



DESIGN PRACTICES

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Revision Memo

12/99

The highlights of this revision are:

1. A table listing operating limits for bubble cap trays has been added.
2. References to PRO/II and PROVISION have been added.
3. The **COMPUTER PROGRAMS** section has been updated to include references to the PEGASYS bubble cap tray design and rating program.
4. Design criteria for ACN extractive distillation have been added to **Table 2**.
5. The Surface Tension-Viscosity Parameter ($K_{\sigma\mu}$) is depicted in a new **Figure 2**.
6. The **BUBBLE CAP TRAY CALCULATION FORMS** have been corrected to calculate bubble cap seal using the minimum liquid rate through the use of $h_{1(\min)}$ (**Eq. 4e2** and **4e2M**).



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SCOPE

This section covers the techniques for specifying or rating the process design features of bubble cap 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 bubble cap trays are the best choice for the design. Detailed mechanical design, as well as beam and cap layout, are normally handled by the tray fabricator. A calculation form, showing the step-by-step calculation procedure, is at the end of this section. Computer programs are available to perform these calculations. (See discussion under *Computer Programs*). 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](#).

REFERENCES

Some of the following literature has been used in the preparation of this section.

INTERNATIONAL PRACTICE

[IP 5-2-1](#) Internals for Towers, Drums and Fixed Bed Reactors

OTHER LITERATURE

1. Becker, P. W., *Sieve Tray Capacity Correlations Have Been Improved*, Report No. EE.76E.72, June, 1972.
2. Hofmann, L., *No. 3 Sidestream Drawoff Limitations, Lubes Vacuum Pipestill T-3001, Singapore Refinery*, ER&E Memorandum No. 95 CET 150, January 12, 1996.
3. Kokoska, R. J. and Perry, D., *Downcomer Capacity Correlations Have Been Improved*, Report No. EE.49E.80, June, 1980.

BACKGROUND

Bubble cap trays were used extensively in the petroleum and chemical industries until the early 1950's. They found wide acceptance because of their high efficiency and good capacity and their ability to operate over a wide range of liquid and vapor loadings. The bubble cap tray's biggest deficiency is its cost, other types of trays being as much as 50 percent cheaper. Thus, as adequate design technology was developed for less expensive fractionating devices, the bubble cap tray lost its popularity and today is used infrequently within Exxon. Sieve trays are now considered to be the first choice for most refinery and chemical plant operations.

The equations given in this section for predicting bubble cap tray capacity and downcomer limitations are identical to those used for sieve trays. The pressure drop and entrainment equations, however, are specific to bubble cap trays. They have been derived largely from Fractionation Research, Inc., (FRI) data, supplemented by data from simulator and commercial tests. These equations represent the data far more accurately than do the correlations prepared by FRI, various vendors, or those available in the literature.

DEFINITIONS / EQUATIONS

For a discussion of such concepts as jet flooding, efficiency, flexibility, etc., see [Section III-A](#), *Device Selection and Basic Concepts*. See the **NOMENCLATURE** section for symbol definitions.

All equations in the text of this section are numbered in the same way as they appear on the **BUBBLE CAP TRAY CALCULATION FORMS**. Those equations not discussed in the text are shown in the appropriate section of the **BUBBLE CAP TRAY CALCULATION FORMS**. Wherever possible, both the Customary and the Metric equations are shown in the text. However, if the equation is complex, the Metric version has been omitted in the text for clarity but can be found on the **BUBBLE CAP TRAY CALCULATION FORM (METRIC)**.

APPLICATION

For most towers, sieve trays with 2/1 or 3/1 flexibility are normally adequate and should be used. If greater flexibility is required, and the system is non-fouling, valve trays should be specified. If the system is fouling or corrosion of valve trays is expected to be a serious problem, then bubble cap trays should be provided.

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APPLICATION (Cont)

- The table below, which is based on operating experience, lists the lower and upper operating limits for most bubble cap tray designs. If your case does not fall within these limits, contact your FRACTIONATION SPECIALIST to see what, if any, problems may exist.

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)	45 (13,700)
Physical properties surface tension, dyne/cm (mN/m)	1 (1)	75 (75)
liquid viscosity, cP (mPa•s)	0.05 (.05)	10 (10)
vapor density, lb/ft ³ (kg/m ³)	0.005 (.08)	5 (80)
liquid density, lb/ft ³ (kg/m ³)	20 (320)	80 (1300)
Tray spacing, in. (mm)	12 (300)	36 (910)
Cap size	see Table 3A and 3B for standard dimensions	
DC clearance, in. (mm)	1 (25)	3.5 (90)
DC inlet area as % of A _s	7 %	40 % sloped; 25 % straight
Number of passes	1	4
Outlet Weir height, in. (mm)	0 (0)	4 (100)
Flow path length, in. (mm)	16 (410) for access	15 ft (4600 mm)

BASIC DESIGN CONSIDERATIONS

The design procedure outlined later in this section requires either: a) the selection of a trial diameter and tray layout for new designs, or b) tray hardware details for revamps. The design is then checked against critical performance limitations including jet flooding, ultimate capacity, downcomer limitations, etc. These limitations, which are common to all types of trays, are discussed fully in **Section III-A**. Only those items requiring further explanation are discussed below.

VAPOR CAPACITY LIMITATIONS

Jet Flooding - Occurs when the vapor rate is sufficiently high to "jet" liquid from a given tray to the tray above. It is the primary cause of tower flooding. It is a strong function of diameter and tray spacing and a lesser function of the number of liquid passes used. These relationships are discussed below.

- **Tray Spacing** - The optimum combination of diameter, tray spacing, and number of liquid passes is the one which minimizes total investment, subject to the limitations outlined under **DETAILED DESIGN PROCEDURE** discussed later in this section. The optimum spacing usually lies between 18-24 in. (450-600 mm).
- **Number of Liquid Passes** - The vapor handling capacity of towers with high liquid rates can usually be increased by the use of multipass trays. Since multipass trays 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 14 gpm/in. of weir/pass (35 dm³/s/m of weir/pass), the FRACTIONATION SPECIALIST should be consulted because of the lack of reliable design data above this liquid rate. More detailed selection criteria are given in **Table 1**. Specific guidelines for 3 and 4 pass trays are given in **Table 5** of **Section III-B**.
- If the tower is limited by downcomer filling which cannot be reduced by other hardware changes, the use of multipass trays should also be considered.
- **Tower Diameter** - The tower diameter must provide enough cross-sectional area to avoid both downcomer and jet flooding limitations. Downcomer sizing will be discussed later. The equations for jet flooding are given below. (The equation numbers are the same as those used on the Bubble Cap Tray Calculation Forms.)

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BASIC DESIGN CONSIDERATIONS (Cont)

- Jet Flooding Equations:**

For hydrocarbon systems:

$$\left[\frac{V_L}{A_f} \right]_{\text{Allow}} = 0.296 K_{HL} K_{\sigma\mu} \quad (\text{Customary}) \quad \text{from Eq. (3c4)}$$

$$= 0.090 K_{HL} K_{\sigma\mu} \quad (\text{Metric}) \quad \text{from Eq. (3c4)M}$$

For aqueous systems:

$$\left[\frac{V_L}{A_f} \right]_{\text{Allow}} = 0.204 K_{HL} K_{\sigma\mu} \quad (\text{Customary}) \quad \text{from Eq. (3c5)}$$

$$= 0.0622 K_{HL} K_{\sigma\mu} \quad (\text{Metric}) \quad \text{from Eq. (3c5)M}$$

where: V_L = Vapor load, ft³/s (m³/s) at conditions = $q_v \left[\frac{\rho_v}{\rho_L - \rho_v} \right]^{0.5}$

A_f = Free area, ft² (m²). See [Section III-A, Figure 13](#). For two pass trays, both passes must be checked.

K_{HL} = Tray spacing - liquid rate factor, dimensionless [[Figures 1A and 1C for Eq. \(3c4\)](#), [Figures 1B and 1D for Eq. \(3c5\)](#)]. When checking a two pass tray with inboard downcomers, the liquid rate, L , should be based on the **inboard** weir length l_o^* . The outboard pass should be based on l_o .

$K_{\sigma\mu}$ = Surface tension - viscosity factor, dimensionless ([Figure 2](#)).

q_v = Volumetric vapor rate, ft³/s (dm³/s) at conditions.

ρ_v = Vapor density at conditions, lb/ft³ (kg/m³).

ρ_L = Liquid density at conditions, lb/ft³ (kg/m³).

Eq. (3c4) should be used for all hydrocarbon systems and for other systems when the surface tension is equal to or less than 40 dynes/cm (mN/m). **Eq. (3c5)** should be used for aqueous systems and whenever the surface tension is greater than 40 dynes/cm (mN/m). If a predominantly aqueous system has a surface tension equal to or less than 40 (e.g., alcohol/water), **Eq. (3c4)** should be used. The following list outlines which equation to use for various systems. Any systems known to foam should be designed for 60% of the allowable jet flood velocity for that system. However, if the system is listed in Part 3 of [Table 2](#), use that value. If in doubt, contact your FRACTIONATION SPECIALIST.

EQUATION (3c4)	EQUATION (3c5)
All hydrocarbon light ends towers. All sidestream and bottoms strippers. Aqueous systems containing alcohols, ketones, aldehydes, etc., if surface tension ≤ 40 dynes/cm (mN/m). Other non-aqueous chemical plant towers (i.e., oxo-alcohols, butyl rerun, etc.). Aromatics separations. Atmospheric and vacuum pipestills. Cat, steam cracker, coker, FLEXICOKER, and HYDROCRACKER primary fractionators above the bottom pumparound. Hydrocarbon absorbers. Prefractionators and outboard flash towers.	Absorption of HCl, H ₂ SO ₄ , etc. in water. Amine and FLEXSORB scrubbers and regenerators. Ammonia fractionators. Catacarb absorbers and regenerators. Caustic scrubbers. Sour water strippers. Water wash sections. Foaming aqueous systems. Other aqueous liquid/steam stripped towers.

In addition, the above equations must be used in conjunction with the appropriate percentage of the jet flood velocity permitted by [Table 2](#).

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BASIC DESIGN CONSIDERATIONS (Cont)

Ultimate Capacity - The ratio of design vapor load (V_L) to the vapor load for ultimate capacity $V_{L(Ult)}$, **Eq. (5a1)** must be kept below 90%. If necessary, the tower diameter must be increased, even though **Eq. (3c4)** or **(3c5)** has already been satisfied for jet flooding. However, the diameter calculation from **Eq. (3c4)** or **(3c5)** usually provides sufficient free area to satisfy the ultimate capacity limitation.

$$V_{L(Ult)} = 0.62 A_f \left[\frac{\beta}{1+\beta} \right] \left[\frac{\sigma_L}{\rho_L - \rho_v} \right]^{0.25} \quad \text{(Customary)} \quad \text{from Eq. (5a1)}$$

$$\text{where: } \beta = 1.4 \left[\frac{\rho_L - \rho_v}{\rho_v} \right]^{0.5}$$

For the Metric equation, use a coefficient of 0.378 vs. the 0.62 shown above.

Entrainment - Two equations have been added to the calculation form to calculate the entrainment rate [see **Eq. (5c1)** or **(5c2)**]. Both equations were developed by FRI. If the entrainment rate, expressed as a percentage of the liquid entering the tray exceeds 20%, the tray design must be modified. At rates above 20%, tray efficiency begins to drop sharply and tray flooding may occur (see **Section III-A** for more details).

Since entrainment is not normally a problem if the jet flooding limitations are met, the entrainment equations are **not** built into the design loop but are used only to check the final design (Step 5 of the **BUBBLE CAP CALCULATION FORM**).

LIQUID CAPACITY LIMITATIONS

Downcomer Design Considerations

- 1) **Downcomer Sizing** - The required downcomer inlet area is set by froth disengaging limitations. This calculated velocity is a function of the froth density and the physical properties of the system and therefore varies from system to system. **Figures 3A** and **3B** or **Table 2** provide the maximum allowable downcomer entrance velocity for most systems. However, if the ρ_v/ρ_L ratio is greater than 0.03, contact your FRACTIONATION SPECIALIST to see if a more restrictive entrance velocity procedure should be used, such as the one used with sieve trays in **Section III-B**.

For **foaming systems**, a velocity of 0.2 ft/s (0.06 m/s) should be used. However, if the foam is very stable, even a very low velocity still may not prevent tower flooding. If the designer expects to face this situation, 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 expensive solution to the problem since anti-foam must be added continuously.

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. Thus, vapor recycling will cause an increase in the vapor load leaving a tray and will adversely affect both tray capacity and efficiency. Therefore, for both new designs and revamps, the downcomer size should be increased to avoid vapor recycle. See **Section III-A** for more background on vapor recycling.

Downcomer sloping criteria are discussed under *Detailed Design Procedure - Step 2 - Downcomer Area*. Areas and lengths of chords are given in **Section III-K**.

- 2) **Downcomer Filling** - Downcomer filling as a percentage of tray spacing, should not exceed the values in **Figure 4A** or **4B**. For hydrocarbon and aqueous systems that are known to foam, use 80% of the value given in **Figure 4A** or **4B**. In addition, special downcomer filling criteria for specific aqueous towers are listed in **Table 2**. If these criteria cannot be met, the tray spacing, the number of liquid passes, and/or perhaps the tower diameter should be increased.

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BASIC DESIGN CONSIDERATIONS (Cont)

- 3) **Downcomer Clearance** - Downcomer clearance (c) 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 a normal head loss (h_{ud}) of 0.5 to 1.5 in. (13 to 38 mm) of hot liquid, according to the submerged weir formula given below. This range was chosen to avoid excessive liquid velocity at the tray inlet.

$$h_{ud} = 0.06 \left[\frac{Q_L}{c N_p l_{ud}} \right]^2 \quad \text{(Customary)} \quad \text{from Eq. (4h1)}$$

$$h_{ud} = 160 \left[\frac{1000 Q_L}{c N_p l_{ud}} \right]^2 \quad \text{(Metric)} \quad \text{from Eq. (4h1)M}$$

where: Q_L = Liquid rate, gpm (dm^3/s) at conditions
 N_p = Number of liquid passes
 l_{ud} = Length of bottom edge of downcomer, in. (mm)

A shaped downcomer lip should not be used on bubble cap trays because the obstruction presented by the caps would cause turbulence and defeat the purpose of the shaped downcomer lip.

- 4) **Downcomer Sealing** - To prevent some of the vapor from bypassing a tray by traveling up the downcomer, the downcomer must be sealed at minimum 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 the minimum liquid flow rate. This sum plus 1/4 in. (6 mm) must be at least equal to the downcomer clearance. If a seal is not obtained (rare on a bubble cap tray), consider:

- Increasing the outlet weir height.
- Reducing the clearance to 1 in. (25 mm) provided the downcomer filling is not exceeded at design rates.
- Adding an inlet weir.
- Using a recessed inlet box provided the liquid rate is below 11 gpm/in. of diameter/pass (28 $\text{dm}^3/\text{s}/\text{m}$ of diameter/pass).

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. See discussion and figures in [Section III-A](#) for more background.

- 5) **Anti-jump Baffles** - Must be provided on all inboard downcomer(s) of multipass trays if the liquid rate exceeds 4.2 gpm/in. of diameter/pass (10 $\text{dm}^3/\text{sec}/\text{m}$ of diameter/pass). This is to prevent liquid from jumping across (choking) the downcomer and causing premature flooding (see [Section III-A](#) for further background information on downcomer choking).

OTHER BASIC DESIGN CONSIDERATIONS

Tray and Cap 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 uncapped area farther than 3 in. (75 mm) from the edge of the nearest cap. Normally, there is no waste area on a bubble cap tray unless a very low cap area is required (part of the tray is left uncapped).

Tray Hydraulics - Downcomer filling, as a percent of tray spacing, should not exceed the values given as a function of pressure in [Figure 4A](#) or [4B](#). In addition, special downcomer filling criteria for aqueous towers are given in [Table 2](#). If downcomer filling is excessive and cannot be reduced by lowering weir height, increasing the downcomer clearance, etc. the tray spacing should be increased.

Tray Turndown - Turndown is the ratio of the maximum to minimum vapor loadings between which good tray efficiency is maintained. It is limited by jet flooding (excessive entrainment) at high vapor rates and by loss of interfacial area at very low vapor rates. A turndown ratio of between 3 and 4/1 is usually achievable with bubble cap trays.

Turndown requirements are dictated by combining two effects. The first is operating turndown and the second is the inherent variation in the loading profile over a tower section. If this loading variation is 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.

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BASIC DESIGN CONSIDERATIONS (Cont)

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 for other reasons. See [Sections III-I](#) and [F](#) for more information on tray efficiency and heat transfer, respectively.

Startup Considerations - At very low vapor velocities (such as during startup), even bubble cap trays may weep through the inlet rows of caps, with the result that insufficient liquid is maintained on the tray feeding the reboiler drawoff box. Hence, when thermosyphon reboilers are used on bubble cap 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 jumper line from the tower bottoms drawoff line to the reboiler inlet. The jumper 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](#).

DETAILED DESIGN PROCEDURE

The step-by-step procedure for designing or revamping a bubble cap tray is given on the **BUBBLE CAP TRAY CALCULATION FORM**. Reminder: A Computer Program (# 3583 or PEGASYS) is available to perform these calculations. See discussion under *Computer Programs* later in this section.

For new designs, the procedure involves assuming a trial design with the help of the principles given above, checking it against various potential operating limitations, and then modifying it as required to arrive at the optimum tray design.

For revamps, all of the tower hardware is given. It must be checked against the various potential operating limits and modified as required. Deciding how to modify the various hardware parameters will require judgment and application of the basic design considerations already discussed as well as those contained in [Table 1](#). If help is needed, contact your FRACTIONATION SPECIALIST. The calculation step numbers used below correspond to those used on the calculation form.

VAPOR AND LIQUID LOADINGS (STEP 1)

♦ This information is normally calculated as part of the heat and material balance(s) for the tower and usually comes from a computer program like PRO/II and PROVISION, etc. Traditionally, designers have assumed 33% of the design loadings when minimum liquid and vapor loadings have not been specified; however, this assumption can have a large impact on the tray design and operation, and the proper minimum loadings for a given situation should be used. Tray spacing, and the presence of drawoff boxes or other internals can impact on which tray is limiting a given tower. Designers should verify by inspection (not auto-selection) the minimum and maximum loaded trays in a section that are used for tray design or rating. This is done by determining the vapor load for the trays in a section (using data from the tray loading summary in PRO/II output) and selecting the trays with the largest and smallest vapor load. Vapor loadings are **to** the tray in question; liquid loadings are **from** the tray in question since these are nearly always the maximum values for the tray in question. However, the designer should be aware that loadings will occasionally increase significantly across a given theoretical tray. If this is the case and the overall efficiency is less than about 70%, the vapor loading from the tray in question may be higher. The designer must then prorate loadings between the loadings to and from the theoretical tray in question. In the case of bottoms and sidestream strippers for pipestills, guidelines are presented in [Section III-I](#), *Tray Efficiency*, for 4 and 6 tray strippers.

In the design of heavy hydrocarbon/steam strippers (e.g., pipestill sidestream and bottoms strippers), the tray hydraulics are normally checked for an assumed vapor rate to the top tray equal to the stripping steam rate plus 60 mole percent (for 4-tray strippers) of the total hydrocarbon vapor stripped out. Once the top tray is designed, lower trays may require modified designs due to the large decrease in vapor rate. The optimum design of trays for these strippers is detailed in [Section III-I](#) (*Tray Efficiency*).

TRIAL TRAY SPACING, SIZE AND LAYOUT (STEP 2)

Tray Spacing - A low tray spacing between 18 and 24 in. (450 to 600 mm) is often the most economical. For the first trial, a tray spacing of 18 in. (450 mm) or that shown below (whichever is larger) should be used. The values given are the minimum for most applications, as determined by maintenance considerations and support beam depth.

In special cases, however, even smaller spacings may be justified (especially if the required number of trays can be contained in one shell vs. two), but this makes maintenance more difficult. On the other hand, downcomer filling 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.

DETAILED DESIGN PROCEDURE (Cont)

MINIMUM TRAY SPACING				
Tower Diameter, ft (mm)	Clean Service		Fouling Service	
	in.	mm	in.	mm
5 or less (≤ 1500)	18*	450*	21*	525*
> 5 to 8 (> 1500 to 2400)	21*	525*	24*	600*
> 8 to 10 (> 2400 to 3000)	24*	600*	30	750
> 10 to 20 (> 3000 to 6000)	27	675	33	825
greater than 20 (> 6000)**	30	750	36	900

Notes:

- * If there is no manhead between trays. Minimum tray spacing with a manhead present is the greater of (a) normal tray spacing or (b) 1.5 x (manway diameter) plus 4 in. (100 mm).
- ** 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.)

Trial Tower Diameter - The trial diameter (D_{tr}) is calculated from [Eq. \(2a4\)](#) on the calculation sheet. It may need to be adjusted either upward or downward when the trial design is checked against various performance limitations. [Eq. \(2a4\)](#) is a sieve tray capacity equation which has been verified with FRI and commercial data. It is the same equation used in [Section III-B](#) as [Eq. \(2a4\)](#).

Number of Liquid Passes - The number of passes should be selected on the basis of the criteria given in [Table 1](#). The number is not likely to change when the trial design is finalized, unless the tower diameter is changed substantially. The calculation sheet is designed to handle one and two pass trays. For three and four pass trays, refer to [Table 5](#) in [Section III-B](#).

Downcomer Areas - The maximum velocity of the liquid entering the downcomer(s) should be determined from [Figures 3A](#) and [3B](#) or [Table 2](#), whichever gives the lower value. For known foaming systems, a very low downcomer inlet velocity (about 0.2 ft/s; 0.06 m/s) should be used. There is no lower limit on the downcomer inlet velocity. However, if long liquid residence time in the downcomer promotes fouling, consider either the use of segmental downcomers or baffles, etc. to reduce downcomer volume.

For a sloped or stepped downcomer, the downcomer outlet area is based on the following table:

MAXIMUM V_{di}		MAXIMUM V_{do}	
ft/s	m/s	ft/s	m/s
< 0.3	< 0.09	2 times maximum entrance velocity	
> 0.3 and < 0.6	> 0.09 and < 0.18	0.6	0.18
> 0.6	> 0.18	Equal to V_{di} (downcomers are straight)	

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 6.8% of A_s . This applies to all single pass trays and the outboard downcomer of multipass trays. This assures that the chord length is at least 65% of the tower diameter for chordal downcomers. If the tower diameter exceeds 6 ft (1800 mm) and the liquid rate requires a downcomer area much less than 6.8% of A_s , consider the use of a **segmental downcomer** (modified arc). If a segmental downcomer is used, it must be at least 6 in. (150 mm) wide. (See [Section III-K](#), [Figure 3](#), for sizing segmental downcomers.)

If the sum of $A_{di} + A_{do}$ exceeds 60% of A_s , the tower diameter should be increased and both K_{HL} and A_f corrected. Remember that K_{HL} is based on the liquid rate per in. (m) of weir length and will change if the diameter changes. In addition, for segmental downcomers, use the projected weir length, not the total weir length. (See discussion in [Section III-A](#) on downcomers for more details.)

This sets the downcomer areas to be used for the first trial. However, any changes in tower diameter made during the remainder of the design procedure could also necessitate changes in downcomer sizing.

Outlet Weirs and Downcomer Clearances - Criteria for selecting outlet weir heights and downcomer clearances are given in [Table 1](#). For tray geometry relationships, see [Section III-K](#).

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DETAILED DESIGN PROCEDURE (Cont)

FINAL TRAY SPACING, SIZE AND BUBBLE CAP LAYOUT (STEP 3)

Tower Area - To permit the trial design to be checked against the jet flooding and ultimate capacity limitations, the quantities listed under Step 3a on the calculation form must first be calculated, based on the trial design.

Ultimate Capacity - The vapor load factor corresponding to ultimate capacity is calculated from **Eq. (5a1)**. The ratio of design to the ultimate capacity vapor rate must be kept below 90%.

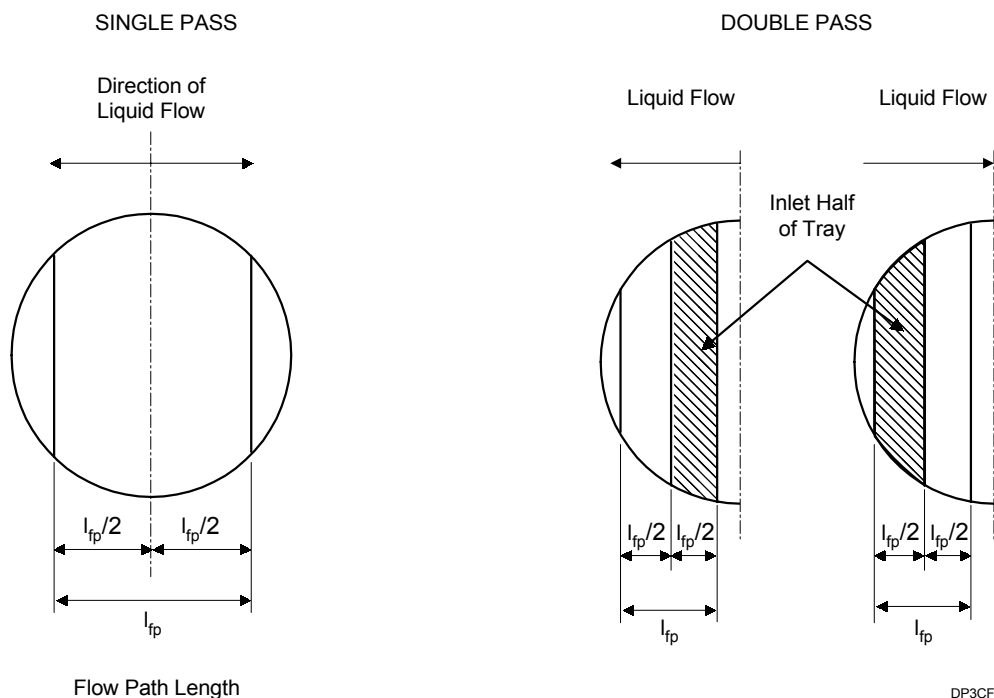
Jet Flooding - The allowable vapor load for jet flooding is calculated from **Eqs. (3c4)** and **(3c5)**. The ratio of the design vapor load to that for jet flooding should not exceed the percentages recommended in **Table 2**. For systems not covered by **Table 2**, your FRACTIONATION SPECIALIST should be consulted for the proper value.

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**.

Bubble Cap Layout - The following general guides can be used for checking an existing tray layout or for designing a new tray. If the detailed tray layout is handled by the vendor, the Exxon Design Specification should indicate whether square pitch or triangular pitch is desired. The cap size should also be specified. Other cap details do not need to be specified, since they are covered by **IP 5-2-1**.

Pitch - Square pitch should be specified for new designs, since liquid gradients are smaller than with triangular pitch.

Spacing - On all bubble cap trays, 10% more caps **per sq ft (or per sq m) of contacting area** should be specified for the inlet half of the tray than for the outlet half. The inlet half is defined as the contacting area within the first one-half of the flow path length, l_{fp} as shown below.



This can usually be achieved if the following criteria are met. Use a center-to-center row spacing of about 8-1/2 in. (227 mm) with 6 in. caps and 6 in. (150 mm) with 4 in. caps on the liquid inlet third (flow path) of the tray; 9 and 6-1/2 in. (225 and 157 mm), respectively, on the liquid outlet third. Use an intermediate value for the center third of the tray. On vacuum tower trays, the spacings may be reduced by 1 in. (25 mm). Since square pitch is recommended, these values also set the cap spacings within a given row.

Cap Size - Because of their lower pressure drop, 6 in. raised caps are generally specified for vacuum service or for debottlenecking existing towers. 4 in. bubble caps are used on trays with diameters 3 ft (1 m) and less. 6 in. caps are specified for trays larger than 3 ft (1 m) in diameter. If towers over 3 ft (1 m) in diameter would have too few 6 in. caps per tray (because of low vapor rates) and good distribution cannot be obtained with 6 in. caps, then 4 in. caps can be used. Standard caps used by Exxon are illustrated in **Tables 3A** and **3B**.

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Distance from Weir - The centerline of the end row of caps should be 6 to 7 in. (150 to 175 mm) away from the overflow weir when 6 in. caps are used, and 5 to 6 in. (125 to 150 mm) away for 4 in. caps.

Number of Caps - Use 2 caps per sq ft (22 caps/m²) as a starting point.

Blanking - For revamps, the ways to reduce capped area are to use blanking strips or replace the tray deck panels with ones having a smaller number of caps. Also, some vendors fabricate blank chimney inserts that can be bolted in place after removing the cap.

The caps **must** be removed prior to blanking. If blanking 50% or less of the capped area, blank single rows or pairs of rows of caps. Leave at least two consecutive rows unblanked.

For large amounts of blanking:

- Use a combination of items mentioned above plus waste area.
- Consider adding vertical baffles to restrict flow path width. (See [Figure C](#) in [Section III-I](#) under *How Can Trays Be Improved.*)
- Check adverse impact on tray efficiency (if any) because of the added waste area. For these rare cases, consult your FRACTIONATION SPECIALIST for help.

TRAY HYDRAULICS AND DOWNCOMER FILLING (STEP 4)

This part of the calculation form permits calculation of the various components of tray pressure drop and downcomer filling.

Vapor Distribution and Pressure Drop - Vapor flowing through a tray must overcome the frictional resistance in the bubble cap and chimney plus the liquid head above the point where vapor leaves the bubble cap slots. Uniform vapor flow over the tray cross-section depends on an equal **total** resistance through **all** sections of the tray. Test data have shown that the liquid head is greatest at the tray inlet and decreases toward the outlet. A minimum liquid head exists between the outlet row of caps and the overflow weir.

The liquid head contour assumed for design purposes is shown in [Figure 7](#). To compensate for the reduction in liquid head from the tray inlet toward the outlet, the bubble cap pressure drop should be less on the inlet portion of the tray. This is accomplished by providing approximately 10% more caps per sq ft (or per sq m) of contacting area on the inlet half than on the outlet half of the tray, as discussed earlier.

To insure that all caps are active, the cap pressure drop for a given liquid rate must be at least as great as that shown by the bottom curve of [Figure 6A](#) or [6B](#). The "poor" distribution region below this curve represents the liquid rates above which the inlet caps cease to carry vapor and therefore dump liquid. When the liquid rate exceeds that obtained from the "good" distribution curve in [Figure 6A](#) or [6B](#), the cap pressure drop should be increased. This can be accomplished by blanking every third cap in each row on the outlet side of the tray. Other means of raising pressure drop when revamping existing trays include installing restriction chokes at the base of the chimneys and/or lowering the cap position if adjustable caps have been provided. Also see earlier discussion on blanking.

- ▶ Note that [Figures 6A](#) and [6B](#) do not contain liquid gradient (which is expected to increase with flow path length) as an explicit variable. Therefore, these figures, as well as [Figures 5A](#) and [5B](#), may not be conservative for flow path lengths outside the experimental database, that is, greater than 15 ft (4600 mm).

- ▶ **Weir Height, Liquid Gradient and Slot Sealing** - The outlet weir height is determined from [Eq. \(4f1\)](#) on the calculation form. The weir height should be high enough that the liquid level on the tray seals the cap openings at all rates. That is, the liquid height, h_o , should be at least as high as h_{ds} (refer to [Table 3A](#) or [3B](#) and [Figure 7](#)). Because of the gradient, the limiting seal requirement occurs at the outlet row of caps at the lowest turndown liquid rates. The calculation procedure to determine weir height ensures that the outlet row of caps is sealed by 1/4 in. (6 mm) of liquid. The calculated value of the weir height should be rounded up to the nearest 1/4 in. (6 mm). The procedure is also based on an assumed liquid head depression of 1 in. (25 mm) at the tray outlet (see [Figure 7](#)).

[Figure 5A](#) or [5B](#) should be used for estimating the liquid gradient on the tray. The liquid gradient affects the total vapor pressure drop by increasing the average liquid head on the tray. [Eq. \(4g2\)](#) on the calculation form shows the effect of liquid gradient on tray pressure drop. For design purposes, it is assumed that the liquid level at the average cap is equal to h_o , the outlet head plus 1/3 of the liquid gradient, (G).

Downcomer Filling - The downcomer filling, as a percent of tray spacing, should not exceed the values given for specific services in [Table 2](#). For all other services, use the value obtained from [Figure 4A](#) or [4B](#).

The clear liquid height (h_l) at the tray inlet must be checked at the minimum liquid flow rates to make sure that the downcomer is sealed (see earlier discussion under *Downcomer Sealing*). If a seal is not obtained, consider the use of a higher outlet weir, a smaller downcomer clearance, or a recessed inlet box.

The slot pressure drop (h_{sl}) should not exceed 2.25 in. (57 mm) for foaming systems and 4.5 in. (114 mm) for non-foaming systems.

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DETAILED DESIGN PROCEDURE (Cont)

CHECKING PROCESS LIMITATIONS (STEP 5)

After the tray design has been established, be sure that the ultimate capacity and the fractional entrainment criteria have been met. If any of these criteria have been violated, the trial tray design must be modified. If all of the criteria cannot be met simultaneously, consult your FRACTIONATION SPECIALIST.

TRAY EFFICIENCY (STEP 6)

Whenever possible, past experience should be used as a guide for determining bubble cap efficiency. In the absence of data, it can be assumed that a bubble cap tray designed according to the procedure outlined in this section will have the same efficiency as that of a well-designed sieve tray. Sieve tray efficiency can be calculated from the procedure described in [Section III-I, Tray Efficiency](#). If questions arise, consult your FRACTIONATION SPECIALIST.

BALANCED DESIGN (STEP 7)

Even when a new tray design or revamp meets all the above criteria, the designer should check to see if the design is as "balanced" as possible. That is, the "ideal" balanced design would have the jet flood velocity, the downcomer entrance velocity and downcomer filling all at approximately the same percentage of their respective limits (e.g., say 85% of maximum jet flood, 85% of the allowable downcomer entrance velocity, and 85% of the allowable downcomer filling limits, respectively). 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 consider running parametric computer cases to balance a design rather than carrying out several lengthy calculations by hand.

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.).

TOWER CHECKLIST (STEP 8)

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

NOMENCLATURE

A_a	=	Cap annular area, ft ² (m ²) (Table 3A or 3B)
A_b	=	Bubble Area, ft ² (m ²) (see Figure 12 in Section III-A)
A_c	=	Chimney inside cross-sectional area, ft ² (m ²) (Table 3A or 3B)
A_{cap}	=	Cap inside cross-sectional area, ft ² (m ²) (Table 4A or 4B)
A_{di}	=	Total downcomer inlet area, ft ² (m ²)
A_{do}	=	Total downcomer outlet area, ft ² (m ²)
A_f	=	Free area, ft ² (m ²) (superficial area minus arithmetic average of inlet and outlet area of downcomer(s) above the tray minus the waste area); for multipass trays, use the tray having the smallest value of A_f . (See Figure 13 in Section III-A .)
A_m	=	The smaller of the annular area between cap and chimney (A_a) or the reversal area (A_r), ft ² (m ²) (Table 4A or 4B)
A_r	=	Cap reversal area, i.e., area between top of chimney and underside of cap, ft ² (m ²) (Table 3A or 3B)
A_s	=	Superficial (total) tower area, ft ² (m ²)
A_{sl}	=	Slot area per cap, ft ² (m ²) (Table 3A or 3B)
A_w	=	Waste area, ft ² (m ²) (normally zero for bubble cap trays)
c	=	Clearance between tray and downcomer apron at tray inlet, in. (mm) (see Figure 6 in Section III-A)
C_b	=	Capacity factor based on bubble area, V_L/A_b , ft/s (m/s)
d	=	Chimney inside diameter, ft (mm) (Table 4A or 4B)
D_t	=	Tower diameter, ft (mm)
D_{tr}	=	Trial tower diameter, ft (mm)
E_O	=	Overall efficiency, % (see Section III-I)
G	=	Tray liquid gradient, in. (mm) of hot liquid

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NOMENCLATURE (Cont)

H	=	Tray spacing, in. (mm)
H_s	=	Cap slot height, in. (mm) (Table 3A or 3B)
H'_s	=	Vertical distance from top of slot to some assumed point below bottom edge of cap, in. (mm) [i.e., $(H_s + E) > H'_s > H_s$. See Table 3A or 3B]
h_{cap}	=	Cap pressure drop, in. (mm) of hot liquid
h_{ch}	=	Total chimney pressure drop, in. (mm) of hot liquid
h_d	=	Downcomer filling, in. (mm) of hot liquid
h_{ds}	=	Distance from top of tray to top of slot, in. (mm) (Table 3A or 3B)
h_i	=	Tray inlet head, in. (mm) of hot liquid
h_o	=	Liquid level on tray outlet, in. (mm) of hot liquid
h_r	=	Portion of chimney pressure drop for non-standard caps, in. (mm) of hot liquid (Table 4A or 4B)
h_s	=	Slot pressure drop, in. (mm) of hot liquid
h_t	=	Total tray pressure drop, in. (mm) of hot liquid
h_u	=	Portion of chimney pressure for non-standard caps, in. (mm) of hot liquid (Table 4A or 4B)
h_{ud}	=	Head loss under downcomer, in. (mm) of hot liquid
h_{wi}	=	Inlet weir height, in. (mm) (see Figure 11 , Section III-A)
h_{wo}	=	Outlet weir height, in. (mm) (see Figure 6 , Section III-A)
h_1	=	Liquid head over outlet weir, in. (mm) of hot liquid at design rate
$h_{1(min)}$	=	Liquid head over outlet weir, in. (mm) of hot liquid at minimum liquid rate
K_{HL}	=	Tray spacing - liquid rate factor, dimensionless (see Figures 1A through 1D)
K_c	=	Chimney pressure drop coefficient, dimensionless (Table 3A or 3B)
$K_{\sigma\mu}$	=	Surface tension - viscosity factor, dimensionless (see Figure 2)
K_w	=	Outlet weir height factor, dimensionless (Table 3A or 3B)
L	=	Liquid rate, gpm/in. of weir /pass ($\text{dm}^3/\text{s}/\text{m}$ of weir /pass)
L'	=	Liquid rate, gpm/in. of diameter /pass ($\text{dm}^3/\text{s}/\text{m}$ of diameter /pass)
L_L	=	Liquid load, ft^3/s (dm^3/s) at conditions
$L_{L(Min)}$	=	Minimum liquid load, ft^3/s (dm^3/s) at conditions
l_{fp}	=	Flow path length: distance between inlet and outlet downcomer, ft (mm) (see figure in text)
l_i	=	Inlet weir length, in. (mm)
l_o	=	Outlet weir length, in. (mm) (see Figure 12 in Section III-A)
l_o^*	=	Outlet weir length on inboard tray, in. (mm) (see Figure 12 in Section III-A)
l_{ud}	=	Length of bottom edge of outboard downcomer, in. (mm) (see Figure 12 in Section III-A)
l_{ud}^*	=	Length of bottom edge of inboard downcomer, in. (mm)
N_A	=	Number of actual trays
N_p	=	Number of liquid passes
N_T	=	Number of theoretical trays
Q_L	=	Liquid rate, gpm (dm^3/s) at conditions
$Q_{L(min)}$	=	Minimum liquid rate, gpm (dm^3/s) at conditions
q_v	=	Volumetric vapor rate, ft^3/s (m^3/s) at conditions
r	=	Downcomer inlet rise, in. (mm)
r_o	=	Downcomer outlet rise, in. (mm)
S_L	=	Liquid specific gravity at conditions, dimensionless

