1 INTRODUCTION TO PROCESS INTEGRATION

The process industries are among the most important manufacturing facilities. They span a wide range of industries including chemical, petroleum, gas, petrochemical, pharmaceutical, food, microelectronics, metal, textile, and forestry products. The performance of these industries is strongly dependent on their engineering and engineers. So, what are the primary responsibilities of process engineers in the process industries? Many process engineers would indicate that their role in the process industries is to design and operate industrial processes and make them work faster, better, cheaper, safer, and greener. All of these tasks lead to more competitive processes with desirable profit margins and market share. Specifically, these responsibilities may be expressed through the following specific objectives:

- Process innovation
- Profitability enhancement
- Yield improvement
- Capital-productivity increase
- Quality control, assurance, and enhancement
- Resource conservation
- Pollution prevention
- Safety
- Debottlenecking

These objectives are also closely related to the seven themes identified by Keller and Bryan (2000) as the key drivers for process-engineering research, development, and changes in the primary chemical process industries. These themes are:

- Reduction in raw-material cost
- Reduction in capital investment
- Reduction in energy use
- Increase in process flexibility and reduction in inventory
- Ever greater emphasis on process safety
- Increased attention to quality
- Better environmental performance

The question is how? What are the challenges, required methodologies, and enabling tools needed by engineers to carry out their responsibilities. In order to shed some light on these issues, let us consider the following motivating example.

1.1 GENERATING ALTERNATIVES FOR DEBOTTLENECKING AND WATER REDUCTION IN ACRYLONITRILE PROCESS

Consider the process shown in Figure 1-1a for the production of acrylonitrile (AN, C_3H_3N). The main reaction in the process involves the vapor phase

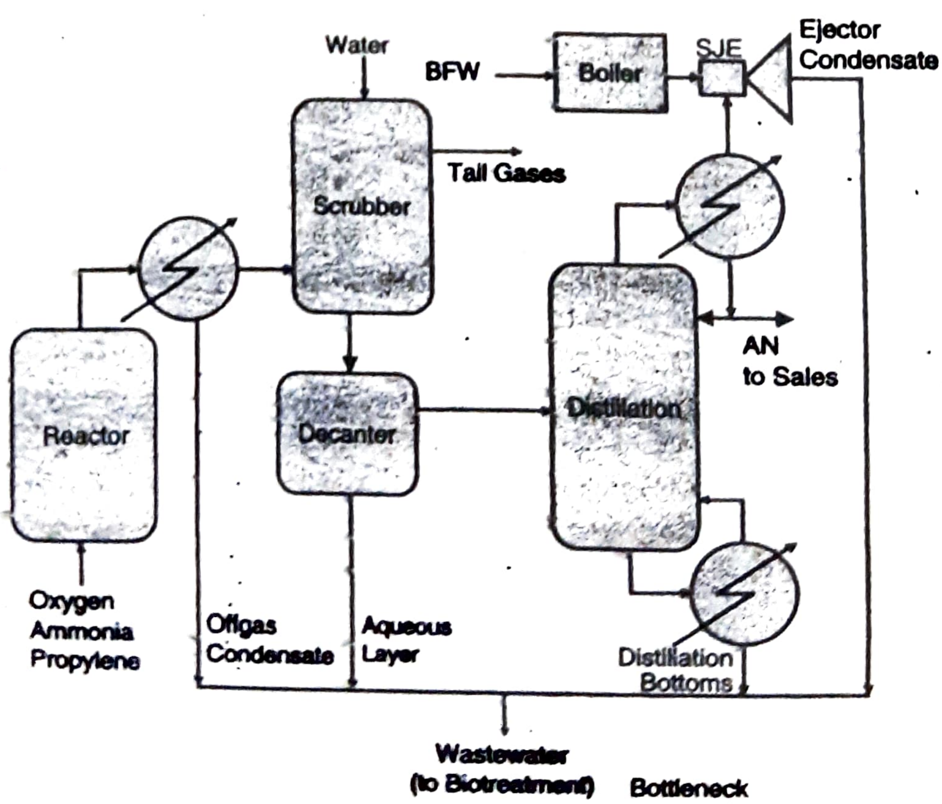


FIGURE 1-1a PROCESS FOR AN MANUFACTURE (EL-HALWAGI 1997)

catalytic reaction of propylene, ammonia, and oxygen at 450°C and 2 atm. To produce AN and water, i.e.

$$C_3H_6 + NH_3 + 1.5O_2 \xrightarrow{\text{catalyst}} C_3H_3N + 3H_2O$$

The reaction products are quenched in an indirect-contact cooler/condenser which condenses a portion of the reactor off-gas. The remaining off-gas is scrubbed with water, then decanted into an aqueous layer and an organic layer. The organic layer is fractionated in a distillation column under slight vacuum which is induced by a steam-jet ejector. Wastewater is collected from four process streams: off-gas condensate, aqueous layer of decanter, distillation bottoms, and jet-ejector condensate. The wastewater stream is fed to the biotreatment facility. At present, the biotreatment facility is operating at full hydraulic capacity and, consequently, it constitutes a bottleneck for the plant. The plant has a sold-out profitable product and wishes to expand. Our task is debottleneck the process.

The intuitive response to debottlenecking the process is to construct an expansion to the biotreatment facility (or install another one). This solution focuses on the symptom of the problem: the biotreatment is filling up, therefore we must expand its capacity. A legitimate question is whether there are other solutions, probably superior ones, that will address the problem by making in-plant process modifications as opposed to "end-of-pipe" solution? Invariably, the answer in this case and most other process design problems is "yes". If so, how do we determine the root causes of the problem (not just the symptoms) and how can we generate superior solutions? Where do we start and how to address the problem?

For now, let us start with a conventional engineering approach involving a brainstorming session among a group of process engineers who will generate a number of ideas and evaluate them. Since the objective is to debottleneck the biotreatment facility, then an effective approach may be based on reducing the influent wastewater flowrate into biotreatment. One way of reducing wastewater flowrate is to adopt a wastewater recycle strategy in which it is desired to recycle some (or all) of the wastewater to the process. For instance, let us recycle some of the wastewater to the distillation column (Figure 1-1b). After analyzing this solution, it does not seem to be effective. The fresh water to the process is still the same, water generated by the main AN-producing reaction is the same, and therefore the wastewater leaving the plant will remain the same. So, let us employ a recycle strategy that replaces fresh water with wastewater. This way, the fresh water into the process is reduced and, consequently, the wastewater leaving the process is reduced as well. One option is to recycle the wastewater to the scrubber (Figure 1-1c) assuming that it is feasible to process the wastewater in the scrubber without negatively impacting the process performance. In such cases, both fresh water and wastewater will be reduced. Alternatively, it may be possible to recycle the wastewater to the boiler (Figure 1-1d). Along the same lines, the wastewater may be recycled to both the scrubber and the boiler (Figure 1-1e).

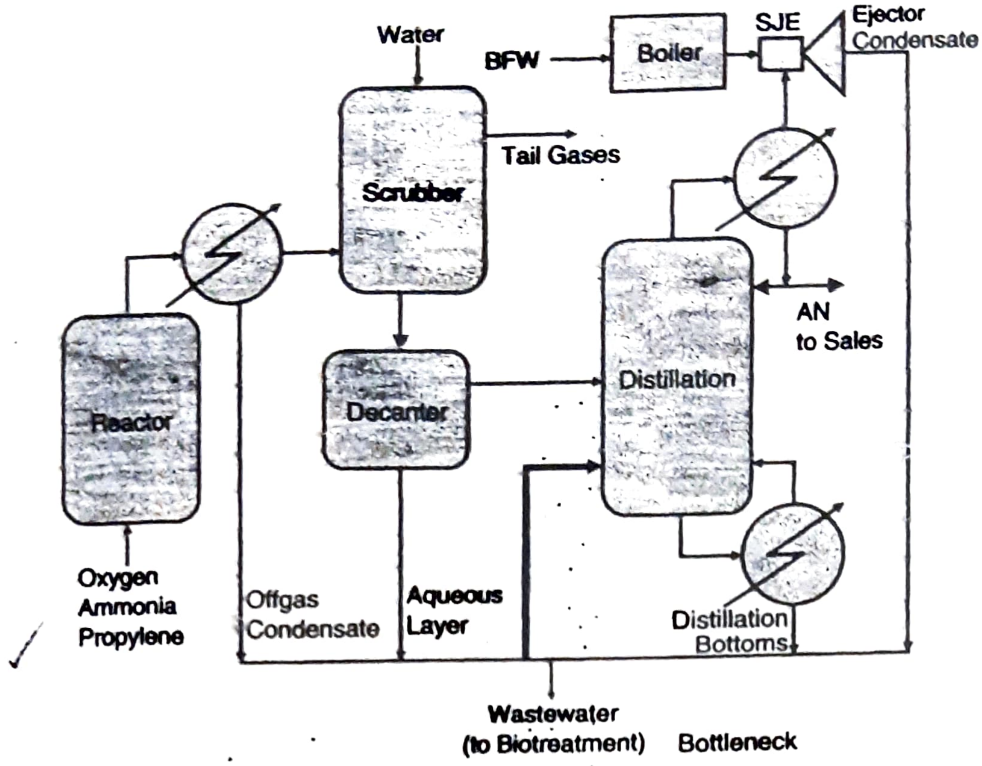


FIGURE 1-1b RECYCLE TO THE DISTILLATION COLUMN

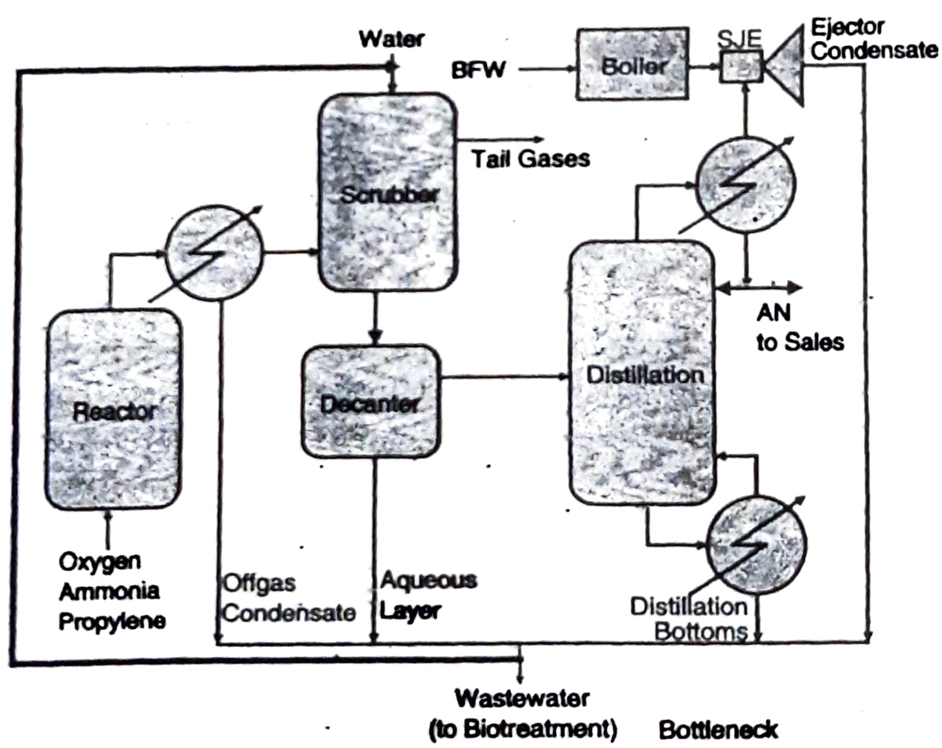
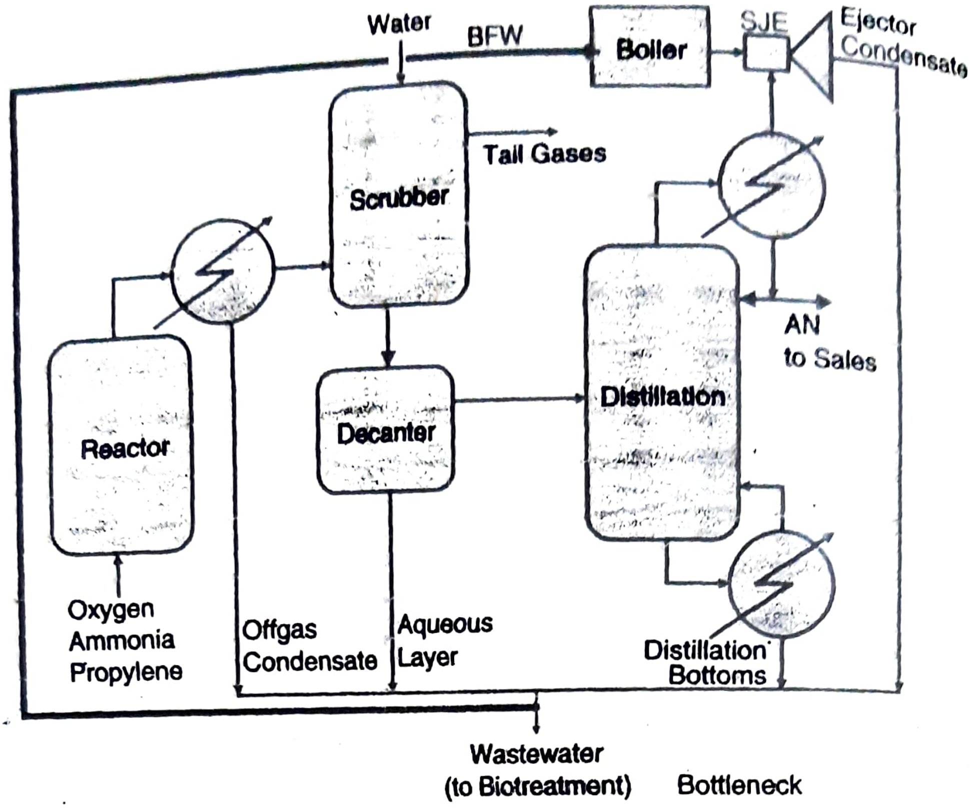
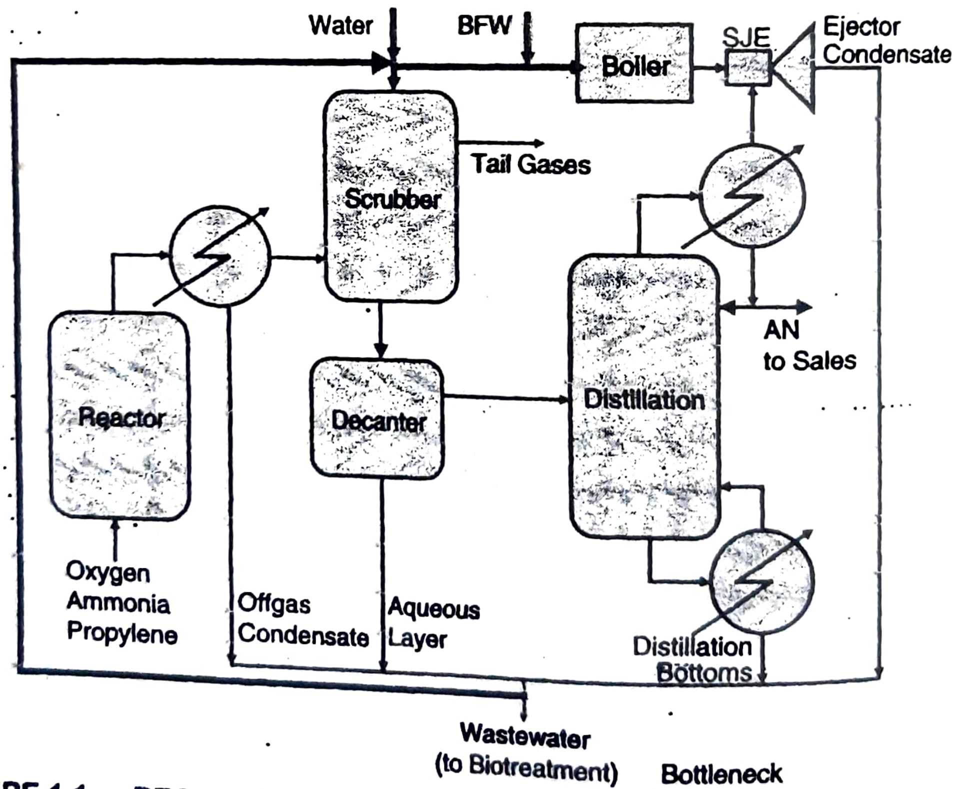


FIGURE 1-1c RECYCLE TO REPLACE SCRUBBER WATER

How should the wastewater be distributed between the two units? One can foresee many possibilities for distribution (50-50, 51-49, 60-40, 99-1, etc.). Another alternative is to consider segregating (avoiding the mixing of) the wastewater streams. Segregation would prevent some wastewater streams



[redacted] FIGURE 1-1d RECYCLE TO SUBSTITUTE BOILER FEED WATER



[redacted] FIGURE 1-1e RECYCLE TO BOTH SCRUBBER AND BOILER

from mixing with the more polluted streams, thereby enhancing their likelihood for recycle. For instance, the off-gas condensate and the decanter aqueous layer may be segregated from the two other wastewater streams and recycled to the scrubber and the boiler (Figure 1-1f). Clearly, there are many

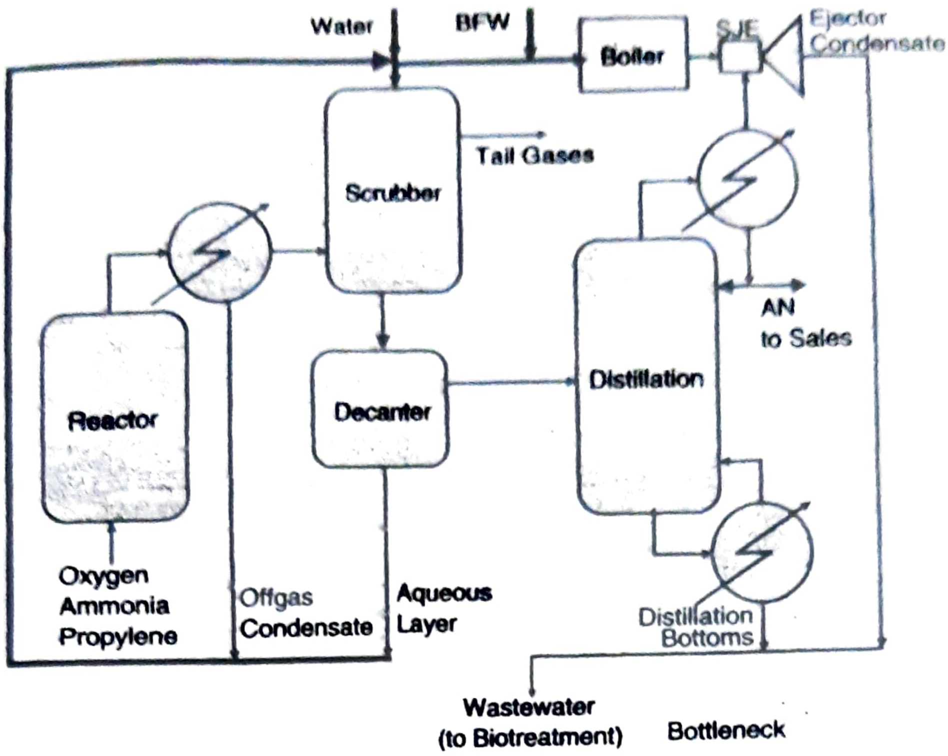


FIGURE 1-1f SEGREGATION OF WASTEWATER AND RECYCLE OF TWO SEGREGATED STREAMS

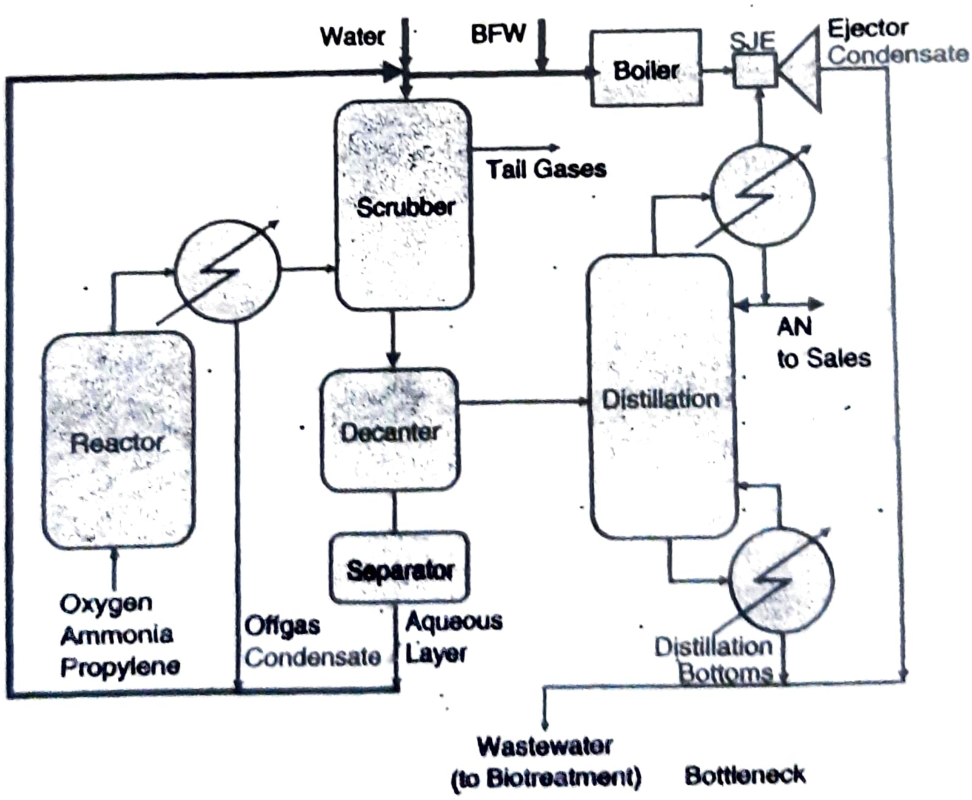


FIGURE 1-1g COMBINED SEPARATION AND RECYCLE

alternatives for segregation and recycle. In order to safeguard against the accumulation of impurities or the detrimental effects of replacing fresh water with waste streams, it may be necessary to consider the use of separation technologies to clean up the streams and render them in a condition acceptable for recycle. For example, a separator may be installed to treat the decanter wastewater (Figure 1-1g). But, what separation technologies

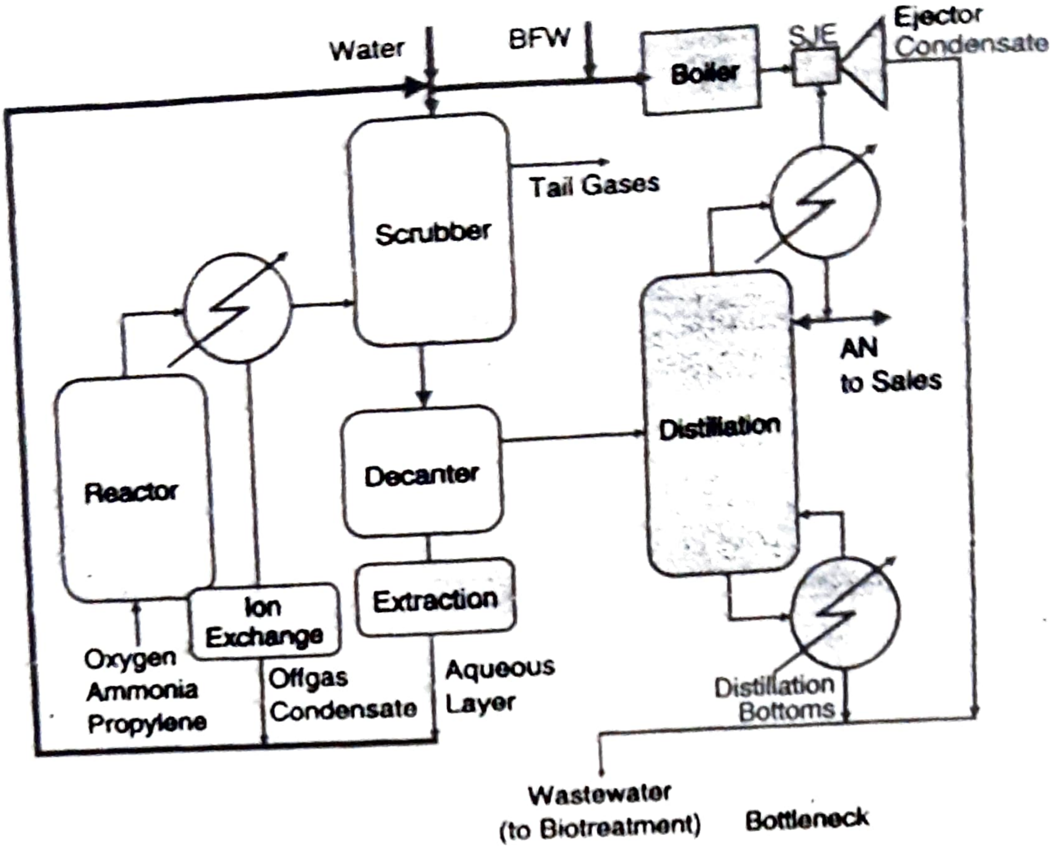


FIGURE 1-1h DEFINING SEPARATION TECHNOLOGIES

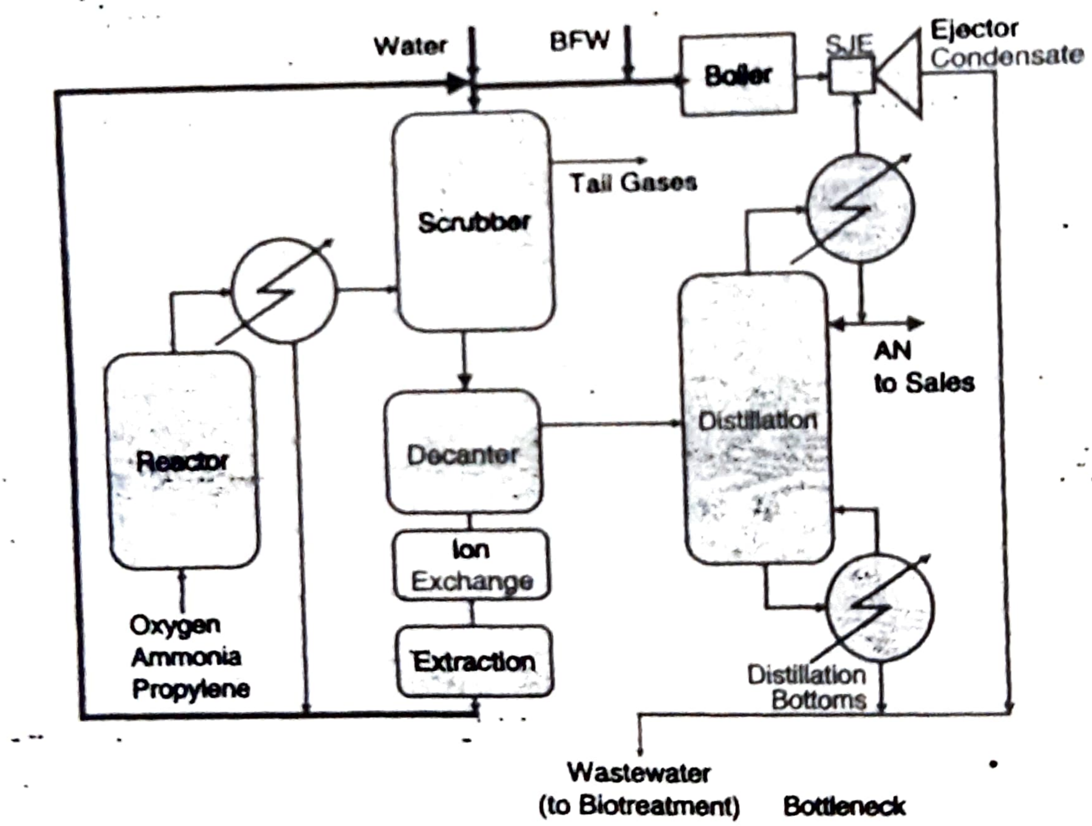


FIGURE 1-1i HYBRID SEPARATION TECHNOLOGIES FOR THE DECANTER WASTEWATER

should be used? To remove what? From which streams? Figures 1-1h–1-1j are just three possibilities (out of numerous alternatives) for the type and allocation of separation technologies. And so on! Clearly, there are *infinite number of alternatives* that can solve this problem. So many decisions have to be made on the rerouting of streams, the distribution of streams, the

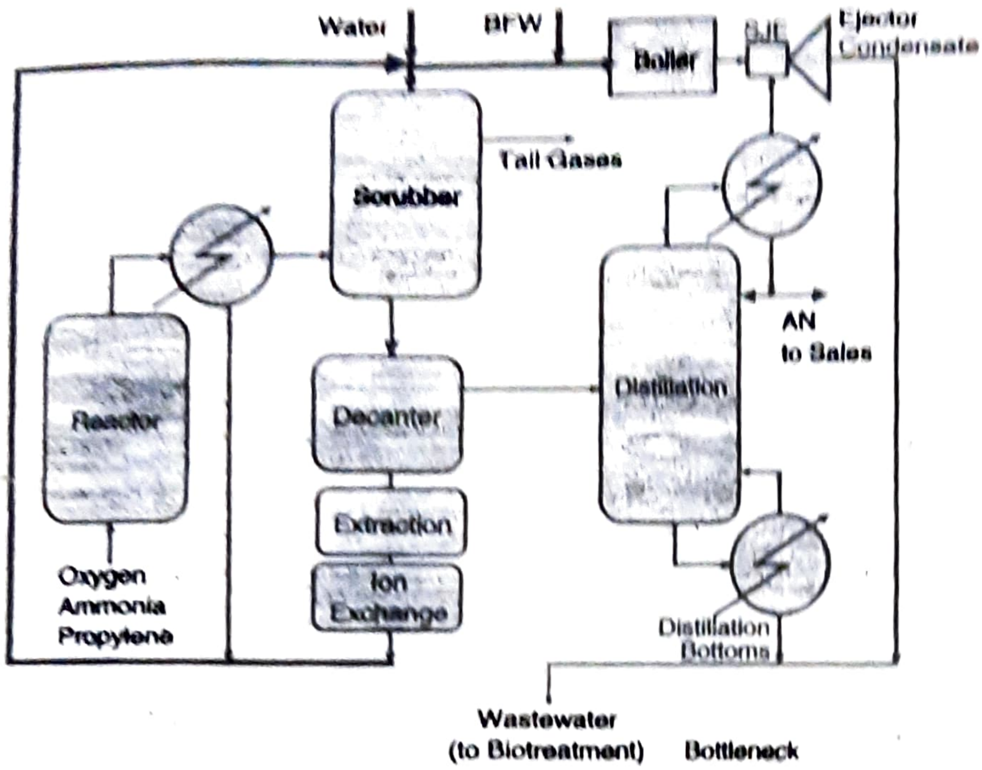


FIGURE 1-1j SWITCHING THE ORDER OF SEPARATION TECHNOLOGIES

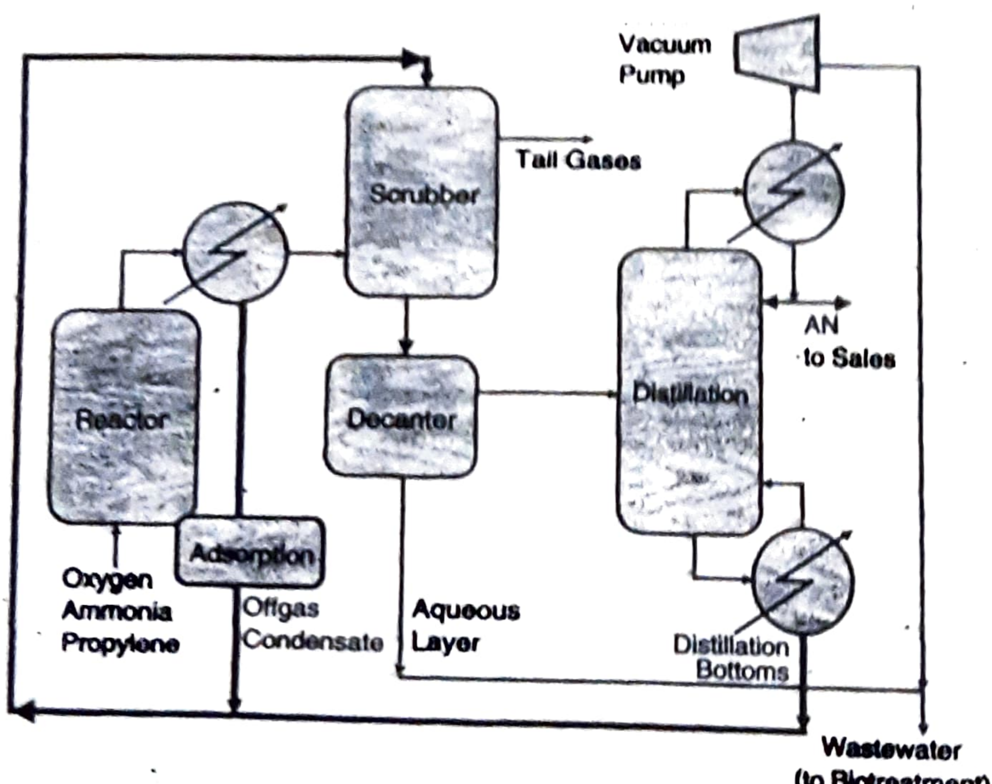


FIGURE 1-1k OPTIMAL SOLUTION TO AN CASE STUDY

changes to be made in the process (including design and operating variables), the substitution of materials and reaction pathways, and the replacement or addition of units. It is worth describing the optimum solution (in terms of cost) to this problem as shown in Figure 1-1k. The development of this solution is shown in detail in Chapter Five.

The following observations may be inferred from the foregoing discussion:

- There are typically numerous alternatives that can solve a typical challenging process improvement problem
- The optimum solution may not be intuitively obvious
- One should not focus on the symptoms of the process problems. Instead, one should identify the root causes of the process deficiencies
- It is necessary to understand and treat the process as an integrated system
- There is a critical need to systematically extract the optimum solution from among the numerous alternatives without enumeration.

1.2 TRADITIONAL APPROACHES TO PROCESS DEVELOPMENT AND IMPROVEMENT

Until recently, there have been three primary conventional engineering approaches to address process development and improving problems:

- Brainstorming and Solution through Scenarios: A select few of the engineers and scientists most familiar with the process work together to suggest and synthesize several conceptual design scenarios (typically three to five). For instance, the foregoing exercise of generating alternatives for the AN case study falls under this category. Each generated scenario is then assessed (e.g., through simulation, techno-economic analysis, etc.) to examine its feasibility and to evaluate some performance metrics (e.g., cost, safety, reliability, flexibility, operability, environmental impact, etc.). These metrics are used to rank the generated scenarios and to select a recommended solution. This recommended solution may be inaccurately referred to as the "optimum solution" when in fact it is only optimum out of the few generated alternatives. Indeed, it may be far away for the true optimum solution.
- Adopting/Evolving Earlier Designs: In this approach, a related problem that has been solved earlier is identified. The problem may be at the same plant or another plant. Then, its solution is either copied, adopted, or evolved to suit the problem at hand and to aid in the generation of a similar solution.
- Heuristics: Over the years, process engineers have discovered that certain design problems may be categorized into groups or regions each having a recommended way of solution. Heuristics is the application of experience-derived knowledge and rules of thumb to a certain class of problems. It is derived from the Greek word "heuriskein" which means "to discover". Heuristics

have been used extensively in industrial applications (e.g., Harmsen 2004).

Over the years, these approaches have provided valuable solutions to industrial problems and are commonly used. Notwithstanding the usefulness of these approaches in providing solutions that typically work, they have several serious limitations (Sikdar and El-Halwagi 2001):

- Cannot enumerate the infinite alternatives: Since these approaches are based on brainstorming few alternatives or evolving an existing design, the generated alternatives are limited.
- Is not guaranteed to come close to optimum solutions: Without the ability to extract the optimum from the infinite alternatives, these approaches may not provide effective solutions (except for very simple cases, extreme luck, or near-exhaustive effort). Just because a solution works and is affordable does not mean that it is a good solution. Additionally, when a solution is selected from few alternatives, it should not be called an optimum solution. It is only optimum with respect to the few generated alternatives.
- Time and money intensive: Since each generated alternative should be assessed (at least from a techno-economic perspective), there are significant efforts and expenses involved in generating and analyzing the enumerated solutions.
- Limited range of applicability: Heuristics and rules of thumb are most effective when the problem at hand is closely related to the class of problems and design region for which the rules have been derived. However, they must be used with extreme care. Even subtle differences from one process to another may render the design rules invalid.
- Does not shed light on global insights and key characteristics of the process: In addition to solving the problem, it is beneficial to understand the underlying phenomena, root causes of the problem, and insightful criteria of the process. Trial and error as well as heuristic rules rarely provide these aspects.
- Severely limits groundbreaking and novel ideas: If the generated solutions are derived from the last design that was implemented or based exclusively on the experience of similar projects, what will drive the "out-of-the-box" thinking that leads to process innovation.

These limitations can be eliminated if these three conventional approaches are incorporated within a systematic and integrative framework. The good news is that recent advances in process design have led to the development of systematic, fundamental, and generally applicable techniques can be learned and applied to overcome the aforementioned limitations and methodically address process-improvement problems. This is possible through *process integration and its vital elements of process synthesis and analysis*.