

stated in terms of screen mesh size according to the following U.S. standard (ASTM E11), where not all mesh sizes are given:

Mesh (Openings/inch)	Sieve Opening, mm
4	4.75
6	3.35
8	2.36
12	1.70
16	1.18
20	0.841
30	0.600
40	0.420
50	0.300
70	0.212
100	0.149
140	0.106
200	0.074
270	0.053
400	0.037

Heuristic 49: *Crushing of coarse solids. Use a jaw crusher to reduce lumps of hard, abrasive, and/or sticky materials of 4 inches to 3 feet in diameter to slabby particles of 1 to 4 inches in size. Use a gyratory crusher to reduce slabby materials of 8 inches to 6 feet in size to rounded particles of 1 to 10 inches in diameter. Use a cone crusher to reduce less hard and less sticky materials of 2 inches to 1 foot in diameter to particles of 0.2 inch (4 mesh) to 2 inches in diameter.*

Heuristic 50: *Grinding to fine solids. Use a rod mill to take particles of intermediate hardness as large as 20 mm and reduce them to particles in the range of 10 to 35 mesh. Use a ball mill to reduce particles of low to intermediate hardness of 1 to 10 mm in size to very small particles of less than 140 mesh.*

Heuristic 51: *Particle-size enlargement. Use compression with rotary compression machines to convert powders and granules into tablets of up to 1.5 inches in diameter. Use extruders with cutters to make pellets and wafers from pastes and melts. Use roll compactors to produce sheets from finely divided materials; the sheets are then cut into any desired shape. Use rotating drum granulators and rotary disk granulators with binders to produce particles in the size range of 2 to 25 mm.*

Heuristic 52: *Size separation of particles. Use a grizzly of spaced, inclined, vibrated parallel bars to remove large particles greater than 2 inches in diameter. Use a revolving cylindrical perforated screen to remove intermediate-size particles in the size range of 0.25 inch to 1.5 inches in diameter. Use flat, inclined woven screens (U.S. standard) that are vibrated, shaken or impacted with bouncing balls to separate small particles in the size range of 3 to 80 mesh. Use an air classifier to separate fine particles smaller than 80 mesh.*

5.9 REMOVAL OF PARTICLES FROM GASES AND LIQUIDS

Fine particles are most efficiently removed from dilute suspensions in gases and liquids by using centrifugal force in cyclones and hydroclones, respectively.

Heuristic 53: *Use a cyclone separator to remove, from a gas, droplets or solid particles of diameter down to 10 microns (0.01 mm). Use a hydroclone separator to remove, from a liquid, insoluble liquid droplets or solid particles of diameter down to 5 microns (0.005 mm). However, small amounts of entrained liquid droplets are commonly removed from gases by vertical knock-out drums equipped with mesh pads to help coalesce the smallest droplets.*

5.10 SUMMARY

Having studied this chapter, the reader should

1. Be able to implement the steps in Section 3.4 for process synthesis more effectively, using the many heuristics presented herein, and summarized in Table 5.2. The examples and exercises should enable him or her to gain experience in their application.
2. Recognize the limitations of the heuristics in Table 5.2 and the role of the process simulator in permitting the systematic variation of parameters and the examination of alternative designs. The reader should also recognize that the heuristics listed are a subset of the many rules of thumb that have been applied by design teams in carrying out process synthesis.

Table 5.2 Heuristics in Chapter 5

Heuristic	
Reaction operations	
1	Select raw materials and chemical reactions to avoid, or reduce, the handling and storage of hazardous and toxic chemicals.
Distribution of chemicals	
2	Use an excess of one chemical reactant in a reaction operation to consume completely a valuable, toxic, or hazardous chemical reactant. The MSDSs will indicate which chemicals are toxic and hazardous.
3	When nearly pure products are required, eliminate inert species before the reaction operations when the separations are easily accomplished and when the catalyst is adversely affected by the inert, but not when a large exothermic heat of reaction must be removed.
4	Introduce purge streams to provide exits for species that enter the process as impurities in the feed or are formed in irreversible side reactions, when these species are in trace quantities and/or are difficult to separate from the other chemicals. Lighter species leave in vapor purge streams, and heavier species exit in liquid purge streams.
5	Do not purge valuable species or species that are toxic and hazardous, even in small concentrations (see the MSDSs). Add separators to recover valuable species. Add reactors to eliminate, if possible, toxic and hazardous species.
6	Byproducts that are produced in <i>reversible</i> reactions, in small quantities, are usually not recovered in separators or purged. Instead, they are usually recycled to extinction .
7	For competing reactions, both in series and parallel, adjust the temperature, pressure, and catalyst to obtain high yields of the desired products. In the initial distribution of chemicals, assume that these conditions can be satisfied. Before developing a base-case design, obtain kinetics data and check this assumption.
8	For reversible reactions especially, consider conducting them in a separation device capable of removing the products, and hence driving the reactions to the right. Such reaction-separation operations lead to very different distributions of chemicals.

(Continued)

Table 5.2 (Continued)

Separation operations— liquid and vapor mixtures	
9	Separate liquid mixtures using distillation, stripping, enhanced (extractive, azeotropic, reactive) distillation, liquid-liquid extraction, crystallization, and/or adsorption. The selection between these alternatives is considered in Chapter 7.
10	Attempt to condense or partially condense vapor mixtures with cooling water or a refrigerant. Then, use Heuristic 9.
11	Separate vapor mixtures using partial condensation, cryogenic distillation, absorption, adsorption, membrane separation and/or desublimation. The selection among these alternatives is considered in Chapter 7.
Separation operations— involving solid particles	
12	Crystallize inorganic chemicals from a concentrated aqueous solution by chilling when solubility decreases significantly with decreasing temperature. Keep the solution at most 1 to 2°F below the saturation temperature at the prevailing concentration. Use crystallization by evaporation, rather than chilling, when solubility does not change significantly with temperature.
13	Crystal growth rates are approximately the same in all directions, but crystals are never spheres. Crystal growth rates and sizes are controlled by limiting the extent of supersaturation, $S = C/C_{saturation}$, where C is concentration, usually in the range $1.02 < S < 1.05$. Growth rates are influenced greatly by the presence of impurities and of certain specific additives that vary from case to case.
14	Separate organic chemicals by melt crystallization with cooling, using suspension crystallization, followed by removal of crystals by settling, filtration, or centrifugation. Alternatively, use layer crystallization on a cooled surface, with scraping or melting to remove the crystals. If the melt forms a solid solution instead of a eutectic, use repeated melting and freezing steps, called fractional melt crystallization, or zone melting to obtain nearly pure crystalline products.
15	Using multiple evaporators (called effects) in series, the latent heat of evaporation of water is recovered and reused. With a single evaporator, the ratio of the amount of water evaporated to the amount of external steam supplied to cause the evaporation is typically 0.8. For two effects, the ratio becomes 1.6; for three effects 2.4, and so forth. The magnitude of the boiling-point elevation caused by the dissolved inorganic compounds is a controlling factor in selecting the optimal number of effects. The elevation is often in the range of 3 to 10°F between solution and pure water boiling points. When the boiling-point rise is small, minimum evaporation cost is obtained with 8 to 10 effects. When the boiling-point rise is appreciable, the optimal number of effects is small, 6 or less. If necessary, boost interstage steam pressures with steam-jet or mechanical compressors.
16	When employing multiple effects, the liquid and vapor flows may be in the same or different directions. Use forward feed, where both liquid and vapor flow in the same direction, for a small number of effects, particularly when the liquid feed is hot. Use backward feed, where liquid flows in a direction opposite to vapor flows, for cold feeds and/or a large number of effects. With forward feed, intermediate liquid pumps are not necessary, whereas they are for backward feed.
17	When crystals are fragile, effective washing is required, and clear mother liquor is desired, use: gravity, top-feed horizontal pan filtration for slurries that filter at a rapid rate; vacuum rotary-drum filtration for slurries that filter at a moderate rate; and pressure filtration for slurries that filter at a slow rate.
18	When cakes of low moisture content are required, use: solid-bowl centrifugation if solids are permitted in the mother liquor; centrifugal filtration if effective washing is required.
19	For granular material, free flowing or not, of particle sizes from 3 to 15 mm, use continuous tray and belt dryers with direct heat. For free-flowing granular solids that are not heat sensitive, use an inclined rotary cylindrical dryer, where the heat may be supplied directly from a hot gas or indirectly from tubes, carrying steam, that run the length of the dryer and are located in one or two rings concentric to and located just inside the dryer rotating shell. For small, free-flowing particles of 1 to 3 mm in diameter, when rapid drying is possible, use a pneumatic conveying dryer with direct heat. For very small free-flowing particles of less than 1 mm in diameter, use a fluidized-bed dryer with direct heat.
20	For pastes and slurries of fine solids, use a drum dryer with indirect heat. For a liquid or pumpable slurry, use a spray dryer with direct heat.

Table 5.2 (Continued)

Heat removal and addition	
21	To remove a highly exothermic heat of reaction, consider the use of excess reactant, an inert diluent, or cold shots. These affect the distribution of chemicals and should be inserted early in process synthesis.
22	For less exothermic heats of reaction, circulate reactor fluid to an external cooler, or use a jacketed vessel or cooling coils. Also, consider the use of intercoolers between adiabatic reaction stages.
23	To control temperature for a highly endothermic heat of reaction, consider the use of excess reactant, an inert diluent, or hot shots. These affect the distribution of chemicals and should be inserted early in process synthesis.
24	For less endothermic heats of reaction, circulate reactor fluid to an external heater, or use a jacketed vessel or heating coils. Also, consider the use of interheaters between adiabatic reaction stages.
Heat exchangers and furnaces	
25	Unless required as part of the design of the separator or reactor, provide necessary heat exchange for heating or cooling process fluid streams, with or without utilities, in an external shell-and-tube heat exchanger using countercurrent flow. However, if a process stream requires heating above 750°F, use a furnace unless the process fluid is subject to chemical decomposition.
26	Near-optimal minimum temperature approaches in heat exchangers depend on the temperature level as follows: 10°F or less for temperatures below ambient. 20°F for temperatures at or above ambient up to 300°F. 50°F for high temperatures. 250 to 350°F in a furnace for flue gas temperature above inlet process fluid temperature.
27	When using cooling water to cool or condense a process stream, assume a water inlet temperature of 90°F (from a cooling tower) and a maximum water outlet temperature of 120°F.
28	Boil a pure liquid or close-boiling liquid mixture in a separate heat exchanger, using a maximum overall temperature driving force of 45°F to ensure nucleate boiling and avoid undesirable film boiling as discussed in Section 13.1.
29	When cooling and condensing a stream in a heat exchanger, a zone analysis, described in Section 13.1, should be made to make sure that the temperature difference between the hot stream and the cold stream is equal to or greater than the minimum approach temperature at all locations in the heat exchanger. The zone analysis is performed by dividing the heat exchanger into a number of segments and applying an energy balance to each segment to determine corresponding stream inlet and outlet temperatures for the segment, taking into account any phase change. A process simulation program conveniently accomplishes the zone analysis.
30	Typically, a hydrocarbon gives an adiabatic flame temperature of approximately 3,500°F when using the stoichiometric amount of air. However, use excess air to achieve complete combustion and give a maximum flue-gas temperature of 2,000°F. Set the stack gas temperature at 650 to 950°F to prevent condensation of the corrosive components of the flue gas.
31	Estimate heat-exchanger pressure drops as follows: 1.5 psi for boiling and condensing. 3 psi for a gas. 5 psi for a low-viscosity liquid. 7–9 psi for a high-viscosity liquid. 20 psi for a process fluid passing through a furnace.
32	Quench a very hot process stream to at least 1,150°F before sending it to a heat exchanger for additional cooling and/or condensation. The quench fluid is best obtained from a downstream separator as in Figure 4.21 for the toluene hydrodealkylation process. Alternatively, if the process stream contains water vapor, liquid water may be an effective quench fluid.
33	If possible, heat or cool a stream of solid particles by direct contact with a hot gas or cold gas, respectively, using a rotary kiln, a fluidized bed, a multiple hearth, or a flash/pneumatic conveyor. Otherwise, use a jacketed spiral conveyor.

(Continued)

Table 5.2 (Continued)

Pressure increase operations											
34	Use a fan to raise the gas pressure from atmospheric pressure to as high as 40 inches water gauge (10.1 kPa gauge or 1.47 psig). Use a blower or compressor to raise the gas pressure to as high as 206 kPa gauge or 30 psig. Use a compressor or a staged compressor system to attain pressures greater than 206 kPa gauge or 30 psig.										
35	Estimate the theoretical adiabatic horsepower (THp) for compressing a gas from: $\text{THp} = \text{SCFM} \left(\frac{T_1}{8,130a} \right) \left[\left(\frac{P_2}{P_1} \right)^a - 1 \right] \quad (5.1)$ <p>where SCFM = standard cubic feet of gas per minute at 60°F and 1 atm (379 SCF/lbmol), T_1 = gas inlet temperature in °R, inlet and outlet pressures, P_1 and P_2, are absolute pressures, and $a = (k - 1)/k$, with k = the gas specific heat ratio, C_p/C_v.</p> Estimate the theoretical exit temperature, T_2 , for a gas compressor from: $T_2 = T_1(P_2/P_1)^a \quad (5.2)$										
36	Estimate the number of gas compression stages, N , from the following table, which assumes a specific heat ratio of 1.4 and a maximum compression ratio of 4 for each stage. <table border="1" style="margin-left: auto; margin-right: auto;"> <thead> <tr> <th>Final Pressure/Inlet Pressure</th> <th>Number of Stages</th> </tr> </thead> <tbody> <tr> <td><4</td> <td>1</td> </tr> <tr> <td>4 to 16</td> <td>2</td> </tr> <tr> <td>16 to 64</td> <td>3</td> </tr> <tr> <td>64 to 256</td> <td>4</td> </tr> </tbody> </table> <p>Optimal interstage pressures correspond to equal Hp for each compressor. Therefore, based on the above equation for theoretical compressor Hp, estimate interstage pressures by using approximately the same compression ratio for each stage with an intercooler pressure drop of 2 psi or 15 kPa.</p>	Final Pressure/Inlet Pressure	Number of Stages	<4	1	4 to 16	2	16 to 64	3	64 to 256	4
Final Pressure/Inlet Pressure	Number of Stages										
<4	1										
4 to 16	2										
16 to 64	3										
64 to 256	4										
37	For heads up to 3,200 ft and flow rates in the range of 10 to 5,000 gpm, use a centrifugal pump. For high heads up to 20,000 ft and flow rates up to 500 gpm, use a reciprocating pump. Less common are axial pumps for heads up to 40 ft for flow rates in the range of 20 to 100,000 gpm and rotary pumps for heads up to 3,000 ft for flow rates in the range of 1 to 1,500 gpm.										
38	For liquid flow, assume a pipeline pressure drop of 2 psi/100 ft of pipe and a control valve pressure drop of at least 10 psi. For each 10-ft rise in elevation, assume a pressure drop of 4 psi.										
39	Estimate the theoretical horsepower (THp) for pumping a liquid from: $\text{THp} = (\text{gpm})(\text{Pressure increase, psi})/1,714 \quad (5.3)$										
Pressure decrease operations											
40	Consider the use of an expander for reducing the pressure of a gas or a pressure recovery turbine for reducing the pressure of a liquid when more than 20 Hp and 150 Hp, respectively, can be recovered.										
41	Estimate the theoretical adiabatic horsepower (THp) for expanding a gas from: $\text{THp} = \text{SCFM} \left(\frac{T_1}{8,130a} \right) \left[1 - \left(\frac{P_2}{P_1} \right)^a \right] \quad (5.4)$										
42	Estimate the theoretical horsepower (THp) for reducing the pressure of a liquid from: $\text{THp} = (\text{gpm})(\text{Pressure decrease, psi})/1,714 \quad (5.5)$										
Pumping liquid or compressing gas											
43	To increase the pressure of a stream, pump a liquid rather than compress a gas, unless refrigeration is needed.										

Table 5.2 (Continued)

Vacuum	
44	Estimate inlet leakage of air by: $w = kV^{0.667} \quad (5.7)$ <p>where, w = lb/hr of air inlet leakage, V = ft³ of volume of the equipment under vacuum, and k = 0.2 for pressures greater than 90 torr, 0.15 for pressures between 21 and 89 torr, 0.10 for pressures between 3.1 and 20 torr, and 0.051 for pressures between 1 and 3 torr.</p>
45	To reduce the amount of gas sent to the vacuum system if its temperature is greater than 100°F, add a condenser using cooling water before the vacuum system. The gas leaving the condenser will be at a dew-point temperature of 100°F at the vacuum pressure.
46	For pressures down to 10 torr and gas flow rates up to 10,000 ft ³ /min at the inlet to the vacuum system, use a liquid-ring vacuum pump. For pressures down to 2 torr and gas flow rates up to 1,000,000 ft ³ /min at the inlet to the vacuum system, use a steam-jet ejector system (one-stage for 100 to 760 torr, two-stage for 15 to 100 torr, and three-stage for 2 to 15 torr). Include a direct-contact condenser between stages.
47	For a three-stage steam-jet ejector system used to achieve a vacuum of 2 torr, 100 pounds of 100 psig steam per pound of gas are required.
Conveying granular solids	
48	If the solid particles are small in size, low in particle density, and are not sticky or abrasive, use pneumatic conveying with air at 1 to 7 ft ³ /ft ³ of solids and 35 to 120 ft/s air velocity for distances up to 400 ft. Otherwise, for sticky and/or abrasive solids of any size and density, use a screw conveyor and/or bucket elevator for distances up to 150 ft. For solid particles of any size and shape, and not sticky, use a belt conveyor, with inclination up to 30° if necessary, for long distances up to a mile or more.
Solid particle size change and separation	
49	Crushing of coarse solids. Use a jaw crusher to reduce lumps of hard, abrasive, and/or sticky materials of 4 inches to 3 feet in diameter to slabby particles of 1 to 4 inches in size. Use a gyratory crusher to reduce slabby materials of 8 inches to 6 feet in size to rounded particles of 1 to 10 inches in diameter. Use a cone crusher to reduce less hard and less sticky materials of 2 inches to 1 foot in diameter to particles of 0.2 inch (4 mesh) to 2 inches in diameter.
50	Grinding to fine solids. Use a rod mill to take particles of intermediate hardness as large as 20 mm and reduce them to particles in the range of 10 to 35 mesh. Use a ball mill to reduce particles of low to intermediate hardness of 1 to 10 mm in size to very small particles of less than 140 mesh.
51	Particle-size enlargement. Use compression with rotary compression machines to convert powders and granules into tablets of up to 1.5 inches in diameter. Use extruders with cutters to make pellets and wafers from pastes and melts. Use roll compactors to produce sheets from finely divided materials; the sheets are then cut into any desired shape. Use rotating drum granulators and rotary disk granulators with binders to produce particles in the size range of 2 to 25 mm.
52	Size separation of particles. Use a grizzly of spaced, inclined, vibrated parallel bars to remove large particles greater than 2 inches in diameter. Use a revolving cylindrical perforated screen to remove intermediate-size particles in the size range of 0.25 inch to 1.5 inches in diameter. Use flat, inclined woven screens (U.S. standard) that are vibrated, shaken, or impacted with bouncing balls to separate small particles in the size range of 3 to 80 mesh. Use an air classifier to separate fine particles smaller than 80 mesh.
53	Use a cyclone separator to remove, from a gas, droplets or solid particles of diameter down to 10 microns (0.01 mm). Use a hydroclone separator to remove, from a liquid, insoluble liquid droplets or solid particles of diameter down to 5 microns (0.005 mm). However, small amounts of entrained liquid droplets are commonly removed from gases by vertical knock-out drums equipped with mesh pads to help coalesce the smallest droplets.