# Accelerating Process and Product Development

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**These simple strategies can be used to speed up and increase the success rates of R&D projects**

Research and development (R&D) projects usually require significant time, effort and manpower to become successful. Despite the significant resources spent on R&D projects, only 5–10% of the projects are statistically believed to be successfully commercialized, in terms of both timing and technological advances. Many projects fail because they cannot achieve the desired results on timing of commercialization and licensing.

This article is focused on providing systematic strategies to speed up both technical and non-technical aspects of R&D projects — especially new process development. It addresses certain aspects that have not been mentioned in previous technical references [*1–5*], such as basing R&D project management on manpower resource characteristics. It also presents strategies to speed up process development projects visually in a diagram (Figure 1) that is easy to follow and use.

## OVERVIEW

### Types of R&D projects

Research and Development projects can generally be classified into the four types listed below [*1*]:

- Basic research
- New application research
- New product development — In this article, new products are limited to those that are an intrinsic part of new process development, such as new catalysts and solvents
- New process development — As mentioned above, this can sometimes incorporate new products, such as catalysts and solvents. New process development is the focus of this article

Basic research and new-application R&D generally require less time and manpower, and involve a smaller group of people than do the development of new products and processes. This is because the goal of basic research is to develop fundamental knowledge that might be applicable for further development and commercialization in the future, and new application research focuses only on finding and developing new applications for existing products and processes, thus allowing much of the existing knowledge on existing products and processes to be utilized.

The most time-consuming part of R&D is often new process and product development on pilot and commercial scales. Accelerating new process and product development gives earlier and higher overall project-life benefits (Figure 2).

New process development often involves development of new products such as new catalysts, solvents and chemicals to be used in the new process. Thus, we define the scope of this article to also include development of new products that are an intrinsic part of the new process development, though not final products per se.

For example, a new butadiene extractive distillation process development requires the development of a new butadiene extraction solvent, but the solvent is not a final product of this process. Later in the article, we will refer to our new products as new catalysts and solvents (C&S) to avoid confusion.

### Typical development steps

New product and new process development typically include the following steps toward commercialization. Figure 1 shows a flow chart visualizing all steps and strategies to speed up development projects during each step.

***1. Laboratory-scale new product (C&S) development and validation.*** Consider using special tools to speed up screening of C&S; Consider outsourced laboratory-scale product development and validation, or sublicensing of C&S from outside sources

***2. Conceptual design of the envisioned commercial process.*** Utilize available laboratory data from the developed C&S to conceptualize a desired commercial process. Involve chemical process engineers early at this stage

***3. Pilot and commercial scale product (C&S) manufacturing.*** Consider outsourced manufacturing of the developed C&S

***4. Pilot-plant process development and basic design.*** Use a pilot plant as a scale-down of the envisioned commercial plant — the primary objective is to collect sufficient data for scaleup. Also, consider skipping pilot plants

***5. Pilot-plant detailed design and construction.*** Consider outsourcing pilot-plant design and construction

***6. Pilot-plant process validation.*** Involve not only engineers but also researchers directly. Consider outsourcing pilot plant validation

***7. Commercial-process development and basic design.*** Scaleup from to a commercial plant based on data from the pilot plant, and re-check scaleup issues

***8. Commercial-process detailed design and construction.*** Consider outsourcing commercial-process design and construction.

***9. Commercial process demonstration and validation.*** Con-

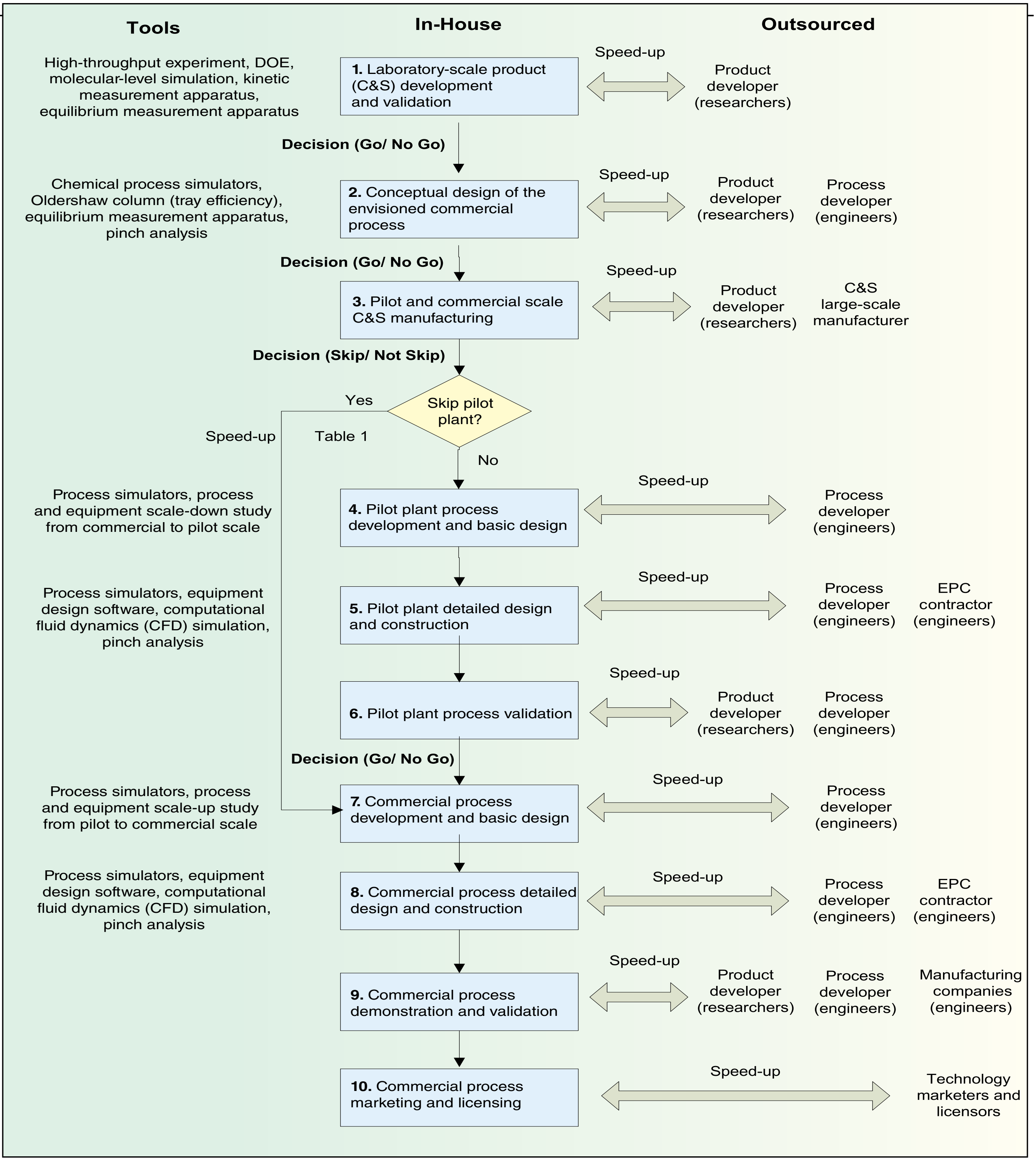


**FIGURE 1. Strategies to speed up process development projects are presented visually in this diagram**

sider a partnership with manufacturing companies

***10. Commercial process marketing and licensing.*** Consider outsourcing process marketing and licensing

## STRATEGIES

Systematic strategies are required in all stages of process development to speed up a project. The most important thing is to always begin with the end by having the desired commercial process concept in mind. Project goals and objectives should be clarified from the beginning. After conceptualizing the commercial process, tactics to speed up the project in each stage can then be defined clearly. Effective and strategic use of both in-house and external resources are key to success. Before spending your own resources on something you are unfamiliar with in product and process development, always consider an option to outsource some parts of a project to a qualified third party.

Four simple strategies can be used to speed up and increase the success rates of projects. These steps include the following:

A. Assess your project goals
B. Assess your manpower resource characteristics
C. Assess your new process and identify key issues
D. Plan your acceleration strategies early with the end in mind

These four strategies are explained in the following sections.

### Assess your project goals

In order to speed up your project, it is necessary to make the final goals of the project clear to the team. In general, there are three kinds of project goals:

***Product development.*** The goal of research can be purely to develop new promising C&S that might have the potential to be further developed into a commercial process. For example, a propane dehydrogenation catalyst was developed by one company and sub-licensed to another company to develop a new process that could use the developed catalyst successfully under various constraints, such as catalyst deactivation concerns and on-line regeneration requirements and so on.

The benefits in this situation are then shared between the new C&S and new process developers. A major advantage of this approach is reduced time to commercialization because the R&D scope is reduced.

However, disadvantages of this approach include reduced benefits to the C&S developer and increased risks associated with a potentially unqualified process developer, and difficult know-how management and transfer between the two parties.

There are more complicated cases where the catalyst developers on a laboratory-scale and catalyst manufacturers on a commercial-scale belong to different companies. The pilot-plant developer and commercial-process developer can also be members of different companies. In all of these cases, the most important thing is to make it clear from the beginning of a project which parties are to be involved in the commercialization of this process so that resources can be allocated to the project appropriately.

***Process development.*** The goal of research can also be purely to develop a new process without developing new C&S. It may be a new process configuration and concept improvement without new C&S, or a new process that utilizes new C&S developed by another party.

For instance, let's say a process development company purchases a license to use a new propane dehydrogenation catalyst from another company, and develops a new process based on that catalyst. The process developer can become a technology licensor and license out the new process under its own tradename, but clients need to buy the new catalyst either directly from the catalyst manufacturer or via the technology licensor. The benefits are then shared between the new C&S and new process developers. Advantages and disadvantages are similar to those mentioned above.

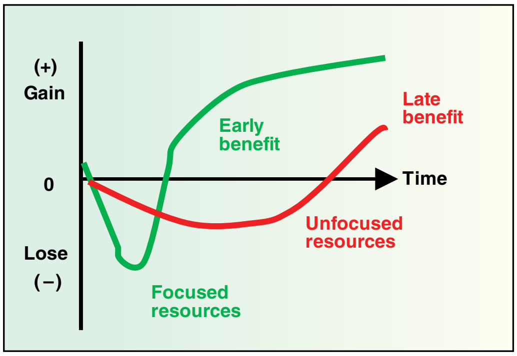


**FIGURE 2. This graphical presentation demonstrates that accelerating new process and product development gives earlier and higher project-life benefits**

***Combined product and process development.*** A single project can combine both new C&S and new process development. For instance, a company may develop a new catalyst at laboratory scale and then go further in developing its own proprietary process to use the newly developed catalyst.

Major advantages of this approach are maximized benefits from licensing and commercializing the process. Disadvantages are significantly more time and manpower resources required, and more risks involved in the commercialization if that company lacks expertise in either new C&S or new process development. There are few companies really competent in both C&S and process development at the same time. Research institutes, universities and some chemical companies are more specialized in new C&S development, whereas technology licensing companies tend to be more specialized in new process development.

### Assess manpower resources

It is of great importance to assess manpower resource characteristics when selecting a project goal to be pursued. Let your project economics help guide manpower resource deployment (increase and adjust manpower to accelerate high-impact projects).

***Is the majority comprised of researchers or engineers?*** If researchers form the majority, it is possible to speed up projects by focusing on new C&S development. Researchers are good at developing new C&S at laboratory scale, but tend to lack know-how on how to commercialize them.

If engineers form the majority, it is possible to speed up projects by focusing on new process development.

***Is the majority comprised of chemists or chemical engineers?*** If the majority is chemical engineers, it is possible to speed up projects by focusing on new process development because chemical engineers are good at conceptualizing a process scheme to commercialize the developed C&S, while they may lack the strong chemistry background required to develop innovative and unique C&S.

On the other hand, chemists are good at developing new C&S because they understand the chemistry and mechanisms involved very well, but are often weak at process commercialization and scaleup.

It is thus imperative to have a well-balanced team of chemists and chemical engineers, depending on the project goals. Conversely, it is important to make project goals clear from the beginning in order to effectively allocate resources to the project.

***Integrated project team for process development.*** For combined product and process development, it is important to have an integrated team of researchers and engineers, chemists and chemical engineers.

To speed up a project, it should be

| TABLE 1. GUIDELINE FOR A DECISION TO SKIP PILOT PLANTS | | |
|---|---|---|
| **Unit Operation** | **Can pilot plants be skipped?** | **Comments** |
| Distillation | Usually yes, but pilot plants are sometimes needed to get tray efficiency or height equivalent to a theoretical plate (HETP) data | Sometimes required for making product samples to customers. Foaming should be checked when skipping pilot plants |
| Fluid flow | Usually yes for single phase. Frequently no for multiphase flow and polymer systems | Some polymer flow properties are very difficult to predict, especially viscosity versus temperature |
| Heat exchangers, evaporators, reboilers, condensers | Usually yes, unless there is a possibility of fouling, coking and polymerization | Sometimes required for new unconventional types of heat exchangers only |
| Reactors | Frequently yes for simple types of reactors, such as batch, continuous stirred-tank reactors (CSTR) and fixed-bed plug-flow reactors (PFR) | Scaleup from laboratory sometimes justified for homogeneous or single-phase heterogeneous heat-neutral reactions |
| Dryers | Frequently no. Should pilot in equipment of a similar type to the commercial plant | Usually vendor equipment |
| Extraction | Frequently no. Should pilot in equipment of a similar type to the commercial plant | Usually vendor equipment |
| Crystallization | Frequently no. Should pilot in equipment of a similar type to the commercial plant | Usually vendor equipment |
| Solids handling | Frequently no | Usually vendor equipment |
| Hybrid separation-reaction (such as reactive and extractive distillation) | Almost always no | Usually proprietary equipment |
| Processes with impurities and recycle streams | Sometimes no, if undesired impurities can accumulate due to process recycles, or if unable to check effects at laboratory scale | Pilot plant should be designed to incorporate effects of impurities and recycle streams |

made clear from the beginning of a project what parties are required for process development. For example, if a qualified, outsourced pilot-plant contractor is to be used, it is not necessary to develop an integrated team of engineers in-house, and only process engineers may suffice. However, if a pilot plant is to be designed and built essentially by an in-house engineering team, it is often necessary to have various engineering disciplines in-house, such as instrumentation engineers and mechanical engineers.

Forming a strategic alliance with complementary partners is a key to speeding up process development projects. Understanding the strengths and weaknesses of an existing project team is indispensable to creating a successful partnership to speed up a project significantly. The only drawbacks are fewer shared benefits and the extra risk of ineffective collaboration.

## Assess the process

Understanding reactions and phenomena involved during process development is a key, not only to the project's success, but also to speeding up process development.

***Reactions — Single phase or multiphase; homogeneous or heterogeneous; reaction mechanism.*** Simple reactions in simple reactor types can significantly reduce the time required for process development. For example, a single-phase reaction in a fixed-bed reactor can be much more confidently scaled up than a multiphase reaction in a moving-bed reactor.

Reactions that may allow skipping certain steps — such as pilot plant validation — are those that take place in a single or homogeneous phase, those with high selectivity and consequently few byproducts, those with a simple reaction mechanism and those that are relatively heat neutral (Table 1). Ref. 6 provides useful insights on how to scale up a fixed-bed reactor directly from laboratory to commercial scale by verifying reaction-rate-limiting steps from laboratory experiments and use those data for scaleup.

However, this method neglects effects of heat transfer and is thus not applicable to highly endothermic or exothermic reactions. Ref. 7 provides guidelines in judging whether to scale up batch processes directly from laboratory to plant scale.

Reactions that frequently require pilot plant validation are those that involve complex multiple or heterogeneous phases (for example, an air-bubbling reactor), and have many side reactions (for example, thermal cracking), complex mechanisms, and significant exothermicity or endothermicity (such as in dehydrogenation). These reactions often dictate the need for kinetic studies and detailed reactor modeling. Reactions that involve multiphase operation, such as bubble-column and fluidized-bed reactors, often require pilot plant validation to collect sufficient data for scaleup to a commercial process.

***Separations — single phase or multiphase.*** Chemical processes generally require numerous separations to purify the final products. Most separation operations separate desired products based on equilibrium conditions. Thus, accurate thermodynamic-equilibrium data are necessary for scaling up the separation operations correctly and confidently.

Some conventional separation operations, such as distillation, allow skipping pilot plant validation. Vapor-liquid equilibrium (VLE) and tray efficiency data can be obtained from laboratory scale experiments, and heat-and-material balance models can be developed from those laboratory data. The number of trays, reflux rates, and vapor-liquid loading for tray hydraulics calculations can be obtained from the models and used to scale up.

However, other separation operations, such as extraction, drying, crystallization, solids handling and most hybrid operations (such as reactive distillation) almost always require pilot plants unless well-proven vendor equipment for a similar service is used (Table 1).

One of the most powerful concepts in separation design is the residue curve. This curve describes the equilibrium relationships for ternary mixtures and the change of the liquid residue composition in a one-stage batch distillation of the mixture. Multiple curves for a single system, called residue curve maps, provide a rapid, graphical means to visualize separation possibilities and constraints of azeotropic ternary systems. To accelerate process development, it is helpful to have an expert on the residue curve who can conceptually design the separation operations.

***Combined reactions and separations.*** It is wise to consider reactions and separations together, since total investment and operating costs (termed "combined costs") are the sum of total costs from both reaction and separation sections. Separately optimizing reaction and separation sections tends to lead to suboptimal solutions. For example, increasing reactor size and energy consumption to achieve higher conversion and thus higher purity of desired products can sometimes significantly reduce combined costs of the downstream separation section [*2*].

***Heat transfer — single phase or multiphase.*** Heat transfer is one of the most common unit operations in both reactions and separations. Conventional heat-transfer-equipment design (for example evaporators, reboilers and condensers) is usually well understood, thereby allowing pilot plant validation to be skipped. For example, shell-and-tube heat exchangers and double-pipe heat exchangers are well understood, and only thermodynamic and properties data are needed to design and scale them up. Commercial software, such as that from Heat Transfer Research Inc. (HTRI) called HTRI Xchanger Suite, is also rigorous enough to design them confidently.

However, unconventional types of heat transfer equipment often require pilot plant validation for the first unit of its kind. For example, a heat transfer operation that involves simultaneous mass transfer (for example, an ethylene-plant quench oil tower), unconventional types of heat exchangers, and unfamiliar multiphase flow regimes frequently require a pilot plant to collect data for commercial scaleup.

***Materials transfer — fluids or solids; single-phase or multiphase.*** In general, solids handling and transfer are more problematic than fluids transport. In contrast to fluids, which are typically transferred through pipelines with pumps or blowers, solids are carried or pushed along by various kinds of conveyer equipment. Solids in granular form are also transported as slurries in inert liquids, or as suspensions in air (pneumatic conveying) or another gas.

Multiphase transfer poses more challenges than single-phase transfer. In multiphase flow, it is typically desirable to design a flow regime to be annular and avoid a slug-flow regime. Unit operations involving solid and multiphase transport tend to require pilot plant validation due to their complexity. During the conceptual design stage of a commercial process, the type of materials transfer to be used in the process should be addressed.

***Safety.*** Safety aspects must be considered in as early a stage as possible, even before the Hazop (hazard and operability) review. Failure to do so may result in project delays.

For example, a hydrocracking process requires special high-pressure and high-temperature safety considerations, such as breech-lock type heat exchangers, and emergency reactor quenching and depressuring because of highly exothermic hydrogenation reactions taking place at high pressure and temperature (up to 200 barg and over 400°C). Low-density polyethylene (LDPE) plants operate the polymerization reactor at 2,500 barg pressure or more, thus requiring a special concrete enclosure built around the LDPE reactor.

***Environmental.*** One of the most common mistakes is to ignore environmental aspects of a project in an early stage. Byproducts from a reaction are potential wastes that need treatment and disposal. Effluent waste streams should be considered at an early stage of a project. An environmental impact assessment (EIA) process can significantly delay projects when process developers fail to foresee or predict environmental impacts before they are addressed by the EIA approval committee. Thus, considering environmental aspects of both pilot and commercial plants as early as possible in a project can speed up a project and avoid unnecessary delays.

***Metallurgy.*** Special metallurgy requirements can sometimes delay process development projects. Inappropriate specification of the materials of construction from the beginning can later increase project costs and even invalidate the process design. For example, special metallurgy (such as specific grades of stainless steels and alloys) often requires particular welding procedures and expertise that may make it too expensive or difficult to find a fabricator locally.

Over-specifying materials of construction can also make a promising process seem economically infeasible. It is thus recommended to have a metallurgy consultant either in-house or outsourced to consult on metallurgy issues.

***Additional potential issues in process development.*** Other potential issues that may need to be considered are mentioned here:
- Unclear or unachievable product specifications
- Sophisticated process control strategies
- Lack of process simulation capability
- Lack of key physical properties
- Identification of "black boxes" or unknowns
- High pressure and temperature systems
- Sophisticated mechanical design

## Plan strategies early

Companies that plan acceleration strategies early with the end in mind have greater chances of success. Early planning allows one to foresee potential problems along the way toward process commercialization more clearly, and it allows one to utilize internal and external resources more effectively.

***Laboratory-scale new product (C&S) development and validation.*** To speed up new C&S development, two major tools are recommended: high-throughput screening and design-of-experiments (DOE). When it is inevitable to investigate various combinations of catalysts (such as catalytic element types, compositions or morphology) to screen and select for further testing, high-throughput screening is an efficient tool to help. Although the accuracy of how closely the high-throughput screening apparatus simulates the real commercial reactor conditions may be arguable, the technique nevertheless provides useful preliminary comparisons for different compositions and formulas of catalysts.

DOE is another tool to speed up new C&S development because it provides a systematic method to minimize the number of experiments needed to obtain the same results with the same level of confidence and coverage that one might obtain from many more experiments without using DOE. Not all researchers need to be specialized in DOE, but it is helpful to have someone who is knowledgeable about DOE and can advise researchers how to design experiments efficiently. In addition, smart use of other tools, such as computer molecular simulation and commercial kinetic-measurement apparatus can also help accelerate the process development.

Another way to speed up new C&S development is by outsourcing or purchasing a product license directly from product developers. Numerous research institutes and universities have developed promising C&S that process developers can adopt to a commercial process using available laboratory and pilot plant data.

In most cases, however, process developers may not obtain enough information from the C&S developers because of know-how secrecy issues, thus making it difficult for process developers to scale up the process confidently. To avoid this issue, process developers must understand parameters that are key to the success of scaleup and convince the C&S developers to conduct additional tests that will answer those scaleup issues.

***Conceptual design of the envisioned commercial process.*** C&S developers (researchers) often have chemistry or materials-science backgrounds, and may not be knowledgeable about process scaleup. One of the most common mistakes is to start the conceptual design of the envisioned commercial process too late in a project.

For example, a researcher may test a new catalyst's performance and optimize operating conditions (such as temperature and pressure) in a batch laboratory reactor, without realizing that the commercial scale reactor will not be batch. If the commercial process will use a fluidized bed reactor, for example, the flow regimes and rate-limiting steps are different from a batch reactor, and the generated laboratory data may be misleading or irrelevant to the design of the pilot plant and commercial process.

To speed up this step, it is a good practice to involve chemical process engineers early and encourage an engineering study between the C&S innovator and process developer [*11*] in order to conceptualize the commercial process early so that laboratory and pilot-plant validation strategies can be adjusted to better match the envisioned commercial process.

***Pilot- and commercial-scale product (C&S) manufacturing.*** Major issues related to this step are mass production in tons instead of kilograms, lower-purity starting materials, catalyst attrition and crush strength.

To speed up this step, if catalyst developers (formulators) lack the know-how to manufacture catalysts on a large scale, it is a good strategy to form a partnership with a well-proven catalyst manufacturer to scale up the catalyst production.

***Pilot-plant process development and basic design (scale-down from commercial to pilot plants).*** A pilot plant is an important tool to obtain technical data and investigate effects of feed impurities and process recycle for a confident scaleup. Thus, pilot plants should be a scale-down of the envisioned commercial plants instead of a scaleup of the laboratory scale [*5, 11*]. It is more practical to save time and money by selecting only key critical equipment systems to pilot, rather than including all commercial process equipment into a pilot plant.

To speed up this step, it should be carefully assessed whether a pilot plant is really necessary or can be skipped (Table 1). Pilot plants are occasionally used just for producing product samples for clients to test and evaluate. Pilot plants are sometimes needlessly used for some purposes that can be achieved at laboratory scale or by good process modeling. For example, reactor kinetics can be done by laboratory kinetic measurement, and heat-and-material balances can be obtained using reliable thermodynamic data and properties from laboratory experiments or literature data without using pilot plants.

***Pilot-plant detailed design and construction.*** Apart from previously published strategies to fast-track pilot plant projects [*8–10*], key strategies to speed up pilot plant design and construction include the folowing:

- Have an integrated project team in-house that includes all necessary engineering disciplines
- Hire a pilot plant contractor that has abundant experience in designing and commissioning similar pilot-plant processes. For example, do not hire a pilot plant contractor who has designed only fixed bed reactors to design fluidized bed reactors
- Let the design team work under the same roof with a pilot plant fabricator in order to be able to respond to unplanned design and fabrication issues without delays
- Make as small and simple a pilot plant as is practical for scaleup purposes. For example, some companies build their pilot plants using simple tubing as lines and large-diameter pipes as vessels, which are then supported by nuts and bolts on vertical grating walls. Instruments are connected by tube fittings, thus simplifying the construction and allowing easy assembly and disassembly. Multi-tubular reactors are typically scaled up from only a single "show tube" representing actual operating conditions of thousands of tubes in the commercial reactor

***Pilot-plant process validation.*** It is important to clearly identify and communicate pilot-plant testing objectives to the project team to eliminate repeated and unnecessary work. To speed up this step, it is desirable to educate pilot plant operators well in advance on the commissioning and testing plan, as well as continue to involve product developers (researchers) in process troubleshooting and important decisions during the pilot-plant testing program.

***Commercial process development and basic design (scaleup from pilot to commercial plants).*** This step can be accelerated considerably if the pilot plant has been scaled down properly to collect valid necessary data for scaleup and if there have been no major changes to the conceptualized commercial process design. To further speed up this step, consider use of an outsourced process developer who has proven know-how on scaleup of similar processes, especially when experienced in-house resources are unavailable. The greater the quality and the larger the quantity of the scaleup data collected during the pilot-plant process validation, the faster the progress of this step and the higher the chances of success.

***Commercial-process detailed design and construction.*** The considerations to speed up this step are similar to those in pilot-plant design and construction.

***Commercial-process demonstration and validation.*** For the first process of its kind, it is often necessary for process developers to build their own demonstration plants to convince potential customers that the process can be operated commercially and successfully without unforeseen troubles. To speed up this step, process developers may form a partnership with manufacturing companies who have similar types of processes and equipment that can be used for the demonstration plants, or those who are willing to share the benefits if the process can be successfully commercialized.

***Commercial-process marketing and licensing.*** Marketing and licensing of the commercial process can be a problem for inexperienced product and process developers, especially for manufacturing companies carrying out their own in-house R&D. It is worth considering a partnership with a company that has considerable experiences in commercial-process marketing and licensing to save marketing and licensing costs and reduce risks. By collaborating with an experienced, technology marketing and licensing company, a process-developer company can learn what the key issues for marketing and licensing are. Moreover, the process-developer company can hire fewer people and still be successful in marketing and licensing. However, major disadvantages are benefit sharing and risks of know-how losses despite a well-written confidentiality agreement.

## Concluding remarks

All strategies above have been extracted from validated technical references and years of the author's experience in process development. The ideas of conceptualizing commercial process design early and designing a pilot plant based on a scale-down of a commercial plant are in good agreement with references [*5,11*] and also with actual observations of the importance of beginning with the end in mind. There was a real case where commercialization of an olefins polymerization reactor was significantly delayed because pilot plant data and collected laboratory data were inapplicable as they did not represent or reflect the real phenomena well enough to be used as valid data for reactor scaleup. The researchers and pilot plant developers failed to think beforehand about how the commercial polymerization reactor would look and what the commercial reactor size and internal flow regime would be. ■

*Edited by Dorothy Lozowski*

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