DESIGN DATA AND THE ROLE OF THE PILOT PLANT

W.L. Larcamp

Engineering Department

Union Carbide Chemicals Company

South Charleston, West Virginia

Engineering designs can be divided into two broad categories: (1) designs which will be mass-produced, and (2) designs which will not be mass-produced. Examples of the former type of design include airplanes, automobiles, television sets and even the proverbial mouse trap. These designs are intended to be mass-produced to provide many identical items. The approach to this type of design is to develop plans and specifications on paper, and then to construct a full scale model of the design prior to any manufacturing operations. This "sample" of the design is then subjected to many performance tests to determine if the design target specifications have been met. Based on these performance tests, the design can be modified as required before it is finalized and mass-production operations are begun. Although the research and development costs for a mass-produced article can be quite high, the success of the design itself is assured in advance of the full capital investment in production facilities, which is an important business factor.

Examples of designs which are not intended for mass-production of the design include chemical plants, power plants and even fixed structures, such as office buildings and bridges. This type of design can be called custom design and is characterized by the fact that a full-scale model is not feasible - the prototype and the final design are one and the same. The design, as an entity, must be committed long before it can be tested. From a business standpoint, this means that the full capital investment of such projects must be made in advance of a proven design. It is somewhat like "buying a pig in a poke". In certain fields of engineering - for example, structural engineering - this situation does not pose any real engineering risks. There is always a degree of personal suspense for any custom designer, but the architect or civil engineer rarely has any doubts about the engineering sufficiency of his design. This is true for several reasons:

1. The number of engineering variables is small, and the fundamental relationships among these variables are well established.
2. The properties of the building materials are known.
3. Each custom design is so similar to existing proven designs that past experience and engineering judgment can be fully utilized to compensate for any lack of theory or precise data.

The situation is far different for the chemical engineer engaged in process design. The number of variables involved in chemical reactions and chemical processing are many, the properties of the materials handled (particularly in mixtures) are not always well known or predictable, and the science of chemical engineering is still so young that many of the engineering fundamentals are not clearly understood. The chemical process designer thus approaches a design problem with these general technological limitations:

1. There is no practical opportunity to build a "sample" of the design to determine the sufficiency of the design in advance of its commitment.
2. There is frequently no assured way to "calculate" the design based on engineering fundamentals, either because the fundamental data are not available or because the engineering relationships are not known.

In order to minimize these technological risks, the process design engineer must have certain specific experimental data on which to base a process design. To a point, he can over-design to compensate for the unknowns and assure the target design performance. However, liberal over-design may result in a technical success and an economic failure, which in the chemical industry means the designer failed. That fact should always be understood and appreciated by the student, the educator and the practicing engineer. Research in glassware and bench-scale development studies provide considerable information about a process, but frequently do not provide sufficient data to allow reasonably certain extrapolation to large-scale facilities. The ultimate in experimentation to assure target performance is to imitate the designers of mass-produced article and build a model. However, economics dictate that this model must be a small-scale model because the design will not be mass-produced. The designers of mass-produced articles, such as airplanes, also resort to the use of scale models in some areas to save time and reduce development costs prior to building an expensive prototype for final tests.

The small-scale model employed by the chemical industry is called a pilot plant. A pilot plant is basically a miniature chemical processing unit, although it need not be a complete assembly of the entire process. Some of the steps of the process may be by-passed in a pilot plant design because they are well known and can be scaled up by classical methods. The primary role of the pilot plant is to supply data to permit the process design engineer to span the gap between bench-scale equipment and commercial processing facilities with reasonable assurance. The term, semi-works plant, usually denotes a complete miniature of a large-scale chemical process, which is used to actually process chemicals from the basic raw materials to the finished product or intermediate. Semi-works plants are nearly always operated as miniature production units (even though useful design data are collected) and tend to approach a prototype of a larger-scale plant.

ADVANTAGES OF PILOT PLANTS

Many benefits can be realized by utilizing a pilot plant in the development of a design for large-scale processing facilities. The obvious advantage is that an opportunity is provided to test a model of the process in advance of finalizing the design, in much the same way that models of mass-produced designs are tested. Of course, the pilot plant is a small-scale model, whereas the prototype of a mass-produced design is a full-scale model. Nevertheless, the pilot plant performance can serve as a useful preview of the commercial plant performance.

A pilot plant ideally should be "designed" in essentially the same manner as a large-scale plant is designed. The available bench-scale data should be analyzed and used as a basis for the pilot plant design. Whenever reaction mechanisms or other performance characteristics are unknown, they should be postulated from the bench-scale data and theory to help predict the pilot plant performance. This approach forces the early assumption of a mathematical model. After the pilot plant is built and operated, actual performance can be compared to the design performance. Any departures from the expected design performance of a pilot plant should be examined and explained; otherwise, the pilot plant data provides little more than empirical, pseudo-geometric scale-up factors. Analysis of pilot plant data can thus prove useful for establishing a true mathematical model of a process, which can be used to calculate the plant design. If the predicted performance of the pilot plant is realized, the original mathematical model assumed for the pilot plant design is confirmed. If not, the mathematical model must be adjusted to reconcile the bench-scale data and the pilot plant data (and still be consistent with theory). These objectives cannot always be realized in practice; nevertheless, the approach should always be attempted in order to obtain the maximum potential benefits from a pilot plant program.

It is often difficult to obtain consistent data on process efficiencies and losses from small, bench-scale equipment. In many cases, the overall economics of a chemical process are very sensitive to the useful efficiency of the raw materials, and the financial success of a project might depend on whether the plant efficiency will be, say 90 percent or 95 percent. The pilot plant serves to add a needed measure of precision to the material balances (and also heat balances) estimated for a large-scale process.

The pilot plant serves to alert the designer to many potential problems that might not be anticipated or seen in bench-scale laboratory equipment. The operation of a pilot plant with "real equipment" over many hours will uncover such things as fouling of heat exchangers or other equipment, the formation of residues, and the effect of minor contaminant build-up in the process. The instrumentation of a pilot plant often closely resembles that of a large-scale plant, and control problems can be recognized in advance of plant operation. All of these pilot plant general observations are helpful in establishing a successful final plant design.

A very important corrollary benefit of the pilot plant is in the area of corrosion. Pilot plants can, and in most cases should, be built of the same materials of construction being planned for the commercial plant. Whenever possible, specimens of other feasible materials of construction should be placed in the pilot plant equipment to determine corrosion resistance under simulated service conditions. Laboratory corrosion tests can frequently be misleading, as any metallurgist can attest. In some cases, it is advisable to construct identical parts of the pilot plant from two different materials, one believed to be a conservative material (and the most expensive) and one believed to be just adequate for the service. The wrong materials of construction can by equally as disastrous as a poor process scale-up. Conversely, the choice of ultra-conservative materials of construction represents a type of over-design that can erode the profitability of a process.

PITFALLS OF PILOT PLANTS

In order for the pilot plant to fulfill its objective of providing useful design data for the transition between bench-scale facilities and large-scale commercial facilities, the pilot plant should be designed at some reasonable intermediate scale. As a bare minimum, the pilot plant should be scaled an order of magnitude above bench-scale facilities, say a factor of 50-100. The exact factor depends on the plant scale-up and the nature of the process. In any event, the pilot plant is usually large enough that its erection cost alone represents a considerable expense. In addition, the operating costs are high. Most pilot plants are operated on a continuous basis, and operating labor must be provided around the clock. The design, operation, and analysis of results for a pilot plant involves several engineers and many more operating technicians for a period of one year or more. Thus, the total costs of "pilot planting" are quite high and considerable time is expended. These costs (both time and money) are expected to be recovered by a more economical plant design. However, because pilot plant costs are appreciable, there is a natural temptation to take shortcuts and minimize these development costs. The net result can lead to superficial pilot plants. Unless a pilot plant operation is carefully planned and executed to secure the maximum potential benefits to the ultimate plant design, it can lead to routine operation and token design data. A pilot plant should never be allowed to become a stereotyped phase of a process development program.

Some pilot plants are built for the development of products that are not characterized by specific chemical properties. For example, synthetic resins and fibers require such empirical properties as melt points, clarity, dyeability and "hand"- properties that result from processing techniques and that are not always related to chemical composition. These types of materials are not always amenable to production in bench-scale equipment and a pilot plant, or miniature plant, is required. Such a pilot plant is utilized primarily to produce materials or establish the necessary processing techniques. When the time comes to design large-scale processing facilities, it often comes as a rude shock that this type of "pilot plant" has not generated fundamental design data for scale-up. Careful planning and advance engineering studies are necessary to avoid this pitfall.

There is a tremendous financial incentive to quickly get a new product to market or a new process onstream. In order to compress timetables, design work on the commercial-scale facilities is sometimes started in advance of completion of the pilot plant work. If delays in the pilot plant program occur (as frequently happen for any experimental work), the plant design may be essentially complete and waiting for the pilot plant data for confirmation. When this happens, there is a great tendency to "prove the tentative design" and thus defer or by-pass the remainder of the fundamental design data. Such expedient action, while possibly justified by circumstances, dilutes the effectiveness of the pilot plant and eliminates the opportunity of exploring alternate process designs that might be more economical. Thus, a pitfall to be recognized in the early planning of pilot plants is the possibility that insufficient time will be available for completing the program, in which case the full potential benefits of the pilot plant program will not be realized.

Some modern chemical processes are extremely complex and, with the present state of chemical engineering technology, a pilot plant cannot be "designed" from the usual bench-scale data. In this case, it may also be unlikely that a large-scale plant can be "designed" from the pilot plant data. A rigorous approach to the development of these complex processes might require years of fundamental research studies in advance of pilot plant work. The total cost of such a program might well exceed the cost of a commercial-scale processing unit. Thus, there are some processes for which a speculative plant design is more economical than extensive research and development.

JUDGEMENT OF NEED FOR PILOT PLANTS

A minimum amount of specific experimental data must be available for any new process before a design engineer can prepare a realistic plant design. Such information as the effect of pressure, temperature, and contact time on the yield and efficiency of a chemical reaction are usually obtained during the preliminary research and development work in bench-scale equipment. Physical and thermodynamic properties are either available from the literature or can be determined experimentally on a small scale. This package of data is typical of that supplied in most design courses in chemical engineering curricula and does permit a basic process design to be calculated to some degree. The chemical industry must choose between two alternate approaches to chemical process design:

1. Utilize the data available from bench-scale studies alone and develop the plant design from chemical engineering fundamentals, judgement and past experience.
2. Obtain additional design data from an intermediate-scale pilot plant to better establish the factors affecting scale-up.

The former approach saves time and reduces process development costs, but the performance of the plant design is less predictable. The latter approach extends the time and costs of process development, but the performance of the plant design is more predictable. Neither approach, of course, will result in a certain design. There are no hard and fast rules to judge which approach is better, and every new process should be separately evaluated and analyzed to provide a basis for decision.

For some processes, an engineering evaluation will show clearly that a pilot plant program is not mandatory for a reasonably certain process scale-up. If the reaction mechanisms and rates are available or can be readily obtained in the laboratory (as for many slow homogeneous reactions), it is usually possible to calculate a process design from chemical engineering fundamentals. If the potential mechanical problems that might be encountered in large equipment are judged to be minor or solvable during a plant startup, the pilot plant can be safely eliminated. Even if equipment mechanical problems are anticipated, there is no assurance that a pilot plant program will provide solutions. Thus, a technological judgement alone may rule out the need for a pilot plant.

Unfortunately, many new processes today are complex and involve such steps as polymerizations, heterogeneous reactions and catalysis - areas in which the present state of technology is limited. It is virtually impossible to develop a mathematical model from laboratory data, and scale-up to commercial facilities is difficult to predict with assurance. Based on a technological judgement, a pilot plant may appear mandatory for a satisfactory design. However, there are other factors that are pertinent in the ultimate decision whether to build a pilot plant. The estimated economics of the overall project and the policy of the particular chemical company weigh heavily in this decision. One quantitative evaluation technique is to estimate the probable range of the economics of the project with and without pilot plant effort. Such economic analysis requires good engineering judgement, but it is usually possible to predict the optimistic and pessimistic project economics to a confidence level of, say 90 percent or better. These estimates, together with the sales potential of the project and the financial risks a particular chemical company is willing to assume, can be used as a basis for the decision whether to build a pilot plant.