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Calculation of Flows for HB Line Eductor Systems

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Abstract
An Excel spreadsheet calculation was set up to model the HB-Line Phase II Eductor Systems. Two eductors are used for Phase II processing. One is in the Column Line and is used to pump the contents of the Recycle Tanks to H Canyon. The other is in the Mechanical Line and is used to pump the contents of the Filtrate Tanks to H Canyon. The eductors serve the functions of both pumping and diluting product bearing solutions. Dilution must be reliably controlled because of criticality concerns with H Canyon Tanks. The results of the nominal calculation and measurements for Filtrate transfers exhibited fair agreement. For Recycle transfers, agreement was poor.

An uncertainty analysis was performed to determine if uncertainties such as manufacturing tolerances could explain the discrepancies between measured and calculated values. These uncertainties could explain some, but not all, of the discrepancies. Numerical experiments were conducted to investigate possible causes for the disagreement. Adding or subtracting resistances to the lines did not create satisfactory agreement. However, two other mechanisms showed the potential to eliminate the disagreement. The first possible mechanism was if the nozzle in the eductor was oversized. The discrepancies could be eliminated if the Filtrate Eductor nozzle was 10% oversized or if the Recycle Eductor nozzle was 50% oversized. The second possible mechanism was if valves leaked. For Filtrate transfers, the measurements were consistent with a small leak of eductant through both valve 2684HV and valve 2227HV. For Recycle transfers, the measurements were consistent with a large leak of eductant through both valve 2683HV and valve 2608HV. It is recommended that the possibility of a large leak during Recycle transfers be checked by temporarily blanking off valve 2683HV and then observing whether the dilution ratio changes significantly.

Failure of Line 104 to break a siphon during a transfer to Tank 8.8 was also examined. If Line 104 became plugged, the resulting siphon would continue at a flowrate of 1.87 gpm (7.1 L/m) after the Partition Pump was de-energized until the contents of the Filtrate Tank or the Recycle Tank were exhausted.

General Description of Hardware
The Partition Pump pumps eductant, the motive fluid, at 45 feet of head to the high pressure inlet of one of two 1/2" Schutte and Koerting eductors. The suction connection of one eductor is connected to the Recycle Tanks and the suction connection of the other eductor is connected to the Filtrate Tanks. The discharge of each eductor contains a mixture of eductant and either the contents of the Filtrate Tank or Recycle Tank. The discharge is generally sent to Tank 8.8. Another calculation was previously performed for the Phase I Eductor System [Steimke, 1998].

Eductor Equations
Figure 1 shows a cutaway view of the eductor. A high velocity jet of eductant flows out of the nozzle, entraining flow from the suction connection. Table 1 lists manufacturer's test data taken from a handbook [Karassik, 1976] for a Schutte and Koerting 1" eductor for water pumping water. The manufacturer stated that ½" eductors, which are used in

Phase II, have flows that are 36% as large as for a 1" eductor. Define a capacity factor, C_f, as that percentage. The manufacturer listed performance data for eductant pressures up to 100 psig. However, the highest eductant pressure of interest for the present work is 40 psig. Therefore, only data for eductant pressures of 10, 20, 30 and 40 psig were used to prepare a correlation for eductor performance. Eductant flows through a nozzle from the operating pressure to the suction pressure. Suction lift in feet of water is converted to suction pressure with the conversion factor of 0.433 psi per foot of water. Figure 2 shows that the difference in pressure is related to the eductant flow squared and is correlated by the following equation.

$$\Delta P_{noz} = P_{op} - P_{suc} = P_{op} + 0.433\ H = 0.81\ (F_{educ})^2 \qquad (1)$$

Equation 1 is valid for a 1" eductor where pressures are in psig, H is suction head in feet and flow is in gpm of water. The manufacturer states that the nozzle pressure difference is proportional to eductant specific gravity, S. This allows a generalization of equation 1.

$$P_{op} - P_{suc} = 0.81\ S\ (F_{educ}/C_f)^2 \qquad (2)$$

The eductor generates a pressure gain. The eductor pressure gain is defined as the discharge pressure plus the suction head converted to pressure

$$\Delta P_e = P_{dis} + 0.433\ H \qquad (3)$$

where ΔP_e, P_{dis} and H have units of psid, psig and feet, respectively. The eductor pressure gain was correlated with the following equation.

$$\frac{\Delta P_{educ} + C_{educ} P_{suc}}{P_{op}} = 0.326 - 0.0347 F_{suc} \qquad (4)$$

Trial and error was used to determine the constant C_{educ}. The best fit was for C_{educ} equal to -0.39 and R-squared was equal to 0.897. Figure 3 shows a plot of the left hand side of equation 4 versus F_{suc} in gpm. Equation 4 was rearranged to give an expression for ΔP_{educ}.

$$\Delta P_{educ} = P_{op}(0.326 - 0.0347 F_{suc}) + 0.39 P_{suc} \qquad (5)$$

Equations for Associated Piping

The equation for pressure drop for single-phase flow in a pipe is given below (Crane, 1988).

$$\Delta P = \rho g \Delta h + \left(\frac{Lf}{D} + \sum_{i=1}^{n} K_i\right)\frac{\rho V^2}{2} \qquad (6)$$

The terms ρ, g, Δh, L, f, D, K_i, V are fluid density, acceleration of gravity, elevation change, pipe length, friction factor, inside diameter of the pipe, resistance coefficient for the i-th component and fluid velocity, respectively. The friction factor is computed using the following equation [Jain, 1976].

$$f = \left[1.14 - 2\log_{10}\left(\frac{\varepsilon}{D} + \frac{21.25}{Re^{0.9}}\right)\right]^{-2} \qquad (7)$$

The terms ε and Re are the roughness of the pipe and Reynolds number, respectively. Roughness was taken from the Crane manual. Tubing has a roughness of 0.00006". Pipe has a roughness of 0.0018". Equation 7 is valid for turbulent Reynolds numbers up to 1,000,000. The maximum Reynolds number of interest in the present work is 100,000. The equation for the Reynolds number follows where the term μ is viscosity.

$$Re = \frac{V D \rho}{\mu} \quad (8)$$

The following resistance factors in Table 2 [Crane, 1988] were used for pipe components where β is the ratio of the smaller diameter to the larger diameter for an orifice plate, sudden expansion or sudden contraction. The equation for resistance factor for an orifice plate is from Blevins [1984] as well as tabular data for the orifice discharge coefficient, C, and the dimensionless coefficient, ζ. The strainer between the Partition Tank and the Partition Pump consists of 100 mesh wire screen. The equation for frictional loss for a wire screen is from Perry, et al [1984]. The screen discharge coefficient, C_s, is about 1.1 for the Reynolds numbers of interest and the fractional openness of the wire mesh, α, was estimated to be 0.5. Resistance factors for sudden expansions or sudden contractions were taken from Blevins [1984]. The areas A_1 and A_2 are located before and after the sudden expansion or contraction.

Table 2 Hydraulic Resistance Factors

Component	K
pipe inlet	0.78
standard 90° elbow	30 f
standard tee, flow through run	20 f
standard tee, flow through branch	60 f
welded miter joint, 90°	60 f
pipe bend 90°, r/D = 1.5	14 f
pipe bend 90°, r/D = 2	12 f
pipe bend 90°, r/D = 3	12 f
orifice plate	$\frac{\zeta}{C^2} \frac{1}{\beta^2} [1 - \beta^4]$
wire screen	$\frac{1-\alpha^2}{C_s^2 \alpha^2}$
abrupt contraction	$0.5 \frac{1-\beta^2}{\beta^4}$
abrupt expansion	$\frac{(1-\beta^2)^2}{\beta^4}$

Generally for solution transfers the molarity of the eductant or plutonium solution was recorded but not the specific gravity. Therefore, a capability was needed to convert molarity to specific gravity. Data for the specific gravities, S, of solutions of nitric acid with a range of molarities were found in Perry, et al., [1984] and fit with the following polynomial as shown in Figure 4.

$$S = 1.00 + 0.0315\,M \qquad (9)$$

The viscosities of the eductant and plutonium solution were not measured for the plutonium solution or the eductant. For the purpose of estimating viscosity the fluid was assumed to be an aqueous solution of nitric acid. Data for viscosities of solutions of nitric acid with a range of specific gravities were found in Perry, et al. [1984] and fit with the following polynomial as shown in Figure 4 where viscosity is in units of cp.

$$\mu = 1.00 + 0.0137\,M + 0.0072\,M^3 \qquad (10)$$

Piping Codes

Document 15060-01-R lists piping codes, which appear on drawings. Code P61 refers to Schedule 40 pipe in sizes ranging from ½" to 6". Code P138 refers to tubing sizes ranging from 1/4" to 1" with a wall thickness of 0.049". The minimum radii of curvature for bends in ½", ¾" and 1" tubing are 9/16", 15/16" and 1.25", respectively.

Piping from Filtrate Tanks to Filtrate Eductor

Drawing W717648 shows that the Filtrate Tanks (NT-51 and NT-52 aka H364-120-3 and H364-120-4) are on the Fifth Level, which has a floor elevation of 359' 10". The top and bottom of the tank are at elevations of 3'4" and 1.03' above the floor and there are suction tubes suspended from the tops of the tanks. Both tubes have an inlet with a K factor equal to 0.78. All of the tubing from the Filtrate Tank to the eductor is ½" with a wall thickness of 0.049" and a flow diameter of 0.402". Each suction tube (Lines 338 and 321) passes through a valve (2505HV and 2475HV) and then they tee together to form Line 338. This calculation will assume that the valves are ball valves with no reduction in flow area. Drawings W719123 and W719124 show ten smooth bends and a bend radius specification of 1.25". Using the scale on drawing W719124, there are 11.4 feet of tubing. Line 338 continues on drawing W723144, which indicates 22.3 feet of tubing. All tubing bends on that drawing appear to be very gentle so no losses were assumed at the bends. The line continues on drawings W720034 and W717380, which indicate 5.6' of tubing, six bends, a set of flanges and the ½" eductor. On the drawing, flange 2612F was specified to contain an orifice plate with a 0.181" orifice, however, J. W. Posnick stated that the plate was not installed. Therefore, no loss was included for the flanges. In summary, Line 338 contains one pipe inlet and a total of 16 bends and one tee with a flow through the branch for a total $K = 0.78 + 16*12\,f + 60\,f = 0.78 + 252\,f$. The total length is 39.3'.

The line from the Filtrate Tanks to the eductor includes a change in elevation. The Filtrate Eductor is located 5' 1" above the Fifth Level. Therefore, the elevation increase going from the bottom of the Filtrate Tanks to the eductor is 5.08' – 1.03' = 4.05'. This is offset by the height of liquid in the Filtrate Tank. The total height of the tank is 3.33' – 1.03' = 2.3'. After defining a fractional tank fullness W, the elevation increase from the surface of the Filtrate Tanks to the Filtrate Eductor, expressed in feet, is 4.05 – 2.3 W. For the basic calculation, tank fullness was set equal to 0.5.

Piping from Partition Tank to Filtrate Eductor

The Partition Tank is the source of eductant to the eductor. Drawing W718118 shows that the Partition Tank, H368-130-15 is connected with 1" pipe (Line 519) including one bend to the eductant pump, H368-130-15, which is described in BPF 213667. The frictional loss in the relatively short 1" line was ignored but the elevation change was included. The pump curve shows the head is 46 feet for zero flow and 44 feet for 10 gpm. The pump discharge is a ¾" flange connected to ¾" pipe (Line 526) which contains five bends and a 100 mesh "y" strainer. The K value for the strainer was evaluated to be 2.5. Tees branch to either valve 2684HV and Line CF 531, which goes to the Recycle Eductor, or valve 2683HV and Line CF 530, which goes to the Filtrate Eductor. The lines transition from ¾" pipe to ½" pipe just downstream of the two valves. The total length of ¾" pipe is 15'.

The pump and Partition Tanks are located on the Sixth Level, which is at an elevation of 378' 8" as shown on drawing W715401. The Partition Tanks are 17' from the north wall and 33' from the west wall of Phase I. The Filtrate Eductor is 12' on the other side of the north wall and 41' from the west wall. The sum of the changes in the north, west and vertical directions is 56'. Including an additional 20% for less than optimal piping placement gives an estimated pipe length of 67'. The liquid level is estimated to be 3" above the floor of the Sixth Level and the eductor is located 5' 1" above the floor of the Fifth Level. Therefore, there is an elevation decrease of 16' 9" for this piping section. Drawing W720034 shows one bend and one 90° miter joint in the ½" pipe. Estimate an additional three bends at other locations in the ½" pipe.

Piping from Filtrate Eductor to Tank 8.8

According to Drawing W720034 the mixed effluent from the filtrate eductor flows through ½" tubing through Line 416, a tee, Line 417, valve 2608HV and to a ½" to ¾" tubing transition. This section of tubing is 5.0' long and includes six bends and one straight run tee and has almost no elevation change. After Line 417 transitions to ¾" tubing there is 6.1' of tubing including five bends and an elevation increase of 2.5'. Drawing W720034 shows that Line 417 transitions to 1" pipe near the top of the Filtration Glovebox, 91" above the Fifth Floor. Drawing W717380 shows that Line 417 tees into Line 129 (1" pipe) above the glovebox and about 9' above the floor. Drawing W722230 shows that Line 129 tees into Line 104 (1" tubing) above the Fifth Level floor. According to drawing W726000 Line 104 goes generally downward through Line 253 and Line 254 and into Tank 8.8 on the Fourth Level Floor. That floor has an elevation of 339' 6.5". According to J. W. Posnick Line 104 is vented. Therefore, the piping from Line 104 to Tank 8.8 should have no hydraulic effect on flow in the piping that precedes it. Lines 417 and 129 together contain two branch tees and an estimated five bends. The section of 1" pipe starts 91" above the floor, rises to 9' and drops to floor level where it is vented for an overall elevation decrease of 7.6'. Using the drawing and assuming that Line 104 passes through the floor opening east of the filtrate tanks the estimated length of Line 129 is 56'. If the velocities in the last 9' of line 129 were low enough it would be possible for air to enter the vented end. A typical flow and velocity in that pipe are 4 gpm and 1.5 ft/sec. According to Wallis [1969] the rise velocity in slug flow for gas bubbles in liquid is given by the following equation.

$$V_s = 0.345\,(g\,D)^{0.5} \qquad (11)$$

This equation predicts a bubble rise velocity of 0.58 ft/sec. Since this is much less than the downward liquid velocity, air is not expected to enter the vented end of the pipe.

Piping from Recycle Tanks to Recycle Eductor
Drawing W719125 shows that the Recycle Tanks (NT-31 and NT-32 aka 362-110-4 and 362-110-5) are on the Fifth Level, which has a floor elevation of 359' 10". The top and bottom of the tanks are at elevations of 3' 5.75" and 9" above the floor and there are suction tubes suspended from the tops of the tanks. All of the tubing from the filtrate tank to the eductor is ½" with a wall thickness is 0.049" and a flow diameter of 0.402". Each suction tube (Lines 161 and 180) passes through a valve (2276HV and another valve not numbered on drawing W719125) and then they tee together to form Line 161. This calculation will assume that the valves are ball valves with no reduction in flow area. Drawing W719125 shows six smooth bends and a bend radius specification of 1.25". Using the scale on drawing W719125, there are 12.9 feet of tubing. Line 161 continues on drawing W719557, which indicates 17.8 feet of tubing. All tubing bends on drawing W719557 appear to be very gentle so no losses were assumed at the bends. Line 161 continues on W719077 for 9.8 feet. Line 161 continues on drawings W719142 and W719141, which indicate 9.9' of tubing and two large radius 45° bends. Line 161 continues on drawings W718899 and W718900, which indicate 6.2' of tubing and one 90° bend. Line 161 continues on drawing W743422 which indicates 6.8' of tubing, four bends, a set of flanges and the ½" eductor. On the drawing flange 2235F was specified to contain an orifice plate with a 0.181" orifice, however, J. W. Posnick stated that the plate was not installed. Therefore, no loss was included for the flanges. In summary, Line 161 from the Recycle Tanks to the Recycle Eductor contains one inlet, a total of 11 90° bends and one tee with a flow through the branch for a total $K = 0.78 + 16 * 12\ f + 60\ f$ and a total length of 63.4'.

The line from the Recycle Tanks to the eductor includes a change in elevation. The Recycle eductor is located 3' 2" above the floor of the Fifth Level. Therefore, the elevation increase going from the bottom of the Recycle Tanks to the eductor is 3.17' – 0.76' = 2.41'. This is offset by the height of liquid in the Recycle Tank. The total height of the tank is 3.5' – 0.76' = 2.74'. After defining a fractional tank fullness W, the elevation increase from the surface of the Recycle Tanks to the Recycle Eductor, expressed in feet, is 2.41 – 2.74 W.

Piping from Partition Tank to Recycle Eductor
The Partition Tank is the source of eductant to the eductor. Drawing W718118 shows that the Partition Tank, H368-130-15 is connected with 1" pipe (Line 519) including one bend to the eductant pump, H368-130-15, which is described in BPF 213667. The frictional loss in the relatively short 1" line was ignored but the elevation change was included. The pump curve shows the head is 46 feet for zero flow and 44 feet for 10 gpm. The pump discharge is a ¾" flange connected to ¾" pipe (Line 526) which contains five bends and a 100 mesh "y" strainer. The K value for the strainer was evaluated to be 2.5. Tees branch to either valve 2684HV and Line CF 531, which goes to the Recycle Eductor, or valve 2683HV and Line CF 530, which goes to the Filtrate Eductor. The lines transition from ¾" pipe to ½" pipe just downstream of the two valves. The total length of ¾" pipe is 15'.

According to Drawing W715401, the Recycle eductor is 38' further from the Partition Pump than the Filtrate Eductor. Using a previous section, the total length of line is then 67' + 38' = 105'. Drawing W720034 shows one bend and one 90° miter joint in the ½" pipe. Estimate an additional three bends at other locations in the ½" pipe. The liquid level in the Partition Tank is estimated to be 3" above the floor of the Sixth Level and the eductor is located 3' 2" above the floor of the Fifth Level. Therefore, there is an elevation decrease of 18' 8" for this piping section.

Piping from Recycle Eductor to Tank 8.8

According to Drawing W743422 the outlet of the Recycle Eductor has ½" pipe threads and is connected Line 129. One adapter transitions to ½" tubing and a second adapter transitions to ¾" tubing. There are 4' of ¾" tubing including five 90° bends and one through tee. An adapter transitions to ½" tubing and valve 2227HV. No loss is assumed for the valve. On the downstream side of the valve another adapter transitions from ½" to ¾". The equation for the loss for a sudden expansion gives a K value equal to 2.65. The K value for the sudden contractions is 4.57. Line 129 has another 6.6' of length of ¾" tubing and three more 90° bends. The extremity of Line 129 on Drawing W743422 has an elevation of 6' 8.75". Line 129 continues on Drawing W719133 which shows an additional five bends and 3.7' of length. Line 129 then transitions to 1" pipe at an elevation of 8' above the floor near the Resin Catch Tank. In summary, the ¾" tubing has a total length of 14.3', two contractions, two expansions and thirteen bends and one through tee. The total K factor, excluding straight pipe, is then $K = 2 * 4.57 + 2 * 2.65 + 13*12 f + 20 f = 14.4 + 176 f$. The increase in elevation for the ¾" tubing is 8' – 3' 2" = 4' 10".

As was mentioned previously, Line 129 transitions to 1" pipe near the Resin Catch Tank. Drawing W717366 indicates that Line 129 passes near the Spent Resin Glovebox. Drawing W717380 shows that Line 417 from the Filtrate Eductor tees into Line 129 above the glovebox and about 9' above the floor. Drawing W722230 shows that Line 129 tees into Line 104 (1" tubing) above the Fifth Level floor. According to drawing W726000 Line 104 goes generally downward through Line 253 and Line 254 and into Tank 8.8 on the Fourth Level Floor. That floor has an elevation of 339' 6.5". According to J. W. Posnick, Line 104 is vented. Therefore, the piping from Line 104 to Tank 8.8 should have no hydraulic effect on flow in the piping that precedes it. The portion of Line 129 made from 1" pipe contains one through tee, one branch tee and an estimated five bends. The section of 1" pipe starts 8' above the floor and drops to floor level where it is vented for an overall elevation decrease of 8'. Using drawing W717648 and assuming that the Line 104 passes through the floor opening east of the filtrate tanks the estimated total length of Line 129 is 85' of which 14.3' is ¾" tubing and the remainder is 1" pipe.

Solution of Equations

Estimated flowrates for eductant and suction were input to the Excel spreadsheets listed in the Attachment, which is a computation for nominal conditions. The spreadsheet computes velocities, Reynolds numbers, friction factors and a number of miscellaneous velocity head losses for each segment of pipe or tubing. Using equation 6 and the known elevation changes, the spreadsheet computes the pressure drop for each pipe segment. The pressures in the gas spaces of the tanks are very nearly equal to atmospheric pressure. There are three ways to compute the pressure at the suction inlet of the eductor. That pressure is equal to (P1) atmospheric pressure in the Filtrate Tank or Recycle Tank minus the total pressure drop in the suction line from that tank to the eductor. That pressure is also equal to (P2) the pressure at the outlet of the eductant pump minus the total pressure drop from the pump to the high pressure inlet of the eductor minus the pressure drop across the nozzle of the eductor. That pressure is also equal to (P3) atmospheric pressure in Tank 8.8 plus the total pressure drop from Tank 8.8 to the outlet of the eductor minus the pressure gain of the eductor. All three pressures, P1, P2 and P3 should be equal. The method of solution was to iteratively change the eductant flow and the suction flow in the spreadsheet until both of the differences P1-P2 and P2-P3 were zero. This method was used to compute the flows when 8 M nitric acid was used to pump water from one of the Filtrate Tanks or one of the Recycle Tanks to Tank 8.8. The source tanks were assumed to be 50% full. The computed flows are a weak function of tank fullness. For Filtrate transfers the attached Excel spreadsheet shows that the suction flow and the eductant flow are 1.52 gpm and 2.16 gpm, respectively, for a dilution ratio of 1.43 (see Table 4). This computation was repeated assuming that the nozzle diameter of the eductor is actually 10% larger than the nominal diameter of 3 mm or 0.118". The only difference in the equation set was that the right hand side of equation 2 was divided by the factor 1.1^4 to account for the lower velocity in the nozzle. The second case gave suction and eductant flows of 1.38 and 2.57 gpm, respectively, and a dilution ratio of 1.87. Calculations were also performed for Recycle transfers for both the nominal nozzle diameter and a diameter 50% larger. The nominal calculation for Recycle transfers did not agree with measurements. Agreement improved greatly by assuming that the eductor nozzle was 50% oversized.

Plugging of Vent Line

As was mentioned previously, Line 129 is vented at its junction with Line 104. If Line 104 were plugged, a siphon might form during a transfer, which would continue to drain the Filtrate Tanks or the Recycle Tanks, even after the Partition Pump had been de-energized. To explore this possibility, the Excel spreadsheet for Filtrate transfers was altered by setting the pressure increase across the eductor to zero, increasing the elevation decrease for eductor discharge by 15', increasing the discharge pipe length by 30' and adding five additional bends to the discharge pipe. The calculated flow was 1.87 gpm or 7.1 L/m. The velocity in the 1" pipe is 0.7 ft/s, which is sufficient to prevent air from entering the end of the pipe and breaking the siphon. Once started, the siphon is expected to persist until the source tank is emptied.

Experimental Data

Data for twenty seven transfers from the Filtrate Tanks (NT-51 and NT-52) and the Recycle Tanks (NT-31 and NT-32) occurring from 1988 to the present are listed in Table 3. For most of the transfers the elapsed time was also measured. Flowrate is equal to volume change divided by elapsed time. The dilution ratio is defined as the eductant volume divided by the volume of liquid pumped from the Recycle Tank or the Filtrate Tank. Dilution ratio, partition tank volume change divided by volume change for Recycle Tank or Filtrate Tank, is plotted in Figure 5 in chronological order. Data point #18 was not used to compute averages because the elapsed time was short, 3 minutes. There is an obvious difference between dilution ratios for Recycle and Filtrate transfers, but there are no trends with time. Transfers in 1988 and 2000 have about the same flows.

Figure 6 shows flowrates of eductant. Flowrates of eductant for Recycle transfer were twice as large as flowrates for Filtrate transfer. Material balance was checked in Figure 7 by plotting the volume collected in Tank 8.8 by the total of the volume lost by the Partition Tank and the volume lost by either the Recycle Tank or the Filtrate Tank. There is scatter in this ratio but the values are clustered around the theoretical value of unity. This gives confidence that the volume measurements were reasonably accurate and that no liquid was being lost into other piping. Some statistics of the flows and ratios are listed below in Table 4.

Table 4 Calculated and Measured Results for Transfers

Flows for Filtrate Transfers	**L/m**	**st. dev. (L/m)**	**gpm**
average measured Filtrate eductant flow	9.77	3.70	2.58
calculated Filtrate eductant flow, nominal	8.18		2.16
calculated Filtrate eductant flow, nozzle 10% large	9.73		2.57
average measured Filtrate suction flow	5.13	1.71	1.36
nominal calculated Filtrate suction flow	5.75		1.52
calculated Filtrate suction flow, nozzle 10% large	5.22		1.38
Ratios for Filtrate Transfers	**ratio**	**st. dev.**	
average measured Filtrate ratio	1.92	0.16	
calculated Filtrate ratio, nominal	1.43		
calculated Filtrate ratio, nozzle 10% large	1.87		
Flows for Recycle Transfers	**L/m**	**st. dev. (L/m)**	**gpm**
average measured Recycle eductant flow	16.39	1.95	4.33
calculated Recycle eductant flow, nominal	8.37		2.21
calc. Recycle eductant flow, nozzle 50% large	16.17		4.27
average measured Recycle suction flow	3.20	0.53	0.84
calculated Recycle suction flow, nominal	5.83		1.54
calc. Recycle suction flow, nozzle 50% large	3.37		0.89
Ratios for Recycle Transfers	**ratio**	**st. dev.**	
average measured Recycle ratio	5.17	0.38	
calculated Recycle ratio, nominal	1.44		
calculated Recycle ratio, nozzle 50% large	4.80		

The spreadsheet calculation was used to perform a sensitivity analysis. One at a time, the important variables in the calculation were changed by the maximum expected uncertainty in that variable while all other variables were held at the nominal value. Manufacturer's tolerance was used to set the smallest tubing or pipe diameter. Other variabilities were estimated. The results are summarized in Table 5. For example, when the only change was to decrease the pump head from 45 feet to 42 feet, the suction flow, the eductant flow and the dilution ratio decreased by 1.4%, 2.2% and 0.9%, respectively. The largest contributors to variability were smaller than average tubing diameters, longer than nominal discharge piping and eductor pressure gain and eductor nozzle diameter different than manufacturer's specification. The method of root sum squares was used to combine all of the uncertainties. The resulting maximum expected deviation in suction flow, eductant flow and dilution ratio from all sources is 15.2%, 9.6% and 20.6%, respectively.

Table 5 Uncertainty Analysis for Transfer from Filtrate Tanks to Tank 8.8

base case solution, suction flow = 1.52 gpm, eductant flow = 2.16 gpm, ratio = 1.42

variable		change in suction flow, %	change in eductant flow, %	change in dilution ratio
eductant pump head	decrease pump head from 45 to 42 ft.	-1.4	-2.2	-0.9
eductant molarity	decrease molarity from 8 to 6	-1.5	0.4	1.9
tank fullness	increase fullness from 0.5 to 1.0	2.6	-0.4	-2.9
suction tubing diameter	decrease from 0.402" to 0.382"	-5.4	0.8	6.6
eductant pipe 3/4"	decrease from 0.824" to 0.791"	0.0	0.0	0.0
eductant pipe 1/2"	decrease from 0.622" to 0.59"	-0.4	-0.7	-0.3
discharge tubing 1/2"	decrease from 0.402" to 0.382"	-7.4	-0.7	7.2
discharge tubing 3/4"	decrease from 0.652" to 0.632"	0.0	0.0	0.0
suction tubing length	increase from 39.3' to 44'	-2.2	0.3	2.5
eductant pipe length	increase from 15"+67' to 18"+75'	-0.2	-0.3	-0.1
disch. pipe and tub. length	increase from 5'+6.1'+56' to 7'+8'+62'	-8.1	-0.7	8.0
misc. suction losses	increase by 20%	-0.8	0.1	0.9
misc. discharge losses	increase by 20%	-2.7	-0.3	2.5
misc. eductant losses	increase by 20%	0.0	0.0	0.0
eductor pressure gain	decrease by 10%	-6.1	-0.6	5.9
eductor nozzle diameter	increase by 5%	-4.5	9.2	14.3
	combination of all variables using root sum square	15.2	9.6	20.6

Table 4 shows that there was fair agreement between measured and nominal calculated flows and dilution ratio for Filtrate transfers. The measured and calculated dilution ratios were 1.92 and 1.43, respectively. The uncertainty analysis concluded that the calculated ratio might be as much as 20% larger, or 1.72. However, that still leaves a discrepancy between the measured and calculated ratios. Agreement was poor for Recycle transfers, far exceeding the variability from the uncertainty analysis. Two sources of the unexplained discrepancy were considered. Increasing the nozzle diameter by 10% for Filtrate transfers and by 50% for Recycle transfers gave excellent agreement for measured and calculated values. Leakage past valves also has the potential to explain the discrepancy between calculated and measured flows. For example, consider Recycle transfers. Hypothesize that valves 2683HV and 2608HV have large leaks, even when closed. The Partition Pump has a nearly flat head curve. In this situation, the Recycle Eductor and the Filtrate Eductor consume nearly equal flowrates of eductant, all of which eventually flows to Tank 8.8. The amount of liquid pumped out of one of the Recycle

Tanks is actually less than if there had been no valve leakage. The reason is that more liquid must flow through the piping from the eductor to Tank 8.8, which increases the back pressure at the eductor. Increasing the back pressure at the outlet of an eductor decreases its ability to pump. Therefore, a large bypass leak is expected to increase the dilution factor by more than a factor of two.

References

A. K. Jain, "Accurate Explicit Equation for Friction Factor", ASCE J. Hydraulics Div., **102**, pp. 674-677, (1976).

Robert D. Blevins, **Applied Fluid Dynamics Handbook**, 1984.

J. L. Steimke, "Analysis of Eductor Performance", WSRC-TR-98-00208, 1998.

I. J. Karassik, W. C. Krutzsch, W. H. Fraser and J. P. Messina, **Pump Handbook**, 1986.

Crane Co., **Flow of Fluids Through Valves, Fittings and Pipe**, Technical Paper No. 410, 1988.

Robert H. Perry, Cecil H. Chilton and Sidney D. Kirkpatrick, **Chemical Engineers' Handbook**, Fourth Edition, 1984.

Figure 1 General Purpose Schutte and Koerting Eductor

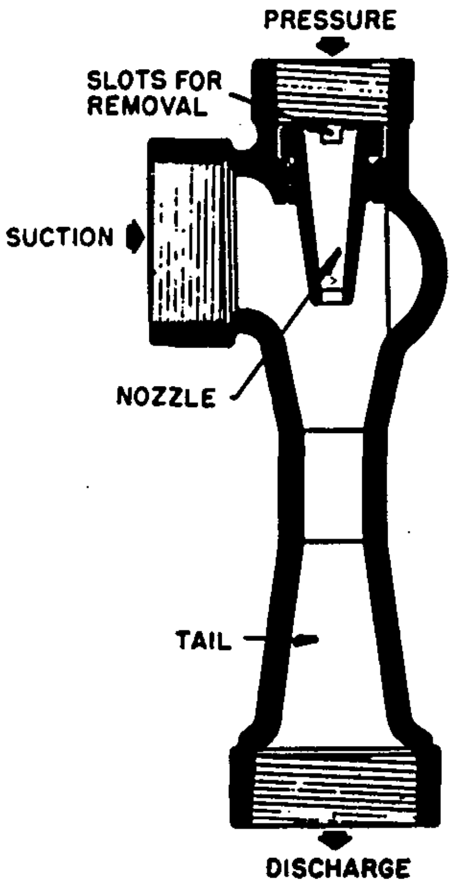

FIG. 1 General purpose eductor. (Schutte and Koerting)

Figure 2 Nozzle Pressure Drop for 1" Eductor and Water

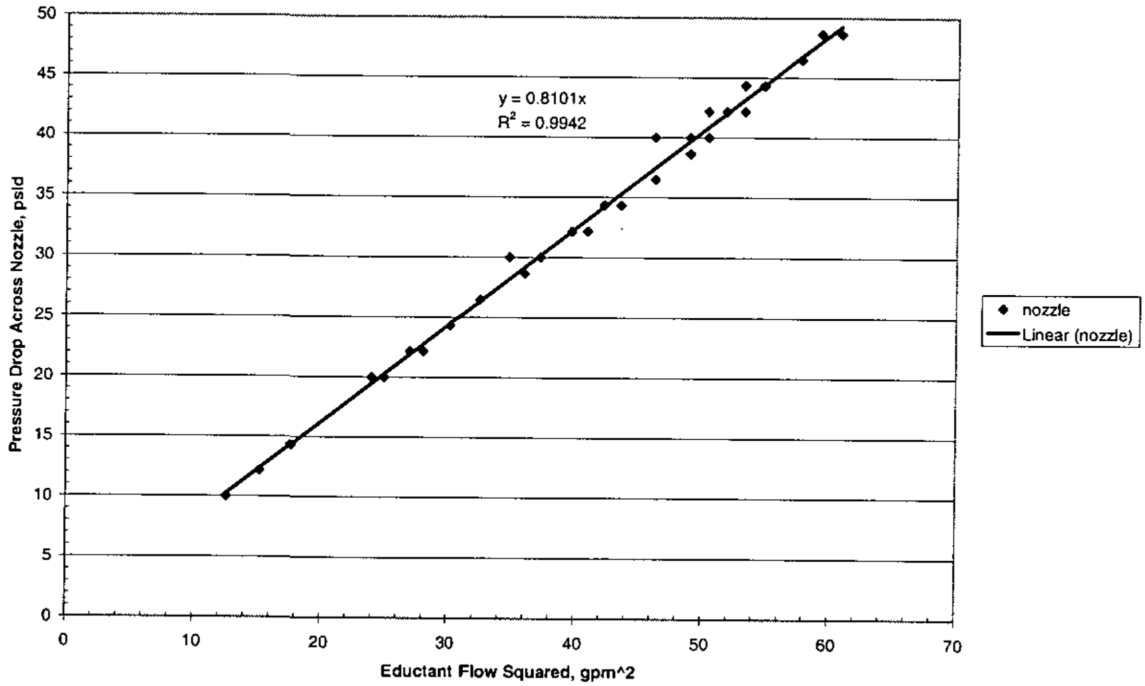

Figure 3 Eductor Pressure Gain

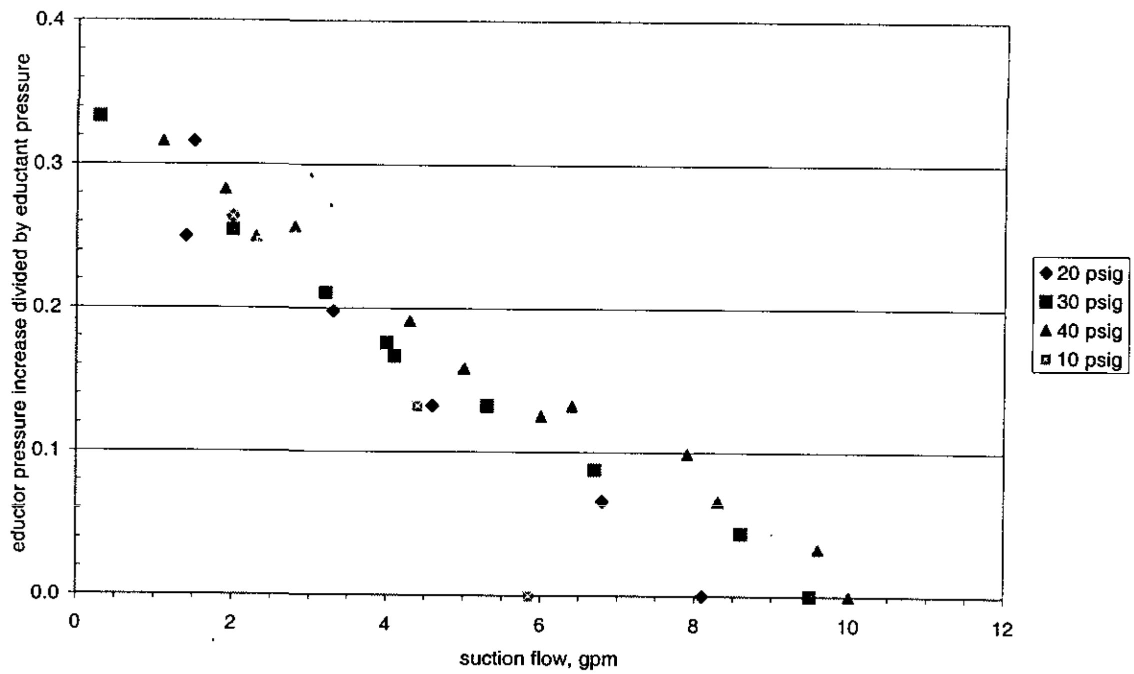

Figure 4 Nitric Acid Solution Density and Viscosity

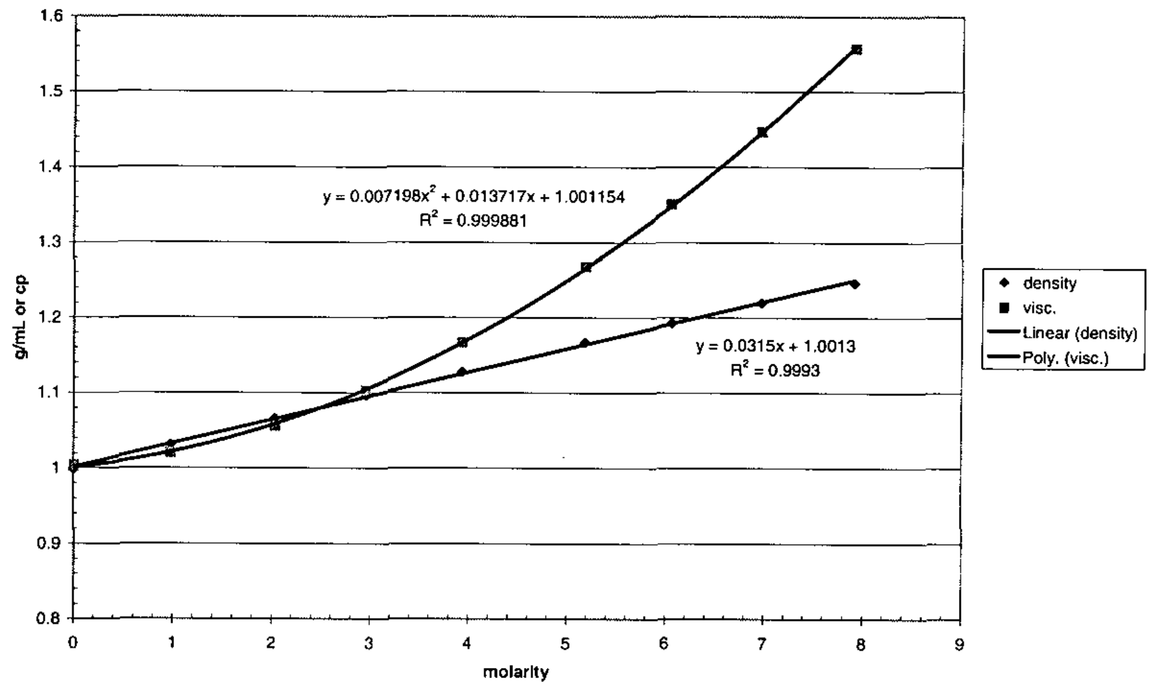

Figure 5 Dilution Ratios for Transfers

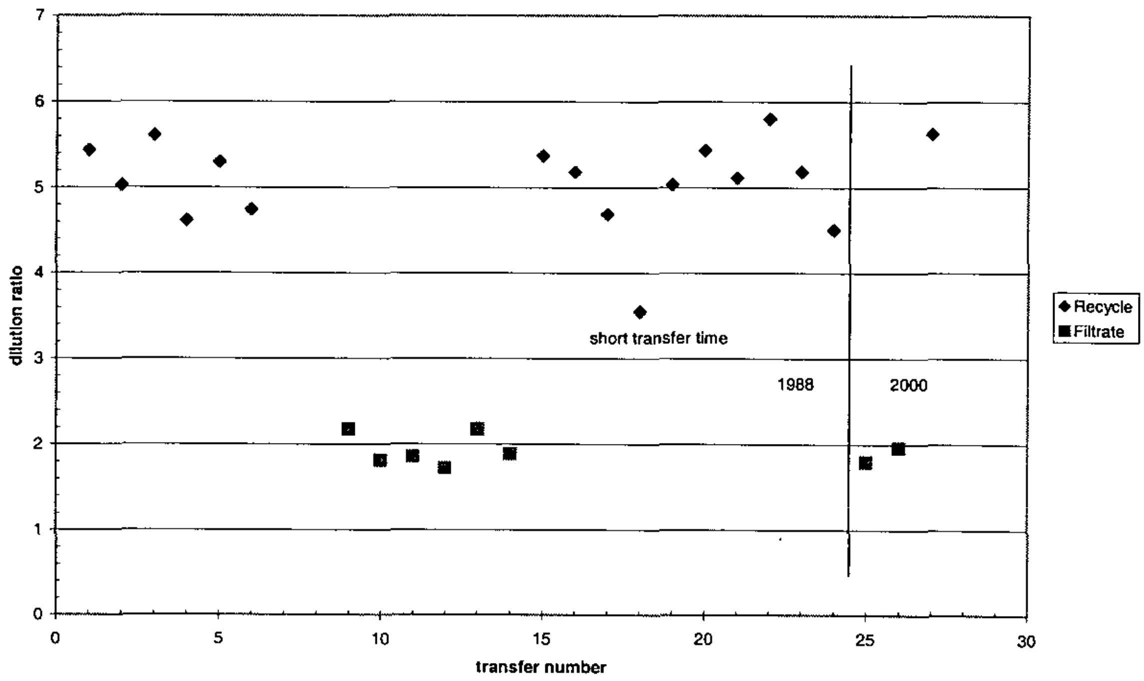

Figure 6 Eductant Flows for Transfers

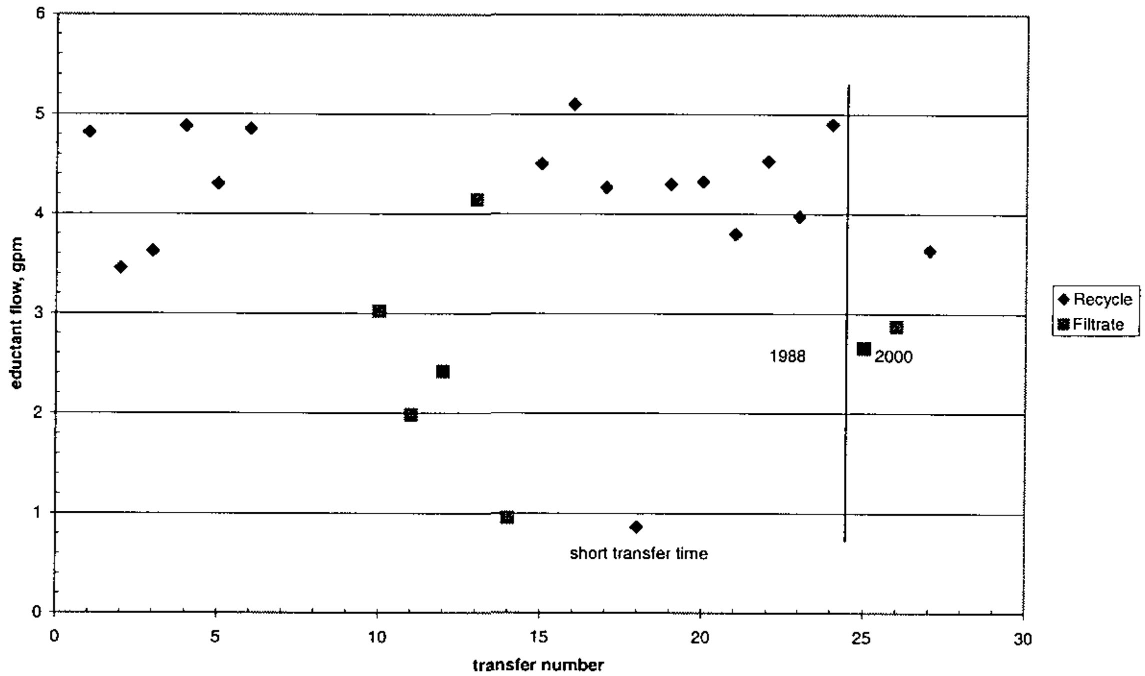

Figure 7 Comparison of Volume Received by Tank 8.8 to Total of CP Tank and NT Tank

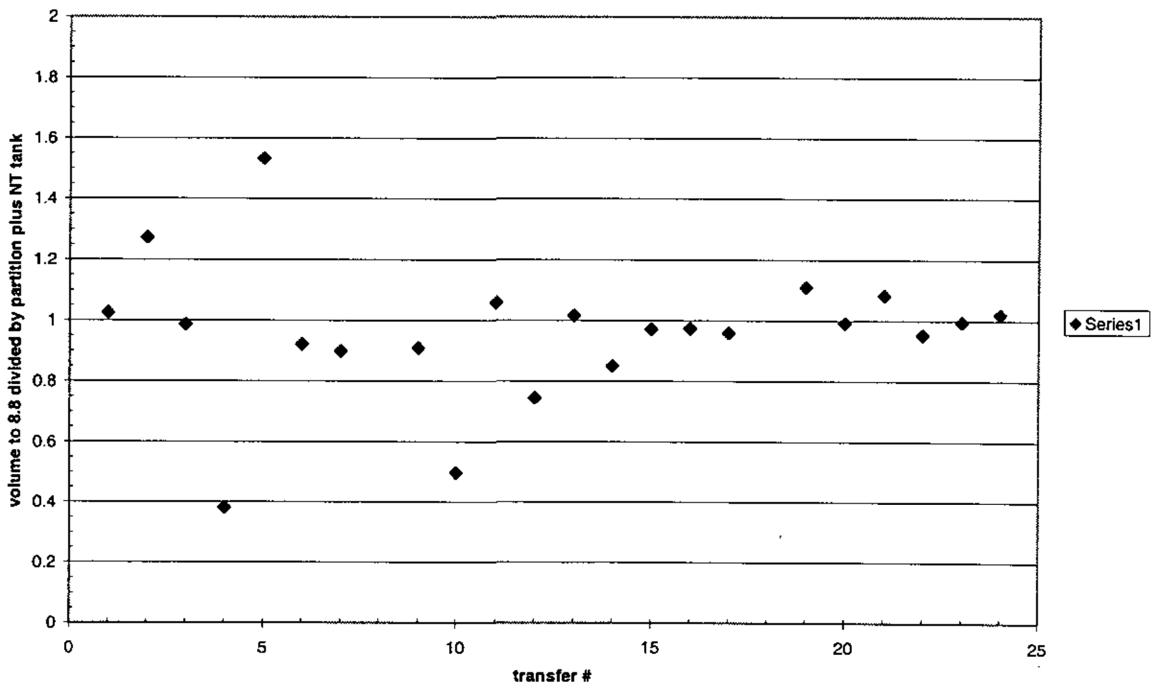

TABLE 1 Capacity Table of Standard 1-in (25.4-mm) Water-Jet Eductors, gpm[a]

Suction lift, ft (m)	Discharge pressure, lb/in² (bar) gage	Function	Operating water pressure, lb/in² (bar) gage: 10 (0.69)	20 (1.4)	30 (2.1)	40 (2.8)	50 (3.4)	60 (4.1)	80 (5.5)	100 (6.9)
0 (0)	0 (0)	Suction	5.85	8.1	9.5	10.0	12.0	12.0	12.0	12.0
		Operating	3.55	5.0	6.1	7.1	7.9	8.7	10.0	11.0
	5 (0.34)	Suction	...	1.4	4.1	6.0	8.0	10.0	11.0	12.0
		Operating	...	4.9	6.1	7.0	7.9	8.6	10.0	11.0
	10 (0.69)	Suction	...	..	0.28	2.3	4.8	6.4	8.8	11.0
		Operating	...	..	5.9	6.8	7.8	8.5	9.8	11.0
	15 (1.0)	Suction	...	..	...	...	1.2	3.4	5.9	8.6
		Operating	...	..	...	...	7.7	8.4	9.8	11.0
	20 (1.4)	Suction	...	..	...	...	...	0.3	3.5	5.9
		Operating	...	..	...	...	...	8.2	9.7	11.0
	25 (1.7)	Suction	...	..	...	...	...	...	0.83	3.9
		Operating	...	..	...	...	...	...	9.6	11.0
	30 (2.1)	Suction	...	..	...	...	...	...	...	1.7
		Operating	...	..	...	...	...	...	...	11.0
5 (1.5)	0 (0)	Suction	4.4	6.8	8.6	9.6	11.0	11.0	12.0	12.0
		Operating	3.9	5.3	6.4	7.3	8.1	8.8	10.0	11.0
	5 (0.34)	Suction	...	1.5	3.2	5.0	7.0	9.0	11.0	11.0
		Operating	...	5.2	6.3	7.2	8.0	8.7	10.0	11.0
	10 (0.69)	Suction	...	..	...	1.9	3.6	5.6	8.6	10.0
		Operating	...	..	...	7.1	7.9	8.6	10.0	11.0
	15 (1.0)	Suction	...	..	...	...	1.1	2.6	5.8	8.3
		Operating	...	..	...	...	7.8	8.6	9.9	11.0
	20 (1.4)	Suction	...	..	...	...	...	...	3.3	5.6
		Operating	...	..	...	...	...	...	9.8	11.0
	25 (1.7)	Suction	...	..	...	...	...	...	0.47	3.6
		Operating	...	..	...	...	...	...	9.8	11.0
	30 (2.1)	Suction	...	..	...	...	...	...	...	1.5
		Operating	...	..	...	...	...	...	...	11.0
10 (3.0)	0 (0)	Suction	2.0	4.6	6.7	8.3	9.0	10.0	10.0	10.0
		Operating	4.2	5.5	6.6	7.4	8.2	9.0	10.0	11.0
	5 (0.34)	Suction	...	..	2.0	4.3	5.9	7.7	9.9	10.0
		Operating	...	..	6.5	7.4	8.2	8.9	10.0	11.0
	10 (0.69)	Suction	...	..	...	1.1	3.0	4.5	8.1	9.6
		Operating	...	..	...	7.3	8.1	8.8	10.0	11.0
	15 (1.0)	Suction	...	..	...	...	1.1	2.1	5.6	7.3
		Operating	...	..	...	...	8.0	8.7	10.0	11.0
	20 (1.4)	Suction	...	..	...	...	...	...	2.8	5.3
		Operating	...	..	...	...	...	...	9.9	11.0
	25 (1.7)	Suction	...	..	...	...	...	...	...	2.8
		Operating	...	..	...	...	...	...	...	11.0
	30 (2.1)	Suction	...	..	...	...	...	...	...	1.1
		Operating	...	..	...	...	...	...	...	11.0
15 (4.6)	0 (0)	Suction	...	3.3	5.3	7.9	8.4	8.9	8.9	9.1
		Operating	...	5.7	6.8	7.6	8.4	9.1	10.0	12.0
	5 (0.34)	Suction	...	..	...	4.0	4.9	7.3	8.6	9.1
		Operating	...		...	7.6	8.3	9.0	10.0	11.0
	10 (0.69)	Suction	...	..	...	...	2.4	4.0	6.4	8.6
		Operating	...	..	...	...	8.2	9.0	10.0	11.0
	15 (1.0)	Suction	...	..	...	...	...	...	4.2	6.8
		Operating	...	..	...	...	...	...	10.0	11.0
	20 (1.4)	Suction	...	..	...	...	...	...	2.1	4.5
		Operating	...	..	...	...	...	...	10.0	11.0
	25 (1.7)	Suction	...	..	...	...	...	...	...	1.9
		Operating	...	..	...	...	...	...	...	11.0
20 (6.1)	0 (0)	Suction	...	2.0	4.0	6.4	7.8	7.8	7.8	7.8
		Operating	...	6.0	7.0	7.8	8.6	9.3	11.0	12.0
	5 (0.34)	Suction	...	..	...	2.8	8.9	6.3	7.8	7.8
		Operating	...	..	...	7.7	8.5	9.2	10.0	12.0
	10 (0.69)	Suction	...	..	...	...	1.2	8.1	5.7	7.1
		Operating	...	..	...	...	8.3	9.1	10.0	12.0
	15 (1.0)	Suction	...	..	...	...	...	...	8.6	5.4
		Operating	...	..	...	...	...	...	10.0	11.0
	20 (1.4)	Suction	...	..	...	...	...	...	1.4	8.8
		Operating	...	..	...	...	...	...	10.0	11.0
	25 (1.7)	Suction	...	..	...	...	...	...	...	1.5
		Operating	...	..	...	...	...	...	...	11.0

Relative capacities of standard sizes

Size eductor, in (mm)	½ (12.7)	¾ (19.1)	1 (25.4)	1½ (38.1)	2 (50.8)	2½ (63.5)	3 (76.2)	4 (102)	6 (152)
Capacity ratio	0.36	0.64	1.00	2.89	4.00	6.25	9.00	16.00	36.00

[a]gpm × 0.227 = m³/h.
SOURCE: Schutte and Koerting.

Table 3 Filtrate and Recycle Transfer Data

Old Eductor Data	1	2	3	4	5	6	7	8	9	10	11
date	7/25/88	7/20/88	7/25/88	8/2/88	8/2/88	8/4/88	7/14/88	7/28/88	7/7/88	7/25/88	7/25/88
partition tank	CP-24	CP-24	CP-25	CP-24	CP-25	CP-25	CP-25	CP-25	CP-24	CP-24	CP-25
Recycle or filtrate tank	NT-31	NT-32	NT-32	NT-32	NT-31	NT-32	NT-51	NT-52	NT-51	NT-51	NT-52
Receiving tank	Tank 8.8	Tank 8.8	Tank 8.8	Tank 8.8	Tank 8.8	Tank 8.8	Tank 8.8	Tank 8.8	Tank 8.8	Tank 8.8	Tank 8.8
time interval, min	23	15	19	13	20	12	na	na	na	12	20
NT vol. Change, L	77.18	39.04	46.5	52.08	61.5	46.5	32.35	50.55	74.27	75.73	81.06
CP vol change, L	419.6	196.2	260.8	240.4	325.9	220.7	65.26	90.2	161.8	137.4	150.4
Tank 8.8 vol change, L	509.2	299.4	303.1	111.7	593.7	246.2	87.76	721	214.77	106	245
sp. gr. NT	1.02	1.02	1.02	1.02	1.02	1.03					
sp.gr. CP											
measurement error. %	2.4	21.4	-1.4	-161.8	34.7	-8.5	-11.2	80.5	-9.9	-101.1	5.5
suction flow, L/m	3.36	2.60	2.45	4.01	3.08	3.88				6.31	4.05
suction flow, gpm	0.89	0.69	0.65	1.06	0.81	1.02				1.67	1.07
eductant flow, L/m	18.24	13.08	13.73	18.49	16.30	18.39				11.45	7.52
eductant flow, gpm	4.82	3.45	3.63	4.88	4.30	4.86				3.02	1.99
vel in 1" pipe	2.12	1.54	1.59	2.21	1.90	2.18				1.74	1.13
ratio	5.44	5.03	5.61	4.62	5.30	4.75	2.02	1.78	2.18	1.81	1.86
	L/m	sigma	gpm	high error	high error		no time	no time	no time		
aver. educt. flow NT-31	16.39	1.95	4.33								
aver. educt flow NT-51	9.77	3.70	2.58								
aver. suc. flow NT-31	3.20	0.53	0.84								
aver. suc. flow NT-51	5.13	1.71	1.36								
aver. dil. ratio NT-31	5.17	0.38									
aver. dil. ratio NT-51	1.92	0.16									
capacity ratio 3/4:1/2	1.78										
NT-31/NT-51 educ ratio	1.68										

Table 3 Filtrate and Recycle Transfer Data

Old Eductor Data	12	13	14	15	16	17	18	19	20	21	22
date	7/13/88	7/13/88	7/14/88	7/27/88	7/27/88	7/28/88	8/12/88	8/15/88	8/23/88	8/23/88	8/17/88
partition tank	CP-24	CP-24	CP-25	CP-25	CP-24	CP-25	CP-24	CP-24	CP-24	CP-25	CP-25
Recycle or filtrate tank	NT-51	NT-52	NT-52	NT-31	NT-32	NT-31	NT-31	NT-32	NT-32	NT-31	NT-31
Receiving tank	Tank 8.8	Tank 8.8	Tank 8.8	Tank 8.8	Tank 8.8	Tank 8.8	Tank 8.8	Tank 8.8	Tank 8.8	Tank 8.8	Tank 8.8
time interval, min	15	10	15	20	16	18	3	21	18	15	19
NT vol. Change, L	79.84	72	28.78	63.5	59.6	62	2.76	67.9	54.2	42.15	56.2
CP vol change, L	137.4	156.9	54.4	341.1	309	290.8	9.8	342	294.7	215.6	326
Tank 8.8 vol change, L	161.7	232.45	70.74	393	359	338.3	282.6	455	346	279.07	364
sp. gr. NT				1.02	1	1	1.02	0.93	1.02	1.01	0.93
sp.gr. CP											
measurement error. %	-34.3	1.5	-17.6	-3.0	-2.7	-4.3	95.6	9.9	-0.8	7.6	-5.0
suction flow, L/m	5.32	7.20	1.92	3.18	3.73	3.44	0.92	3.23	3.01	2.81	2.96
suction flow, gpm	1.41	1.90	0.51	0.84	0.98	0.91	0.24	0.85	0.80	0.74	0.78
eductant flow, L/m	9.16	15.69	3.63	17.06	19.31	16.16	3.27	16.29	16.37	14.37	17.16
eductant flow, gpm	2.42	4.14	0.96	4.50	5.10	4.27	0.86	4.30	4.32	3.80	4.53
vel in 1" pipe	1.42	2.24	0.54	1.98	2.26	1.92	0.41	1.91	1.90	1.68	1.97
ratio	1.72	2.18	1.89	5.37	5.18	4.69	3.55	5.04	5.44	5.12	5.80
	high error						short time big error				

Table 3 Filtrate and Recycle Transfer Data

	23	24	25 filtrate	26	27
date	8/18/88	8/19/88	8/30/00	8/30/00	8/31/00
partition tank	CP-25	CP-25	CP-25	CP-25	CP-25
Recycle or filtrate tank	NT-31	NT-31	NT-51	NT-52	NT-31
Receiving tank	Tank 8.8	Tank 8.8	Tank 8.8	Tank 8.8	Tank 8.8
time interval, min	20	15	10	12	23
NT vol. Change, L	58	61.7	55.95	66.4	56.2
CP vol change, L	301	278.4	100.5	130.6	316.5
Tank 8.8 vol change, L	357	347			
sp. gr. NT	1.02	1.01	1	1	1
sp.gr. CP			1.247	1.247	1.247
measurement error, %	-0.6	2.0			
suction flow, L/m	2.90	4.11	5.60	5.53	2.44
suction flow, gpm	0.77	1.09	1.48	1.46	0.65
eductant flow, L/m	15.05	18.56	10.05	10.88	13.76
eductant flow, gpm	3.98	4.90	2.65	2.87	3.63
vel in 1" pipe	1.76	2.22	1.53	1.61	1.59
ratio	5.19	4.51	1.80	1.97	5.63

Attachment

Filtrate Tank to Tank 8.8				
pump head, feet	45	from vendor pump curve	nozzle ratio	1
molarity suc	0.01	molarity of pumped liquid		
molarity educ	8	molarity of eductant		
molarity discharge	4.72	molarity of eductor discharge		
gpm suc	1.511	flowrate of pumped liquid	sucerr	2.5831E-06
gpm educ	2.175	flowrate of eductant	nozerr	-0.021811397
tank fullness	0.5	fractional fullness of NT tank	educerr	0.021808814
discharge void	0	average void fraction in discharge line		
suction diameter, inch	0.402	ID of suction pipe		
eductant A diameter, inch	0.824	ID of section A of eductant pipe	DPpump	7.791382235
eductant B diameter, inch	0.622	ID of section B of eductant pipe		
discharge A diameter, inch	0.402	ID of section A of discharge pipe	Peduc	31.72482195
discharge B diameter, inch	0.652	ID of section B of discharge pipe	DPnoz	37.19281983
discharge C diameter, inch	1.049	ID of section C of discharge pipe	Re suc	12139.72224
suction length, ft	39.3	piping length	f suc	0.029640488
eductant A length, ft	15	piping length	DP dis	2.301575538
eductant B length, ft	52	piping length		
discharge A length, ft	5	piping length	DP suc	5.48980928
discharge B length, ft	6.1	piping length		
discharge C length, ft	56	piping length		
suction sp gr	1.002			
eductant sp gr	1.253			
discharge sp gr	1.150			
viscosity suction, lb/ft sec	0.000659			
viscosity educ, lb/ft sec	0.001034			
viscosity discharge,lb/ft sec	0.000807			
vel suc, ft/sec	3.82	superficial velocity		
vel educ A, ft/sec	1.31	superficial velocity		
vel educ B, ft/sec	2.30	superficial velocity		
vel dis A, ft/sec	9.32	superficial velocity		
vel dis B, ft/sec	3.54	superficial velocity		
vel dis C, ft/sec	1.37	superficial velocity		
n suc	8.25	number of velocity heads, misc. loss		
n dis A	2.23	number of velocity heads, misc. loss		
n dis B	3.24	number of velocity heads, misc. loss		
n dis C	2.20	number of velocity heads, misc. loss		

Attachment

n educ A	7.50	number of velocity heads, misc. loss
n educ B	3.46	number of velocity heads, misc. loss
Re suction	12140	Reynolds number
Re educ A	6797	Reynolds number
Re educ B	9004	Reynolds number
Re dis A	27758	Reynolds number
Re dis B	17115	Reynolds number
Re dis C	10637	Reynolds number
rough, inch	0.002	
rough new, inch	0.00006	
f suction laminar	0.00527	friction factor
f suction turbulent	0.02964	friction factor
f suction transition	0.15961	friction factor
f 2000	0.03200	friction factor
f 3000	0.04459	friction factor
f non turbulent	0.15961	friction factor
f suction	0.02964	friction factor
f educ A	0.03461	friction factor
f educ B	0.03201	friction factor
f dis A	0.02423	friction factor
f dis B	0.02704	friction factor
f dis C	0.03052	friction factor
DP suction, psid	5.490	
DP eductant A, psid	-1.953	
DP eductant B, psid	-5.332	
P eductant, psig	31.725	eductant pressure at eductor
G = gpmsuc*spgrsuc^.5	1.6916	
eductor capacity ratio, ECR	0.36	fraction of the flow capacity of a 1" eductor
DP pump, psid	7.791	
DP discharge A, psid	3.928	
DP discharge B, psid	1.856	
DP discharge C, psid	-3.482	
DP nozzle, psid	37.193	equation from vendor data, assumes new
Psat, psia	0.33	
dilution ratio	1.439	
noz DP error, psid	-0.022	
suc DP error, psid	0.000	