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Revision Memo

Revision marks are not included in this revision because this is essentially a complete rewrite.

12/03 The highlights of this revision are:

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1. The Jet Flood, Ultimate Capacity, Probability of non-flood, Weeping, and TABLE 2 "Design Criteria" have been replaced with EMoTIP correlations and/or values.
2. Overall Flood has been added.
3. Downcomer Flood has been added.
4. Foaming Factor and Fouling Factor have been added.
5. Froth to Spray Transition correlation design limits have been modified.
6. Downcomer Seal correlations have been modified.
7. M-Method Entrainment correlation has been added.
8. Universal Ultimate Capacity correlation has been added.
9. Tray balancing explanation has been modified.
10. New design limits have been added.
11. Deleted all Figures in the Appendix that represented old correlations.
12. Deleted **SIEVE TRAY CALCULATION FORMS** at the end of the Section.
13. Added clear liquid height term used in deck frothing, as well as clear liquid height term used in the total tray pressure drop and downcomer backup calculations.
14. Added a discussion of the EMoTIP design algorithm.
15. Updated discussion of general design considerations.
16. Added figure showing tray performance diagram calculated with EMoTIP for three pressure levels.
17. Added figures showing the design consideration weighting function for the various design variables.
18. Added the EMoTIP weep point and weep rate correlation.
19. Changed the "Detailed Design Procedure" section to a "Capacity/Performance Restriction Mechanism" section to reflect the EMoTIP approach.
20. Restructured the "Basic Design Considerations" section to better reflect the EMoTIP approach.
21. Mention of old programs have been replaced with EMoTIP.
22. Updated TABLE 3 EQUATIONS FOR DETRMINING LIQUID AND VAPOR SPLITS

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SCOPE

This section covers the techniques for specifying the process design features of sieve trays for new designs or revamps. It is assumed that the designer has already read Section III-A, *Device Selection and Basic Concepts,* and determined that sieve trays are the best choice for the design. The ExxonMobil Tower Internals Program (EMoTIP) utilizes the equations and criteria presented in this section for new tray designs and for rating existing trays. A discussion of the ExxonMobil Tower Internals Program (EMoTIP) design algorithm is included in this section. Detailed mechanical design as well as beam and hole layout are normally handled by the tray fabricator and therefore are not discussed in this section. A list of FRACTIONATION SPECIALISTS to contact for help is provided at the beginning of Section III.

For the design of tray-related tower internals, such as nozzles, drawoff boxes and reboiler connections, refer to Section III-H, *Tower Internals*. For the design of heat transfer trays, see Section III-F. To calculate tray efficiency, see Section III-I. Areas and lengths of chords are given in Section III-K.

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DESIGN PRACTICES

Section III, Fractionating Towers

GLOBAL PRACTICES

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16. Stober, B. K., *EMoTIP Sieve Tray Hydraulics Equations*, EMR&E Memorandum No. 2003 APTD 7, March 17, 2003.
17. Guarda, C. F., *Design Practices Section III-B Sieve Trays 1999,* EMR&E Memorandum No. 2003 APTD 14, March 14, 2003.

* Tower Internal Design Memorandum No. 1-15 have been archived in electronic form under 2003 APTD 121.

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BACKGROUND

The equations presented in this section for calculating sieve tray capacity and hydraulics are either ExxonMobil developed models or Fractionation Research, Inc. developed models that have been modified by ExxonMobil to improve the fit to the available Fractionation Research, Inc., (FRI) data and data from simulator and commercial tests. These equations represent the overall data more accurately than the correlations prepared by FRI, various vendors, or those available in the literature. These equations supercede those used in the Sieve Tray Design Program 1133 and the Multipass Sieve Tray Design Program 1143.

DEFINITIONS / EQUATIONS

For a discussion of such concepts as weeping, dumping, spray regime transition, jet flooding, downcomer flooding, overall flood, choking, efficiency, entrainment, flexibility, etc., see Section III-A, *Device Selection and Basic Concepts.* See **NOMENCLATURE** at the end of this section for symbol definitions.

Because of the complexity of the new models described in this section, they are no longer appropriate for hand calculation. Therefore, the **SIEVE TRAY CALCULATION FORMS** have been deleted from this revision. For those engineers who need to refer to the previous version of this Design Practice Section to access the **SIEVE TRAY CALCULATION FORMS** or to check the 1133 or 1143 program results, it has been archived as Reference 17. It can be accessed through the ExxonMobil eMemory application. Also, in some cases full details of the hydraulic models are not presented in this section. Those engineers who would like full details of the hydraulic models should retrieve Reference 16 which contains all the equations necessary to hydraulically rate a standard single pass sieve tray. The ExxonMobil Tower Internals Program (EMoTIP) incorporates all the calculations discussed in this section and is the recommended ExxonMobil tool for designing and rating sieve trays.

Equations that do appear in this version have been renumbered. They are presented in a form to calculate one pass of a tray only. By and large, only the customary unit versions of the equations are presented in the text. The main purpose for presenting any equations in this Design Practice is to give the design engineer an understanding of the functional forms and, where possible, the effects of the various design parameters on the hydraulics of a sieve tray. **The equations presented here have been validated in customary units only and are not recommended for hand calculations. EMoTIP should be used for all calculations and for design purposes.**

APPLICATION

Sieve trays can be used in almost all services. Their capacity and efficiency are at least as high as that of other standard trays used commercially. Flexibility is generally around 2/1, but ranges up to a maximum of about 3/1. For greater than 3/1 flexibility, valve trays are a better choice.

Sieve trays may be used in moderately fouling services, provided that large holes (3/4 to 1 in. [19 to 25 mm]) are used.

The following table lists the lower and upper operating limits based on the database used to develop the correlations and operating experience. This table contains the current limits over which the correlations contained in this design practice are considered to be accurate. If your case does not fall within these limits, contact your FRACTIONATION SPECIALIST to see what, if any, problems may exist. These are not recommended design values, for that see Table 1 and the other information contained in this section.

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VARIABLE	LOWER LIMIT	UPPER LIMIT
Pressure, psia (kPa)	3 (21)	450 (3100) distillation 900 (6200) absorption
Temperature, °F (°C)	– 130 (– 90)	800 (430)
Diameter, ft (mm)	1.0 (300)	50 (15,240)
Physical properties surface tension, dyne/cm (mN/m) liquid viscosity, cP (mPa•s) vapor density, lb/ft^3 (kg/m^3) liquid density, lb/ft^3 (kg/m^3)	 1 (1) 0.05 (.05) 0.005 (.08) 20 (320)	 75 (75) 20 (20) 5 (80) 80 (1300)
Tray spacing, in. (mm)	12 (300)	36 (910)
Open Area as % of A_b	3.5%	15%
Downcomer clearance, in. (mm)	1 (25)	3.5 (90)
Downcomer inlet area as % of A_s	6%	40% sloped; 25% straight
Number of passes	1	4
Outlet weir height, in. (mm)	0 (0)	4 (100)
Hole diameter, in. (mm)	1/8 (3)	1 (25)
Flow path length, in. (mm)	16 (410) for access	180 (4600 mm)

BASIC DESIGN CONSIDERATIONS

The ExxonMobil Tower Internals Program (EMoTIP) is available for designing and rating trays for fractionation columns. However, before using EMoTIP, it is essential that the designer have a basic understanding of the key parameters that influence tray design. This section provides a discussion of these key parameters and presents most of the equations used by the EMoTIP to calculate them. This section also includes certain "rules of thumb" that can aid the designer in achieving an optimum tray design.

The optimum combination of tower diameter, tray spacing, and number of liquid passes is the most significant consideration in new designs affecting tower cost and maintenance.

TOWER DIAMETER

See the above table for the limits on the minimum and maximum tower diameter when using this Design Practice. A FRACTIONATION SPECIALIST should be consulted on tower designs outside these limits. The tower diameter must provide enough cross-sectional area to avoid downcomer flood, jet flood, and ultimate capacity limitations. Large towers are sometimes designed in sections, with each section having a different diameter. This practice is not suggested for small towers.

TRAY SPACING

Tray spacing is normally set to allow easy access for maintenance. A tray spacing of 24 in. (610 mm) is the most common for columns 4 ft (1219 mm) and larger in diameter. This spacing is large enough to allow a worker to freely crawl between trays. For columns where frequent maintenance is expected, such as fouling and corrosive services, a tray spacing of at least 24 in. (610 mm) is recommended. A tray spacing of at least 24 in (610 mm) is also preferred for systems with a high foaming tendency. For columns smaller than 4 ft (1219 mm), a tray spacing of 18 in. (457 mm) is adequate for maintenance. Here, crawling between trays is uncommon because a worker can reach the column wall from the manway. A tray spacing smaller than 18 in. (457 mm) should be avoided because it makes access for maintenance difficult. However, in columns containing 100 - 200 trays, such as C2/C3 splitters, tray spacing can be as low as 12 to 18 in. (305 to 457 mm) to prevent excessive column height. Downcomer flood and jet flood requirements may require the use of tray spacings larger than the minimum. Spacings up to 36 in. (900 mm) may be used to permit a higher superficial vapor velocity or downcomer flood. While the ExxonMobil Tower Internals Program (EMoTIP) design algorithm selects tray spacings at 3 in. (75 mm) intervals for convenience, the designer is free to use any tray spacing desired as long as it is within the acceptable range of 18 to 36 in. (457 to 900 mm). The following table gives the minimum recommended tray spacing values determined by maintenance considerations and support beam depth.

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TOWER DIAMETER, ft (mm)	MINIMUM RECOMMENDED TRAY SPACING					
	CLEAN SERVICE (FOULING FACTOR = 0 OR 1)		FOULING SERVICE (FOULING FACTOR > 1)			
			1-Pass		2 or More Passes	
	in.	Mm	in.	mm	in.	mm
5 or less (≤ 1500)	18*	457	18*	457	–	–
5 to 8 (1500 to 2400)	18*	457	24	610	18*	457
8 to 10 (2400 to 3000)	18*	457	24	610	24	610
10 to 20 (3000 to 6000)	18*	457	24	610	24	610
Greater than 20 (> 6000)**	24	610	27	686	27	686

Notes:

* If there is no manhole between trays. Minimum tray spacing with a manhole is 24 in.

** For towers larger than 20 ft (> 6000 mm) in diameter, "lattice" type trusses must be used to facilitate maintenance and permit good vapor distribution. (See Section III-H for a picture of a lattice truss.)

NUMBER OF LIQUID PASSES

The capacity of towers with high liquid rates can usually be increased by the use of multipass trays. Since multipass trays increase the sensitivity to maldistribution, which may result in decreased efficiency, and are more expensive than single pass trays, they can be justified only if their use reduces the overall tower cost. Generally, this means that a capacity advantage of at least 5 to 10% for multipass trays is required. However, each case must be studied on its own merits, since overall tower cost depends on many factors, including height, diameter, operating pressure and materials of construction. If the liquid rate is greater than 17.5 gpm/in. of outboard weir/pass (43.5 dm3/s/m of outboard weir/pass), a FRACTIONATION SPECIALIST should be consulted because of the lack of reliable design data above this rate. More detailed selection criteria are given in Table 1.
If an existing tower is limited by downcomer flooding, which cannot be reduced by other hardware changes, the use of multipass trays should also be considered.
If a two pass design can be found, it will generally be preferred over a four pass design, due to increased cost for four pass designs and increased risk due to tray balancing and installation tolerances that are critical for four pass designs.

Transitions

Changeover from one number of liquid passes to another is frequently required where a feed stream or a circulating reflux stream is introduced. It is important to verify that such transitions do not restrict flow, cause maldistribution, or result in downcomer sealing problems. One to two pass transitions and two to four pass transitions are the most common transitions. This is because rectifying sections tend to have lower liquid rates than stripping sections and therefore require fewer passes. Refer to Section III-H for methods for achieving successful transitions from one number of liquid passes to another.

TRAY AND DOWNCOMER LAYOUT

Two important features of the tray layout are the bubble area A_b and the free area A_f (see Figures 12 and 13 in Section III-A). These in turn, depend on the liquid handling areas (downcomers) and waste area A_w, defined as any unperforated area farther than 3 in. (75 mm) from the edge of the nearest perforation. Normally, there is no waste area on a sieve tray unless a very low hole area is required (part of the tray is left unperforated) or if a shaped downcomer lip, recessed inlet box, or inlet weir is present.

Hole Area

The hole area on the tray should be large enough to avoid operating in the spray regime and small enough to ensure that excessive weeping is avoided. Hole area has a direct effect on dry tray pressure drop. The only way to obtain the desired dry tray pressure drop is to adjust the hole area. Increased hole area also helps reduce downcomer flood by reducing downcomer backup.

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Hole Size

Hole diameters on sieve trays usually range from 1/8 in (3 mm) to 1 in (25 mm). For most cases, a hole size of 1/2 in. (13 mm) should be used. The allowable range of hole sizes is outlined in Table 1. Determining the appropriate hole size for sieve trays depends on various factors such as: the nature of the service, tray hydraulics, and turndown. Small holes are not recommended for fouling or corrosive services because they may plug or partially plug the orifices on the tray, resulting in excessive pressure drops, decreased capacity, and lower efficiency. However, smaller holes increase jet flood capacity, particularly at low liquid loadings when operating in the spray regime. They will reduce the entrainment rate and reduce slightly the dry tray pressure drop. Small holes have a higher weeping tendency. While R&D studies have indicated that smaller hole sizes (0.125 in. [3 mm]) do have better entrainment characteristics for some systems, small holes on carbon steel trays have a tendency to "rust over" during tower hydrotesting or storage. 410 SS trays should always be compared with carbon steel, because their favorable corrosion characteristics for most refinery applications means that the thinner 410 SS decks are cost competitive with thicker carbon steel decks that include a corrosion allowance. There is a small but distinct process performance advantage for thinner trays. For moderately fouling services, hole sizes of 3/4 to 1 in. (19 to 25 mm) are recommended. Sieve trays are not recommended for highly fouling services. Do not mix panels with different hole sizes on the same tray.

Blanking

For revamps, hole area may be reduced by either using blanking strips or replacing the panels with ones having a smaller hole area. If blanking 50% or less of the hole area, blank single rows or pairs of rows of holes. If pairs of rows are blanked, leave single rows open; conversely, if single rows are blanked, leave pairs of rows unblanked. This minimizes the channeling of froth over the blanked tray. Blanking patterns should begin with either the second or third row adjacent to the outlet weir (depending on which blanking pattern is chosen), and shall proceed towards the inlet side of the tray. Blanking strips must always be perpendicular to the froth flow on the tray.

For large amounts of blanking (50% of the hole area or more):

- Use a combination of items mentioned above, but make sure that all panels have the same effective hole to bubble area ratio. Otherwise, channeling may result.
- Consider adding vertical baffles to restrict flow path width and create what is commonly referred to as a rectangular bubble area design. (See Figure C in Section III-I**,** *Improved Stripper Tray Design.*)
- Check adverse impact on tray efficiency (if any) because of the added waste area.

Downcomer Width And Area

The downcomer should have adequate area to prevent premature column flooding. The downcomer top and bottom width should result in a chord length at least 62.5% of the column diameter for the side downcomer on a one pass tray.

As a general rule, a sloped or stepped downcomer should be used if A_{di} is greater than 12% of A_s. To ensure good liquid distribution to the tray below, however, the downcomer outlet area also must be at least 6% of A_s. This assures that the chord length is at least 62.5% of the tower diameter for chordal downcomers. For two and four pass trays, the total downcomer outlet area for the side downcomers (or side plus center in the case of four pass) should be 10% and 14% of A_s, respectively. If the tower diameter exceeds 6 ft (1800 mm) and the liquid rate requires a downcomer area much less than 6% of A_s, consider the use of a modified arc (segmental) downcomer. (See Section III-K for sizing segmental downcomers.) If a segmental downcomer is used, it must be at least 6 in. (150 mm) wide. (See discussion in Section III-A on downcomers for more details.)

Outlet Weirs And Downcomer Clearances

Criteria for selecting outlet weir heights and downcomer clearances are given in Table 1. The downcomer clearance is the vertical distance between the bottom edge of the downcomer and the tray deck. This clearance should be no smaller than 1 in. (25 mm) and is based on avoiding excessive liquid velocity at the tray inlet and to provide an acceptable downcomer seal. Most refinery and chemical plant applications should have a downcomer clearance of 1.5 in. (38 mm) or larger.

Tray Balancing

Even when a new tray design or revamp meets all ExxonMobil criteria, the designer should check to see if the design is well balanced. A well balanced tray design will have the jet flood and downcomer flood at approximately the same percentage of their respective limits (e.g., 85% jet flood and 85% downcomer flood). This prevents building a potential bottleneck into a tower and permits the unit to be pushed to its maximum by plant personnel. The designer should run parametric cases in EMoTIP to balance a design for all potential operating points. Likewise, the designer should try to get all sections of the tower as balanced as possible (i.e., above the feed vs. below the feed, etc.). Some towers, such as low pressure, low liquid rate fractionators, will always be controlled by jet flood and/or entrainment rates. It will not be possible to balance these designs without violating geometric constraints on downcomer sizing. In this case a balanced design should not be attempted.

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Multipass Trays

Multipass trays allow an increase in tower capacity by lowering the tray or downcomer liquid load by splitting the tray liquid into two or more paths. Although multipass trays increase tray and downcomer capacity and lower tray pressure drop, they result in shorter flow path lengths. Shorter flow path lengths (smaller than 22 in. [559 mm]) reduce tray efficiency, and if very short, may be inadequate for accommodating tray manways. A flow path length smaller than 16 in. (406 mm) is not wide enough for a tray manway. A minimum flow path length of 18 in. (457 mm) is considered adequate for internal access purposes. Three-pass trays are not available within the EMoTIP design algorithm since their panels are much less symmetrical than two or four-pass trays, which makes it particularly difficult to achieve balanced liquid distribution. Three-pass trays are only available in rating mode within EMoTIP. Two-pass trays, if an acceptable design can be found, are generally preferred over four or three-pass trays.

Anti-jump Baffles must be provided on all center and off-center downcomer(s) of multipass trays if the liquid rate exceeds 4.2 gpm/in. of diameter/pass (10 dm^3/s/m of diameter/pass). This is to prevent liquid from jumping across (choking) the downcomer, and causing premature flooding (see Section III-A for further information on downcomer choking).

Multipass Tray Balancing

Three- and four-pass trays are more complex than one or two pass trays, in part due to additional tray balancing considerations. For a tray with multiple passes (see Figures 8 and 9), the design which provides the maximum flexibility is the one where the total tray pressure drop is equal or nearly equal for each pass. However, it is also desirable to maintain about an equal ratio of liquid to gas rate per pass for good efficiency. Furthermore, the percent of flood should be roughly in balance to avoid premature flooding by one pass only. Single pass trays obviously meet these criteria since there is only one flow path for the liquid and one for the vapor to travel. The criteria are also met in two pass trays since there is a common chamber at alternate trays that permits equal vapor and liquid flow as well as pressure drop per pass. However, since four pass trays do not have a chamber common to all passes at a given elevation, special care must be taken to ensure well-balanced operation.

To minimize the effects of maldistribution on efficiency, the designer should provide approximately equal bubble areas and equal hole areas for each pass (alternatively, an equal number of valves for valve trays). This will enable each pass to handle approximately the same vapor loading and have the same dry tray pressure drop. The designer should verify that equal liquid flow is provided to each pass. This can be achieved by specifying a picket fence weir on the center downcomer pass (the B pass, see Figure 9) that reduces the B pass outlet weir effective length to approximately the chordal weir length of the A pass. An alternate method of balancing is to use a different outlet weir height and/or downcomer clearance for each pass to promote or retard the liquid flow on specific pass(es) as needed. However, this is not the preferred method, because fine tolerances and adjustments on downcomer clearance are required and these are difficult to make during installation.

Another common tray balancing problem is that the percent of flood on the passes flowing toward the side of the tower (the A passes for three and four pass [see Figures 8 and 9], may be higher than the other passes. This is because the side downcomer weir length is relatively short, giving a high liquid weir loading and thus raising the calculated percent of flood. If the difference in overall flood is greater than about 4% between passes, the designer may choose to reduce the relative bubble area (keeping A_o / A_b constant) for the outboard passes to reduce the vapor rate to those passes. The liquid flow should then be re-balanced. Alternatively, the vapor split per pass can be varied by changing the A_o/A_b ratio per pass. This technique is more useful in designing revamps, where bubble and downcomer areas are already fixed.

The distribution ratio calculated by EMoTIP is the ratio of q_v/Q_L for two passes – the pass with the highest divided by the pass with the lowest gas to liquid ratio. The distribution ratio should be within 8% of unity at design conditions, in order to have the tray passes balanced from a hydraulic and efficiency point-of-view.

Another means of balancing the vapor split is to provide the center and off-center downcomers with vapor crossover pipes through the downcomers (also known as vapor tunnels), so vapor can flow from one chamber to another. This provides a means of vapor crossover between adjacent passes and helps equalize the pressure among other passes at the same elevation. The "vapor tunnel" area is an input in EMoTIP, which uses the area to calculate the degree of pressure equalization between the chambers afforded by the vapor tunnel or crossover. The equations for liquid, vapor, and pressure distribution are presented in Table 3 for three and four-pass trays.

Column Access

Entry into the shell of a distillation tower is possible only through manholes. Recommended manhole diameters are in the range of 18 to 30 in. (460 to 760 mm). Usually, each manhole serves 10 to 20 trays. For clean and noncorrosive services, each manhole may serve more than 20 trays. The manhole diameter affects the number of parts that are used to assemble each tray and other tower internals. Larger manholes are necessary if personnel entering the column need to wear special bulky protective equipment. Frequently, tray spacings must be locally increased to be larger than the manhole diameter. Therefore, it is good practice to install manholes in the space above the feed trays where the tray spacing is normally lengthened.

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Startup Considerations

At very low vapor velocities (such as during startup), sieve trays may dump, with the result that no liquid level is maintained on the tray feeding the reboiler drawoff box. Hence, when thermosyphon reboilers are used on sieve tray towers, special provisions may be necessary to ensure that the reboiler will have liquid feed during startup. This can be done by either:

- Installing a jumpover line from the tower bottoms drawoff line to the reboiler inlet. The jumpover line must have a valve, so that it can be closed when the reboiler is generating enough vapor to support the liquid on the drawoff tray, or
- By providing a chimney tray as the drawoff tray. For the design of chimney trays, drawoffs and other tower internals, see Section III-H.

PROCESS CONSIDERATIONS

Tray Turndown And Weeping

Turndown is the ratio of the maximum to minimum vapor loadings between which good tray efficiency is maintained. It is limited by flooding at high vapor and liquid rates and by excessive weeping at low vapor rates. A turndown ratio of between 2/1 and 3/1 is usually achievable with sieve trays.

Turndown requirements are dictated by the combination of two effects. The first is operating turndown and the second is the inherent variation in the loading profile over a tower section. Operational turndown should not be overestimated since this could result in decreased tray open area. If the loading profile variations are significant and the trays cannot meet the required turndown, consider breaking the original section into two (or more) smaller sections. If this reduces the loadings range to an acceptable level, develop a tray design for each of the new smaller sections. If the number of sections becomes too large, however, valve trays should be considered.

Weeping is the portion of the liquid flow on a tray that "leaks" or "weeps" downward through the perforations. The remaining portion proceeds to the tray below in a normal fashion via flow over the weir and into the downcomer. The weeping rate can be characterized by the parameter "fractional weepage," f_w, defined as the fraction of the total liquid rate that weeps. That is,

$$f_w = \frac{Q_w}{Q_L}$$

where: Q_w = Weep rate, gpm (dm^3/s) at conditions
Q_L = Total liquid rate, gpm (dm^3/s) at conditions

Referring to Figure 1, the vapor rate at which liquid starts to weep through the perforations is called the weep point. As the vapor rate is reduced further, the weeping rate increases and the tray efficiency begins to drop. The region between $f_w > 0$ and $f_w < 1$ is called the weeping region. For a well designed tray, this region normally begins at or below 50% of the jet flooding vapor velocity.

The weir load affects clear liquid height and thereby tray residence times. Liquid bypassing is another effect that reduces efficiency in the weeping region. This is due to the fact that the liquid that weeps is not fully contacted with vapor on the tray, and thus proceeds to the next lower tray at a different composition than the liquid entering the tray through the downcomer. This reduces the apparent efficiency. Weeping at the inlet of a tray is more severe than weeping at the outlet of tray. Weeping at the inlet of a tray, misses the cross flow efficiency boost of two trays (the liquid falls into the outlet side of the tray below). Weeping at the outlet side of a tray has little effect.

As the vapor rate is reduced still further, the point at which all the liquid weeps through the holes defines the dump point (see Figure 1). Vapor rates at and below this point are said to be in the dumping region ($f_w = 1$).

The only practical way to reduce weeping is by reducing the hole area on the tray. The hole area should be reduced until the hole velocity at minimum rates is equal to or exceeds the hole velocity at 20% fractional weepage, or until another hole area restriction is reached. The final hole area must insure that the hole area to bubble area ratio exceeds 3.5% and that operation in the spray regime is avoided. Lower hole areas can still be used, however, by blanking a portion of the tray while keeping a 3.5% minimum hole area in the remaining active portion.

It should be noted that 20% fractional weepage can be tolerated without significant efficiency loss. However, on drawoff trays a more restrictive limit on weeping may be appropriate (see GP 05-02-01, Par. 10.2). This may dictate the use of less hole area than that allowed on the adjacent trays. If the weeping rate cannot be reduced to acceptable levels by decreasing hole area, the use of valve trays should be considered or a chimney tray used. Creating a bottleneck in a tower due to a drawoff tray design should be avoided; usually tray spacing is increased to help compensate for reduced hole area and/or bubble area. (See Section III-H, Figure 16.)

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For revamps and some grassroots cases where initial operation rates are less than design, the simplest way to reduce weeping is to decrease the tray's hole area by blanking. If blanking cannot reduce the fractional weepage to 20% (or less) without hitting other hydraulic limitations, then the designer should study:

- Whether the predicted efficiency with weeping is still satisfactory, i.e., are there more trays present than needed (run EMoTIP to confirm the effect of weeping on efficiency and refer to Section III-I), or
- Whether economic considerations permit increasing loadings by "over-refluxing" the tower during turndown operations, or
- Whether valve trays with their greater flexibility are economically justified.

Tray Efficiency And Heat Transfer

The designer should recognize that efficiency calculations are necessary for each section in a fractionation tower. In addition, the trays selected to check hydraulics are sometimes not suited for efficiency calculations due to concentration profile reversals or other reasons. The tray efficiency should be calculated by the procedures given in Section III-I. The number of actual trays required for a tower or tower section is then calculated by dividing the number of theoretical trays (which are developed during the process simulation stage of the design) by the efficiency expressed as a fraction. See Sections III-I and III-F respectively for more information on tray efficiency and heat transfer.

Low Liquid Rate Tray Design

When designing a tower to operate at low liquid rates, it may become necessary to design the tray specifically with minimal entrainment in mind. Note that for E-Method entrainment, Eq. (24) should be used to predict entrainment when L is equal to or less than 1.5 gpm/in. of weir/pass (< 3.7 dm^3/s/m/pass of weir/pass). Refer to the discussion on Froth to Spray Regime Transition later in this section for ways to reduce entrainment. Installing picket fence weirs is one method to reduce entrainment rates and also avoid spray regime operation. Another option that can reduce entrainment is to use smaller holes.

One of the most common ways to reduce entrainment is to increase the hole area. Unfortunately, this increases the rate of liquid weeping. Even with an optimum design, the tray may weep and entrain at the same time (i.e. there is no "operating window" or turndown available). See the discussion in Section III-A on the "operating window" for more background. If sufficient flexibility cannot be obtained with sieve trays, the designer should consider valve trays or packing. Because of the complex design problems involved, your FRACTIONATION SPECIALIST should always be consulted.

Furthermore, when excessive entrainment occurs at low liquid loading, an insufficient clear liquid height could result in an unsealed downcomer or poor fractionation efficiency due to an inaccurate calculation of liquid residence time on the tray.

High Liquid Rate Tray Design

There are cases where high liquid rates require use of either a large downcomer clearance (over 3 in. [75 mm]) or a deep recessed inlet box. In past 1133 designs, shaped downcomer lips were also often used in these services. While shaped downcomer lips may still help reduce head loss under the downcomer and are mandatory for foaming services, because of the new limit on velocity under the downcomer, they will not be as widely applied. A shaped downcomer lip must not be used when either a recessed inlet box or an inlet weir has been specified. This is because the obstruction presented by the vertical face of the recessed inlet box, or by the inlet weir, would cause turbulence and defeats the purpose of the shaped downcomer lip. The downcomer clearance with a shaped lip should also be set so as not to exceed the V_{ud} limit of 1.3 ft/sec (0.4 m/sec). For multipass trays requiring a shaped lip, it should be specified for both center, off-center and side passes. The most common shaped lip radius specified is 1 in. (25 mm), although EMoTIP can handle any lip radius. Radius lips larger than 2 inches (50 mm) are not recommended. 1133 designs did not allow specification of the lip radius, but assumed a fixed 2 in. (50 mm) radius lip in the calculation of hud_L.

Trays With Drawoff Sumps - A drawoff box generally creates waste area (A_w) on the tray and may also obstruct the flow of vapor from the tray below. This dictates a conservative design approach. The design criteria for such trays are outlined in Section III-H, *Tower Internals*.

Foaming

Foaming in fractionation and absorption towers can significantly reduce capacity and lead to premature flooding, liquid carryover, and solvent losses. Tray design for foaming services is difficult, but the key is proper downcomer sizing. Include features such as a large downcomer inlet area, large downcomer residence time, a large downcomer clearance with a radius tip, and a high hole area to keep the dry tray pressure drop below 2.25 in. (57 mm) of hot liquid. Larger hole sizes are often recommended to reduce the tendency toward an emulsion flow regime on the deck that small holes promote.

Foam factors are used by the EMoTIP program to account for the foaming tendency of a chemical system. They are applied to both the jet flood and in several key locations in the downcomer flood and downcomer choke calculations. A foam factor of 1.0

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signifies a non-foaming system; 1.2 or greater is a definite foaming system. Foam factors based on hydrocarbon molecular weight are used for heavy hydrocarbon fractionators such as crude and vacuum towers (pipestills), because production well injection chemicals or corrosion inhibitors often induce foaming in these towers. Foam factors are applied to very low surface tension systems close to the critical point to account for the effect of inaccuracy in the prediction of surface tension. Foam factors are often "best guess" numbers and are normally derived from experience, not measurement. Many "foaming" systems such as gas treating solutions exhibit foaming only under degraded conditions. The foam factors provide enough hardware upside flexibility to accommodate some solution degradation, but will not prevent flooding in all cases. See Table 2 for the list of foam factors recommended for use in EMoTIP based on service and tower section. If the foam is very stable, even a very low downcomer inlet velocity and a large downcomer may not prevent tower flooding. If the designer is confronted with a new chemical system, for which a foam factor is not available, a FRACTIONATION SPECIALIST should be consulted regarding appropriate lab or pilot plant scale tests. If the designer expects a chemical system to be a stable foam, then:

a) Process changes should be considered to eliminate the source of the foaming (removal of entrained hydrocarbons into aqueous systems, elimination of suspended solids, etc.)

b) Consider using packing and consult your FRACTIONATION SPECIALIST.

c) If the foam source can't be eliminated, then an anti-foam agent may be required. This is usually an effective but expensive solution to the problem since anti-foam must be added continuously.

Vapor Recycling

When the liquid velocity entering the downcomer is greater than the velocity of the bubbles rising through it, **vapor recycling** occurs. The vapor cannot disengage and this results in vapor being swept through the downcomer and recycled onto the tray below. EMoTIP calculates the volume fraction vapor carryunder based on the liquid volumetric rate. This calculation is based on high pressure FRI sieve tray data with non-foaming systems. This vapor recycle is not normally enough to affect the tray capacity, but a good downcomer design should keep the volume fraction vapor carryunder below 0.15 for high pressure towers. See Section III-A for more background on vapor recycling.

Fouling

Fouling is the accumulation of any type of solid deposit on a tower internal device. Fouling on a sieve tray reduces the effective hole size of the sieve holes and will eventually plug the tray. Fouling results in diminished tower performance (efficiency, capacity, etc.) or even complete inoperability. Larger holes (3/4 to 1 in.; 19 to 25 mm) should be used in sieve trays operating in moderately or heavy fouling services. Solid deposits may also accumulate under the downcomer in fouling services and therefore restrict the downcomer exit flow area. This may cause excessive downcomer backup, premature flooding, and liquid maldistribution to the tray. To avoid blockage in this area due to fouling, a downcomer clearance of at least 1.5 in. (38 mm) should be used. Also, recessed boxes and inlet weirs should not be used in fouling services. The probability and consequences of fouling in the column must be fully evaluated. EMoTIP includes a fouling factor (FF) to automatically set the fouling tendency based on historical experience with service and location in the tower. Both the tower service and the tower internal location must be specified so that EMoTIP can correctly set the fouling factor. The fouling factor is currently only used in the design algorithm to set hole size, minimum downcomer clearance, minimum recommended tray spacing, and the use of inlet weirs. Refer to Table 2 for the fouling factor recommended for each tower service. The table below shows the effect on the tray design algorithm for a given fouling factor:

Fouling Factor	Description	Hole Size, in. (mm) Fixed	DCC, in. (mm) Starting point	Other Considerations
0	Ultra-clean	0.375 (9.5)	1.5 (38)	
1	Clean	0.5 (13)	1.5 (38)	
2	Moderate Fouling	0.75 (19)	2.0 (51)	Do not use float valve design. Consider fixed valves. No Inlet weir.
3	Heavy Fouling	1 (25)	2.5 (64)	Do not use float valve design. Consider large fixed valve. No Inlet weir.
4	Severe Fouling	XXXXXXXX	XXXXXXXX	Do not use trayed design. Consider sheds or grid.

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Corrosion

Corrosion is a process where some materials gradually wear away usually by chemical action or chemical action combined with fluid velocity (erosion/corrosion). The likelihood of corrosion and its potential effect on column internals must be reviewed. Holes smaller than 3/8 in. (9 mm) in diameter on carbon steel trays may rust over during hydrostatic testing and should be avoided. Thinner 410 SS trays should be evaluated as an alternate to thick carbon steel trays (with high Corrosion Allowance) to avoid the equipment reliability issues due to excessive corrosion products forming in wet service towers. Price will typically be about the same. Always confirm materials selection with a MATERIALS SPECIALIST.

TOWER CHECKLIST

Table 7 of **Section III-A** contains a detailed tower checklist that should be reviewed for all new designs as well as revamps.

CAPACITY/ PERFORMANCE RESTRICTION MECHANISMS

This subsection presents the different mechanisms that restrict column throughput and/or affect tower performance. It also provides the designer with the most important equations and design criteria used in determining the limitations of a particular design. Suggestions for improving tray and downcomer designs to meet ExxonMobil design limits are also included in this subsection. All the major capacity limits described in this section are calculated using EMoTIP and graphically depicted in Figure 2A, B, and C for a single tray design at three different pressure levels. This is commonly referred to as a tray performance diagram. Figure 2 shows how the various capacity limits change as a function of vapor to liquid ratio and pressure level. The reader may want to compare these figures with the generic Figure 22 in Section III-A.

OVERALL CAPACITY

The overall capacity of any fractionating tower is determined from a combination of different vapor and liquid flooding mechanisms. For this reason, an "overall flood" correlation has been developed for cross flow fractionation devices.

Overall Flood

Overall flood is a statistical combination of jet flood, downcomer flood and ultimate capacity flood, and depends primarily on the limiting flooding mechanism. These different parameters are discussed independently in detail in Section III-A. The overall flood model uses the following equation developed to combine jet flood and downcomer flood.

$$\text{Overall Flood (Jet, DC)} = \max\,(\text{Jet Flood, DC Flood}) - \gamma \left| \text{Jet Flood - DC Flood} \right| \qquad \text{(Customary or Metric)} \qquad \text{Eq. (1)}$$

The second term on the right hand side of Eq. (1) is a correction term designed to improve the statistics and therefore the probability of successful designs. The correction is limited to a maximum of 6% flood. If the jet flood is close to the downcomer flood, the tray design is well balanced and only a small correction is needed. On the other hand, if one or the other flood dominates, a larger correction is necessary. The optimal value of the correction coefficient gamma, obtained from a statistical study, is given below:

$$\gamma = \begin{cases} 0.17 \text{ for JetFlood} \geq \text{DC Flood;} \\ -0.12 \text{ for JetFlood} < \text{DC Flood.} \end{cases} \qquad \text{(Customary or Metric)} \qquad \text{Eq. (1a)}$$

The positive value of gamma for trays limited by jet flood decreases the overall flood, because the jet flood model slightly under-predicts the tray capacity. The negative value for gamma for trays limited by downcomer flood is required because the downcomer flood model over-predicts the tray capacity. The overall flood model also takes into account the ultimate capacity check; the final Overall Flood is then the maximum of Overall Flood (Jet,DC) and the ultimate capacity flood,

$$\text{Overall Flood} = \max\,[\text{Overall Flood (Jet, DC), Ultimate Capacity Flood}] \qquad \text{(Customary or Metric)} \qquad \text{Eq. (2)}$$

Designs up to a maximum of 85% Overall Flood by this correlation are acceptable. For services where fractionation is not critical, such as pumparound trays, designs up to a maximum of 90% Overall Flood by this correlation are acceptable.

Probability Of Non-Flooding Operation

EMoTIP reports the probability that a given sieve tray design will not be flooding at a given percent of overall flood. The probability model used in EMoTIP is based on almost all known flood runs from the FRI sieve tray database. The probability

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model is a function of overall flood only. The only screening performed on the FRI flood runs was to remove runs with a liquid rate over the weir of less than 1.5 gpm/inch (3.7 dm^3/s/m) of weir and to also remove runs which had less than 1.25 in. (32 mm) of hot liquid dry tray pressure drop at 85% overall flood. The probability of non-flooding operation of a tower at a given percent of overall flood can be estimated from the table below.

DESIGN % OF OVERALL FLOOD	% PROBABILITY OF NON-FLOODING DESIGN
75	99.6
80	98.3
85	94.4
90	85.7
95	70.5
100	50.4
105	30.3
110	14.8
115	5.8
120	1.8

It is important to note that this table does not predict the probability of successful operation. Much more than avoiding tray hydraulic flood is involved in the successful design and operation of a sieve tray tower. For instance, inlet, reboiler and drawoff internals must be correctly designed; the foam factor must be correctly estimated; the tray efficiency must be correctly determined; the design basis must be accurate; control systems and instrumentation must be without defect; and such things as fouling or damage must not have occurred. It is also important to note that in the case of foaming service tray designs, any uncertainty in the foam factor will reduce the probability of non-flooding for a given overall flood.

VAPOR HANDLING LIMITATIONS

Jet Flooding

Jet flooding is the limitation that most commonly sets the vapor handling capacity for cross-flow trays. Jet flooding occurs when the vapor rate is sufficiently high to "jet" or "entrain" liquid from a given tray to the tray above. It is the primary cause of tower flooding for lower pressure towers. The following independent variables are used in the jet flood model: liquid density, vapor density, tray spacing, free area, bubble area, hole diameter, hole area, vapor rate, liquid rate, outlet weir length, downcomer inlet area, and tower area. Jet flooding is a strong function of tower diameter and tray spacing and a lesser function of the number of liquid passes used. See Section III-A for more background information.

Jet Flood Equations - The jet flood equation includes a foaming factor term. Refer to Table 2, System Factors for a list of foaming factors for different services. Whereas the old Table 2, "Design Criteria for Specific Towers" in Reference 17 sets the allowable percent of jet flood based on the service, the new jet flood model keeps the allowable jet flood constant and changes a service factor, known as the foam factor, to achieve the same end. The foam factor is a qualitative measure of the foaminess of the system at hand and is based on experience. It is always equal to or greater than 1.0. Following are the equations to calculate percent jet flood for a single pass.

$$\text{Jet Flood} = \left(\frac{C_b}{C_{bF}}\right) ff \qquad \text{(Customary or Metric)} \qquad \text{Eq. (3)}$$

where: ff = foaming factor (≥ 1.0)

Where the capacity factor is based on the bubble area:

$$C_b = \left(\frac{q_V}{A_b}\right)\left(\sqrt{\frac{\rho_V}{(\rho_L - \rho_V)}}\right) \qquad \text{(Customary or Metric)} \qquad \text{Eq. (4)}$$

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The capacity factor at jet flood is defined as:

$$C_{bF} = 0.0795\left(\frac{\rho_v}{\rho_L - \rho_v}\right)^{0.04}(H)^{0.5}\left(\frac{A_f}{A_b}\right)^{0.5}\exp\left(\frac{0.046}{d_o + 0.028}\right)(APC)\,(X_L) \qquad \text{(Customary)} \qquad \text{Eq. (5)}$$

The hole area correction term, APC, is given as:

$$APC = 1 + 0.02\left[\left(\frac{A_o}{A_b} * 100\right) - 10\right]\left[\exp\left[\frac{0.3}{(\rho_v + 0.25)}\right] - 1\right] \qquad \text{(Customary)} \qquad \text{Eq. (6)}$$

The liquid rate correction term, XL is given as:

$$\text{if}\left[\frac{Q_L}{l_o} \le 4\right],\ X_L = 1 \qquad \text{(Customary)} \qquad \text{Eq. (7)}$$

$$\text{if}\left[\frac{Q_L}{l_o} > 4\right],\quad X_L = \exp\left[-0.36\left(\frac{A_{di}}{A_s}\right)^{-0.2}\left(1 - \frac{4}{\left(\frac{Q_L}{l_o}\right)}\right)^2(\rho_v)^{0.2}\right] \qquad \text{(Customary)} \qquad \text{Eq. (8)}$$

There is no specific design limit placed on the jet flood value, since it is incorporated in the Overall Flood. However, the calculated value can be used to help determine if the tray design is well balanced and if the tray is jet flood limited or limited by some other flood mechanism or secondary design parameter.

This jet flood model includes effects for hole size, hole area, downcomer inlet area as a fraction of tower area, and bubble area. These effects were not present in the previous jet flood model based solely on tower free area, liquid rate over the weir, tray spacing and physical properties. Smaller holes will yield more capacity by Eq. (5), for instance about 6% more capacity can be achieved on going from a 0.75 inch (19 mm) hole to a 3/8 inch (9.5 mm) hole. The APC term, Eq. (6), has a coupled effect of hole area and vapor density. A hole area of 10% is vapor density neutral. At a low vapor density, increasing the hole area has a larger effect on jet flood capacity, than at a high vapor density. For instance, at a vapor density of 0.15 lb/ft^3 (2.4 kg/m^3), a 14% boost in jet flood capacity will be obtained by going from an 8% hole area tray to a 14% hole area tray (on bubble area). The same change in hole area will yield a 2.4% increase in jet flood capacity at a vapor density of 1.35 lb/ft^3 (21.6 kg/m^3). At low vapor density, with low liquid rates, changing downcomer size has almost no effect on jet flood. At high liquid rates, going from a 6% downcomer top area to a 25% top downcomer area will increase capacity by 2.5% at 0.15 lb/ft^3 (2.4 kg/m^3) and 4.8% at 3 lb/ft^3 (48 kg/m^3) vapor density.

Ultimate Capacity

Ultimate capacity is the maximum available capacity for vapor flow in a given column diameter with a known liquid rate and physical properties. Two versions of the ultimate capacity are determined for trays, the Tray Ultimate capacity and the Universal Ultimate capacity. For trays, ultimate capacity usually only limits in hydrocarbon distillation systems above 250 psia (1730 kPa).

Tray Ultimate Capacity - provides an upper bound to the capacity of a cross flow fractionating tower regardless of tray design and tray spacing. It is the highest vapor load a conventional trayed column can handle. Tray ultimate capacity cannot be increased with hardware modifications that do not affect the free area since it is solely dependent on the vapor load, system properties (composition, temperature, and pressure), and the tower free area. Any tray modification that increases free area (such as sloping the downcomer) will make a small improvement in tray ultimate capacity. In addition, because the packing ultimate capacity equation includes a liquid rate term, switching from trays to packing or vice-versa will yield a different ultimate capacity. For new column designs, the designer must determine whether the ultimate capacity has been reached. If so, the designer should increase the column diameter of the design. For revamps, a tray with greater free area or packing may provide some relief. A

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tower limited by tray ultimate capacity. Also, some non-conventional internals that rely on enhanced deentrainment may be able to function at high values of ultimate capacity. The equations below are used to calculate the tray ultimate capacity of a conventional tray, cross-flow fractionating tower.

$$C_{ult} = 0.65\left[\frac{\beta}{1+\beta}\right]\left[\frac{\sigma_L}{\rho_L - \rho_v}\right]^{0.25} \qquad \text{(Customary)} \qquad \text{Eq. (9)}$$

$$\textbf{where:} \quad \beta = 1.4\left[\frac{\rho_L - \rho_v}{\rho_v}\right]^{0.5} \qquad \text{(Customary and Metric)} \qquad \text{Eq. (10)}$$

For the metric equation, use a coefficient of 0.396 vs. the 0.65 in Eq. (9).

$$\text{Ultimate Capacity Flood} = \left(\frac{C_f}{C_{ult}}\right) \qquad \text{(Customary or Metric)} \qquad \text{Eq. (11)}$$

Where the capacity factor based on the free area is:

$$C_f = \left(\frac{q_v}{A_f}\right)\left(\sqrt{\frac{\rho_v}{(\rho_L - \rho_v)}}\right) \qquad \text{(Customary or Metric)} \qquad \text{Eq. (12)}$$

Since the overall flood limit is typically 85%, the ultimate capacity flood limit is also 85%. It is important to note that the tray ultimate capacity is one of the correlations for sieve trays with a high degree of uncertainty. Of the 894 flood runs in the FRI database only 27 are limited by tray ultimate capacity (i.e. the ultimate capacity sets the overall flood). Many of these runs also have high values of either jet or downcomer flood.

Universal Ultimate Capacity - is another way to view ultimate capacity, and considers the entire tower area rather than just the free area; it appears to be a better indicator of the true ultimate capacity of a given tower shell. The universal ultimate capacity may be applied to both trayed and packed towers. Universal ultimate capacity is independent of tray design and tray spacing or type of packing. It is dependent only on the system properties (composition, temperature, and pressure) and on the tower cross sectional area. The system properties determine a drop size, which places a limit on achievable capacity independent of hardware design. The universal ultimate capacity uses the tower cross sectional (superficial) area instead of the free area that is used in the existing tray ultimate capacity correlation; this move toward using superficial area is consistent with FRI's newest ultimate capacity correlation. The correlation also includes the effect that increasing the liquid rate has on decreasing the vapor capacity. The universal ultimate capacity correlation also considers the Reynolds number dependency on the drag coefficient.

The critical Weber number forms the basis for this calculation. FRI data suggests that:

$$We_c = 0.7 \qquad \text{(Customary or Metric)} \qquad \text{Eq. (13)}$$

Using a lower We_c will predict ultimate capacity limitations for a greater percentage of runs, i.e. is more conservative from a design perspective. The critical Weber number and the critical Reynolds number are defined by:

$$We_c = \frac{(D_p/12)\cdot\rho_v\cdot u_t^2}{2\cdot(\sigma_L\cdot 0.00220462)} \qquad \text{(Customary)} \qquad \text{Eq. (14)}$$

$$Re_c = \frac{\rho_v\cdot u_t\cdot(D_p/12)}{(\mu_v\cdot 0.00067197)} \qquad \text{(Customary)} \qquad \text{Eq. (15)}$$

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Where the drop size can be calculated from:

$$D_p = \left(\frac{3}{4} u_t^2 \frac{c_D \cdot \rho_v}{g_c \cdot \Delta\rho}\right) \cdot 12 \qquad \text{(Customary)} \qquad \text{Eq. (16)}$$

The drag coefficent depends on whether the drop size yields an Re_c which is in the Stokes Law Intermediate region or Newton's law region of applicability:

$$C_D = 0.44 \qquad Re_c > 500$$

$$C_D = \frac{18.5}{Re_c^{0.6}} \qquad 2 < Re_c < 500 \qquad \text{(Customary or Metric)} \qquad \text{Eq. (17)}$$

$$C_D = \frac{24}{Re_c} \qquad Re_c < 2$$

The following equation calculates the terminal velocity of a liquid droplet from the superficial area, the vapor volumetric rate, the vapor and liquid densities, and the liquid volumetric rate.

$$u_t = \left[\left(\frac{1000 \cdot w`_v}{3600 \cdot \rho_v}\right) \Big/ A_s\right] \cdot \left(\frac{1+\beta}{\beta}\right) + (1+\beta) \cdot \left(\frac{L_L}{A_s}\right) \qquad \text{(Customary)} \qquad \text{Eq. (18)}$$

Equations (14) through (18) represent five equations in five unknowns: u_t, D_p, $w`_v$, Re_c, and c_D and can be solved simultaneously for the unknowns.

The limiting capacity factor for the universal ultimate capacity is then:

$$C_{univ} = \left[\frac{1000\ w`_v}{A_s\ \rho_v\ 3600}\right] \left[\frac{\rho_v}{\rho_L - \rho_v}\right]^{0.5} \qquad \text{(Customary)} \qquad \text{Eq. (19)}$$

Percent Universal Ultimate Capacity is the ratio of the capacity factor based on superficial tower area to the capacity factor at ultimate capacity:

$$C_s = \left[\frac{q_v}{A_s}\right] \left[\frac{\rho_v}{\rho_L - \rho_v}\right]^{0.5} \qquad \text{(Customary or Metric)} \qquad \text{Eq. (20)}$$

$$\text{Universal Ultimate Capacity} = \left(\frac{C_s}{C_{univ}}\right) \qquad \text{(Customary or Metric)} \qquad \text{Eq. (21)}$$

If the Universal Ultimate Capacity is greater than 85%, a larger diameter tower should be designed.

Spray Regime And Entrainment

Spray regime and entrainment are both secondary design parameters that are primarily vapor handling limitations. Spray regime is a transition from froth to a spray of discrete droplets. It is also referred to as "blowing" when it is extreme. In such cases, the spray appears to be suspended above the deck, a condition known as "blowing dry". Entrainment is the lifting of tray deck liquid to the next tray above. It increases rapidly with increasing vapor rate as the flood point is reached, but can also be high as a percentage of tray liquid rate, even at low values of jet flood, when the tray liquid load is low. Refer to Section III-A for additional discussion.

Froth To Spray Regime Transition - Spray regime operation occurs primarily at high vapor velocities and low liquid rates. Such conditions are likely to occur in distillation towers operating below 50 psia (345 kPa), water wash towers, and atmospheric pipestill

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wash zones. In the spray regime, the liquid becomes suspended as a dispersed phase above the tray deck, interphase contact becomes poor, and the tower fractionation efficiency deteriorates. See Figure 16, Section III-A.

R&D studies have shown that the transition from froth to spray is primarily an inertial phenomenon related to the ability of the vapor jet to penetrate the liquid on the tray. The resulting correlation, which gives the vapor load per unit tower bubble area at which the transition from froth to spray occurs, is:

$$\left[\frac{V_L}{A_b}\right]_{SF} = c_1 \left[\frac{A_o}{A_b}\right]^{0.3} [H]^{0.3} \left[\frac{1}{d_o}\right]^{0.2} \left[\frac{Q_L}{l_o}\right]^{0.2} \qquad \text{Eq. (22)}$$

Where: $c_1 = 0.214$ (Customary)

$c_1 = 0.04$ (Metric)

Note the dependence of the equation on tray spacing, hole size, and liquid rate per inch of weir. For trays with more than one pass, all passes should be checked even though the pass leading to the center downcomer will usually limit.

For definitions of the terms and information on units to be used in this equation, refer to the **NOMENCLATURE** section. The appropriate fraction of the transition point to use for design calculations can be found from the table below. The maximum allowable percent of Spray/Froth transition velocity has been increased by 10% from the values given in Reference 17. This is due to tighter limits on entrainment (now 10% maximum vs. previously 20% maximum) and a more accurate and robust jet flood correlation at low liquid rates.

MAXIMUM ALLOWABLE PERCENT OF THE SPRAY/FROTH VELOCITY		
VAPOR DENSITY lb/ft^3 (kg/m^3)	**L ≤ 1.5 gpm/in. (≤ 3.7 dm^3/s/m)**	**L > 1.5 gpm/in. (> 3.7 dm^3/s/m)**
$\rho_v \le 0.08$ (≤ 1.28)	66	93.5
$0.08 \le \rho_v < 0.6$ ($1.28 \le \rho_v < 9.6$)	60.5 (1.0 + 0.9 ρ_v) 60.5 (1.0 + 0.057 ρ_v)	93.5
$\rho_v \ge 0.6$ (≥ 9.6)	110	110

Alternatives are available to the designer to avoid operating in the spray regime. Note that increasing the weir height will **not** help solve this problem. These alternatives are presented in the order in which they should be considered:

NEW DESIGNS	REVAMPS
• Increase the hole area	• Increase the hole area
• Decrease the hole diameter	• Decrease the hole diameter
• Install picket fence weirs*	• Install picket fence weirs*
• Increase the tray spacing	• Consider packing
• Increase the bubble area	
• Use packing	

*For more details contact your FRACTIONATION SPECIALIST.

Mini-valves (either fixed or moveable) should also be considered as a spray regime remedy.

Intertray Entrainment - The quantity of entrainment generated is dependent on vapor rate, liquid rate, and certain hardware parameters. There are two methods for predicting entrainment used by the ExxonMobil Tower Internals Program, the E-Method and the M-Method. Neither one of these methods is very accurate due to the inherent problems in measuring entrainment rate and the exponential nature of entrainment as a function of vapor rate. However, if the calculated entrainment values from both

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methods lie within the acceptable limit of 10%, it is unlikely that the column will experience entrainment problems. Descriptions of the E-Method and M-Method correlations are below.

E-Method Entrainment - Entrainment is based on data from Fractionation Reasearch Inc. (FRI) and ExxonMobil test programs. This correlation takes into account the effect of system physical properties and tray hardware parameters on entrainment rates. Nevertheless, if the fractional entrainment f_e, (i.e., the entrainment rate divided by the design liquid rate) exceeds 10%, the hole area should be increased and the fractional entrainment rate recalculated. Use this equation if the volumetric liquid rate is greater than 1.5 gpm/in. of weir/pass (is greater than 3.7 $dm^3/s/m$ of weir/pass), otherwise use Eq. (24).

$$f_e = K_\phi \; K_L \; K_\sigma \; K_\varepsilon \left[\frac{A_b}{1000\; w_L}\right] \qquad \text{(Customary)} \qquad \text{Eq. (23)}$$

$$f_e = K_\phi \; K_L \; K_\sigma \; K_\varepsilon \left[\frac{A_b}{w_L}\right] \qquad \text{(Metric)} \qquad \text{Eq. (23M)}$$

Where:

f_e = Fractional entrainment, dimensionless. For 2 pass trays, calculate for both center and side passes.

K_ϕ = Tray geometry factor (see Figure 3).

K_L = Liquid rate/tray spacing factor (see Figure 4A or 4B). For two pass trays, determine K_L for each pass.

K_σ = System properties factor (see Figure 5).

K_ε = Vapor energy dissipation factor (see Figure 6A or 6B).

A_b = Tray bubble area ft^2, (m^2). For two pass trays, calculate for both inboard and outboard passes.

w_L = Liquid mass flow rate, k lb/hr (kg/s).

The equation below should be used to calculate fractional entrainment (f_e) when the liquid rate is less than or equal to 1.5 gpm/in. of weir/pass ($\leq$ 3.7 $dm^3/s/m$ of weir/pass). For term definitions, refer to **NOMENCLATURE**.

$$f_e = 0.1\; C_4 \left[\frac{\left[\frac{V_L}{A_b}\right]\left[\frac{d_o}{0.5}\right]^{0.45}\left[\frac{3.96\; A_b}{l_c}\right]^{0.15}}{0.8042\,[L]^{0.27}\,[h_{wo}]^{0.54}\left[\frac{A_o}{A_b}\right]^{0.59}\left[\frac{H}{24}\right]^{0.55}\; K_{\sigma\mu}}\right]^n \qquad \text{(Customary)} \qquad \text{Eq. (24)}$$

$$f_e = 0.1\left[\frac{324\left[\frac{V_L}{A_b}\right][d_o]^{0.45}\left[\frac{1083\; A_b}{l_c}\right]^{0.15}}{[L]^{0.27}\,[h_{wo}]^{0.54}\left[\frac{A_o}{A_b}\right]^{0.59}[H]^{0.55}\; K_{\sigma\mu}}\right]^n \qquad \text{(Metric)} \qquad \text{Eq. (24M)}$$

For the inboard pass on tow pass trays, substitue l_c^* for l_c.

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when: $\rho_v > 0.08$, $C_4 = \dfrac{0.08}{\rho_v}$; otherwise $C_4 = 1$ (Customary)

where: f_e = Fractional entrainment, dimensionless

$n = 9.4\left[\rho_V\right]^{1/6}$ (if $\rho_V > 0.12$; $n = 6.6$) (Customary)

Note: If h_{wo} > 2 in. (> 50 mm); set h_{wo} = 2 in. (50 mm)
If h_{wo} < 1 in. (< 25 mm); set h_{wo} = 1 in. (25 mm)

M-Method Entrainment - Entrainment depends on the vapor rate at flooding conditions and is thus dependent on the jet flood model.

$$w_E = C_{bF}\, A_b \sqrt{\left[\rho_v(\rho_l - \rho_v)\right]} * 10^{\left(\frac{(C_b - C_{bF}) * \left[23 + 31\sqrt{\frac{Q_L}{l_o}}\right]}{\left(\frac{\rho_l - \rho_v}{\rho_v}\right)^{0.20}}\right)}$$ (Customary) Eq. (25)

LIQUID HANDLING LIMITATIONS

Liquid flows across the tray and is contacted by the ascending vapor. At the downstream end of the tray, the liquid enters a downcomer, which carries it to the tray below where the contacting process is repeated. The contacting area must be large enough to handle the required liquid and vapor rates while promoting the desired mass transfer. Likewise, the downcomer must be large enough to handle the froth from the tray deck and clarify this froth. Premature tower flooding can occur as a result of either inadequate downcomer area or depth.

Downcomer capacity has been an active area of research at FRI and ExxonMobil since the early 1980's. Models of downcomer capacity have been developed which not only predict the downcomer froth density and froth height but also accurately predict when the downcomer floods. Earlier design procedures for downcomers (Ref. 17 for example) relied on satisfying a series of design constraints, instead of actually determining the downcomer flood point. More recent models of downcomer flood, such as the one included in EMoTIP, provide an accurate means to predict the liquid handling capacity of the tray and therefore improve the design.

Downcomer Flood

Percent downcomer flood is the criterion that determines how close a tower is to flooding as a result of excessive froth height in the downcomer. Percent downcomer flood represents the ratio of the actual vapor and liquid rates to the rates that would result in 100% downcomer froth backup. Downcomer flood solves the following equation for x. (h_d and Ψ are shown as functions of x in this equation.)

$$H_B + h_{wo} = \frac{h_d(x)}{\Psi(x)}$$ (Customary or Metric) Eq. (26)

where: x = Multiplier on Liquid and Vapor rates at which tray is rated, dimensionless
H_B = Tray spacing below the deck, in. (mm)

Then, downcomer flood for the loads at which the tray is rated is given by:

$$\text{DC Flood} = \frac{1}{x}$$ (Customary or Metric) Eq. (27)

Using x to scale both vapor and liquid rates (keeping a constant ratio of vapor to liquid), is the appropriate way to handle a downcomer flood calculation for most towers. Even for absorbers or strippers where gas or liquid rates alone are changing, it is usually sufficiently accurate and will be slightly conservative.

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The EMoTIP downcomer flood model includes a tray hydraulic model to calculate the froth density on the tray and therefore the amount of froth that the downcomer must handle. For downcomer limited trays, reducing the bubble area on the tray increases the frothing action and will reduce the downcomer capacity, i.e. increase the downcomer flood. Downcomer flood is also strongly affected by the tray pressure drop through the conventional downcomer filling. This increases the numerator in Eq. (26). Downcomer filling components are described next.

Downcomer Filling (h_d) - Downcomer filling is defined as the clear liquid height (i.e. collapsed froth height) in the downcomer. It is composed of the inlet head (h_i) on the tray, the tray pressure drop (h_t) across the tray immediately upstream of the downcomer being considered, the head loss under the downcomer (h_{ud}), and the frictional head loss due to two-phase flow through the downcomer (h_{dc}). See Figure 19 in Section III-A.

$$h_d = h_i + \left(h_t + h_{ud} + h_{dc}\right) * \frac{\rho_l}{\rho_l - \rho_v} \qquad \text{(Customary or Metric)} \qquad \text{Eq. (28)}$$

Inlet Head (h_i) - The inlet head is equal to the clear liquid height (h_c) on a tray if there is no inlet weir present. If an inlet weir is present, downcomer filling will increase due to the weir height, the crest over the weir, and added pressure drop of the liquid flowing between the downcomer apron and the inlet weir.

$$h_i = h_c \text{ (tray without inlet weir)} \qquad \text{(Customary or Metric)} \qquad \text{Eq. (29)}$$

$$h_i = 0.48 * \left(Q_L / l_i\right)^{2/3} + h_{wi} \text{ (with inlet weir)} \qquad \text{(Customary)} \qquad \text{Eq. (30)}$$

Tray Clear Liquid Height (h_c) - Clear liquid height is the height of liquid on a tray expressed in inches (mm) of hot liquid. The clear liquid height is a function of the liquid rate, outlet weir height, hole pitch, % hole area, and bubble area. The clear liquid height must be high enough to provide sufficient contact time between the liquid and the vapor for mass transfer to occur. Excessive clear liquid heights should be avoided, because they increase the tray's pressure drop, increase downcomer filling, and may cause premature weeping. If the tower is heavily liquid loaded and h_c is too high, consider increasing the number of liquid passes to reduce the liquid rate per length of weir for each pass. The clear liquid height used in the downcomer flood model is the Hofhuis equation, which avoids a trial and error calculation of clear liquid height and was found to give a better fit to the downcomer flood data by FRI.

$$h_c = 2.0785\sqrt{\Omega} * \left(\frac{P}{b}\right)^{0.25} \Phi^{0.25} \qquad \text{(Customary)} \qquad \text{Eq. (31)}$$

where: $\Omega = \dfrac{3\,h_w + 2}{h_w + 2}$, weir height term

P = Calculated Hole pitch, in.; given by: $P = \sqrt{\dfrac{\pi * d_o^2 * A_b}{4 * A_o * 0.866}}$

$b = \dfrac{l_o}{A_b}$, weir length term

$\Phi = \dfrac{Q_L}{q_v} * \dfrac{1}{(60 * 7.48)} \sqrt{\dfrac{\rho_L}{\rho_v}}$, Lockhart-Martinelli Flow Parameter

Tray Pressure Drop (h_t) - The tray pressure drop (h_t) is composed of the dry tray pressure drop (h_{ed}) and the clear liquid height (h'_c). Each of the pressure drops (or heads) is expressed in inches (mm) of hot clear liquid. Tray pressure drop is critical in tray design since it is one of the major components of downcomer filling and therefore downcomer flood.

$$h_t = h_{ed} + h'_c \qquad \text{(Customary or Metric)} \qquad \text{Eq. (32)}$$

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Note that the clear liquid height term (h'_c) used in the tray pressure drop calculation is calculated from the FRI method found in Topical Report 88 and therefore differs in value from the clear liquid height term (h_c) used for the inlet head in the downcomer calculations. Both terms represent the collapsed froth clear liquid height on a tray. Using the FRI TR 88 method results in the tray pressure drop calculation results in better agreement with tray pressure drop data. The FRI method for pressure drop calculates the clear liquid height from:

$$h'_c = 0.4F_w * (Q_L / l_o)^{2/3} + S_6 h_{wo} \qquad \text{(Customary)} \qquad \text{Eq. (33)}$$

The dry tray pressure drop is calculated from:

$$h_{ed} = \varphi * S_5 * (q_v/A_o)^2 * \frac{\rho_v}{\rho_L} \qquad \text{(Customary)} \qquad \text{Eq. (34)}$$

where: $\phi = e^{\left(\frac{-S_9 \cdot h'_c}{h'_c + 5.338}\right)}$, $\phi =$ Liquid head correction for dry tray pressure drop

F_w = Weir constriction factor, f(l_o/D_t)

S_5 , S_6 and S_9 = Functions of l_o/D_t , A_o/A_b , t, d_o

Head Loss Under the Downcomer (h_{ud}) - The head loss under the downcomer uses a correlation of the froth clarification action of the downcomer to correct the standard clear liquid head loss to an aeration corrected head loss.

$$h_{ud} = \frac{hud_L}{(1-\zeta)^2}\left(\frac{\rho_m}{\rho_L}\right) \qquad \text{(Customary or Metric)} \qquad \text{Eq. (35)}$$

$$hud_L = c_{oe}\left(\frac{Q_L}{c\, l_{db}}\right)^2 \qquad \text{(Customary)} \qquad \text{Eq. (36)}$$

where ζ = vapor fraction of aerated liquid flowing under downcomer

ρ_m = Mixture density under downcomer, lb/ft^3 (kg/m^3)

c_{oe} = Downcomer exit coefficient based on the radius of shaped lip dc:

0.06 for sharp edge
0.036 for 1 in. (25 mm) radius
0.020 for 2 in. (51 mm) radius

Head Loss Due to Two-Phase Flow Through the Downcomer (h_{dc}) - This is a new term not found in the conventional downcomer filling clear liquid height.

$$h_{dc} = K_D * dP_{dc} \qquad \text{(Customary or Metric)} \qquad \text{Eq. (37)}$$

K_D is a correction factor that accounts for the fact that frictional pressure drop will occur mainly in the entrance region of the downcomer. It is a function of the hardware dimensions (A_{di}/A_s), (A_{di}/A_{do}) and H_B. dP_{dc} is the two phase pressure drop in downcomer, and is a complex function of the downcomer entrance velocity, the tray deck froth density, the tray deck interfacial

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area, the liquid physical properties and the total available downcomer height. The dependence of this downcomer two-phase pressure drop on liquid viscosity is conservative and therefore a liquid viscosity cut off of 1 cP is implemented in EMoTIP. Reference 13 contains more background on the validity of the EMoTIP correlation at high liquid viscosity.

The frictional head loss term can be a significant factor in the calculation of downcomer flood. High values can be expected if the tray froth density is low. The term was developed by regarding the two-phase bubbly flow in a downcomer as liquid flowing through a packed bed of bubbles. Downcomer flooding will occur if this frictional head loss due to two-phase flow through the downcomer is excessive. This is often the case if the choke term in EMoTIP is excessive. This model is considered accurate for high-pressure systems but may be conservative at medium and low pressures. For details on the development of this model, the reader is referred to Reference 15, FRI Topical Report (TR) 101. The EMoTIP model is a modified version of the model in TR 101. A more accurate method of accounting for average downcomer area was developed for the EMoTIP model and a correction factor developed based on fitting the model to downcomer flood data using convergence on a constant vapor/liquid ratio basis. (See Reference 10.) Reference 16 contains all the equations currently in the EMoTIP downcomer flood model and can be used for hand checks of EMoTIP results.

Downcomer Froth Backup - Percent downcomer froth backup is the froth height in the downcomer divided by the distance from the bottom of the downcomer to the top of the outlet weir.

$$\%\,\text{DC Froth Backup} = \left(\frac{h_d}{\psi * (H_B + h_{wo})}\right) * 100 \qquad \text{(Customary or Metric)} \qquad \text{Eq. (38)}$$

There is no separate design criteria for % DC Froth Backup. All downcomer flood effects are captured through the downcomer flood model, combined with downcomer choking and the secondary parameter: Square Root of (% DC Froth Backup x % DC Choke). (See below.) The downcomer froth density used in the downcomer flood and froth backup calculations is divided by the foam factor (ff).

SECONDARY DESIGN PARAMETERS

Secondary design parameters are constraints on tray design that are important, but not critical. Some of these parameters help keep the tray design within acceptable bounds where the capacity correlations are valid. Others pick up specific issues that may occur from time to time with tray designs. Still others are thought to have a role in tray performance from the physics of fluid flow on the tray, but for one reason or another (such as confounding with another variable) do not have enough data backup to prove that they do not affect tray design. In this last case, the chosen criteria reflect value that are known historically to be acceptable. In general, all grass root tray designs should meet all secondary parameter criteria. In revamp situations, a FRACTIONATION SPECIALIST should be consulted about whether a given secondary criterion can be violated.

Liquid Entrainment - The design criteria for liquid entrainment is 10% of the liquid flowing on the tray by either the M-method or the E-method. This is a reduction from the earlier 1133 program limit of 20%, but an increase from the MoTIP limit of 5%. Lower pressure towers that tend to be limited by jet flood can have stable operation with some level of entrainment. This is often referred to as a state of "incipient flood". As the entrainment rate increases above 10%, tray efficiency will suffer, then when entrainment levels are high enough, a full hydraulic flood will result. Because predicting absolute values of entrainment is difficult, conservative entrainment limits are recommended for design. Entrainment effects are included in the M-method efficiency calculation, but not in the E-method efficiency. Entrainment effects (additional liquid due to entrainment) are not included in either the jet flood or the downcomer flood calculation. E-method entrainment reduction for new or revamp designs can be achieved by methods similar to those to control spray regime operation. M-method entrainment reduction can be achieved by reducing the jet flood.

Downcomer Choking Due to Velocity - The downcomer choking criteria is based on an ultimate-capacity like analysis of bubble separation in liquid. The allowable downcomer entrance velocity limit is given by:

$$V_{di(Ult)} = \left(\frac{\beta}{1+\beta}\right) * \left(\sigma \cdot \frac{\rho_L - \rho_V}{\rho_L^{\,2}}\right)^{0.25} * \frac{1}{ff^2} \qquad \text{(Customary)} \qquad \text{Eq. (39)}$$

The percent of downcomer choke is then given by:

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$$\%\,DC\,Choke = \frac{V_{di}}{V_{di(Ult)}} * 100 \qquad \text{(Customary or Metric)} \qquad \text{Eq. (40)}$$

The previous limit for this parameter was 75% in MoTIP. The limit has been increased to 100% in EMoTIP, because statistical analysis of this variable has shown it is not a very significant predictor of flood above and beyond the basic downcomer flood model itself. However, high values of the DC choke parameter do usually indicate that the downcomer mouth area is restrictive and extra downcomer capacity can be obtained by increasing the downcomer mouth area. The foam factor also appears in this equation squared. In MoTIP, the foam factor was to the first power in this equation. With an allowable value of 100%, squaring the foam factor keeps entrance velocities at about the same absolute value as allowed by MoTIP with a design limit of 75%. These entrance velocities are similar to those used in the 1133 program. Tray design for foaming systems require large downcomers and a large downcomer mouth area to provide sufficient residence time for foam collapse in the downcomer.

Square Root of (% DC Froth Backup x % DC Choke) - A better predictor of downcomer flooding than the choke parameter alone is the square root of the product of choke and downcomer froth backup. The criterion for this parameter is to keep it below 70%.

$$SQRT(\,DC\,Backup * DC\,Choke) = \sqrt{(\%\,DC\,Froth\,Backup * \%\,DC\,Choke)} \qquad \text{(Customary or Metric)} \qquad \text{Eq. (41)}$$

Liquid Rate per Unit Length Weir - To keep within the bounds of the data used to develop the capacity correlations, the liquid rate per unit length of weir should be within the criteria of 1.5 to 17.5 gpm/inch of weir (3.7 to 43.5 dm^3/s/m). Picket fence weirs may be used to increase the liquid rate should it be less than 1.5 gpm/inch (3.7 dm^3/s/m). Likewise, swept back weirs or modified arc downcomers may be used to decrease the liquid rate per unit length on side downcomers. Increasing the number of passes should be evaluated provided sufficient diameter exists. Multi-downcomer trays such as the HiFi tray or the ECMD tray are also options for high liquid rate conditions.

Froth/Spray Transition - Statistical analysis has shown that the 1133 program limits on froth to spray transition can be safely increased by 10%. This increase is already reflected in the table under **Froth to Spray Regime Transition** earlier in this section and the allowable criteria are also printed out by EMoTIP.

Universal Ultimate Capacity - This new correlation is still in the testing stage but should be a good indicator of whether a tower is too small for any internal, except perhaps non-conventional devices that use centrifugal or impaction deentrainment. If the limit of 85% is reached, an increased diameter is required.

Dry Tray Pressure Drop - To keep within the bounds of data used for both the capacity and efficiency correlation development, it is recommended to maintain the dry tray pressure drop in the range of 1.25 to 5.5 inches (32 to 140 mm) of hot liquid. Maintaining a dry tray pressure drop is an old rule of thumb for sieve tray design to maintain a stable tray frothing action. The research on the EMoTIP probability of flooding provided support for this old rule of thumb, in that trays with low dry tray pressure drop at a fixed 85% of overall flood, exhibit markedly increased scatter in the flood point, either high or low. EMoTIP performs this test and will not print out a probability of non-flooding design for the tray if a minimum dry tray pressure drop of 1.25 inches of hot liquid (32 mm) is not maintained at 85% of overall flood.

Velocity Under the Downcomer (V_{ud}) - Excessive velocity in the inlet area of the tray can result in channeling across the tray, which could reduce tray efficiency. It can also cause a blocking effect of the holes on the inlet side of the tray due to momentum, and result in excessive froth heights on the outlet side of the tray and premature flooding (commonly referred to as a rooster-tail effect or outlet side flood). This latter effect tends to be worse with low dry tray pressure drops, low tray spacing, and longer flow path lengths. The current criterion in EMoTIP is 1.3 ft/sec (0.4 m/sec), which is an increase from the 1.1 ft/sec (0.33 m/sec) limit in MoTIP. There was no limit on this parameter in 1133 designs. With tighter downcomer sealing criteria, and a recommended hud_L of up to 1.5 in. (38 mm), many 1133 designs will have high V_{ud}. The downcomer clearance should be increased if this limit is not reached. Recessed inlet pans or inlet weirs may also be used to prevent a high velocity under the downcomer from adversely affecting tray action. However, inlet weirs will cause increased downcomer backup. Both recessed inlet pans or inlet weirs should be avoided in situations of potential liquid born foulant, as they increase the plugging potential of the tray. In those cases, a small breaker bar, 3/8 to 1/2 inch (9.5 to 13 mm) high may be used in place of an inlet weir to help alleviate the effects of high velocity under the downcomer. Please consult with a FRACTIONATION SPECIALIST if this criteria can not be met during revamps or re-ratings.

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Vapor Fraction Under the Downcomer (Vapor Recycle) - There is no limit on this parameter in EMoTIP, but downcomer design should attempt to minimize it. In high pressure and heavily liquid loaded towers it may not be possible to reduce the value below 15-18%. This number is the vapor as a fraction of the total volumetric flow in the downcomer, so as a percentage of the total vapor flow in the tower it is small. Therefore, it usually has no appreciable effect on jet flood or tray efficiency and is not included in those calculations.

Downcomer Sealing - To prevent some of the vapor from bypassing a tray by traveling up the downcomer, the downcomer should be sealed at design rates by the liquid on the tray below. Therefore, it is necessary to check the sum of the clear liquid height at the inlet to the tray (h_i) and the head loss under the downcomer (h_{ud}) at design liquid rates. This sum plus 1/2 in. (13 mm) must be at least equal to the downcomer clearance. Downcomer seal is also calculated at minimum rates, if a turndown rate is defined. Larger degrees of unseal are allowable at turndown. If a seal is not obtained, consider:

- Increasing the outlet weir height.
- Reducing the clearance to 1.5 in. (38 mm) provided the downcomer filling is not exceeded at design rates and the velocity under the downcomer limit is not exceeded. A downcomer clearance of 1 in. (25 mm) is acceptable in very clean services.
- Adding an inlet weir.
- Using a recessed inlet box.

Note that designing near the high end of the head loss range may unnecessarily increase downcomer filling if a higher clearance will still seal the downcomer. Therefore, there is no justification for setting downcomer clearance any lower than that required for downcomer sealing.

Downcomer unsealing up to 1.0 – 1.5 in. (25 to 38 mm) at turndown in high liquid rate services are acceptable or in services where there is a need to minimize downcomer fouling. Downcomer unsealing at turndown does not seem to adversely effect tray efficiency according to available FRI data.

Liquid Weeping at Conditions - Weeping as a percentage of the total liquid rate on a tray will generally have limited effect on tray efficiency if weeping is less than 20%. The estimated weeping is calculated both at the design conditions and the turndown conditions (if they differ from the design). It should be maintained at less than 20%. Both the E-Method and M-Method efficiency calculations have corrections for weeping so an estimate of the effect of weeping on tray efficiency can be made. Hole area has the largest effect on weeping and should be reduced to reduce the weeping if it is excessive. If the turndown requirements for the tower cannot be met with a sieve tray, a moveable valve tray should be evaluated. The EMoTIP weeping correlation is a variation of the FRI TR 119 model, and is the same model that was used in MoTIP. The basic equations for weep point and weeping rate are given below, but are only suitable for computer calculation, because the clear liquid height must be determined simultaneously. The clear liquid for these equations is the public domain version of hExxon 1133 clear liquid height (referred to as the Colwell model in the literature). Details on this method for weeping may be found in FRI TR 119 and Reference 12.

$$V_{bwp} = 14.5 * \left(\frac{\left(A_o / A_b \right)^{1.44}}{\sqrt{\rho_v}} \right) * \left(\frac{\rho_L - \rho_v}{\rho_v} \right)^{0.094} * \left(\frac{d_o}{t} \right)^{-0.22} * \left(\rho_L \cdot h''_{cwp} \right)^{0.144} \qquad \text{(Customary)} \qquad \text{Eq. (42)}$$

where: V_{bwp} = Vapor velocity through the bubble area at the weep point, ft/s

t = Tray thickness, inch

h''_{cwp} = FRI TR 119 clear liquid height at the weep point, inch

The weeping rate is determined from the following equation:

$$Q_w = 94.6 * 1.09 * \alpha^2 * e^{\left(-0.043 \cdot \frac{d_0}{t} \cdot u_L \right)} \left(\left(1 - \sqrt{\frac{V_b}{V_{bwp}}} \right) * \sqrt{2 g_c \cdot \left(\frac{h''_c}{\alpha} - h''_t \right)} \right) * A_o \qquad \text{(Customary)} \qquad \text{Eq. (43)}$$

where: Q_w = Weep rate, gal/min

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