# CHAPTER

# 30

# A Report-Writing Case Study

The purpose of this chapter is to illustrate some of the principles of report writing presented in Chapter 29. In order to accomplish this, we present a written report for a project that a junior engineer might be given in the first several years of employment. This chapter is split into several sections. Each section addresses some of the common errors that are made in report writing. Examples of poor and improved cover memoranda, poor and improved graphics, and poor and improved writing styles are given. A checklist of common errors is also included. Finally, an example is presented of a improved written report that illustrates many of the principles outlined in this chapter and Chapter 29.

It should be noted that the figures and tables concerning the toluene hydrodealkylation problem are presented to illustrate examples of strong and weak graphics and to highlight common mistakes. The absolute values shown for equipment and operating costs are not necessarily accurate.

## 30.1 THE ASSIGNMENT MEMORANDUM

The assignment memorandum for the project considered in this chapter is shown in Figure 30.1.

This is a good assignment memorandum because it communicates to the junior engineer in a concise manner *what* to do, *why* to do it, *when* to have it completed, and *who* else is involved or interested in the project. Everything is stated clearly; nothing is left for interpretation.

Because the memo indicates *who* is being copied on the memo, the junior engineer knows all of those involved in the loop. The engineer also knows for whom the final report will be prepared. An essential step in preparing a report is knowing the audience.

Because the memo indicates that there are attachments to the memorandum, the recipient of the memo knows whether the document is complete.

The first paragraph provides perspective on the problem (*why* it is assigned). This is essential for the junior engineer to make rational decisions during the assignment.

## MEMORANDUM

TO: Lee Madera, Junior Process Engineer

FROM: Chris Stafford, Senior Process Engineer

RE: Benzene Production

DATE: September 12, 2011

COPIES: R. T. Hemrick, Principal Process Engineer
M. R. Johnson, VP Engineering
S. E. Kelley, VP Project Engineering
W. C. Lin, VP Sales

ATTACHMENTS: Preliminary design of benzene process

Currently, the prices of benzene and toluene are such that the production of benzene from toluene via the catalytic hydrodealkylation of toluene is not profitable. However, the price of benzene over the past 15 years has fluctuated wildly (from a low of \$0.21/kg to nearly \$0.67/kg). Our company is interested in carrying out a feasibility study to determine the minimum price differential between benzene and toluene that will allow the toluene hydrodealkylation process to be profitable. It is recognized that currently the preferred method of producing benzene from toluene is via the disproportionation reaction to yield both benzene and xylenes. However, at present our company has no use for the xylene and would prefer to make just benzene.

With this in mind, your assignment is to determine the process that will minimize the price differential between toluene and benzene required to yield an NPV = 0. This design represents a discounted break-even analysis of the process and will be used as an internal benchmark for comparing competing alternatives to produce benzene. In your analysis, you should use the following economic parameters:

(i) Internal after-tax hurdle rate of 10%, and a taxation rate of 35%
(ii) MACRS depreciation over 6 years for all fixed capital investment
(iii) A project life of 15 years
(iv) A production rate of 68,000 tonne per year of 99.5 wt% pure benzene

The attached preliminary design for a toluene HDA process should be used as a starting point (base case) for your study.

Submit your findings as a short report, not exceeding 8 pages of double-spaced text, plus any tables and figures. Put the details of all your calculations, a PFD, flow table, and so on, in a clearly indexed appendix.

This report is due on September 26, 2011, and will be read by several managers as well as other technical and sales executives. You will also present your major findings in a 15-minute oral presentation on September 27, 2011.

**Figure 30.1** Example of a Good Assignment Memorandum

The second and third paragraphs clearly outline *what* is to be done, what the constraints are, and what the deliverables are. If this section were not clear, the junior engineer would either have to guess about the constraints or the specifics of the assignment or have to go back to the senior engineer and ask. If the senior engineer were unavailable to answer questions, this might delay the project. In any case, time would be wasted.

The final paragraph states *when* the assignment is due and when the presentation will be made.

## 30.2 RESPONSE MEMORANDUM

An example of a poor response memorandum is given in Figure 30.2. An example of an improved response memorandum is given in Figure 30.3.

In order to explain the difference between the improved and poor response memos, it is necessary to understand who reads different portions of reports. A secretary reads only the cover memorandum subject in order to determine where to file the report. The senior process engineer, the person who gave you the assignment, may read the entire report. The principal process engineer reads the entire report only if the results are interesting or controversial. The vice presidents will probably not read the entire report. For those who do not read the entire report or who need to decide whether to read the report, the information provided in the cover memorandum is essential.

At any time, there will be many reports circulating within a company. Occasionally, a report may become detached from its cover memorandum. If the attachment is listed as *The Benzene Report*, the cover memorandum may never be matched with the correct report if they become separated. If your company makes benzene, there will probably be many "benzene reports" circulating at one time. Therefore, the complete title should be included on the cover memorandum.

On the "poor" memorandum, report copies are sent to only two individuals. The assignment memorandum was copied to four individuals. Always provide copies of your final product to everyone in the loop based on the original memorandum.

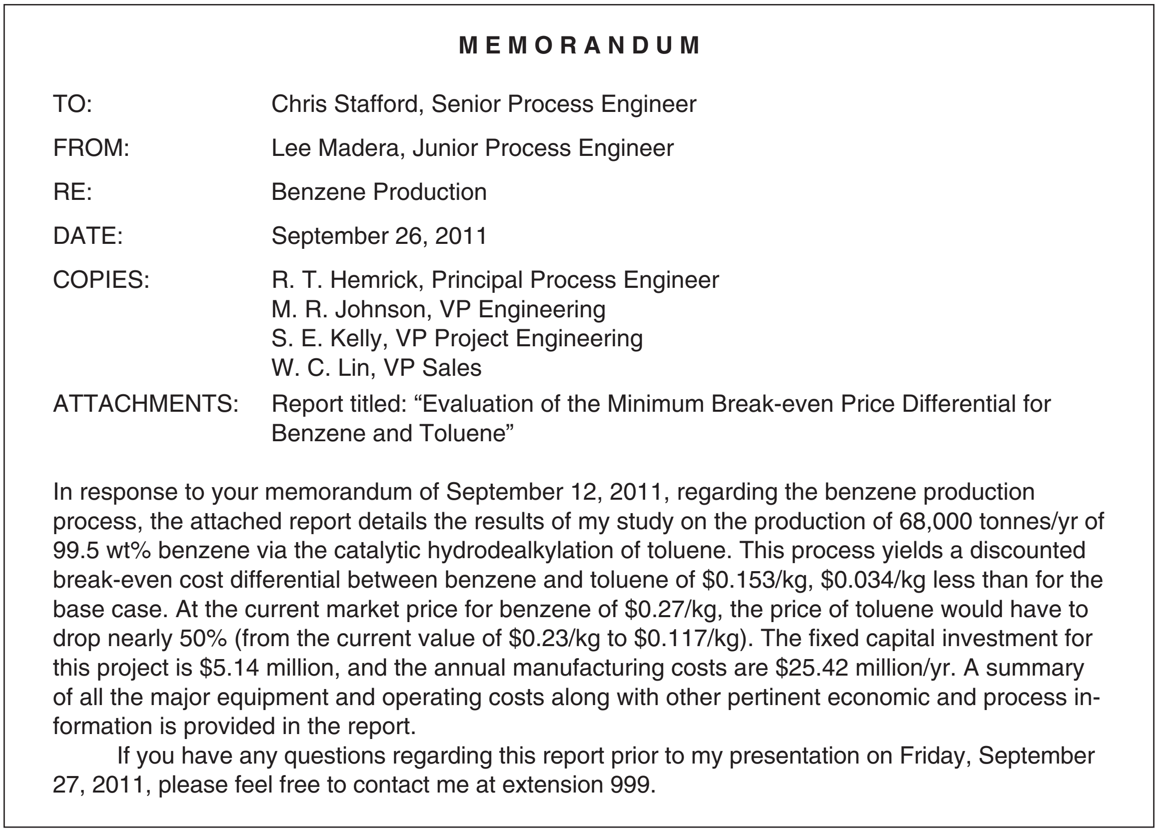
The key problem with the poor memorandum is that it basically states, "Here it is" and nothing else. The poor memorandum provides no information to allow any of the people who receive the report to determine rapidly what the conclusions were or to decide whether they want to read the entire report. Suppose that the conclusion, if the company invested $100,000 in a process modification, the break-even purchase price of toluene would rise to $0.25/kg. It is essential that everyone in the loop know that piece of information immediately. Therefore, a cover memorandum must summarize the key conclusions. What was found, how much it will cost up front (capital cost, if applicable), and

**MEMORANDUM**

TO: Chris Stafford, Senior Process Engineer
FROM: Lee Madera, Junior Process Engineer
RE: Benzene Production
DATE: September 26, 2011
COPIES: R. T. Hemrick, Principal Process Engineer
M. R. Johnson, VP Engineering
ATTACHMENTS: The Benzene Report

In response to your memorandum, the attached report details the results of my study on the production of benzene via the catalytic hydrodealkylation of toluene. This process is based on the production of 68,000 tonnes per year of 99.5 wt% benzene. A summary of all the major equipment and operating costs along with other pertinent economic and process information is provided in the report.

**Figure 30.2** Example of a Poor Response Memorandum



**MEMORANDUM**

TO: Chris Stafford, Senior Process Engineer
FROM: Lee Madera, Junior Process Engineer
RE: Benzene Production
DATE: September 26, 2011
COPIES: R. T. Hemrick, Principal Process Engineer
M. R. Johnson, VP Engineering
S. E. Kelly, VP Project Engineering
W. C. Lin, VP Sales
ATTACHMENTS: Report titled: "Evaluation of the Minimum Break-even Price Differential for Benzene and Toluene"

In response to your memorandum of September 12, 2011, regarding the benzene production process, the attached report details the results of my study on the production of 68,000 tonnes/yr of 99.5 wt% benzene via the catalytic hydrodealkylation of toluene. This process yields a discounted break-even cost differential between benzene and toluene of \$0.153/kg, \$0.034/kg less than for the base case. At the current market price for benzene of \$0.27/kg, the price of toluene would have to drop nearly 50% (from the current value of \$0.23/kg to \$0.117/kg). The fixed capital investment for this project is \$5.14 million, and the annual manufacturing costs are \$25.42 million/yr. A summary of all the major equipment and operating costs along with other pertinent economic and process information is provided in the report.

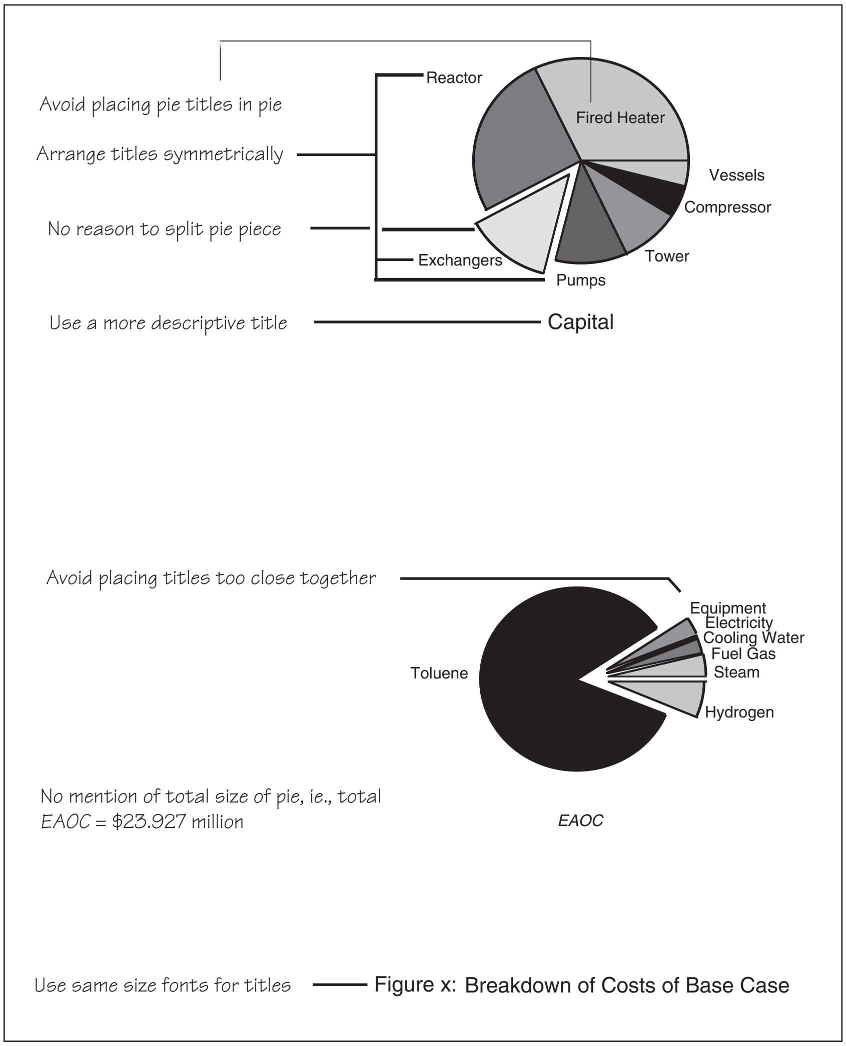
If you have any questions regarding this report prior to my presentation on Friday, September 27, 2011, please feel free to contact me at extension 999.

**Figure 30.3** Example of an Improved Response Memorandum

what the profitability is (NPV, DCFROR, raw material purchase price) must be stated. In a short report, which is likely to be the rule in industry, the cover memorandum takes the place of an abstract. Therefore, it is imperative to include key results in the cover memorandum.

## 30.3 VISUAL AIDS

Figures 30.4 through 30.9 show examples of poor and improved pie charts, tables, and plots. Major points of criticism are shown on the "poor" figures (Figures 30.4, 30.6, and 30.8) in script font, and these errors have been remedied in the corresponding "improved" figures (Figures 30.5, 30.7, and 30.9). Not all the common errors can be shown on these figures, and a comprehensive checklist for figures, tables, and written text is included in Section 30.5.



Avoid placing pie titles in pie

Arrange titles symmetrically

No reason to split pie piece

Use a more descriptive title

Avoid placing titles too close together

No mention of total size of pie, ie., total *EAOC* = $23.927 million

Use same size fonts for titles

**Figure 30.4** Some Common Mistakes Made in Pie Chart Presentation

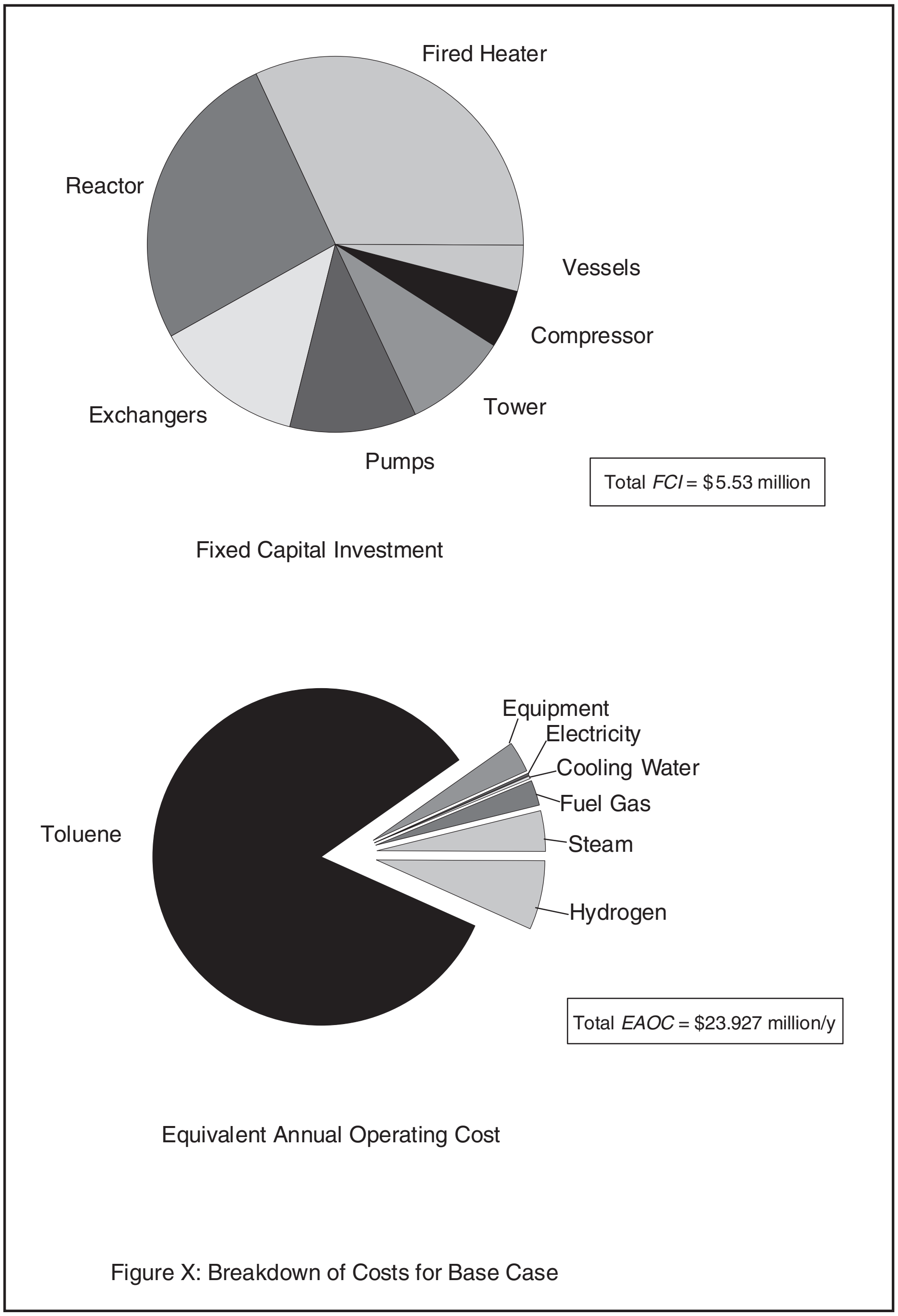
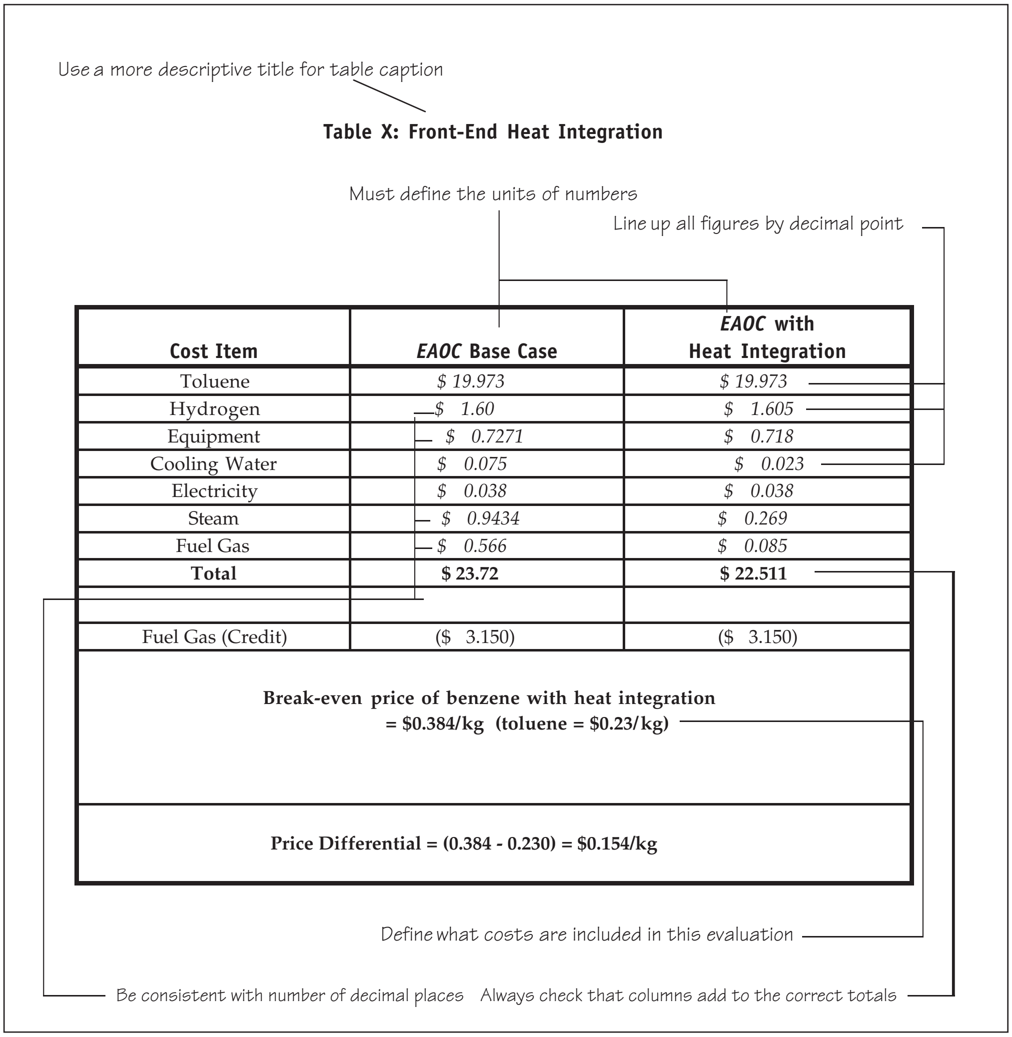


**Figure 30.5** Corrected Version of the Pie Chart Shown in Figure 30.4



Use a more descriptive title for table caption

**Table X: Front-End Heat Integration**

Must define the units of numbers

Line up all figures by decimal point

| Cost Item | *EAOC* Base Case | *EAOC* with Heat Integration |
|---|---|---|
| Toluene | *$ 19.973* | *$ 19.973* |
| Hydrogen | *$ 1.60* | *$ 1.605* |
| Equipment | *$ 0.7271* | *$ 0.718* |
| Cooling Water | *$ 0.075* | *$ 0.023* |
| Electricity | *$ 0.038* | *$ 0.038* |
| Steam | *$ 0.9434* | *$ 0.269* |
| Fuel Gas | *$ 0.566* | *$ 0.085* |
| **Total** | **$ 23.72** | **$ 22.511** |
| | | |
| Fuel Gas (Credit) | ($ 3.150) | ($ 3.150) |

**Break-even price of benzene with heat integration**
**= $0.384/kg (toluene = $0.23/kg)**

**Price Differential = (0.384 - 0.230) = $0.154/kg**

Define what costs are included in this evaluation

Be consistent with number of decimal places

Always check that columns add to the correct totals

**Figure 30.6** Some Common Mistakes Made in Table Presentations

**Table X: Economic Impact of Front-End Heat Integration on Process Economics (all *EAOC* cost figures in millions)**

| Cost Item | *EAOC* Base Case | *EAOC* with Heat Integration |
|---|---|---|
| Equipment | \$ 0.727 | \$ 0.718 |
| Steam | \$ 0.943 | \$ 0.269 |
| Fuel gas | \$ 0.566 | \$ 0.085 |
| Cooling water | \$ 0.075 | \$ 0.023 |
| Electricity | \$ 0.038 | \$ 0.038 |
| Toluene | \$ 19.973 | \$ 19.973 |
| Hydrogen | \$ 1.605 | \$ 1.605 |
| **Total** | **\$ 23.927** | **\$ 22.711** |
| | | |
| Fuel gas (credit) | (\$ 3.150) | (\$ 3.150) |
| **Break-even price of benzene with heat integration = \$0.384/kg (toluene = \$0.23/kg)**<br>Break-even costs include utilities, raw materials, maintenance, labor, fixed capital investment, etc. | | |
| **Price Differential = (0.384 – 0.230) = \$0.154/kg** | | |

**Figure 30.7** An Improved Version of the Table Shown in Figure 30.6

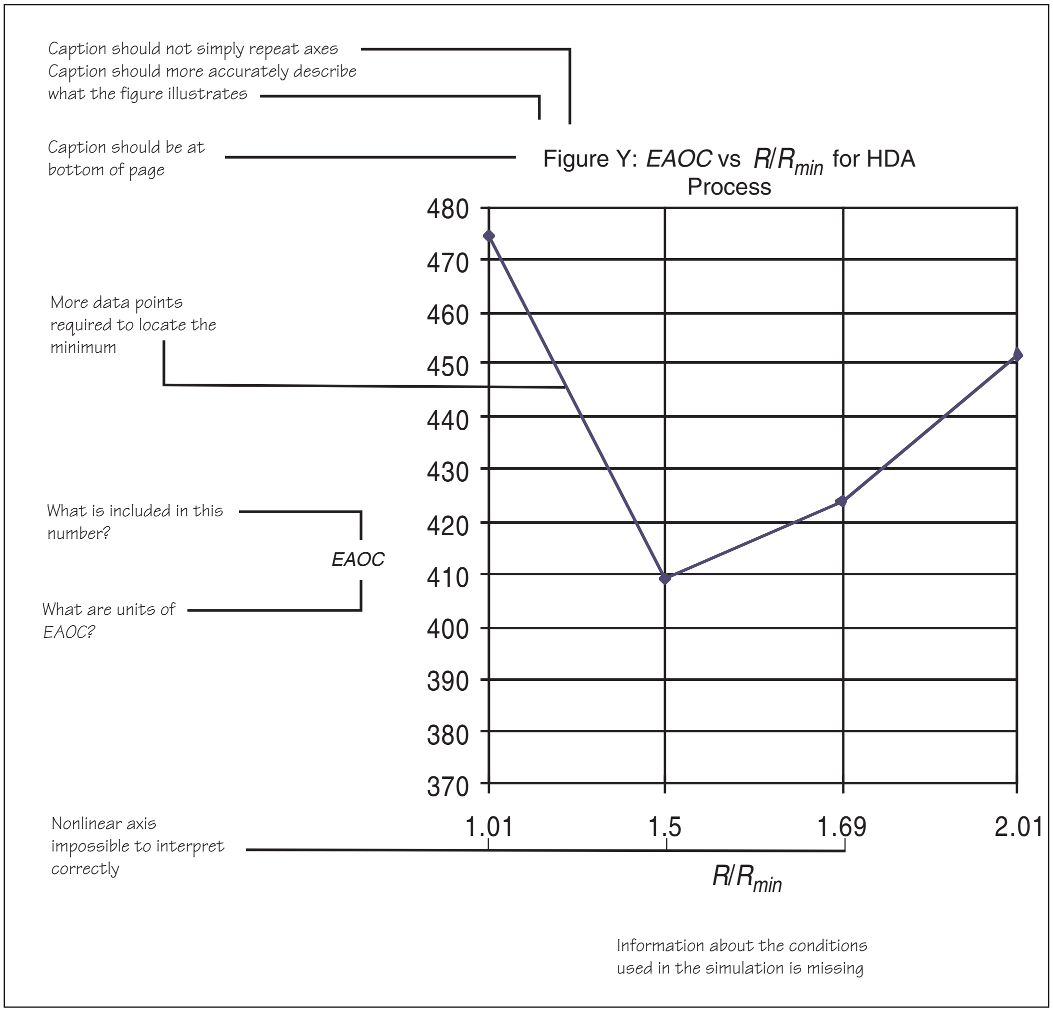


**Figure 30.8** Some Common Mistakes Made in Graphical Presentations

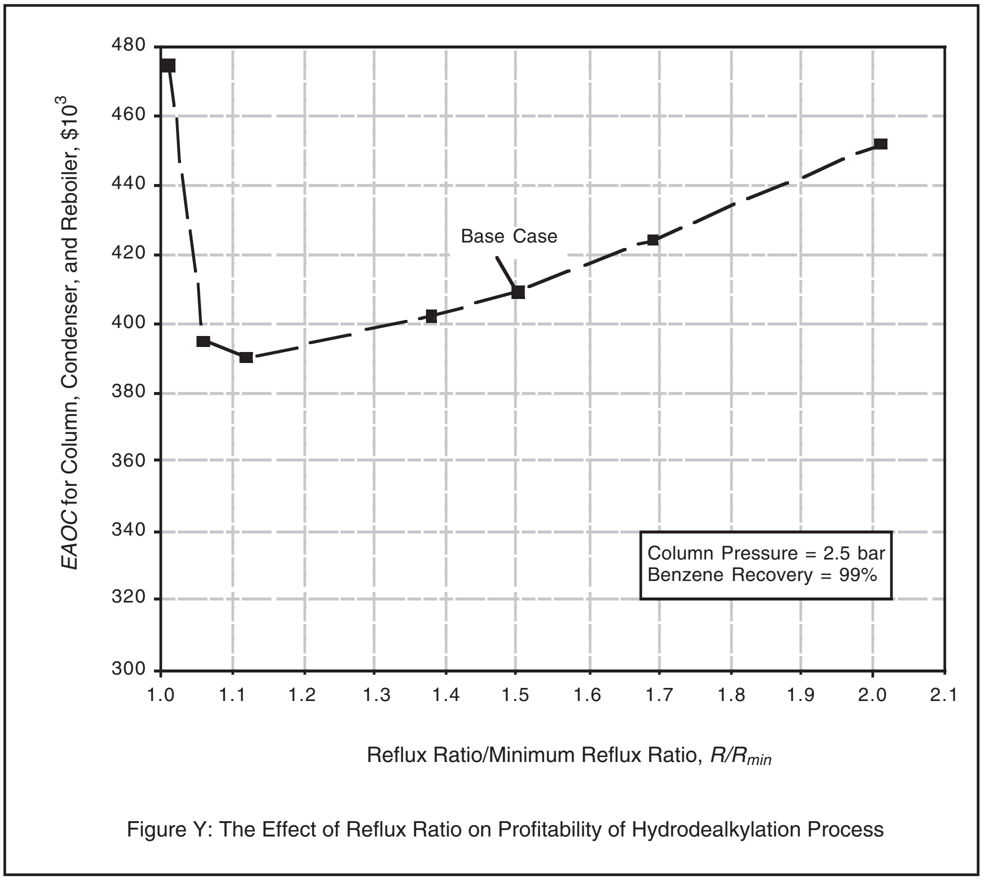


**Figure 30.9** Corrected Version of the Graph Shown in Figure 30.8

## 30.4 EXAMPLE REPORTS

Two examples of student reports follow. Section 30.4.1 contains an example of a portion of a student report with suggestions for improvement. Section 30.4.2 contains an example of an improved report.

### 30.4.1 An Example of a Portion of a Student Written Report

#### 1. Introduction

The purpose of this report is to establish the minimum break-even price differential between benzene and toluene for the production of benzene using the catalytic hydrodealkylation of toluene. In this process, toluene is converted to benzene over a solid catalyst via the following reaction:

$$C_7H_8 + H_2 \rightarrow C_6H_6 + CH_4$$

This reaction is normally carried out at temperatures in the range of 580°C–660°C and at pressures of 35–70 bar. With the development of new catalysts, lower operating pressures, down to 25 bar, may be possible and I assumed this was feasible in this analysis. In the base-case process provided, the reactor consisted of a single-stage adiabatic packed bed of catalyst into which a small stream of recycle gas was fed for temperature control. Over the range of conditions considered here, there are essentially no side reactions.

Use words as well as symbols to identify the major substances in the reaction.

Didn't this info. come from Refs. 1 and 2? If so, you need to include the footnote here.

Reference 3?

Poor wording. Isn't this already the basis of the prelim. design provided with the assignment?

Some readers are very uncomfortable with personal pronouns in technical reports. Are you sure that "I" is appropriate for your audience?

#### 2. Base-Case Evaluation

See your format instructions for ways to improve the organization and usefulness of your report.

The first step was the analysis of the base case provided. The PFD for this base case is shown in Figure 1. According to the base-case report, the reactor inlet conditions of 600°C and 25 bar have been established to be close to the optimum. As a result, these parameters were not varied in the present study. A summary of the fixed capital investments, operating costs, and the break-even price differential for the base case is given in Table 1 and Figure 1. In order to compare all the costs, I set up an Excel spreadsheet and the data for the base case was input into the program. These numbers are presented as equivalent annual operating costs by amortizing the one-time capital investments over

Your readers want to know what process is best and when it should be used; they don't want a step-by-step history of what you did. Remember to focus on their needs.

This is your 2nd Figure 1. Also "EAOC" is used in the figure but hasn't been defined yet.

All the info. in the pie charts (Fig. 1) is given in Table 1. You don't need the figure.

Please use the guidelines. These details are not of interest to the readers.

*data* were

the life of the project using a 10% discount rate. The break-even price of benzene for this base case is \$0.417/kg ~~compared to the cost of toluene of~~ \$0.23/kg. This yields a break-even cost differential of \$0.187/kg. The details of the break-even analysis are given in the appendix. The cost of manufacturing was estimated from the following equation:

with toluene costing

$$COM_d = 0.180 * FCI + 2.73 \times C_{OL} + 1.23 * (C_{UT} + C_{RM})$$

Don’t include both * and × multiplication symbols.

where $FCI$ = fixed capital investment, $C_{OL}$ = cost of operating labor, $C_{UT}$ = cost of utilities, and $C_{RM}$ = cost of raw materials.

From Table 1, it is evident that the major costs will be associated with the purchase of toluene and hydrogen. The overall conversion of toluene in the base case will be 99.3%. Potential savings in toluene cost of approximately \$140,000/yr may be realized. This savings would have a minor impact on the differential break-even price of benzene (approx. \$0.003/kg), therefore, the overall conversion of toluene is not considered a variable in the cases studied here. However, the hydrogen cost can be reduced significantly if a suitable separation technique can be found to purify the recycle gas, Streams 5 and 7. Of the remaining costs, the steam, fuel gas, and equipment are the most significant.

Use present tense here.

;

The above items provide a focus on where to concentrate the major optimization effort. In this regard, a two level optimization strategy was

Wordy. Try “are the keys to the optimization.”

Unnecessary and misleading.

two-level

### 30.4.2 An Example of an Improved Student Written Report

#### 1. Introduction

The purpose of this report is to establish the minimum break-even price differential between benzene and toluene for the production of benzene using the catalytic hydrodealkylation of toluene. In this process, toluene is converted to benzene over a solid catalyst via the following reaction:

$$\underset{\text{toluene}}{C_7H_8} + H_2 \rightarrow \underset{\text{benzene}}{C_6H_6} + CH_4$$

This reaction is normally carried out at temperatures of 580°C– 660°C and at pressures of 35–70 bar [1, 2]. With the development of new catalysts, operating pressures as low as 25 bar may be possible [3] and are assumed to be feasible in this analysis. In the base-case process provided, the reactor consists of a single-stage adiabatic packed bed of catalyst into which a small stream of recycle gas is fed for temperature control. Over the range of conditions considered here, there are essentially no side reactions.

## 2. Base-Case Evaluation

The PFD for this base case is shown in Figure 1. The previously reported optimum reactor inlet conditions of 600°C and 25 bar are used. A summary of the fixed capital investments, operating costs, and the break-even price differential for the base case is given in Table 1. They are presented as equivalent annual operating costs by amortizing the one-time capital investments over the life of the project using a 10% discount rate. The break-even sales price of benzene for this base case is $0.417/kg for a toluene purchase price of $0.23/kg (a break-even cost differential of $0.187/kg). The details of the break-even analysis are given in the appendix. The cost of manufacturing is estimated using the following equation:

$$COM_d = 0.180FCI + 2.73C_{OL} + 1.23(C_{UT} + C_{RM}) \qquad (1)$$

where $FCI$ = fixed capital investment, $C_{OL}$ = cost of operating labor, $C_{UT}$ = cost of utilities, and $C_{RM}$ = cost of raw materials.

Table 1 shows that the major cost is for toluene. The overall conversion of toluene in the base case is 99.3%, allowing a potential savings in toluene cost of approximately $140,000/yr. This savings would have only a minor impact (approx. $0.003/kg) on the differential break-even price of benzene; therefore, the overall conversion of toluene is not considered a variable in the cases studied here. However, the hydrogen cost can be reduced significantly if a suitable separation technique can be found to purify the recycle gas, Streams 5 and 7. Of the remaining costs, the steam, fuel gas, and equipment are the most significant.

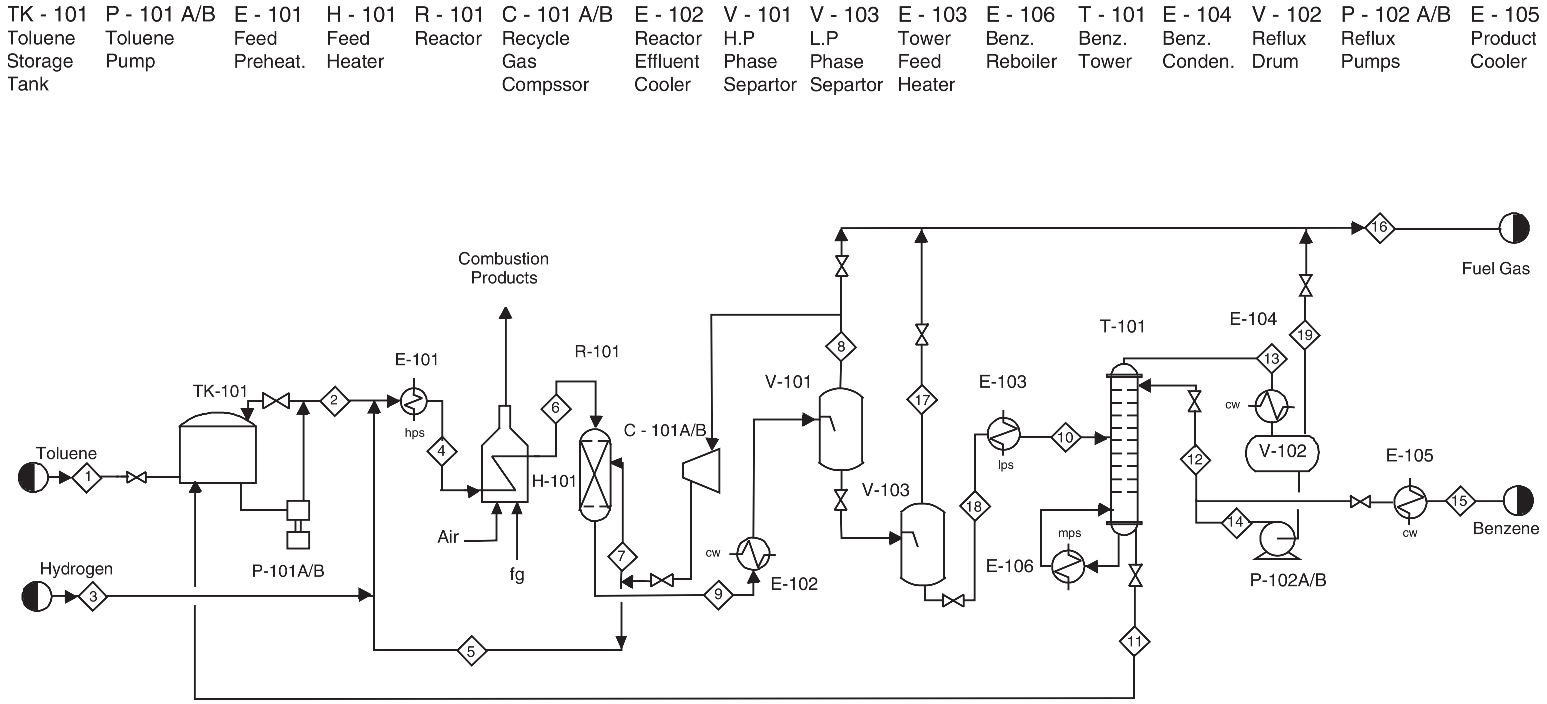


**Figure 1** Skeleton Process Flow Diagram (PFD) for the Production of Benzene via the Hydrodealkylation of Toluene

**Table 1 Cost Summary for the Base-Case Evaluation of Toluene HDA Process (All fixed capital and *EAOC* cost figures are given in millions.)**

| Equipment Type | Fixed Capital Investment | % of Total Fixed Costs |
|---|---|---|
| Fired heater | $ 1.795 | 32 |
| Reactor | $ 1.447 | 26 |
| Exchangers | $ 0.695 | 13 |
| Pumps | $ 0.579 | 11 |
| Tower | $ 0.497 | 9 |
| Compressor | $ 0.289 | 5 |
| Vessels | $ 0.232 | 4 |
| **Total** | **$ 5.534** | **100** |

| Cost Item | Equivalent Annual Operating Cost (*EAOC*) | % of Total *EAOC* |
|---|---|---|
| Equipment | $ 0.727 | 3.0 |
| Steam | $ 0.943 | 3.9 |
| Fuel gas | $ 0.566 | 2.4 |
| Cooling water | $ 0.075 | 0.3 |
| Electricity | $ 0.038 | 0.2 |
| Toluene | $19.973 | 83.5 |
| Hydrogen | $ 1.605 | 6.7 |
| **Total** | **$23.927** | **100.0** |
| Fuel gas (credit) | ($ 3.150) | |

**Break-even price of benzene = $0.417/kg (for toluene at $0.23/kg)**

Break-even costs include utilities, raw materials, maintenance, labor, fixed capital investment, and so on.

**Price Differential = (0.417 − 0.230) = $0.187/kg**

To concentrate the major optimization effort on costs of hydrogen, steam, fuel gas, and equipment, a two-level optimization strategy was employed. The first level focused on topological changes to the process and included the addition of a membrane separation unit to purify the recycle gas (Streams 5 and 7) and the implementation of a heat integration scheme. The second level of optimization focused on changes in operating parameters, particularly the column reflux ratio and the single-pass conversion in the reactor, because significant savings in utilities may be realized by changing these variables. The results of these optimizations are presented in the next sections.

## 3. Topological Changes to Base-Case PFD

### 3.1. Membrane Separator

The first topological change attempted was the addition of a membrane separation unit to Stream 8 leaving the high-pressure phase separator. The membrane separation unit separates the recycle gas, sending a hydrogen-rich stream back through the compressor, C-101. This separation reduces the amount of methane in the recycle, and the amount of hydrogen feed required is reduced. Several different cases were screened, and Table 2 shows the results of the best case, where significant reductions in steam, fuel gas, and hydrogen feed costs were obtained. However, these gains were more than offset by the increased cost of electricity (for the compressor), the decrease in fuel gas credit,

**Table 2 Economic Impact of Membrane Separation Unit on Process Economics (Permeate available at 10 bar and 85% $H_2$ purity, all *EAOC* cost figures in millions.)**

| Cost Item | *EAOC* for Base Case | *EAOC* with Membrane Separator |
|---|---|---|
| Equipment | $ 0.727 | $ 1.370 |
| Steam | $ 0.943 | $ 0.780 |
| Fuel gas | $ 0.566 | $ 0.456 |
| Cooling water | $ 0.075 | $ 0.065 |
| Electricity | $ 0.038 | $ 0.320 |
| Toluene | $19.973 | $19.973 |
| Hydrogen | $ 1.605 | $ 1.338 |
| **Total** | **$23.927** | **$24.302** |
| Fuel Gas (Credit) | ($ 3.150) | ($ 2.632) |
| **Break-even price of benzene with membrane separator = $0.434/kg (toluene = $0.23/kg)**<br>Break-even costs include utilities, raw materials, maintenance, labor, fixed capital investment, etc. | | |
| **Price Differential = (0.434 − 0.230) = $0.204/kg** | | |

and the increase in equipment costs due to the larger compressor and the addition of the membrane separation unit. The net result was that the membrane separation unit provided no economic advantage. Consequently, this topological change is not recommended.

### 3.2. Heat Integration

The second topological change to the PFD was the addition of heat integration around the reactor, where the benefit would be greatest. Exchanging heat between the reactor effluent, Stream 9, and the high-pressure steam, Stream 4, can significantly reduce cooling water and fuel gas utilities. In addition, the cost of the front-end heat exchange equipment (E-101, E-102, and H-101) might also be reduced. Figure 2(a) shows the base-case configuration, and Figure 2(b) shows the optimized heat exchange configuration around the reactor. Table 3 lists the savings in equipment and utility costs. The use of heat integration eliminates the high-pressure steam usage and reduces significantly the cost and utility demands of the fired heater, yielding a significant economic

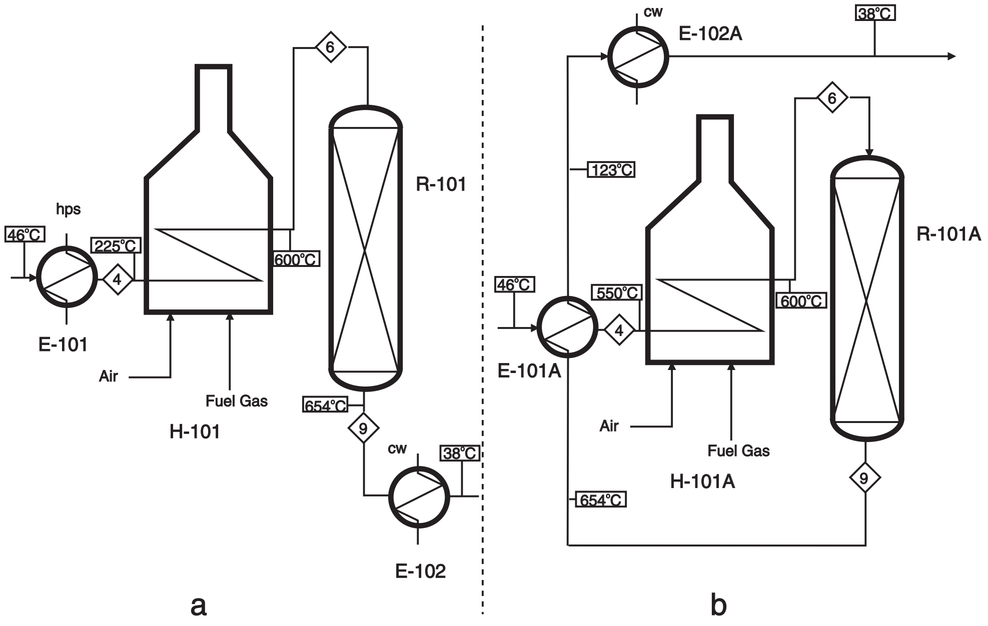


**Figure 2** Front End of Toluene HDA Process (a) without Heat Integration and (b) with Heat Integration

**Table 3 Economic Impact of Front-End Heat Integration on Process Economics (All *EAOC* cost figures in millions.)**

| Cost Item | *EAOC* Base Case | *EAOC* with Heat Integration |
|---|---|---|
| Equipment | $ 0.727 | $ 0.718 |
| Steam | $ 0.943 | $ 0.269 |
| Fuel gas | $ 0.566 | $ 0.085 |
| Cooling water | $ 0.075 | $ 0.023 |
| Electricity | $ 0.038 | $ 0.038 |
| Toluene | $19.973 | $19.973 |
| Hydrogen | $ 1.605 | $ 1.605 |
| **Total** | **$23.927** | **$22.711** |
| Fuel gas (Credit) | ($ 3.150) | ($ 3.150) |
| **Break-even price of benzene with heat integration = $0.384/kg (toluene = $0.23/kg)**<br>Break-even costs include utilities, raw materials, maintenance, labor, fixed capital investment, etc. | | |
| **Price Differential = (0.384 − 0.230) = $0.154/kg** | | |

improvement by reducing the break-even price of benzene to $0.384/kg (break-even price differential of $0.154/kg).

## 4. Parametric Changes to Base-Case Operation

### 4.1. Reflux Ratio

Table 1 shows that the two largest utility costs are steam and fuel gas. The heat integration scheme outlined above can reduce these costs significantly. The next largest steam user after E-101 is E-106, the reboiler of T-101. The optimum reflux ratio for column T-101 is 1.12 times the minimum (Figure 3), significantly different from the 1.5 of the base case. For this calculation, it is assumed that costs other than the *EAOC* of the column, reboiler, and condenser are substantially unaffected by changes in column operation. The costs for the optimum reflux are compared to those of the base-case operation ($R/R_{min}$ = 1.5)

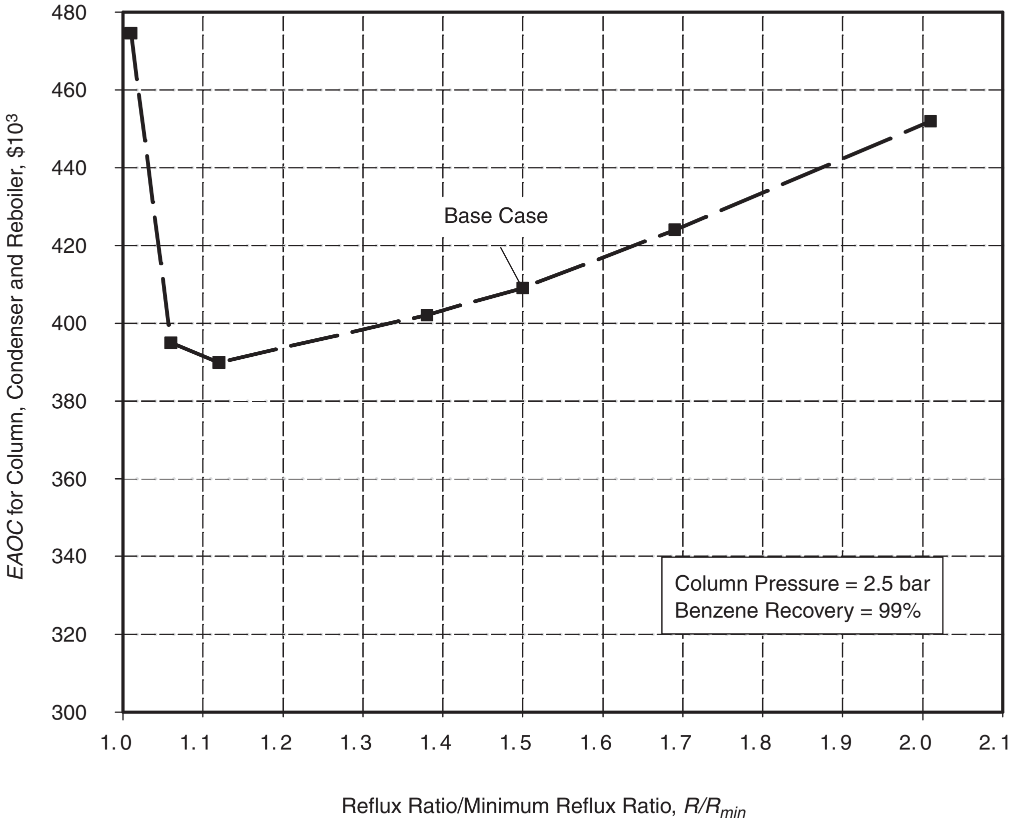


**Figure 3** The Effect of Reflux Ratio on Profitability of Hydrodealkylation Process

in Table 4. The overall effect is a small decrease in the break-even price differential of \$0.0002/kg.

### 4.2. Conversion

The final optimization attempted involved the single-pass conversion in the reactor (base-case conditions, $T$ = 600°C, $P$ = 25 bar, conversion = 0.75). The rationale for changing the conversion was that potential savings could be obtained by reducing the amount of toluene recycle; i.e., the size of equipment and utility usage in the recycle loop could be reduced. The results of this optimization are shown in Figure 4, where the break-even price for benzene is plotted as a function of single-pass conversion. The optimum conversion is seen to occur at about 85%, with a break-even price for benzene of \$0.383/kg. The results for

**Table 4 Economic Impact of Column Optimization on Process Economics (All *EAOC* cost figures in thousands.)**

| Cost Item | *EAOC* for Base Case $R/R_{min}$ = 1.50 | *EAOC* for Optimized Case $R/R_{min}$ = 1.12 |
|---|---|---|
| Column equipment (T-101, E-102, E-106, V-102, P-102A/B) | $ 132.11 | $ 148.03 |
| Cooling water | $ 11.04 | $ 9.32 |
| Steam | $ 275.90 | $ 239.04 |
| **Total** | **$ 418.05** | **$ 396.39** |
| **Break-even price of benzene with column optimization = $0.4168/kg (toluene = $0.23/kg)**<br>Break-even costs include utilities, raw materials, maintenance, labor, fixed capital investment, etc. | | |
| **Price Differential = (0.4168 − 0.230) = $0.1868/kg** | | |

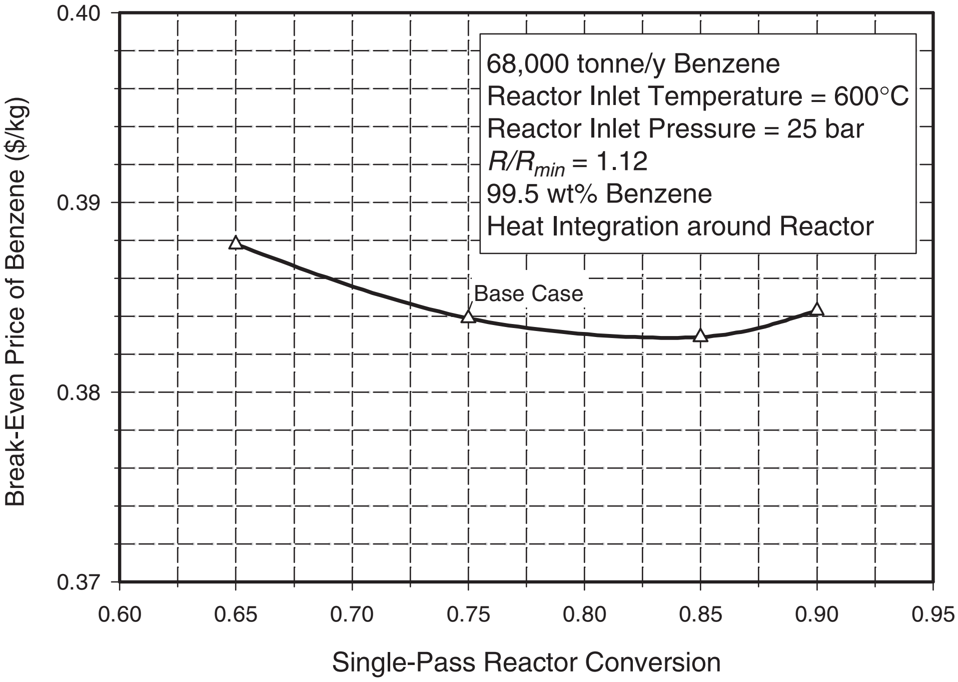


**Figure 4** The Effect of Single-Pass Conversion on Break-Even Selling Price of Benzene

**Table 5 Economic Impact of Single-Pass Reactor Conversion (Plus Heat Integration) on Process Economics (All *EAOC* cost figures in millions.)**

| **Cost Item** | ***EAOC* Base Case with Heat Integration Conversion = 0.75** | **EAOC Optimized Case with Heat Integration Conversion = 0.85** |
|---|---|---|
| Equipment | $ 0.718 | $ 0.675 |
| Steam | $ 0.269 | $ 0.243 |
| Fuel gas | $ 0.085 | $ 0.068 |
| Cooling water | $ 0.023 | $ 0.020 |
| Electricity | $ 0.038 | $ 0.035 |
| Toluene | $ 19.973 | $ 20.065 |
| Hydrogen | $ 1.605 | $ 1.605 |
| **Total** | **$ 22.711** | **$ 22.711** |
| Fuel gas (credit) | ($ 3.150) | ($ 3.161) |
| **Break-even price of benzene with conversion = 0.85 = $0.383/kg (toluene = $0.23/kg)**<br>Break-even costs include utilities, raw materials, maintenance, labor, fixed capital investment, etc. | | |
| **Price Differential = (0.383 − 0.230) = $0.153/kg** | | |

the optimum conversion are compared to the base case in Table 5. The increase in break-even price for conversions greater than 85% is attributed to an increase in the amount of benzene leaving in the fuel gas. The recovery of this "lost" benzene was not considered in the present analysis but is addressed below in the recommendations section.

## 5. Discussion

The results of the present study are summarized in Figure 5, where the results of the different case studies are compared. The minimum break-even price for benzene using the catalytic hydrodealkylation of toluene is $0.383/kg. The recommended process uses significant heat integration around the reactor, with a single-pass conversion in the reactor of 85%. For all cases considered, the ratio of hydrogen to toluene entering the reactor was maintained at 5.1:1 in order to suppress carbon formation. Finally, a reflux ratio of 1.12 times the minimum

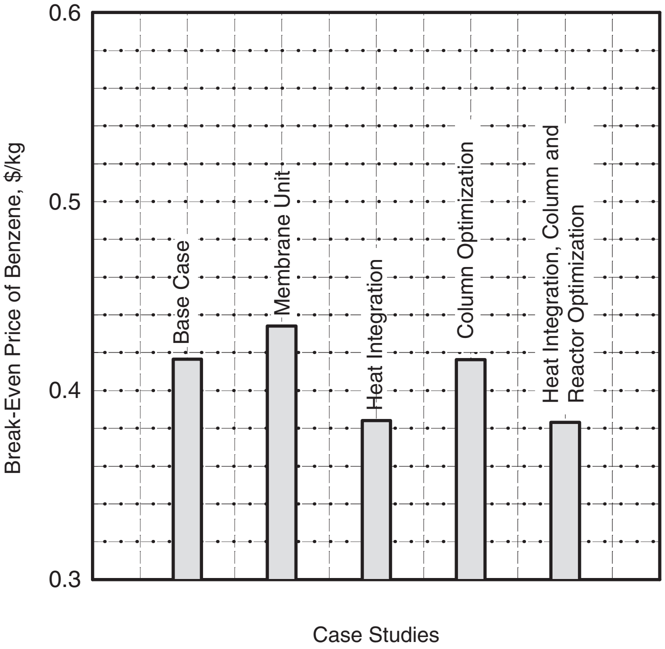


**Figure 5** Summary of Results for Process Optimization of Toluene HDA Process

value was used in the benzene tower, which was determined to be the optimum. The use of a membrane separation unit to purify the recycle hydrogen stream was not found to be economically attractive. The proposed process represents a significant improvement over the base case.

## 6. Conclusions

The optimum break-even price for benzene using this technology is estimated to be $0.383/kg. With toluene priced at $0.23/kg, this gives a break-even price differential of $0.153/kg. Significant improvements from the base case were made, including heat integration in the front end, column optimization, and increasing the single-pass reactor conversion. The addition of a membrane separation unit to purify the recycle gas stream was found not to be profitable. In summary, the production of benzene from the hydrodealkylation of toluene is not profitable at current market conditions. A significant increase in the price differential between benzene and toluene (>$0.16/kg) must occur before this process becomes economically feasible.

## 7. Recommendations for Future Work

The loss of benzene to the fuel gas for the improved process presented above represents approximately $640,000/yr in extra raw material (toluene) costs. Although appropriate fuel credit was given in this study, it is recommended that a further study be carried out to investigate methods for recovering this lost benzene. An example of one such method is the use of a pre-fractionator prior to T-101, instead of the two flash separations, to obtain a sharper separation between the noncondensables and benzene and toluene. The maximum potential benefit of this recovery is a reduction in the break-even cost of benzene of $0.012/kg; hence, this option should be considered.

The base-case operating conditions (temperature and pressure) of the reactor were used throughout this study. It is not expected that significant savings can be realized by altering these conditions since the reactor cost has very little impact on the overall break-even price of benzene.

## 8. References

1. Weiss, A. H., and L. Friedman, "Development of Houdry Detol Process," *Ind. Eng. Chem. Proc. Des. & Dev.* 2 (1963): 163–168.
2. Tarhan, M. O., *Catalytic Reactor Design* (New York: McGraw-Hill, 1983), p. 111.
3. Walas, S. M., *Chemical Process Equipment: Selection and Design* (Stoneham, MA: Butterworth, 1988), p. 29.

## 9. Appendix

- A.1 Calculations for Base-Case Economics
  - A.1.1 Material and energy balances
  - A.1.2 Capital cost estimation for equipment and utility cost estimations
  - A.1.3 Calculation of break-even price of benzene
- A.2 Calculations for Membrane Separation Unit
  - A.2.1 Material and energy balances
  - A.2.2 Capital cost estimation for equipment and utility cost estimations
  - A.2.3 Calculation of break-even price of benzene
- A.3 Calculations for Column Optimization
  - A.3.1 Material and energy balances
  - A.3.2 Capital cost estimation for equipment and utility cost estimations
  - A.3.3 Calculation of break-even price of benzene
- A.4 Calculations for Optimization of Conversion
  - A.4.1 Material and energy balances

A.4.2 Capital cost estimation for equipment and utility cost estimations
A.4.3 Calculation of break-even price of benzene

## 30.5 CHECKLIST OF COMMON MISTAKES AND ERRORS

The following checklist should be used before finalizing any presentation or report.

### 30.5.1 Common Mistakes for Visual Aids

1. When including columns of data in tables, the sum of the columns should be included and doubled-checked for correctness.
2. If numbers are included in a table but are not to be added, then care should be taken not to list these numbers in an unbroken vertical column. The natural tendency is for the reader to add the numbers, which may be inappropriate.
3. Either the number of decimal places or the number of significant figures should be the same for all numbers appearing in a table (or report).
4. Place figure numbers and captions below the figure, and table numbers and titles above the table.
5. A note regarding the units of the numbers appearing in a table should be included—for example, “All numbers are in $millions” or similar notation.
6. Pie charts should include the total value of the pie—for example, “The total fixed capital investment is $500,000.”
7. Avoid the use of redundant graphics. For example, a pie chart would be redundant if all the same information were included in a table.
8. When presenting comparisons between different cases in the form of multiple tables, make sure that the order of items appearing in these tables is the same for all tables. If the order is changed, then comparisons are made very difficult.
9. When plotting data in the form of a figure, make sure that enough data are plotted. An example of insufficient data is given in Figure 30.8, where the optimum $R/R_{min}$ value is almost certainly not at 1.50 as shown. Figure 30.9 shows a figure with an appropriate number of data points.
10. All figure and table numbers should be followed by a meaningful caption. Do not simply repeat the axis titles in the caption—for example, “A plot of $x$ vs. $y$.” An additional caption describing the figure, separate from the one with the figure number, should not be included.
11. Never use line graphs. Line graphs are graphs that use an arbitrary $x$-axis scale having equal spacing between consecutive data points. Figure 30.8 illustrates this type of graph. These graphs are very difficult to interpret and are often misleading.
12. Remember to place all landscape-oriented pages facing outward; rotate 90° counterclockwise.
13. Line up decimal points in columns of tables.
14. The same-size font should be used for axis labels and axis titles. The font size should also be the same for all of the figure and table titles and be the same as that in the main text of the report.

15. If case studies are used in the report, the identification should be consistent throughout the report. For example, in a report with many different case studies, Case 2 should not be referred to as Case B in a table and Case II in a figure.

### 30.5.2 Common Mistakes for Written Text

It is impossible to list all the errors that might appear in a written report. However, some of the more common mistakes are listed in this section.

**Memoranda (Memos)**

1. The list of people to copy in a reply memo should be the same as that used in the initiation memo.
2. Be careful to use the correct descriptive titles for attachments and memo subject. For example, for the cover memorandum in Figure 30.3, the subject should read "Evaluation of the Minimum Break-even Price Differential for Benzene and Toluene," and not "Benzene Production" as shown.
3. The significant results of the study or report should be briefly summarized in the memorandum. This enables the person reading it to quickly ascertain the major findings and prioritize the reading of the report (see Section 30.1).

**Main Body of Written Report**

1. An alternative to using first-person narrative is the passive voice. Some authors claim (insist) that first person (In this report, *I* present *my* findings of a study on . . .) is often clearer and more concise than the passive voice (In this report *the* findings of a study on . . . *are* presented). However, for the novice, a report written in the first person often sounds (reads) unprofessional(ly), and it is safer to stick with the passive voice.
2. When writing chemical reactions, name all ambiguous chemicals in the reactions. For example, the reaction of toluene to yield benzene should be written as

$$\underset{toluene}{C_7H_8} + H_2 \rightarrow \underset{benzene}{C_6H_6} + CH_4$$

3. Details of calculation methods and software used should not appear in the main body of the report but rather in the appendix. Software may be cited if specific information is used—for example, if the second virial coefficient for methylene chloride was obtained from the CHEMCAD databank.
4. Equation numbers should be included in parentheses and be right justified, level with the equation. For example:

$$COM_d = 0.180FCI + 2.73C_{OL} + 1.23(C_{UT} + C_{RM}) \qquad (1)$$

   In addition, the terms in the equation should always be defined either directly after the equation (which is preferred for written reports) or in a separate notation section at the back of the report (for books and technical papers).
5. The word *data* is plural: The optimization data *are* . . .

6. New results should not be included in the Conclusions section of a report. Such information should have already been included in a separate Discussion section.
7. Try to make specific recommendations that can be quantified. Avoid stating the obvious—for example, "Find cheaper utilities or raw materials." These statements do not improve the report writer's credibility with the reader. Unless one has specific ideas in mind, this type of wishful thinking is detrimental to the credibility of the report.
8. In the References section, only references cited in the report should be included.