DR. JOEL SHERTOK

THE ART OF SCALE-UP

The Successful Chemical Practitioner's Guide to Creating Profitable Processes

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To my parents, who kept me
on the straight and narrow

WHY PILOT WORK AND CAREFUL SCALE-UP ARE IMPORTANT

The adage of "measure twice, cut once" is as true in the process industries as it is in tailoring. In industrial environments, the emphasis on getting things done quickly and straightening out issues later has led many a company into some very bad swamps. As a senior engineer once remarked to me, "There is never time to do it right, but there is always time to do it twice."

I define "piloting a process" as setting up a sequence of chemical engineering operations that mimic the proposed commercial operations as closely as possible but at a greatly reduced scale. What is feasible in glassware may not be feasible in the real world.

I can think of circumstances where failure to carry out proper piloting led to a series of negative outcomes. A company where I worked had contracted with a design organization to build a machine to manufacture carbon blocks: powdered activated carbon (PAC) held together with a thermoplastic resin. The heart of the process was squeezing the PAC/polymer mixture at high compression and high temperatures using

a rubber bladder at each station. The contractor also committed to fabricating a small pilot unit to test out formulations and manufacturing conditions. Since the commercial unit was completed before the pilot unit was off the drawing board, testing was done using the full commercial unit.

The result was a disaster: the rubber compression bladders acted as insulators, impeding heat flow and preventing solidification of the PAC into a block. The machine typically ran for 15-30 minutes before it broke down. After about six months of constant effort, it was obvious the project was going nowhere, and the million-dollar machine was sold as scrap.

If the pilot unit had been built and operated first, the insulator issue would have been detected in a machine designed for easy dismantling and cleanup.

It is necessary to pilot all aspects of a chemical operation to gain process expertise. In fact, all-glass pilot facilities are common. The glass construction allows for internal observations that are invaluable compared to operations implemented in a standard steel construction.

A great deal of forethought should be invested before a final pilot design is considered, with pilot unit flexibility critical. Some considerations:

- **Feed system:** powder, liquid, or gas?

- **Reactor system:** CSTR, Plug, or Batch?
- **Separations:** distillation, filtration, solvent extraction?

The more thought and pilot work that is done on the unit, the fewer surprises there will be. The attached sections outline some important considerations that must go into scale-up of reactors and separation devices.

You may download a PDF of the figures used in this book from here:

ArtOfScaleUp.com/figures

SECTION I

REACTOR CONSIDERATIONS

CHAPTER ONE

REACTION KINETICS

In many cases, the chemist who had original responsibility for product sample development will have made only a preliminary foray into developing the process reaction kinetics that control reactor design.

There are three types of reactor system used in the Chemical Process Industries:

1. **Constant Volume, Stirred Tank Reactor (CSTR):** This is simply a well-mixed tank (perhaps 10-25 gallons in a first-pass pilot unit) in which reactants are fed in, and a product stream withdrawn, at such rates that the volume of reacting materials is kept constant. This is the simplest reactor to run and analyze.

2. **Batch Reactors:** A batch reactor is a discontinuous reactor. It is a stirred tank that is filled with the reactants before the reaction starts and emptied after it has run to completion. An example is baking a cake: the ingredients (raw materials) are added to a baking pan (the reactor), and the contents are

heated to the proper temperature for an appropriate amount of time. At the end of this time, the pan (reactor) is removed and the cake is ready (reaction completed).

3. **Plug Flow/Tubular/Continuous Reactors:** In a Plug Flow Reactor, one or more fluid reactants are pumped through a pipe or tube. The chemical reaction proceeds as the materials travel through the PFR. At the inlet to the PFR the rate is very high, but as the concentrations of the reagents decrease and the concentration of the product(s) increases the reaction rate slows.

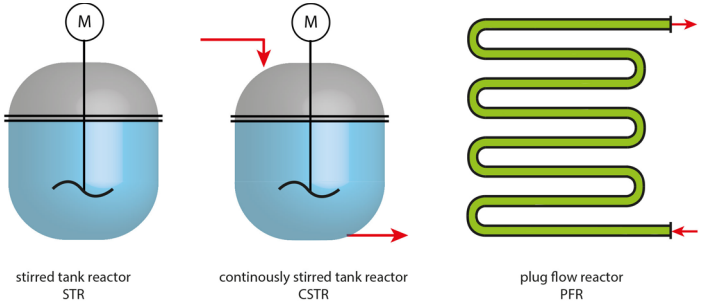

Figure 1: Reactor Types

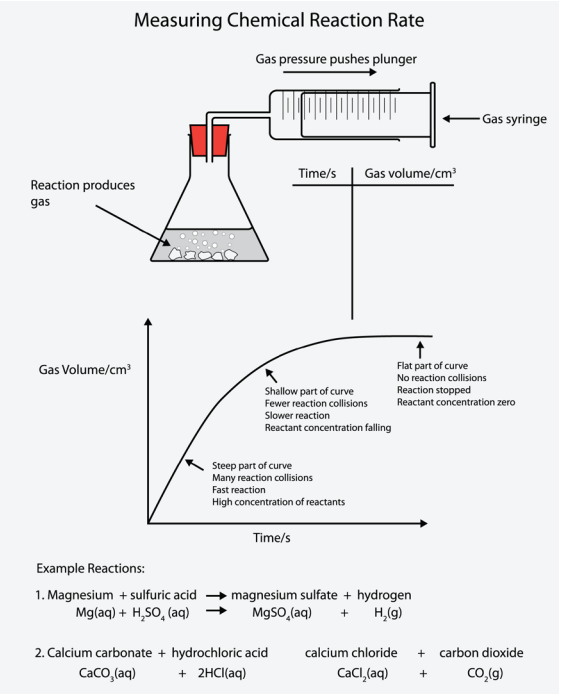

Figure 2: Batch/Plug Flow Reaction Curves

The equations describing a plug flow tubular reactor are the same as those which describe a batch reactor.

EXAMPLE I

One of the units for which I had Process Research & Development (R/D) responsibility was designed to produce styrene oxide from the reaction of styrene and peracetic acid. The reaction train consisted of five tubular reactors in series, each at a constant temperature; the temperature increased with each reactor.

The unit had long been plagued by poor process efficiency – I was asked to improve the process. As a first step, I developed the reaction kinetics of styrene and peracetic acid reacting to form styrene oxide and byproducts. I then created a computer program to model each reactor and looked at temperature profile effects on efficiency.

I concluded that the profile was the exact reverse of what it should have been: a *decreasing* temperature profile, rather than an increasing profile. When this new profile was applied, reaction efficiency dramatically improved

EXAMPLE II

The federal government asked my company to design a manufacturing unit that would make a specific diene precursor for an epoxide needed for a special application. The chemists and engineers collaborated and developed a process that would achieve this. A small pilot unit was built both to test the process and to produce sample material for evaluation. Because of manpower and cost constraints, the unit was only operated for six hours per day, not the 24 hour/5 day manufacturing period that would normally be anticipated.

All went well with pilot operations, and a manufacturing facility was designed and built based on the pilot unit. Startup was uneventful. However, after a week of operation, plant engineers noted an alarming buildup of a yellow, granular polymer in the diene product. The amount of this polymer appeared to increase as time went on. After much frantic investigation, R/D personnel found that the yellow polymer was the result of a side-reaction that took time to build up to a point of significance. Because the pilot unit was only operated for limited time periods, the polymer had not been detected earlier.

ENERGY CONSIDERATIONS

Energy plays a key role in chemical processes. Energy is absorbed to break bonds and is released as bonds are created. In some reactions, the energy required to break bonds is larger than the energy evolved making new bonds. A reaction is *exothermic* if energy is released. A reaction is *endothermic* if energy is absorbed.

CHAPTER TWO

MASS TRANSFER: THE IMPORTANCE OF MIXING IN SCALE-UP

A fundamental understanding of the mixing process is essential for scale-up in chemical development. Mixing is the reduction or elimination of inhomogeneity of phases that are either miscible or immiscible. Laboratory reactors must be operated under conditions that will allow meaningful mixing characterization and scale-up.

Figure 3: Typical Mixer

LABORATORY MIXING STUDIES

Development and scale-up of a chemical process can be challenging because exact conditions are unknown. Matching performance and mixing between small and large-scale reactors is difficult when relying only upon agitation rate, geometry, agitator design, or other mechanical measurements. A better approach is to measure mass transfer coefficients directly in the actual reaction system.

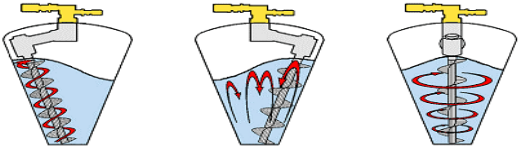

Figure 4: Various Types of Mixing Patterns

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EXAMPLE I

A poorly designed mixing process can play havoc with the operations of a chemical plant. One of the plants in which I worked made what are classified as formulated products: products made by simple mixing of reactants.

One persistent mystery was why a relatively viscous, dense raw material took hours to adequately mix. This was in spite of the fact that studies done in large glass beakers showed rapid mixing. No matter how fast the unit mixing agitators turned, the mixing continued at a seemingly glacial pace.

We took a very close look at how the component mixing was performed. In any mixing process, the most intense mixing takes place in the mixing vortex at the center of the tank. The least intense mixing takes place at the tank inner surface, where viscous drag is pronounced. It turned out that plant operators were introducing the viscous component at the tank edge; and because it was a dense liquid, the material accumulated at the bottom of the tank where it was difficult to mix.

Once the liquid was introduced into the vortex region in the tank middle, the problem was eliminated, and process time substantially improved.

CHAPTER THREE

MASS TRANSFER VS. KINETIC CONTROL

1. **Mass transfer** is the net movement of mass from one location to another and occurs in many processes. A common example is the evaporation of water from a pond to the atmosphere. Mass transfer can be applied to a number of chemical engineering problems.

2. **Mass Transfer (diffusion)-controlled Reactions** are those which occur so quickly that the reaction rate is the rate of transport of the raw materials to the reaction site, such as a catalytic reaction.

Catalytic reactions involve both mass transfer and chemical reaction. The overall reaction rate typically relies on the mass transfer or diffusion between liquids or gas to the catalytic structure.

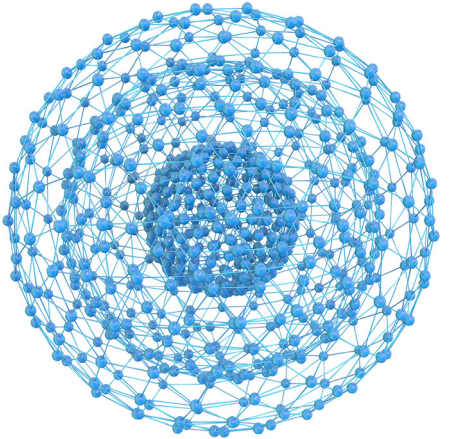


Figure 5: Catalyst Particles Showing Diffusion

Catalyst Particles Showing Diffusion

The catalytic reaction takes place after the reactants diffuse through the fluid layer surrounding the catalyst particles, into the pores within the particle (internal diffusion). The internal diffusion of the molecules competes with the reaction.

The kinetic data obtained from catalytic reactors under these conditions cannot be used for formulating meaningful kinetic expressions because of distorting mass transfer effects.

3. **Kinetic Control** determines the final composition of the product when competing reaction pathways are slower than mass transfer. Potentially, competing reaction pathways influence the selectivity of the reaction – i.e., which pathway is taken.

EXAMPLE I

One of my first assignments as a research engineer was to optimize a series of cumene oxidizers located at a petrochemical plant. In these types of units, cumene is oxidized to cumene hydroperoxide (CHP), which is decomposed to form phenol and acetone.

The technical problem which I was asked to tackle was the development of an optimum temperature profile for the cumene oxidizer system. These were five isothermal 10,000-gallon tanks in series, with air bubbled up at the bottom.

Each tank's temperature needed to be kept in the kinetic regime – where the chemical kinetic reaction between the cumene and oxygen predominated. The key for process optimization was determining that

temperature for each oxidizer where kinetic control just came into equivalence with mass transfer control.

I wrote a computer optimization program that balanced chemical oxidation kinetics (temperature) with oxygen mass transfer (bubble size) to balance the two processes. The resulting optimum profiles boosted efficiency by 5% – saving the company $100,000 per year.

SECTION II

SEPARATIONS

CHAPTER FOUR

DISTILLATION

Distillation is used to separate components in a feed mixture based upon their relative boiling points. A simple, continuous column can separate two mixed components into distinct product streams.

Our understanding of the performance of both plate and/or random/structured packings in distillation has improved over the years. However, process engineers still cannot predict column properties using only the thermal and physical properties of the system being distilled.

Pilot plant distillation tests are usually required because critical scale-up data is missing or contradictory. Pilot tests are performed because management wants to minimize risk when building an expensive facility.

During distillation design, engineers need to determine the correct designs and material for construction: whether materials are corrosive or noncorrosive, and whether a high vacuum, or atmospheric, or high-pressure system will characterize the column. Atmospheric or pressure operation of the column is preferable to using a vacuum system.

The principal parameter upon which all column design is based depends on the relative volatility of the key components to be separated.

Once the top and bottom stream compositions are specified in the design phase, the condensation point of the top stream and the boiling point of the bottom stream can be determined at various pressures.

The temperature of the cooling water can be variable as well, changing by season or weather conditions. Cooling tower water used for condensing is typically supplied at 90 deg. F ("worst-case" summer temperature). City water, river water or chilled water may be available to provide a lower coolant temperature. River water in winter can be cooler than plant-chilled water in the summer. A facility located at Taft, Louisiana, on the Mississippi River showed this effect in the extreme: chilled river water in January developed vacuums that were superior to those of plant-chilled water in July.

A term commonly used is "Height Equivalent to a Theoretical Plate," or HETP – the height of packing to provide an ideal single stage of separation. Typically, the pilot tower diameter should be at least 10 times the size of the packing.

A large number of pilot plant tests are performed during the various stages in process development. This is especially true if novel packings or trays are used. Also important are the chemical analytical tools used (GC, LC, boiling point).

EXAMPLE I

Distillation can be used to purge impurities from an operation. In the operation of an acetone unit distillation train, production personnel realized that impurities were building up in the unit, and "burping" into the product. The question was posed to R/D as to how to prevent this.

Computer modeling of the distillation train showed that these impurities were building up in one of the distillation purification columns, where two immiscible organic components were coming into contact.

An engineering assessment, based on these simulations, suggested that a practical method of removing the concentrating impurities was to install a series of taps within the column, several inches apart. These could be opened to partially drain column accumulations. This fix was installed, and acetone quality improved markedly.

CHAPTER FIVE

CRYSTALLIZATION/ FRACTIONAL CRYSTALLIZATION

Crystallization processes are widely used for purifying solid materials. These processes are the best choices for processing solid materials needing high purity, such as pharmaceuticals. A crystallization process must be robust, reproducible and scalable. To guarantee reliable scale-up of a crystallization process, process experience and a robust pilot system are essential.

COOLING CRYSTALLIZATION

This is the most straightforward system – a solution is cooled until the solute crystallizes out, as illustrated here:

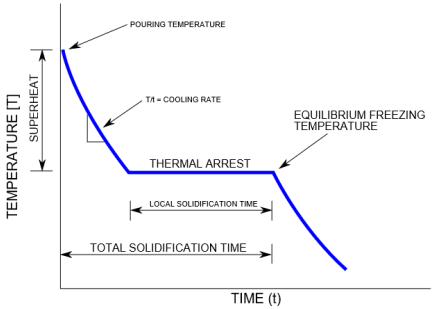


Figure 6: Cooling Crystallization Curve

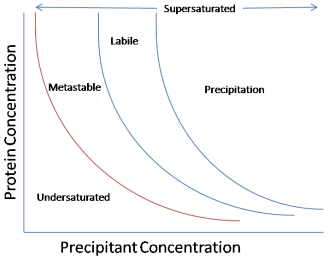


Figure 7: Phase Changes during Crystallization

The simplest cooling crystallizers are tanks equipped with a mixer for internal circulation, as a temperature decrease is obtained by heat exchange with an intermediate fluid circulating in a jacket. Operations can be batch or continuous. Batch processes normally provide a relatively variable quality of product as a function of batch time.

CRYSTALLIZATION DEVELOPMENT

The key step toward a robust crystallization process is a detailed solid-state phase diagram of the system. This provides an overview of the possible phases a solid can demonstrate and an understanding of the temperature-dependent behavior of the crystals.

Based on the chemical compatibility of the substance with various solvents, a first set of solvents or solvent mixtures is selected to determine the temperature-dependent solubility of the solutes.

Initial seeding is important to avoid supersaturation. Temperature and crystal size are important to prevent premature dissolution or uncontrolled crystallization (“crashing”).

Optimizing the Process: Once an initial crystallization process is established, further work is needed for optimization. Small changes in a

crystallization process may lead to undesirable events such as agglomeration, phase conversion, or premature nucleation.

Scaling up from Multigram to Multi-Kg capacities: The design process is repeated on a larger scale for proof of concept or direct delivery. All relevant information gained during the design and optimization stages, involving specialists from all disciplines, allows for a reliable piloting process.

EXAMPLE I

The final processing step for Bisphenol A is a crystallization step to separate the crude Bis-A from the mother liquor, followed by centrifugation and washing to remove the remaining liquids. A plant where I was responsible for R/D wanted to expand their Bis-A unit capacity, but plant engineers were uncertain if the crystallizers could handle the additional load. I was asked to look into the issue.

Fortunately, the R/D facility where I worked had a pilot crystallization unit where I could do the study. However, it was a vacuum crystallization unit, in which crystallization was initiated by removing liquids via vacuum – which presented a unique set of challenges. To maintain atmospheric conditions in the crystallizer, the unit was 32 feet off the ground (32 feet H20 = 1 atm. static pressure). The Bis-A unit

used cooling crystallization; that is, crystallization was initiated by cooling the hot solution. The vacuum design of the pilot unit was antithetical to good cooling design. Vacuum crystallizers tend to plug up during cooling operations.

After consultation with other R/D engineers, the secret to preventing plugging appeared to be a very slow cooling process. A special automatic control system was developed to cool the Bis-A solution to saturation over 24 hours, with the hope of preventing plugs from developing in the cooling heat exchanger.

After several shakedown runs, the experimental run was performed, using flow parameters mimicking the Bis-A plant. We cut it close but were able to complete the run just before plugging occurred, and demonstrated that the plant crystallizers could manage the additional load.

CHAPTER SIX

OTHER SEPARATION METHODS: ACTIVATED CARBON, ION EXCHANGE, FILTRATION

ACTIVATED CARBON

Many utilities and their communities are concerned about the presence of trace organics (TO) in their source waters. TOs include EPA-regulated contaminants, such as pesticides and volatile organic compounds (VOCs). One effective treatment option for the control of many TOs, even at their low levels of occurrence, is the use of carbon absorbers.

The cost of carbon treatment consists of the capital costs of the absorbers and their ancillary facilities, as well as operation and maintenance costs which are driven by the carbon replacement frequency. To accurately assess the carbon use rate, the operation time to the target effluent concentration, or “breakthrough,” is needed.

The most common bench scale test is the Rapid Small Scale Column Test (RSSCT), a quick method to design a large-scale adsorbent column from small-scale column studies. The RSSCT can be used to successfully replicate a pilot-scale test column study. The only thing required to design the pilot scale column is an understanding of the breakthrough and column tests required for conducting the experiments.

CHAPTER SEVEN

ION EXCHANGE

Ion exchange is an adsorption phenomenon whereby the mechanism of adsorption is electrostatic. Electrostatic forces hold ions to charged functional groups on the surface of the ion exchange resin. The adsorbed ions replace ions that are on the resin surface on a 1:1 charge basis.

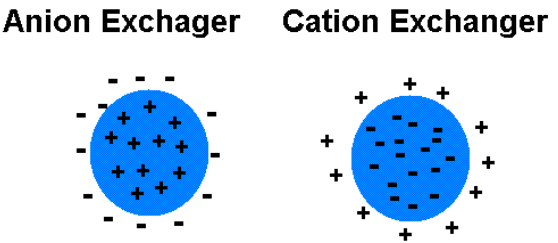


Figure 8: Typical Ion Exchange Resins

Figure 9: Ion Exchange Resins

Ion Exchange Resin Beads 2 by Tomásdearg92 under (CC BY-SA 3.0)

RESIN CLASSIFICATION

The design of resin is similar to that of carbon absorbers. Resins are classified by the type of functional group they contain and their percentage of cross-linkages:

Cationic Exchangers (attracted to negative charges):

- Strongly acidic
- Weakly acidic

Anionic Exchangers (attracted to positive charges):

- Strongly basic
- Weakly basic

CHAPTER EIGHT

FILTRATION

Filtration is one of the most commonly used manufacturing operations. Available formats include direct or normal flow filtration (NFF), or cross or tangential flow filtration (TFF).

Common objectives of filtration include separation of particulates and/or impurities from the process stream.

Filtration may also be used to significantly concentrate the feed stream (through ultrafiltration) to reduce the process stream's total volume or to reach a targeted product concentration.

Scaling up from laboratory bench to process scale is complex and requires consideration of several factors to ensure process robustness. Due to variability among raw materials and processes, most process developers use generous safety factors to ensure that their systems are not undersized.

The results from several investigations reveal that successful scale-up and improved process efficiency could be realized by one or more of the following:

- Selecting small-scale process development tools that maximize performance consistency.
- Modeling filter scale-up device performance differences.
- Instituting controls to minimize manufacturing variability.
- Accounting for process hydraulic effects associated with fittings and elevation.

Process developers favor small-scale sizing units for initial evaluations of filter performance in process streams and for estimating membrane area requirements for a full-scale process. Ideally, test-volume requirements are minimized and small-scale process development devices scale linearly to corresponding larger-sized devices.

FACTORS AFFECTING SCALING PREDICTIONS

A number of factors can complicate scaling predictions, including differences in flow configurations between pilot and commercial units, differences between expected and effective filtration areas (pleat

designs), pressure losses associated with plumbing and elevation, and variability in fluid properties and membranes.

However, even taking into consideration those issues, large safety factors (typically between about 1.5 and 2) are commonly used to allow for variability in realistic process conditions.

Research results reveal several important recommendations for achieving successful scale-up without introducing very large safety factors:

- Scale-up uncertainties can be minimized using a pilot design of similar configuration.
- Disagreements between reported and actual device filtration area (pleat design) should be identified and quantified for use in scale-up calculations.
- Variability in membrane performance can contribute significantly to large scale-up safety factors.

Accounting for such factors will result in more consistent and reliable scaling and translates directly into reduced risk and greater operational efficiency.

AN EXAMPLE: PILOT PLANT SEMI-PRODUCTION AND SCALE-UP

The formulation of chewing gum is a complex process for a seemingly simple, commonplace material. An important component is polyvinyl acetate polymer (PVA), which gives the gum its mouth "feel."

Counterintuitively, "soft" chewing gums require a harder, nonstandard high molecular weight (MW) PVA. A company for which I worked wanted to enter this market, and I was asked to create and scale the proper MW PVA.

Via gel permeation chromatography (GPC), we found that the MW of the required PVA was 26K versus 8K for the standard PVA. We then created a small-scale tubular polymerization reactor, where we imposed different reaction parameters (temperature, flow rate, etc.) and collected the resulting material for GPC analyses. When the correct GPC analysis was obtained, the reactor was operated to obtain a Kg sample to send to a gum formulator. The gum manufacturers confirmed that this PVA was satisfactory in their soft gum formulation.

The pilot unit conditions were then imposed on the commercial production unit. GPC analysis confirmed the correct MW, and several drums of material were made for a full commercial trial.

AN EXAMPLE: WHEN “NO CHANGE” IS INDEED A “CHANGE”

Polyethersulfone (PES) filtration membrane is made by dissolving PES polymer in a set of specific solvents, extruding the solution onto a steel belt, and drying off the solvents.

My company had qualified a specific PES for use in our processes, and the material had behaved consistently for years. Our supplier was sued for patent infringement by another supplier, and to get around the patent issue, our supplier added a small amount of Bis-Phenol A to their PES. My company was assured that this additional substance would have “no effect” on our processes. Based on this assurance, and to save time and money, the “new” PES was placed into our process without qualification testing.

It did not take long for the process to fall apart. The addition of Bis-A created a radical change in filtration properties and our customers were outraged (not least of all because we had “no change” policies in our contracts). All our formulations had to be changed and revalidated. This took years – literally – and cost an untold amount of money.

SECTION III

MATERIALS OF CONSTRUCTION (MOC)

CHAPTER NINE

MATERIALS OF CONSTRUCTION

There are many options for construction materials to consider in chemical process plants. Common building materials used for process plants include carbon steel, stainless steel, steel alloys (Monel/Hastalloys), carbon composite, glass, titanium, plastic, and many more. Each has specific areas of use and specific weaknesses.

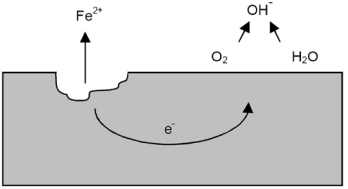


Figure 10: Chemistry of Corrosion

SELECTION CRITERIA

There are several criteria that will influence decisions when selecting the best MOCs. Three principal issues are:

- **Corrosion resistance –** What chemicals are you processing? As an example, chlorides such as hydrochloric acid (HCl) or salt will stress-crack stainless steel.
- **Cost** – What is the budget? You can build everything using Monel and PTFE if you have infinite funding (which some projects, usually DoD or DoE, do indeed have). But for most projects, an analysis of the available budget should be considered.
- **Expected operating life** – How long do you plan to keep the system in operation? Will operations be continuous or batch process; what is the on-stream time, and over how many years of service?

MATERIALS OF CONSTRUCTION (MOC) OPTIONS: CORROSION RESISTANCE

MOC for highly corrosive environments require careful consideration:

- **Hastalloys** – Nickel-molybdenum-chromium alloys containing tungsten.
- **Inconel** – Used in high-temperature applications, this material forms an oxide layer (similar to Al) to protect the surface from chemical attack.
- **Titanium** – This alloy combines high strength with low density to provide good corrosion resistance.
- **Monel** – Similar in concept to Hastelloy; a nickel-copper alloy that is resistant to sea water/salt solutions.
- **Plastics** (PTFE, PP, PVC, etc.) – A variety of plastic polymers can be used to provide extended service in hostile environments.

Glass – Borosilicate glass and glass-lined steel deserve additional considerations:

Glass has many benefits:

- Excellent corrosion and chemical resistance
- Surface properties
- Visibility
- Chemical inertness

However, several chemicals can cause corrosion of the glass: hydrofluoric acid, concentrated phosphoric acid and strong caustic solutions at elevated temperatures. Therefore, care must be exercised when specifying glass as a material of construction

In addition, glass is brittle and susceptible to thermal and mechanical shocks. Therefore, operating personnel need to be carefully trained if they are operating glass or glass-lined vessels, since operators tend to have heavy hands.

CHAPTER TEN

ENERGY SOURCES & ENERGY USES

The types of fuels used in each facility or plant vary due to production issues, weather, changes in the product mix, etc.

Process applications account for 80% of industrial energy use, and usually require fossil fuels:

- Process heating
- Chemical reactions, distillation and other processes
- Motor driven equipment: 15% of industrial energy use

Auxiliary Facilities – HVAC, lighting, etc. – account for 5% of industrial energy use.

COMMON ENERGY EFFICIENCY PRACTICES

Industrial facilities and manufacturing plants engage in a variety of practices to save energy:

- Energy assessments/management
- Energy standards: ISO 50001
- Energy-efficient processes and technologies: Best practice documentation is available

AN EXAMPLE: HEAT TRANSFER CONSIDERATIONS

An important part of pilot operations is understanding the heat transfer/energy considerations that go into a good design study.

One of my process responsibilities was designing a unit that would melt blocks of B-Staged (partially reacted) thermoset polymers used to make carbon fiber pre-pregs: sheets of carbon fiber impregnated with a thermoset polymer, supported on paper, that are heat cured to make parts. The idea was to make large volume runs of these resins, freeze the product into blocks, and thaw them out as needed. The melted resin

would then be used to make the coated paper that was part of the manufacturing process.

The Engineering Department, based upon calculated heat transfer parameters, developed a design for a resin melter of the desired capacity. R/D decided to pilot the design, at a reduced scale, to test out the design using real-world resin blocks. We found that the heat transfer of the unit, because of the insulating properties of the resin, was only 1/3 of the design requirements.

Engineering was warned of this issue but elected to go ahead with the original design of the production scale heater. As predicted, it was 1/3 too small. The unit had to be torn down and redesigned, at added expense. As the Vice President-GM later told the Engineering Department, “R/D warned you.”

Joel Shertok grew up in The Bronx, New York, a member of the first generation that was brought up on TV and computers. He was fortunate to attend a science and math high school that had an exceptional program, laying a sound groundwork for his future endeavors. Although his first love is European history, when it came time to pick a career path he chose chemical engineering because he saw great possibility and potential there.

Joel went on to receive his B.E. in Chemical Engineering from The Cooper Union in New York City and his Ph.D. in Chemical Engineering from Princeton University. His career has encompassed a wide breadth of experience and roles. He has worked for Fortune 500 companies, startups, publicly owned companies and private organizations.

Joel opened Process Industries Consultants in 2014 with the purpose of providing expertise on technical issues related to process and product scale-up and commercialization. He finds consulting work interesting and gratifying, and enjoys the variety and challenges it brings. He has, for example, consulted with a medical device company, a plasma torch company, a marketing firm, venture investors, an assisted living facility, advised on intellectual property rights, been an expert witness in a

lawsuit, consulted on Health, Safety, Environmental and Workplace regulation (OSHA, EPA), and merger and acquisitions.

He credits his travel with giving him an enriched perspective that has taught him to appreciate people of all backgrounds and cultures. Not only has he lived in and visited places across the U.S., but he also has international travel experience, having spent time in the UK, Ireland, Germany, and Russia.

European history is still a focus and a hobby for him, and although it doesn't overlap with chemical engineering, he finds it has enabled him to see the world from a broader perspective. He continues to enjoy reading widely on various aspects of history.

In addition to his diverse background, education and expertise, he truly enjoys the clients he is privileged to work with. He has a personal commitment to meeting deadlines, is a good writer and communicator, and has a pretty sunny disposition.

Joel counts himself lucky to be immersed in such a fascinating career. He has seen lots of things, lived in many places, and has tons of stories. Although he could be retired, he has every intention of continuing apace, as he enjoys the challenges of his work too much to stop.

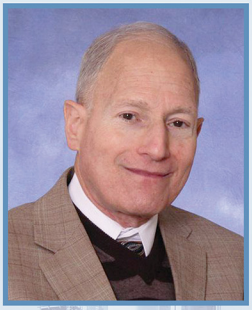
Joel lives in Newark, Delaware, with his wife, and enjoys spending time with his children and grandchildren.

CONTACT JOEL

Dr. Joel Shertok is owner/sole proprietor of a Process Chemical Engineering consultancy: Process Industries Consultants, Inc. (www.processindconsultants.com). Dr. Shertok is interested in helping your process company reach its technical and revenue goals. To this end, Dr. Shertok wants to work with your organization, and offers a free-of-charge initial consultation on your particular technical issue so he can better establish a line of communication. Contact him at: jshertok@processindconsultants.com.

THE ART OF SCALE-UP

DR. JOEL SHERTOK addresses chemical engineering concerns in an industrial environment, and the importance of piloting a reduced scale process to mimic proposed commercial operations. Topics include reactor considerations, separations, and materials of construction (MOC). Subtopics include descriptions, illustrations, and examples of reaction kinetics, mass transfer, mixing, kinetic control, distillation, crystallization and fractional crystallization, separation methods, ion exchange, filtration, selection criteria for materials of construction, energy sources and uses.



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