# APPENDICES

## APPENDIX A: MATHEMATICAL RELATIONS FOR PLCB MODEL

The PLCB model is defined by two differential equations:

$$\frac{dC}{dH} = \frac{A\beta\rho_p*(1-\varepsilon)(1+C_0)}{\alpha\rho QL}G$$

and

$$\frac{dL}{dH} = -\frac{(1-\varepsilon)[A\beta G]}{3N\alpha^2 L^3} \quad ,$$

where:

$$A = \left(\frac{\pi}{4}\right)\left[W_0 + \frac{H}{H_t}(W_t - W_0)\right]^2 ,$$

$G$ =

$$\frac{mk'\{([M]_0 - 7.331[C-C_0])([A]_0 - 7.331[C-C_0])([P]_0 - 7.331[C-C_0]) - P_e\}\rho_p\left(\frac{\varepsilon}{1-\varepsilon}\right)\left(\frac{\alpha L}{\beta}\right)}{3(7.331[C-C_0])^2 - 2([M]_0 + [A]_0 + [P]_0)(7.331[C-C_0]) + ([M]_0[A]_0 + [A]_0[P]_0 + [P]_0[M]_0)},$$

and

$$\varepsilon = \frac{\ln\left(\dfrac{Q}{\dfrac{\pi}{4}\left[W_0 + \dfrac{H}{H_t}(W_t - W_0)\right]^2}\right) - \ln\left(10^{\frac{-L\gamma}{W_0 + \frac{H}{H_t}(W_t - W_0)}}\left(\dfrac{4(\rho_p - \rho)^2 g^2}{225\rho\mu}\right)^{\frac{1}{3}}(L\gamma)\right)}{4.4\left[\dfrac{\rho(L\gamma)^2}{\mu}\left(\dfrac{4(\rho_p - \rho)^2 g^2}{225\rho\mu}\right)^{\frac{1}{3}}\right]^{-0.1}} .$$

## APPENDIX B: OPENING SIZES CORRESPONDING WITH STANDARD SIEVE NUMBERS

The following table shows the diameter of the openings in screens in the range used in the experiments described in the present document. Note that increasing standard sieve numbers correspond with finer screens, which have smaller openings.

**Table 25: Opening Diameter (mm) of Screens with Various Standard Sieve Numbers***

| Standard Sieve Number | Diameter (mm) of Opening |
|---|---|
| 8 | 2.380 |
| 10 | 2.000 |
| 12 | 1.680 |
| 14 | 1.410 |
| 16 | 1.190 |
| 18 | 1.000 |
| 20 | 0.840 |
| 25 | 0.710 |
| 30 | 0.590 |
| 35 | 0.500 |
| 40 | 0.420 |
| 45 | 0.350 |
| 50 | 0.297 |
| 60 | 0.250 |
| 70 | 0.210 |
| 80 | 0.177 |
| 100 | 0.149 |
| 120 | 0.125 |
| 140 | 0.105 |
| 170 | 0.088 |
| 200 | 0.074 |
| 230 | 0.063 |
| 270 | 0.053 |
| 325 | 0.044 |

*Source: Cleveland Wire Cloth

# APPENDIX C: DETAILS ON DESIGN OF FIELD-SCALE CRYSTALLIZER

This appendix provides details on the design for the field-scale crystallizer. Figure 50, a schematic diagram of the crystallizer, appears on the following page. On the diagram, each component is indicated with a number that keys to Table 26, the complete list of components for the crystallizer. The table, which follows the diagram, describes each component and identifies its material of construction.

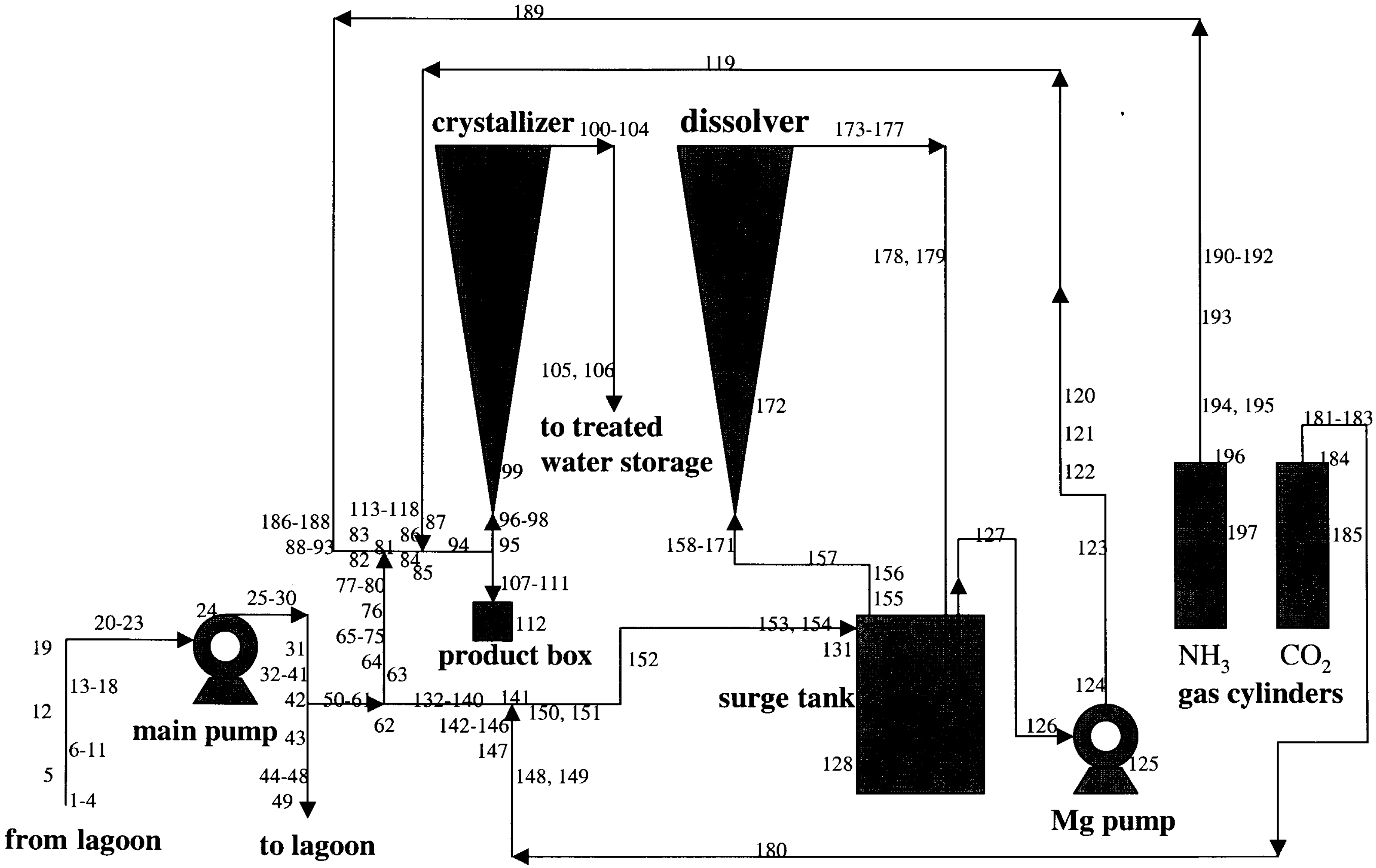


**Figure 50: Schematic Diagram of Field-Scale Crystallizer, Identifying All Components**

(Component Numbers Key to Table 26)

**Table 26: Complete List of Components for Field-Scale Crystallizer**

| Item # | Description | Material |
|---|---|---|
| 1 | Intake strainer with 2" connection | PVC |
| 2 | Check valve; 2" connection for strainer and outlet is NPT(M) 1 1/4" | PVC |
| 3 | Elbow, 1 1/4", NPT(F) connections | PVC |
| 4 | Boss-Dixon "combination nipple" hose/pipe adaptor, 1 1/4", hose side is barb insert (M), pipe side is 1 1/4" NPT(M) | plated steel |
| 5 | 1 1/4" rigid suction hose, cut to length to stretch from item 4 (elbow at intake) to item 6 (adaptor for mowing disconnect) | vinyl |
| 6 | Boss-Dixon "combination nipple" hose/pipe adaptor, 1 1/4", hose side is barb insert (M), pipe side is 1 1/4" NPT(M) | plated steel |
| 7 | Threaded reducer coupling, 1 1/4" NPT(F) x 1 1/2" NPT(F) | PVC |
| 8 | 1 1/2" quick disconnect (M) with 1 1/2" NPT(M) connection | PP |
| 9 | 1 1/2" quick disconnect (F) with 1 1/2" NPT(M) connection | PP |
| 10 | Threaded reducer coupling, 1 1/4" NPT(F) x 1 1/2" NPT(F) | PVC |
| 11 | Boss-Dixon "combination nipple" hose/pipe adaptor, 1 1/4", hose side is barb insert (M), pipe side is 1 1/4" NPT(M) | plated steel |
| 12 | 1 1/4" rigid suction hose, length of in-stock roll remaining after using first section (item 5) | vinyl |
| 13 | Boss-Dixon "combination nipple" hose/pipe adaptor, 1 1/4", hose side is barb insert (M), pipe side is 1 1/4" NPT(M) | plated steel |
| 14 | Threaded reducer coupling, 1 1/4" NPT(F) x 1 1/2" NPT(F) | PVC |
| 15 | 1 1/2" quick disconnect (M) with 1 1/2" NPT(M) connection | PP |
| 16 | 1 1/2" quick disconnect (F) with 1 1/2" NPT(M) connection | PP |
| 17 | Threaded reducer coupling, 1 1/4" NPT(F) x 1 1/2" NPT(F) | PVC |
| 18 | Boss-Dixon "combination nipple" hose/pipe adaptor, 1 1/4", hose side is barb insert (M), pipe side is 1 1/4" NPT(M) | plated steel |
| 19 | 1 1/4" rigid suction hose, cut to length to stretch from item 18 (adaptor at second quick disconnect) to item 20 (adaptor at quick disconnect at pump intake) | vinyl |
| 20 | 1 1/4" quick disconnect (M) with 1 1/4" hose barb (M) connection | PP |
| 21 | 1 1/4" quick disconnect (F) with 1 1/4" NPT(M) connection | PP |
| 22 | 1 1/4" ball valve with 1 1/4" NPT(F) union connections | PVC |
| 23 | 1 1/4" NPT(M) nipple | PVC |
| 24 | Jet pump with 1 1/4" NPT(F) intake and 3/4" NPT(F) discharge | |
| 25 | 3/4" NPT(M) nipple | PVC |
| 26 | 3/4" tee with NPT(F) connections | PVC |
| 27 | Reducer bushing, 3/4" NPT(M) x 1/4" NPT(F) | PVC |
| 28 | Pressure gauge, 0-100 psi, 1/4" NPT(M) connection | various |
| 29 | 3/4" NPT(M) nipple | PVC |
| 30 | Adaptor, 3/4" NPT(F) x 3/4" socket (F) | PVC |
| 31 | 3/4" pipe, sch. 40, plain ends for socket fittings, cut to ca. 1' to stretch from item 30 to item 32 (order quantity 10', 40.77 cents per foot) | PVC |
| 32 | Adaptor, 3/4" NPT(F) x 3/4" socket (F) | PVC |
| 33 | 3/4" NPT(M) nipple | PVC |
| 34 | Gate valve, both connections 3/4" NPT(F) | PVC |

Table 26 (continued)

| | | |
|---|---|---|
| 35 | 3/4" NPT(M) nipple | PVC |
| 36 | Adaptor, 3/4" NPT(F) x 3/4" socket (F) | PVC |
| 37 | 3/4" pipe, sch. 40, plain ends for socket fittings, cut to ca. 1' to stretch from item 36 to item 38 (price included in item 31) | PVC |
| 38 | Elbow, 3/4" socket (F) connections | PVC |
| 39 | 3/4" pipe, sch. 40, plain ends for socket fittings, cut to ca. 1' to stretch from item 36 to item 38 (price included in item 31) | PVC |
| 40 | Elbow, 3/4" socket (F) connections | PVC |
| 41 | 3/4" pipe, sch. 40, plain ends for socket fittings, cut to ca. 6" to stretch from item 36 to item 38 (price included in item 31) | PVC |
| 42 | 3/4" tee with with socket (F) connections | PVC |
| 43 | 3/4" pipe, sch. 40, plain ends for socket fittings, cut to ca. 4" (price included in item 31) | PVC |
| 44 | Adaptor, 3/4" NPT(F) x 3/4" socket (F) | PVC |
| 45 | 3/4" NPT(M) nipple | PVC |
| 46 | Gate valve, both connections 3/4" NPT(F) | PVC |
| 47 | 3/4" NPT(M) nipple | PVC |
| 48 | Adaptor, 3/4" NPT(F) x 3/4" socket (F) | PVC |
| 49 | 3/4" pipe, sch. 40, plain ends for socket fittings, cut to ca. 4' to stretch from item 48 to settling basin (price included in item 31) | PVC |
| 50 | Adaptor, 3/4" NPT(F) x 3/4" socket (F) | PVC |
| 51 | 3/4" NPT(M) nipple | PVC |
| 52 | 3/4" tee with NPT(F) connections | PVC |
| 53 | Reducer bushing, 3/4" NPT(M) x 1/4" NPT(F) | PVC |
| 54 | Pressure gauge, 0-100 psi, 1/4" NPT(M) connection | various |
| 55 | Threaded reducer bushing, 3/4" NPT(M) x 1/2" NPT(F) | PVC |
| 56 | 1/2" NPT(M) nipple | PVC |
| 57 | V-strainer assembly with 24-mesh strainer insert and 1/2" NPT(F) inlet and outlet connections | bronze |
| 58 | 1/2" NPT(M) nipple | PVC |
| 59 | Pressure regulator with 1/2" NPT(F) inlet and outlet connections and 1/4" NPT(F) connection for pressure gauge | brass |
| 60 | Pressure gauge, 0-100 psi, 1/4" NPT(M) connection | various |
| 61 | 1/2" NPT(M) nipple | PVC |
| 62 | 1/2" tee with NPT(F) connections | PVC |
| 63 | Lock-on barb for adapting pipe thread to hose. 1/2" NPT(M) connection on one side, 1/2" hose barb (M) connection on other (minimum order quantity is 10, $2.45 each) | brass |
| 64 | 1/2" pressure hose, cut to stretch from item 63 (adaptor near first pressure regulator) to item 65 (adaptor near flow control valve on lagoon liquid line into crystallizer cone bottom), about 10' (minimum order is 100 feet at $1.4405 per foot) | various synthetic materials |
| 65 | Lock-on barb for adapting pipe thread to hose. 1/2" NPT(M) connection on one side, 1/2" hose barb (M) connection on other (price included in item 63) | brass |
| 66 | Union, 1/2" NPT(F) connections | PVC |

Table 26 (continued)

| | | |
|---|---|---|
| 67 | ½" NPT(M) nipple | PVC |
| 68 | Threaded reducer bushing, ¾" NPT(M) x ½" NPT(F) | PVC |
| 69 | Gate valve, both connections ¾" NPT(F) | PVC |
| 70 | Threaded reducer bushing, ¾" NPT(M) x ½" NPT(F) | PVC |
| 71 | ½" NPT(M) nipple | PVC |
| 72 | Flowmeter, 0-210 gallons per hour, with ½" NPT(F) connections | various |
| 73 | ½" NPT(M) nipple | PVC |
| 74 | Union, ½" NPT(F) connections | PVC |
| 75 | Lock-on barb for adapting pipe thread to hose. ½" NPT(M) connection on one side, ½" hose barb (M) connection on other (price included in item 63) | brass |
| 76 | ½" pressure hose, cut to stretch from item 75 (adaptor near flow control valve) to item 77 (adaptor at check valve on crystallizer inlet manifold), about 3' (price included in item 64) | various synthetic materials |
| 77 | Lock-on barb for adapting pipe thread to hose. ½" NPT(M) connection on one side, ½" hose barb (M) connection on other (price included in item 63) | brass |
| 78 | ½" check valve with ½" NPT(F) union-type connections | PVC |
| 79 | ½" NPT(M) nipple | PVC |
| 80 | Threaded reducer bushing, ½" NPT(F) x 2"NPT(M) | PVC |
| 81 | 2" tee with NPT(F) connections | PVC |
| 82 | 2" NPT(M) nipple | PVC |
| 83 | 2" cap with NPT(F) connection | PVC |
| 84 | 2" NPT(M) nipple | PVC |
| 85 | 2" tee with NPT(F) connections | PVC |
| 86 | 2" NPT(M) nipple | PVC |
| 87 | 2" cap with NPT(F) connection | PVC |
| 88 | Two tubing inserts for stabilizing ends of 3/8" OD x ¼" ID tubing for compression fittings | PVDF |
| 89 | Bulkhead union for 3/8" OD tubing | PVDF |
| 90 | Tubing, black UV-resistant, 3/8" OD x ¼" ID, cut to ca. 1-2" to set item 93 (ammonia dispersion tube) at proper extension from item 89 into intake manifold (minimum order quantity 100' for $11.03) | LLDPE |
| 91 | Two tubing inserts for stabilizing ends of 3/8" OD x ¼" ID tubing for compression fittings | PVDF |
| 92 | Union for 3/8" OD x ¼" ID tubing | PVDF |
| 93 | Gas dispersion tube, 12" long with 1" diameter porous bell, 3/8" OD tube connection (minimum order quantity is four at $7.25 each) | PE |
| 94 | 2" NPT(M) nipple | PVC |
| 95 | 2" tee with NPT(F) connections | PVC |
| 96 | 2" NPT(M) nipple | PVC |
| 97 | 2" flange with NPT(F) connection | PVC |
| 98 | Four nuts, four bolts, eight washers, and gasket for joining 2" flanges | steel, rubber |
| 99 | Crystallizer cone, 2" flange connection at bottom and 3" flange connection at overflow at top. 60" height, 1.5" diameter at bottom and 10" diameter at top. | FRP |

Table 26 (continued)

| | | |
|---|---|---|
| 100 | 3" flange with socket (F) connection | PVC |
| 101 | Four nuts, four bolts, eight washers, and gasket for joining 3" flanges | steel, rubber |
| 102 | 3" pipe, schedule 40, cut to ca. 4" to join item 100 and item 103 (minimum order quantity 10', $2.64/foot) | PVC |
| 103 | 3" elbow with socket (F) connections | PVC |
| 104 | 3" pipe, schedule 40, cut to ca. 6" to join items 103 and 105 (price included in item 102) | PVC |
| 105 | 3" light-weight hose, to slide over lip of item 104 and cut to ca. 8' to extend over edge of settling basin (minimum order quantity 25'; $1.45 per foot) | PP |
| 106 | Clamp to secure item 84 to item 83 | steel |
| 107 | 2" NPT(M) nipple | PVC |
| 108 | 2" ball valve with union-type connections; use NPT(F) connection on one side and socket-type (F) on other | |
| 109 | 3" pipe, schedule 40, cut to ca. 8" to stretch from item 87 to item 89 (price included in item 81) | PVC |
| 110 | 2" flange with socket (F) connection | PVC |
| 111 | Four nuts, four bolts, eight washers, and gasket for joining 2" flanges | steel, rubber |
| 112 | Product collector box and product collector basket | stainless steel |
| 113 | Tubing, black UV-resistant, 3/8" OD x ¼" ID, cut to ca. 4" to extend to center of item 85 (price included in item 90) | LLDPE |
| 114 | Two tubing inserts for stabilizing ends of 3/8" OD x ¼" ID tubing for compression fittings | PVDF |
| 115 | Bulkhead union for 3/8" OD tubing | PVDF |
| 116 | Tubing, black UV-resistant, 3/8" OD x ¼" ID, cut to ca. 6" to extend from item 117 (check valve for Mg solution) to item 115 (union for Mg solution tubing connection to crystallizer intake manifold) (price included in item 90) | LLDPE |
| 117 | 3/8" check valve with barb insert (M) connections | PVDF |
| 118 | Two clamps (1/4" to 5/8") for securing item 117 to items 116 and 119 | steel |
| 119 | Tubing, black UV-resistant, 3/8" OD x ¼" ID, cut to ca. 10' to extend from item 100 to item 121 (flowmeter for Mg solution) (price included in item 90) | LLDPE |
| 120 | Adaptor to join tubing to pipe thread, 3/8" OD tube connection on one side and ¼" NPT(F) on other | PVDF |
| 121 | Flowmeter, 0-22 gallons per hour, ¼" NPT(F) connections | various |
| 122 | Adaptor to join tubing to pipe thread, 3/8" OD tube connection on one side and ¼" NPT(F) on other | PVDF |
| 123 | Tubing, black UV-resistant, 3/8" OD x ¼" ID, cut to ca. 3' to extend from item 122 (adaptor at Mg solution flowmeter) to item 124 (connector at Mg solution feed pump) (price included in item 90) | LLDPE |
| 124 | Adaptor to join tubing to pipe thread, 3/8" OD tube connection on one side and 1/8" NPT(M) on other | PVDF |

Table 26 (continued)

| | | |
|---|---|---|
| 125 | Feed pump for Mg solution, variable speed gear-type, ca. 3 – 50 gallons per hour, 1/8” NPT(F) connections | various |
| 126 | Adaptor to join tubing to pipe thread, 3/8” OD tube connection on one side and 1/8” NPT(M) on other | PVDF |
| 127 | Tubing, black UV-resistant, 3/8” OD x ¼” ID, cut to ca. 10’ to extend from item 126 (adaptor at Mg solution feed pump) to item 128 (Mg solution surge tank) (price included in item 90) | LLDPE |
| 128 | Surge tank for Mg solution | PE |
| 129 | Float valve, ½” NPT(M) connections for pipe and ¼”-20 threaded stem end for float | bronze |
| 130 | Float with ¼”-20 thread connection for valve stem | copper |
| 131 | Bulkhead fitting with ½” NPT(F) connections on both ends | PVC and Flourel |
| 132 | ½” NPT(M) nipple | PVC |
| 133 | V-strainer assembly with 24-mesh strainer insert and ½” NPT(F) inlet and outlet connections | bronze |
| 134 | ½” NPT(M) nipple | PVC |
| 135 | Pressure regulator with ½” NPT(F) inlet and outlet connections and ¼” NPT(F) connection for pressure gauge | brass |
| 136 | Pressure gauge, 0-100 psi, ¼” NPT(M) connection | various |
| 137 | ½” NPT(M) nipple | PVC |
| 138 | ½” check valve with ½” NPT(F) union-type connections | PVC |
| 139 | ½” NPT(M) nipple | PVC |
| 140 | Threaded reducer bushing, ½” NPT(F) x 2”NPT(M) | PVC |
| 141 | 2” tee with NPT(F) connections | PVC |
| 142 | 2” NPT(M) nipple | PVC |
| 143 | 2” cap with NPT(F) connection | PVC |
| 144 | Two tubing inserts for stabilizing ends of 3/8” OD x ¼” ID tubing for compression fittings | PVDF |
| 145 | Bulkhead union for 3/8” OD tubing | PVDF |
| 146 | Gas dispersion tube, 1” diameter porous bell, 3/8” OD tube connection, cut to length to position bell in center of tee (price included in item 93) | PE |
| 147 | Tubing, black UV-resistant, 3/8” OD x ¼” ID, cut to ca. 6” to extend from item 148 (check valve for carbon dioxide) to item 145 (union for carbon dioxide tubing connection to carbonator tee) (price included in item 90) | LLDPE |
| 148 | 3/8” check valve with barb insert (M) connections | PVDF |
| 149 | Two clamps (1/4” to 5/8”) for securing item 148 to items 147 and 150 | steel |
| 150 | Threaded reducer bushing, ½” NPT(F) x 2”NPT(M) | PVC |
| 151 | Lock-on barb for adapting pipe thread to hose. ½” NPT(M) connection on one side, ½” hose barb (M) connection on other (price included in item 63) | brass |
| 152 | ½” pressure hose, cut to ca. 15’ length (price included in item 64) | various synthetic materials |
| 153 | Lock-on barb for adapting pipe thread to hose. ½” NPT(M) connection on one side, ½” hose barb (M) connection on other (price included in item 63) | brass |

Table 26 (continued)

| | | |
|---|---|---|
| 154 | Union, ½" NPT(F) connections | PVC |
| 155 | ½" coupling, NPT(F) connections | PVC |
| 156 | Lock-on barb for adapting pipe thread to hose. ½" NPT(M) connection on one side, ½" hose barb (M) connection on other (price included in item 63) | brass |
| 157 | ½" pressure hose, cut to ca. 8' length to stretch from item 156 (adaptor at float valve outlet in surge tank to item 158 (adaptor at dissolver bottom) (price included in item 64) | various synthetic materials |
| 158 | Lock-on barb for adapting pipe thread to hose. ½" NPT(M) connection on one side, ½" hose barb (M) connection on other (price included in item 63) | brass |
| 159 | Union, ½" NPT(F) connections | PVC |
| 160 | ½" NPT(M) nipple | PVC |
| 161 | Reducer bushing, ½" NPT(F) x ¾" NPT(M) | PVC |
| 162 | Gate valve, both connections ¾" NPT(F) | PVC |
| 163 | Reducer bushing, ½" NPT(F) x ¾" NPT(M) | PVC |
| 164 | ½" NPT(M) nipple | PVC |
| 165 | ½" check valve with ½" NPT(F) union-type connections | PVC |
| 166 | ½" NPT(M) nipple | PVC |
| 167 | Threaded reducer bushing, ½" NPT(F) x 2"NPT(M) | PVC |
| 168 | 2" ball valve with NPT(F) union-type connections | |
| 169 | 2" NPT(M) nipple | PVC |
| 170 | 2" flange with NPT(F) connection | PVC |
| 171 | Four nuts, four bolts, eight washers, and gasket for joining 2" flanges | steel, rubber |
| 172 | Mg dissolver, with 2" bottom flange and 3" flange at overflow at top. Same as # 99. | FRP |
| 173 | 3" flange with socket (F) connection | PVC |
| 174 | Four nuts, four bolts, eight washers, and gasket for joining 3" flanges | steel, rubber |
| 175 | 3" pipe, schedule 40, cut to ca. 4" to join item 173 and item 176 (price included in item 102 ) | PVC |
| 176 | 3" elbow with socket (F) connections | PVC |
| 177 | 3" pipe, schedule 40, cut to ca. 6" to join items 103 and 105 (price included in item 102) | PVC |
| 178 | 3" light-weight hose, to slide over lip of item 104 and cut to ca. 6' to extend into surge tank (price included in item 84) | PP |
| 179 | Clamp to secure item 178 to item 179 | steel |
| 180 | Tubing, black UV-resistant, 3/8" OD x ¼" ID, cut to ca. 15' to extend from item 148 (check valve for carbon dioxide) to item 181(adaptor at carbon dioxide flow/pressure regulator) (price included in item 90) | LLDPE |
| 181 | Adaptor for tubing (3/8" OD) to 3/8" NPT(M) | PVDF |
| 182 | Tubing insert for stabilizing end of 3/8" OD x ¼" ID tubing for compression fitting | PVDF |
| 183 | Carbon dioxide pressure/flow regulator, with 3/8" NPT(F) connection on one end and CGA connection to fit carbon dioxide cylinder on other | various |
| 184 | Carbon tank, with CGA connection | steel |

Table 26 (continued)

| | | |
|---|---|---|
| 185 | Cylinder clamp | various |
| 186 | Tubing, black UV-resistant, 3/8" OD x 1/4" ID, cut to ca. 3' to extend from item 83 (cap at crystallizer inlet manifold) to item 187 (check valve for ammonia) (price included in item 90) | LLDPE |
| 187 | 3/8" check valve with barb insert (M) connections | PVDF |
| 188 | Two clamps (1/4" to 5/8") for securing item 187 to items 186 and 189 | steel |
| 189 | Tubing, black UV-resistant, 3/8" OD x 1/4" ID, cut to ca. 25' to extend from item 187 (ammonia check valve) to item 190 (adaptor at ammonia flowmeter) (price included in item 90) | LLDPE |
| 190 | Adaptor to join tubing to pipe thread, 3/8" OD tube connection on one side and 1/8" NPT(M) on other | PVDF |
| 191 | Ammonia flow meter, 1/8" NPT(F) connections | various synthetic materials |
| 192 | Adaptor to join tubing to pipe thread, 3/8" OD tube connection on one side and 1/8" NPT(M) on other | PVDF |
| 193 | Tubing, black UV-resistant, 3/8" OD x 1/4" ID, cut to ca. 3' to extend from item 193 (ammonia flow meter) to item 194 (adaptor at ammonia pressure regulator) (price included in item 90) | LLDPE |
| 194 | Adaptor, 3/8" OD tube connection on one side and 1/4" NPT(M) on other | PVDF |
| 195 | Ammonia presssure regulator, with 1/4" NPT(F) outlet connection and CGA 240 inlet connection | various |
| 196 | ammonia cylinder, with CGA 240 connection | steel |
| 197 | cylinder clamp | various |

# APPENDIX D: DETAILS ON OPERATING METHOD FOR THE FIELD-SCALE CRYSTALLIZER

The following are general procedures for starting up and shutting down the field-scale system and for removing product. Referring to Figure 50 in Appendix C will ease understanding of the procedures.

**Starting Up**

To start up the system, first start up the liquid flows and adjust their pressures and flow rates. To begin, open the valve on the line that recycles back to the lagoon at the discharge of the raw lagoon water pump. If the system has been idle long enough for liquid to drain through the foot valve in the pump suction line, it will be necessary to prime the pump by filling the suction line with water at one of the connections near the pump. Start up the pump, and once strong, constant flow out the recycle line is observed, the valve on the line into the crystallizer can be opened. If the plug valve at the crystallizer has been firmly seated into the cone bottom, it will have to be loosened or removed to allow flow through the crystallizer. The valve on the recycle line can then be closed enough to raise the pressure on the pump discharge gauge to about 60 psi, which is 414 kilopascals (kPa). The first pressure regulator should then be adjusted to provide a pressure of about 40 psi (276 kPa) on the gauge downstream from it. The second pressure regulator should be adjusted to provide about 20 psi (138 kPa) on the gauge downstream from it. To adjust this pressure properly, the float valve should be open at the Mg surge tank to ensure some flow through the second pressure regulator. If the float valve is closed, it can be opened by pushing down on the float or by removing liquid from the tank. Also, in the event the plug valve in the dissolver bottom has become tightly seated, it should be loosened to ensure liquid can flow through the dissolver.

Once the regulators have been adjusted to provide the proper pressures, the valve at the flowmeter to the crystallizer can be set to the desired flow rate of about 117 gal per h (443 L/h). The bed in the crystallizer can be viewed through the crystallizer wall to note the position of the bed top and the character of bed motion. The Mg pump can then be started, and the motor speed control used to bring the flow rate as read on the flowmeter to 10 gal per h (37.9 L/h). The flow rate can be adjusted as necessary to achieve the target supplementation of 30 ppm to the liquid entering the crystallizer, based on sampling and analysis of the Mg solution from the surge tank. The bed in the dissolver should also be viewed to ensure there is motion, indicating the liquid is percolating through the bed. If the bed top has fallen to below the desired level of about 8 in (20.3 cm) from the bottom, magnesite can be added by filling a bottle or small can half full with magnesite, then wetting it with liquid and pouring it into the dissolver top. If the float has been pushed down to achieve flow at the float valve for start-up, the float valve can now be released.

The pressures and flows of the gases can then be started. Open the valve at the ammonia tank and at the ammonia flowmeter. Set the ammonia pressure regulator to 10 to 15 psi (69 to 103 kPa), then the flow meter to the rate necessary to achieve the desired pH rise in the crystallizer. In the current design, a pH rise of about three-quarters of a pH point is called for, and a flowmeter reading of 10% to 15% will likely be needed. This reading will permit 20 to 40 g/h of ammonia to flow, or about 25 to 50 L/h at standard temperature and pressure. To measure the pH rise, use a pH meter to compare the pH in the raw liquid against the pH in the liquid at the crystallizer top. Now check the Mg surge tank to see if its liquid level has stabilized. If so, open the valve on the $CO_2$ tank and set the pressure regulator to about 22 psi (152 kPa), or about 2 psi (14 kPa) above the pressure indicated downstream of the second pressure regulator on the liquid lines. Set the valve on the $CO_2$ flow meter to achieve a pH in the dissolver overflow of about one point below the raw lagoon water pH. If the valve at the flowmeter is opened all the way, yet the pH at the dissolver top remains too high, increase the pressure on the $CO_2$ pressure regulator by 2 psi (14 kPa). Several minutes should be allowed after adjusting the $CO_2$ flow rate before checking the pH at the dissolver top, because it will take a few minutes for a change in $CO_2$ flow to result in pH change.

**Shutting Down**

The shut-down procedure will be in general the reverse of the start-up. Turn the $CO_2$ pressure regulator to zero and close the valves at the $CO_2$ tank and flowmeter. Turn the ammonia pressure regulator also to zero, and close the valves at the ammonia tank and flowmeter. Turn off the Mg pump. Place the plug valve loosely in the crystallizer bottom if it has been removed. Open fully the valve on the recycle line from the main pump discharge and close the valve at the flowmeter into the crystallizer to shut off flow to the crystallizer. Turn off the main pump and then close the recycle valve to prevent slow leakage of liquid in the suction through the foot valve. Slowing the leakage will better maintain the prime on the main pump for easier start-up.

**Removing Product**

Product should be removed from the crystallizer periodically to prevent the bed top from rising so high that bed material could overflow into the exiting treated liquid. Keeping the bed from growing too heavy will also minimize chances that the bed will develop a channel instead of fluidizing evenly.

Product can be removed without shutting the system down. First, check to make sure the cap has been screwed onto the drain of the product chamber. Then, if the chamber is not already filled with liquid, remove the cap from the fill line and, using a hose, fill the chamber with water and replace the cap. Bail one or two buckets of liquid from the crystallizer top to lower the liquid level to several in below the overflow. Then, immediately open the ball valve above the product chamber to release any remaining trapped air before the liquid level rises to the overflow level, thus providing an opportunity for any bed material stirred up by the escaping air to settle before liquid again begins to overflow. Turn the Mg liquid and ammonia flows to one-quarter or less of their normal flow rates. Using the valve at the flowmeter for liquid into the crystallizer, reduce the flow rate until bed material can be seen falling into the collector basket.

When the basket appears nearly full, increase the crystallizer liquid flow, the Mg liquid flow, and the ammonia flow to their normal levels again. Close the ball valve above the product chamber and place the plug valve loosely into the crystallizer bottom. Drain the liquid from the product chamber by removing the drain cap. Unfasten the door on the chamber and remove the filled basket. Slide an emptied one back into the chamber and re-secure the door. Screw the cap back onto the drain and open the fill line, re-fill the chamber with water, and screw the cap onto the fill line. Empty the product from the filled basket onto a smooth surface and spread into a thin layer to dry.

## APPENDIX E: EXAMPLE CALCULATIONS FOR ESTIMATING RATE CONSTANT

This appendix illustrates how the data presented in Figure 10 on page 43 was used in estimating the rate constant. The method is illustrated here by showing the calculations for the fifth time segment in Figure 10, which stretches from 152 sec (0.0422 hr) to 377 sec (0.1047 hr).

By solving equation (4) on page 39 for k', the rate constant, we find that it is the product of three factors:

$$k' = \left(\frac{-dP}{dt}\right)\left(\frac{1}{m}\right)\left(\frac{1}{(P-P_e)}\right) \tag{47}$$

The first factor can be approximated by the drop in *P*, the product of the Mg, TAN, and OP molarities during the time segment, divided by the time elapsed during the segment. Analyses indicated that the sample pipeted at the beginning of the segment contained 0.00207 mol/L Mg, 0.0290 mol/L TAN, and 0.00381 mol/L OP. Multiplying the three together yields the beginning *P*, 0.000000229 $(mol/L)^3$. The sample pipeted at the end of the segment contained 0.00193 mol/L Mg, 0.0284 mol/L TAN, and 0.00362 mol/L OP, yielding a *P* of 0.000000198 $(mol/L)^3$. Subtracting the ending *P* from the beginning *P* and dividing by the time elapsed, 0.0625 hr, gives 0.000000496 $(mol/L)^3$/hr, the estimate for the first factor in equation (47).

The second factor in equation (47) is the reciprocal of *m*, the struvite surface area per volume of liquid. The quantity 1/*m*, then, can be estimated by dividing the volume during the segment, which was 0.324 $dm^3$, by the estimated surface area, 2.73 $dm^2$. The result, 0.119 dm, is the estimate for the second factor. The surface area was estimated by multiplying the surface-to-volume ratio of spheres ($4\pi r^2/[4/3]\pi r^3$, or 3/r) to the estimated volume of the struvite. Here r, the radius, of the struvite particles is estimated at 0.109 cm, which is half of the average of the opening diameters of the two sieves used to select the struvite particles. The estimated volume was 9.94 cc, which is its weight

(16.9 g) divided by the density of struvite (1.7 g/cc). Multiplying this volume by 3/(0.109 cm) gives the estimated surface area of 273 $cm^2$, or 2.73 $dm^2$.

To estimate the third factor in equation (47), the quantity ($P - P_e$) was averaged over the segment, using the beginning and ending values. The pH was measured at 8.95 at both the beginning and end of the segment, therefore the value of $P_e$ at both the beginning and end can be read as approximately $10^{-8.7}$, or 0.000000002, from Figure 1 on page 12. The average ($P - P_e$), then, is [(0.000000229 – 0.000000002) + (0.000000198 – 0.000000002)]/2, or 0.000000212 $(mol/L)^3$. The third factor is the reciprocal of this estimate, or 4,720,000 $(mol/L)^{-3}$.

Multiplying the three factors [0.000000496 $(mol/L)^3$/hr, 0.119 dm, and 4,720,000 $(mol/L)^{-3}$] together yields the estimate for k': 0.279 dm/hr.