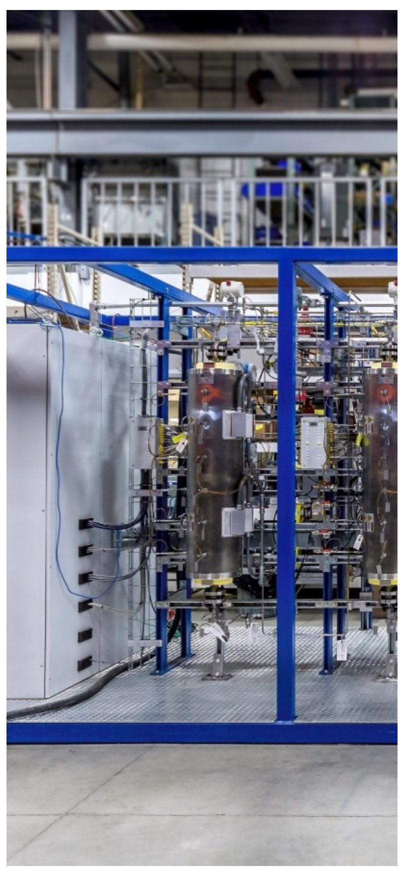
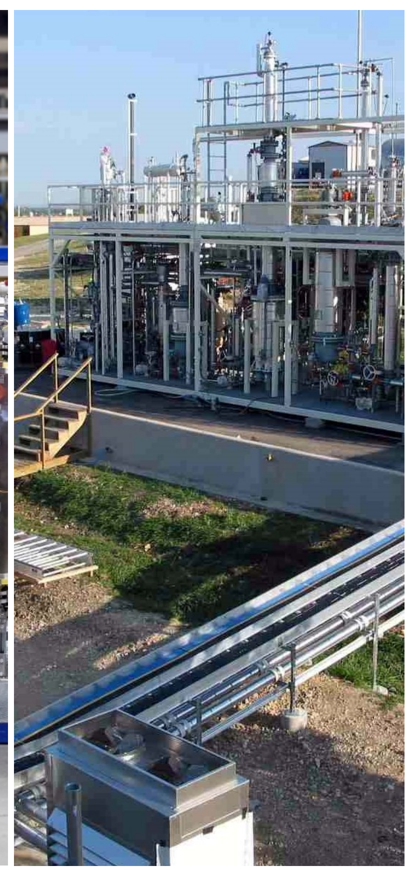
# Small is Beautiful: Concepts of Scale-up in Process Technology

## Choosing the Right Road

Moving from an idea to a profitable commercial scale is not a straight or short road. Taking the time to test the viability of an idea before commercial implementation makes sense on both a technological and economical level.

## Taking it Step-by-Step

Process technology development benefits from a measured, step-by-step approach where the viability of the technology is confirmed at one scale before moving to the next. Lab scale systems and pilot plants are the cornerstone of process development, but test stands and demonstration plants round out the spectrum of process technology scale-ups, each with their own benefits to the team looking to take their ideas to commercialization. In this paper, we will look at each system in turn, outlining why one would be chosen over another and giving an overview of how they all work together as a complete system of investigation.

## Lab Scale Systems

Lab scale systems, also referred to as laboratory or bench-scale units, are the first step up from the glass beaker used to evaluate whether a certain chemistry shows promise. This is where chemical engineers first put the wheels in motion on the long road toward commercialization. For a novel chemistry, this isn't likely to be a smooth journey. Many process parameters will need to be explored and determined and hurdles will need to be overcome, but these small, flexible systems are vital early-stage tools for new technologies.

A lab scale system is chosen because of its flexibility. It is built to investigate and test quickly and easily, and important process parameters, such as temperature and pressure, can be adjusted and controlled to give insight into the yield and selectivity of reactions under varying conditions. This flexibility can be found not only in process conditions, but also in the modes of operation. Batch, semi-batch, or continuous operations can be tested with relative ease and even the type of reactor itself (e.g., CSTR, PFR, fixed bed, fluidized bed, or ebullated bed) can be swapped out or changed with minimal difficulty.

As engineering and experimentation at this scale is the most cost effective and expeditious of all the process scale-up choices, these small units can be found in almost every research and development laboratory in the world. More often than not, such testing is done using equipment already in-house that can be reconfigured for new experiments on a weekly or monthly basis with the operator having a very hands-on role in controlling the system.

At the lab scale, initial tests are often done in batch mode with confirmation of proof-of-concept for the chemistry as the first goal and identification of the optimum process conditions as the desired outcome of the test program. This means that upstream feedstock preparation, downstream product purification, and the continuous recycle of unreacted components are usually not part of the system at the lab scale. After all, if the main reaction goal is not achieved, why worry about anything else?

*Figure 1. A lab scale gas-to-liquids catalyst test system*

The focus at the lab scale is clearly on experimenting with different process setups and utilizing its flexibility. A company beginning here, at the simplest of systems, will reap the rewards of the choice when in subsequent phases of testing the process flow sheet converges toward a fixed setup for fine-tuning the details, and when making major changes to fundamental aspects such as catalyst selection, solvent selection, reactor configuration, or optimal operating conditions will become more difficult.

## Pilot Plants

If it were possible to predict with absolute certainty that a lab-scale innovation would pass smoothly through the piloting step, it would be possible to eliminate the pilot-scale step entirely. However, this is generally only the case for the most basic and well understood chemistry. Most innovative processes are complex and their behaviour difficult to predict, and pilot plants offer the next step in learning on the road to commercialization.

Lab scale undoubtedly offers the most flexibility in testing, but it often comes at the cost of a limit to the complexity it can handle. Pilot plants, on the other hand, balance a certain degree of flexibility with a much higher degree of complexity. This means that a pilot plant can be used to confirm what conditions are optimal for a process, and it means that a pilot plant is vital to mitigate scale-up risks to the company and its investors. The cost and time of pilot experimentation is usually easily balanced against the risk of proceeding to a larger scale on the basis of incomplete information, which may result in expensive delays in commercial start-up that, in some cases, can be so severe that they threaten the entire enterprise.

### The Zeton Advantage

Since 1986, Zeton has been a premier supplier of modular pilot plants, introducing new ideas and methodologies to pilot-scale applications.

Pilot plants can be quite large compared to the lab and they can be used to make quantities of product for evaluation by end user customers; however, generally, the primary product of the pilot plant is the data required to move the process to the next scale, which will be either a demonstration plant or commercial production. In order to get the data needed, a pilot plant will build off the knowledge gained from the lab scale and choose hardware and the preferred mode of operation based on those results before deciding on a batch, semi-batch, or fully-continuous process. Once these process steps are decided upon, the complete process flow sheet starts to take shape.

In general, a pilot plant uses commercially available feedstocks in upstream sections, with feedstocks pre-processed only if necessary to meet the scale-specific nature of the plant (e.g., grinding wood chips into sawdust before feeding to a pilot-scale pyrolysis reactor). Notably, for continuous plants, recycle loops for unreacted feed and intermediate product streams are often integrated with the feed and reaction steps, with sections downstream of the reactor designed to deal with product separation and purification to facilitate closing of the mass balance.

The plant is controlled in a semi-autonomous mode in order to run a campaign continuously while balancing the complexity of the operation against the need for reliability, safety, and ease-of-operation. If necessary, and where feasible, automated online sample analysis can provide direct feedback to the operation of the plant and can be combined with “grab” samples taken for offline laboratory analysis. Parameters can still be set freely by an operator to allow for tuning of the process window and to experiment with the many variables left open, but the need for a


*Figure 2. An oil blending pilot plant*

semi-autonomous mode is necessary because longer duration runs are essential to gathering data in such areas as the durability of catalysts, the build-up of undesirable compounds in recycle streams, and the possibility of corrosion.

Ultimately, a pilot plant will discover flaws and successes in the process. If the pilot experiments discover flaws with the original process concept that cannot be addressed, further lab-scale innovations may be required or the whole development program may end there until a new idea or situation arises that fundamentally changes the original process concept or process economics. But a pilot plant program has found success when the process simulation of the plant at the commercial scale is validated against the real-world data obtained from the pilot plant. Assuming that the scale of commercial production leads to favourable economics, a pilot plant can demonstrate that a commercially viable process can be achieved based on its results.

It is rare for a pilot plant to go from initial design through durability campaigns without many minor and sometimes very major modifications, as process knowledge needs to be developed and acted upon. And even after a process is successfully commercialized, a pilot plant can have an ongoing life as a process development and troubleshooting tool where new catalysts, new formulations, new feedstock sources, and more advanced process equipment can be trialled with the goal of continuous improvement. If fact, this is almost always the case when the underlying process technology is commercially licensed to others.

While the lab scale is still the primary place where chemistry innovations occur, the pilot plant is where chemical engineering innovations occur. It can handle a great degree of complexity and yet is flexible in terms of its ability to accommodate process modifications resulting from advancements in knowledge made through the pilot program. As a result, pilot plants are the scale at which companies often discover their patentable inventions and trade secrets.

## The Pilot Plant Test Stand

A test stand is a familiar concept in many industries where systems such as fuel cells, batteries, or engines are supplied with necessary feeds and products and process parameters are monitored and controlled. Such test stands are typically specific to a particular industry and are not very flexible to testing new technology. In adapting the idea of a test stand to pilot plants, an emphasis was placed on testing combined with flexibility to adapt to new technologies. A well-designed pilot plant has the foundation for this unique combination of abilities. It may already be set up to offer a useful infrastructure platform for future experimentation because it has been designed with flexibility for in-process change. In fact, if a little extra thought is given to the future re-use of a pilot plant's infrastructure during the design stage, it can easily serve as a test stand in future pilot work—sometimes for decades—following the natural changes in chemistry, technology, or a company's business.

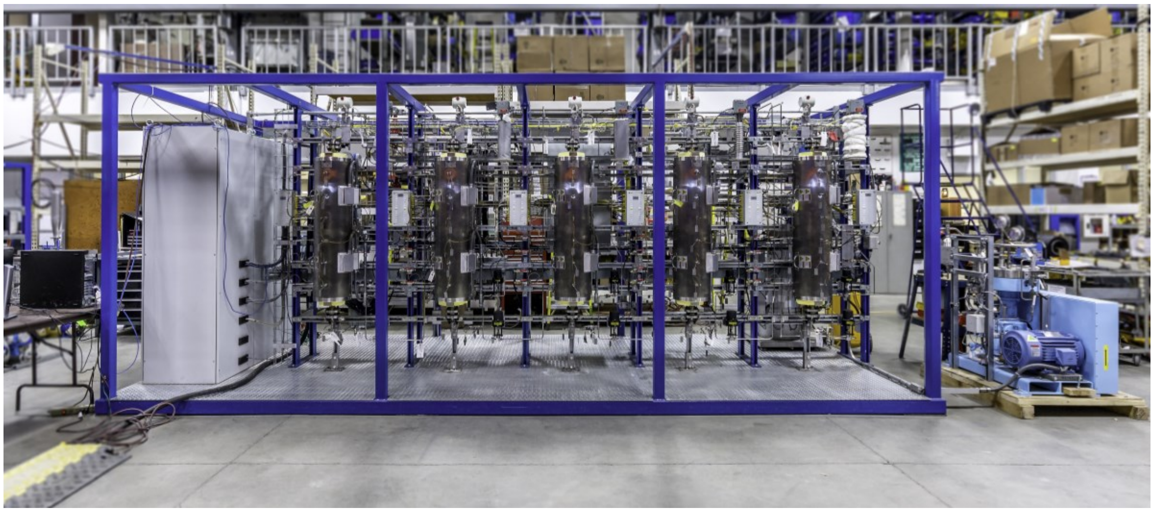


*Figure 3. A pilot plant test stand for a chemical-to-fuel conversion application*

Already this test stand approach has proven beneficial to many companies, with some designing pilot plants with one or more empty bays in anticipation of future use. There are, of course, limitations to a pilot plant's ability to offer the flexibility of a future test stand. For example, if the plant will only ever be used for the testing of a specific process, such as a scale-down of an existing commercial plant (See "Pilot Plants as Scale-Downs" in the section below) or if a plant's layout requirements to fit an existing test cell or fume hood are restrictive, then it will not be able to offer this flexibility. But for many projects, a test stand may make economic sense, as even if the unit is never modified, it will offer significantly higher value to future users.

For many years, this adaptation has been a happy by-product of a well-designed pilot plant that may find itself with substantial infrastructure beyond the needs of a client's initial development program. However, some companies have now taken the initiative to formalize the required forethought for reconfiguration of its pilot units in future process development campaigns. Zeton has done this in a formulation called the "Pilot Plant Test Stand," which is an open architecture process development platform that is based on the ideas of standardization, efficient design layout, and an eye to future development. The attributes of Zeton's formulation are detailed below.

By thinking of future uses right from the first days of a design, companies like Zeton are able to offer clients a flexible and economically forward thinking model not only to scale to commercialization but to continue testing and experimentation in the years to come.

### Designed for Standardization

- Standard size skids: If possible, skids are based on the optimization of shipping dimensions rather than customizing the unit to fit a floor space.
- Laboratory control valves: Valves with a wide variety of trim sizes available are specified, allowing for re-use of the units for new services.
- Tubing compression fittings: This allows for easy re-use and reconfiguration of instruments and valves since every fitting is a union.

### Designed with an Efficient Layout

- Use of bays: The plant is divided into bays, each of which is supplied with all necessary utilities.
- Unistrut backplanes: These flexible mounting channels are used to lay out structural components.
- Table mounts: Components can be mounted to a table while support equipment is mounted underneath.
- Electrical and control cabinets: These are installed at one end of a skid for easy access, and wiring distribution has a separate layer.
- Utility streams: A central vertical corridor or overhead horizontal layer of the skid carries utility streams to and from any point.
- Instrument air manifolds: Manifolds are mounted in each bay, allowing easy installation of future air-operated valves, pumps, etc.

### Designed for Now and the Future

- Utilities: These are designed with excess capacity for future uses.
- Increased spare capacity: Control system cabinets, I/O racks, and individual I/O cards have installed spare capacity of 15 to 20 percent.
- Patch panels: Home-run wiring is not used between instruments on the skid and the control system.
- Plug disconnects: Clients can repurpose thermocouples and analog and digital inputs and outputs.
- Low voltage heat tracing: Minor changes due to reconfiguration of tubing lines can be made without an electrician.
- Modular, fixed capacity heat trace circuits: This offers more flexibility than circuit-by-circuit for the individual loads of the plant.
- Hose and flexible lines: Rather than rigid connections, these are used, where appropriate, for ease of retrofitting.
- Ventilation and gas detection: To mitigate flammability risk, these are used rather than electrical area classification for increased flexibility and cost savings.

## Pilot Plants as Scale-downs

While most may think of scaling as an inevitable upward motion, lab-scale and pilot-scale units can be designed as scaled down versions of commercial plants. Such scale reversals are a well-established tool to allow commercial facilities to be run at their most efficient. Variations in the commercial process, whether they be to the catalyst, process mode, or feedstock selection, can easily be tested first at a smaller scale before being implemented, and this minimizes the risk from unforeseen and adverse effects that might happen if tested directly on a full-scale plant.

By setting up a lab or pilot unit to emulate situations encountered in commercial mode and troubleshoot on a manageable scale, a company can protect its capital assets by simplifying operational experiments and minimizing costs. Thus, not only does this scale down from commercial to pilot plant and lab scale prevent downtime in operating facilities, it also gives the user a tool on which to try multiple different solutions without serious consequences to day-to-day business.

## Demonstration Plants as the Final Scale Up

Pilot plants are considered the gold standard for testing in most scenarios, and some processes are simple enough that thorough, careful piloting at a substantial scale may give sufficient information for commercialization. However, as processes become more complex, more heterogeneous—with catalysts, products or reagents in different states of matter—more recycle intensive, or more inherently hazardous, the need for smaller scale-up steps becomes greater. This is where the demonstration plant, or "demo" plant, shines. Between the pilot and commercial scale, this plant is frequently required as the final step in minimizing scale-up risk. Extended operating runs in a demonstration plant permit catalyst lifetime studies over a long period of time and significant quantities of final product can be generated for market development and end user testing, and they are often located adjacent to a commercial operating plant to benefit from existing infrastructure and for ease of feed and product material handling. In general, demonstration plants quantify any simplifications made in the pilot plant, such as operating at partial recycle or on simulated feeds, which might lead to commercial risk if not otherwise addressed.

*Figure 4. A Grace DCR fluidized catalytic cracking (FCC) pilot plant*

The key to demonstration plant success often comes from the pilot plant before it. If a pilot plant has been designed as a fully scalable solution in its own right, then all of the original design know-how can be directly transferred into

*Figure 5. A lithium extraction demonstration plant*

the engineering of a demonstration plant. Furthermore, using the same team of engineers to design and work with plants at both the pilot and demonstration scales maintains continuity and will ensure that the value of that know-how is transferred.

## In Conclusion

Moving from an idea to an economically profitable commercial scale is not a straight or short road. Taking the time to test the viability of an idea before commercial implementation makes sense on both a technological and economical level. Of course, each of the test scales has its benefits and limitations. Lab scale and pilot scale are the most flexible and therefore the most commonly used test systems both for scaling up a new idea from scratch and scaling down to test technological innovation at an operating commercial system. However, even these scales have limitations: lab scale can be too simplistic and temporary and pilot scale can be too rigid in its design. As processes become more complex, plant designers, such as Zeton, have created their own design innovations to allow for the possibility that their pilot plants can become test stands for future development and prove to be long-term testing assets for a company. However, there will be cases when even a pilot plant or test stand will fall short of being able to offer the long-term or quantity processing needed, and a company will look to a demonstration plant as the final step in scaling up.

It is through careful consideration of what is needed—not only now but in the future—that a company can make the most of its scale-up decisions. Taking this time in the early design stages makes the difficult road from an idea to commercial process a little bit straighter and a little bit easier, and a company will reap these benefits for many years to come.


## Contact Zeton to discuss the most efficient way to scale your next process technology project!

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