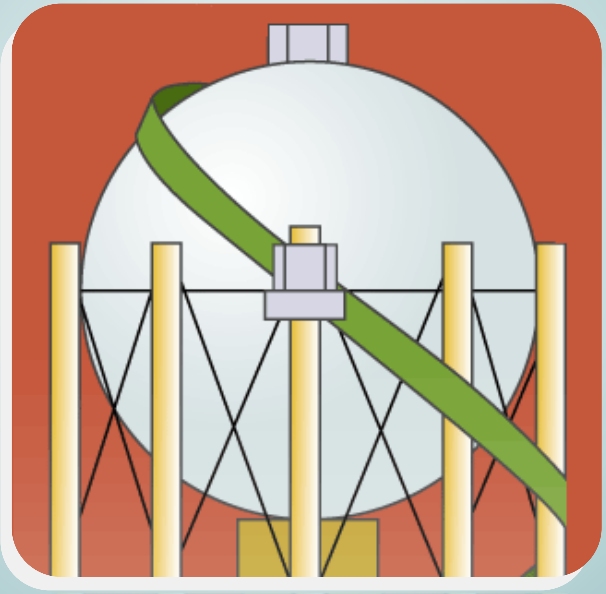
Chemical Process Design



INDEX

1.- INTRODUCTION

Process Alternatives Synthesis (candidate flowsheet)
Analysis (Preliminary mass and energy balances)
SIZING (Sizes and capacities)
COST ESTIMATION (Capital and operation)
Economic Analysis (economic criteria)

SIZING

Calculation of all physical attributes that allow a unique costing of this unit

- **Capacity, Height**
- **Cross sectional area**
- **Pressure rating**
- **Materials of construction**

Short-cut, approximate calculations (correlations) → Quick obtaining of sizing parameters → Order of magnitude estimated parameters

COST

Total Capital Investment or Capital Cost: **Function of the process equipment → The sized equipment will be costed**

*** Approximate methods to estimate costs**

Manufacturing Cost: **Function of process equipment and utility charges**

Categories of total capital cost estimates

based on accuracy of the estimate

ESTIMATE	BASED ON	Error (%)	Obtention	USED TO
ORDER OF MAGNITUDE (Ratio estimate)	Method of Hill, 1956. Production rate and PFD with compressors, reactors and separation equipments. Based on similar plants.	40 - 50	Very fast	Profitability analysis
STUDY	Overall Factor Method of Lang, 1947. Mass & energy balance and equipment sizing.	25 - 40	Fast	Preliminary design
PRELIMINARY	Individual Factors Method of Guthrie, 1969, 1974. Mass & energy balance, equipment sizing, construction materials and P&ID. Enough data to budget estimation.	15 - 25	Medium	Budget approval
DEFINITIVE	Full data but before drawings and specifications.	10 -15	Slow	Construction control
DETAILED	Detailed Engineering	5 -10	Very slow	Turnkey contract

Cost Estimation Method of Guthrie

• **Equipment purchase cost:** **Graphs and/or equations.**

Based on a power law expression: Williams Law $C = BC = Co\ (S/So)^{\alpha}$ →

→ **Economy of Scale** (incremental cost C, decrease with larger capacities S)

Based on a polynomial expression $BC = \exp\{A_0 + A_1 [\ln(S)] + A_2 [\ln(S)]^2 + \ldots\}$

• **Installation: Module Factor, MF, affected by BC, taking into account labor, piping instruments, accessories, etc.**

Typical Value of MF=2.95 → equipment cost is almost 3 times the BC.

Installation = (BC)(MF)-BC = BC(MF-1)

• **For special materials, high pressures and special designs abroad base capacities and costs (Co, So), the Materials and Pressure correction Factors, MPF, are defined.**

Uninstalled Cost = (BC)(MPF) **Total Installed Cost = BC (MPF+MF-1)**

• **To update cost from mid-1968, an Update Factor, UF to account for inflation is apply.**

UF: Present Cost Index/Base Cost index
Updated bare module cost: BMC = UF(BC) (MPF+MF-1)

Materials and Pressure correction Factors: MPF

Empirical factors that modified BC and evaluate particular instances of equipment beyond a basic configuration: Uninstalled Cost = (BC x MPF)

MPF = Φ (Fd, Fm, Fp, Fo, Ft)

Fd: Design variation
Fm: Construction material variation
Fp: Pressure variation
Fo: Operating Limits (Φ of T, P)
Ft: Mechanical refrigeration factor Φ (T evaporator)

EQUIPMENT	MPF
Pressure Vessels	Fm . Fp
Heat Exchangers	Fm (Fp + Fd)
Furnaces, direct fired heaters, Tray stacks	Fm + Fp + Fd
Centrifugal pumps	Fm . Fo
Compressors	Fd

Equipment Sizing Procedures

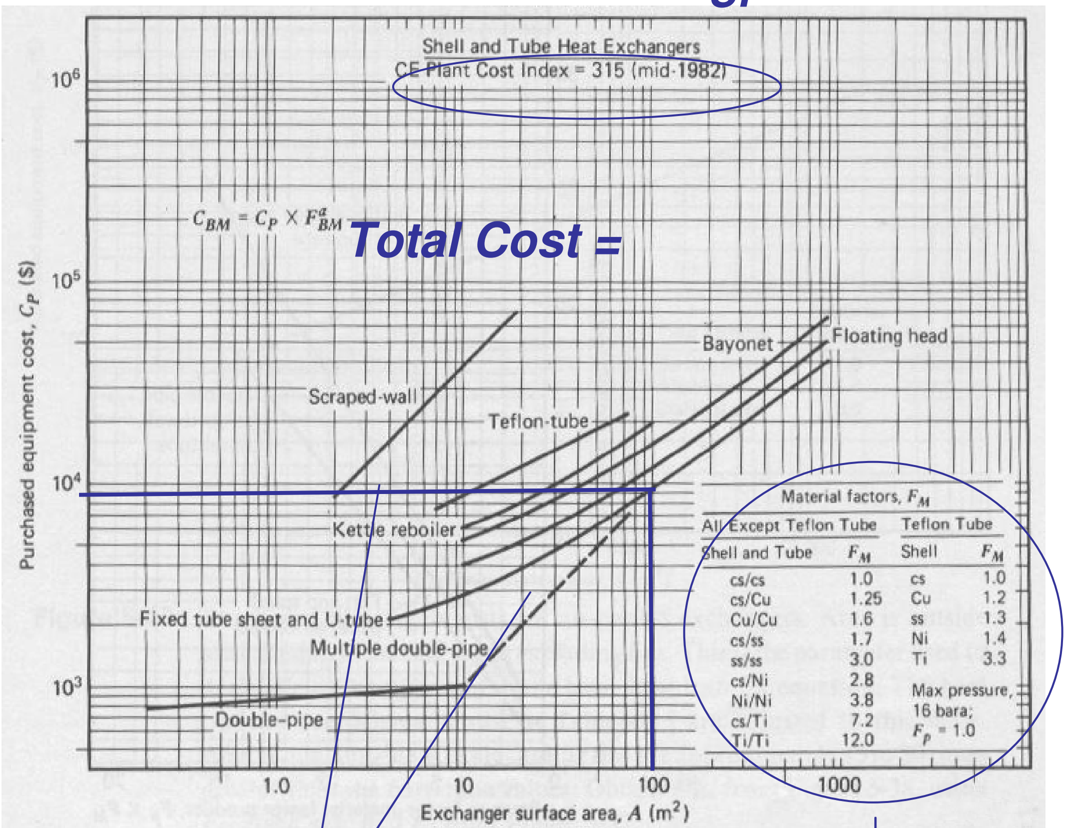
Need C and MPF → required the flowsheet mass and energy balance (Flow, T, P, Q)

An example of Cost Estimation

Equipment purchase price

Cp

UF



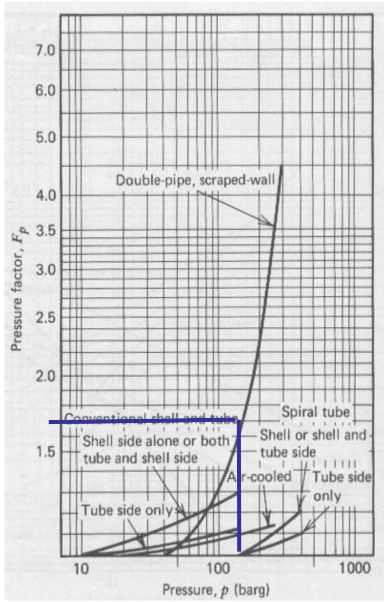
Total Cost =

Design Factor

Fd

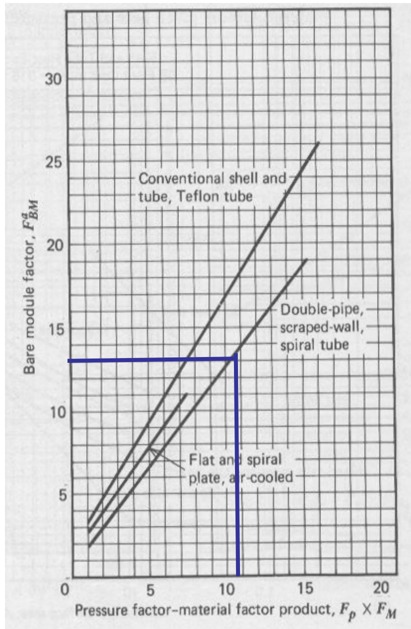
Material Factor

Fm



Pressure Factor

Fp



Factor Base

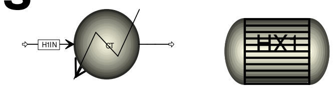
Modular

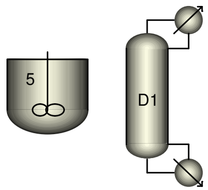
Fbm

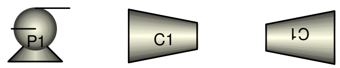
2.- EQUIPMENT SIZING PROCEDURES

Short-cut calculations for the main equipment sizing

Q, P maintenance	**Vessels**
Δ Heat contents	**Heat transfer equipment: Heat exchangers** **Furnaces and Direct Fired Heaters** **Refrigeration**
Δ Composition	**Reactors** **Columns, distillation and Absorption**
Q, P streams setting	**Pumps, Compressors and Turbines**



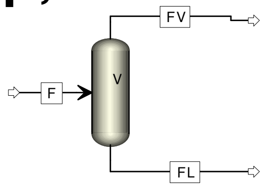




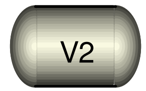
SHORTCUTS for VESSEL SIZING (Flash drums, storage tanks, decanters and some reactors)

1) Select the V for liquid holdup; τ= 5 min + equal vapor volume

$V=(F_L/\rho_L * \tau)*2$



2) Select L=4D



$V=\pi D^2/4*L \rightarrow$ **$D=(V/\pi)^{1/3}$**; If D $\leq$1.2 m Vertical, else Horizontal

•Materials of Construction appropriate to use with the Guthrie´s factors and pressure (P_{rated} =1.5 P_{actual})

• Basic Configuration for pressure vessels

- Carbon steel vessel with 50 psig design P and average nozzles and manways
- Vertical construction includes shell and two heads, the skirt, base rings and lugs, and possible tray supports.
- Horizontal construction includes shell, two heads and two saddles

MPF = Fm . Fp; Fm depending shell material configuration (clad or solid)

Materials of Construction for Pressure Vessels

High Temperature Service

Tmax (°F)	Steel
950	Carbon steel (CS)
1150	502 stainless steels (SS)
1300	410 SS; 330 SS
1500	304,321,347,316 SS. Hastelloy C, X Inconel
2000	446 SS, Cast stainless, HC

Low Temperature Service

Tmin (°F)	Steel
-50	Carbon steel (CS)
-75	Nickel steel (A203)
-320	Nickel steel (A353)
-425	302,304,310,347 (SS)

Guthrie Material and pressure factors for pressure vessels: MPF = Fm Fp

Shell Material	Clad, Fm	Solid, Fm
Carbon Steel (CS)	1.00	1.00
Stainless 316 (SS)	2.25	3.67
Monel (Ni:Cr/2:1 alloy)	3.89	6.34
Titanium	4.23	7.89

Vessel Pressure (psig)

Up to	50	100	200	300	400	500	900	1000
Fp	1.00	1.05	1.15	1.20	1.35	1.45	2.30	2.50

SHORT CUT for REACTORS SIZING

First step of the preliminary design → Not kinetic model available.

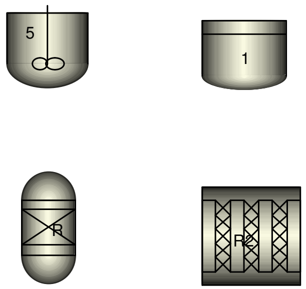
Mass Balance based on Product distribution → High influence in final cost

Assumptions: Reactor equivalent to laboratory reactor, adiabatic reactors are isotherm at average T.

Assume space velocity (S in h^{-1})

$$S = (1/\tau) = \mu / \rho\, V_{cat}\ ; \quad V = V_{cat} / 1- \varepsilon$$

μ = Flow rate; ρ= molar density; V_{cat}= Volume of catalyst; ε= Void fraction of catalyst (e.g. ε=0.5)



HEAT TRANSFER EQUIPMENT SIZING

Heat exchanger types used in chemical process

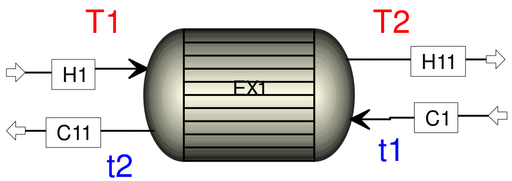
By function

- Refrigerants (air or water) - Condensers (v, v+l → l) - Reboilers, vaporizers (l→v) - Exchangers in general

By constructive shape

- Double pipe exchanger: the simplest one
- Plate and frame exchangers
- Direct contact: used for cooling and quenching
- Fired heaters: Furnaces and boilers
- Shell and tube exchangers: used for all applications
- Air cooled: used for coolers and condensers
- Jacketed vessels, agitated vessels and internal coils

Shell and tube countercurrent exchanger, steady state



$Q = U\ A\ \Delta T_{lm}$

Q: From the energy balance

U: Estimation of heat transfer coefficient. Depending on configuration and media used in the Shell and Tube side: L-L, Condensing vapor-L, Gas-L, Vaporizers). (Perry's Handbook, 2008; www.tema.org).

A: Area

ΔT_{lm}: Logarithmic Mean ΔT = (T1-t2)-(T2-t1)/ln (T1-t2/T2-t1)

- If phase changes → Approximation of 2 heat exchangers (A=A1+A2)
- Maximum area A ≤ 1000 m^2, else → Parallel HX

MPF: Fm (Fp + Fd)

Heat exchanger: Countercurrent, steady state

Guthrie Material and pressure factors for Heat Exchangers: MPF: Fm (Fp + Fd)

Design Type	Fd
Kettle Reboiler	1.35
Floating Head	1.00
U Tube	0.85
Fixed tube sheet	0.80

Vessel Pressure (psig)

Up to	150	300	400	800	1000
Fp	0.00	0.10	0.25	0.52	0.55

Shell/Tube Materials, Fm

Surface Area (ft^2)	CS/ CS	CS/ Brass	CS/ SS	SS/ SS	CS/ Monel	Monel Monel	CS/ Ti	Ti/ Ti
Up to 100	1.00	1.05	1.54	2.50	2.00	3.20	4.10	10.28
100 to 500	1.00	1.10	1.78	3.10	2.30	3.50	5.20	10.60
500 to 1000	1.00	1.15	2.25	3.26	2.50	3.65	6.15	10.75
1000 to 5000	1.00	1.30	2.81	3.75	3.10	4.25	8.95	13.05

FURNACES and DIRECT FIRED HEATERS (boilers,reboilers, pyrolysis, reformers)

Q = Absorbed duty from heat balance

• Radiant section (q_r=37.6 kW/m^2 heat flux) + Convection section (q_c=12.5 kW/m^2 heat flux). Equal heat transmission (kW) → A_{rad}=0.5 x kW/q_r; A_{conv}=0.5 x kW/q_c

• Basic configuration for furnaces is given by a process heater with a box or A-frame construction, carbon steel tubes, and a 500 psig design P. This includes complete field erection.

• Direct fired heaters is given by a process heater with cylindrical construction, carbon steel tubes, and a 500 psig design.

Guthrie MPF for Furnaces: MPF= Fm+Fp+Fd

Design Type	Fd
Process Heater	1.00
Pyrolisis	1.10
Reformer	1.35

Vessel Pressure (psig)

Up to	500	1000	1500	2000	2500	3000
Fp	0.00	0.10	0.15	0.25	0.40	0.60

Radiant Tube Material, Fm

Carbon Steel	0.00
Chrome/Moly	0.35
Stainless Steel	0.75

Guthrie MPF for Direct Fired Heaters

MPF: Fm + Fp + Fd

Design Type	Fd
Cylindrical	1.00
Dowtherm	1.33

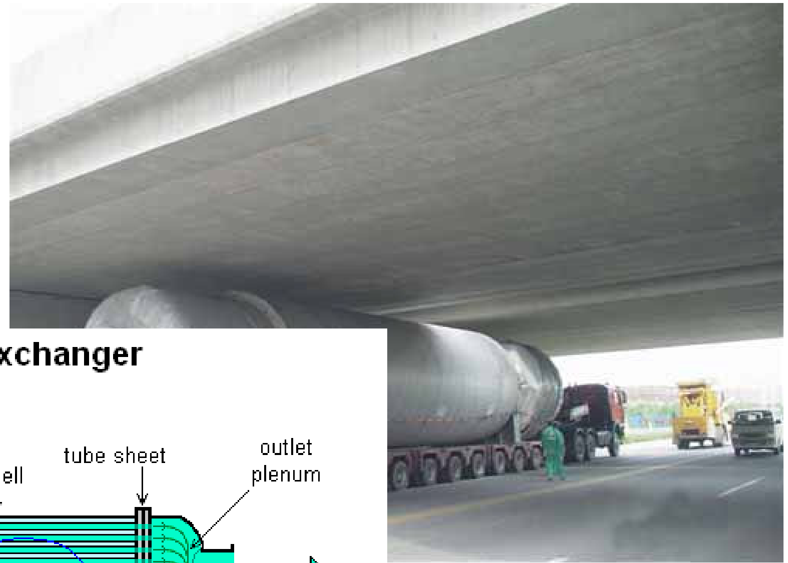
Vessel Pressure (psig)

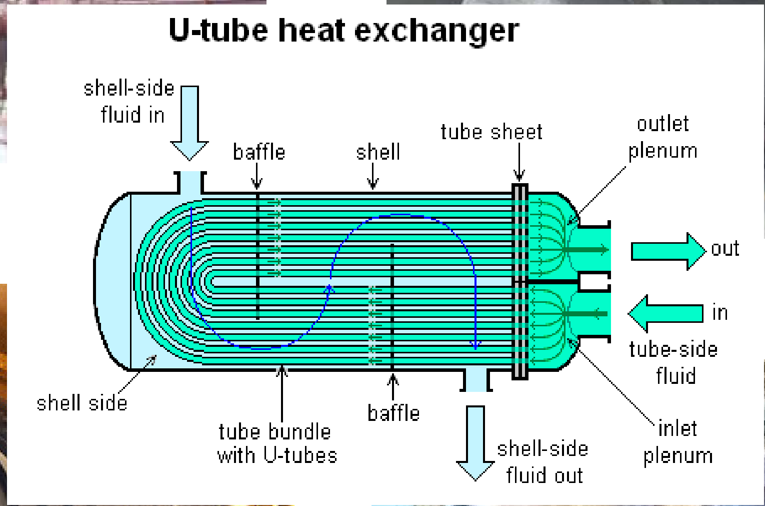
Up to	500	1000	1500
Fp	0.00	0.15	0.20

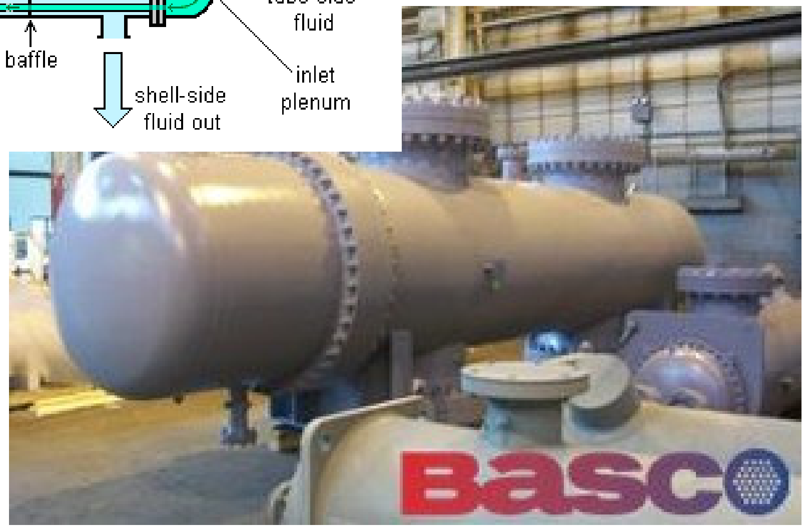
Radiant Tube Material, Fm

Carbon Steel	0.00
Chrome/Moly	0.45
Stainless Steel	0.50

HEAT EXCHANGERS







SHORT CUT for DISTILLATION COLUMS SIZING

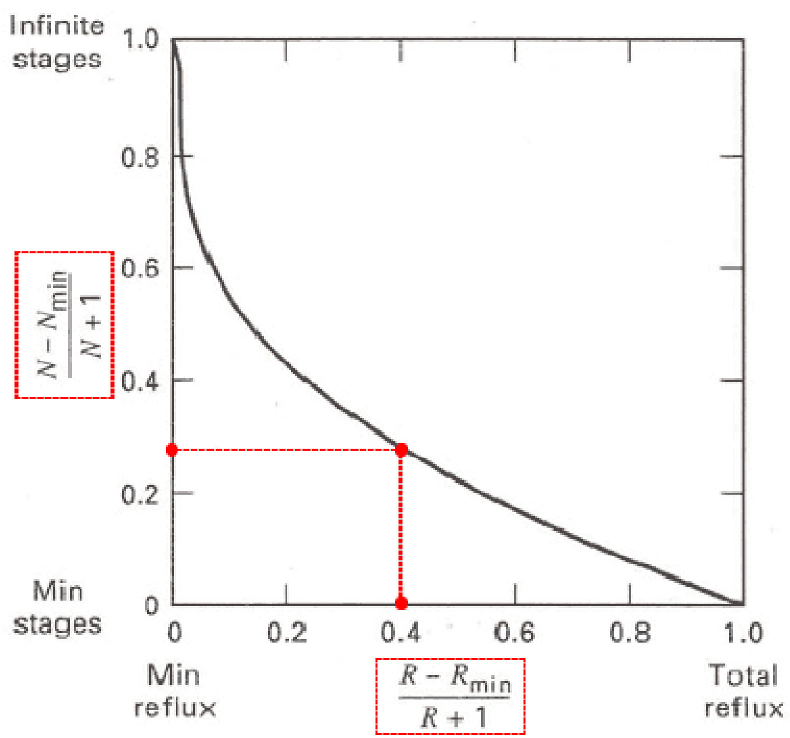
Fenske's equation applies to any two components lk and hk at infinite reflux and is defined by N_{min}, where αij is the geometric mean of the α's at the T of the feed, distillate and the bottoms.

$$N_{\min} = \frac{\log\left(\dfrac{x_{Dlk}/x_{Blk}}{x_{Dhk}/x_{Bhk}}\right)}{\log\left(\overline{\alpha}_{lk/hk}\right)} \qquad \overline{\alpha}_{lk/hk} = \left(\alpha_{D\,lk/hk}\,\alpha_{F\,lk/hk}\,\alpha_{B\,lk/hk}\right)^{1/3}$$

R_{min} is given by **Underwood** with two equations that must be solved, where q is the liquid fraction in the feed..

$$1 - q = \sum \frac{\alpha_i\, x_{Fi}}{\alpha_i - \phi} \qquad R_{min} + 1 = \sum \frac{\alpha_i\, x_{Di}}{\alpha_i - \phi}$$

Gilliland used an empirical correlation to calculate the final number of stage N from the values calculated through the Fenske and Underwood equations (N_{min}, R, R_{min}). The procedure use a diagram; one enters with the abscissa value known, and read the ordinate of the corresponding point on the Gilliland curve. The only unknown of the ordinate is the number of stage N.



SHORT CUT for DISTILLATION COLUMS SIZING

Simple and direct correlation for (nearly) ideal systems (Westerberg, 1978)

- Determine $\alpha_{lk/hk}$; $\beta_{lk} = \xi_{lk}$; $\beta_{hk} = 1 - \xi_{hk}$
- Calculate tray number Ni and reflux ratio Ri from correlations (i= lk, hk):

Ni $= 12.3 / (\alpha_{lk/hk}-1)^{2/3} \cdot (1-\beta_i)^{1/6}$ **Ri** $= 1.38 / (\alpha_{lk/hk}-1)^{0.9} \cdot (1-\beta_i)^{0.1}$

- Theoretical nº of trays $\mathbf{N_T}$ = 0.8 max[Ni] + 0.2 min[Ni]; **R**= 0.8 max[Ri] + 0.2 min[Ri]

- Actual nº of trays **N** = $N_T/0.8$

- For **H** consider 0.6 m spacing (H=0.6 N); Maximum H=60 m → else, 2 columns

* Calculate column diameter, **D,** by internal flowrates and taking into account the vapor fraction of F. Internal flowrates used to sizing condenser, reboiler

Design column at 80% of linear flooding velocity

$$U_f = C_{sb}\left[\frac{\rho_L - \rho_G}{\rho_G}\right]^{0.5}\left(\frac{20}{\sigma}\right)^{0.2}$$

$$A = \frac{\pi D^2}{4} = \left[\frac{\overline{V}}{0.8\, U_f\, \varepsilon\, \rho_G}\right]$$

If D> 3m → Parallel columns

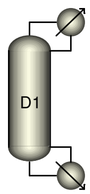
* Calculate heat duties for reboiler and condenser

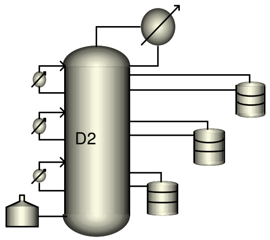
$$Q_{cond} = H_V - H_L = \sum_{k=1}^{n}\left(\mu_D^k + \mu_L^k\right)\Delta H_{vap}^k = \frac{V}{D}\sum_{k=1}^{n}\mu_{dk}\Delta H_{vap}^k$$

$$Q_{reb} = V\ \Delta H_{vap}^k$$

* Costing vessel and stack trays (24" spacing)

DISTILLATION COLUMNS





Guthrie MPF for Tray Stacks

MPF: Fm + Fs + Ft

Tray Type	**Ft**
Grid	0.0
Plate	0.0
Sieve	0.0
Valve o trough	0.4
Bubble Cap	1.8
Koch Kascade	3.9

Tray Spacing, Fs

(inch)	24"	18"	12"
Fs	1.0	1.4	2.2

Tray Material, Fm

Carbon Steel	0.0
Stainless Steel	1.7
Monel	8.9

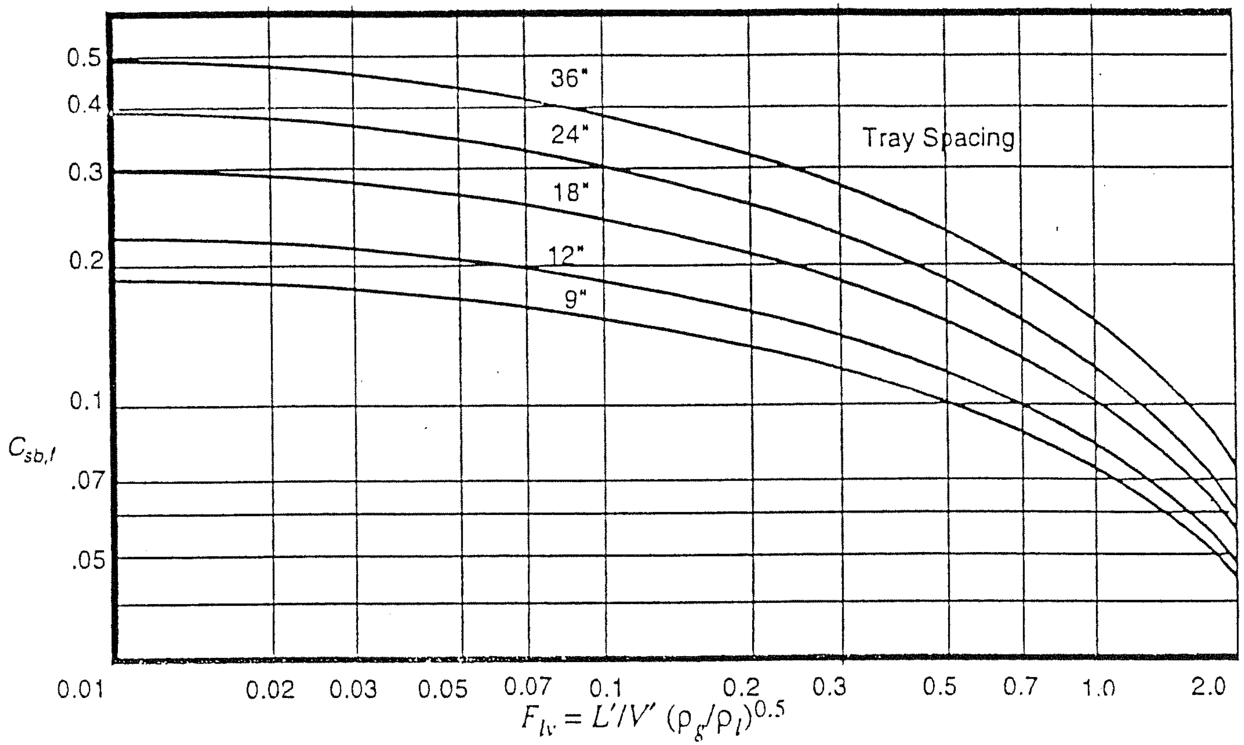
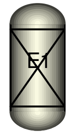


FIGURE 4.4 Flooding limits for bubble cap and perforated trays. L'/V' is the liquid/gas mass ratio at the point of consideration. (Data taken from Fair, 1961.)

DISTILLATION COLUMNS

SHORT CUT for ABSORBERS COLUMS SIZING



Sizing similar to the distillation columns

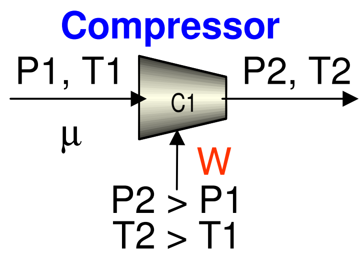
N_T → Kremser equation

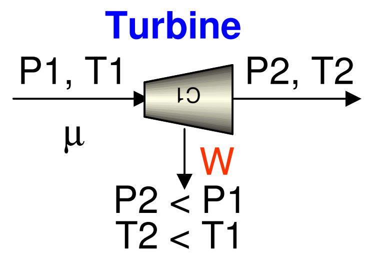
$$N = \ln\left[\frac{l_0^n + (r^n - A_E^n)\, v_{N+1}^n}{l_0^n - A_E^n(1-r^n)\, v_{N+1}^n}\right] / \ln(A_E^n)$$

• Assumption: v-l equilibrium → but actually there is mass transfer phenomena (e.g. simulation of CO_2- MEA absorption) → 20% efficiency in nº trays → **$N = N_T/0.2$**

• Calculate H and D for costing vessel and stack trays (24” spacing)

SHORT CUT for COMPRESSORS (or TURBINES) SIZING





Centrifugal compressors are the most common compressors (High capacities, low compression ratios –r-) *vs.* Reciprocating compressors (Low capacities, high r)
Assumptions: Ideal behavior, isentropic and adiabatic

Drivers

1) Electric motors driving compressor; η_M=0.9; η_C=0.8 (compressor)

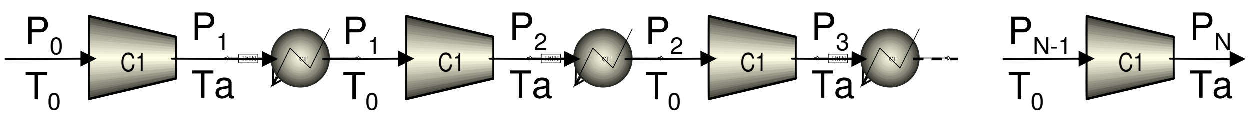
   Brake horsepower $W_b = W/\eta_M \eta_C = 1.39\ W$

2) Turbine diving compressor (e.g.IGCC where need decrease P); η_T=0.8; W_b=1.562 W

Max. Horsepower compressor = 10.000 hp = 7.5 MW

Max Compression ratio $r = P_2/P_1 < 5$.

Staged compressors → to decrease work using intercoolers in N stages



Work is minimised when compression ratios are the same

$P_1/P_0 = P_2/P_1 = \dots = P_N/P_{N-1} = (P_N/P_0)^{1/N}$

Rule of thumb → $(P_N/P_0)^{1/N} = 2.5$ → **N**

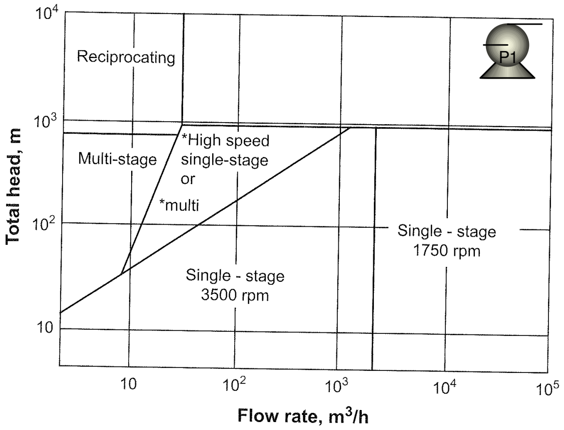
$$W = \mu N R T_0 \left(\frac{\gamma}{\gamma-1}\right)\left[\left(\frac{P_N}{P_0}\right)^{\frac{\gamma-1}{N\gamma}} - 1\right]$$

STEAM TURBINE

SH-25 GAS TURBINE

COMPRESSORS

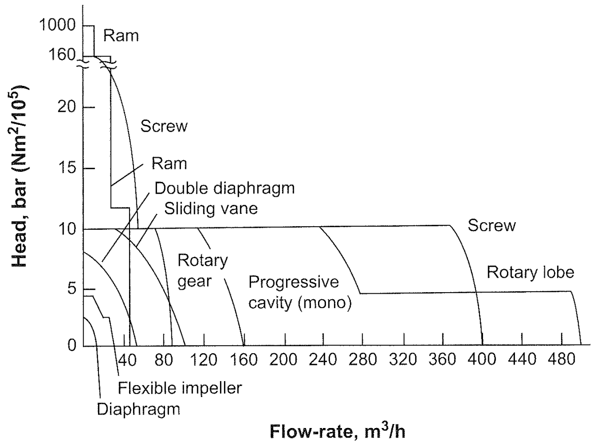
SHORT CUT for PUMPS SIZING



Centrifugal pumps selection guide.
(*)single-stage > 1750 rpm, multi-stage 1750 rpm
(Sinnot, R, Towler, G., 2009)

Normal operating range of pumps

Type	Capacity Range (m³/h)	Typical Head (m of water)
Centrifugal	0.25 - 10^3	10-50 3000 (multistage)
Reciprocating	0.5 - 500	50 - 200
Diaphragm	0.05 - 500	5 - 60
Rotary gear and similar	0.05 - 500	60 - 200
Rotary sliding vane or similar	0.25 - 500	7 - 70



Selection of positive displacement pumps
(Sinnot, R, Towler, G., 2009)

Centrifugal pumps the most common. **Assumptions:** Isothermal conditions

Brake horsepower: $$W_b = \mu \frac{(P_2 - P_1)}{\rho\, \eta_P\, \eta_M}$$

Pump: η_P=0.5 (less than η_C=0.8 because frictional problems in L); Motor: η_M=0.9

$W_b << W_c$ → $€_b << €_c$ in 2 orders of magnitude → Change P in pumps during heat integration in distillation columns is not much money

Use electrical motors not turbine as drivers in pumps

PUMPS

SPECIFICATIONS

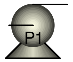
Pump Type: Centrifugal
Flow / P Specifications
Liquid Flow: 170.000 GPM
Discharge P: 43.0 psi
Inlet Size: 2.000 inch
Discharge Size: 1.500 inch
Media Temperature; 250 F
Power Specifications
Power Source AC; 100/200Single
Market Segment: General use; Paper Industry

Pump Type: Centrifugal
Flow / P Specifications
Liquid Flow:1541.003 GPM
Discharge P: 507.6 psi
Media Temperature: 662 F
Power Specifications: Power Source DC **Market Segment:** General use; Petrochemical or Hydrocarbon; Chemical Industry.

Pump Type: Centrifugal
Flow / P Specifications
Liquid Flow 15400.000 GPM
Discharge P: 212.0 psi
Inlet Size 16.000 inch
Discharge Size 16.000 inch
Media T: 572 F
Power Specifications:
Power Source AC; Electric Motor
Market Segment General use**;** Mining; Chemical Industry

Guthrie Material and Pressure Factors for Centrifugal Pumps and Drivers, Compressors and Mechanical Refrigeration.

PUMPS



Guthrie MPF for Centrifugal Pumps and Drivers

MPF: Fm.Fo

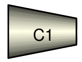
Material Type, Fm

Cast iron	1.00
Bronze	1.28
Stainless	1.93
Hastelloy C	2.89
Monel	3.23
Nickel	3.48
Titanium	8.98

Operating Limits, Fo

Max. Suction P (psig)	150	500	1000
Max. T (ºF)	250	550	850
Fo	1.0	1.5	2.9

COMPRESSORS



Guthrie MPF for Compressors

MPF: Fd

Design Type, Fd

Centrifugal/motor	1.00
Reciprocating/steam	1.07
Centrifugal/turbine	1.15
Reciprocating/motor	1.29
Reciprocating/gas engine	1.82

REFRIGERATION

Guthrie MPF for Mechanical Refrigeration

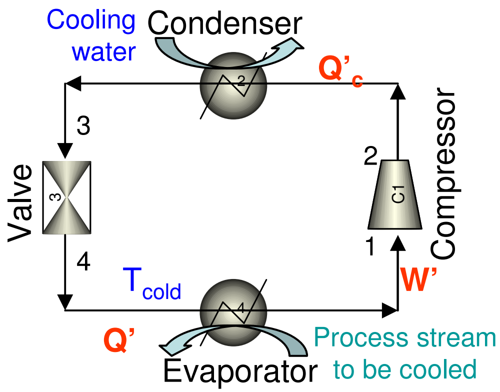
MPF: Ft

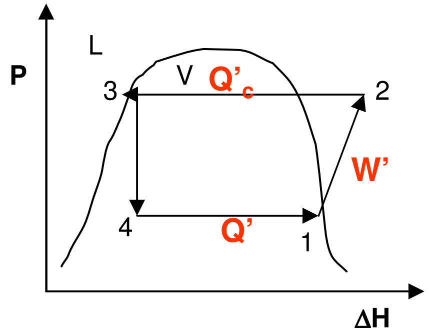
Evaporator Temperature, Ft

278 K / 5 C	1.00
266 K / -7 C	1.95
255 K / -18 C	2.25
244 K / -29 C	3.95
233 K / -40 C	4.54

SHORT CUT for REFRIGERATION SIZING

Short cut model (one cycle/one stage)





1 cycle for process stream T not too low
Coefficient of performance (CP)

CP = Q/W, typically CP ≈ 4 → Compressor W=Q/4

For h=0.9; hcomp=0.8 → Wb = W/0.72; Cooling duty Qc= W+Q = 5/4 Q

Short cut model (multiple stages)

Multiple stages for low T process stream
Refrigerant R must satisfy

a) $T_{cond} < T_c^R$ max T_{cond} = 0.9 Tc (critcal component)
b) $T_{evap} > T_{boil,R}$ → $P_{evap} = P_R^0 > 1$ atm. (To prevent decreasing η due to air in the system)
c) T_{evap} and T_{cond} must be feasible for heat exchange; $\Delta T \approx 5K$

More steps → Less energy vs. More capital investment (compressors) → Trade-off

Rule of Thumb: One cycle for 30 K below ambient →**Nº cycles = N = (300-T_{cold})/30**

$$W = Q\left[\left(1+\frac{1}{CP}\right)^N - 1\right]; \qquad Q_c = \left[1+\frac{1}{CP}\right]^N Q$$

3.- COST ESTIMATION OF EQUIPMENT: Base Costs for equipment units

[Tables 4.11-4.12; p.134 (Biegler et al., 1997) → Table 22.32; p.591-595 (Seider et al., 2010)]

Base Costs for Pressure Vessels

Equipment Type	C_0 ($)	L_0(ft)	D_0(ft)	α	β	MF2/MF4/MF6/MF8/MF10
Vertical fabrication 1≤D ≤10 ft; 4 ≤ L ≤100 ft	1000	4.0	3.0	0.81	1.05	4.23/4.12/4.07/4.06/4.02
Horizontal fabrication 1≤D ≤10 ft; 4 ≤ L ≤100 ft	690	4.0	3.0	0.78	0.98	3.18/3.06/3.01/2.99/2.96
Tray stacks 2≤D ≤10 ft; 1 ≤ L ≤500 ft	180	10.0	2.0	0.97	1.45	1.0/1.0/1.0/1.0/1.0

Base Costs for Process Equipment

Equipment Type	C_0 ($$10^3$)	S_0	Range (S)	α	MF2/MF4/MF6/MF8/MF10
Process furnaces *S=Absorbed duty (10^6Btu/h)*	100	30	100-300	0.83	2.27/2.19/2.16/2.15/2.13
Direct fired heaters *S=Absorbed duty (10^6Btu/h)*	20	5	1-40	0.77	2.23/2.15/2.13/2.12/2.10
Heat exchanger *Shell and tube, S=Area (ft^2)*	5	400	100-10^4	0.65	3.29/3.18/3.14/3.12/3.09
Heat exchanger *Shell and tube, S=Area (ft^2)*	0.3	5.5	2-100	0.024	1.83/1.83/1.83/1.83/1.83
Air Coolers *S=[calculated area (ft^2)/15.5]*	3	200	100-10^4	0.82	2.31/2.21/2.18/2.16/2.15
Centrifugal pumps *S= C/H factor (gpm x psi)*	0.39	10	10-2.10^3	0.17	3.38/3.28/3.24/3.23/3.20
	0.65	2.10^3	2.10^3 -2.10^4	0.36	3.38/3.28/3.24/3.23/3.20
	1.5	2.10^4	2.10^4 -2.10^5	0.64	3.38/3.28/3.24/3.23/3.20
Compressors *S=brake horsepower*	23	100	30-10^4	0.77	3.11/3.01/2.97/2.96/2.93
Refrigeration *S=ton refrigeration (12,000 Btu/h removed)*	60	200	50-3000	0.70	1.42

3.- COST ESTIMATION OF EQUIPMENT

Guthrie´s modular method to preliminary design.

Updated Bare Module Cost = UF · BC · (MPF + MF -1)

BC

Williams Law: $C = BC = Co\,(S/So)^{\alpha}$

Non-linear behaviour of Cost, C *vs.,* Size, S → Economy of Scale (incremental cost decrease with larger capacities

$$C = BC = Co\,(S/So)^{\alpha} \qquad \log C = \log (Co/So)^{\alpha} + \alpha \log S$$

Tables for each equipment

Co, So. Parameters of Basic configuration Costs and Capacities

α. Parameter < 1 → economy of scale

Base Cost for Pressure Vessels: Vertical, horizontal, tray stack

$$C = Co\,(L/Lo)^{a}\,(D/Do)^{b}$$

Base Cost for Process Equipment

$$C = Co\,(S/So)^{\alpha} \text{ ; Range of S}$$

MF: Module Factor, affected by BC, taking into account labor, piping instruments, accessories, etc.

MF 2 : < 200.000 $
MF 4 : 200.000 - 400.000 $
MF 6 : 400.000 - 600.000 $
MF 8 : 600.000 - 800.000 $
MF 10 : 800.000 - 1.000.000 $

MPF: Materials and Pressure correction Factors Φ (Fd, Fm, Fp, Fo, Ft)

Empirical factors that modified BC and evaluate particular instances of equipment beyond a basic configuration: Uninstalled Cost = (BC x MPF)

Fd: Design variation
Fm: Construction material variation
Fp: Pressure variation
Fo: Operating Limits (Φ of T, P)
Ft: Mechanical refrigeration factor (Φ T evaporator)

UF: Update Factor, to account for inflation.

UF = Present Cost Index (CI_{actual}) / Base Cost Index (CI_{base})

CI: Chemical Engineering Plant Cost Index (www.che.com)			
YEAR	CI	YEAR	CI
1957-59	100	1996	382
1968	115 (Guthrie paper)	1997	386.5
1970	126	1998	389.5
1983	316	2003	402
1993	359	2009	539.6
1995	381	2010	532.9

Process Equipment Cost Estimating by Ratio and Proportion

Course Overview

Students of this one-hour course will be provided with two simple methods to arrive at approximate equipment costs during preliminary estimate preparation.

Learning Objective

At the conclusion of this course the student will:

- Understand the applicability of ratio and proportion estimating methods;
- Learn the technique to factor costs to correspond to varying equipment sizes and capacities;
- Learn the technique to escalate or otherwise adjust historical costs.

Intended Audience

This course is intended for anyone involved with cost estimate generation.

Benefits for Attendees

This course will provide new methods of estimating for some and refresher information for others. The course material can be used as a reference source for actual future situations.

The course includes a true-false test at the end.

Introduction

This course provides the student with an understanding of the estimating technique known as *The Rule of Six-tenths* and when appropriate, use of this rule in combination with cost indices. The various types of estimates are discussed as prerequisite background. Equations are provided to enable the student to escalate or otherwise adjust historical equipment cost data.

Content

Cost Estimate Types and Accuracy

Regardless of accuracy, capital cost estimates are typically made-up of direct and indirect costs. Indirect costs consist of project services, such as overhead and profit, and engineering and administrative fees. Direct costs are construction items for the project and include property, equipment, and materials. This course deals with the equipment component of direct cost.

In order for the student to fully understand the applicability of ratio and proportion estimating, it will be helpful to list the types of estimates that exist. Cost estimates fall into the following categories and generally accepted accuracy:

- Order of Magnitude (OME) estimate ± 50%
- Study estimate ± 30%
- Preliminary (budget, scope) estimate ± 20%
- Definitive estimate ± 10%
- Detailed estimate ± 5%

As the names imply, the main difference between these types of estimates is their accuracy. The first three types serve as a cost indicator at a very early stage of the project design stage. They are developed with a minimum amount of detailed engineering and advise a client or a management group of that first look at project cost. The preparation of a preliminary estimate is done by an estimator based on his assessment of the design, past cost estimates, in-house estimating information, and previous contracts and purchase orders. It is not normal to obtain formal quotations from equipment manufactures in support of a preliminary estimate. Informal telephone *budget* quotations on identified major equipment such as vessels, filters, *etc.* are acceptable. However, even these types of "expedient" quotations can prove to be time restrictive to obtain sometimes. Even with the advent of sophisticated estimating software it is sometimes simply easier to manually approximate an equipment cost. That is the subject of this course.

Definitive and detailed cost estimates are full-blown exercises that are undertaken to produce a competitive bid submission or otherwise produce an accurate (plus or minus 10% or better) cost estimate, for say, a corporation's management approval for appropriation of funds. The ratio and proportion methods presented in this course would not be normally suitable for inclusion in a definitive estimate.

The equipment cost estimating methods that will be outlined in this course are suitable for use with the first three types of estimates; definitive and detail estimates require formal, firm equipment cost quotations from equipment manufacturers and suppliers.

Ratio and proportion estimating

A ratio indicates the relationship between two (or more) things in quantity, amount, or size. Proportion implies that two (or more) items are similar, differing only in magnitude. Using these well-known mathematical tools is a simple process.

When preparing preliminary estimates, two methods for estimating the cost of equipment are the *Rule of Six-tenths* and the use of cost indices to adjust historic costs to current prices. Each will be discussed and a single example will be offered to demonstrate the use of both.

The Rule of Six-tenths

Approximate costs can be obtained if the cost of a similar item of different size or capacity is known. A rule of thumb developed over the years known as the *rule of six-tenths* gives very satisfactory results when only an approximate cost within plus or minus 20% is required. An exhaustive search in conjunction with the development of this course left this author with no indication of any single individual who developed this concept. One is forced to assume that the relationship naturally evolved in the public domain after large quantities of actual cost data were analyzed retrospectively. The earliest mention of this concept was found in a reference accredited to a December 1947 *Chemical Engineering* magazine article by Roger Williams, Jr. entitled "Six-tenths Factor Aids in Approximating Costs".

$$\boxed{(ratio)^{0.6}}$$

At any rate, the following equation expresses the *rule of six-tenths*:

$$C_B = C_A \left(\frac{S_B}{S_A} \right)^{0.6}$$

Where C_B = the approximate cost ($) of equipment having size S_B (cfm, Hp, ft^2, or whatever)

C_A = is the known cost ($) of equipment having corresponding size S_A (same units as S_B),

and S_B/S_A is the ratio known as the *size factor*, dimensionless.

The "N" exponent

An analysis of the cost of individual pieces of equipment shows that the size factor's exponent will vary from 0.3 to unity, but the average is very near to 0.6, thus the name for the rule of thumb. If a higher degree of sophistication is sought, Table 1 below can be used. It lists the value of a *size exponent* for various types of process equipment. The Table 1 values have been condensed from a vast, comprehensive tabulation of estimating cost data presented in the March 24, 1969 issue of *Chemical Engineering* magazine. This article by K.M. Guthrie is entitled "Data and Techniques for Preliminary Capital Cost Estimating". While the source for the concept and the presented exponential data is somewhat dated, *i.e.*1947 and 1969 respectively, there is indication that this material is still relevant and valid.

Using Table 1 size exponents transforms the previously presented formula into,

$$C_B = C_A \left(\frac{S_B}{S_A} \right)^N$$

Where the symbols are identical to those already described and *N* is the *size exponent*, dimensionless, from Table 1:

PROCESS EQUIPMENT SIZE EXPONENT (N) - TABLE 1		
EQUIPMENT NAME	UNIT	SIZE EXPONENT (N)
Agitator, propeller	Hp	0.50
Agitator, turbine	Hp	0.30
Air compressor, single stage	cfm	0.67
Air compressor, multiple stage	cfm	0.75
Air dryer	cfm	0.56
Boiler, industrial, all sizes	lb/hr	0.50
Boiler, package	lb/hr	0.72
Centrifuge, horizontal basket	dia (inches)	1.72
Centrifuge, solid bowl	dia (inches)	1.00
Conveyor, belt	feet	0.65
Conveyor, bucket	feet	0.77
Conveyor, screw	feet	0.76
Conveyor, vibrating	feet	0.87
Crystallizer, growth	ton/day	0.65
Crystallizer, forced circulation	ton/day	0.55
Crystallizer, batch	gallons	0.70

PROCESS EQUIPMENT SIZE EXPONENT (N) - TABLE 1		
EQUIPMENT NAME	UNIT	SIZE EXPONENT (N)
Dryer, drum and rotatory	sq. ft.	0.45
Dust collector, cyclone	cfm	0.80
Dust collector, cloth filter	cfm	0.68
Dust collector, precipitator	cfm	0.75
Evaporator, forced circulation	sq. ft.	0.70
Evaporator, vertical and horizontal tube	sq. ft.	0.53
Fan	Hp	0.66
Filter, plate and press	sq. ft.	0.58
Filter, pressure leaf	sq. ft.	0.55
Heat exchanger, fixed tube	sq. ft.	0.62
Heat exchanger, U-tube	sq. ft.	0.53
Mill, ball and roller	ton/hr	0.65
Mill, hammer	ton/hr	0.85
Pump, centrifugal carbon steel	Hp	0.67
Pump, centrifugal stainless steel	Hp	0.70
Tanks and vessels, pressure, carbon steel	gallons	0.60
Tanks and vessels, horizontal, carbon steel	gallons	0.50
Tanks and vessels, stainless steel	gallons	0.68

Cost Indices

The names and purpose of today's cost indices are too numerous to mention. Probably the most widely known cost index to the general public is the Consumer Price Index (CPI) generated by the U.S. Department of Labor, Bureau of Labor Statistics. While the CPI could probably serve our needs, more specific data is available for use in engineering and technical applications.

Cost indices are useful when basing the approximated cost on other than current prices. If the known cost of a piece of equipment is based on, for instance 1998 prices, this cost must be multiplied by the ratio of the present day index to the 1998 base index in order to proportion the value to present day dollars. (Incidentally, the inverse of this operation can be performed to estimate what a given piece of equipment would have cost in some prior time). Mathematically, this looks like,

$$C = C_O \left(\frac{I}{I_O} \right)$$

Where C = current cost, dollars
C_O = base cost, dollars
I = current index, dimensionless
I_O = base index, dimensionless

Many sources exist for technical indices but two of the more popular ones which are readily available are those published monthly in *Chemical Engineering* magazine under "Economic Indicators, Marshall and Swift Equipment Cost Index" and weekly in *Engineering News Record* magazine under "Market Trends". Both work equally well but as with other indices, they cannot be used interchangeably. Incidentally, current *Engineering New Record* cost information is accessible on the Internet at www.enr.com. Click on the ECONOMICS file tab and scroll down to "Current Cost Indices". Unfortunately no cost index information is offered at the *Chemical Engineering* magazine website.

MARSHALL & SWIFT EQUIPMENT COST INDEX			
(1926 =100)	4th Q **2006**	3rd Q **2006**	4th Q **2005**
M & S INDEX	1353.8	1333.4	1274.8
	Annual Index		
2001 = 1093.9	2003 = 1123.6	2005 = 1244.5	
2002 = 1104.2	2004 = 1178.5	2006 = 1302.3	

Example Tabulation of Magazine Cost Index Data

Let us take an illustrative example:

The following example illustrates a combined use of both of these ratio and proportion methods to produce an approximate cost. Please note that the costs presented here are purely hypothetical and should not be used as a basis for anything other than an illustration.

Let us assume that a rough estimate is being prepared for a project in which a 5,000-gallon capacity stainless steel pressure vessel is involved. Let us further assume that our past project purchasing data shows that a 2,000-gallon stainless steel pressure vessel, very similar to that currently required, was purchased in 2001 for $15,000.

We now have all of the necessary components to approximate the present day cost (C_B) of a 5,000-gallon vessel. We have, two dates, past and of course current; two known capacities (S_B and S_A); and one historical cost (C_O) (that of the 2001 purchased vessel).

The first step is to determine the cost index for our two dates. Consulting a recent issue of *Chemical Engineering* magazine, the M & S Equipment Cost Index for 2001 is found to be 1093.9 (our base index for this example). In like fashion, the 2006 4th Quarter index is found to be 1353.8 (the current index). The student may be interested to know that the M & S Cost Index base is 1926 = 100; this provides an astonishing indication of the amount of inflation that has taken place.

This complied data allows us to substitute,

$$C = C_O\left(\frac{I}{I_O}\right) = (\$15{,}000)\left(\frac{1353.8}{1093.9}\right) = \$18{,}565$$

Therefore, the 4th Quarter 2006 cost of the 2,000-gallon capacity vessel is estimated to be $18,565.

Now, having determined the current estimated cost of the smaller capacity vessel, we need to adjust this amount to correspond to the larger volume (5,000 gallons). Referring to Table 1, we find a size exponent corresponding to stainless steel vessels equal to 0.68. Substituting in the equation presented earlier results in,

$$C_B = C_A\left(\frac{S_B}{S_A}\right)^N = (\$18{,}565)\left(\frac{5{,}000}{2{,}000}\right)^{0.68} = \$34{,}617$$

Contents

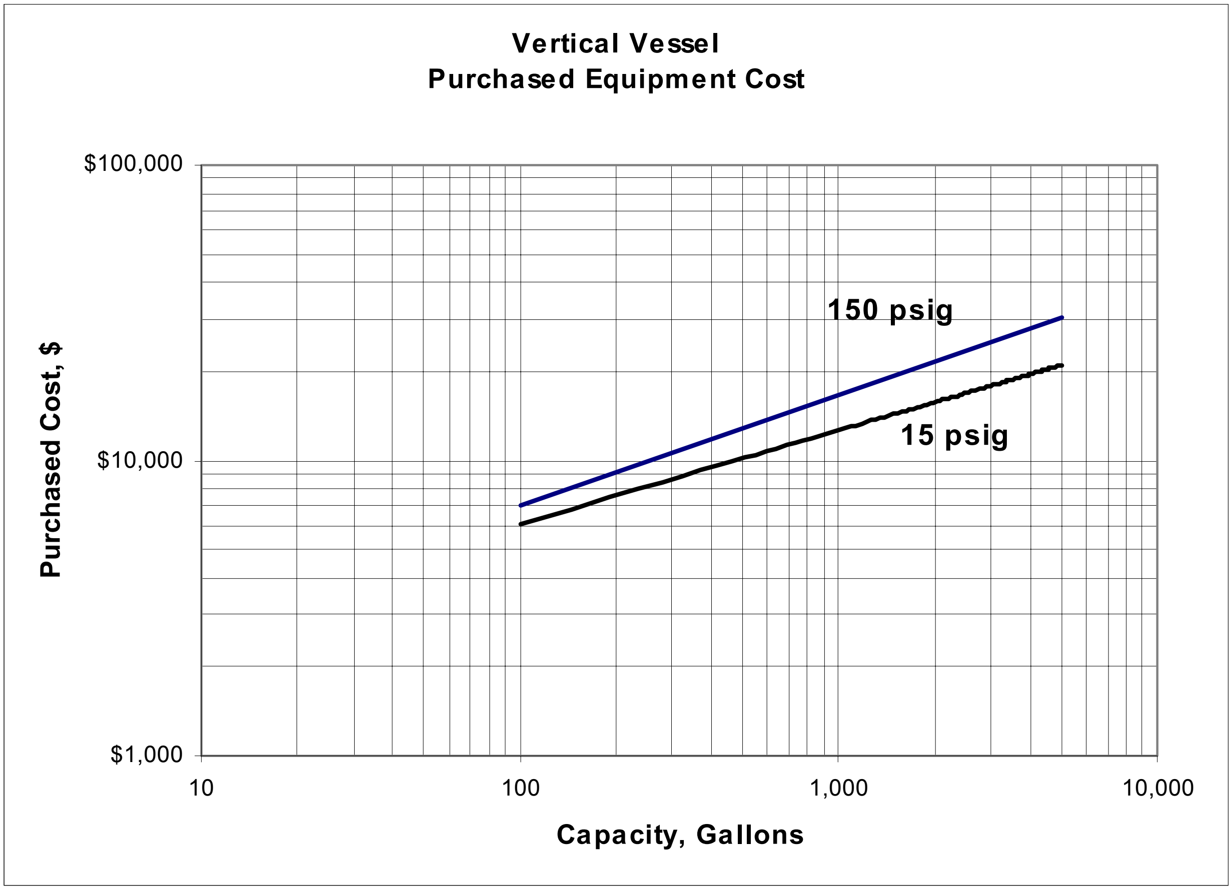
List of Tables

Cost Curves

Vertical Vessel

Description: The vertical process vessel is erected in the vertical position. They are cylindrical in shape with each end capped by a domed cover called a head. The length to diameter ratio of a vertical vessel is typically 3 to 1. Vertical tanks include: process, storage applications liquid, gas, solid processing and storage; pressure/vacuum code design for process and certain storage vessel types; includes heads, single wall, saddles, lugs, nozzles, manholes, legs or skirt, base ring, davits where applicable.

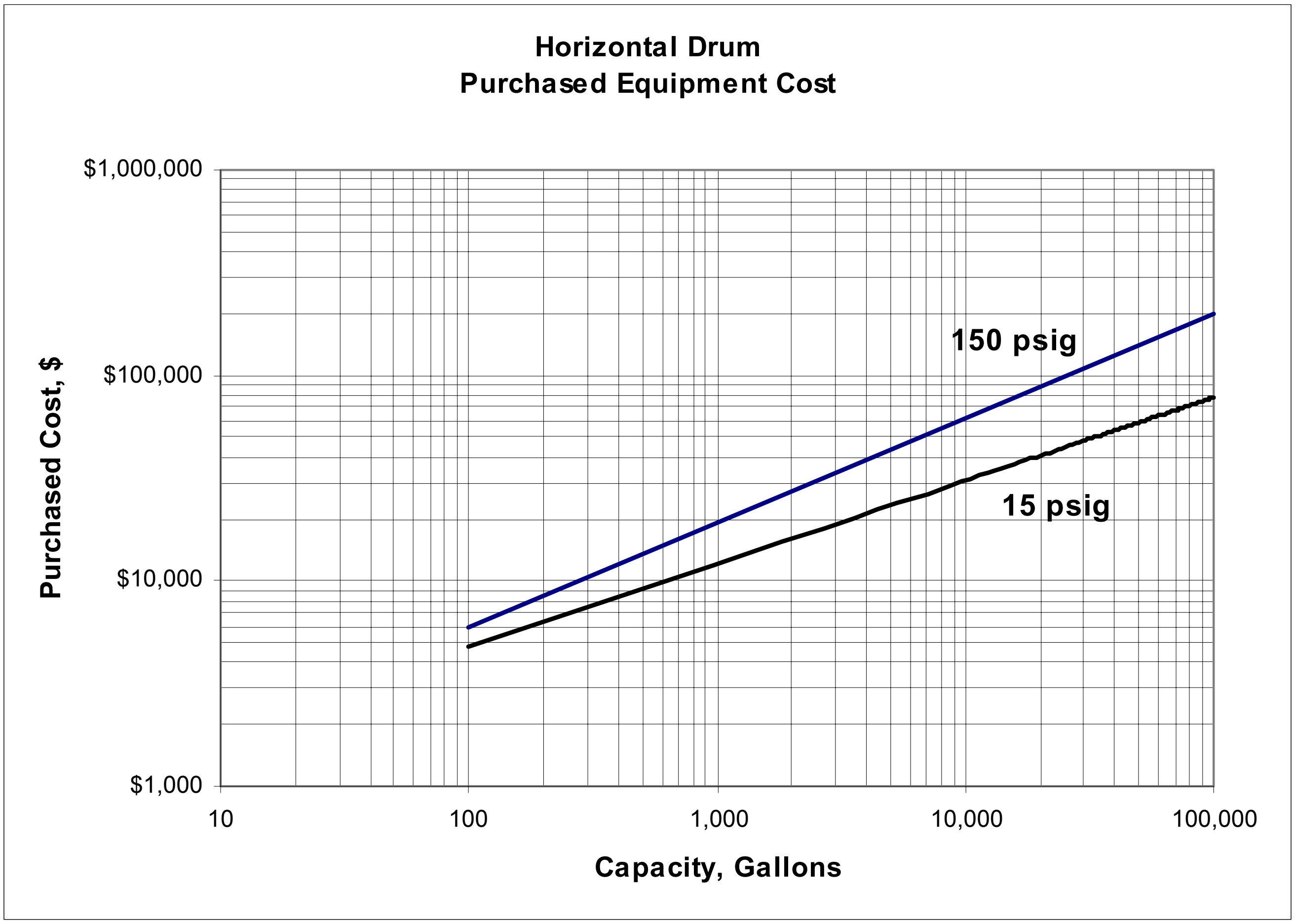
Design Basis:
1st Quarter 1998 Dollars
Shell Material: A515
(Carbon Steel Plates for pressure vessels for intermediate and higher temperature service)
Design Temperature: 650 °F
Design Pressure: 15 psig and 150 psig
Diameter: 2.5 – 8 feet
Length: 2.7 – 13.3 feet
Total Weight: 1,000 –7,100 pounds



Horizontal Vessel

Description: The horizontal vessel is a pressure vessel fabricated according to the rules of the specified code and erected in the horizontal position. Although the horizontal vessel may be supported by lugs in an open steel structure, the more usual arrangement is for the vessel to be erected at grade and supported by a pair of saddles. Cylindrical, pressure/vacuum, code design and construction, includes head, single wall (base material, clad/lined), saddles/lugs, nozzles and manholes.

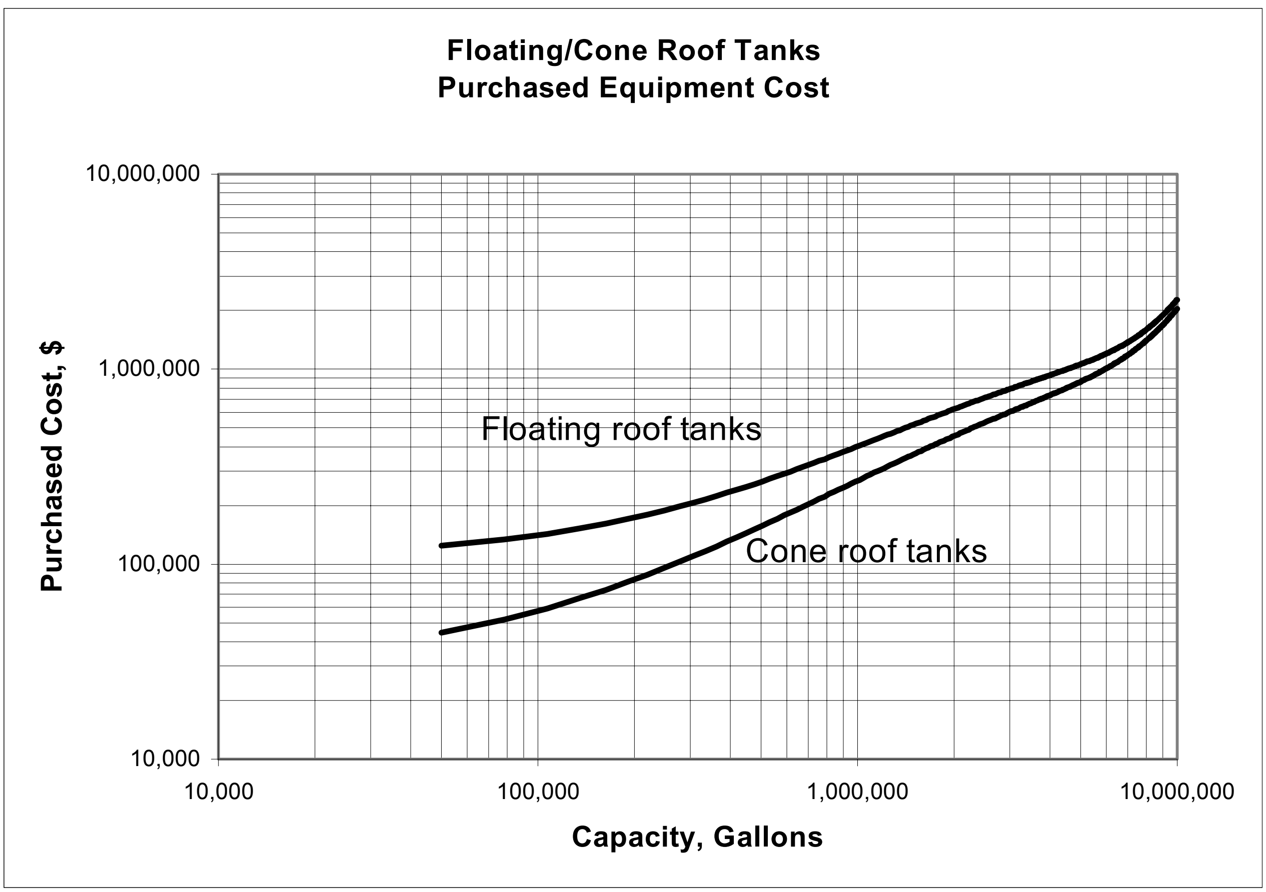
Design Basis:
1st Quarter 1998 Dollars
Shell Material: A515
(Carbon Steel Plates for pressure vessels for intermediate and higher temperature service)
Design Temperature: 650 °F
Design Pressure: 15 psig
Diameter: 2 – 14 feet
Length: 4.3 – 81 feet
Total Weight: 1100 –59,400 pounds



Storage Tanks

Description:
Floating Roof: Typically constructed from polyurethane foam blocks or nylon cloth impregnated with rubber or plastic, floating roofs are designed to completely contact the surface of the storage products and thereby eliminate the vapor space between the product level and the fixed roof. Floating roof tanks are suitable for storage of products having vapor pressure from 2 to 15 psia.
Cone Roof: Typically field fabricated out of carbon steel. They are used for storage of low vapor pressure (less than 2 psia) products, typically ranging from 50,000 – 1,000,000 gallons.

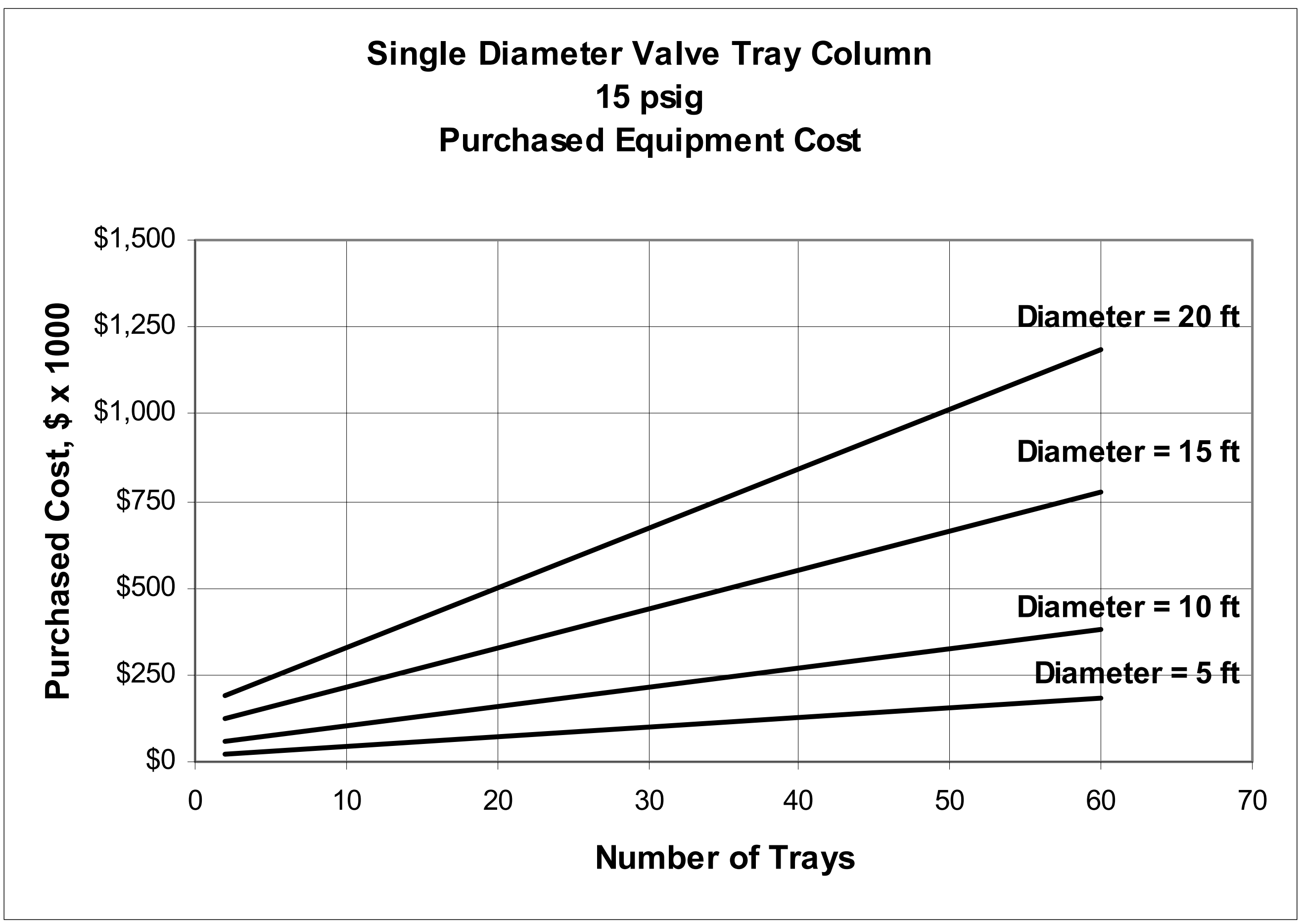
Design Basis:
1st Quarter 1998 Dollars
Shell Material: A515
(Carbon Steel Plates for pressure vessels for intermediate and higher temperature service)
Design Temperature: 650 °F
Design Pressure: 15 psig
Diameter: 2 – 14 feet
Length: 4.3 – 81 feet
Total Weight: 1100 –59,400 pounds



Valve Tray Column – 15 psig

Description: Pressure/vacuum column includes vessel shell, heads, single base material (lined or clad, nozzles, manholes (one manhole below and above tray stack or packed section and one manhole every tenth tray or 25 feet of packed height), jacket and nozzles for heating or cooling medium, base ring, lugs, skirt or legs; tray clips, tray supports (if designated), distributor piping, plates.

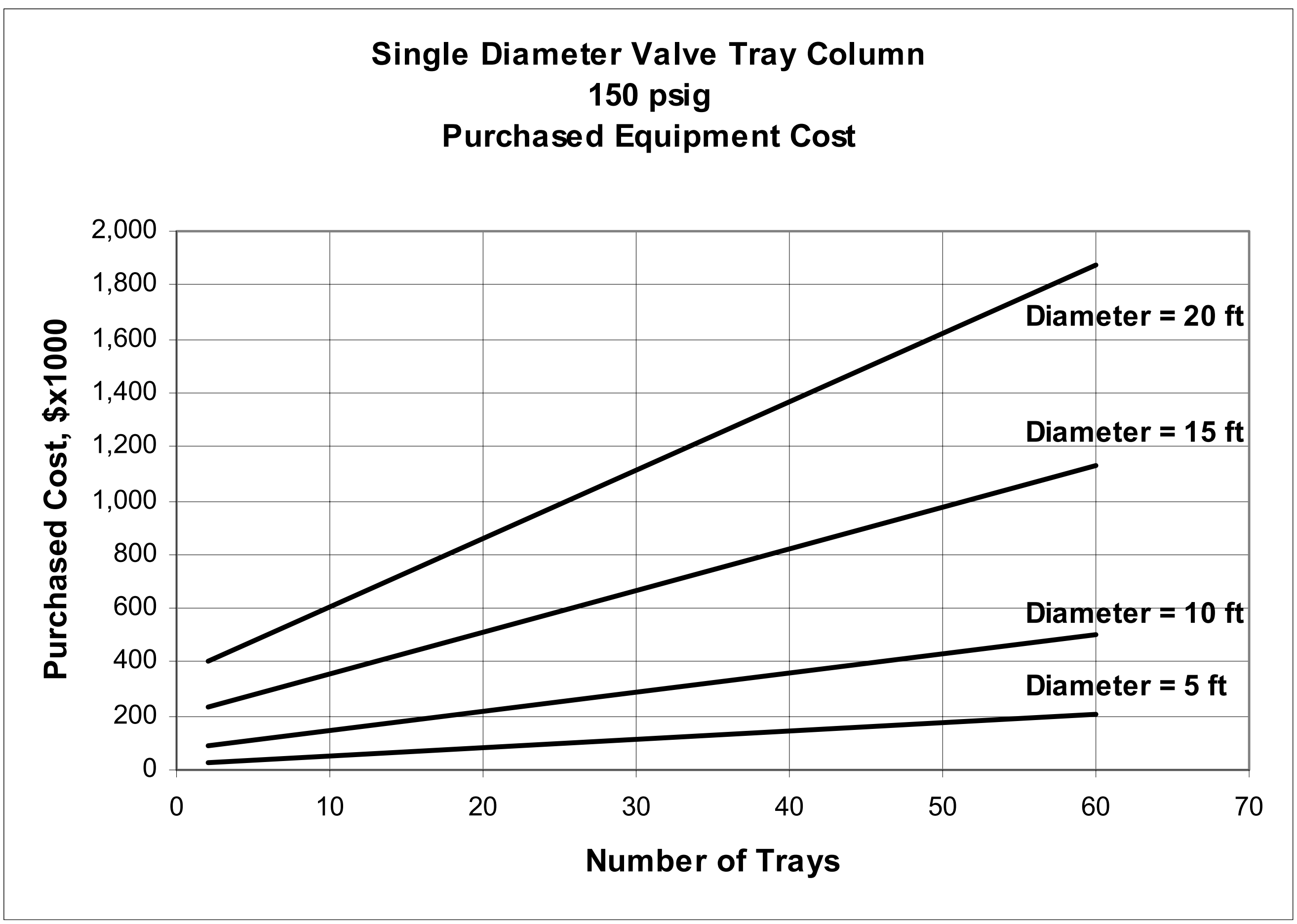
Design Basis:
1st Quarter 1998 Dollars
Shell Material: A515
(Carbon Steel Plates for pressure vessels for intermediate and higher temperature service)
Design Temperature: 650 °F
Design Pressure: 15 psig
Height: 17 - 133 feet
Application: Distillation
Tray Type: Valve
Tray Spacing: 24 Inches
Tray Material: A285C
(Low and intermediate strength carbon steel plates for pressure vessels.)
Tray Thickness: 0.19 Inches



Valve Tray Column – 150 psig

Description: Pressure/vacuum column includes vessel shell, heads, single base material (lined or clad, nozzles, manholes (one manhole below and above tray stack or packed section and one manhole every tenth tray or 25 feet of packed height), jacket and nozzles for heating or cooling medium, base ring, lugs, skirt or legs; tray clips, tray supports (if designated), distributor piping, plates.

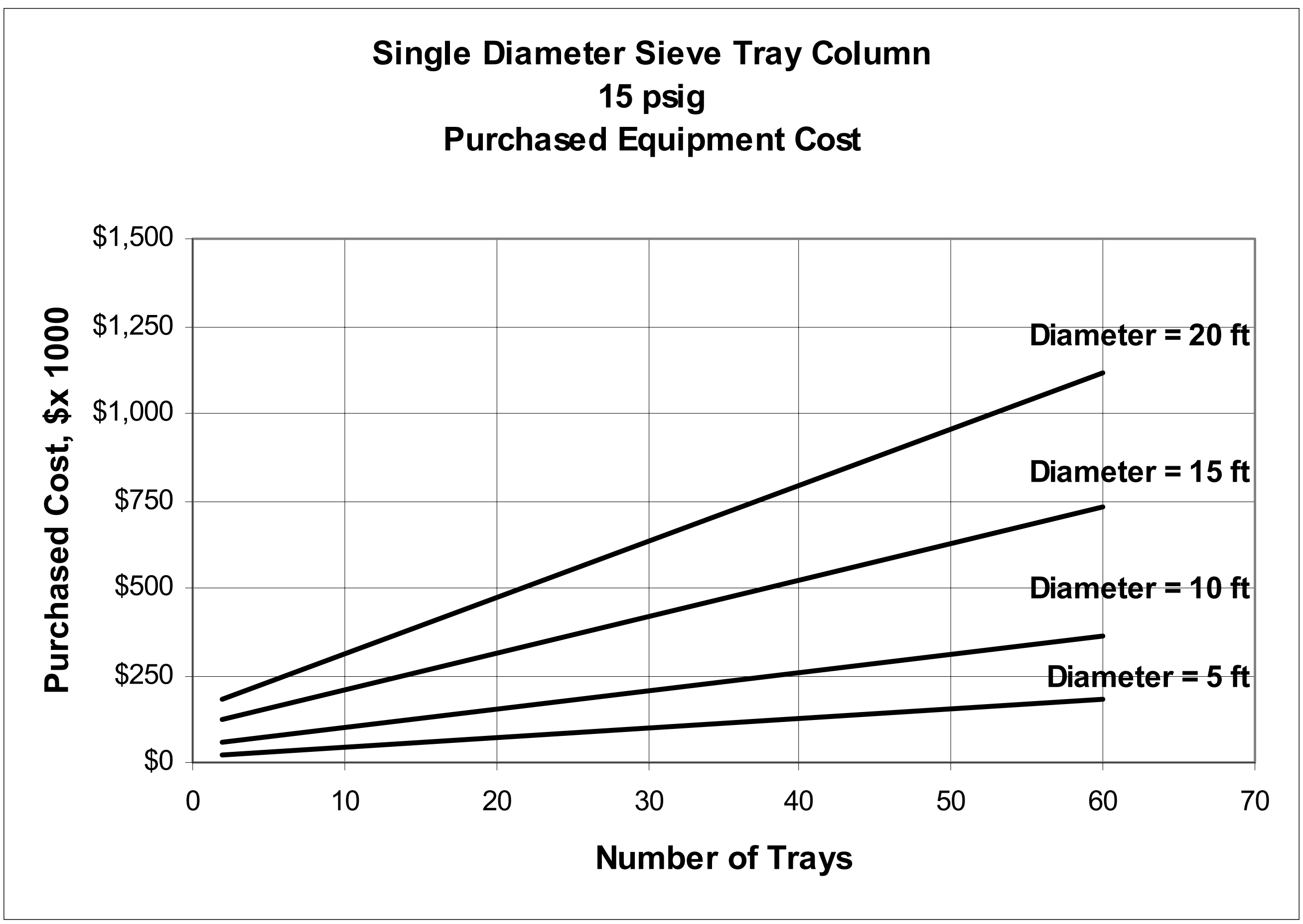
Design Basis:
1st Quarter 1998 Dollars
Shell Material: A515
(Carbon Steel Plates for pressure vessels for intermediate and higher temperature service)
Design Temperature: 650 °F
Design Pressure: 150 psig
Height: 17 - 133 feet
Application: Distillation
Tray Type: Valve
Tray Spacing: 24 Inches
Tray Material: A285C
(Low and intermediate strength carbon steel plates for pressure vessels.)
Tray Thickness: 0.19 Inches



Sieve Tray Column – 15 psig

Description: Pressure/vacuum column includes vessel shell, heads, single base material (lined or clad, nozzles, manholes (one manhole below and above tray stack or packed section and one manhole every tenth tray or 25 feet of packed height), jacket and nozzles for heating or cooling medium, base ring, lugs, skirt or legs; tray clips, tray supports (if designated), distributor piping, plates.

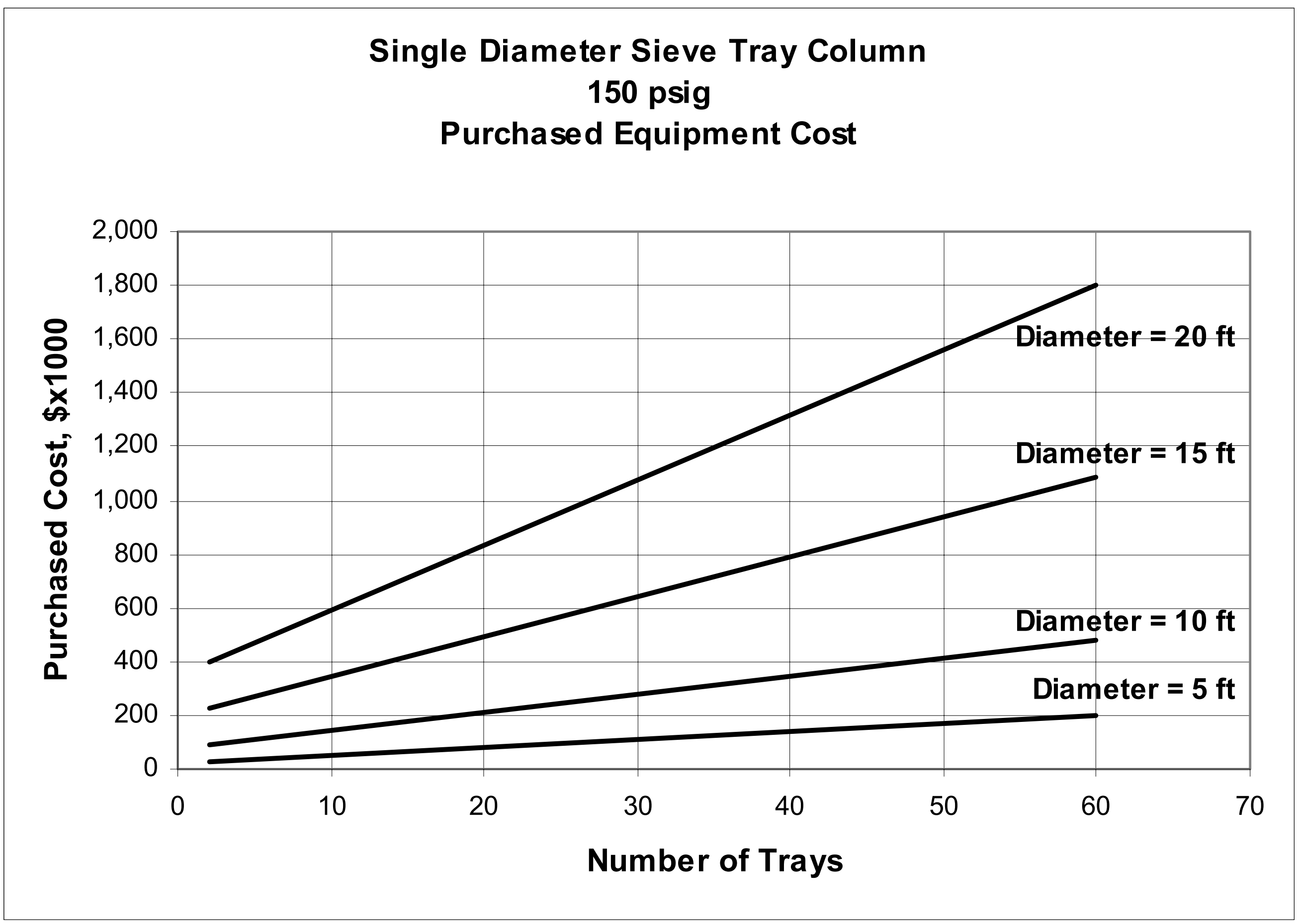
Design Basis:
1st Quarter 1998 Dollars
Shell Material: A515
(Carbon Steel Plates for pressure vessels for intermediate and higher temperature service)
Design Temperature: 650 °F
Design Pressure: 15 psig
Height: 17 - 133 feet
Application: Distillation
Tray Type: Sieve
Tray Spacing: 24 Inches
Tray Material: A285C
(Low and intermediate strength carbon steel plates for pressure vessels.)
Tray Thickness: 0.19 Inches



Sieve Tray Column – 150 psig

Description: Pressure/vacuum column includes vessel shell, heads, single base material (lined or clad, nozzles, manholes (one manhole below and above tray stack or packed section and one manhole every tenth tray or 25 feet of packed height), jacket and nozzles for heating or cooling medium, base ring, lugs, skirt or legs; tray clips, tray supports (if designated), distributor piping, plates.

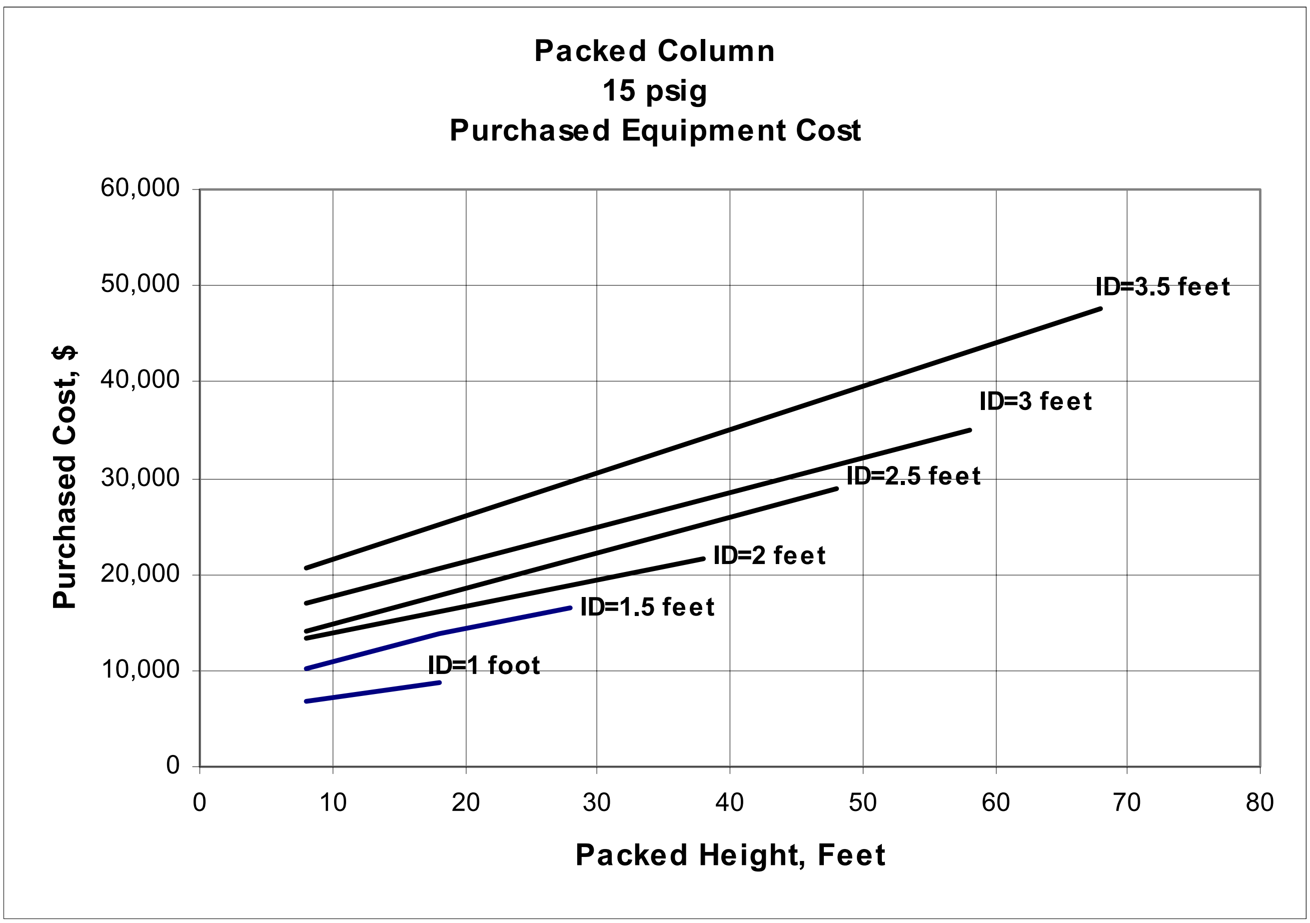
Design Basis:
1st Quarter 1998 Dollars
Shell Material: A515
(Carbon Steel Plates for pressure vessels for intermediate and higher temperature service)
Design Temperature: 650 °F
Design Pressure: 150 psig
Height: 17 - 133 feet
Application: Distillation
Tray Type: Sieve
Tray Spacing: 24 Inches
Tray Material: A285C
(Low and intermediate strength carbon steel plates for pressure vessels.)
Tray Thickness: 0.19 Inches



Packed Column – 15 psig

Description: Pressure/vacuum column includes vessel shell, heads, single base material (lined or clad, nozzles, manholes (one manhole below and above tray stack or packed section and one manhole every tenth tray or 25 feet of packed height), jacket and nozzles for heating or cooling medium, base ring, lugs, skirt or legs; tray clips, tray supports (if designated), distributor piping, plates, packing not included (see Table 1).

Design Basis:
1st Quarter 1998 Dollars
Shell Material: A515
(Carbon Steel Plates for pressure vessels for intermediate and higher temperature service)
Design Temperature: 650 °F
Design Pressure: 15 psig
Application: Absorption



Packed Column – 150 psig

Description: Pressure/vacuum column includes vessel shell, heads, single base material (lined or clad, nozzles, manholes (one manhole below and above tray stack or packed section and one manhole every tenth tray or 25 feet of packed height), jacket and nozzles for heating or cooling medium, base ring, lugs, skirt or legs; tray clips, tray supports (if designated), distributor piping, plates, packing not included (see Table 1).

Design Basis:
1st Quarter 1998 Dollars
Shell Material: A515
(Carbon Steel Plates for pressure vessels for intermediate and higher temperature service)
Design Temperature: 650 °F
Design Pressure: 150 psig
Application: Absorption

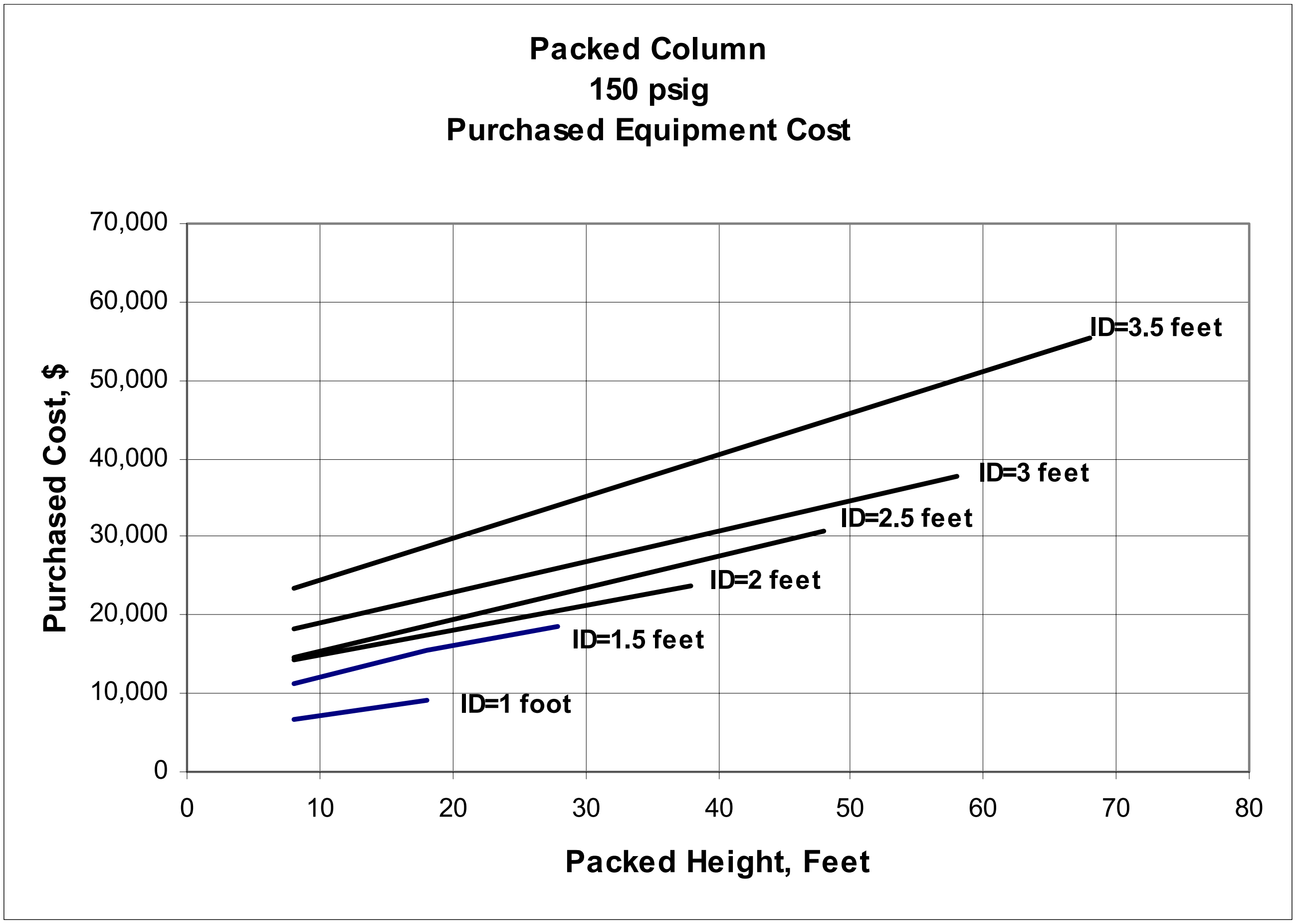


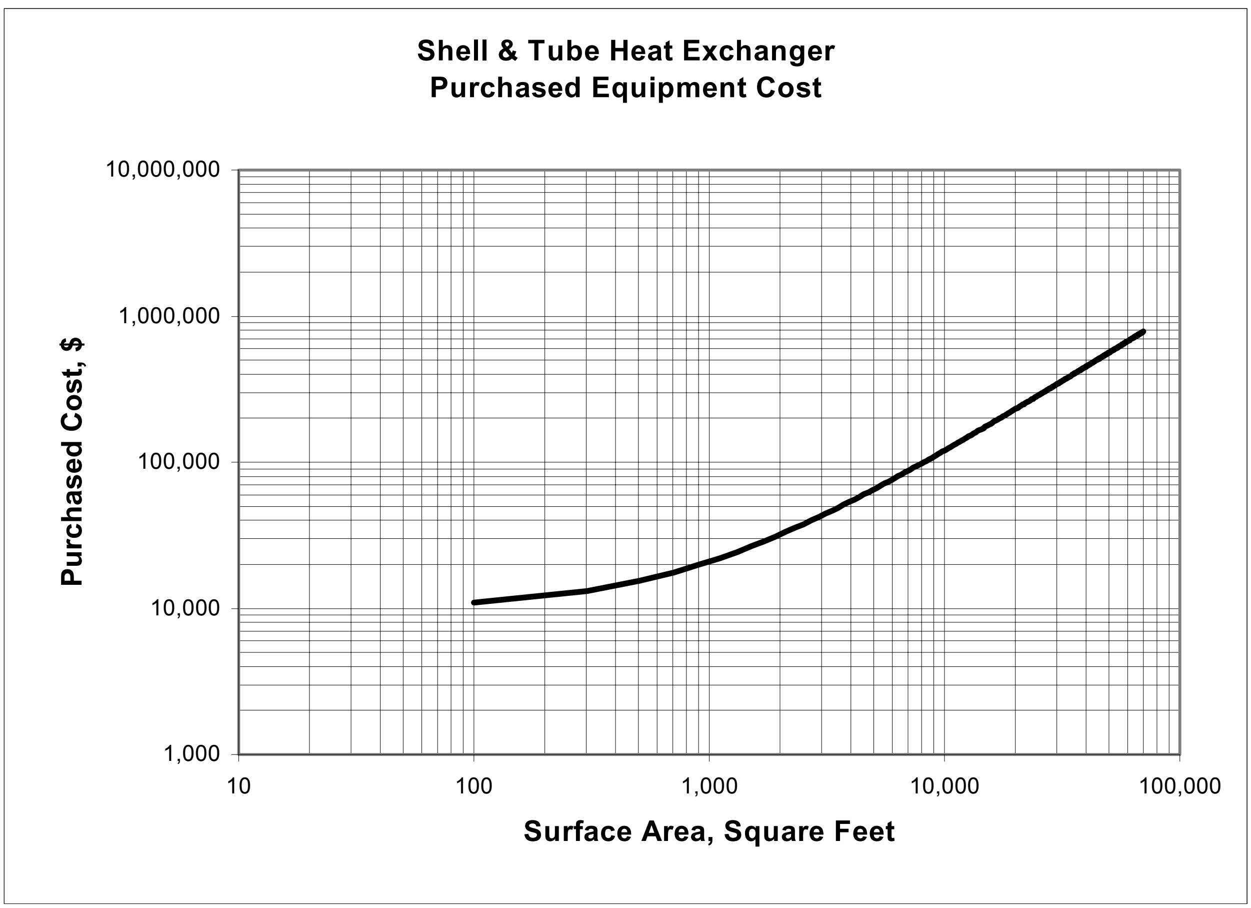
Table 1
Packing Costs
Uninstalled cost, dollar per cubic feet
1st Quarter 1998 Dollars

Diameter (Inches)	0.5	1.0	1.5	2.0	3.0
Pall Rings					
Polypropylene	33	29	21	8	-
Stainless Steel	130	118	92	76	-
INTALOX Saddles					
Ceramic	31	28	23	21	-
Porcelain	32	29	24	21	-
Raschig Rings					
Ceramic	119	14	12	12	11
Porcelain	-	17	15	12	11
Stainless Steel	-	111	94	59	54
Carbon Steel	-	37	31	20	18
Activated Carbon	25				
13X Molecular Sieve	61				
Silica Gel	94				
Calcium Chloride	11				

Shell and Tube Heat Exchanger

Description: Shell and tube heat exchanger consists of a bundle of tubes held in a cylindrical shape by plates at either end called tube sheets. The tube bundle placed inside a cylindrical shell. The size of the exchanger is defined as the total outside surface area of the tube bundle. Maximum shell size is 48 Inches.

Design Basis:
1st Quarter 1998 Dollars
Type: Floating Head (BES)/ Fixed Head (BEM)
Shell Material: A285C
(Low and intermediate strength carbon steel plates for pressure vessels.)
Shell Temperature: 650 °F
Shell Pressure: 150 psig
Tube Material: A214
(Electric-resistance-welded carbon steel heat exchanger and condenser tubes)
Tube Temperature: 650 °F
Tube Pressure: 150 psig
Tube Length: 10– 20 Feet
Tube Diameter: 1 Inch

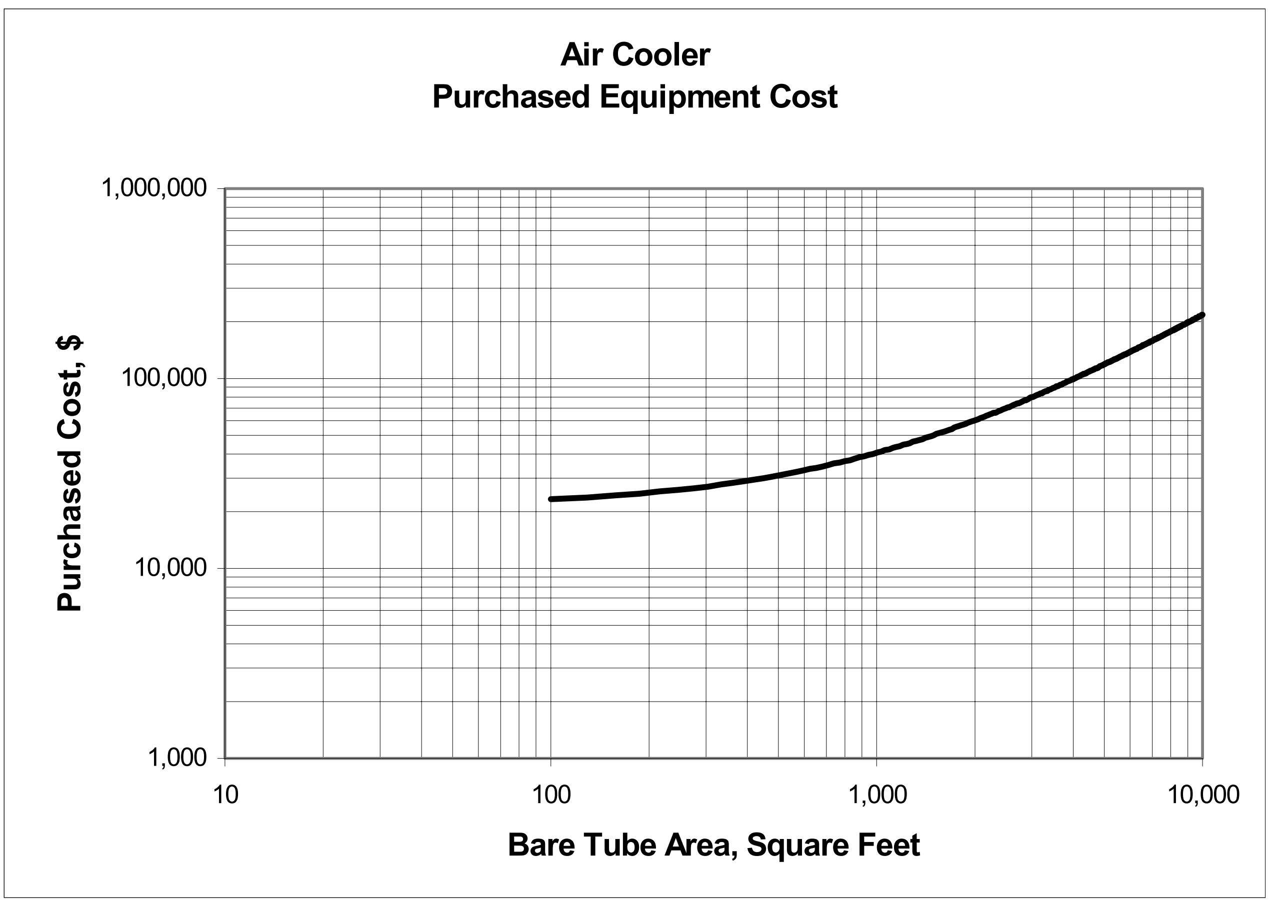


Air Cooler

Description: Variety of plenum chambers, louver arrangements, fin types (or bare tubes), sizes, materials, free-standing or rack mounted, multiple bays and multiple services within a single bay.

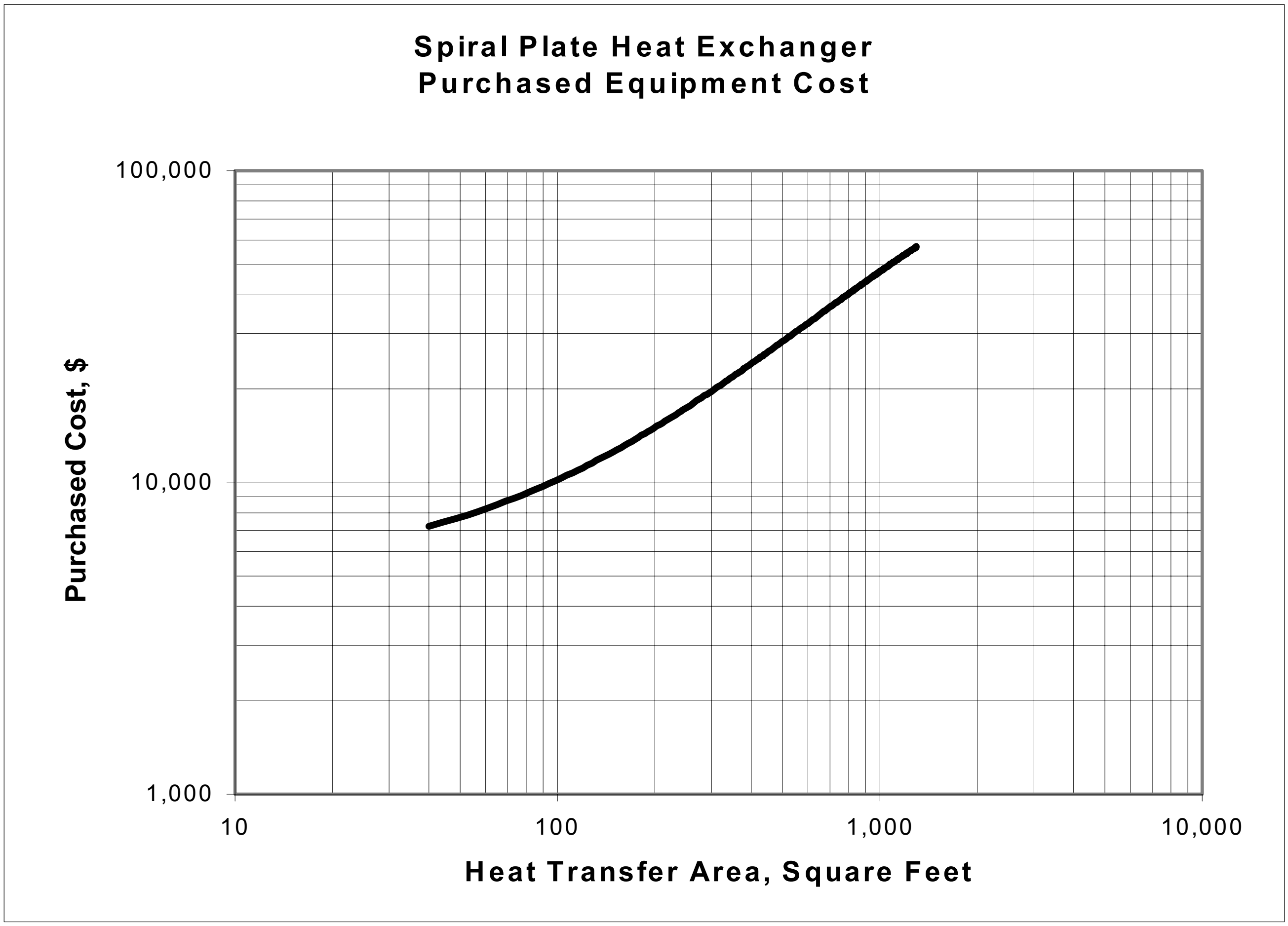
Design Basis:
1st Quarter 1998 Dollars

Tube Material:	A214
(Electric-resistance-welded carbon steel heat exchanger and condenser tubes)	
Tube Length:	6 – 60 Feet
Number of Bays:	1 – 3
Power/ Fan:	2 – 25 Horsepower
Bay Width:	4 – 12 Feet
Design Pressure:	150 psig
Inlet Temperature:	300 °F
Tube Diameter:	1 Inch
Plenum Type:	Transition shaped
Louver Type:	Face louvers only
Fin Type:	L-footed tension wound Aluminum



Spiral Plate Heat Exchanger

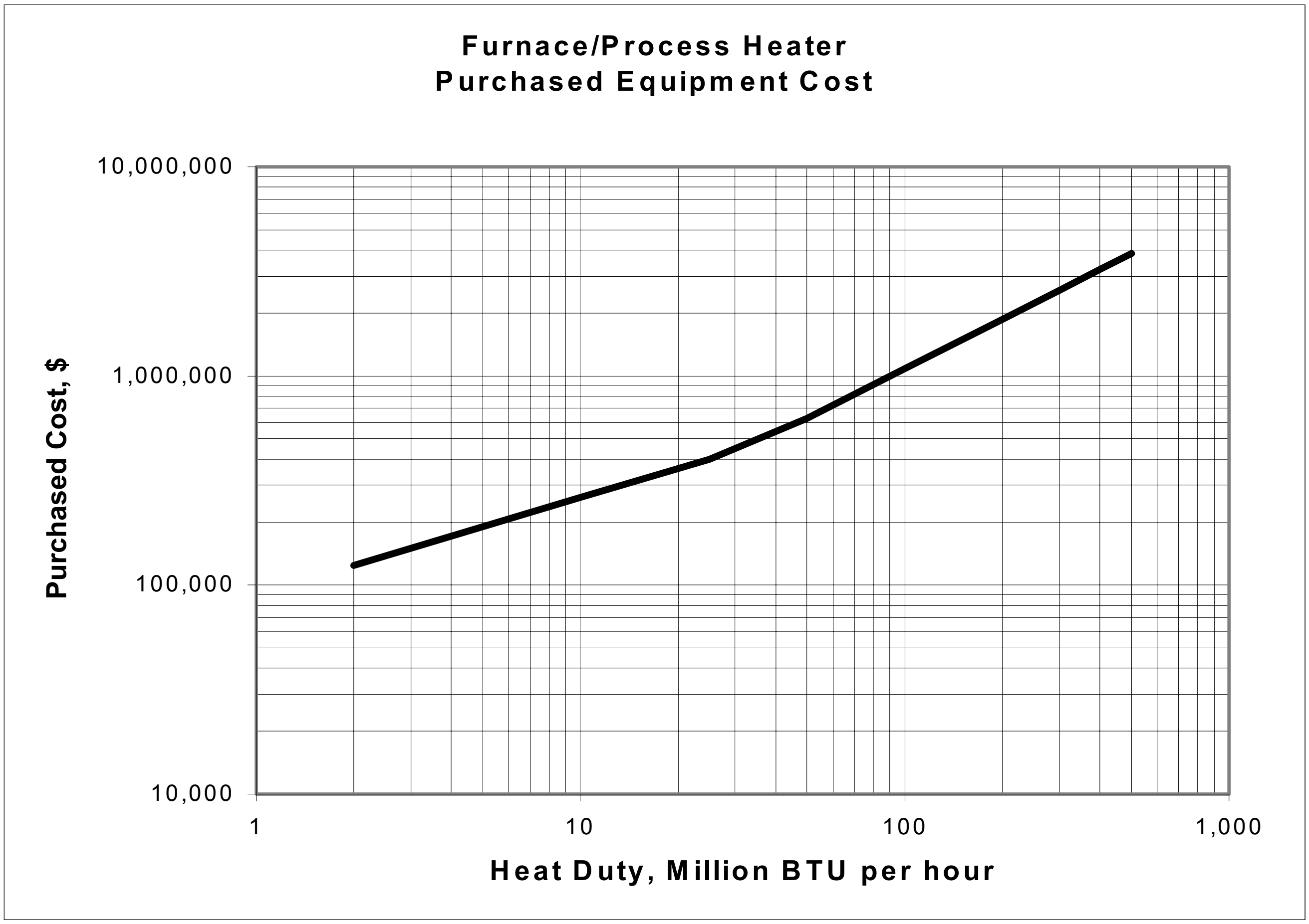
Design Basis:
1st Quarter 1998 Dollars
Material: SS304
(High Alloy Steel - Chromium-Nickel stainless steel plate, sheet and strip for fusion-welded unfired pressure vessels)
Tube Pressure: 150 psig



Furnace

Description: Gas or Oil fired vertical cylindrical type for low heat duty range moderate temperature with long contact time. Walls of the furnace are refractory lined.

Design Basis:
1st Quarter 1998 Dollars
Tube Material: A214
(Electric-resistance-welded carbon steel heat exchanger and condenser tubes)
Design Pressure: 500 psig
Design Temperature: 750 °F

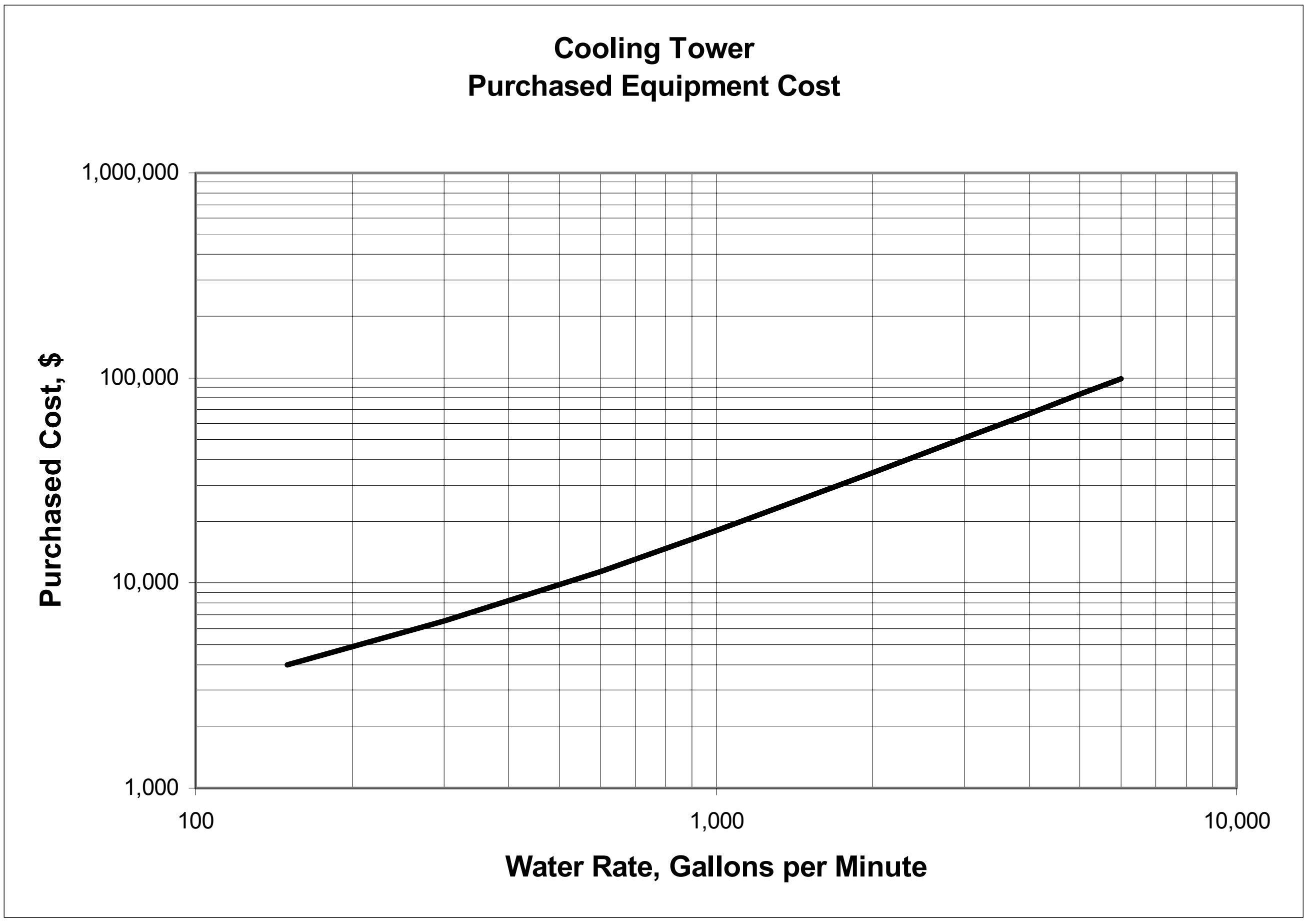


Cooling Tower

Description: Factory Assembled cooling tower includes fans, drivers and basins

Design Basis:
1st Quarter 1998 Dollars

Temperature Range:	15 °F
Approach Gradient:	10 °F
Wet Bulb Temperature:	75 °F



Package Steam Boiler

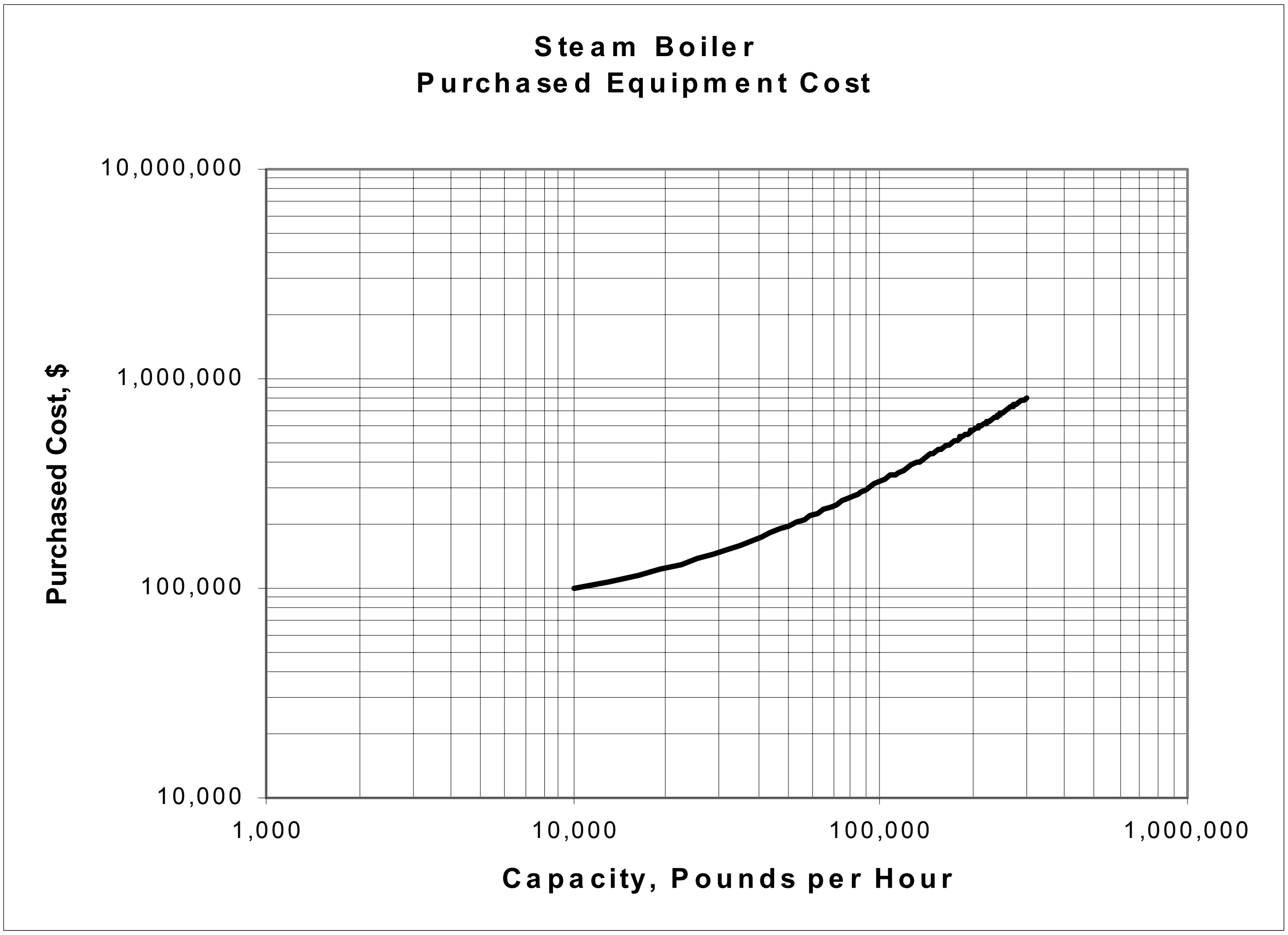
Description: Package boiler unit includes forced draft fans, instruments, controls, burners, soot-blowers, feedwater deaerator, chemical injections system, steam drum, mud drum and stack. Shop assembled.

Design Basis:
1st Quarter 1998 Dollars

Material: A285C
(Low and intermediate strength carbon steel plates for pressure vessels.)

Pressure: 250 psig

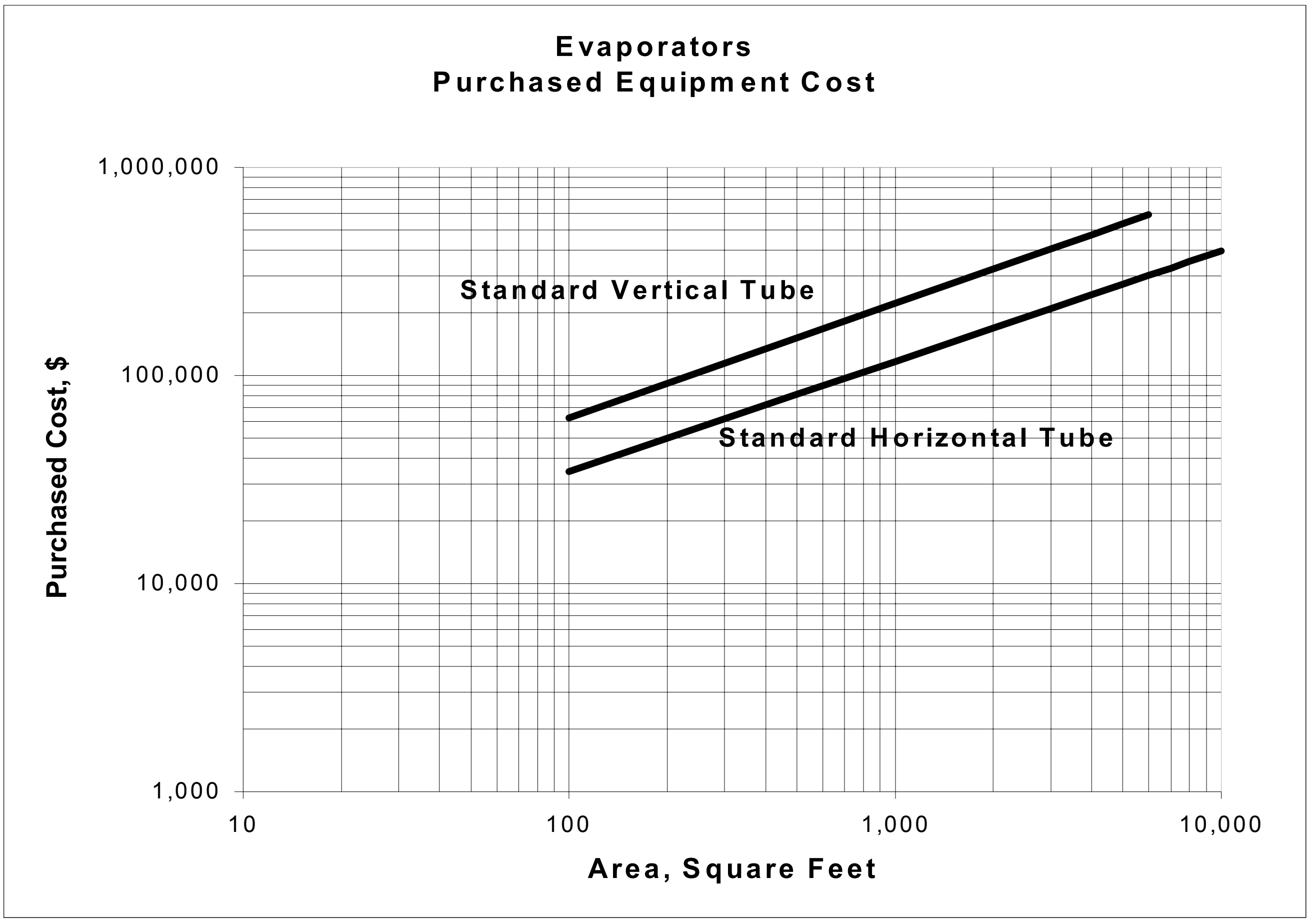
Superheat: 100 °F



Evaporators

Description: Standard vertical tube evaporator and standard horizontal tube evaporator.

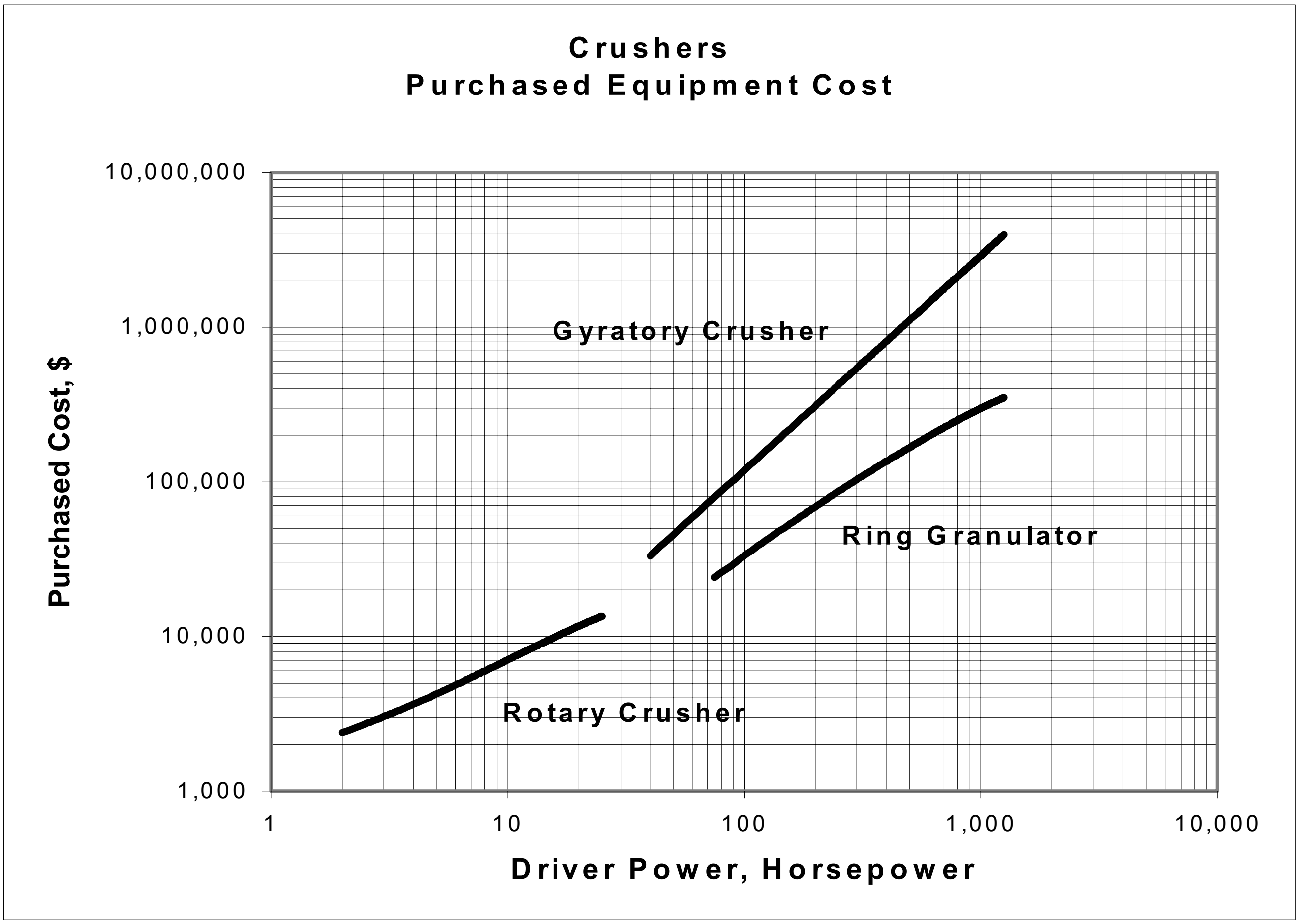
Design Basis:
1st Quarter 1998 Dollars
Material: A285C
(Low and intermediate strength carbon steel plates for pressure vessels.)
Tube Material: Carbon Steel



Crushers

Description: All crushers include motor and drive unit.
Gyratory: Primary crushing of hard and medium hard materials.
Rotary: For course, soft materials.
Ring Granulator: For primary and secondary crushing of bituminous and subbituminous coals, lignite, gypsum and some medium hard minerals.

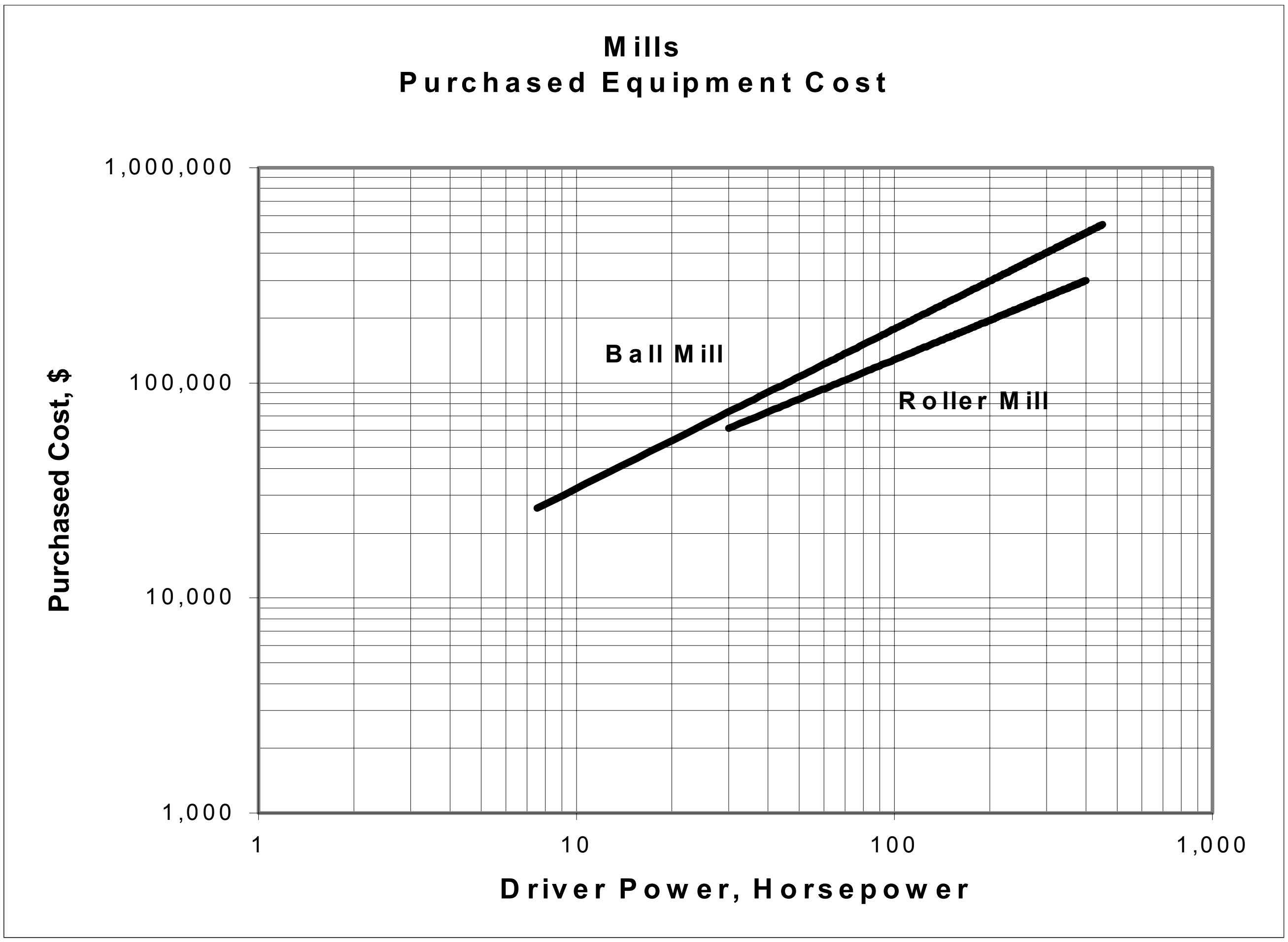
Design Basis:
1st Quarter 1998 Dollars
Material: A285C
(Low and intermediate strength carbon steel plates for pressure vessels.)



Mills

Description: All units include mill, bearings, gears, lube system and vendor-supplied instruments. Ball mill includes initial ball charge.

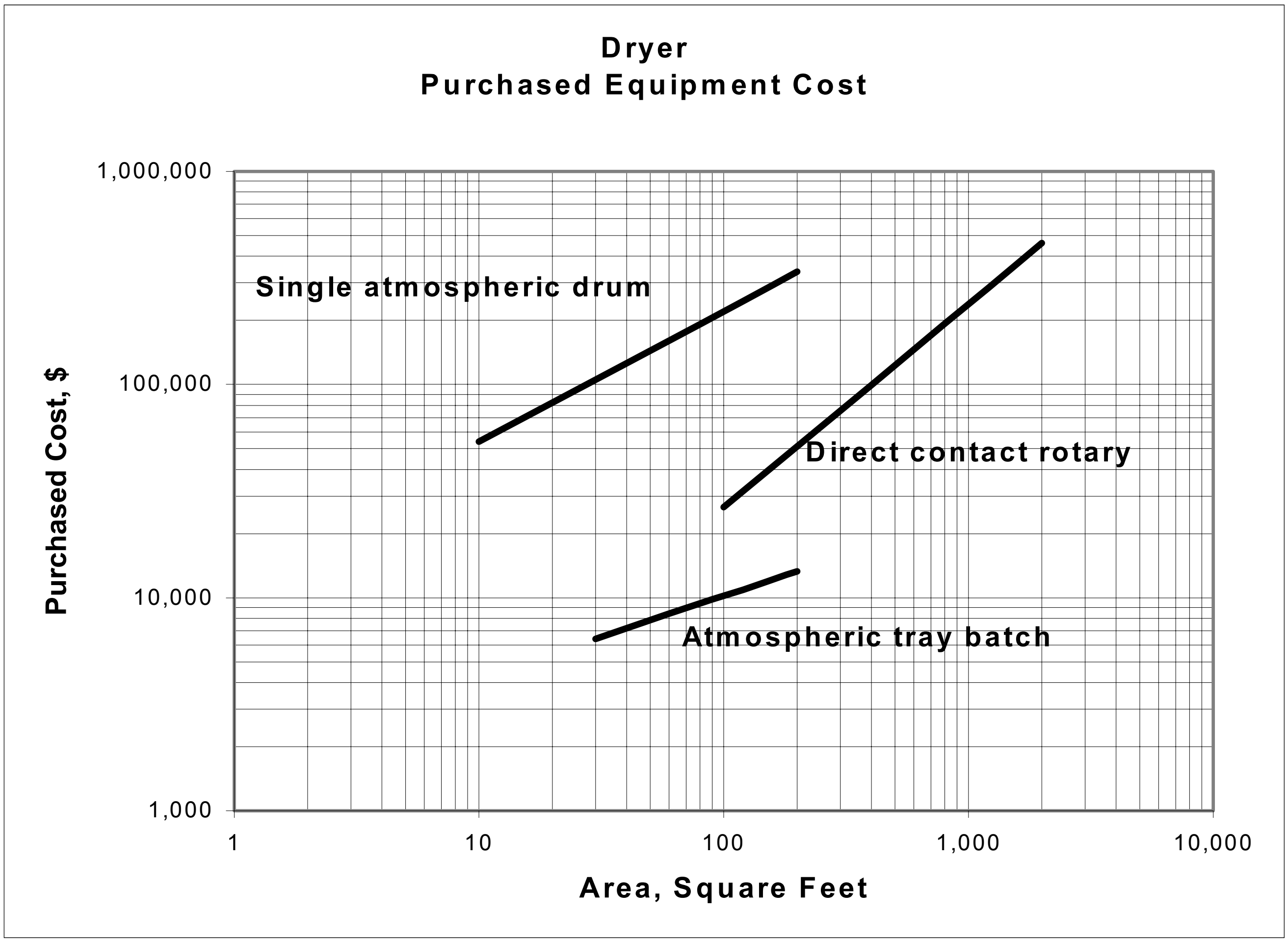
Design Basis:
1st Quarter 1998 Dollars
Material: A285C
(Low and intermediate strength carbon steel plates for pressure vessels.)



Dryers

Description:
Atmospheric tray batch dryer includes solid materials.
Rotary and Drum dryers include motor and drive unit.

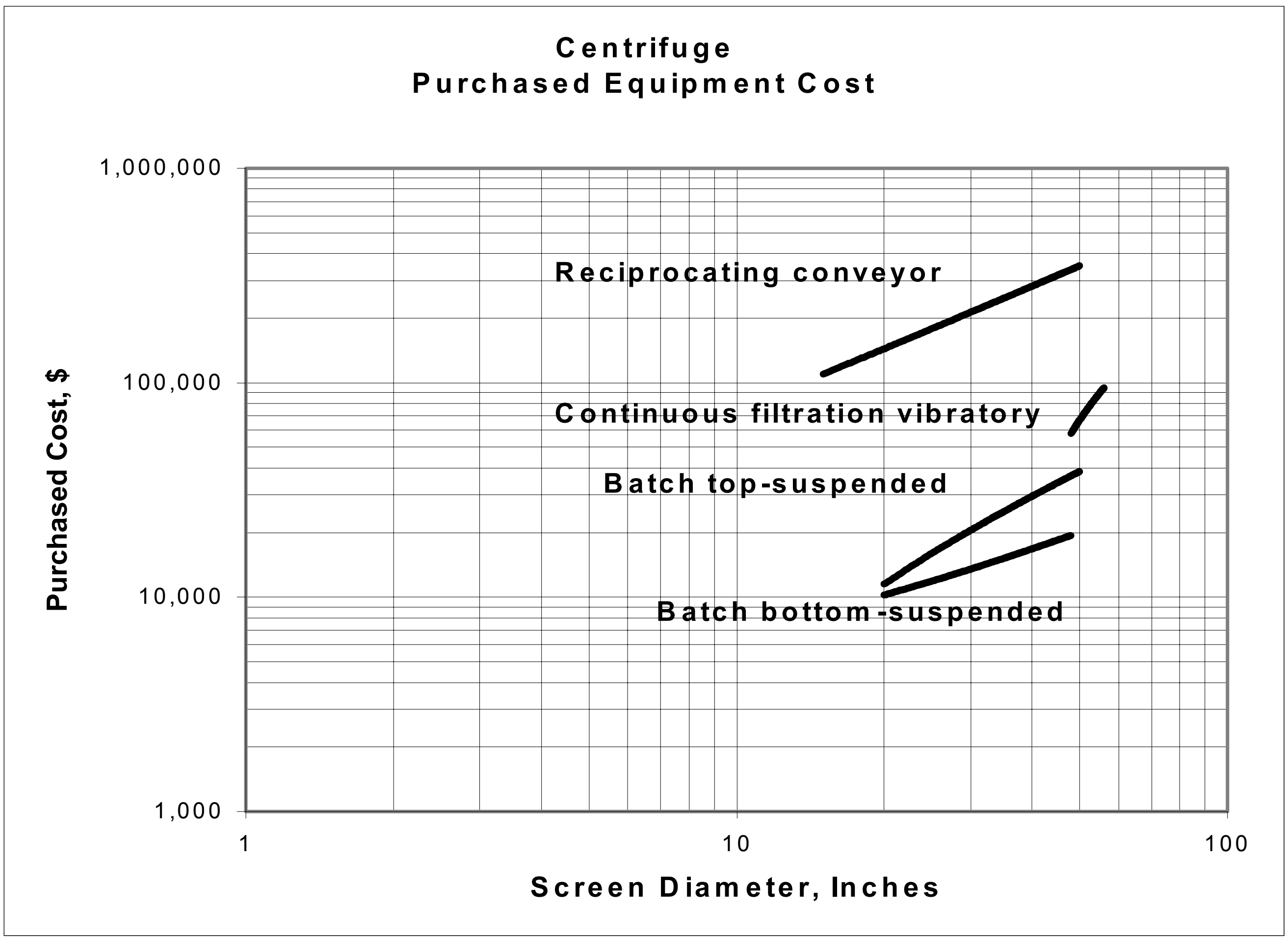
Design Basis:
1st Quarter 1998 Dollars
Material: A285C
(Low and intermediate strength carbon steel plates for pressure vessels.)



Centrifuges

Description: Centrifuges include motor and drive unit.
Reciprocating Conveyor with continuous filtering centrifuge for free-draining granular solids, horizontal bowl, removal by reciprocating piston.
Continuous Filtration Vibratory Centrifuge with solids removal by vibratory screen for dewatering of course solids.

Design Basis:
1st Quarter 1998 Dollars
Material: A285C
(Low and intermediate strength carbon steel plates for pressure vessels.)



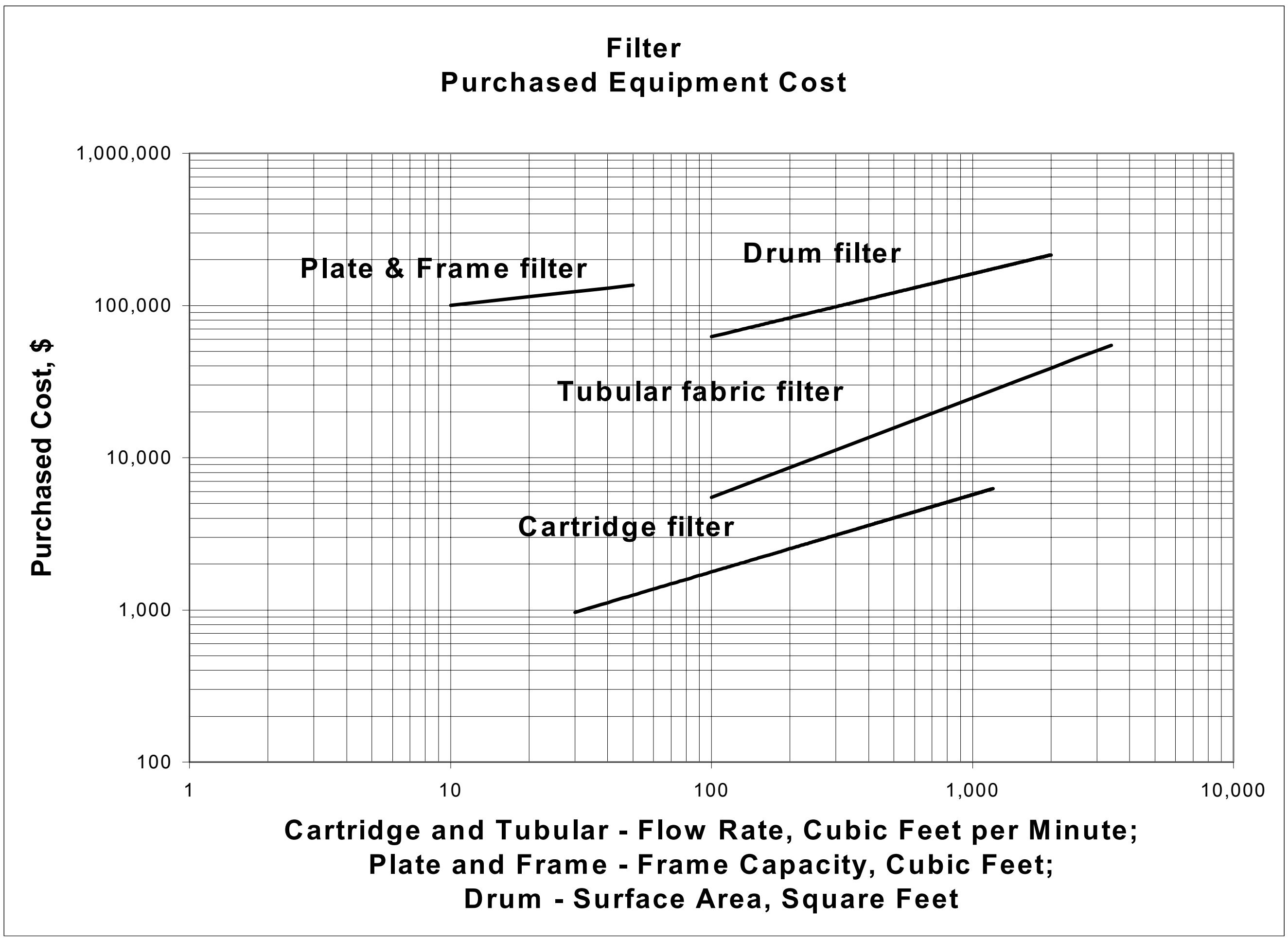
Filters

Description:
Cartridge Filter consists of a tank containing one or more disposable cartridges. Contains 5-micron cotton filter.
Drum Filter is a vacuum type, multi compartment cylinder shell with internal filtrate piping with polypropylene filter cloth, feed box with inlet and drain nozzles, suction valve, discharge trough, driver consisting of rotor, drive motor base plate, worm, gear reducer and two pillow block bearing with supports.

> **Defaults** for Drum Filter
> medium filtration rate,
> 0.5 tons per day/ square feet solids handling rate,
> 20% consistency (percent of solids in feed stream).

Tubular Fabric Filters are a bank of three without automatic cleaning option.
Plate and Frame Filter default material is rubber-lined carbon steel.

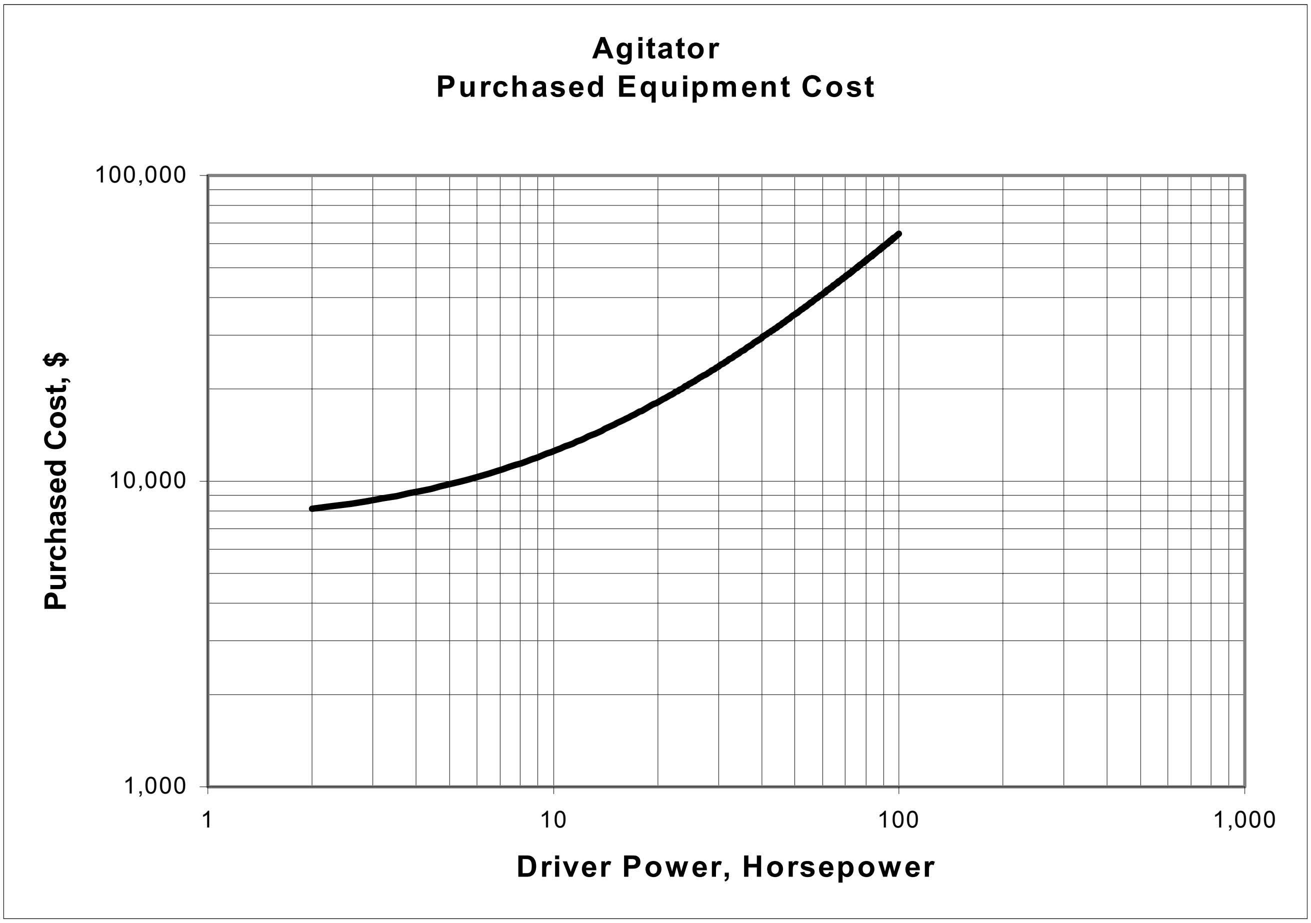
Design Basis:
1^{st} Quarter 1998 Dollars
Material: A285C
(Low and intermediate strength carbon steel plates for pressure vessels.)



Agitator

Description: Fixed propeller mixer with motor and gear drive. Includes motor, gear drive, shaft and impeller.

Design Basis:
1st Quarter 1998 Dollars
Material: A285C
(Low and intermediate strength carbon steel plates for pressure vessels.)
Speed: 1800 RPM

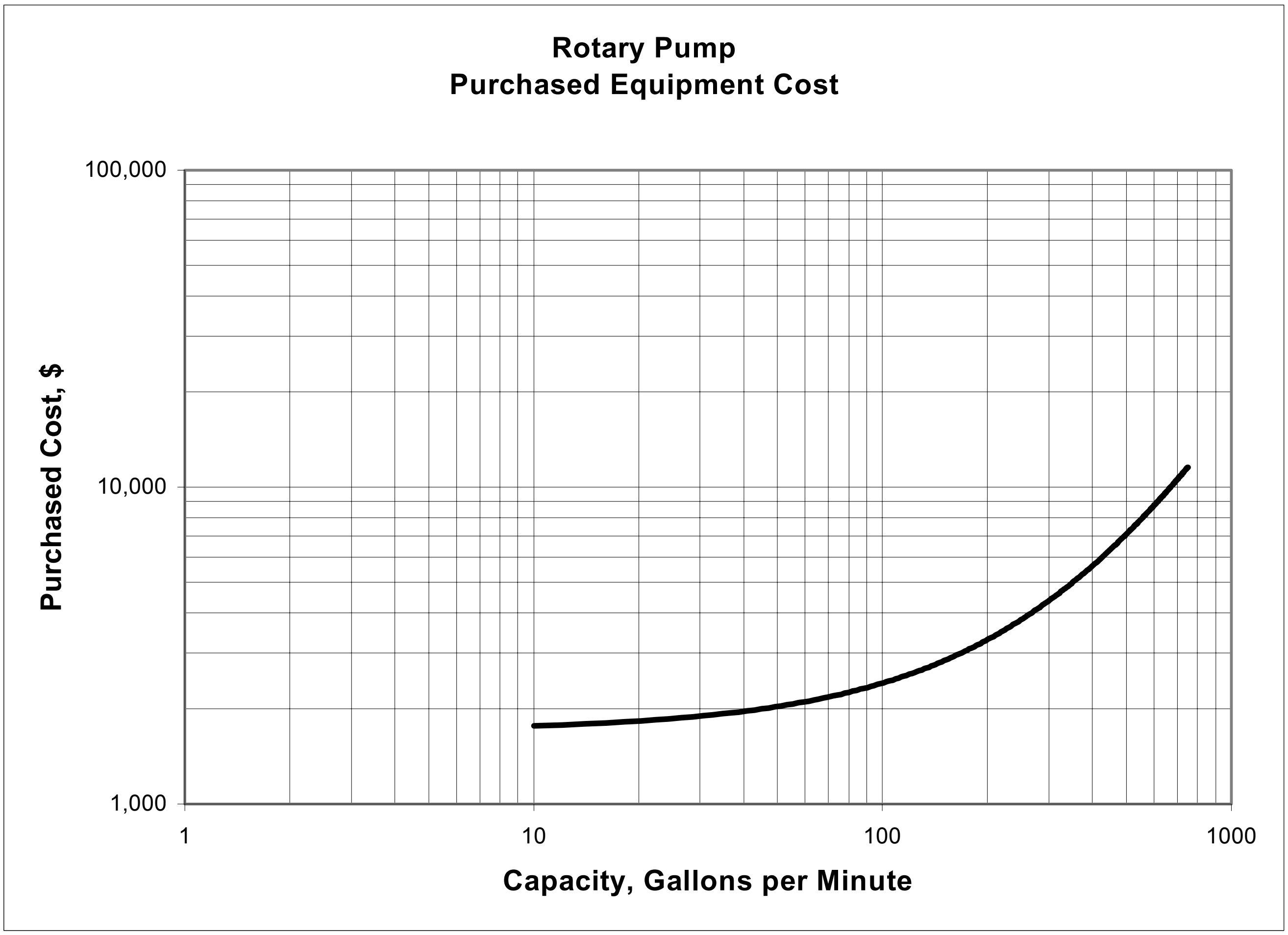


Rotary Pump

Description: Rotary (sliding vanes) pump includes motor driver.

Design Basis:
1st Quarter 1998 Dollars

Material:	Cast Iron
Temperature:	68 °F
Power:	25 – 20 Horsepower
Speed:	1800 RPM
Liquid Specific Gravity:	1
Efficiency:	82%

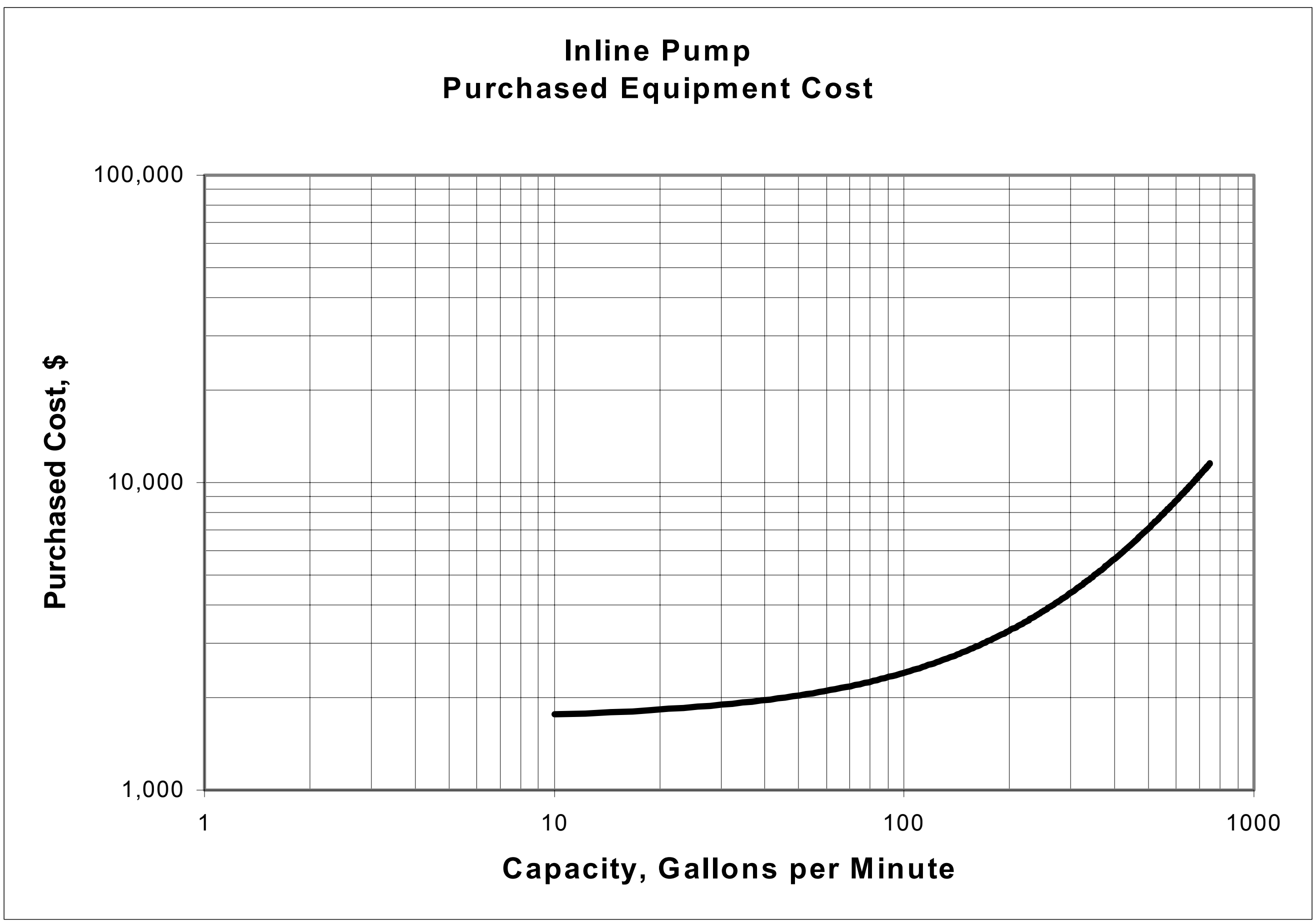


Inline Pump

Description: General service in-line pump includes pump and motor driver.

Design Basis:
1st Quarter 1998 Dollars

Material:	Carbon Steel
Temperature:	120 °F
Speed:	1800 RPM
Liquid Specific Gravity:	1
Efficiency:	<50 GPM = 60%
	50 – 199 GPM = 65%
	100 – 500 GPM = 75%
	> 500 GPM = 82%
Driver Type:	Standard motor
Seal Type:	Single mechanical seal

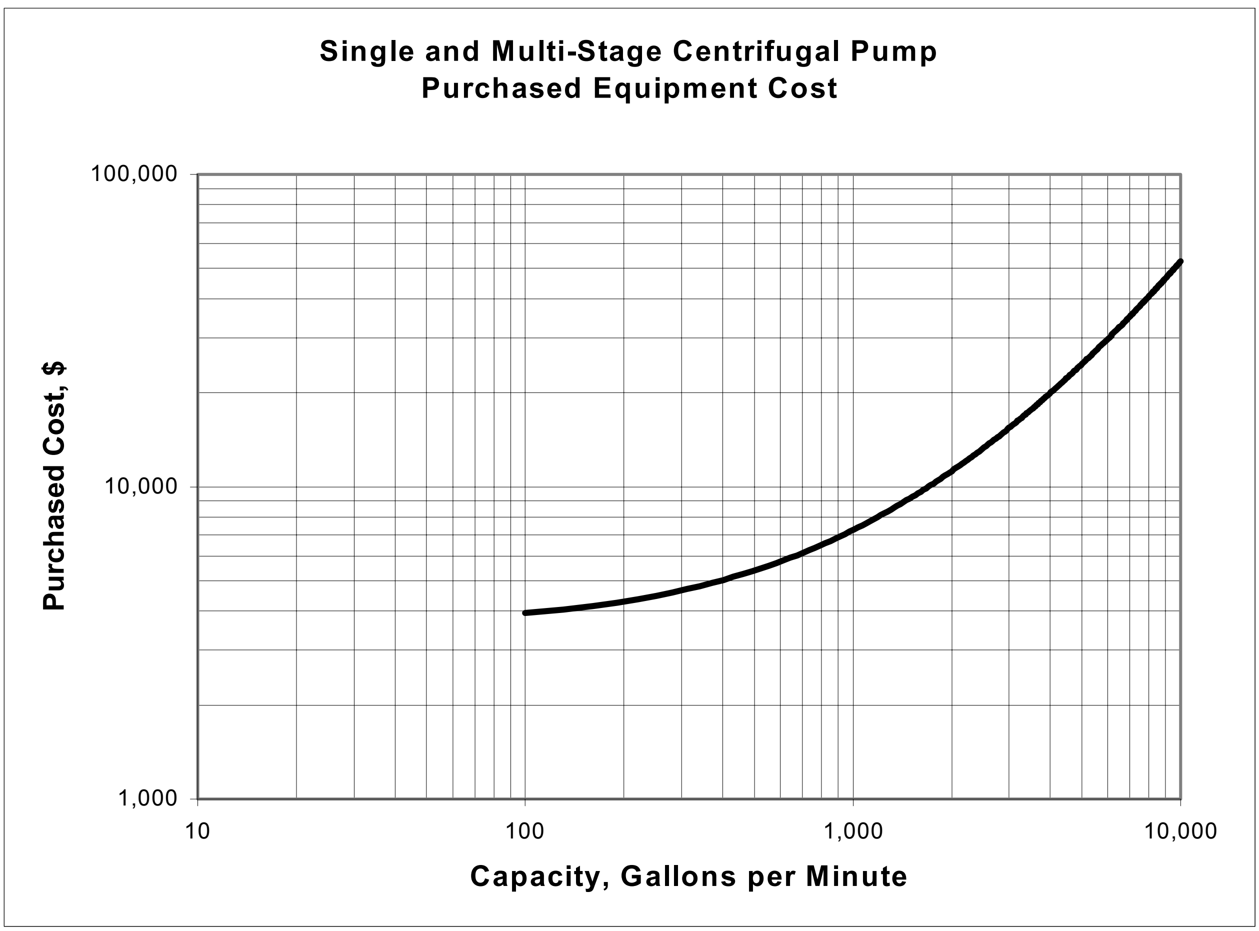


Centrifugal Pump

Description: Single and multistage centrifugal pumps for process or general service when flow/head conditions exceed general service. Split casing not a cartridge or barrel. Includes standard motor driver.

Design Basis:
1st Quarter 1998 Dollars

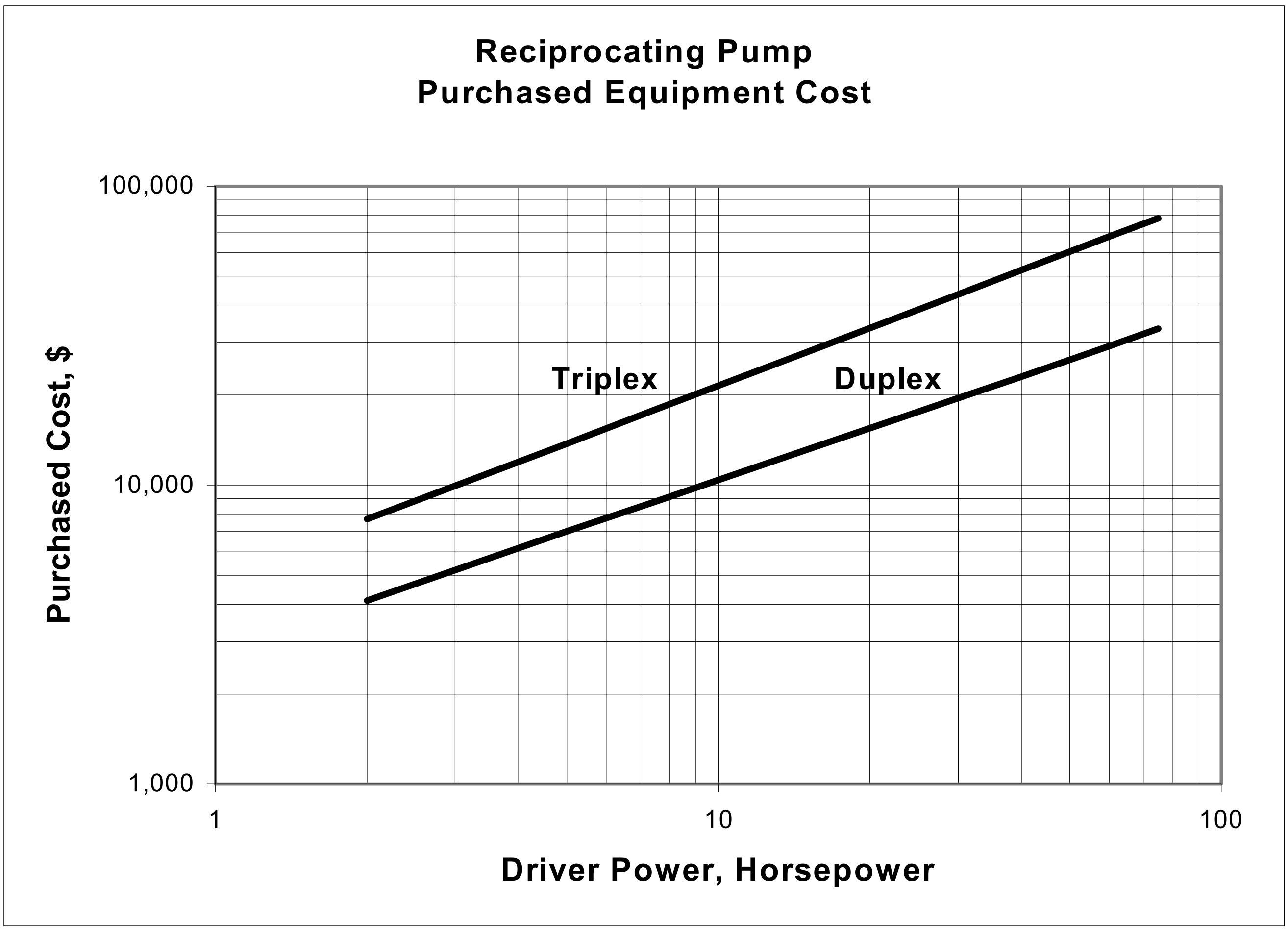
Material:	Carbon Steel
Design Temperature:	120 °F
Design Pressure:	150 psig
Liquid Specific Gravity:	1
Efficiency:	<50 GPM = 60%
	50 – 199 GPM = 65%
	100 – 500 GPM = 75%
	> 500 GPM = 82%
Driver Type:	Standard motor
Seal Type:	Single mechanical seal



Reciprocating Pump

Description: Reciprocating duplex with steam driver. Triplex (plunger) with pump-motor driver.

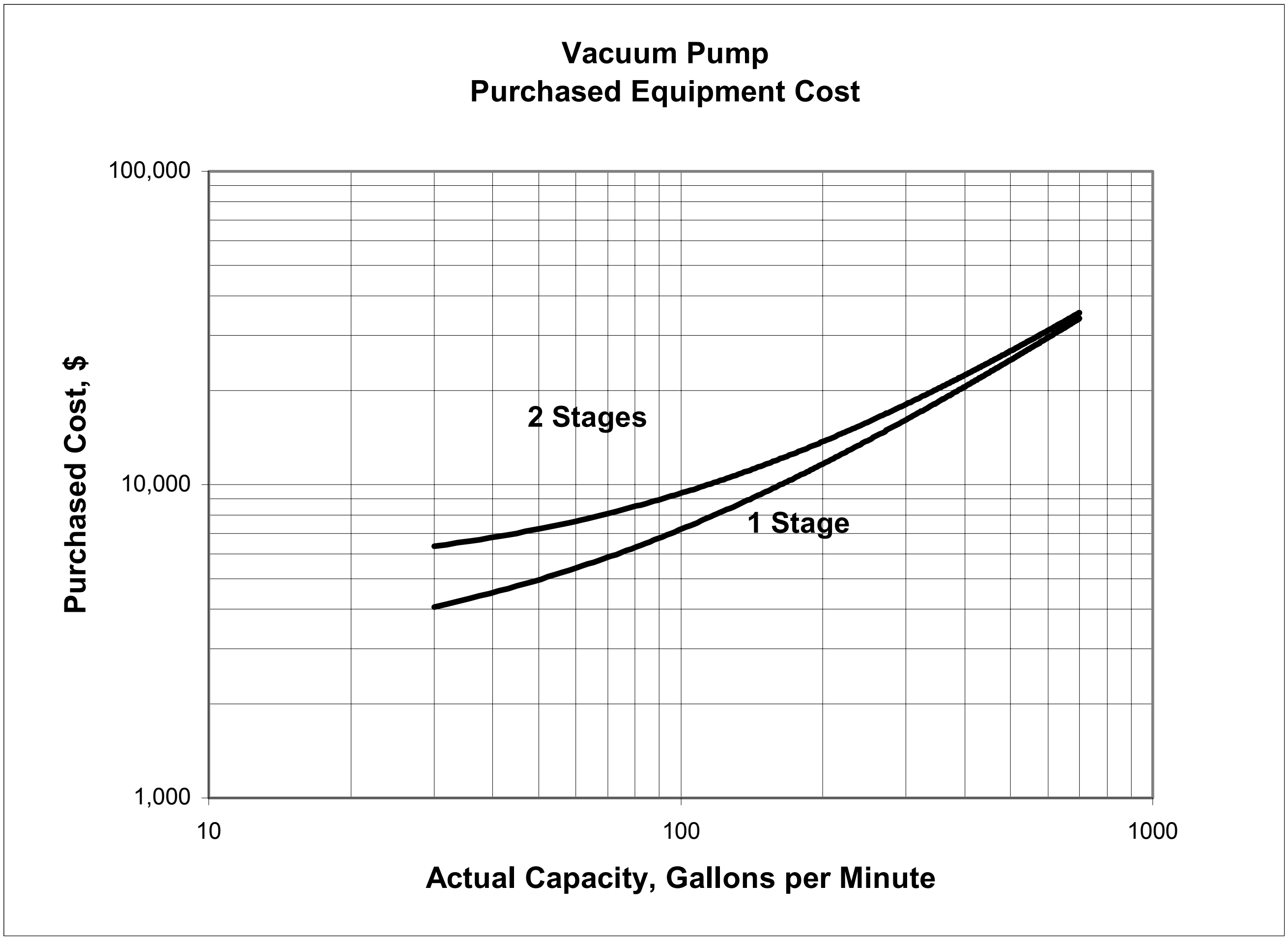
Design Basis:
1st Quarter 1998 Dollars
Material: Carbon Steel
Design Temperature: 68 °F
Liquid Specific Gravity: 1
Efficiency: 82%



Vacuum Pump

Description: Mechanical oil-sealed vacuum pump includes pump, motor and drive unit.

Design Basis:
1st Quarter 1998 Dollars
Material: Carbon Steel
First Stage: 0.01 MM HG (Mercury)
Second Stage: 0.0003 MM HG (Mercury)

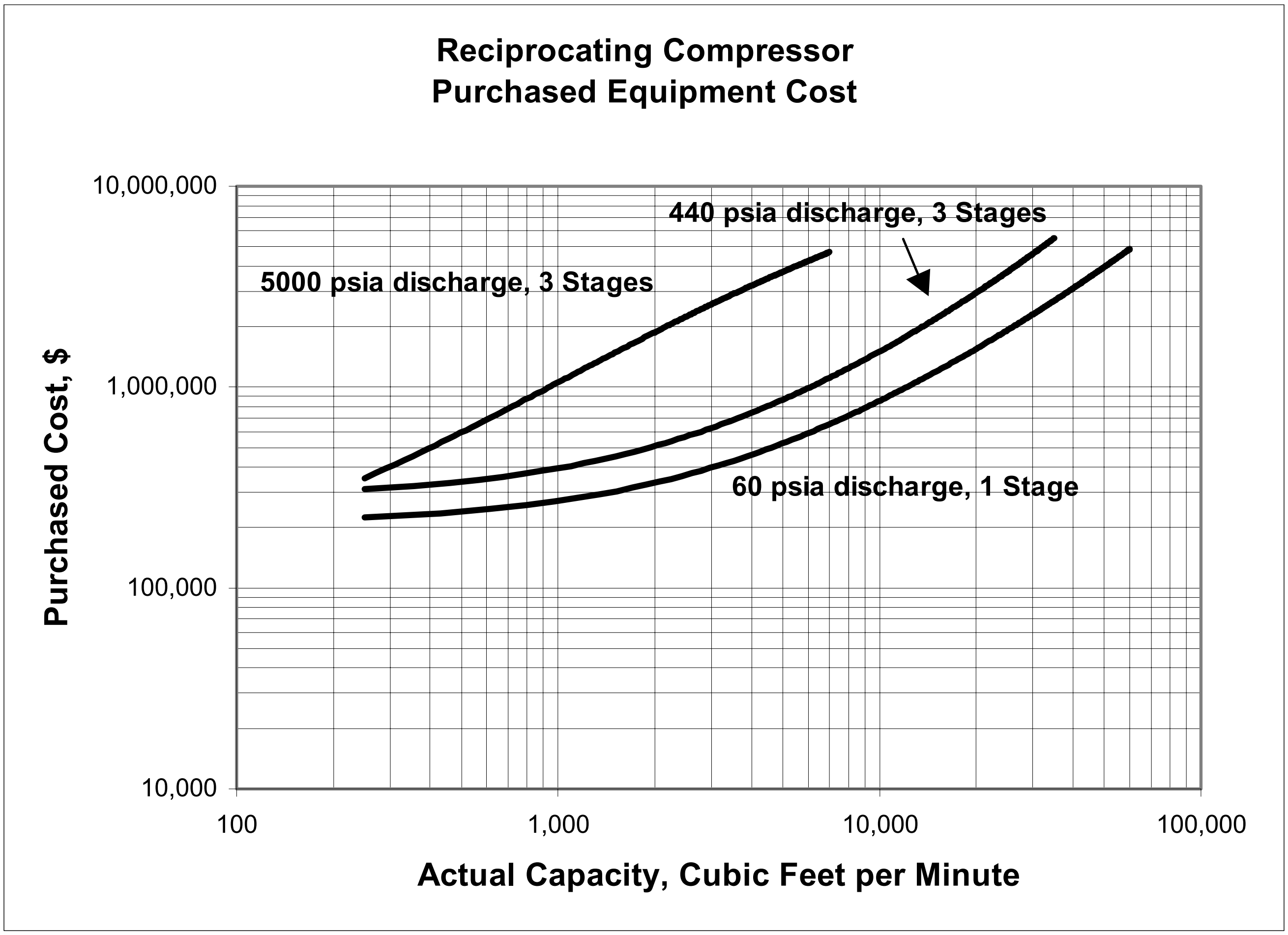


Reciprocating Compressor

Description: Reciprocating compressor with gear reducer, couplings, guards, base plate, compressor unit, fittings, interconnecting piping, vendor-supplied instruments, lube/seal system. Does not include intercoolers or aftercoolers and interstage knock-out drums.

Design Basis:
1st Quarter 1998 Dollars

Material:	Carbon Steel
Inlet Temperature:	68 °F
Inlet Pressures:	14.7/ 14.7/ 165 psia
Pressure Ratios:	4:1/ 30:1/ 30:1
Molecular Weight:	30
Specific Heat Ratio:	1.22

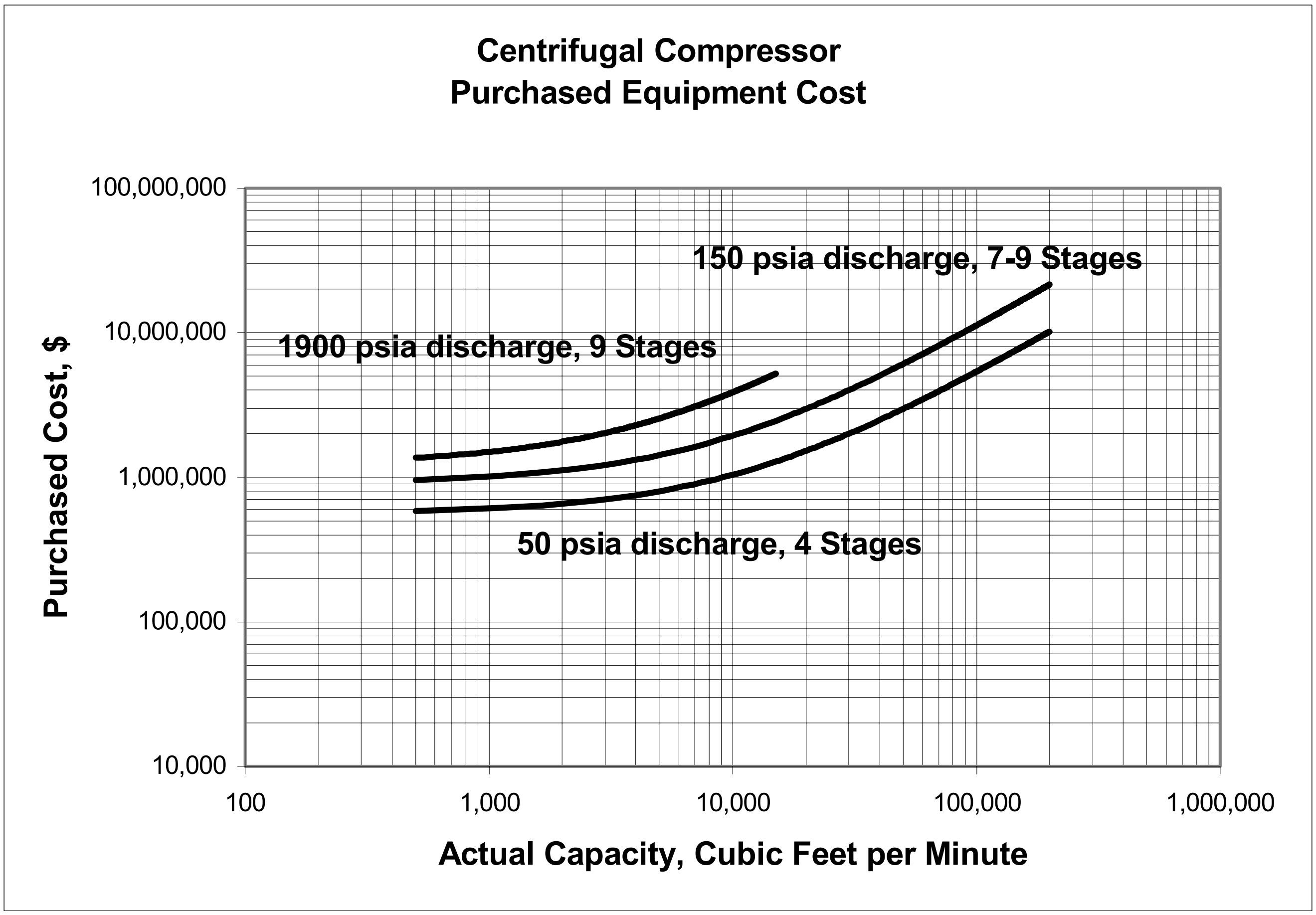


Centrifugal Compressor

Description: Axial (inline) centrifugal gas compressor with motor driver. Excludes intercoolers and knock-out drums.

Design Basis:
1st Quarter 1998 Dollars

Material:	Carbon Steel
Inlet Temperature:	68 °F
Inlet Pressures:	14.7/ 14.7/ 190 psia
Pressure Ratios:	3:1/ 10:1/ 10:1
Molecular Weight:	29
Specific Heat Ratio:	1.4

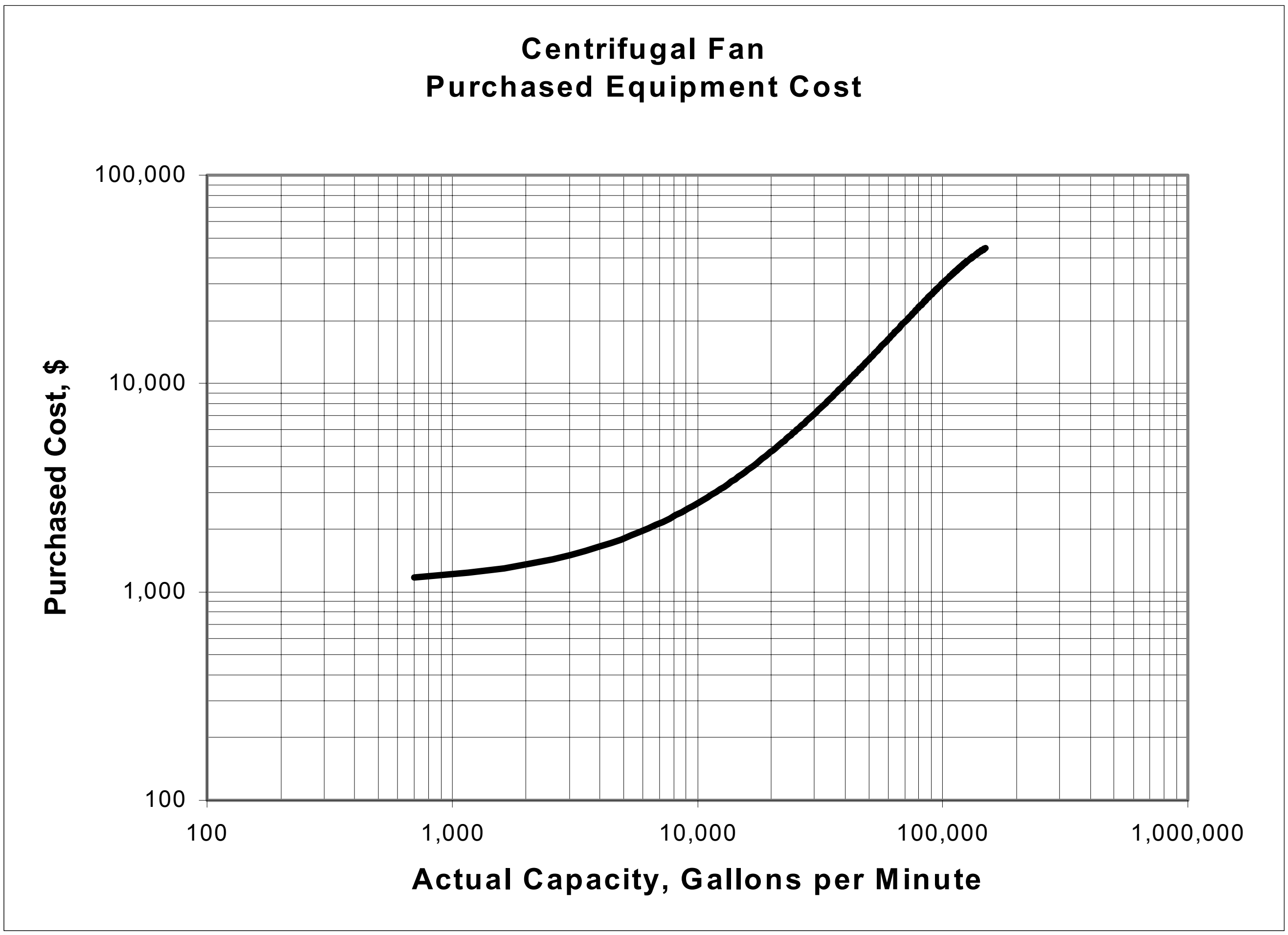


Centrifugal Fan

Description: Centrifugal fans move gas through a low pressure drop system. Maximum pressure rise is about 2 PSI.

Design Basis:
1st Quarter 1998 Dollars

Material:	Carbon Steel
Power:	1.5 - 300 Horsepower
Speed:	1800 RPM
Exit Pressure:	6 In H2O

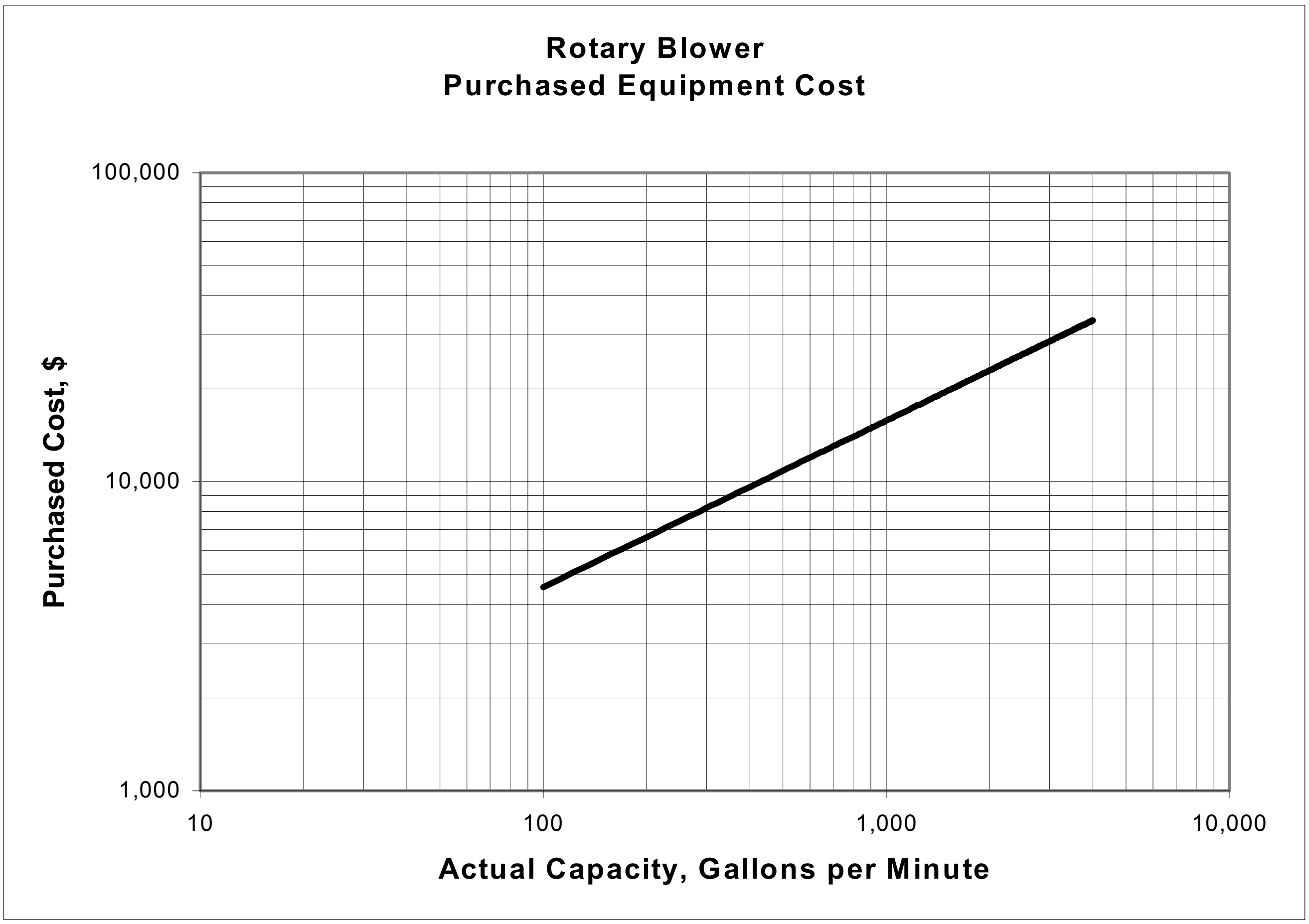


Rotary Blower

Description: This general-purpose blower includes inlet and discharge silencers. The casing of the rotary blower is cast iron and the impellers are ductile iron.

Design Basis:
1st Quarter 1998 Dollars

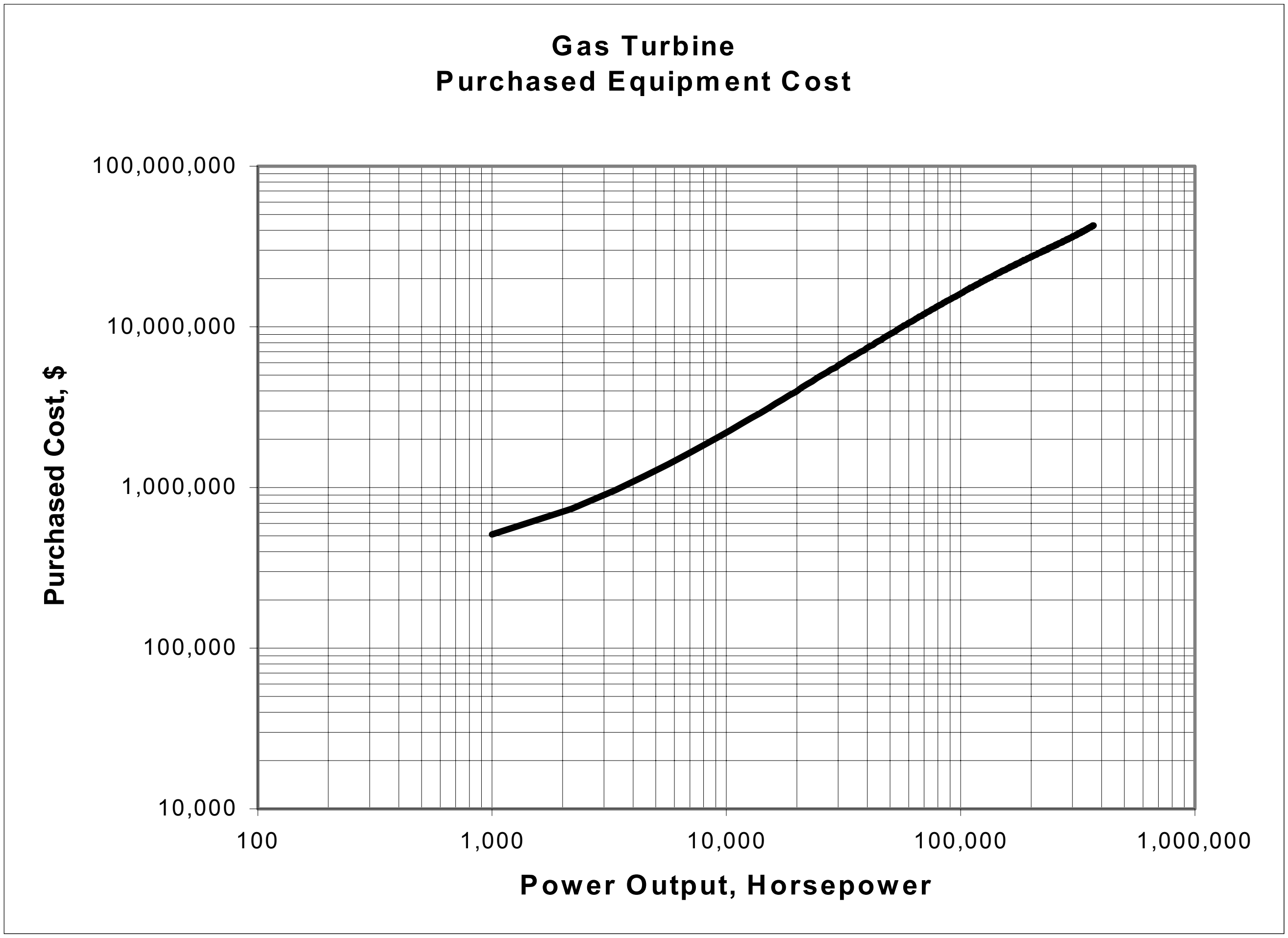
Material:	Carbon Steel
Power:	5 - 200 Horsepower
Speed:	1800 RPM
Exit Pressure:	8 psig



Gas Turbine

Description: Gas turbine includes fuel gas combustion chamber and multi-stage turbine expander.

Design Basis:
1st Quarter 1998 Dollars
Material: Carbon Steel

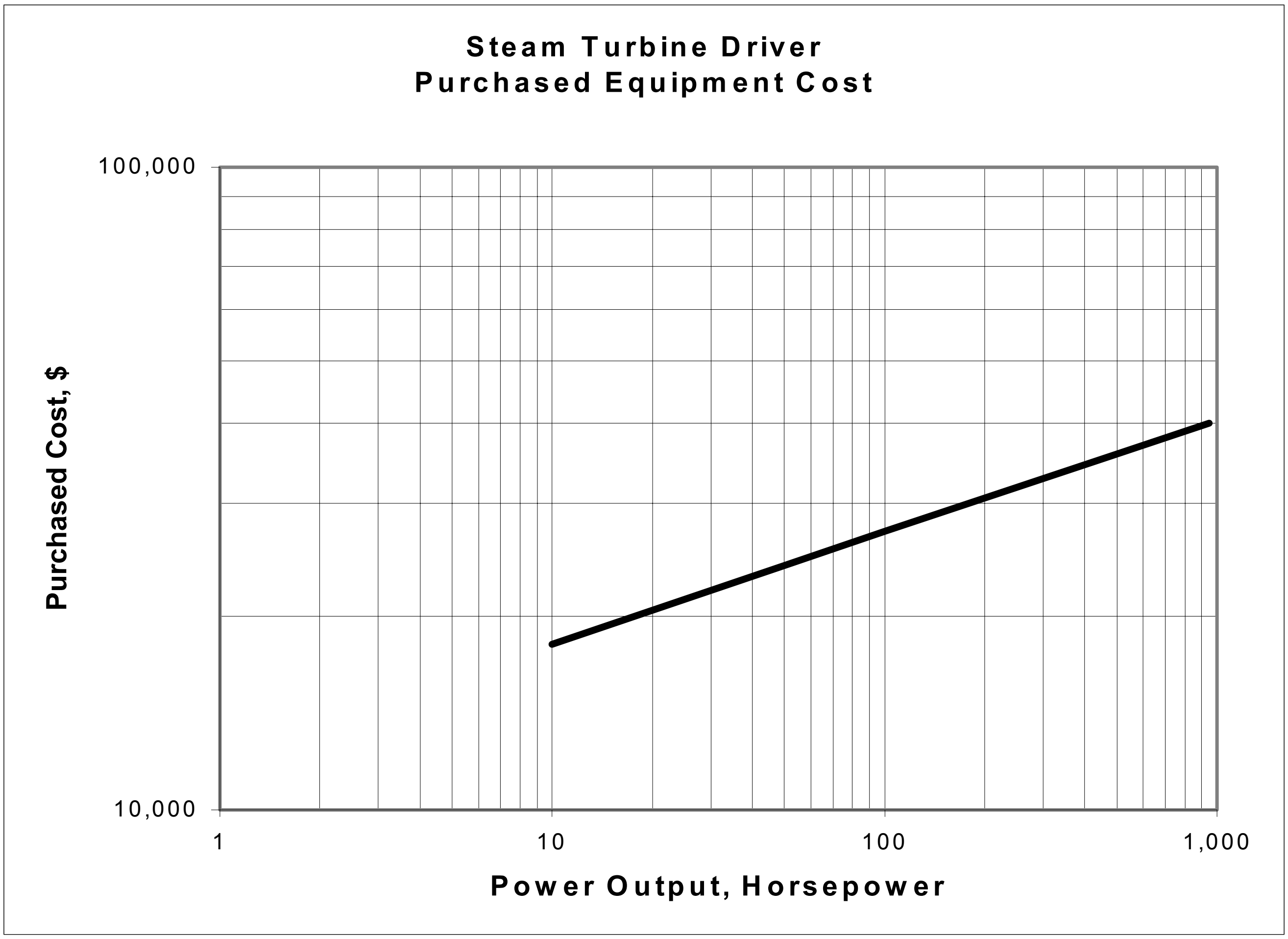


Steam Turbine – under 1000 Horsepower

Description: Steam turbine driver includes condenser and accessories.

Design Basis:
1st Quarter 1998 Dollars

Material:	Carbon Steel
Steam Pressure:	400 psig
Speed:	3600 RPM



Steam Turbine – over 1000 Horsepower

Description: Steam turbine driver includes condenser and accessories.

Design Basis:
1st Quarter 1998 Dollars

Material:	Carbon Steel
Steam Pressure:	400 psig
Speed:	3600 RPM

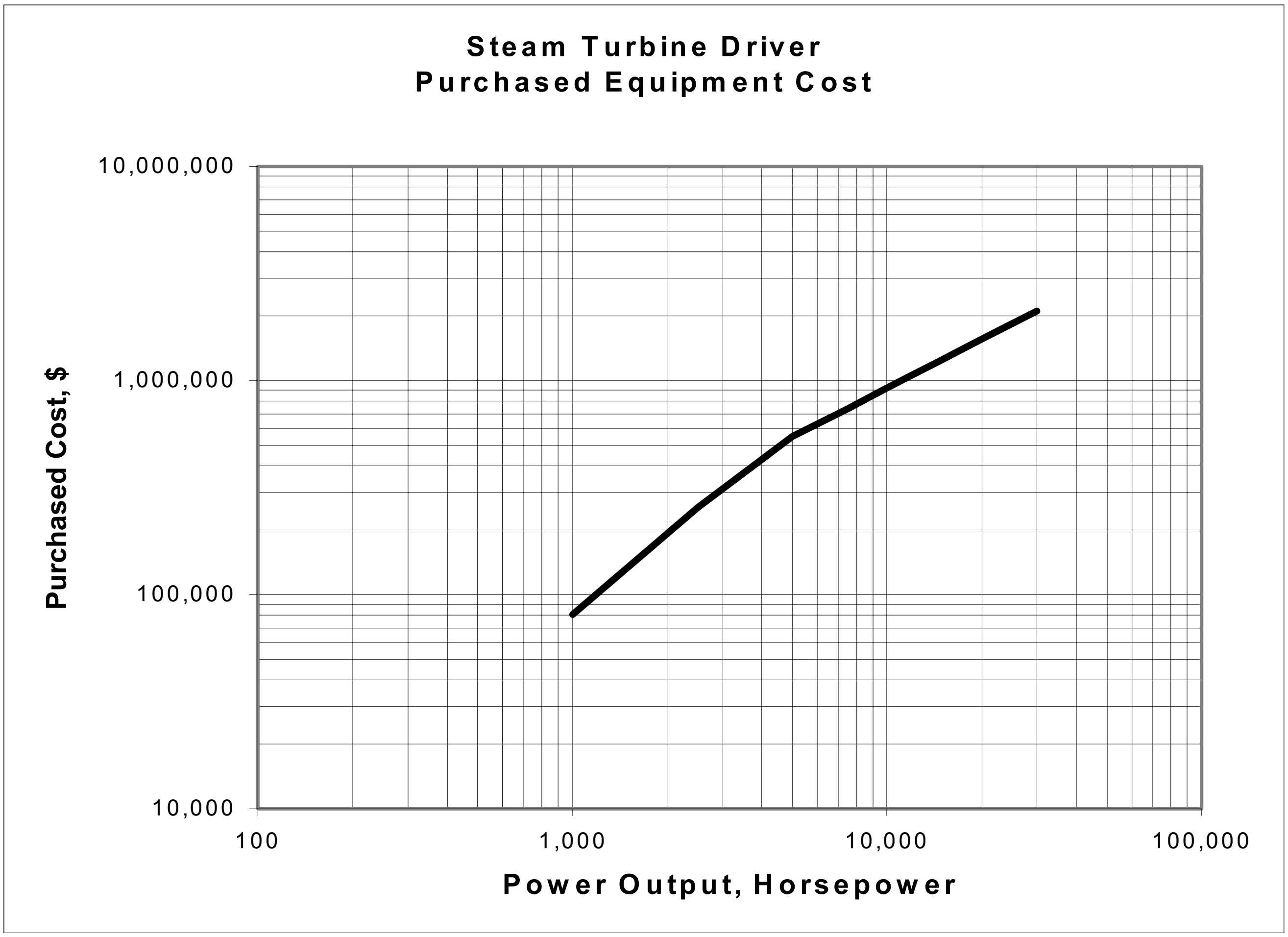


Table 2

Distributive Factors for Bulk Materials - Solids Handling Processes

Temperature		**≤400 °F (%)**	**>400 °F (%)**
Foundations	*Material*	4	5
	Labor	133	133
Structural Steel	*Material*	4	2
	Labor	50	100
Buildings	*Material*	2	2
	Labor	100	100
Insulation	*Material*	---	1.5
	Labor	---	150
Instruments	*Material*	6	6
	Labor	10	40
Electrical	*Material*	9	9
	Labor	75	75
Piping	*Material*	5	5
	Labor	50	50
Painting	*Material*	0.5	0.5
	Labor	300	300
Miscellaneous	*Material*	3	4
	Labor	80	80

Table 3

Distributive Factors for Bulk Materials – Solids - Gas Processes

Temperature		**≤400 °F**		**>400 °F**	
Pressure		**≤ 150 psig (%)**	**>150 psig (%)**	**≤ 150 psig (%)**	**>150 psig (%)**
Foundations	*Material*	5	6	6	6
	Labor	133	133	133	133
Structural Steel	*Material*	4	4	5	6
	Labor	100	100	50	50
Buildings	*Material*	2	2	5	4
	Labor	100	50	50	100
Insulation	*Material*	1	1	2	2
	Labor	150	150	150	150
Instruments	*Material*	2	7	7	8
	Labor	40	40	40	75
Electrical	*Material*	6	8	7	8
	Labor	75	75	75	75
Piping	*Material*	35	40	40	40
	Labor	50	50	50	50
Painting	*Material*	0.5	0.5	0.5	0.5
	Labor	300	300	300	300
Miscellaneous	*Material*	3.5	4	4	4.5
	Labor	80	80	80	80

Table 4

Distributive Factors for Bulk Materials - Liquid and Slurry Systems

Pressure		**≤ 150 psig (%)**	**>150 psig (%)**
Foundations	*Material*	5	6
	Labor	133	133
Structural Steel	*Material*	4	5
	Labor	50	50
Buildings	*Material*	3	3
	Labor	100	100
Insulation	*Material*	1	3
	Labor	150	150
Instruments	*Material*	6	7
	Labor	40	40
Electrical	*Material*	8	9
	Labor	75	75
Piping	*Material*	30	35
	Labor	50	50
Painting	*Material*	0.5	0.5
	Labor	300	300
Miscellaneous	*Material*	4	5
	Labor	80	80

Table 5

Distributive Factors for Bulk Materials - Gas Processes

Temperature		**≤400 °F**		**>400 °F**	
Pressure		**≤ 150 psig (%)**	**>150 psig (%)**	**≤ 150 psig (%)**	**>150 psig (%)**
Foundations	*Material*	5	6	6	5
	Labor	133	133	133	133
Structural Steel	*Material*	5	5	5	6
	Labor	50	50	50	50
Buildings	*Material*	3	3	3	4
	Labor	100	100	100	100
Insulation	*Material*	1	1	2	3
	Labor	150	150	150	150
Instruments	*Material*	6	7	7	7
	Labor	40	40	75	40
Electrical	*Material*	8	9	6	9
	Labor	75	75	40	75
Piping	*Material*	45	40	40	40
	Labor	50	50	50	50
Painting	*Material*	0.5	0.5	0.5	0.5
	Labor	300	300	300	300
Miscellaneous	*Material*	3	4	4	5
	Labor	80	80	80	80

Table 6
Distributive Labor Factors for Setting Equipment

Equipment Type	**Factor** (%)	**Equipment Type**	**Factor** (%)
Absorber	20	Hammermill	25
Ammonia Still	20	Heater	20
Ball Mill	30	Heat Exchanger	20
Briquetting machine	25	Lime Leg	15
Centrifuge	20	Methanator (catalytic)	30
Clarifier	15	Mixer	20
Coke Cutter	15	Precipitator	25
Coke Drum	15	Regenerator (packed)	20
Condenser	20	Retort	30
Conditioner	20	Rotoclone	25
Cooler	20	Screen	20
Crusher	30	Scrubber (water)	15
Cyclone	20	Settler	15
Decanter	15	Shift converter	25
Distillation column	30	Splitter	15
Evaporator	20	Storage Tank	20
Filter	15	Stripper	20
Fractionator	25	Tank	20
Furnace	30	Vaporizer	20
Gasifier	30		

Table 7

Factors for Converting Carbon Steel to Equivalent Alloy Costs

Material	Pumps, etc.	Other Equipment
All Carbon Steel	1.00	1.00
Stainless Steel, Type 410	1.43	2.00
Stainless Steel, Type 304	1.70	2.80
Stainless Steel, Type 316	1.80	2.90
Stainless Steel, Type 310	2.00	3.33
Rubber-lined Steel	1.43	1.25
Bronze	1.54	
Monel	3.33	

Material	Heat Exchangers
Carbon Steel Shell and Tubes	1.00
Carbon Steel Shell, Aluminum Tubes	1.25
Carbon Steel Shell, Monel Tubes	2.08
Carbon Steel Shell, 304 Stainless Steel Tubes	1.67
304 Stainless Steel Shell and Tubes	2.86

Cost Indexes

Cost indexes are used to update costs from the base time, in this case First Quarter 1998 dollars, to the present time of the estimate. Cost indexes are used to give a general estimate, but can not take into account all factors. Some limitations of cost indexes include:[3]

1. Accuracy is very limited. Two Indexes may yield much different answers.
2. Cost indexes are based on averages. Specific cases may be much different from the average.
3. At best, 10% accuracy can be expected for periods up to 5 years.
4. For periods over 10 years, indexes are suitable only for order of magnitude estimates.

The most common indexes are Engineering News-Record Construction Cost Index, Table 8, (published in the *Engineering News-Record*), Marshall and Swift Equipment Cost Indexes, Table 9, (published in *Chemical Engineering*), Nelson-Farrar Refinery Construction Cost Index, Table 10, (published in the *Oil and Gas Journal*) and the Chemical Engineering Plant Cost Index, Table 11, (published in *Chemical Engineering*). Annual averages for each of these indexes are included in this report.

The Marshall and Swift Equipment Cost Indexes are divided into two categories, the all-industry equipment index and the process-industry equipment index. The indexes take into consideration the cost of machinery and major equipment plus costs for installation, fixtures, tools, office furniture, and other minor equipment. The Engineering News-Record Construction Cost Index shows the variation in the labor rates and materials costs for industrial construction. The Nelson-Farrar Refinery Construction Cost Index uses construction costs in the petroleum industry as the basis. The Chemical Engineering Plant Cost Index uses construction costs for chemical plants as the basis.

Two cost indexes, the Marshall and Swift equipment cost indexes and the Chemical Engineering plant cost indexes, give very similar results and are recommended for use with process-equipment estimates and chemical-plant investment estimates. The Engineering News-Record construction cost index, relative with time, has increased much more rapidly than the other two because it does not include a productivity improvement factor. Similarly, the Nelson-Farrar refinery construction index has shown a very large increase with time and should be used with caution and only for refinery construction.[4]

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[3] Humphreys, Dr. Kenneth K. PE CCE, "Preliminary Capital and Operating Cost Estimating (for the Process and Utility Industries)," course notes.

[4] Peters, Max S. and Klaus D. Timmerhaus, "Plant Design and Economics for Chemical Engineers" McGraw-Hill, Inc. 1991.

Table 8

Engineering News Record Construction Cost Index
Published in the *Engineering News-Record*

Year		Annual Average
1913		**100**
1960		824
1965		971
1970		1381
1975		2212
1980		3237
1985		4195
1990		4732
1995		5471
1996		5620
1997		5825
1998		5920
1999		6060
2000		6222
2001		
	January	6281
	February	6273
	March	6280
	April	6286
	May	6288

Table 9

Marshall and Swift Installed-Equipment Index
Published in *Chemical Engineering*

	Annual Average	
Year	**All Industry**	**Process Industry**
1926	**100**	**100**
1964	242	241
1965	245	244
1970	303	301
1975	444	452
1980	560	675
1985	790	813
1990	915	935
1995	1027.5	1037.4
1996	1039.2	1051.3
1997	1056.8	1068.3
1998	1061.9	1075.9
1st Quarter	1061.2	1074.6
2nd Quarter	1061.8	1075.2
3rd Quarter	1062.4	1077.2
4th Quarter	1062.3	1076.6
1999	1068.3	1083.1
1st Quarter	1062.7	1078.8
2nd Quarter	1065.0	1080.7
3rd Quarter	1069.9	1084.0
4th Quarter	1075.6	1088.7
2000	1089.0	1102.7
1st Quarter	1080.6	1093.5
2nd Quarter	1089.0	1102.2
3rd Quarter	1092.0	1106.3
4th Quarter	1094.5	1108.7
2001		
1st Quarter	1092.8	1106.9

Table 10

Nelson-Farrar Refinery Construction Index
Published in the *Oil and Gas Journal*

Year	Annual Average	Pumps, Compressors, etc	Heat Exchangers	Misc. Equipment Average
1946	**100**			
1964	252			
1965	261			
1970	365			
1975	576			
1980	823	777.3	618.7	578.1
1985	1074	969.9	520	673.4
1990	1225.7	1125.6	755.7	797.5
1995	1392.1	1316.7	758.6	879.5
1996	1418.9	1354.5	793.3	903.5
1997	1449.2	1383.9	773.6	910.5
1998	1477.6	1406.7	841.1	933.2
1999	1497.2	1433.5	715.8	920.3
2000	1542.7	1456.4	662.2	917.8
2001				
January	1565.9	1473.2	722.7	936.2
February	1563.6	1478.9	722.7	937.1

Table 11

Chemical Engineering Plant Cost Index
Published in *Chemical Engineering*

Year	Annual Average
1957-59	**100**
1964	103
1965	104
1970	126
1975	182
1980	261
1985	325
1990	357.6
1995	381.1
1996	381.8
1997	386.5
1998	389.5
1999	390.6
2000	394.1
2001	
January	395.4

Appendix A

The following is an example of the usage of the cost curves and tables to estimate the installed cost of a 5,000 square foot gas-gas shell and tube heat exchanger with a design temperature of 650°F and a design pressure of 150 psig.

From the chart on page 16, the estimated purchased equipment cost is $62,000. From Table 6, the factor for setting a heat exchanger is 20%. Column 3 of Table 5 is used to estimate the bulk material and labor costs.

Bare cost:			$62,000
Setting Cost:		$62,000*0.2	$12,400
Bulk Installations:			
Foundations			
	Material	$62,000*0.06	$3,720
	Labor	$3,720*1.33	$4,948
Structural Steel			
	Material	$62,000*0.05	$3,100
	Labor	$3,100*0.5	$1,550
Buildings			
	Material	$62,000*0.03	$1,860
	Labor	$1,860*1.0	$1,860
Insulation			
	Material	$62,000*0.02	$1,240
	Labor	$1,240*1.5	$1,860
Instruments			
	Material	$62,000*0.07	$4,340
	Labor	$4,340*0.75	$3,255
Electrical			
	Material	$62,000*0.06	$3,720
	Labor	$3,720*0.4	$1,488
Piping			
	Material	$62,000*0.4	$24,800
	Labor	$24,800*0.5	$12,400
Painting			
	Material	$62,000*0.005	$310
	Labor	$310*3.0	$930
Miscellaneous			
	Material	$62,000*0.04	$2,480
	Labor	$2,480*0.8	$1,984
Total Installed Cost:			$150,245

From ICARUS-generated results (page 59):

Purchased Equipment Cost	$62,100
Total Installed Cost	$141,800

Appendix B

Vertical Vessels
1st Quarter 1998 dollars

15 psig					
Diameter (Feet)	**Height (Feet)**	**Capacity (Gallons)**	**Total Weight (Pounds)**	**Purchased Equipment Cost ($)**	**Installed Cost ($)**
2.5	2.7	100	1,000	$6,400	$51,800
3.0	4.7	250	1,400	$7,400	$61,000
4.0	5.3	500	2,000	$9,800	$68,400
4.0	8.0	750	2,700	$12,200	$89,700
5.0	6.8	1,000	3,000	$13,000	$96,000
6.0	9.5	2,000	4,200	$16,500	$122,300
7.0	10.4	3,000	5,200	$18,000	$132,300
7.0	13.9	4,000	6,300	$18,600	$135,100
8.0	13.3	5,000	7,100	$21,000	$139,700

150 psig					
Diameter (Feet)	**Height (Feet)**	**Capacity (Gallons)**	**Total Weight (Pounds)**	**Purchased Equipment Cost ($)**	**Installed Cost ($)**
2.5	2.7	100	1,300	$7,000	$48,800
3.0	4.7	250	1,800	$8,300	$52,500
4.0	5.3	500	2,800	$11,300	$60,900
4.0	8.0	750	3,600	$13,700	$76,900
5.0	6.8	1,000	4,500	$15,600	$84,800
6.0	9.5	2,000	7,000	$20,900	$100,700
7.0	10.4	3,000	9,600	$24,200	$112,800
7.0	13.9	4,000	11,400	$24,900	$115,800
8.0	13.3	5,000	14,200	$30,500	$124,000

Horizontal Vessels
1st Quarter 1998 dollars

15 psig					
Diameter (Feet)	Length (Feet)	Capacity (Gallons)	Total Weight (Pounds)	Purchased Equipment Cost ($)	Installed Cost ($)
2.0	4.3	100	1,100	$5,700	$51,900
2.5	6.8	250	1,500	$7,400	$62,200
3.0	9.5	500	2,200	$8,900	$79,600
4.0	8.0	750	2,600	$10,200	$81,600
4.0	10.6	1,000	3,000	$11,200	$88,500
6.0	14.2	3,000	5,600	$17,500	$24,600
7.0	17.4	5,000	7,600	$21,800	$32,300
8.0	18.6	7,000	9,400	$24,800	$144,800
9.0	21.0	10,000	11,500	$29,500	$153,100
11.0	35.2	25,000	21,500	$40,100	$202,600
14.0	43.4	50,000	33,300	$58,200	$251,500
14.5	60.7	75,000	47,000	$76,400	$304,900
14.5	81.0	100,000	59,400	$94,800	$383,500

150 psig					
Diameter (Feet)	Length (Feet)	Capacity (Gallons)	Total Weight (Pounds)	Purchased Equipment Cost ($)	Installed Cost ($)
2.0	4.3	100	1,400	$6,300	$48,900
2.5	6.8	250	1,800	$8,000	$53,200
3.0	9.5	500	2,500	$9,700	$66,000
4.0	8.0	750	3,500	$12,000	$69,200
4.0	10.6	1,000	4,000	$13,100	$76,400
6.0	14.2	3,000	8,900	$23,500	$104,800
7.0	17.4	5,000	13,500	$32,100	$117,200
8.0	18.6	7,000	18,300	$39,900	$148,000
9.0	21.0	10,000	24,800	$51,800	$163,800
11.0	35.2	25,000	54,100	$90,300	$267,800
14.0	43.4	50,000	101,900	$160,400	$373,200
14.5	60.7	75,000	155,000	$230,300	$482,200
14.5	81.0	100,000	198,700	$285,700	$606,700

Storage Tanks
1st Quarter 1998 dollars

Diameter (Feet)	Height (Feet)	Total Weight (Pounds)	Capacity (Gallons)	Purchased Equipment Cost ($)	Installed Cost ($)
Floating Roof					
17.0	32.0	41,300	50,000	$118,000	$163,400
20.0	32.0	46,700	75,000	$128,200	$180,700
24.0	32.0	55,000	100,000	$143,200	$205,100
37.0	32.0	89,300	250,000	$197,700	$250,000
47.0	40.0	142,400	500,000	$267,800	$332,400
57.0	40.0	195,000	750,000	$335,700	$411,700
66.0	40.0	245,700	1,000,000	$396,600	$480,200
134.0	48.0	858,900	5,000,000	$1,061,200	$1,250,900
175.0	56.0	2,219,100	10,000,000	$2,273,000	$2,564,300
Cone Roof					
17.0	32.0	21,000	50,000	$42,400	$87,800
20.0	32.0	26,400	75,000	$48,900	$101,400
24.0	32.0	34,800	100,000	$59,200	$121,100
37.0	32.0	69,400	250,000	$98,600	$150,900
47.0	40.0	123,100	500,000	$157,800	$222,400
57.0	40.0	176,400	750,000	$214,800	$296,800
66.0	40.0	228,000	1,000,000	$266,100	$349,700
134.0	48.0	853,600	5,000,000	$864,300	$1,054,000
175.0	56.0	2,226,100	10,000,000	$2,040,700	$2,332,000

Valve Tray Columns
1st Quarter 1998 dollars

		15 psig		150 psig	
Diameter (ft)	**Number of Trays**	**Purchased Equipment Cost ($)**	**Installed Cost ($)**	**Purchased Equipment Cost ($)**	**Installed Cost ($)**
5	2	$30,600	$159,500	$35,200	$161,300
5	6	$42,300	$175,700	$50,000	$180,600
5	10	$49,000	$192,100	$57,300	$192,000
5	14	$56,100	$203,400	$67,300	$206,200
5	20	$69,700	$225,900	$84,700	$232,500
5	26	$82,300	$246,200	$95,800	$251,000
5	34	$99,800	$285,800	$118,500	$285,300
5	40	$115,200	$310,300	$134,500	$315,300
5	46	$132,000	$335,200	$145,000	$332,700
5	52	$164,900	$378,000	$185,200	$382,600
5	60	$204,900	$429,700	$226,000	$435,000
10	2	$62,500	$249,000	$89,600	$269,500
10	6	$88,400	$282,100	$122,800	$309,900
10	10	$109,700	$311,100	$151,800	$346,700
10	14	$128,600	$349,700	$180,700	$386,000
10	20	$160,400	$394,800	$220,900	$443,400
10	26	$188,500	$436,200	$254,200	$492,200
10	34	$233,600	$498,700	$312,500	$565,800
10	40	$263,800	$558,700	$356,300	$624,000
10	46	$297,100	$605,000	$391,300	$678,300
10	52	$343,000	$666,100	$450,000	$754,600
10	60	$388,400	$727,700	$501,900	$822,100
15	2	$119,900	$396,200	$221,500	$475,100
15	6	$171,000	$469,300	$293,000	$559,000
15	10	$225,700	$539,500	$364,500	$652,400
15	14	$262,500	$587,100	$425,800	$725,200
15	20	$332,400	$677,700	$522,400	$843,700
15	26	$387,000	$767,500	$600,200	$943,900
15	34	$473,900	$878,600	$722,100	$1,089,500
15	40	$538,600	$958,700	$808,900	$1,191,500
15	46	$620,900	$1,061,600	$907,000	$1,314,300
15	52	$689,200	$1,147,900	$997,700	$1,423,400
15	60	$786,500	$1,269,800	$1,145,800	$1,594,100
20	2	$174,900	$574,900	$402,000	$806,800
20	6	$247,900	$674,400	$517,300	$945,200
20	10	$359,400	$815,300	$605,100	$1,064,600
20	14	$421,000	$892,200	$715,700	$1,190,500
20	20	$508,000	$1,023,200	$857,000	$1,363,200
20	26	$585,300	$1,114,100	$993,600	$1,520,800
20	34	$726,300	$1,285,400	$1,203,000	$1,762,200
20	40	$834,300	$1,421,000	$1,347,900	$1,931,400
20	46	$952,800	$1,560,900	$1,526,400	$2,138,200
20	52	$1,051,100	$1,682,200	$1,669,100	$2,314,600
20	60	$1,195,500	$1,856,100	$1,892,600	$2,568,700

Sieve Tray Columns
1st Quarter 1998 dollars

			15 psig		150 psig	
Diameter (ft)	Number of Trays	Tangent/ Tangent Height	Purchased Equipment Cost ($)	Installed Cost ($)	Purchased Equipment Cost ($)	Installed Cost ($)
5	2	17	$30,000	$158,900	$34,700	$160,800
5	6	25	$41,200	$174,600	$48,900	$179,500
5	10	33	$47,500	$190,600	$55,800	$190,500
5	14	41	$54,200	$201,400	$65,400	$204,300
5	20	53	$67,400	$223,500	$82,300	$230,000
5	26	65	$79,500	$243,200	$93,000	$248,100
5	34	81	$96,300	$282,200	$115,000	$281,700
5	40	93	$111,000	$305,900	$130,300	$310,900
5	46	105	$126,800	$329,700	$140,200	$327,700
5	52	117	$159,500	$372,400	$179,800	$377,000
5	60	133	$203,300	$428,100	$218,900	$427,500
10	2	17	$60,600	$247,100	$87,700	$267,600
10	6	25	$84,600	$278,200	$119,000	$306,100
10	10	33	$104,500	$305,800	$146,500	$341,300
10	14	41	$122,100	$343,100	$174,200	$379,400
10	20	53	$152,300	$386,500	$212,800	$435,000
10	26	65	$178,900	$426,300	$244,700	$482,300
10	34	81	$221,100	$485,700	$300,000	$552,800
10	40	93	$248,400	$542,700	$341,500	$608,600
10	46	105	$280,200	$587,400	$374,400	$661,000
10	52	117	$324,600	$647,000	$430,900	$735,100
10	60	133	$366,300	$704,700	$479,800	$798,100
15	2	17	$115,900	$392,100	$217,600	$471,200
15	6	25	$163,200	$461,400	$285,200	$551,100
15	10	33	$214,900	$528,600	$353,700	$641,300
15	14	41	$249,100	$573,400	$412,300	$711,400
15	20	53	$315,600	$660,400	$505,600	$826,600
15	26	65	$367,100	$746,900	$580,400	$923,600
15	34	81	$446,800	$850,800	$696,200	$1,063,100
15	40	93	$509,300	$928,700	$778,400	$1,160,300
15	46	105	$585,800	$1,025,700	$871,800	$1,278,100
15	52	117	$645,700	$1,103,400	$958,000	$1,382,600
15	60	133	$739,400	$1,221,700	$1,100,000	$1,546,900
20	2	17	$168,200	$568,100	$395,400	$800,100
20	6	25	$234,600	$661,000	$504,000	$931,700
20	10	33	$341,200	$796,700	$586,800	$1,046,100
20	14	41	$398,500	$869,100	$693,100	$1,167,600
20	20	53	$479,700	$994,300	$828,800	$1,334,500
20	26	65	$551,900	$1,080,000	$960,300	$1,486,500
20	34	81	$681,100	$1,239,200	$1,159,400	$1,717,400
20	40	93	$781,300	$1,365,200	$1,296,600	$1,876,900
20	46	105	$892,200	$1,498,500	$1,467,400	$2,075,600
20	52	117	$988,200	$1,624,000	$1,602,400	$2,246,100
20	60	133	$1,120,200	$1,778,700	$1,815,600	$2,489,600

Packed Columns
1st Quarter 1998 dollars

				15 psig		150 psig	
Diameter (Feet)	Tangent/ Tangent Height (Feet)	Packed Height (Feet)	Number of Sections	Purchased Equipment Cost ($)	Installed Cost ($)	Purchased Equipment Cost ($)	Installed Cost ($)
1	10	8	1	$6,700	$64,000	$6,600	$62,000
1	20	18	3	$8,700	$73,400	$9,000	$67,800
1.5	10	8	1	$10,300	$75,500	$11,300	$69,800
1.5	20	18	2	$13,900	$83,000	$15,400	$77,600
1.5	30	28	3	$16,600	$89,700	$18,700	$84,800
2	10	8	1	$12,900	$82,800	$13,900	$76,500
2	20	18	2	$16,900	$90,900	$18,500	$85,000
2	30	28	2	$18,600	$97,000	$20,100	$90,900
2	40	38	3	$21,500	$105,500	$23,600	$101,400
2.5	10	8	1	$14,700	$92,200	$15,400	$82,400
2.5	20	18	1	$16,700	$98,700	$17,600	$89,000
2.5	30	28	2	$22,400	$112,000	$23,800	$104,200
2.5	40	38	2	$23,200	$116,000	$24,600	$108,000
2.5	50	48	3	$30,000	$127,800	$31,800	$119,800
3	10	8	1	$16,200	$98,700	$17,200	$89,400
3	20	18	1	$21,900	$110,800	$23,500	$101,900
3	30	28	2	$24,300	$119,700	$25,900	$112,100
3	40	38	2	$26,500	$125,300	$29,200	$118,500
3	50	48	3	$31,200	$135,400	$34,700	$129,500
3	60	58	3	$35,400	$147,400	$37,500	$135,900
3.5	10	8	1	$20,600	$112,300	$23,100	$100,000
3.5	20	18	1	$26,400	$125,000	$30,600	$118,200
3.5	30	28	2	$30,400	$135,800	$35,000	$126,300
3.5	40	38	2	$31,500	$140,800	$36,300	$131,300
3.5	50	48	3	$38,700	$157,600	$45,000	$145,700
3.5	60	58	3	$43,400	$166,600	$48,000	$152,500
3.5	70	68	4	$48,400	$178,500	$57,600	$168,000

Shell and Tube Heat Exchangers
1st Quarter 1998 dollars

Surface Area, (Square feet)	Purchased Equipment Cost ($)	Installed Cost ($)
100	$13,200	$48,300
200	$13,600	$55,800
300	$14,500	$57,300
400	$16,100	$59,100
500	$16,200	$68,000
600	$16,600	$68,400
700	$18,000	$70,000
800	$18,400	$70,400
900	$20,300	$72,600
1000	$20,800	$73,100
2000	$31,900	$95,800
3000	$44,700	$109,600
4000	$53,900	$132,900
5000	$62,100	$141,800
6000	$70,800	$151,100
7000	$99,600	$203,500
8000	$107,900	$212,400
9000	$117,100	$222,100
10000	$124,200	$229,800
15000	$186,300	$321,500
20000	$248,400	$427,000
30000	$354,000	$573,900
40000	$479,100	$767,500
50000	$582,500	$953,000
60000	$708,300	$1,106,600
70000	$839,000	$1,425,600

Air Cooler
1st Quarter 1998 dollars

Surface Area, (Square feet)	Purchased Equipment Cost ($)	Installed Cost ($)
100	$21,300	$47,600
200	$24,100	$51,800
300	$26,100	$54,800
400	$29,100	$58,100
500	$30,900	$59,900
600	$33,000	$62,000
700	$36,000	$65,300
800	$38,100	$67,400
900	$40,300	$69,900
1,000	$42,000	$71,600
2,000	$60,800	$94,100
4,000	$96,900	$144,700
6,000	$135,400	$184,700
8,000	$179,100	$239,000
10,000	$217,300	$278,200

Spiral Plate Heat Exchanger
1st Quarter 1998 dollars

Heat Transfer Area, (Square feet)	Purchased Equipment Cost ($)	Installed Cost ($)
40	$6,700	$19,200
100	$9,100	$25,100
200	$13,200	$34,000
300	$21,100	$49,400
400	$25,500	$57,400
500	$29,900	$65,000
600	$34,400	$72,400
700	$42,600	$85,300
800	$35,500	$74,200
900	$40,000	$81,300
1,000	$44,700	$88,500
1,100	$49,600	$95,700
1,200	$54,700	$102,900
1,300	$60,100	$110,400

Furnace
1st Quarter 1998 dollars

Heat Duty (MMBTU per hour)	Purchased Equipment Cost ($)	Installed Cost ($)
2	$124,600	$96,300
10	$263,100	$355,100
25	$399,000	$518,600
50	$625,400	$771,100
100	$1,081,500	$1,272,800
200	$1,868,900	$2,641,500
300	$2,573,100	$3,534,400
400	$3,228,000	$4,354,800
500	$3,848,400	$5,126,000

Cooling Tower
1st Quarter 1998 dollars

Water Rate (Gallons/ minute)	Purchased Equipment Cost ($)	Installed Cost ($)
150	$4,000	$60,200
300	$6,500	$65,000
600	$11,400	$70,500
1,000	$18,000	$81,700
2,000	$34,400	$106,100
3,000	$50,900	$134,200
4,000	$67,100	$158,800
5,000	$83,200	$180,400
6,000	$99,200	$211,100

Package Steam Boiler
1st Quarter 1998 dollars

Capacity (Pound per hour)	Purchased Equipment Cost ($)	Installed Cost ($)
10,000	$91,700	$283,100
25,000	$148,100	$368,900
50,000	$212,700	$468,900
100,000	$305,700	$607,300
150,000	$439,400	$783,600
200,000	$568,400	$920,600
250,000	$694,000	$1,109,100
300,000	$816,900	$1,238,600

Evaporator
1st Quarter 1998 dollars

	Vertical Tube		Horizontal Tube	
Area (Square feet)	Purchased Equipment Cost ($)	Installed Cost ($)	Purchased Equipment Cost ($)	Installed Cost ($)
100	$62,600	$120,800	$34,500	$73,300
500	$151,600	$273,500	$81,100	$161,300
1,000	$221,900	$388,400	$117,100	$226,300
2,000	$324,700	$555,200	$169,000	$317,100
3,000	$405,700	$689,100	$209,500	$386,300
4,000	$475,200	$803,300	$244,100	$444,300
5,000	$537,100	$904,700	$274,400	$496,800
6,000	$593,700	$997,000	$302,600	$545,600
7,000			$328,300	$590,500
8,000			$352,400	$632,400
9,000			$375,100	$671,900
10,000			$396,600	$709,200

Crusher
1st Quarter 1998 dollars

Diameter (Inches)	Driver Power (Horsepower)	Purchased Equipment Cost ($)	Installed Cost ($)
Gyratory Crusher			
20	40	$29,300	$52,400
40	150	$253,600	$294,400
60	350	$698,200	$787,200
80	600	$1,400,900	$1,553,600
100	900	$2,415,500	$2,666,100
120	1250	$3,778,800	$4,171,200
Rotary Crusher			
	2	$2,300	$5,200
	4	$3,700	$6,800
	8	$6,100	$9,500
	12	$8,100	$11,800
	16	$9,900	$13,900
	20	$11,600	$15,800
	25	$13,600	$18,100
Ring Granulator			
	75	$23,400	$28,100
	125	$50,700	$58,000
	250	$75,900	$85,900
	600	$197,400	$218,700
	1000	$303,300	$335,600
	1250	$346,400	$382,200

Mill
1st Quarter 1998 dollars

Diameter/ Length (Inches)	Driver Power (Horsepower)	Purchased Equipment Cost ($)	Installed Cost ($)
Ball Mill			
3/3	7.5	$25,100	$62,900
4/4	20	$57,500	$97,900
5/5	50	$109,100	$153,500
6/6	100	$182,900	$234,400
	200	$255,600	$311,700
	300	$411,300	$478,500
	400	$492,200	$573,100
	450	$585,200	$673,100
Roller Mill			
	30	$61,400	$76,900
	75	$107,500	$131,100
	150	$164,200	$197,000
	200	$195,800	$233,100
	250	$224,400	$265,800
	300	$250,900	$296,100
	350	$275,700	$324,400
	400	$299,100	$351,000

Dryers
1st Quarter 1998 dollars

Area (Square feet)	Driver Power (Horsepower)	Purchased Equipment Cost ($)	Installed Cost ($)
Direct Contact Rotary Dryer			
100		$26,500	$42,400
400		$99,500	$142,800
800		$192,700	$264,800
1200		$283,600	$380,800
1600		$373,100	$493,400
2000		$461,500	$603,500
Single Atmospheric Drum Dryer			
10	5	$53,900	$73,800
40	10	$125,800	$162,900
80	15	$192,300	$243,800
120	20	$246,500	$309,100
160	20	$293,900	$365,900
200	25	$337,100	$417,400
Atmospheric Tray Batch Dryer			
30		$6,400	$10,900
60		$8,400	$13,900
90		$9,800	$16,000
120		$10,900	$17,700
150		$11,900	$19,200
180		$12,800	$20,500
200		$13,300	$21,300

Centrifuge
1st Quarter 1998 dollars

Screen Diameter (Inches)	Driver Power (Horsepower)	Purchased Equipment Cost ($)	Installed Cost ($)
Batch Bottom-Suspended Filtering Centrifuge			
20	1.5	$10,100	$21,500
25	2	$11,900	$23,500
30	3	$13,600	$25,500
35	5	$15,300	$27,400
40	7.5	$16,900	$29,300
45	10	$18,400	$31,100
48	10	$19,300	$32,200
Batch Top-Suspended Filtering Centrifuge			
20	1.5	$12,000	$23,400
25	2	$16,000	$27,700
30	3	$20,200	$32,300
35	5	$24,700	$37,100
40	7.5	$29,300	$42,100
45	10	$34,100	$47,300
50	15	$39,100	$52,800
Continuous Filtration Vibratory Centrifuge			
48	30	$58,600	$91,900
50	40	$66,700	$100,900
52	50	$75,500	$113,000
54	60	$85,000	$124,000
56	75	$95,400	$135,800
Reciprocating Conveyor, w/Continuous Filtering Centrifuge			
15		$112,900	$140,500
25		$175,200	$213,200
35		$246,100	$295,100
45		$317,200	$376,200
50		$352,900	$416,800

Filter
1st Quarter 1998 dollars

Flow Rate (Gallons per minute)	Frame Capacity (Cubic feet)	Surface Area (Square feet)	Purchased Equipment Cost ($)	Installed Cost ($)
Cartridge Filter				
30			$1,100	$5,200
100			$1,700	$6,800
300			$2,400	$8,300
600			$4,200	$10,300
900			$5,800	$13,500
1200			$7,300	$15,200
Automatic Plate and Frame				
	10		$100,200	$145,500
	20		$114,200	$160,400
	30		$123,300	$170,100
	40		$130,200	$177,500
	50		$135,900	$183,600
Tubular Fabric Filter				
100			$5,500	$13,000
500			$15,700	$27,100
1000			$24,700	$39,900
1500			$32,200	$51,200
2000			$38,800	$59,500
2500			$44,900	$69,200
3000			$50,600	$76,400
3400			$54,900	$81,700
Drum Filter				
		100	$63,400	$104,200
		250	$87,700	$134,400
		500	$120,200	$175,400
		750	$145,000	$205,200
		1000	$168,900	$237,400
		1500	$192,900	$275,700
		2000	$208,300	$298,900

Agitators
1st Quarter 1998 dollars

Driver Power (Horsepower)	Purchased Equipment Cost ($)	Installed Cost ($)
2	$7,700	$9,500
10	$13,900	$15,900
25	$19,500	$21,600
50	$35,400	$37,700
75	$50,200	$52,700
100	$64,300	$67,000

Rotary Pump
1st Quarter 1998 dollars

Capacity (Gallons/ minute)	Purchased Equipment Cost ($)	Installed Cost ($)
10	$1,500	$9,000
50	$2,100	$10,900
100	$2,400	$12,600
150	$3,000	$13,200
200	$3,400	$13,700
250	$4,100	$16,000
300	$4,400	$16,300
400	$5,300	$17,300
500	$7,000	$19,200
600	$8,700	$21,000
700	$10,700	$25,700
750	$11,600	$26,600

Inline Pump
1st Quarter 1998 dollars

Capacity (Gallons/ minute)	Purchased Equipment Cost ($)	Installed Cost ($)
10	$1,500	$9,000
50	$2,100	$10,900
100	$2,400	$12,600
150	$3,000	$13,200
200	$3,400	$13,700
250	$4,100	$16,000
300	$4,400	$16,300
400	$5,300	$17,300
500	$7,000	$19,200
600	$8,700	$21,000
700	$10,700	$25,700
750	$11,600	$26,600

Centrifugal Pump
1st Quarter 1998 dollars

Capacity (Gallons/ minute)	Purchased Equipment Cost ($)	Installed Cost ($)
100	$3,400	$22,800
200	$4,100	$23,800
300	$4,700	$27,700
400	$5,300	$28,500
500	$5,800	$29,000
1,000	$8,700	$37,500
2,000	$10,200	$44,800
3,000	$15,200	$58,100
4,000	$19,500	$72,300
5,000	$23,800	$77,100
6,000	$28,400	$93,400
7,000	$37,800	$103,000
8,000	$41,300	$119,700
9,000	$47,300	$126,200
10,000	$51,200	$144,800

Reciprocating Pump
1st Quarter 1998 dollars

Capacity (Gallons/ minute)	Driver Power (Horse-power)	Duplex Purchased Equipment Cost ($)	Installed Cost ($)	Triplex Purchased Equipment Cost ($)	Installed Cost ($)
25	2	$4,100	$10,600	$7,700	$15,500
50	5	$7,000	$14,600	$13,800	$22,700
100	7.5	$8,800	$17,800	$17,900	$28,200
200	15	$13,100	$22,500	$27,900	$38,600
300	25	$17,600	$28,800	$38,700	$51,200
400	30	$19,600	$31,000	$43,500	$56,200
500	40	$23,100	$34,700	$52,300	$65,300
600	50	$26,300	$38,100	$60,300	$73,400
700	60	$29,200	$43,700	$67,800	$83,700
800	60	$29,200	$43,700	$67,800	$83,800
900	75	$33,300	$48,100	$78,200	$94,500
1,000	75	$33,300	$48,200	$78,200	$94,500

Vacuum Pump
1st Quarter 1998 dollars

Capacity (Gallons/ minute)	Stages	Purchased Equipment Cost ($)	Installed Cost ($)
30	1	$4,100	$18,600
75	1	$6,400	$21,100
150	1	$8,900	$24,000
200	1	$11,500	$26,900
300	1	$16,200	$32,300
400	1	$20,800	$37,100
500	1	$25,200	$41,800
600	1	$29,500	$46,300
700	1	$33,700	$50,800
30	2	$6,100	$20,600
75	2	$8,500	$23,200
150	2	$11,000	$26,100
200	2	$13,600	$29,000
300	2	$18,500	$34,600
400	2	$22,900	$39,200
500	2	$27,100	$43,700
600	2	$31,000	$47,800
700	2	$34,800	$51,900

Reciprocating Compressor
1st Quarter 1998 dollars

Stages	Actual Capacity (Cubic feet/ minute)	Driver Power (Horsepower)	Purchased Equipment Cost ($)	Installed Cost ($)
1	250	40	$186,200	$245,500
1	500	75	$233,700	$300,300
1	1,000	125	$301,700	$380,400
1	5,000	600	$589,600	$717,500
1	10,000	1,250	$810,400	$970,700
1	25,000	3,000	$1,891,500	$2,139,000
1	50,000	5,500	$4,024,800	$4,469,700
1	60,000	7,000	$4,837,400	$5,354,000
3	250	100	$297,000	$358,800
3	500	150	$355,400	$422,200
3	1,000	300	$431,400	$509,700
3	5,000	1,500	$822,400	$932,300
3	10,000	3,000	$1,489,700	$1,646,100
3	25,000	7,000	$3,794,300	$4,135,200
3	35,000	10,000	$5,519,000	$6,038,600
3	250	800	$389,400	$467,200
3	500	1,500	$534,100	$627,400
3	1,000	3,000	$1,080,700	$1,211,500
3	5,000	15,000	$3,750,700	$4,211,800
3	7,000	22,500	$4,712,700	$5,317,700

Centrifugal Compressor
1st Quarter 1998 dollars

Stages	Actual Capacity (Cubic feet/ minute)	Driver Power (Horsepower)	Purchased Equipment Cost ($)	Installed Cost ($)
4	500	60	$595,400	$702,700
4	1,000	125	$626,400	$749,300
4	5,000	600	$719,700	$907,100
4	10,000	1,250	$1,114,800	$1,339,000
4	50,000	6,000	$2,699,800	$3,247,700
4	100,000	12,000	$5,275,800	$6,142,000
4	150,000	17,000	$8,722,600	$9,735,100
4	200,000	25,000	$9,627,600	$10,980,400
9	500	125	$975,600	$1,066,700
9	1,000	250	$1,011,200	$1,118,500
9	5,000	1,250	$1,146,600	$1,286,000
9	10,000	2,500	$1,889,300	$2,060,500
8	50,000	12,000	$4,821,600	$5,356,700
8	100,000	25,000	$12,444,800	$13,267,000
7	150,000	37,500	$18,991,500	$19,966,000
7	200,000	50,000	$19,394,300	$20,624,400
9	500	1,750	$1,446,400	$1,548,200
9	1,000	3,500	$1,560,500	$1,680,300
9	5,000	16,000	$2,258,600	$2,527,000
9	10,000	32,500	$4,053,700	$4,467,800
9	15,000	50,000	$5,171,000	$5,718,400

Centrifugal Fan
1st Quarter 1998 dollars

Actual Capacity (Gallons/ minute)	Purchased Equipment Cost ($)	Installed Cost ($)
700	$1,100	$7,000
1,500	$1,100	$7,400
5,000	$1,800	$9,800
10,000	$2,500	$13,100
25,000	$6,700	$27,900
50,000	$13,300	$49,900
75,000	$19,900	$64,900
100,000	$31,400	$93,400
150,000	$44,600	$126,500

Rotary Blower
1st Quarter 1998 dollars

Actual Capacity (Gallons/ minute)	Purchased Equipment Cost ($)	Installed Cost ($)
100	$4,800	$11,500
500	$10,400	$19,100
1,000	$15,000	$24,900
2,000	$22,000	$34,800
3,000	$28,100	$44,400
4,000	$36,700	$54,600

Gas Turbine
1st Quarter 1998 dollars

Power Output (Horsepower)	Purchased Equipment Cost ($)	Installed Cost ($)
1,000	$476,200	$565,200
5,000	$1,254,100	$1,376,400
10,000	$1,903,000	$2,051,300
50,000	$9,639,300	$9,975,400
100,000	$16,148,100	$16,738,600
150,000	$21,837,300	$22,659,400
200,000	$27,052,000	$28,056,000
250,000	$31,940,100	$33,192,400
300,000	$36,583,000	$37,998,000
350,000	$41,031,000	$42,609,000
370,000	$42,764,000	$44,407,000

Steam Turbine
1st Quarter 1998 dollars

Power Output (Horsepower)	Purchased Equipment Cost ($)	Installed Cost ($)
10	$19,100	$36,000
50	$25,200	$46,500
100	$28,500	$53,600
500	$37,700	$108,800
950	$42,100	$126,700
1,000	$85,000	$169,800
2,500	$269,000	$364,400
5,000	$575,000	$688,000
7,500	$781,400	$907,900
10,000	$971,400	$1,106,600
15,000	$1,320,100	$1,477,100
20,000	$1,641,100	$1,825,200
30,000	$2,230,200	$2,447,300