PILOT PLANTS — PART 1:

Fast-Track Your Pilot Plant Project

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These tried-and-true tips and tricks can help speed the design and construction of your pilot plant, and save you money at the same time.

The pilot plant is on the critical path of many commercialization projects, and its value can be many multiples of its cost. The schedule savings in the design and manufacture of the pilot plant can be disproportionately beneficial to the overall development project. Conversely, inappropriate shortcuts resulting in major oversights can be disproportionately problematic.

This article offers some suggestions and shortcuts, as well as areas requiring extra attention, for pilot plant projects. Some were demonstrated, and others learned the hard way, on a recent pilot plant project.

Design inputs: laboratory data and simulations

The "right way" to do an equipment design project is to have a fully developed process flow diagram with a complete mass and energy balance at the desired operating point from the outset. Unfortunately, the reality of most pilot plant projects is that one of the plant's purposes is to provide that very data for the potential full-scale facility. With pilot plants, uncertainty and multiple potential operating scenarios are the rule rather than the exception.

Laboratory data and simulations are important sources of information for sizing vessels, pumps and instruments. It's far easier, quicker and more cost-effective to use simulations to evaluate the basic feasibility and various process options for a new process than to do it experimentally. Simulations and designed laboratory experiments can help you avert major disasters. It's also important to realize that batch laboratory data and simulations are not a substitute for continuous pilot-plant data. Most importantly, if you wait for the flowsheet and the mass and energy balances to be nailed down completely before beginning the design of the pilot plant, you'll never get started.

Rather than establishing a single design point based on a simulation, we've found that it is better to parameterize the design using the simulation data to establish an operating range for each piece of equipment. The process design of the pilot plant can then be carried out over the full parametric range, to ensure that the plant has the turndown needed to handle a wide range of operational cases. Sometimes, to get the desired rangeability, multiple pieces of equipment or instruments will be required, or different process approaches will need to be designed into the pilot plant. If this is the case, it's better to begin the design process with this in mind than attempt to retrofit the required rangeability later.

Project management and communications

A few common-sense rules apply to the management of a pilot plant project. These can make the difference between a smooth and successful project and one that is a headache for all involved.

The key product of a pilot plant is process knowledge, and possibly samples for customers — not a specific pounds-per-hour production rate. A pilot plant project, therefore, has different goals and requires an approach dis-

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tinct from those used on commercial plants.

We recommend the design/build approach for pilot plants. The conventional approach — having an engineering company design the plant in enough detail that a remote fabricator can build it under the supervision of a construction manager — tends to increase the cost and delivery schedule for small projects like pilot plants. The inefficiency arises from the generation of drawings and other documentation that are unnecessary when the people who designed the plant directly supervise its fabrication.

Get the designer and fabricator involved as early into the planning process as possible. Take advantage of their experience.

Keep project communications simple. Don't insert a third party between the owner and the designer/fabricator. Put the people who can make the process decisions in touch directly with the people doing the design and fabrication.

Keep formal meetings and reports to the minimum necessary to satisfy management.

Bring in subject matter experts on an as-needed basis, but don't let them linger at the table.

Comparison of commercial and typical pilot-scale operations.

Factor	Commercial Scale	Pilot Scale
Key Objectives	Continuous generation of onspec product(s)	Process knowledge and understanding Operational observations Scale-up data Product samples
Scale	ton/h	kg/h
Operation	Continuous, maximizing up-time	Operation in campaigns
Design Life	Tens of years	1–10 yr
Maintenance	During operation as much as possible	Between campaigns
Operational Mode	Steady-state	Chasing steady-state
Data Acquisition and Control	As needed to obtain steady-state	To obtain steady-state and to collect the necessary process data for scale-up
Operating Temperature and Pressure	Commercially optimal conditions	Beyond commercially optimal conditions (to establish optimum)
Design Points	Single	Multiple
Flowsheets	Single	Frequently multiple
Source of Design Data	Pilot plant	Laboratory data and simulations, plus experience
Capital Project Timescale	Several years	1 yr
Need for Operational Flexibility	Modest	Considerable

Choosing the "design point" for pilot plant equipment

Setting the maximum operating pressure and temperature combination for the major pieces of equipment in a pilot plant is one of the key decision processes in any project, and merits significant analysis and thought. Choosing a design point that is too low can render the plant useless. Choosing a point that is inappropriately high can significantly increase the cost and delivery schedule of the plant. It may also hamper operation by unnecessarily limiting the types of equipment, valves and instrumentation that can be used, resulting in increased downtime or a reduction in the ability of the plant to deliver the desired measurements, products and data. Even in a pilot plant, it may not be in the best interest of the project as a whole to merely guess high.

Various strategies can be used to determine natural design points for equipment, even in the face of significant process uncertainty (Tables 1 and 2, Figures 1 and 2). Note that many of these limitations are related to the limits of sealing materials. The limits of 175°C for Viton and 232°C for PTFE correspond with a sudden and dramatic shift in the cost, availability and reliability of a large fraction of the valves, instruments and closures that rely on these materials to function properly. Thus, crossing this threshold arbitrarily is not recommended. Don't set a design limit of 500°F if 450°F will do.

Note also that maximum operating pressure and maximum allowable working pressure (MAWP) are not synonymous. The maximum operating pressure for the plant clearly must be significantly *lower than* the MAWP of the vessels and piping, since relief devices must be set at pressures *no higher than* the MAWP. Even the best relief valves and rupture disks may simmer or prematurely burst at pressures exceeding 90% of their setpoints, so it is necessary to choose an MAWP at least 10–15% greater than the desired maximum operating pressure. Again, excessive over-design can have significant cost, schedule and operability implications and should be avoided.

Rangeability and turndown are key

Since multiple operating cases and significant uncertainty in operating rates are common in pilot plants, it is

Table 1. Natural limits for temperature.	
–177°C	Limit of liquid nitrogen as coolant.
–20°C	Practical lower limit of typical carbon steel as a material of construction. Below this, special "killed" grades or stainless steels are required.
30°C	Lower limit for water as a coolant.
60°C	Limit of polyvinyl chloride (PVC) and polyethylene (PE) as piping and tank materials. Insulation for personal protection is required above this. Onset of stress corrosion cracking concerns for common stainless steels.
80°C	Heat exchangers using untreated water may severely foul with mineral deposits when turned down above this temperature.
100°C	Limit of polypropylene (PP) as a piping and tank material. Close to the practical limit for treated cooling water exchangers.
135°C	Approximate upper service limit for fiberglass-reinforced plastic (FRP) and polyvinylidene fluoride (PVDF) piping and vessel components.
150°C	Upper service limit for Tefzel poly(ethylene-co-tetrafluoroethylene) (ETFE). Practical limit for polytetrafluoroethylene (PTFE, or Teflon) and perfluoroalkoxy (PFA) in unentrapped service.
175°C	Upper service temperature for Viton fluoroelastomer.
232°C	Upper service limit for PFA and PTFE, even when totally entrapped.
315°C	Practical upper service temperature for polyetheretherketone (PEEK). Upper service limit of Kalrez fluoroelastomer. Upper service limit for titanium in pressure-retaining service. Maximum recommended service temperature for heat-transfer oils.
450°C	Maximum temperature for unprotected expanded graphite exposed to air. Above this, only metal and ceramic sealants may be used. Intergranular corrosion range for stainless steels.

important to consider the rangeability of instruments when designing the equipment.

Some instruments claim a very large rangeability, or turndown ratio. However, in a pilot plant operation, there is often only one choice for the instrument in question — the smallest one available from the manufacturer. Consequently, a significant amount of the instrument's turndown may already be counted on to meet the maximum throughput operating case, which therefore reduces the available rangeability of the instrument in service.

Table 2. Natural limits for pressure.	
15 psig	Relief settings below this point permit the use of non-ASME tankage. This approach is faster and cheaper than using pressure vessels.
275 psig	Approximate limit of 150# flanges in carbon steel and stainless steel at room temperature.
720 psig	Approximate limit of 300# flanges in carbon steel and stainless steel at room temperature. The number of available valves drops roughly in half beyond this point.
1,440 psig	Approximate limit of 600# flanges in carbon steel and stainless steel at room temperature. The variety of available valves drops in half again beyond this point.
3,600 psig	Approximate limit of 1,500# flanges in carbon steel and stainless steel at room temperature. Beyond this point, only specialty equipment and valves are available. Special design rules and fabrication methods for vessels, pipe and tubing are required.

This sort of problem frequently arises from the inaccurate selection of design points for key pieces of equipment, where the owner has selected a design pressure, relieving pressure or throughput significantly larger than the required operating pressure or throughput. In these cases, careful consideration should be given to either reducing the design pressure so that it is closer to the actual anticipated operating conditions, or installing multiple, redundant instruments to accommodate the resulting wide turndown range. Where a high design pressure is chosen to protect against a runaway reaction or other relief situation, it is important to select a design point for operation and a design point for pressure retention, and to never confuse them.

Utilities limitations can also result in turndown problems. For instance, cooling water exchangers can be operated with water exit temperatures of about 25–80°C, perhaps stretching to 100–105°C for closed-loop treated chiller or cooling tower water. If the

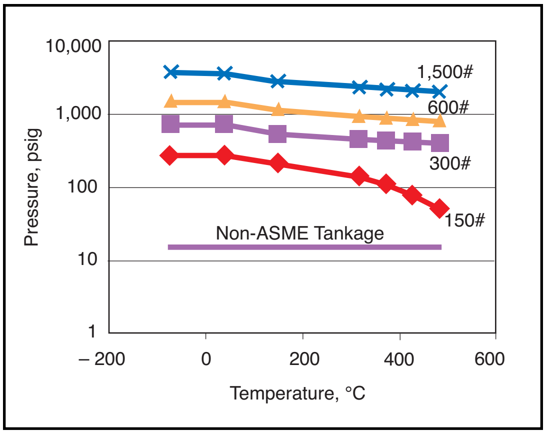

Figure 1. Natural pressure and temperature limits for Type 316 stainless steel ANSI fittings.

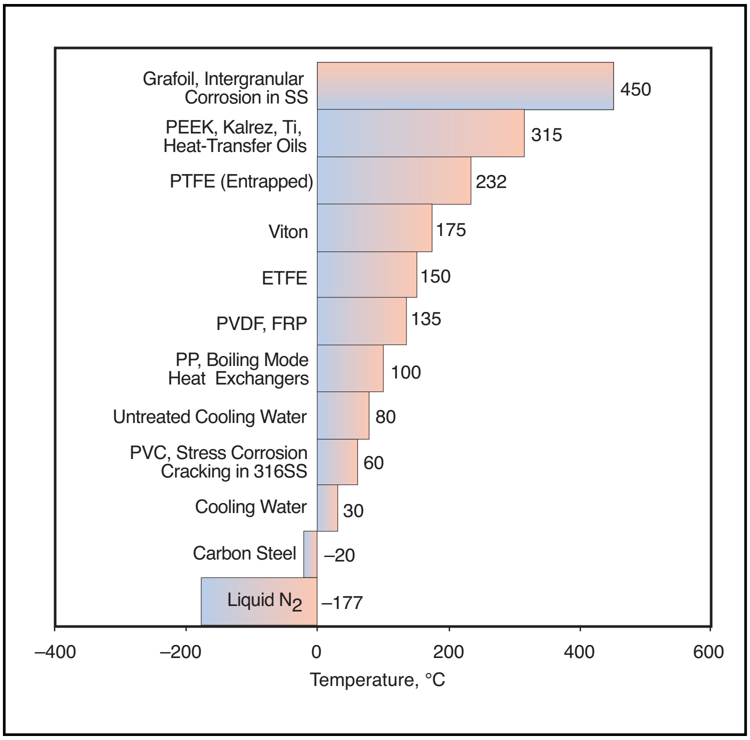

Figure 2. Operating temperature limits for common materials and equipment.

desired process temperature is within this range, turndown is not an issue, provided the cooling-water control valve has adequate rangeability. If the desired process temperature range exceeds 80–100°C, the utility limitation corresponds to an ultimate turndown of only about 4:1 on duty. Boiling-mode operation using condensate may be an option, but may represent undesirable process and safety difficulties. Accordingly, closed-loop tempered water and tempered oil systems are frequently required on pilot plants to offer adequate temperature control rangeability.

Simplify

Unnecessary complexity leads to unnecessary delay and cost — money that could be better spent on additional training for operators, a larger spare parts inventory, etc.

Consider carefully the lifecycle and operating mode of the pilot plant. Will it be essential or even permissible to continue operating while you repair or replace key pieces of instrumentation or equipment, or will a shutdown be inevitable? If the latter is true, block-and-bleed valves on instruments, double-block valves and bypasses around control valves, and the like may merely add unnecessary cost and complexity to the system without adding significant value. Labor costs for installation and testing, procurement, and engineering specification/selection rise in nearly direct proportion to the number of tagged items on the plant, so elimination of unnecessary components can result in significant reductions in the cost and delivery lead-time for a plant.

Sometimes, creative design can even eliminate entire pieces of process equipment. For instance, if a pump is needed to forward a fluid, consider using spill-back from the same pump to mix the tank, rather than using a dedicated mixer. If a centrifugal pump is being used, it's likely operating to the left of the curve (*i.e.,* high head, low flow) and hence wasting energy on internal recirculation that might be better used to mix the tank.

In a recent pilot plant, no mechanically driven agitators were used. Instead, gas/liquid contact, liquid mixing and liquid forwarding were accomplished using centrifugal pumps and venturi eductors. This eliminated a significant number of major pieces of equipment.

Focus on what you need to pilot. If something adds complexity without improving the plant's ability to provide the required data or product, eliminate it.

A good example of this is heat integration and heat recovery. Unless it is a very large demonstration plant, the energy consumption of the plant will probably be minor compared to the labor and materials costs to operate it. By substituting utilities for the process stream, you can eliminate at least one exchanger and its associated controls, while reducing the required surface area for the main exchangers due to improved driving force. More important than the savings in capital, however, is the improvement in control that results from de-coupling two parts of the process so that they can be rapidly and independently adjusted. Some of the savings should be invested in providing sufficient instruments on the exchangers such that overall heat-transfer coefficients (U-values) can be calculated on-line. For similar reasons, electric immersion heaters often replace steam or direct-fired heaters in pilot plants.

Selection of materials and fabrication methods

If the pilot plant is intended to prove a new technology, its lifespan will be relatively short. In this case, it's not sensible to use 30-yr durability when choosing materials of construction, equipment or fabrication methods. If the pilot plant is intended to operate alongside a commercial facility or generate samples for customers, a longer lifespan should be considered.

If you're in new process territory and corrosion service is an issue, don't just trust the charts or the experts. Based on our hard experience, we recommend accelerated corrosion testing done at the lab scale prior to making final materials selections. If possible, choose a material that is completely immune to the type of corrosion you may face. Note also that the experience in the laboratory batch reactor may not accurately simulate the conditions experienced in a continuous pilot plant over the long term.

Keep in mind that the selection of materials for a pilot plant is more limited than for a commercial system. The special alloy being considered for the commercial plant is probably not available in less than full mill runs of pipe, tubing or fittings, especially at the smaller sizes. Fittings, or even pipe, may have to be fabricated from bar stock.

It has also been our experience that more exotic materials such as titanium have only marginally greater fabrication costs at the pilot scale than intermediate alloys such as Cr-Mo carbon steels, super-duplex or 6% molybdenum stainless steels, Alloy 20, etc., and that any of these materials are significantly more expensive and less readily available than the common grades of stainless steel.

In our experience, the relative cost factors found in commercial plant fabrication dramatically underestimate the installed cost differences observed in pilot plant fabrication.

If the service life of materials of construction is key to the success of the pilot program, we recommend constructing the plant from the standard commercially available alloy that best suits the corrosion service requirements for the durability period of the plant, and using corrosion coupons and/or electrically insulated test spools to examine the feasibility of less standard materials.

Resist the urge to over-specify

Use care in applying big-plant specifications for a pilot plant. Otherwise, you risk unnecessary cost and schedule impacts. Some plant specifications, while being perfectly appropriate for a commercial plant with a lifespan of 30+ years, will have a severe impact on the quality, operability and cost of the pilot plant — and sometimes may render the plant either inoperable or unconstructible. The following general experience-based rules can guide the specification of equipment and fabrication methods for a pilot plant.

Don't tie the designer/fabricator's hands with unnecessary or inappropriate specifications. Instead, focus on industry-accepted codes, standards and approvals, then where necessary, supplement these with scale-appropriate specifications or guidance rules for the most critical parts. Allow the designer whatever latitude exists within the codes and standards to save you time and money on the rest.

Keep the operational life of the plant in clear focus. Don't choose 30-yr methods or materials for a 2-yr development plant, or off-shore methods for an indoor pilot plant.

Don't be afraid to use professional judgment. Don't assume a rule is applicable to your pilot plant merely because it's written down.

Avoid painting carbon-steel pipe. If exterior corrosion is an issue, consider galvanized or schedule 10 stainless steel with 150# fittings for utility services. Painting is inordinately expensive and disruptive to production for small plants, and the labor savings from eliminating it will almost certainly pay for the additional cost of stainless steel pipe and fittings.

Use tubing and compression fittings up to 3/4-in. o.d. instead of welded pipe. The labor savings can be dramatic, particularly if changes must be made later.

If you expect to tear down and reconfigure the pilot plant frequently, consider using removable insulating jackets rather than rigid insulation.

Don't be afraid of threaded pipe. With good sealant systems and proper installation, threaded pipe can be very leak-tight and reliable below 2 in. NPS. Fabrication costs are lower and reconfiguration is much easier than with welded pipe systems.

Several items related to materials specification can be eliminated to reduce cost and improve schedule with little impact on

Table 3. Alternative material specification practices can reduce costs.

Normal Practice	Alternative Practice
Total positive materials identification	Mill certs and inward/in-process materials quality-control procedures
Approved manufacturers list for pipe and fittings	If required, approved/disapproved country of origin lists
Full-scale plant valve and instrument specfications	Outcome-oriented specification, with a suggested vendors list if necessary
Full-scale plant pipe, vessel and electrical specifications	Focus on codes and standards (ASME/ANSI, AWS, NEC, etc.)

the overall quality of the installed product. These are shown in Table 3. For instance, instead of giving the designer/fabricator a list of approved valve manufacturers and models, consider providing the basic design requirements (design point, acceptable materials, fire safety etc.) and allowing them to shop the marketplace for the correct, scale-appropriate product.

Lessons learned at the Marathon JLM pilot plant

While the process and operating conditions of this plant are proprietary to Marathon and its partners, we can disclose a few things that worked for us and a few things we would do differently the next time. Among our successes are the recommendations discussed above. The major areas for improvement include:

- Accelerated corrosion testing was skipped in favor of a corrosion consultant's report. This resulted in the selection and use of an inappropriate material of construction.
- Despite the ease of fabrication, chlorinated PVC (CPVC) is not a good material choice for heat exchanger cooling water returns, since its maximum service temperature is 80°C.
- More of the cooling-water-fed exchangers should have used tempered oil loops instead, since insufficient turndown was experienced.
- During start-up and commissioning, corrosive materials traveled to places in the plant that were not designed for them, resulting in severe corrosion. It would have been better to assume that the corrosive materials would move throughout the plant and design on that basis. CEP

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