In recent years, a number of factors have further emphasized the importance of solvent selection in the chemical process industries (CPI). These include the increasing regulatory scrutiny levied on industrial solvents, and an effort by CPI companies to reduce the environmental, health and safety (EHS) impact of their solvent use. In addition, specialized, high-performance solvents are available for some applications [1].

Key tools for determining which solvents are suitable for particular applications have been predicated on the concept that thermodynamic affinity between solvent and solute can help predict solution behavior. Conceptually, when assessing whether or not a molecule will dissolve in a solvent, engineers consider the difference between the energy cost of disrupting the intermolecular attractions of the solvent and solute molecules, compared to the energy gained through the intermolecular interactions. As Hansen and Abbott explain [2], to dissolve something, "you are essentially making a hole in the solvent, and that takes energy." If the solute-solvent interactions are greater than the sum of the energy losses from the two substances, then solute will dissolve.

**THE FOUNDATION OF HSP**

Hildebrand [3] developed a thermodynamics-based, one-dimensional solubility parameter in 1936 as a tool for eliminating certain solvents from consideration in process development. The Hildebrand solubility parameter (represented by lower-case delta) for a pure liquid substance is defined as the square root of the cohesive energy density (the amount of energy needed to remove a volume of molecules from their neighbors to an infinite distance). The same energy needs to be overcome for molecules to separate from each other and be surrounded by solvation. Equation (1) represents the Hildebrand solubility parameter.

\[
\delta = \left( \frac{\Delta H_v - RT}{V_m} \right)^{1/2}
\]

Where $\Delta H_v$ is the heat of vaporization, $V_m$ is the molar volume and $RT$ is the ideal gas term. The units are $(MPa)^{1/2}$.

The Hildebrand method formed the foundation for a later multimolecular solubility parameter system that has been refined over time by Charles Hansen [2]. The resulting Hansen Solubility Parameters (HSP), have become a useful tool in selecting solvents for chemical processes.

**THE HANSEN MODEL**

HSP are a set of three values that describe the thermodynamics of dissolving one substance into another. Solvents with similar Hansen solubility parameters generally are miscible in all proportions, and Hansen values that are different mean limited solubility. As Hansen puts it, "The HSP describe whether things prefer to be near each other or not." HSP attempt to characterize the energies and assign values to them as a way to predict solution behavior. Hansen's model essentially splits the Hildebrand solubility parameter into three components:

- Dispersion forces (Van der Waals interactions) are the attractions experienced by atoms placed at close distances
- Polar (dipole) interactions are electronic forces due to the positive-negative attraction of molecular dipoles
- Hydrogen bonding is a particular type of polar interaction, $b$, can also be considered a form of electron exchange, according to Hansen and Abbott [1]

The three components of the HSP are represented by Equation (2).

\[
\delta = \delta_D + \delta_P + \delta_H
\]

The three terms (in units of pressure) comprising the HSP are calculated for each substance through empirical solubility experiments of various types, depending on the material being measured. The HSP values are known for a large number of solutes. Also, molecular dynamics methods exist that can estimate HSP without the need for experimental data [4].

Once determined, the values are then treated as coordinates in a three-dimensional space, called Hansen space. (Figure 1), with axes corresponding to each of the three HSP components. The nearer to each other that two molecules are in this three-dimensional space, the more likely they are to dissolve into each other. To calculate the distance between the HSP of two substances ($R_{ij}$), the following equation is used:

\[
R_{ij}^2 = 4(\delta_D - \delta_D)^2 + (\delta_P - \delta_P)^2 + (\delta_H - \delta_H)^2
\]

Equation (3) was developed by plotting experimental data, and represents solubility data as a sphere, where solvents inside the sphere are effective at dissolving a given substance, and those outside are progressively less so.

**Polymer solubilities**

For solubilities of polymers, Hansen introduced a concept called the interaction radius ($R_i$). Solubility data determined experimentally on a given polymer for a range of solvents allow engineers to estimate a "volume of solubility" in the three-dimensional Hansen space. For most polymers, this volume of solubility is spherical in shape if the scale of the dispersion axis relative to the other axes is doubled. Solvents whose data values lie within the sphere will generally dissolve the polymer, while those lying outside the sphere will not.

Since it has been established, the ratio of $R_i$ to $R_{ij}$ can be determined. This ratio has been called the relative energy distance (RED) number.

- Systems with RED values less than one are sufficiently alike and will dissolve
- Systems with RED values equal to one mean the system will partially dissolve
- Systems with RED greater than one means the system will not dissolve

**Applications of HSP**

HSP are useful in selecting process solvents, additives in formulations, for the blending of polymers, and for the control of kinetics and monomer-sequence distributions in co-polymers. HSP have been used as the basis for solvent selection models and computerized methods, but they can also be used in manual calculations. The following represents some of the applications in which HSP have been used:

- Predicting effective solvents for polymers
- Studying dispersion of pigments
- Determining solubility properties of carbon nanotubes
- Finding solvent blends that are cheaper, perform better or that have smaller negative environmental impact

**Limitations of HSP**

HSP are often best used for screening purposes, with experimental data then used to validate (or not) the predictions. Limitations of the HSP that are discussed by Hansen include the following:

- The parameters can be difficult to measure
- Molecular size plays a significant role in whether a substance dissolves within a given time period
- The HSP are an approximation
- Parameters vary with temperature

Ongoing work by Hansen, discussed in [2] has begun to address HSP limitations.

**References**

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Listing and temperature range chart for all Paratherm heat transfer fluids.
Earthquake fractionation

Some columns sway with the wind; some columns sway with the waves. In fact, hundreds of columns now reside offshore, on platforms and on barges. Most dry and sweeten gases. Some distill. The trays and packing distributors of such columns are regularly, appreciably out of level. Sloshing occurs. The packings are regularly, appreciably off vertical. Some of what we know about the design of such columns originated with work that was performed at Heriot-Watt University. Other universities and companies performed levelness and swaying research of their own.

In 1985, following the lead of Dr. Mike Lockett, of Praxair (and a winner of this magazine’s Personal Achievement Award), the company I worked for decided to use the University of Buffalo (UB) Earthquake Table to simulate a swaying distillation column. A 4-ft dia. Plexiglas test column was built and was placed on a skid along with a pump to circulate water and a blower to drive air through three test trays. The pump pulled water from the column’s sump and delivered it to the top of the column via a 12-ft tall 3-in. dia. pipe.

A customer was considering building a methanol plant on a barge on the Persian Gulf. That plant would have required distillation columns. The customer asked to witness the testing of specifically designed trays subjected to swaying/rocking motion.

In 1989, the UB Table was rented for one week. On day one, a forklift placed the skid-mounted column (with the pump and blower) onto the table. Eight 500-W spotlights were aimed at the column as were two film cameras. Surrounding the table were computers that were used by UB civil engineering students who studied building destructions. On days two and three, two technicians and I collected data from the column as the table was swayed from side to side. A technician sat in a control room and adjusted tilt angle and swaying speed per requests.

On day four, three client engineers joined the team. First, the pump and blower were turned on, and water and air were circulated through the column. Then, a technician flipped the switches to initiate the column’s swaying. Very unfortunately, the technician flipped the wrong switches. The pistons beneath the concrete table went immediately into earthquake simulation mode. The concrete table slammed the test column up-down-up-down-up-down about three times, until the weak link in the test column was clearly identified — the connection between the water pump and the water line. The bad news: The connection broke. The worse news: The pump kept pumping. A water spout 20-ft tall sprayed the entire laboratory. When the water hit the spotlights, they exploded. Technicians and engineers ran everywhere, none of whom knew exactly what had just transpired. Luckily, there was only enough water in the sump of the test column to allow the geyser to spout for about 2 min. Unfortunately, that was sufficient to cover every computer in water. Broken light bulb pieces were everywhere. Every engineer and technician was drenched. One client engineer looked like he had been swimming underwater in his three-piece suit. And that was my most embarrassing career moment.

Thereafter, several global companies initiated and completed research work on off-shore columns. Now, such columns are designed regularly — and easily — by the people who have experience with them.

Mike Resetarits
resetarits@fri.org
**WHO'S WHO**

**Clifford Johnson**, formerly of NACE International, is now president of the **Pipeline Research Council International** (Falls Church, Va.).

**Andrew Yeghnazar** is named president of **Blach Fluid Control** (Riverside, Calif.).

**John Harrower** is named chief operating officer of the offshore division for **Universal Pegasus International** (Houston), which provides engineering, project and construction management in the energy industry.

**James Hubbard** becomes vice-president of commercial development for toll chemical manufacturer **InChem Corp.** (Rock Hill, S.C.). He will also serve as vice-president of technology for InChem's new subsidiary, Toll Solutions LLC (Duncan, S.C.).

Plastic-tubing manufacturer **New Age Industries** (Southampton, Pa.) appoints **Michael Allard** global distribution sales manager.

**Jarkko Sairanen** has been appointed executive vice-president of engineer-

**John Dalton, Sr.**, executive vice-president of engineering-and-construction company **Mustang** (Houston) is inducted into the National Academy of Construction.

**Andrew Way** has been appointed vice-president of services for **GE Oil & Gas** (Florence, Italy).

_Suzanne Shelley_

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Design Practices Committee Fractionation Research Inc.

The reboiler generally supplies most of the energy required to effect component separation. If too much heat is supplied, the tower may flood; conversely, if too little heat is available, separation performance may decrease via poor reflux ratio (pinching), excessive weeping or poor tray action. Proper design of reboiling systems involves coordinating aspects both outside and inside the tower. This article focuses on both of these aspects to ensure proper operation of the overall reboiler system. Important literature discussing these topics is also cited.

The objectives of reboilers

The design of tower reboiler circuits and bottom sections can be broken into several parts: fluid flow systems, exchanger types, liquid sumps and associated baffling, and drainoff and return arrangements.

Although these are not generally studied as much as the mass transfer equipment above, tower bottom sections should be considered key tower internals. A number of fractionator problems can be attributed to either improper bottom-section design or poor reboiler-circuit layout; taken together, they are thought to be the second-most common cause of tower problems [7]. To better illustrate this, consider the objectives that a properly designed tower bottom and reboiler system must accomplish:

- Provide adequate hydraulics for the reboiler circuit
- Separate and distribute the incoming vapor and liquid phases properly
- Absorb fluid momentum and prevent mechanical damage to surrounding internals
- Prevent entrainment of bottom-tray overflow liquid or bottom-pool liquid by reboiler return fluids
- Provide adequate liquid inventory for startup and step changes in reboiler duty
- Provide sufficient liquid-residence and degassing time for downstream equipment
- Provide adequate net-positive-suction head (NPSH) for any bottoms pumps
- Maximize mass transfer capabilities of the reboiler (nearly one theoretical stage can be obtained via use of a staging baffle)
- Maximize available temperature driving force in the reboiler
- Accommodate transients in the concentration of heavy components in the feed
- Allow removal of fouling material from the tower bottom
- Allow safe column shutdown in the event of a process upset
- Minimize overall column height

Consequently, many factors come into play in designing a successful reboiler and tower bottom arrangement. The available literature does not address the subject in depth, and, especially with regard to multipass trayed towers. This paper is intended to clarify the design process and extend coverage to multipass tray towers.

Preliminary design work

The design process begins by definition of the design basis and selection of the reboiler type that best suits the particular application. “Reboiler type” refers to exchanger and circulation mode, such as vertical thermosyphon, kettle, internal, horizontal forced circulation, and so on. The designers proceed through the following steps:

1. Run tower simulation(s)
2. Determine reboiler type and method of process liquid circulation, using criteria from the next section (Selection of reboiler type) and Tables 1 and 2
3. Select tower bottom configuration (such as once-through, constant head recirculating, and so on) using criteria from the Tower bottom arrangements section and Table 3
4. Choose limiting case(s) for duty and bottoms product rate to be used in detailed design

After this, the designer would be ready to begin developing details of the tower bottom and reboiler circuit.

Selection of reboiler type

As noted above, selecting a reboiler type means determining the method of fluid circulation (thermosyphon, forced or none) and selecting an exchanger type (vertical, horizontal, kettle or internal). These decisions need to be made before any tower bottom internals can be designed, since internals vary substantially for different reboiler types. To aid in the selection process, considerations are discussed below starting with general rules of thumb and progressing to more specific issues. Simple conceptual examples of common reboiler types are shown in Figure 1, and a comparative summary of reboiler types is given in Table 1.

Thermosyphon reboilers are the most widely used type in distillation
<table>
<thead>
<tr>
<th>TABLE 1. COMPARISON OF REBOILER TYPES (ADAPTED FROM REF. 3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boiling side</td>
</tr>
<tr>
<td>--------------</td>
</tr>
<tr>
<td>Typical tube</td>
</tr>
<tr>
<td>Heat transfer rate</td>
</tr>
<tr>
<td>Plot space requirement</td>
</tr>
<tr>
<td>Process piping</td>
</tr>
<tr>
<td>Pump required</td>
</tr>
<tr>
<td>Extra column skirt height requirement (if bottoms product is not pumped)</td>
</tr>
<tr>
<td>ΔT requirement</td>
</tr>
<tr>
<td>Residence time in heated zone</td>
</tr>
<tr>
<td>Process side fouling tendency</td>
</tr>
<tr>
<td>Performance with high viscosity liquids</td>
</tr>
<tr>
<td>Ability to handle large surface area</td>
</tr>
<tr>
<td>Maintenance and cleaning</td>
</tr>
<tr>
<td>Susceptibility to instability</td>
</tr>
<tr>
<td>Design data</td>
</tr>
<tr>
<td>Capital cost</td>
</tr>
<tr>
<td>Operating cost, excluding heating medium</td>
</tr>
<tr>
<td>Safety issues</td>
</tr>
</tbody>
</table>

systems and are usually considered first. A “thermosyphon” reboiler utilizes the density difference between the liquid in the tower bottom and the mixed-phase fluid in the reboiler and return line to drive reboiler process flow. Thermosyphon reboilers are gravity-flow systems. To summarize their advantages, they are relatively compact and economical, require no pumps, and offer relatively high heat-transfer rates (for small exchanger size) with relatively low residence times in the heated zone.

Of course, thermosyphon systems are not applicable in all circumstances. They are recommended for the following conditions:
- High liquid viscosity (viscous-liquids friction loss dampens fluid circulation)
- Fouling systems (pumped systems achieve higher velocities that help mitigate fouling)
- Adequate driving head cannot be attained economically (instead, consider a kettle system)
- Large operating load variations or shutdown rates are required (instead, consider a pumped system)
- High reliability is a key factor (kettle or forced circulation systems are preferred for this) Sometimes thermosyphon reboilers can be troublesome with vacuum systems because even a small liquid head has a large impact on the boiling point, leading to large and head-dependent preheat zones in the exchanger [2]. This is especially true for services where the liquid boiling range or circulation driving-head varies routinely. However, if the driving head is kept steady, a reliable vaporization curve is available and care is taken in modeling the hydraulics, thermosyphon reboilers can be successfully used in vacuum service. Most existing vacuum thermosyphon systems tend to use vertical heat exchangers.

If one of the above thermosyphon limitations applies, a kettle or forced circulation system is generally preferred. For towers in clean services, an internal reboiler may sometimes be considered.

If a thermosyphon system is selected, the next decisions are to determine the flow and exchanger type.

<table>
<thead>
<tr>
<th>TABLE 2. REBOILER EXCHANGER COMPARISON: HORIZONTAL VERSUS VERTICAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Advantages</td>
</tr>
<tr>
<td>Vertical</td>
</tr>
<tr>
<td>Minimal plot space requirement</td>
</tr>
<tr>
<td>Return piping typically short to very short</td>
</tr>
<tr>
<td>Relatively small capital cost</td>
</tr>
<tr>
<td>Fouling process side</td>
</tr>
<tr>
<td>High pressure process side</td>
</tr>
<tr>
<td>Horizontal</td>
</tr>
<tr>
<td>Good for large heat-exchanger area requirement</td>
</tr>
<tr>
<td>Requires moderate ΔT driving force</td>
</tr>
<tr>
<td>Better access for maintenance</td>
</tr>
<tr>
<td>Often requires less tower or skirt height</td>
</tr>
</tbody>
</table>
The choices for flow type are once-through and recirculating; the choices for exchanger type are vertical and horizontal.

Once-through flow is useful for strippers and other low-boilup services where the mass flowrate of vapor in the reboiler return is less than about 40% of the bottoms-product mass flowrate [4]. Recirculating flow is required in services where reflux rates are high compared to product rates, such as splitters. More information about once-through versus recirculating reboilers is given in the Tower bottom arrangements section below.

Selection of a vertical or horizontal exchanger can be made based on each option's advantages and disadvantages as given in Table 2. The published literature gives conflicting accounts about vertical versus horizontal exchangers [5-7], leading to some confusion about selection practices. Sloley [8] provides a detailed discussion of factors affecting this decision, and explains that vertical exchangers predominate in chemical applications, while horizontal exchangers are prevalent in petroleum-refining applications.

Selection by process issues

Fouling service (process side). Fouling service, as used herein, refers to a fouling tendency of process fluid in the tower bottom rather than the heating medium. The preferred bottoms arrangement for fouling service is forced circulation. Forced circulation systems (using a pump) can achieve much larger reboiler-circuit velocities than thermosyphon systems, which aids in keeping exchanger tubes clean. The forced circulation reboiler can be vertical or horizontal, as long as the fouling fluid is on the tube side (this is more typical of vertical exchangers). If a forced system is not suitable, the next best alternative is generally a vertical thermosyphon system. Kettle and internal reboilers should be avoided due to long residence times in the heated zone and high vaporization rates.

Vacuum systems. These can be a problem for thermosyphon systems because even a small liquid head has a large impact on the boiling point, leading to large and head-dependent preheat zones in the exchanger [21]. Thermosyphon reboilers can be successfully used in vacuum service, but the hydraulics must be carefully studied. Small errors in predicted friction losses or hydrostatic head above the exchanger can lead to large errors in the vaporization percentage and return-line-fluid density, which can adversely affect their hydraulics and heat transfer.

Forced circulation systems are easier to design for vacuum services. One particular forced circulation setup for vacuum service is the suppressed-vaporization system (Figure 1D), where the flow control valve is placed downstream from the reboiler [9]. No vaporization occurs in the exchanger itself (sensible heat transfer only), so the heated liquid flashes as it traverses the downstream valve. Another way to suppress vaporization in forced circulation systems is to use an orifice at the column return nozzle. Note that these valves or orifices can experience erosion as the liquid flashes across them under vacuum conditions, producing high exit velocities. For this reason, some practitioners recommend the use of control valves having contoured plugs, and some completely avoid suppressed vaporization systems. Also, the high fluid velocities produced by a valve or orifice at the tower inlet can cause fluid distribution problems or mechanical damage inside the tower unless specific provisions are made to handle these.

FIGURE 1. The common reboiler types are shown here: A. Vertical thermosyphon; B. Horizontal thermosyphon; C. Forced circulation; D. Suppressed vaporization; E. Standard kettle; and F. Trapout kettle (see also Table 1)
With clean process fluids, the designer of a vacuum system may wish to consider a falling film reboiler (which is outside the scope of this paper).

**Safety.** Forced circulation systems require pumps and often pump seals. The hazards of a seal leak should be considered, especially for flammable or toxic fluids. Thermosyphon systems avoid the pump and the seal leakage problems. Internal reboilers have large flange connections that may have substantial moment arms applied by the heavy tube bundles, if they are not supported properly. The flanges are prone to leak and have been known to cause fires.

**Ease of maintenance.** During shutdowns, access space (rather than reboiler type) is generally the prime factor for ease of maintenance, but the reboiler TEMA (Tubular Exchanger Manufacturers Assn.) type is also important. The designer can specify exchanger inlet and outlet heads that allow the tubes to be inspected and cleaned without requiring removal of external piping. The reboiler can also be designed for easy tube bundle removal to facilitate inspection and mechanical cleaning or hydroblasting [10]. Selection of the correct shell type is also very important to ensure proper fluid circulation, minimize fouling potential and maximize on-stream time.

In services where online cleaning is necessary, internal reboilers should be avoided. In fouling services, a spare exchanger is often provided, but this is not practical with internal reboilers.

If the process side is dirtier than the heating medium, a design that allocates process fluid to the tube side is often preferred. Conversely, if the heating medium is dirtier, it is preferred to allocate it to the tube side.

Typically, vertical exchangers have the process fluid on the tubeside, and horizontal exchangers have the process fluid on the shell side — although these are not absolute rules. For kettle and internal reboilers, however, process fluid is always on the shell side.

**Reliability.** From a process standpoint, well-designed kettle reboilers are considered the most reliable, although vertical thermosyphon systems are also considered to be quite good. Forced circulation systems can be robust, but this depends on the reliability of the pump. Horizontal thermosyphon systems and internal reboilers are considered average in terms of reliability.

**Stability when perturbed.** When subjected to tower swings, the most stable systems are forced circulation systems with flow control upstream of the exchanger, followed by kettle systems. Vertical and horizontal thermosyphon systems are more sensitive to operating perturbations; however, use of a constant head baffle in the tower bottom design may greatly improve their stability.

**Approach temperature.** For a given heating medium, once-through systems give the largest cool-end “approach temperature,” or thermal driving force, in the reboiler exchanger. This is because the process side feed to the reboiler is comprised solely of liquid from the bottom tray, which is the coolest possible reboiler feed. Conversely, recirculating systems with high tower reflux ratios provide the smallest driving force because a large percentage of the reboiler feed is material from the reboiler effluent.

As for exchanger types, vertical exchangers require the greatest driving forces, while kettle types require the least. Forced circulation systems allow for the greatest driving forces without concern for process side fouling because they can be designed with high process-fluid velocities.

**Required heat transfer area.** Vertical reboilers are limited in tube length (see below) and are also limited to about four shells per tower [11], so the heat exchange areas they can provide are limited. Horizontal and kettle reboilers are greatly preferred when large area is required. Internal reboilers can also limit available heat-transfer area unless the tower is increased in height or swaged out to accommodate more or larger bundles.

**Capital cost.** Internal reboilers are typically the least expensive because they eliminate external process piping and reboiler exchanger shell(s), although in some cases this advantage is negated by bottom section height or diameter increases to accommodate larger heat-transfer bundles. Vertical thermosyphon systems generally rank second lowest in cost because the return piping is usually very short. Horizontal thermosyphon and forced circulation systems are considered moderately expensive. Vertical and horizontal thermosyphon systems are typically the most capital intensive due to exchanger shell size and foundation requirements.

**Operating cost.** Other than the cost of the heating utility, thermosyphon systems have no operating costs due to the use of gravity acting on density differences to drive reboiler fluid flow. Forced circulation systems are more expensive to operate due to pumping and associated pump-maintenance costs.

**Plot space requirement.** Internal

---

**TABLE 3. COMPARISON OF TOWER BOTTOM ARRANGEMENTS**

<table>
<thead>
<tr>
<th>Type</th>
<th>Primary advantages</th>
<th>Primary disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Once-through trap</td>
<td>Full theoretical stage. No bottoms recontact with hot reboiler tubes</td>
<td>Bailup ratio limited to 40% of the bottoms rate. Gives highest reboiler outlet temperature, incompatibility with forced circulation. Leakage from trap or trap outlet can restrict heat transfer, even make system inoperable</td>
</tr>
<tr>
<td>Once-through collector</td>
<td>Full theoretical stage. No bottoms recontact with hot reboiler tubes. Compatible with forced circulation</td>
<td>Bailup ratio limited to 40% of the bailup rate (thermosyphon reboilers). Produces high reboiler outlet temperature. Chimney tray, fewer active tray(s). Partition baffle: reduction of bottoms product residence time</td>
</tr>
<tr>
<td>Constant head</td>
<td>Thermosyphon flow stability during upsets. Does not limit bailup ratios</td>
<td>Partial theoretical stage only. Constant head compartment(s) must be leak tight. Increased likelihood of reboiler fouling. Battery unnecessary and can be troublesome at high bailup ratios [17]. Complicated baffles can breed hydraulic bottlenecks [16]</td>
</tr>
<tr>
<td>Standard kettle</td>
<td>Simple bottom configuration with vapor only return. Full theoretical stage</td>
<td>High cost. Long residence time of bottoms material in heated zone. Precise exchange elevation required</td>
</tr>
<tr>
<td>Trapout kettle</td>
<td>More product residence time available than standard kettle</td>
<td>Product spends more time at maximum temperature than standard kettle. May require more height than standard kettle</td>
</tr>
<tr>
<td>Unbaffled</td>
<td>Simple, low cost. Good for high bailup ratios</td>
<td>For recirculating systems, gives lowest separation efficiency. For thermosyphon systems, operating perturbations can affect reboiler flow, prolonging upsets</td>
</tr>
<tr>
<td>Internal pool</td>
<td>Low cost</td>
<td>On-stream cleaning nearly impossible. Bottom liquid level difficult to assess. Long residence time of bottoms material in heated zone</td>
</tr>
<tr>
<td>Internal bath</td>
<td>Low cost. Nearly full theoretical stage</td>
<td>On-stream cleaning nearly impossible. Bailup ratios limited, similar to once through. Long residence time of bottoms material in heated zone</td>
</tr>
</tbody>
</table>
reboilers occupy very little (if any) plot space, followed by vertical exchangers, which generally require small plot spaces. Horizontal exchangers and kettle systems require relatively large plot spaces, especially if removable bundles are desired. Proper exchanger-head selection can help minimize plot space requirements.

It is beyond the scope of this article to cover actual design of the reboiler circuit piping and exchanger(s). For thermosyphon and kettle systems, the flow through the reboiler must be calculated from a pressure balance. It is essential that accurate assessments be made of fluid densities, extent of vaporization and friction losses so that the correct flow driving force and resistances are used in the pressure balance.

An article by Kern [22] describes the pressure balance particularly well and gives criteria for piping design. A comprehensive review of design correlations for vertical, horizontal and kettle exchangers is given by Fair [13]. A detailed description of kettle force balances from field data is given by Kister and Chaves [14]. Additional information about horizontal and vertical reboiler systems is contained in articles by Collins [25] and Orrill [16].

Tower bottom arrangements

This section discusses the relative merits and weaknesses of various tower-bottom arrangements that feed the reboiler and provide residence time. The descriptions here pertain to internal features, such as baffles or drawoff configurations, which comprise the tower bottom design. A summary of this information is given in Table 3.

Flow classifications. Bottom arrangements are classified into once-through and circulating. In once-through systems, liquid from the bottom tray traverses the reboiler only once. The liquid portion of the reboiler effluent is collected as net product and is kept separate from bottom tray liquid. Recirculating systems allow a portion of the reboiler effluent liquid to remix into the reboiler feed, thus permitting some of the liquid to traverse the reboiler two or more times. There are two main differences in these flow modes: once-through systems achieve a full stage of mass transfer in the reboiler, but their boilup ratios are limited by the maximum vaporization rate in the reboiler. Conversely, recirculating systems provide only a partial stage of mass transfer in the reboiler, but allow unlimited boilup ratios.

Because liquid leaving the bottom tray is the coolest steam possible for reboiler feed, once-through arrangements also give the greatest cold-end approach temperature in the reboiler exchanger. When their outlet temperatures are not excessive, they are also good for thermally degradable or fouling materials, where it is desirable to avoid repeated contact with hot reboiler tubes.

Un baffled tower bottoms are the most common type of tower bottom arrangement. Note that there are several different reboiler types that lack baffles in the tower bottom:

1. Once-through traps (sump liquid is reboiler return material, unmixed with bottom tray liquid)
2. Kettle systems (sump may hold liquid for residence time, but pre and post reboiler liquids do not mix)
3. Recirculating systems (bottom tray overflow mixes with reboiler return liquid)

Further classifications of the first two cases can be found in the respective sections below. The third item, unbaffled recirculating systems, is the primary subject of this subsection. Unbaffled recirculating systems are simple and inexpensive, which are the main reasons they are so widely employed. They are compatible with both thermosyphon and forced circulation reboilers. Figures 1A through 1D show simplified examples of unbaffled recirculating systems.

Advantages: Simple design requires no baffle inspection or maintenance. Reboiler and product trays may be combined in a single draw nozzle. Like all recirculating systems, it allows unlimited boilup ratios in the tower.

Weaknesses: It forfeits a fraction of a mass transfer stage; the reboiler simply becomes an enthalpy addition point. In thermosyphon applications, swings in the tower bottom liquid level can affect the reboiler circulation rate and duty, sometimes prolonging tower upsets. These swings can be at least partially countered by more-responsive heating fluid controls. These duty and control considerations apply more to exchangers with bare or low-fin tubes; exchangers with nucleate-boiling enhanced tubes provide much more stable heat-transfer rates as circulation varies.

Once-through trapout arrangements involve a total draw via either a downcomer trapout or a collector tray, per Figures 2A and 2C, to capture all of the liquid leaving the bottom tray and feed it directly to the reboiler. The reboiler return is directed to an unbaffled tower bottom, and its liquid drawn as bottom product. None of the bottoms liquid is recycled back to the reboiler, hence the name once-through. Trapout arrangements are generally limited to simple, single-draw configurations; multi-draw configurations, such as dual draws from two or four pass trays, are better handled with chimney trays (see below). Trapouts are used mainly with thermosyphon flow systems because they provide insufficient residence time for a pump.

Advantages: They can achieve one full theoretical stage of separation, if the trapout draw does not leak. The high elevation of the trapout draw generally provides good driving force for thermosyphon flow.

Limitations: With a thermosyphon system, reboil vapor is limited to about 40 wt.% of the bottoms product rate, due to the normal limitation of 30 wt.% maximum vaporization in thermosyphon exchangers [19]. This makes once-through thermosyphon systems appropriate only for low-boilup systems such as strippers. Although use of forced flow could increase the boilup rate, trapout draw systems suffer from a lack of liquid inventory to prevent pump cavitation. Thus a once-through collector system (see below) would be preferred for forced flow. Finally, in cases where the desired vapor-boilup rate exceeds the bottoms product rate, a recirculating reboiler should be used instead.

Weaknesses: The trapout draw box and bottom tray must be carefully designed and constructed to avoid leakage. Even then, leakage may occur during turnaround and startup. A recent malfunction survey [1] found that leakage issues render
Once-through tray thermosyphons are one of the most troublesome reboiler types. As the tray affords little degassing time, rundown lines from once-through thermosyphons must be sized for self-venting flow [20]. Thermosyphon flow is not compatible with high viscosity liquids.

**Once-through collector** systems remove the limitation of low liquid inventory inherent in once-through tray systems (see above). Well-designed collectors provide enough degassing time to overcome rundown line bottlenecks when the lines are slightly under sized from the recommended self-venting flow. The collector smooths out variations in flow to the reboiler caused by perturbations in tower operation. Once-through collector arrangements are compatible with both thermosyphon and forced flow systems. In forced flow applications, additional residence time is needed for liquid level control. As with once-through tray systems, reboiler vapor is limited to about 40% of the bottoms rate for thermosyphon driven flow and equal to the bottoms rate for pump driven flow. For vapor boilup ratios greater than these, a recirculating reboiler should be used.

There are two variations of the once-through collector system:
- Chimney tray collector (Figure 2B)
- Partitioned bottom (Figure 2D)

Both of these options have advantages and weaknesses. Chimney tray arrangements can provide plenty of residence time, but they take up height. Fewer active trays can be installed in a fixed tower height. Partitioned bottom arrangements can increase reboiler feed inventory without reducing tray count as long as sufficient bottoms residence time is available on the product side of the baffle. But they provide less liquid-flow driving head than tray or chimney tray arrangements, and care must be exercised to ensure the baffle is leak tight and mechanically strong.

**Preferential baffle** arrangements are recirculating systems that utilize a baffle in the tower bottom to segregate bottom-tray overflow liquid from reboiler return liquid. An opening in the baffle allows some reboiler return liquid to flow into and mix with bottom tray liquid. Thus the reboiler draw preferentially contains bottom tray liquid, but also contains recirculated liquid to make up the additional reboiler flow demand. The liquid level on each side of the baffle is equal, except for a small differential from liquid flowing through the hole. Preferential baffles are also known in the literature as **baffles with a large hole or baffles with underflow**. They may be used with thermosyphon or forced circulation systems.

Figures 4A and 4B show two configurations for single pass and multipass trayed towers. For multipass trays, extra spacing should be provided between the bottom tray and seal pans to accommodate liquid backup caused by the short overflow notches on the seal pan weirs. Note that some companies do not believe the added complexity and expense of preferential baffles are justified by their performance benefits, and omit these baffles entirely.

**Advantages**: The internal baffle does not need to be liquid tight. It gives more separation than an un baffled arrangement, but less than a full mass transfer stage. Like all recirculating systems, it allows unlimited reflux ratios in the tower.

**Limitations**: Preferential baffle systems do not develop a full equilibrium stage for the reboiler. As the tower reflux ratio increases, the ratio of recirculated material to bottom tray liquid in the reboiler feed also increases, and the usefulness of the reboiler as a separation stage steadily drops. When the ratio of tower bottoms product to reboiler draw rate falls below 50% (for example, splitting close-boiling components), a preferential baffle is considered no longer useful, and it should be omitted to provide an un baffled bottom arrangement. An additional limitation for thermosyphon driven systems is that they cannot handle high viscosity liquids.

**Weaknesses**: The weaknesses of preferential baffle systems are similar to those for un baffled towers. For a thermosyphon, a change in the bottoms liquid level will affect the reboiler circulation rate, and thus the reboiler duty. Some preferential thermosyphon systems have been known to work well only at one particular liquid level. It can be seen that all of these issues are related to duty control, and preferential baffle arrangements may therefore require responsive control schemes on the heating medium. As mentioned previously for un baffled tower arrangements, use of nucleate boiling enhanced reboiler tubes can mitigate these control issues.

**Constant head** arrangements are recirculating systems that maintain a constant-depth liquid pool above the reboiler draw. The most common configuration has a partition baffle, which separates the tower bottom into product- and reboiler-draw compartments (Figures 3A and 3B). Many other design arrangements are also available. Liquid from the bottom tray is directed into the reboiler draw side, as is liquid
Cover Story

from the reboiler return. Then, return liquid in excess of the reboiler draw requirement spills over a weir to the product side, where the level can be varied to provide rate control to downstream equipment. Constant head partition baffles are also referred to in the literature as baffles with overflow. Other constant-head configurations include chimney tray and collector box configurations, where an inventory of liquid is kept inside the tower above the bottom liquid pool, using a tray or box with an overspill weir. These alternative arrangements generally provide less liquid holdup than the partition baffle, although they may be less expensive to build.

The tower bottom should be designed to make the bottom tray liquid pass through the reboiler at least once before proceeding to the product compartment. Constant head arrangements are used only with thermosyphon circulating systems. Extra height should be provided between the bottom tray and the seal pans in certain multipass versions to accommodate liquid backup caused by short overflow notches on the seal pan weirs.

Advantages: Changes in product rate or level do not affect the reboiler circulation rate and duty, thus uncoupling the tower from minor downstream events. Like all recirculating systems, unlimited reflux ratios are allowed in the tower.

Limitations: Baffle tray or box leakage must be less than bottoms product rate, becoming more important as the tower reflux ratio increases. Thermosyphon circulation is not compatible with high viscosity liquids.

Weaknesses: Constant head systems generally require more internal pieces and increase complexity than other bottom arrangements. They also often require more tower height than other options. Because the bottom tray and reboiler return liquids are both directed to the reboiler feed compartment(s), constant head systems can collect fouling products or nonvolatile components in the reboiler loop. The reboiler feed piping should have means to drain these materials at low points.

Constant head systems are troublesome and should be avoided in high reflux ratio systems such as C3 splitters. In these systems the baffle overflow becomes a tiny fraction of the total liquid rate, and the overflow baffle becomes unsuitable to provide a steady flow. One troublesome case was reported [17].

Sometimes the baffle arrangement gets complicated, especially with multipass trays. Complicated baffle designs breed hydraulic bottlenecks. The simpler the baffle geometry, the less likely it is to generate such bottleneck. One case study of a baffle design causing a hydraulic bottleneck was described [18].

Kettle arrangements appear deceptively simple from a process standpoint. Liquid from the bottom tray of the tower is drawn and directed to a kettle reboiler. The kettle is an exchanger that has a tube bundle immersed in a liquid bath, with substantial vapor disengaging space above the bundle. Vapor and liquid are separated in the reboiler's disengaging space, so the return line carries essentially vapor. Kettle arrangements are once-through systems; reboiler effluent liquid does neither recirculate nor backmix with bottom tray liquid.

Kettle reboilers are typically designed with an overflow weir, which creates a separate product compartment within the exchanger shell. Kettle designs with overflow weirs must have removable tube bundles (U-tube bundles or TEMA "S" or "T" type return heads). Some alternative kettle designs do not have overflow weirs; in this case the liquid bath is maintained via level control. Fixed tubesheets (non-removable tube bundles) may be used in this type of exchanger.

There are three types of kettle arrangements. The standard arrangement is most prevalent (Figure 1E). It collects bottom tray liquid in the tower bottom and feeds a kettle exchanger having an internal weir. No level control is needed on the tower bottom because the liquid level in the tower is governed by the weir elevation in the kettle exchanger. Level control is required on the bottoms product compartment of the exchanger.

The trapout kettle arrangement utilizes a trapout draw from the bottom tray, or a chimney collector tray, to feed a kettle exchanger with an internal weir (Figure 1F). Product overflowing the kettle weir drains back to the tower bottom where it is collected for residence time purposes. In this case, level control is placed on the tower bottom rather than the kettle product compartment. The trapout type typically requires more tower height in the bottom section because liquid must flow back from the exchanger to the tower sump. The kettle reboiler elevation also tends to be higher for these systems.

This trapout kettle arrangement can be very troublesome unless using a chimney tray with adequate degassing time as the trapout. Leakage or weep from a trapout tray, especially at startup or low rates, can prevent liquid from reaching the kettle reboiler, stopping its action altogether. This leakage can be avoided with a well-designed chimney tray trapout. Unless the trapout chimney tray provides adequate degassing time, the lines from the trapout to the kettle reboiler need to be designed for self-venting flow [20].

Figure 1P also shows two options for returning vapor from the kettle exchanger: above or below the collector tray. Note that the chimney riser area and riser vapor velocity are very different for these two options. In the case where the return vapor is introduced above the chimney tray, the risers act basically as vents, and very little riser area is required. When the return vapor is introduced below the chimney tray, the riser area must be substantially greater to handle the full process vapor rate.

The third type of kettle arrangement is basically a variation of the first arrangement. The overspill weir inside the kettle exchanger is eliminated, and the entire liquid inventory of the exchanger is placed on level control. Not only does this reduce the buildup of fouling material in the exchanger, it also permits manipulation of the fluid level to affect liquid entrainment into the return line. However, sensing the liquid level in a boiling liquid pool can be difficult, as mentioned below for internal reboilers.

Advantages: A kettle achieves a full theoretical stage of separation. The tower bottom configuration requires no baffles. The tower internals do not need
to separate mixed phase fluids nor absorb large fluid forces. Kettle reboilers with removable tube bundles are relatively easy to inspect and clean.

**Weaknesses:** Kettle reboilers are expensive. They have a long residence time at maximum temperature in the exchanger, and perform poorly with thermally degradable or chemically fouling materials. In addition, they are improperly designed more often than other types of reboilers because they appear so simple. A recent tower malfunction survey [1] found kettle reboilers to be the most troublesome reboiler type. Most all kettle-reboiler failures have been due to an improper force balance. Therefore it is imperative to focus the utmost attention to the kettle pressure balance (described in detail elsewhere [14]). The survey found that kettles whose force balance is adequate are usually not troublesome. The kettle force balance gives the liquid head required to drive flow from the tower to the exchanger and back through the vapor return piping. Sufficient disengaging space must be allotted in the kettle exchanger. Any entrainment increases the static head in the reboiler vapor return lines. Also, the entrainment is knocked out in the tower bottom, and from there it is returned to the reboiler. Increasing the friction pressure drop at the tower inlet and outlet lines. In the extreme case, the entrainment can become so high that the kettle begins to thermosyphon, as demonstrated by field measurements [14]. Practices for minimizing entrainment from kettles were described elsewhere [14].

As system pressure increases, kettle entrainment may become more important due to the decreasing rate of vapor/liquid phase separation at higher operating pressures, which is caused by lower surface tension and smaller phase density differences.

**Internal reboilers**, also known as stab-in reboilers or stab-in bundles, are reboiler exchanger bundles, which are inserted directly into the tower shell below the bottom tray. The bundle is submerged either in the tower bottom liquid pool or in a bath of liquid formed by damming the bottom tray overflow liquid per Figure 5A. With a bath arrangement, lighter materials boil off from the bath and the remaining liquid overflows to the sump as bottoms product, where it is collected for residence time purposes. In some cases, the bathtub arrangement is used further up in the tower as a side reboiler. Note that the Design Practice Committee generally recommends against using internal reboilers because they are known to have caused numerous operating and capacity problems in previous applications.

**Advantages:** A properly designed internal reboiler can achieve nearly a full theoretical stage of separation (similar to kettle types). Internal reboilers can be inexpensive in cases where they eliminate exchanger shells and associated process piping without substantially increasing the tower shell cost.

**Limitations:** Internal reboilers are limited to small diameter towers or special applications because tube-bundle heat-transfer area cannot grow as fast as tower cross-sectional area with increasing tower diameter. Multiple bundles may increase tower height, offsetting any cost advantage. The bath type arrangement is similar to a once-through reboiler and may limit the boilup ratio.

**Weaknesses:** On-stream cleaning is nearly impossible; the tower must be shut down for exchanger maintenance. Similar to kettle reboilers, performance is poor with fouling materials. Internal reboilers require extra tower shell height and incorporate large flange connections, which can leak, especially if the bundle is not supported properly inside the vessel. For the bottom pool arrangement, the tower bottom liquid level can be difficult to assess because of froth generated by the internal exchanger [22]. The tower liquid level tap must also be located well below the tube bundle to ensure that two-phase material cannot reach it and cause a false low-level reading. False level readings can mislead operators about the true froth height in the tower, and result in flooding by entrainment of froth to the tray above the reboiler bundle. For the bath arrangement, excessive frothing and hydraulic restrictions, caused by improper design of the bath basin, often bottleneck towers.

**Reboilers and tower elevation**

To minimize tower and foundation capital costs, it is generally desired to minimize the overall tower height. Typically this means designing the tower (including the reboiler type and bottom section) first, based on process requirements, then selecting the minimum tower skirt height that provides adequate head for all of the following purposes:
Reboiler circulation (thermosyphon driving force or pump NPSH)
• Bottoms product pump NPSH
• Tower or reboiler drainage to downstream equipment, if required

The sections below discuss head considerations for various reboiler types in more detail to allow an assessment of their contribution to required tower skirt height. Note that when an unbaffled bottoms arrangement is specified, the liquid used in the reboiler flow calculations should be based on the lowest operating liquid level allowed (typically designated LLL). But the thermal and hydraulic design of the reboiler circuit should comprehend both HLL (highest operating liquid level allowed) and LLL process limits, and the reboiler inlet and outlet lines should be sized to handle circulation rates at HLL operating conditions. If a constant-head baffle arrangement is used for a thermosyphon system, there will be different liquid levels to consider on the reboiler and product sides of the baffle, and the designer should use LLL on the product side for all product hydraulic calculations.

Vertical thermosyphon systems. Generally this type of exchanger is hung off the tower itself, and the height of the system is determined by the selected length of the exchanger tubes. Common tube lengths are from 6 to 20 ft (2 to 6 m), with the longer lengths applicable to designs that require large heat transfer areas (LTA). Reboiler tube length is often shorter at lower column process pressure (for example, near atmospheric pressure) to minimize liquid hydrostatic head, which maximizes LMTD (log mean temperature difference) because vaporization can start at a lower temperature. If the reboiler feed piping enters the exchanger channel from below, additional skirt height may be required for this as well.

Horizontal thermosyphon systems. In this case, the reboiler exchanger is typically located at a minimum practical distance above grade to allow for piping clearances, ease of maintenance, or condensate drainage if necessary (the reboiler tubeside outlet nozzle is usually located above the top of the condensate drum for this purpose). Then a pressure balance calculation is performed for the reboiler cir-
cuit (including return piping), which gives the required liquid height above the exchanger necessary to drive the desired reboiler flow. 

**Kettle systems.** Properly designed kettle systems do not usually require significant liquid head for reboiler flow, so the skirt height is typically governed by another factor such as bottoms-pump NPSH requirement. The elevation, however, must be high enough to satisfy the force balance without having the liquid level in the sump approach the reboiler return inlet. In the case of a trapout, the trapout must be at an elevation high enough so that the force balance does not lead to liquid overflow into the chimneys [23]. In the case of a tower whose pressure is sufficiently above downstream equipment to drive bottom product onward without a pump, the skirt height may be quite low. Conversely, if bottoms evacuation or drainage requirements dictate a significant skirt height, and it is not desirable to have the liquid level in the kettle inlet pipe, the kettle exchanger itself may need to be situated on a high foundation because of the elevation relationship between kettle over-spill weir elevation and bottom liquid level. This elevation difference is given by the kettle pressure balance as described previously.

**Forced circulation systems.** The liquid head necessary for a forced circulation system is based on the NPSH requirement of the reboiler circulation pump. Typically, the tower bottom tangent line is elevated about 15 ft (4.5 m) [17] to provide sufficient NPSH. If a separate product pump is used, its NPSH requirement may govern.

**Things to avoid**
In Figure 5A, we have an internal reboiler. Note that the Design Practice Committee generally recommends against using internal reboilers because they are known to have caused numerous operating and capacity problems in previous applications.

In Figure 5B, this two-pass arrangement is not recommended because the reboiler return fluid must pass through the downcomer's liquid curtain in an attempt to distribute itself evenly to both passes. The bottom tray should have two side downcomers in this case.

In Figure 5C, the reboiler return fluid is directed toward the bottom tray downcomer and/or seal pan. This design can fail in a number of ways, including: (1) backup of the bottom tray downcomer; (2) entrainment of seal pan overflow liquid by the returning vapor; (3) mechanical failure of the bottom tray downcomer from fluid impingement; or (4) heat transfer from reboiler return fluid to the liquid in the downcomer, causing vaporization and choking inside the downcomer.

In Figure 5D, the reboiler return pipe has been routed through the downcomer. Again, this can fail by vaporizing liquid in the downcomer and choking it. Also, if the bottom section trays are heavily liquid loaded, this design might block enough downcomer area to cause backup flooding.

*Edited by Gerald Ondrey*

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