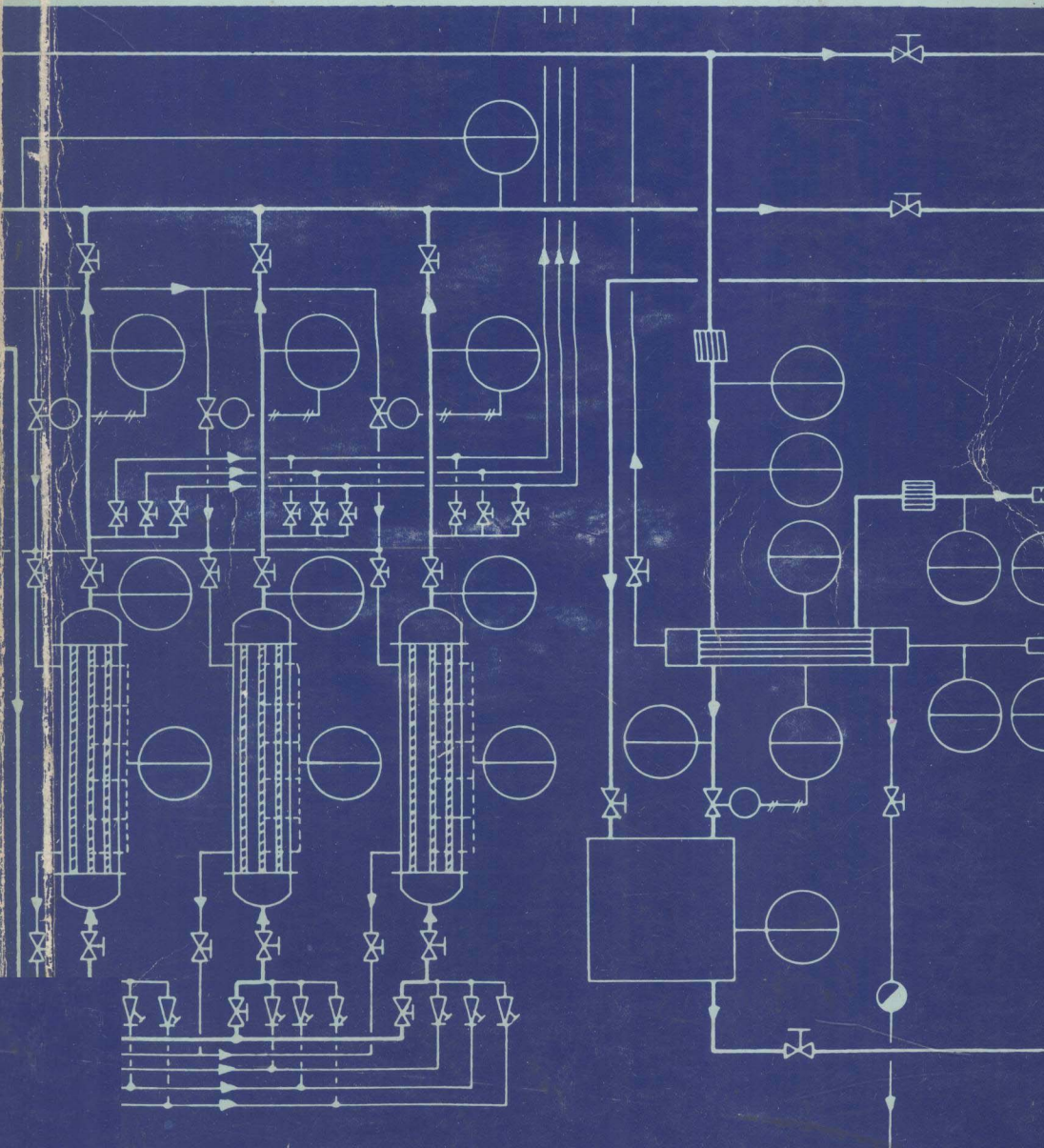


A Worked Solution to a Problem in Chemical Engineering Design

D.G. Austin and G.V. Jeffreys

The Manufacture of Methyl Ethyl Ketone from 2-Butanol



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A WORKED SOLUTION TO A PROBLEM IN
CHEMICAL ENGINEERING DESIGN

by

D. G. Austin and G. V. Jeffreys

*Chemical Engineering Department
University of Aston in Birmingham*

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FOREWORD

This book has been prepared to demonstrate how chemical engineering principles can be applied to the design of process equipment, by reference to the Design Project examination question set in 1974. The object is to demonstrate the application of principles, rather than to design a methyl ethyl ketone process in every detail.

Although written primarily to meet the needs of candidates preparing for the Design Project examination of the Institution of Chemical Engineers, the work, being concerned with the practical application of basic principles, will be of value to all chemical engineers.

For that reason we welcome the commercial publication of a hardback edition in addition to the student paperback published by the Institution. This should be a valuable reference in all chemical engineering libraries and design offices.

The text illustrates how solutions to the design problems involved can be derived by reference to standard chemical engineering texts and other reference books generally available. It is believed that the computer programs included are also generally available and that the numerical solutions given could be obtained with the aid of a pocket calculator.

The Design Project examination of the Institution of Chemical Engineers is intended to test the candidate's knowledge of chemical engineering principles and his understanding of the inter-relationship of the various disciplines already covered in Parts 1 and 2 of the CEI examinations. The principal requirement is that he should demonstrate an adequate knowledge of these disciplines by applying them to a real problem of industrial significance.

Since the last worked solution to a Design Project examination question was published in 1961 there have been many developments in chemical engineering design. Thus, in 1961 design calculations were performed manually, whereas nowadays computers are generally available so that additional parameters can be included in the design calculations. Furthermore there is now a greater emphasis on safety, and in consequence chemical engineers are required to make operability studies at the design stage. The Institution of Chemical Engineers is therefore obliged to test a candidate's knowledge in these subjects.

In working through the Design Project, candidates may not be able to cover all items to the degree of thoroughness illustrated in this text. For each item of design work attempted however, candidates should aim for the standard indicated. Reference is made to previous publications prepared with similar objectives in view, so as to lead into the present edition which is intended to give further assistance in preparing for the examination in its present form.

In commending the book to candidates preparing for the Institution's Design Project examination, I would also on behalf of the Board, like to thank Dr D.G. Austin and Professor G.V. Jeffreys for once again willingly accepting the responsibility for producing it.

R. PARKINS

Chairman – Board of Examiners

ACKNOWLEDGEMENTS

The authors would like to express their thanks to members of staff of the Chemical Engineering Department of Aston University for their helpful discussions during the preparation of this text; particularly Dr A.V. Bridgwater for his advice and generous assistance in the preparation of the economic analysis in Chapter 11 and to Dr D.A. Lihou for preparing and writing the Operability Analysis of the reactors in Chapter 12. In addition our thanks are given to Mr C.L. Hung, a postgraduate student in the Department for preparing the Appendix on the correlation of specific heats. Finally, we are most grateful to Miss Joy Harris for typing the manuscript, photocopying the typescript and generally organising the text for publication.

D.G. Austin and G.V. Jeffreys
Department of Chemical Engineering
University of Aston in Birmingham

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Chapter 1

INTRODUCTION

1.1 Background information

Since 1972 the "Design Project" is the only examination set by the Institution of Chemical Engineers, and is open to candidates who have successfully completed Parts 1 and 2 of the Council of Engineering Institutions examinations, or have obtained exemption from the CEI examinations. This design project test replaces the former "Part 3" in name only and the definition of the exercise is the same as that formulated in 1958. That is, the project is always set in such a way that the design can be performed and the report written with the assistance of the standard chemical engineering texts, the *Chemical Engineers' Handbook* and other handbooks together with the well known journals normally available in most factory, college and public libraries. The examiners of the Institution recognise that programmable calculators and computers are now widely available and encourage their use provided that the programs were written by the candidates or are generally available in recognised technical publications. In addition the Institution expects the complete answer to be prepared from first principles.

In the following example of a design report it has been necessary to discuss in detail certain theoretical points to a far greater extent than would usually be required in an actual report of an intended project. This has been done only when reference cannot be made to one of the excellent chemical engineering texts available. Thus it is assumed that all candidates about to undertake the design project examination would possess the following books as a basis of their own personal technical library.

Chemical Engineering, Vols 1, 2 & 3.

Pergamon Press, London 1978

Coulson, J.M. & Richardson, J.F.

Mass Transfer Operations

McGraw Hill, New York, 1972

Treybal, R.E.

Chemical Reaction Engineering

Wiley, New York, 1973

Levenspiel, O.V.

Absorption & Extraction

McGraw Hill, New York, 1976

Sherwood, T.K. & Pigford, R.E.

Mathematical Methods in Chemical Engineering
Academic Press, 1978
Jenson, V.G. & Jeffreys, G.V.

Finally, it is still worth quoting from the original *Problem in Chemical Engineering Design* by J.M. Coulson and Sir Frederick Warner: "*The design of any chemical installation requires the co-operation of the chemist, chemical engineer and mechanical engineer. Each stage of the development of any design is the result of proposals which have been examined from the standpoint of what is efficient and what is practical. With this co-operation a design is finally arrived at which can be passed to the drawing office for detailing and layout. In practice this initially involves the preparation of flowsheets showing the quantities involved and indicating alternative routes. This is accomplished by the assembly of the necessary physical data which will allow the making of energy balances*".

In some cases a number of calculations have to be made where several operating conditions may be varied. For example in the design of extraction equipment the solvent/feed ratio affects all the design calculations and these must be made repeatedly before an energy balance can be prepared and the equipment specified. Nowadays this is conveniently achieved by computer but it has tended to induce the design engineer to include more variables into his calculations so that the final design is more precise. An example of this is given in the design of the catalytic reactor where both longitudinal and lateral temperature profiles have been considered and the rate of decay of the catalyst activity has been included in the calculations.

Chapter 2

THE PROBLEM

2.1 General

The problem considered here is that set for the 1974 examination and is given in the form in which it was received by the candidates.

The Institution of Chemical Engineers

The Design Project

1st October to 1st December 1974

Instructions for the Design Project, 1974

BEFORE STARTING WORK READ carefully the enclosed copy of *The Regulations for The Design Project* in conjunction with the following details for The Design Project for 1974.

In particular, candidates should note that all the questions should be answered in the section headed "Scope of Design Work Required".

The answers to the Design Project should be returned to The Institution of Chemical Engineers, 15 Belgrave Square, London SW1X 8PT, by 1700 hours on December 1st 1974. In the case of overseas candidates, evidence of posting to the Institution on November 30th will satisfy this requirement. The wrappings must be marked on the OUTSIDE with the Candidate's name and the words: "DESIGN PROJECT".

The Design Project will be treated as a test of the ability of the candidate to tackle a practical problem in the same way as might be expected if he were required to report as a chemical engineer on a new manufacturing proposal. The answers to the Design Project should be derived by the application of fundamental principles to available published data; they should on no account include confidential details of plant or processes which may have been entrusted to the candidate. Particular credit will be given to concise answers.

References must be given of all sources of published information actually consulted by the candidate.

The answers should be submitted on either A4 or foolscap paper but preferably on A4. Squared paper and drawing paper of convenient size may be used for graphs and drawings respectively. The text may be handwritten or, preferably, typewritten; in the latter case it is permissible for another person to type the final copies of the answers. Original drawings should be submitted. Copies, in any form, will not be accepted.

Each sheet and drawing must be signed by the candidate and this signature will be taken to indicate that the sheet or drawing is the candidate's unaided work, except typing. In addition, the declaration forms enclosed must be filled in, signed, witnessed and returned with the answers. The manuscript, drawings, and any other documents should be fastened in the folder supplied, in accordance with the instructions appearing thereon.

Answers to the Design Project itself must be written in the English language and should not exceed 20 000 words excluding calculations.

The use of SI units is compulsory.

Candidates may freely utilise modern computational aids. However, when these aids are employed, the candidate should clearly indicate the extent of his own contribution, and the extent of the assistance obtained from other sources. For computer programs which have been prepared by the candidate himself, a specimen print-out should be appended to the report. Programs from other sources should only be used by the candidate provided adequate documentation of the program is freely and publicly available in recognised technical publications. The candidate must demonstrate clearly that he fully understands the derivation of the program, and the significance and limitation of the predictions.

The answers submitted become the property of the Institution and will not be returned in any circumstances.

1974 DESIGN PROJECT

The Project

Design a plant to produce 1×10^7 kg/year of methyl ethyl ketone (MEK).

Feedstock:— Secondary butyl alcohol.

Services available:—

- Dry saturated steam at 140°C
- Cooling water at 24°C
- Electricity at 440 V 3-phase 50 Hz
- Flue gases at 540°C .

The process

The butyl alcohol is pumped from storage to a steam-heated preheater and then to a vaporiser heated by the reaction products. The vapour leaving the vaporiser is heated to its reaction temperature by flue gases which have previously been used as reactor heating medium. The superheated butyl alcohol is fed to the reaction system at 400°C to 500°C where 90% is converted on a zinc oxide—brass catalyst to methyl ethyl ketone, hydrogen and other reaction products. The reaction products may be treated in one of the following ways:—

- (a) Cool and condense the MEK in the reaction products and use the exhaust gases as a furnace fuel.
- (b) Cool the reaction products to a suitable temperature and separate the MEK by absorption in aqueous ethanol. The hydrogen off gas is dried and used as a furnace fuel. The liquors leaving the absorbers are passed to a solvent extraction column, where the MEK is recovered using trichlorethane. The raffinate from this column is returned to the absorber and the extract is passed to a distillation unit where the MEK is recovered. The trichlorethane is recycled to the extraction plant.

Scope of Design Work Required

All questions must be answered

1. Prepare material balances for the two processes.
2. On the basis of the cost data supplied below decide which is the preferable process.
3. Prepare a material flow diagram of the preferred process.
4. Prepare a heat balance diagram of the preheater—vaporiser—superheater—reactor system.
5. Prepare a chemical engineering design of the preheater—vaporiser—superheater—reactor system and indicate the type of instrumentation required.
6. Prepare a mechanical design of the butyl alcohol vaporiser and make a dimensioned sketch suitable for submission to a drawing office.

Process data

Outlet condenser temperature = 32°C .

Vapour and liquid are in equilibrium at the condenser outlet.

Calorific value of MEK = 41 800 kJ/kg.

Cost data

Selling price of MEK	=	£	9.60 per 100 kg
Steam raising cost	=	£	0.53 per 10^6 kJ
Cost of tower shell	=	£2 000	
Cost of plates	=	£2 000	
Cost of reboiler	=	£2 500	
Cost of heat exchanger (per distillation column)	=	£8 000	
Cost of solvent extraction auxiliaries	=	£1 000	
Cost of absorption and distillation column packing, supports and distributors	=	£2 000	
Cost of tanks (surge, etc)	=	£1 000	
Cost of control of whole plant	=	£9 000	
Cost of instrumentation for control of recovery section	=	£4 500	
Cost of electricity for pumps	=	£5 000	
Pump costs (total)	=	£3 000	
Cost of cooling water for whole plant	=	£5 000	

Reactor data

The "short cut" method proposed in Ref.1 may be used only to obtain a preliminary estimate of the height of catalyst required in the reactor. The reactor should be designed from first principles using the rate equation, below, taken from Ref.1.

$$\tau_A = \frac{C(P_{A,i} - P_{K,i} P_{H,i}/K)}{P_{K,i}(1 + K_A P_{A,i} + K_{AK} P_{A,i}/P_{K,i})}$$

where $P_{A,i}$, $P_{H,i}$, and $P_{K,i}$ are the interfacial partial pressures of the alcohol, hydrogen and ketone in bars, and the remaining quantities are as specified by the semi-empirical equations below:—

$$\log_{10} C = -\frac{5964}{T_i} + 8.464$$

$$\log_{10} K_A = -\frac{3425}{T_i} + 5.231$$

$$\log_{10} K_{AK} = +\frac{486}{T_i} - 0.1968$$

In these equations, the interfacial temperature T_i is in Kelvin, the constant C is in $\text{kmol/m}^2 \text{ h}$, K_A is in bar^{-1} , and K_{AK} is dimensionless.

The equilibrium constant, K , is given in Ref.1 (although the original source is Ref.2) by the equation:—

$$\log_{10} K = -\frac{2790}{T_i} + 1.510 \log_{10} T_i + 1.871$$

where K is in bar.

Useful general information will be found in Ref.3.

References

1. Perona, J. J. and Thodos, G. *A. I. Ch. E. Jl*, 1957, 3, 230.
2. Kolb, H. J. and Burwell, R. L. (jr) *J. Amer. chem. Soc.*, 1945, 67, 1084.
3. Rudd, D. F., and Watson, C. C. "Strategy of Process Engineering", 1968. (New York: John Wiley & Sons Inc.).

2.2 Introduction to the problem

Methyl Ethyl Ketone (MEK), or 2-butanone is an important commercial chemical that is produced in large quantities for a wide variety of processes and products. Chemically it is the next higher homologue of acetone that in addition to displaying the characteristic reactions of ketones, undergoes a number of special reactions, such as condensation with aldehydes to form high molecular weight ketones, cyclic compounds and ketals. It is a powerful solvent, only partially miscible in water, has a lower vapour pressure and correspondingly higher boiling point than acetone and these properties are exploited in surface coating, cellulose manufacture and in acrylic resin and vinyl polymer production. In fact nearly all synthetic and natural resins commonly employed in lacquers are soluble in MEK and furthermore it is employed as a solvent in many extraction processes in the chemical and petroleum industries. The annual production rate in 1977 was 100000 tonnes worldwide¹.

There are three basic methods for the manufacture of MEK. These are

- (i) Synthesis from refinery gases
- (ii) Dehydrogenation from 2-butanol (secondary butyl alcohol)
- (iii) Selective oxidation of 2-butanol

Of the different processes it has been found that dehydrogenation of 2-butanol is the most economical and this process has been chosen for design in the following text.

2.3 Summary of the project

The process for the manufacture of MEK consists of dehydrogenating 2-butanol continuously in a reactor containing a composite catalyst of brass maintained at 400°C to 500°C at atmospheric pressure. 90.0% of the butyl alcohol can be converted to MEK and the feasibility of separating the MEK from the reaction products and using the exhaust gases as a furnace fuel, or separating the MEK, recovering and recycling the unconverted alcohol, drying the hydrogen and using this as furnace fuel must be considered. Both of these proposals have been analysed and the results are presented in Chapter 11.

It will suffice to state here that separation of the unchanged alcohol for recycle is the most economical and the design of the recovery system has been undertaken in this design report. Therefore the products of reaction are cooled and condensed in a water-cooled condenser, and the condensate is passed to a distillation unit where the MEK is obtained as distillate and butyl alcohol as the bottom product is recycled and mixed with the reactor feed for reprocessing. The gaseous effluent from the condenser is absorbed in water and the off-gas from the absorber is dried and pumped into the plant fuel system. The liquid discharged from the absorber is treated with trichlorethane to extract the MEK and alcohol and the extract from this column is fractionated to recover the MEK as product and the small amount of alcohol is recycled. The proposed scheme for the continuous production of 1.0×10^7 kg per annum of methyl ethyl ketone (MEK) from secondary butyl alcohol is presented in Figure 2.1, drawn to comply with BS 1553 Part 1, but extended to include the symbolic representation described in *Drawing Office Guide to Symbols used in the Chemical, Petroleum and Allied Industries*².

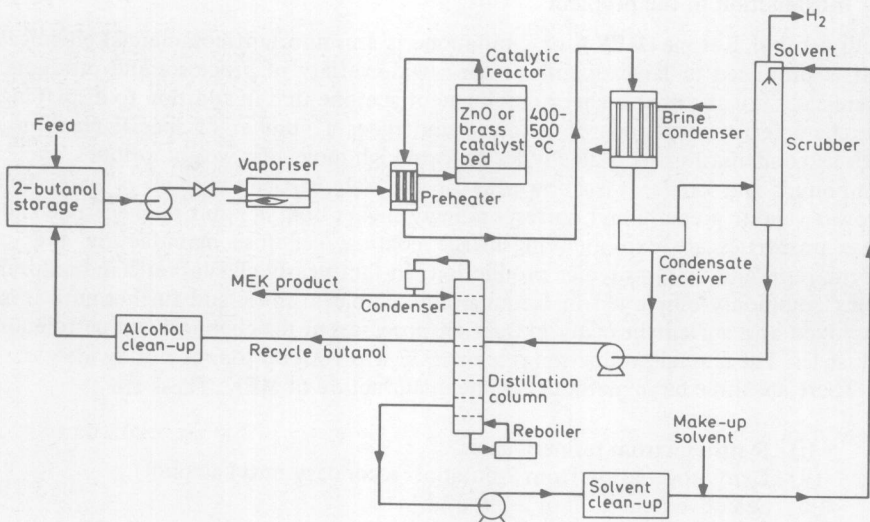


Figure 2.1 — Production of methyl ethyl ketone from 2-butanol.

Chapter 3

GENERAL CONSIDERATIONS

3.1 General considerations of the problem

The catalytic dehydrogenation of 2-butanol has been extensively studied by Thodos and his co-workers^{3,4} and by Ford and Perlmutter⁵. All these investigations have identified ten possible reaction mechanisms, and all the experimental results indicate that one or more of the following steps are rate controlling.

- (i) Adsorption of alcohol vapour on a single active site.
- (ii) Decomposition of the alcohol-active site complex to form MEK vapour leaving molecular hydrogen adsorbed on the catalyst.
- (iii) Desorption of the molecular hydrogen.
- (iv) The adsorbed alcohol molecule reacts with an adjacent vacant active site to produce adsorbed ketone and molecularly adsorbed hydrogen.

Perona & Thodos found that the desorption of hydrogen was the rate-controlling step in the temperature range 350°C to 750°C whereas Thaller & Thodos and Ford & Perlmutter favoured step (iv) over the temperature range 350°C to 400°C. Both the latter research studies confirmed that the rate-controlling step was temperature dependent and it appears that step (iii) becomes rate-controlling outside the close range 350°C to 400°C. Thaller & Thodos' study was undertaken with a differential reactor and Ford & Perlmutter used a stirred vessel reactor whereas Perona & Thodos employed an integral reactor and extrapolated their results to obtain their rate equation. These latter results must therefore be considered to be average results. However, the agreement between their calculated and experimental results is very good and suggests that their rate equation adequately characterises the conversion expected in a commercial scale reactor. Consequently the following rate equation will be utilised for the design of the reactor.

$$r_c = \frac{C_i[p_{Ai} - (p_{Ki}p_{Hi}/K_i)]}{p_{Ki}[1 + K_{Ai}p_{Ai} + K_{AKi}(p_{Ai}/p_{Ki})]} \quad (3.1)$$

where the constants are related to the temperature by the following relations

$$\log C_i = -(5964/T_i) + 8.464 \quad (3.2)$$

$$\log K_{Ai} = -(3422/T_i) + 5.326 \quad (3.3)$$

$$\log K_{AKi} = (269.2/T_i) - 0.1959 \quad (3.4)$$

All the research studies on this reaction report that the butyl alcohol undergoes thermal cracking and that the rate of the cracking reaction was found to increase sharply with temperature above 400°C. However the rate of the dehydrogenation reaction is also temperature dependent and the rate of formation of MEK is negligible below 300°C. Therefore, since this reaction is endothermic, the centre of the reaction tube will have the minimum temperature and this must not be less than 300°C. For the same reason a small amount of cracking must be tolerated and furthermore Perona & Thodos have also shown that the catalyst is regenerated fairly easily so that the upper limit catalyst temperature is 500°C. These two temperatures set the limits for the reactor tube radius.

The products of reaction discharged from the reactor consists of MEK vapour, hydrogen and unchanged alcohol. All these products are reasonably stable below 400°C and it is unnecessary to instal a rapid quench unit. However a considerable amount of heat will be discharged from the reactor which must be recovered by heat exchange with the incoming feed before the MEK and alcohol are condensed.

The majority of the MEK and alcohol discharged from the reactor will be condensed, but since the reaction products contain hydrogen a small amount of MEK and alcohol will leave the condenser saturated in the hydrogen. These vapours will be stripped from the hydrogen by absorption in water, and since the solubility of MEK in water is of the order of 27%, the concentration of the effluent from the absorption should not exceed 27% MEK. The MEK and alcohol in the liquid effluent from the absorber will be recovered by solvent extraction.

The choice of solvent for the recovery of the MEK from the aqueous solution depends on a number of factors which are discussed in depth in Treybal's *Liquid Extraction*.⁶ and will not be re-iterated here. Treybal, Newman & Hayworth⁷ cite a number of possible solvents for the extraction of MEK from water including trichlorethylene, trichlorethane, hexanes, heptanes and other hydrocarbons. However, from the point of view of ease of recovery of the MEK from the extract solution, it appears that 1:1:2 trichlorethane is the preferred solvent and the equilibrium data has been published by Treybal, Newman and Hayworth⁷. The data

Table 3.1 — *Phase equilibria and density of the system methyl ethyl ketone/ water/1.1.2 trichlorethane.*

MEK % wt	Water % wt	1.1.2 Trichlorethane % wt	Density kg/m ³	MEK % wt	Water %wt	1.1.2 Trichlorethane % wt	Density kg/m ³
18.15	81.74	0.11	973.3	75.00	5.08	19.92	890.4
12.78	87.06	0.16	980.4	58.62	2.73	38.65	972.0
9.23	90.54	0.23	985.3	44.38	1.48	54.14	1055.3
6.00	93.70	0.30	990.2	31.20	1.00	67.80	1142.5
2.83	96.80	0.37	994.2	16.90	0.52	82.58	1255.4
1.02	98.57	0.41	996.6	5.58	0.00	94.42	1362.6

are presented in Table 3.1 and Figure 3.1 together with the density of each phase. There it will be seen that an isopicnic exists between the raffinate containing 11.0% MEK and the extract containing 53% MEK. This could cause flooding or phase inversion in the extraction column which must be avoided by ensuring that the

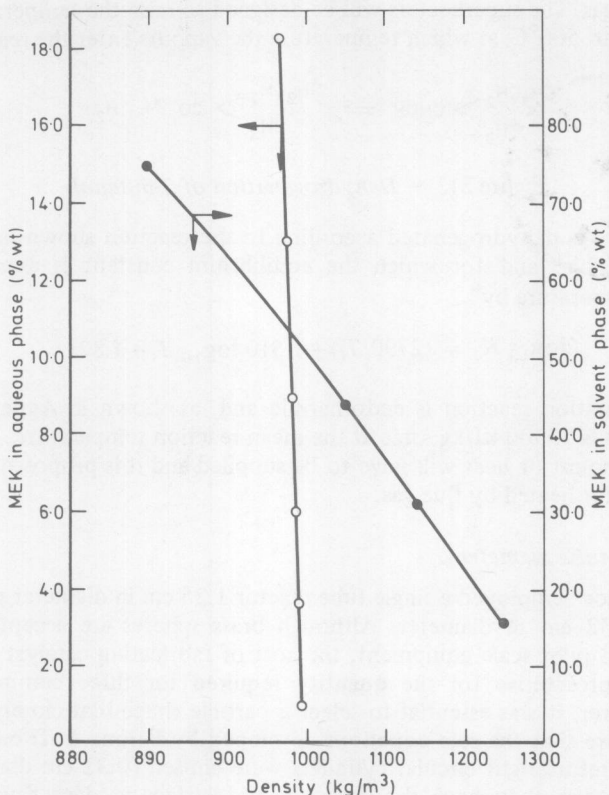


Figure 3.1 — *Location of isopicnic composition.*

concentration of MEK in the effluent from the absorption column fed to the extraction unit does not exceed 10% on a weight basis. The MEK in the extract phase will be recovered by distillation and the regenerated solvent will be recycled to the extraction unit.

The condensate from the condenser will be mixed with the distillate from the solvent recovery column to form the feed to the MEK product distillation unit, and the distillate from this unit will be the MEK product from the process.

3.2 Proposed method of manufacture

The proposed method of manufacture is that summarised in the statement of the problem and will include the general considerations referred to in Section 3.1 above. That is, the cold feed of 2-butanol will be pumped from the feed tank through a steam heater to a vertical thermo-syphon reboiler in which the alcohol is vaporised. The thermo-syphon reboiler will be heated by the reaction products discharged from the reactor and the wet alcohol vapour will be passed to a knock-out drum to remove any entrained liquid. The liquid separated will be recycled and the dry alcohol vapour will be fed to the reactors *via* two superheaters

heated by flue gas. The superheaters will be designed to raise the temperature of the alcohol vapour to 500°C, at which temperature the vapours enter the reactor.

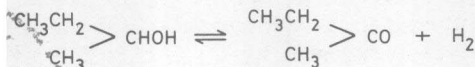


Figure 3.2 — Dehydrogenation of 2-butanol.

The 2-butanol is dehydrogenated according to the reaction shown in Figure 3.2 which is reversible, and for which the equilibrium constant is expressed as a function of temperature by⁹

$$\log_{10} K_i = (2790/T_i) + 1.510 \log_{10} T_i + 1.871 \quad (3.5)$$

The dehydrogenation reaction is endothermic and, as shown in Appendix B, the heat of reaction is 73900 kJ/kg mole at the mean reaction temperature. Therefore a considerable amount of heat will have to be supplied and it is proposed to design a multi-tube reactor heated by flue gas.

3.2.1 Reactor tube diameter

Perona & Thodos³ employed a single tube reactor 1.25 cm in diameter packed with brass beads 0.32 cm in diameter. Although brass spheres are acceptable for an investigation on pilot scale equipment, the cost of fabricating catalyst particles of this shape is prohibitive for the quantity required for three commercial scale reactors. However, it was essential to select a particle shape that closely resembled spheres to ensure that the rate equations developed by Perona & Thodos³ remain applicable. Therefore right circular cylinders were chosen (0.32 cm diameter, 0.32 cm length) because they have the same specific surface voidage fraction¹⁰ and exhibit similar pressure drop characteristics to those of spheres¹¹. Fabrication costs are relatively low since the particles would be manufactured by the cutting of extruded brass rod in one operation. In this experimental reactor some channelling may occur since the ratio (tube diameter/catalyst particle diameter) is only 4:1. However these authors conclude their publication with an example calculation in which they specify a tube diameter of 7.5 cm with catalyst particles 0.32 cm in size. Hence it is necessary to estimate a suitable reactor tube diameter for the commercial scale reactor.

It has been stated above that the reaction is endothermic so that the tube axis temperature will be the minimum and it was shown in Section 3.1 that the reaction rate was very slow below 300°C. Furthermore cracking becomes significant above 500°C and therefore it is necessary to control the reaction between these temperatures. The relationship between heat of reaction, flow rate, tube diameter and temperature can be expressed by the equation^{7,8}

$$\frac{\partial^2 T}{\partial x^2} + \frac{1}{x} \frac{\partial T}{\partial x} - \frac{GC_p \partial T}{k_E \partial z} - \frac{S \Delta H r_c}{k_E} = 0 \quad (3.6)$$

and the reactor tube diameter may be estimated from equation (3.6). This has been done in Section 4.3 where it will be seen that a suitable diameter would be 4.2 cm and this has been chosen as the basis for the design of the reactor. Consequently, 18:8 stainless steel tubes 4.2 cm nominal bore will be recommended.

3.2.2 Mass velocities in reaction tubes

The number of tubes in the reactor depends on the mass rate of flow of alcohol or reaction products permitted. This in turn depends on the allowable pressure drop and the necessity to ensure turbulent flow conditions in the packed tubes. In order to keep the pressure drop to a minimum and obtain turbulent flow conditions the allowable mass rate of flow through the reactor tube will be based on the packed bed modified Reynolds number^{1,2}

$$Re' = \frac{D_p G}{\mu(1-\varepsilon)} \geq 1000 \quad (3.7)$$

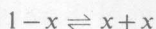
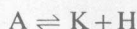
where D_p is the diameter of the particle, 0.32 cm, and ε is the porosity of the packed bed. For random packed cylinders of the same size $\varepsilon = 0.393$.

Then for $Re = 1000$ the permissible mass rate of flow is

$$\begin{aligned} G &= \frac{1000 \times 1.876 \times (1 - 0.393) \times 10^{-5}}{3.175 \times 10^{-3}} \text{ kg/m}^2\text{s} \\ &= 3.588 \text{ kg/m}^2\text{s} \end{aligned}$$

3.2.3 Conversion yield

The definition of the problem states that the conversion of the alcohol was to be 90% and it is desirable to consider the feasibility of this conversion in respect of the data available. Thus, it is well known that the dehydrogenation reaction is reversible and the equilibrium constant is a function of temperature; see equation (3.5). Furthermore the stoichiometric equation Figure 3.2 can be written for a conversion " x ", thus:



and the partial pressure of each component in the system will then be

$$p_A = \frac{\Pi(1-x)}{1+x} \quad : \quad p_K = \frac{\Pi x}{1+x} \quad : \quad p_H = \frac{\Pi x}{1+x}$$

and the equilibrium equation will be

$$K = \frac{\Pi x^2}{(1+x)(1-x)} = \frac{\Pi x^2}{1-x^2} \quad (3.8)$$

where Π is the total pressure of the system

Combining equations (3.5) and (3.8) shows that the equilibrium conversion at different temperatures will be as shown in Table 3.2, which shows that if equilibrium was attained at the reactor exit the temperature of the reaction