5/0.9	0.6/1.0	"	0.2/0.6	.	.	.	.	(Zr0.06/0.12)
		"	"	"	"	"	"	"	"	"