PILOT PLANTS

1. Introduction

The design of a new plant or commercialization of a new chemical process represents a tremendous investment of time and money. The risk is considerable and the economic penalty, if the plant or process fails to produce as expected, is severe. To minimize such risks, companies often undertake lengthy and expensive process research and development programs, typically comprising the following activities: discovery or conceptualization of the process, basic laboratory research, preliminary economic evaluation, process development and engineering, pilot plant studies, scale-up to a demonstration or prototype unit, commercialization. The investment at each stage of the program increases exponentially, and pilot plant studies can be a crucial turning point in the program where the ultimate scalability and economic viability of a process are determined.

There is no single correct definition of a pilot plant. The term generally refers to a collection of equipment designed to allow operation of a novel process at a scale small enough to be safely manageable, but large enough to provide a realistic demonstration of operations and physical principles as they might apply in a commercial facility, and to allow the collection of meaningful engineering data for further scale up. The size and nature of pilot plants vary widely depending on their primary purpose and the type of process involved. Productivities may be measured in milligrams for a new biotech process at one end of the spectrum, up to many tons per day in a coal liquefaction demonstration plant. Sizes can thus range from bench-top units to installations approaching the size of some manufacturing plants. Equipment and operations will vary tremendously depending on whether the plant is designed for, say, the continuous production of a commodity chemical or the batch manufacture of pharmaceutical clinical supplies which must be produced under strict Good Manufacturing Practice (GMP) guidelines.

Pilot plants can provide important information on the best ways to handle reactants, intermediates, products, and waste streams, on energy transfer, on the best choice of separation technologies, and operating procedures. Indeed the benefits are manifold. Table 1 lists some of the many areas of process development in which a pilot plant can play an important role. Ultimately, the reason for pilot plant studies is to minimize the possibility of expensive errors in the design or operation of a commercial unit. Although operating a pilot plant cannot guarantee successful scale up, it can greatly reduce the chances of a complete failure.

2. Types of Pilot Plants

Pilot plants can be classified according to numerous criteria. First and foremost is the fundamental distinction between a pilot plant for a continuous process versus one for a batch or semibatch process. In the case of continuous processes, pilot plants tend to be single purpose, product-dedicated, and generally smaller in size, although this is not universally true. Continuous processes typically require more design data and detailed engineering to correctly scale up, but are well suited to the scale up of exothermic reactions or extreme operating conditions. Batch pilot plants, typical of the fine chemical industry, eg, tend to be multipurpose, and the requisite flexibility to handle a wide variety of products and processes can add considerably to the complexity and cost of the plant. Some *fully integrated* pilot plants are designed to demonstrate the feasibility of an entire process, others to test one specific unit operation. The experimental goals of the program and the nature of the data to be gathered will significantly influence plant design.

3. Design Philosophy

General or multipurpose pilot plants, if well designed, can offer wide flexibility, and can serve as good long-term research tools for investigating poorly understood processes or those at early stages of development. Their higher cost may be justified by their utility and longevity, but they can also be more difficult to design, especially if they are expected to handle processes operated under widely varying conditions. As one can imagine, designers must strike a balance between making a pilot plant applicable to a wide range of situations and risking making it ideally suited to none. The basic goals of the program must be kept clearly in view.

Fully integrated pilot plants, which include all systems and unit operations found in a commercial facility, can be costly indeed, but it is often not necessary to demonstrate all unit operations in a process. In many cases, it is more economical to focus on the key areas of uncertainty for pilot studies. Thus a pilot plant may consist of only a few discontinuous process steps. Such plants can usually be built more quickly and less expensively and may also provide more definitive data for the unit operations for which they were designed by better duplicating the commercial operation. However, their narrow operating range may mean shorter lifetimes and limited utility for studying other types of processes. In certain operations, such as solids handling, little is gained from demonstration at an intermediate pilot scale. In such cases, a short-term full-scale study at an existing facility or at a vendor's site may prove more valuable. Some well-characterized subsystems, heat exchangers, eg, can be scaled up based on fundamental design principles without demonstration on an intermediate scale.

The design approach will also differ radically depending on whether the plant is for process modeling or problem investigation. Modeling the process involves reproducing the specific unit operations on a smaller scale. This provides an opportunity to reproduce all operations of interest, minimizes design time, and promotes safe scale up. In problem investigation, the plant is geared to investigate a specific area of interest. In this case, the pilot plant may not resemble the commercial operation at all. Although usually cheaper and quicker, this approach carries the potential risk of missing the real problem and producing little useful data. The advantages and disadvantages of the various approaches have been addressed elsewhere (1–4).

It is unlikely that any one single pilot plant can meet all of the needs of both accurate process simulation and specific problem solving. An alternative is multiunit pilot plants with multiple reactor trains that offer widely different functionalities. These can often take advantage of the economies of shared utilities and infrastructure, but again, the more purposes a plant is designed to serve, the more complex it will be, the more costly and the more difficult to operate.

4. Pilot Plant Size and Cost

Pilot plants are often categorized into several common sizes:
Lab-scale bench-top units (or microunits) can fit on a bench or in an exhaust hood. They are usually heavily instrumented and automated, and can be valuable research tools. Despite their small size (0.1−1-L operating volumes) they can easily cost up to $250,000.
Development scale (kilo-lab) pilot plants are often skid-mounted units or units occupying a small building or open bay of ~10 m^2. They may cost anywhere from $250,000 to 2 MM depending on existing infrastructure.
Demonstration or prototype units (semiworks) often approach the size of small production plants and can range in cost from $2 to 20 MM and beyond.
Full-fledged multipurpose batch pilot plants in the fine chemical industry, with all utilities and infrastructure and reactor vessels up to 10,000L can easily exceed $100 MM for a greenfield facility.

5. Scale Up

Scale up is the act of transferring a laboratory process to the larger equipment typical of a commercial plant, or designing a piece of commercial equipment based on research scale models. This is often a complex matter in which, for some processes, trial-and-error still has a significant foothold. Even with careful planning and strict methodology, scale up can be fraught with difficulty and unexpected problems. The reasons for this are numerous: many common laboratory methods cannot be applied at the large scale, equipment may exhibit unexpected behavior at sizes never used before, or critical heat or mass transfer phenomena may not be discernible at laboratory scale. For example, heating and cooling times can be orders of magnitude greater at large scale, laboratory mixing intensity can often not be duplicated at scale, and reaction selectivity often takes an unexpected turn for the worse, especially for batch and semibatch processes.

Another commonly used term is scale down, another name for process modeling. Here the designer starts with the full-scale unit in mind, and designs a small test apparatus using scale factors or the principles of geometric, dynamic, or kinetic similarity in an effort to mimic full-scale performance or operating conditions in the model. Designers may attempt to hold any one of a number of critical parameters constant, such as residence time, area per unit volume or dimensionless group equivalence, in the scale-down exercise. Many discussions of scale-up problems and solutions and the use of similarity relationships and scale ratios are available (5−17).

While it is typical to scale up a process or design to an intermediate-sized pilot plant before committing resources to full-scale production, it may be possible to skip this piloting step and safely scale up based on laboratory thermodynamic and kinetic data alone, especially in the case of certain types of continuous gas-phase catalytic systems. For example, American Oil's ultracracking unit in Texas City, Texas was designed based on data from a small pilot plant with a scale-up factor of 80,000 (6). However, it is often not wise or even possible to make such a large jump in scale, particularly in the case of batch operations where macroscopic phenomena such as large-scale mixing and heat transfer can distort the contribution of chemical kinetics to reaction selectivity and process safety. The uncertainty is even greater in batch heterogeneous systems.

Another often underestimated consequence of batch scale up is that operations generally take much longer in the pilot plant than at the bench. This can have many unforeseen consequences for product yield and quality, especially for complex molecules with limited stability at the specified reaction conditions.

The scale up from laboratory to pilot plant usually involves the single largest jump in scale that a fledgling process may experience. But as is so often the case in process development, aggressive timelines and marketplace competition may necessitate commercializing a process before it is thoroughly understood or all design concerns have been addressed. Sometimes it may be more expeditious in the long run to perform the pilot plant experiments, rather than take the time to elucidate a detailed reaction mechanism and construct the theoretical models. Often a combination of the two approaches is applied.

Finally, scale up should never be undertaken without a full understanding of the reaction thermochemistry, including calorimetric studies quantifying reaction exotherm, and identifying any autocatalytic or otherwise exothermic decomposition reactions. Again this is especially true in batch or semibatch reactions, where the ability to control runaway reactions at scale is severely hampered, and where reactor contents can represent a substantial inventory of potentially hazardous materials.

6. Justification for the Pilot-Plant Program

The need to conduct pilot-plant experimental studies is often a measure of the degree of uncertainty in new process development. A minor modification of a well-known process may go directly from basic research to the design of a commercial plant; using this approach for a brand new process risks a significant failure. Hence, one or more intermediate sized units are usually desirable to demonstrate process feasibility and determine safe scale-up factors.

An often implicit role of the pilot plant is to increase management confidence in the ultimate scalability of a process before investing in full-scale production. Ultimately, the decision of whether or not to perform pilot studies is based on many, often competing, factors: the degree of understanding of the reaction chemistry, including side reactions; the similarity to known commercialized processes; the need for lead quantities of materials for process development or product research; and the degree of risk deemed acceptable. In the grand scheme of process development, pilot-plant studies will likely not be the most costly item. The basic research phase is usually by far the most time consuming, and in the case of a new pharmaceutical product, eg, the hundreds of millions of dollars spent on the requisite clinical trials alone can easily dwarf the investment for short-term pilot studies. This is particularly true if an existing pilot facility is available. Nonetheless, pilot plants can consume expensive raw materials at a surprising rate, and the cost of trained labor, technical support and waste disposal can be substantial. And although manufacturing might not routinely be carried out in the pilot plant, it must often still comply with all local, state and federal regulations as strictly as a commercial plant.

Because of the high cost of a new pilot plant, financial justification in terms of return-on-investment alone is not likely possible. But when market pressures force a commitment to the construction of a full-scale plant before all process issues have been resolved, it may still be wise to construct the pilot plant in parallel. The pilot plant will often be completed in 6–18 months, possibly years before the commercial plant is in operation, and can still provide the opportunity to head off mistakes before the commercial unit comes on line. In such cases, a sound experimental plan, rapid data evaluation and good communication between pilot researchers and plant designers are critical to take maximum advantage of the pilot site. Pilot plant experience can also result in smoother start up and more economical operation of the commercial facility.

Finally, although successful pilot-plant operation considerably increases the chances of successful scale up to manufacture, risks are always present, and even with pilot-plant data in hand the step to commercial scale remains one of the most precarious phases of process development because the greatest resources must be committed at a stage when the greatest risks exist.

7. Pilot-Plant Design and Construction

Conventional commercial scale design techniques can be used for pilot-plant design. This usually provides for a safe and operable design using known, proven methods, but the approach is not always ideal or suitable. The proposed scale of the pilot plant may fall outside the range of commercial design techniques, or the resulting design may not be efficient at the scale envisioned. For example, copying a commercial design may limit pilot-plant operating ranges or conditions, which often need to be broader and more flexible than in the commercial plant. Thus design techniques should be customized as much as possible to suit the specialized needs of process research. It is also unwise to strictly impose production plant standards on pilot-plant design, since often the smaller scale allows equally safe, yet less expensive alternatives (18). Since little published design data may be available for pilot-scale equipment, the success of the final design is very dependent on the skill level and experience of the design engineer.

Although all operating ranges may not yet be fully defined, realistic preliminary ranges are required before the design work begins, as is a clear definition of the pilot-plant's purpose. The design should thus be based on as complete an engineering evaluation as possible, using lab data and fundamental principles to size equipment or propose specific technologies.

As with any program, goals must be clearly defined before undertaking an experimental program or designing and constructing a pilot plant. Likewise, the greater the degree of understanding of the process, the more clearly the engineering details of the pilot plant can be specified, resulting in a lower cost and reducing the need for expensive last minute modifications. Jumping into pilot-plant studies without the proper planning costs much more and results in an overall slower rate of progress.

Management must further decide whether to design and construct in house or hire an outside contractor. In-house has obvious labor cost and project management advantages, but such a project requires skilled and experienced personnel with expertise in not only plant construction but familiarity with local codes and regulations. A growing number of companies can provide turn-key modular systems, ranging in size from laboratory test units to full-scale pilot plants, or just the engineering and design services. The option to rent space in an existing facility might also be considered. Many contract manufacturers offer this service. This may shorten lead times and minimize start-up costs, as long as appropriate space is available, but the potential loss of some control over proprietary technology should be kept in mind.

8. Pilot-Plant Control Requirements

Pilot plants are often much more heavily instrumented than commercial facilities, due to the need to collect process data for scale up that is not routinely collected in a manufacturing environment. As a result, pilot-plant instrumentation and automated control systems can represent a significant portion of the initial construction costs. Today, increasing process complexity, the need for more detailed data, and the wider availability of smaller, more user-friendly computerized control systems suitable for pilot-plant application, are driving the trend for increased levels of automation in pilot plants. Virtually all new pilot-plant installations are including some sort of computer-based control or data-logging system (see Process control).

Defining the control requirements for new pilot plants is often difficult because of the unique and rapidly changing nature of pilot-plant work and the specialized instrumentation that may sometimes be needed on a short-term basis. There is often no commercial model of the process upon which to base the control scheme, and the plant is often being designed by personnel with expertise in areas other than instrumentation and control. The plethora of options in terms of software platforms, communication protocols, and proprietary technology further complicate the control design process. Designers must avoid the pitfall of trying to measure virtually everything possible, making the plant much more costly than necessary.

Process data generally consists of temperature, pressure, level, and flow measurements, but may include much more specialized information such as on-line reaction kinetics, particle size distribution, etc. Such on-line analytical methods are evolving rapidly, and although more expensive initially, they offer a number of advantages over manual sampling and off-line analysis including rapid response rate, limited worker exposure, and the option for interactive process control. Not only primary variables (temperature, etc), but secondary variables, such as reaction conversion, can be used for process control (19). Further information on some of the more common instrumentation is available (1,20).

Control systems generally fall into two main types: centralized control networks of simple, usually analogue, field instruments wired to a single PC or programmable logic controller (PLC), and distributed control systems (DCS), in which small localized controllers or digital field instruments with on-board "intelligence" or control capability are deployed throughout the plant. These local controllers then communicate with a central controller or computer. The DCS systems are generally more expensive and require a higher knowledge base for setup and maintenance than centralized PLC-based systems, but they offer more flexibility and a much higher level of functionality, such as field data manipulation and remote calibration. Such capability is more appropriate for large-scale commercial installations, and may not be required in a small pilot plant. Note that the traditional distinction between centralized and distributed control networks is being very blurred by recent hybrid designs and proprietary packages and platforms. One important trend in controls is the increased use of digital wireless field sensors and other devices. Often the cost of wiring an instrumentation network, especially in hazardous environments, is the single largest line item in the controls budget.

Whatever approach is used, it is important that the selected control system be flexible enough meet the rapidly changing operational and data-acquisition needs of the plant. Ease of troubleshooting, reliability, the availability and cost of spare parts and provision of I/O slots for future expansion are important considerations, as is the significant expense of maintaining and periodically calibrating of these advanced instruments. Further information on the different systems including a more detailed discussion of their costs, advantages, and disadvantages (1,21,22) and their actual use (23–28) are available.

9. Safety in Pilot-Plant Design and Operation

Pilot plants are often more hazardous than process plants, even though they may be smaller in size, for a number of reasons. These include the need for wide latitude in operating conditions, the frequent modifications required of experimental work, lack of experience with and information about novel materials, technologies, or chemistries, short-term operation of specific processes, limited automatic safety interlocks, the lack of extensive preventive maintenance programs, and a tendency to relax standard safety review procedures because of the small-scale and aggressive project timelines.

To minimize these concerns, most organizations require a formal series of safety reviews and hazard assessments for each new or modified process or pilot plant. At a minimum, this involves analyzing a proposed pilot plant before construction to identify and eliminate any potential hazards, including toxicity or flammability concerns, feed or product handling, disposal problems, relevant government regulations, and potentially harmful reactions. Such reviews, eg, Hazards and Operability (Haz-Op) studies, should ideally be conducted for all phases of pilot-plant work, including plant decommissioning. Safety review protocols vary considerably between organizations, and have been covered extensively elsewhere (1,21,22).

Pilot plants should be designed so that control and safety systems are "fail-safe" and any unexpected equipment or utility failure brings the unit to a safe and deenergized condition. Unexpected or rapid process changes, if they can herald or lead to dangerous conditions (eg, runaway exothermic reactions), should be monitored by appropriate instrumentation and suitable automatic response (1,29). However, these types of controls alone are not sufficient and must be combined with a comprehensive safety program, including safe operating procedures, contingency plans, safety and response training and safety inspections to afford the greatest protection to personnel and property. Better still, incorporating the principles of inherently safe plant design, error-proof equipment, and green chemistry into the plant or process can go a long way toward hazard prevention. Prevention is ultimately much more economical and effective than engineering hazards controls (39–41).

10. Estimating Construction Costs

There are three principle methods for estimating the costs of designing and constructing a pilot plant:

1. *Similarity* involves estimating the cost of the pilot plant based on the design and construction of a similar unit. This is the fastest method, but it is the least accurate; errors of ±100% are not uncommon due to the fact that few similar units are ever identical, and that the increase in equipment cost with scale is by no means linear.
2. *Cost ratios* develop the estimate by relating the overall cost of the pilot plant or part of the plant to known factors such as the cost of major process equipment, the number of control loops, or the size of the equipment. The cost estimate is built up by using such ratios to develop the cost of individual equipment, separate subsystems, or the entire unit. Unfortunately, cost ratio information is frequently not available for pilot-plant scale equipment and the accuracy of what is available may be suspect. This method usually requires more effort than the method of similarity, but depending on the type of cost ratios used and the experience of those making the estimate, accuracies of ±25–50% can be achieved. Cost ratios can be used more accurately if they are restricted to small subsystems where more applicable information may be available.
3. *Detailed labor and material* estimates involve breaking the pilot-plant construction project down into a detailed series of small tasks and estimating the labor and materials required for each separate task. This method can produce estimates with accuracies of ±10–20% but requires more effort than either of the previous methods. Where a general cost ratio estimate might develop the total cost for, say, the pilot-plant control system from the number of control loops, a detailed labor and material estimate is based on the cost per loop and on the specific type of loop. The total estimate is the sum of a large number of similar estimates (1,42–45) (see Table 2).

In general, similarity or general cost ratio estimates are used when an estimate is required quickly and limited accuracy is acceptable. Detailed cost ratios or detailed labor and materials estimates are generally developed prior to actual appropriation of funds to develop a better estimate for budgeting and cost control purposes. Needless to say, it is important to use the best available economic models of the process when planning the plant design or program.

11. Operating Costs

Pilot-plant operating costs include those of the feedstock, waste disposal, utilities, operating labor, spare parts, maintenance, and support services. Efforts to reduce operating costs have focused on reducing operating labor through automation and unattended operation and controlling waste disposal costs through careful design and planning (1,46,47). Do not neglect startup costs, including the costs of training, environmental permitting, analytical support, engineering and maintenance costs, and the significant expense of plant or process validation in GMP environments. Also, do not fail to account for the lead time and budget for jury rigged or specialized equipment setups, or customization of standard equipment.

12. Pilot-Plant Space Requirements

In general, pilot-plant space can be divided into five basic types: separate buildings, containment cells or barricades, open bays, walk-in hoods, laboratory areas. The advantages and disadvantages of each has been discussed (1). A small unit may require only part of a laboratory, whereas a typical demonstration or multipurpose batch pilot plant may require a large room or building (perhaps 500–2000 m^2), excluding extended feed or product storage. It is important to account for control room space, as well as space for labs, storage, mechanical rooms, utilities, and maintenance shop. It is also wise to leave some versatile free space for installation of novel equipment or for future expansion.

13. Project Timeline

A major concern in all pilot-plant work is minimizing the time between project inception and the generation of meaningful data. A small plant costing <\$1 MM may require from 6 to 18 months to complete this process: 2–8 months for design, materials procurement, and scheduling; 2–6 months for construction; and 1–4 months for start up (up to and including the first actual run). This lead time can be reduced significantly through careful planning, purchasing long lead time items early, and various construction techniques (18,48). Lead times for major pieces of equipment can be 6 months to 1 year or longer. Design time can be reduced if standardized designs have been developed in advance for common subsystems. Construction can begin on certain subsystems before the final design is complete. The pilot plant can be built one subsection at a time, starting up each subsection as it is completed. Both approaches reduce the lead time but with an added element of risk.

14. Feed, Product, and Effluent Handling

One of the most vexing aspects of pilot-plant work can be feed and product handling. The practicalities of storing and transferring process materials are likely to be quite different than envisioned, and can easily rival the pilot-plant's process problems in difficulty. For solids, dust control systems and other engineering controls may be necessary. Specialized weighing or transport systems may be required, especially for highly toxic substances where operator exposure must be minimized. Such matters must of course be considered early in the design stage. Frequently, no MSDS or other safety data is available for novel or proprietary substances, especially isolated process intermediates, and toxicity testing may be required.

Sufficient storage for both feeds and products must be provided and the storage system should be designed to minimize operator handling time. Sufficient surge time must be available at both ends of the process to minimize the need for close operator attention. Level alarms and cut-offs should be considered for all product vessels that could overflow and for all feed vessels that could be emptied. Vented substances may require scrubbing, neutralization, or incineration to conform to environmental codes. Emergency venting must be adequately sized, selected, installed, and directed. If the plant is an electrically classified area, all equipment must be rated accordingly, and atmospheric vapor concentrations must be monitored and controlled. Products or intermediates that are easily oxidized or subject to contamination by atmospheric moisture, etc, must be handled in closed, inerted systems, adding to the difficulty and complexity and increasing handling time. Finally, proper waste disposal requires an understanding of the hazardous nature of waste streams, their potential instabilities, possible decomposition reactions, and environmental impact.

15. Planning the Experimental Program

Experimental planning should begin as soon as the research program objectives are formulated because the type of experimental program affects the type of pilot plant required, and the way the plant needs to operate, and thus the overall program cost and its economic justification. Early planning may help reduce the number of tests required, a key factor in controlling annual operating costs, which can be two to three times the initial construction cost. Early planning may also highlight the need for more laboratory work to support the pilot plant operation and may indicate the need for plant design changes or show that a pilot plant is not the best place to obtain some of the desired information. The required accuracy of analyzers and instruments must of course also be tailored to the experimental needs.

Techniques such as statistical design of experiments (DOE) can maximize information gathering and reduce research time and costs. Such techniques are less likely to miss synergistic factors affecting performance or product quality, minimize the element of human bias, eliminate less productive avenues of experimentation by taking advantage of previous data, and reduce the number of pilot-plant runs needed to understand the effects of variables. Overall, statistical designs increase the confidence level in the experimental results (49–52) (see DESIGN OF EXPERIMENTS).

It is critical to ensure that clear channels exist to communicate deficiencies in the pilot experimental program to the development team so that the necessary process modifications can be incorporated, especially when the pilot work is being performed by an outside firm. It is equally important to have a clear definition of the endpoint for the investigations and the criteria for success. The primary purpose and goals must be kept in mind throughout to prevent the research program from taking on a life of its own. Unfortunately, the need for expediency sometimes outweighs the call for sound engineering and safe practice; this must be resisted as much as possible for the long-term success and viability of the program.

16. Pilot-Plant Start Up

Pilot-plant start up can differ from that of a commercial plant because of the smaller scale of the unit, the fewer resources committed, and limited experience with the pilot-plant process and operation. Nonetheless, pilot plants still have to be staffed with trained operators, engineers and maintenance personnel, QC support staff, and time must be allotted for prestart-up tests such as equipment IQ/OQ. Plans must be made for troubleshooting and contingencies.

Here again, early planning will enable identification of problem areas and concerns in time for successful resolution prior to start up. Preparation of operating manuals and operator training should take place concurrently with the final stages of plant construction. Many companies have found that a specialized start-up group is a primary asset if pilot-plant work is performed on a regular basis. A detailed start-up sequence should be developed listing each task to be performed in chronological order (1). The start-up sequence then allows the development of a list of required resources and a tentative start-up schedule. Safety is also a significant concern during start-up because interlock systems may not be fully functional and equipment and subsystems are being energized for the first time.

Pilot-plant start-up costs and commissioning costs vary widely, from 5 to 50% of construction cost, although 10–20% is more typical. Start-up duration also varies, but a range of 1–3 months is common depending on personnel training and expertise.

17. Future Trends

Bench-top automated units or micro units will continue to play a major role in process development due to their lower construction and operating costs. Conversely, demonstration and prototype units may become rarer, although the operation of batch plants of the 500–2000-gal size range in the specialty chemical industries will remain an indispensable part of process development. Marketplace competition will drive the need for accelerated design and construction: the ability to develop new units quickly as the need arises will become even more important. Modular, turn-key systems will become increasingly available, and consulting groups with expertise in these areas will grow, offering their services to small and large companies alike. Established companies may find they need to develop and maintain specialized groups proficient in design, start up, and pilot-plant operations or increasingly rely on outsourcing to the above mentioned experts.

The safety aspects of pilot-plant construction and operation will continue to improve driven by stricter regulation, an increased awareness of potential hazards, advances in instrumentation and on-line analytical methods and more interest in inherently safe plant design and process intensification. This will also require specialized skills and training at all levels.

Many new pilot plants will be computer controlled and all will be increasingly automated due to the high cost of operating labor, the need for high accuracy and repeatability, and the ease of data collection and manipulation. Standalone computer and programmable logic controller systems will continue to dominate the market because of their low cost and ease of use.

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Francis X. McConville
FXM Engineering & Design

Table 1. **Some of the Many Purposes Served by Pilot Plants in Process Development**

performing basic process research
confirming operational feasibility of a new process
identifying previously unrecognized scale-up effects on selectivity and yield
collecting reaction kinetics or engineering design data
more accurately estimating process economics
testing materials of construction
demonstrating a novel technology
testing the operability of a control scheme
generating material for clinical and market research, safety studies or process development
assessing process hazards and determining safe scale-up factors
identifying the best ways of dealing with feed or effluent streams
examining the use of commercial scale raw materials or alternative feedstocks
testing process recycle steams
process troubleshooting or optimization
completing an accurate mass and/or energy balance
training operators and technology transfer personnel
developing a comprehensive, detailed operating procedure for eventual manufacture
providing technical services to research groups

Table 2. **Methods of Estimating New Pilot Plant Costs**

Method error range, %	Information required	Time to develop, weeks
similarity (±50–100%)	cost of similar unit differences from proposed unit	<1
general cost ratios (±25–50%)	all scaling elements (control loops, size, or similar factors)	1–2
detailed cost ratios (±15–30%)	detailed P&ID complete equipment list preliminary layout	2–4
detailed labor and materials (±10–20%)	detailed P&ID preliminary electrical and instrumentation drawings complete equipment and materials list preliminary layout	4–12