(A) General Design Criteria for Limestone Contactors Installed in Small Water Systems

A designer of limestone contactor should be aware of the various factors affecting limestone dissolution before designing a contactor to ensure its optimal performance. In summary, the factors that can affect the dissolution of limestone include the quality of water to be stabilized and the physical and chemical characteristics of limestone to be used.

Design Criteria	U.S.	Germany	South Africa
Location in the Treatment Train	Limestone contactors are typically placed after filtration, primary disinfection and chlorine contact. (Spencer, 2000). There was also a pilot study conducted in British Columbia (Benjamin et al.,1992) that used a limestone contactor before flocculation to condition the water. Note: Besides the typical locations noted here, there have been suggestions that limestone contactors could also be used as a pretreatment unit to adjust pH for removal of iron, manganese and aluminum.	Limestone contactors should be placed after disinfection (Stauder, 2002).	Limestone contactors should be placed after clarification, filtration and chlorination (Mackintosh, De Souza and De Villiers, 2003a).
Water Quality Characteristics	The water to be treated with a limestone contactor must have low iron and turbidity content (Snoeyink et al., 1997). The USEPA (2003) prepared a flow diagram (Figure 1) to determine whether a limestone contactor would be a feasible option for a water system. The decision would be based on assessing the water quality parameters of the system. In summary, a water system should have a pH < 7.2, calcium < 60 mg/L and alkalinity < 100 mg/L. A special contactor design is required if the iron	In order to determine whether a limestone contactor is feasible to treat a water system, the following water quality parameters must be known (DVGW, 1998): • Acid consumption, $K_{S,4.3}$ The acid consumption, $K_{S,4.3}$ is the acid consumption in meq/liter to achieve a pH of 4.3. This value multiplied by 61 approximately equals the concentration of hydrogen carbonate, HCO_3^- in ppm (Beforth, 2003). • Base consumption, $K_{B,8.2}$ The base consumption, $K_{B,8.2}$ is the amount of base consumed by water in meq/liter to	The iron levels must be < 0.1 mg/L, aluminum levels < 0.15 mg/L and turbidity < 1 NTU (Mackintosh, De Souza and De Villiers, 2003a).

	content is more than 0.2 mg/L and manganese content is more than 0.05 mg/L. This is due to possibility of the iron and manganese coating the contactor, and slows the calcium carbonate dissolution (USEPA, 2003). The Spraystab I design has been used in South Africa for treatment of water that contains more than 0.2 mg/L of iron and 0.05 mg/L or manganese and treated with a limestone contactor. The water can first be aerated, then stabilized with limestone contactor and finally filtered through a sand filter. The values in Figure 1 are similar to those given by Spencer (2000) except that alkalinity was given as < 50 mg/L and hardness < 50 mg/L. In addition to the above, the designer must know the temperature range, total inorganic carbon levels (DIC) and total dissolved solids or conductivity.	achieve a pH of 8.2 (Beforth, 2003). This value multiplied by 44 approximately equals the concentration of carbon dioxide, CO_2 in ppm. • Calcium concentration • Saturation pH value, pHc after addition of calcite. According to Beforth (2003), since the reactivity of limestone is very low, one would find that $K_{S,4.3}$ and $K_{B,8.2}$ should be very low to achieve a pH in a range of 7.7 – 8.0. In addition, iron, manganese and aluminum levels must be less than the following concentrations to prevent formation of residue on the surface of the limestone media (DVGW, 1998): • Iron < 0.2 mg/L • Manganese < 0.05 mg/L • Aluminum < 0.05 mg/L If residues are formed, then iron, manganese, or aluminum removal may be required ahead of the limestone contactor (DVGW, 1998).	
Empty Bed Contact Time (EBCT)	EBCT is in the range of 20 to 40 minutes if water is less than 5 °C, otherwise, EBCT in the range of 15 minutes to 1 hour have been used in successful contactor design. (Spencer, 2000).	EBCT is the most important design criteria in Germany. EBCT usually varies between 20 and 45 minutes (0.33-0.75 h), depending on the CO_2 and HCO_3^- contents in the raw water (Stauder, 2002).	EBCT more than 20 minutes unless determined to be otherwise on-site. (Mackintosh, De Souza and De Villiers, 2003a).
Loading Rate	2.4 m/hr or 1 gpm/ft^2 (Spencer, 2000).	The typical loading rates are in the range of 4 - 8 m/hr or 1.7 - 3.3 gpm/ft^2 for common bed depth of 2 to 3 m. (Stauder, 2003).	Less than 10 m/hr or 4.1 gpm/ft^2 (Mackintosh, De Souza and De Villiers, 2003a).

Flow Requirements	Limestone contactors must be designed to treat the maximum flow of the plant. (Spencer, 2000).	The flow to the limestone contactor must not exceed the maximum design capacity (DVGW, 1998). If dolomite is used as a media, the flow rate should not fall below the design flow rate by more than 30% (DVGW, 1998) to avoid the water from becoming oversaturated with respect to $CaCO_3$ and precipitating in the contactor (Stauder, 2003).	Ensure equal flow into all limestone contactors, and the flow should be less than the maximum design capacity. (Mackintosh, De Souza and De Villiers, 2003a).
Limestone Bed Depth	Limestone bed depth can be determined by calculation using computer programs such as DESCON and Limestone Bed Contactor: Corrosion Control and Treatment Analysis Program Version 1.02. (Please refer to the design aids).	The limestone bed depth can be determined using the appropriate Figure 4 to 8 and the equations discussed in the design aids section. However, the typical limestone bed depth is in the range of 2 to 3 m (Stauder, 2003). If dolomite is used as a media, the total filter bed volume should be distributed across several filters to minimize pH fluctutations.	Minimum limestone bed depth of 2 m is recommended (Mackintosh, De Souza and De Villiers, 2003a).
Limestone Characteristics	Limestone used should be that described in ASTM Standard C51-02 as “sedimentary rock consisting of mainly carbonate and containing no more than 0 to 5% magnesium carbonate” (Spencer, 2000). This standard is available from http://www.astm.org. The weighted sum of aluminum and iron in stone must not exceed 10 mg/g of stone (Letterman, 1995). Testing of constituents of stone must adhere to the ASTM Standard 25-99 (Chemical Analysis of Limestone, Quicklime and Hydrated Lime) (Spencer, 2000). The USEPA (2003) has expressed concern that the limestone should not contain significant amounts of materials such as heavy metals that would be	There are several types of limestone media discussed by DVGW(1998) that can be used in a limestone contactor. These include dense calcium carbonate, porous calcium carbonate and dolomite. Dolomite is suitable to be used in a large contactor since it will provide a lower contact time (Stauder, 2002) although it also has some disadvantages (Please refer to the flow requirements section). The following shows the water quality characteristics that are applicable for each type of the limestone media (DVGW, 1998): **a) Dense Calcium Carbonate** **i. Target pH=8** $K_{S,4.3} + 2K_{B,8.2} < 1.5\ mol/m^3$ $[Ca] < 0.75\ mol/m^3$ **ii. Target pH=saturation pH** $K_{S,4.3} + 2K_{B,8.2} < 1.0\ mol/m^3$ $[Ca] < 0.75\ mol/m^3$ **b) Porous Calcium Carbonate** $K_{S,4.3} + 2K_{B,8.2} < 1.5\ mol/m^3$	Limestone used should consists of high calcium and low magnesium stone. Currently, limestone used to date in several installations in South Africa is the commercially available limestone pebbles from Bredasdorp, South Western Cape (De Souza et. al., 2000 and Mackintosh et. al., 2003a). It consists of 96% calcium, 1.7% silica, 1.3% magnesium and less than 0.1% iron and manganese by mass.

	imparted to the water as the limestone dissolves.	$[Ca] < 0.75$ mol/m^3 **c) Half-Burnt Dolomite** $K_{S,4.3} + 2K_{B,8.2} < 2.5$ mol/m^3 Depending on the type of limestone used (either calcium carbonate or half-burnt dolomite), it must comply with the requirements outlined in the following British Standards: • BS EN 1018:1998 (Chemicals used for treatment of water intended for human consumption – Calcium Carbonate). • BS EN 1017:1998 (Chemicals used for treatment of water intended for human consumption – Half Burnt Dolomite). These documents are available from http://www.techstreet.com/info/bsi.html	
Limestone Grain Sizes	Repeated runs using DESCON revealed that 11 to 14 mm stone (0.4 to 0.55 inch) seems to be an optimal size. (Spencer, 2000).	The following grain sizes are commercially available for calcium carbonate and half-burnt dolomite. • Dense Calcium Carbonate : 0.71-1.25 mm, 1.0-2.0 mm, 1.6-2.5 mm • Porous Calcium Carbonate : 1.0 – 3.0 mm • Half-Burnt Dolomite: 0.5-1.2 mm, 0.5-2.5 mm, 2.0-4.5 mm, 4.0-7.0mm (Note: If undersized or oversize grains are present, they cannot be larger than 10% for the individual group.) However, size range of 1.0-2.0 mm is commonly used in Germany. Although, in some of the older large water treatment plants that are not able to properly backwash, larger media sizes are used. Based on experience, there is not a significant change in the	Limestone used has a grading of +12mm – 15mm (De Souza et. al., 2000). The size of limestone that produced optimal results is 12 mm (Spencer, 2000).

		reactivity of the media for the size range between 0.7-3.0 mm (Stauder, 2003).	
Supporting Media	Supporting media used is based on the AWWA Standards for Filtering and Support Media (Spencer, 2002). The size of the support media used should be larger than the limestone size (Spencer, 2002).	Supporting media consists of 0.2 – 0.3 m in depth of inert materials (DVGW, 1998).	Supporting media consists of 150 mm deep, 25 mm diameter granite aggregrate (Mackintosh, De Souza and De Villiers, 2003a).
Design Aids	DESCON model was developed by Letterman and Kothari (1995) to aid in the design of limestone contactors. This computer program has been used by Spencer (2002) to design the limestone contactor facility in Mars Hill, Maine. This program is also recommended for the design of a limestone contactor by USEPA (2003). DESCON calculates the depth of limestone required in a contactor based on the influent water chemistry, limestone particle size, superficial velocity and the desired effluent water chemistry (Letterman, 1995). Figure 2 shows an output from DESCON using USEPA (2003) data from a typical Western Water System as input to the program. In this system, surface water contributes 80% of the amount of water supplied. The limestone diameter was entered as 12 mm and limestone $CaCO_3$ content as 98%. DESCON calculated the equilibrium pH to be 8.82 and it required user input for the target pH.	A guideline for designing a limestone contactor is available (W 214/II: Entsaurung von Wasser Teil 2: Grundsatze fur Planung, Betrieb und Unterhaltung von Filteranlagen) from DVGW (1998). However, this guideline is based on empirical correlations. Therefore, Stauder (2003) suggests that for smaller plants, the limestone bed volume can be designed using the guideline and for larger plants, the limestone bed volume should be designed based on a pilot plant study. Stauder (2003) also suggests that it is very important (before designing) to obtain a reliable water analysis since any erroneous values can greatly affect the design. Computer software that can determine the calcium carbonate saturation of water is also very useful. Figure 4 to 8 are used to determine contact time using base and acid consumption of water at temperature of 10 °C for each of the following conditions. The contact time is then used to determine the minimum volume of media required in a contactor for several alternatives: (i) Dense calcium carbonate with grain size ranges between 1.0 – 2.0 mm and a target pH value of either 8 or pHc.	$CaCO_3$ saturation characteristics of water can be determined experimentally using the Marble Test. The Marble Test is an experiment based method to determine calcium carbonate saturation characteristics of water. Computer program such as STASOFT also used to determine the $CaCO_3$ saturation and degree of stabilization of water using $CaCO_3$.

	The target pH must be less than the equilibrium pH. Therefore, the target pH was set at 8.5. Based on the DESCON output, the depth of the limestone contactor to reach a target pH of 8.5 for this system was calculated as 3.1 ft. Another program used to design a limestone contactor was developed by Schott (2002) called Limestone Bed Contactor: Corrosion Control and Treatment Process Analysis Program Version 1.02. This program calculates the depth of the limestone bed, empty bed contact time and the limestone dissolved per volume of water treated from the initial to equilibrium condition. Other additional parameters that are calculated using this program include pH, total alkalinity, CO_2 concentration, DIC, calcium content and copper content from the initial to equilibrium condition. Figure 3 shows example of the software output.	(ii) Porous calcium carbonate with grain size ranges between 1.0 – 3.0 mm and a target pH value of either 8 or pHc. (iii)Half-burnt dolomite with grain size ranges between 0.5 – 2.5 mm and a target pH value of pHc. If the grain sizes used are not within the range specified in the figures, manufacturer's recommendations should be used in designing a contactor. Figure 9 is used for temperature correction. Using Figure 4 to 8, the minimum volume of the limestone media required can be calculated as follows (DVGW, 1998): (i) Minimum volume of Limestone,V_M: V_M = Q x t_f x f x 1/60 where: V_M = minimum volume of media, m^3 chosen using the appropriate Figure 4 to 8 (For dense $CaCO_3$, V_M may be lower than calculated if the target pH is less than 8.0 or pHc (Stauder, 2003). Currently in Germany, the enforceable pH for corrosion control is around 7.4 to 7.6. Therefore, the V_M used can be about half of the calculated.) Q = flow rate, m^3/hr t_f = hypothetical contact time, min f = temperature correction factor (refer to Figure 9) Additional media, V_B, is then added to the V_M to account for media consumption during the period between two media fillings and backwashing (Stauder, 2003). Since V_M is the minimum amount of media required in a contactor to achieve the desired pH, therefore	

		V_B must be added so that the volume of the media after consumption will never be less than V_M. According to Stauder (2003), it requires experience to determine V_B. It may depend on several factors besides media consumed due to the acidity of water or backwashing, such as the capacity of the truck used to transport the media, the size of the silo and the distance between the water treatment facility and the limestone supplier facility. However, V_B can be estimated based on the following (Stauder, 2003): *Estimation of V_B:* The amount of media consumed can be calculated based on the acidity of the water or the amount of CO_2 present in the water (can be calculated from $K_{B8.2}$). For example, for every mol of CO_2 reacting with $CaCO_3$ in water, 100 g of $CaCO_3$ is consumed according to the following reaction: $CO_2 + CaCO_3 + H_2O = Ca^{2+} + 2HCO_3^-$ If dolomite is used, for every mol of CO_2 reacting with dolomite in water, 47 g of dolomite is consumed as determined empirically. Using the densities of $CaCO_3$ and dolomite, the volume of media consumed can be calculated. In addition, 10% can be added to account for media losses during backwashing. The sum of V_B and V_M is the volume of the limestone bed, V_F calculated as follows (DVGW, 1998): (ii) Filter Bed Volume, V_F: $V_F = V_M + V_B$ where:	

		V_F = filter bed volume, m^3 V_B = consumption volume, m^3 Click on this link to view an example on how to use Figure 4 to 10.	
Influent Distribution Systems		For small contactor facilities, there is no requirement on the influent distribution system as long as the contactors can be filled with water (Stauder, 2003). Special distribution system is only needed for large contactors.	Use a false bottom feed systems instead of manifold/slotted pipe or other type systems (Mackintosh, De Souza and De Villiers, 2003a).
Piping Requirements	A bypass around the contactor and a drain within the contactor must be available to allow annual maintenance of a contactor (Spencer, 2000).	Limestone contactors need to be equipped with devices for drainage of initial filtrate (DVGW, 1998).	Piping to and from the units should be such that each individual contactor is able to operate independently, be filled independently, be flushed to waste in both upflow and downflow mode and handle excessive flow loading via an overflow pipe to waste (Mackintosh, De Souza and De Villiers, 2003a).
Installation Requirements		The number of contactors that need to be installed depends on the site specification and plant throughput (Stauder, 2003).	At least two contactors should be installed for each water system to allow uninterrupted operation while one of the contactors is under maintenance (Mackintosh, De Souza and De Villiers, 2003a).
Contactor Configuration	Both cylindrical and box-shaped contactors have been designed in the U.S.	Most of the older water systems are rectangular open tanks and most of the newer water systems are cylindrical pressure tanks (Stauder, 2003). However, the configuration depends on the amount of water to treat and the benefit of keeping the pressure (Stauder, 2003).	Cylindrical configuration, with ratio of height to diameter of at least 1:1. The structure should be completely enclosed, with access hatch on top for limestone addition. (Mackintosh, De Souza and De Villiers, 2003a).

			Rectangular configuration is also possible. However, the hydraulics of the system must be taken into consideration. The ratio of height to wall length must be at least 1:1 and the corners of the contactor must be benched/curved. The curved benching must be at least one quarter of the wall length.
Construction Material		Concrete is usually used for open contactors and stainless steel is typically used for closed contactors (Stauder, 2003).	Cement-concrete or fiberglass (Mackintosh, De Souza and De Villiers, 2003a).
Contactor Wall Protection		For open contactors, the wall can be protected from corrosion using ceramic tiles while in the closed contactors, the wall can be protected with epoxy coating (Stauder, 2003).	The internal contactor wall should be coated (for example with epoxy coating) to protect it from aggressive or abrasive reaction. (Mackintosh, De Souza and De Villiers, 2003a).

<table>
<tr><td>Backwash Requirements</td><td></td><td>Depending on the type of media, the limestone contactors should be backwashed at least once a week (DVGW, 1998). If the head loss increases above the allowed value, backwashing needs to be done more frequently.

The following shows a successful backwash practice in Germany (DVGW, 1998):
<table>
<tr><th colspan="2" rowspan="2">Backwash Step</th><th rowspan="2">Duration (minutes)</th><th colspan="2">Backwash Rate (m/hr)</th></tr>
<tr><th>Air</th><th>Water</th></tr>
<tr><td>1</td><td>Air</td><td>3 – 5</td><td>60</td><td>None</td></tr>
<tr><td>2</td><td>Air/Water</td><td>5 – 10</td><td>60</td><td>10 – 12</td></tr>
<tr><td>3</td><td>Water</td><td>None Specified[a]</td><td>None</td><td>12 – 25</td></tr>
</table>[a] The common duration is 10 – 15 minutes (Stauder, 2003).

According to DVGW (1998), the dirty water from the backwash process contains solids (such as iron flocs, manganese flocs, aluminum flocs and undersized media) that may be basic. This is especially true for contactors using half-calcine dolomitic lime and if backwashing is carried out for the first time on a new media or after long idle periods. The backwash water does require proper disposal.</td><td>The limestone contactors must be able to down-flush fines to waste at least once a month until the site-specific frequency is determined (Mackintosh, De Souza and De Villers, 2003a).</td></tr>
<tr><td>Water Quality Monitoring Requirements</td><td></td><td>Limestone contactors must be equipped with water quality monitoring taps before and after stabilization (DVGW, 1998). The most important parameter to measure is pH of the effluent from the contactor especially for a contactor using dolomitic limestone as a media.

Limestone contactors should have visible indicator showing the level for media refilling</td><td>Provide sample taps for water quality monitoring before and after stabilization. (Mackintosh, De Souza and De Villiers, 2003a).

Provide two piezometers on each contactor to measure pressure loss across the limestone bed (Mackintosh, De</td></tr>
</table>

		(DVGW, 1998). The media refill level is determined from the filter bed volume and minimum volume. Limestone contactors must be equipped with devices for measuring head loss (DVGW, 1998).	Souza and De Villiers, 2003a). Pressure loss measurement is necessary to indicate that the limestone fines in the contactor need to be “down flushed”.
Media Refilling Facility		The media can be refilled into the contactor either manually or hydraulically, but hydraulically is preferred (DVGW, 1998).	The media can be refilled in a contactor manually or using a loading gantry facility (Mackintosh, De Souza and De Villiers, 2003). Usually, media refills are done manually if the limestone comes in lighter packages (i.e. 25 kg bags), but typically in the recent large units, a loading gantry facility is used since the limestone comes in heavier packages (1 ton bags).

FIGURES

Figure 1. Limestone Contactor Decision Tree (Spencer, 2003)

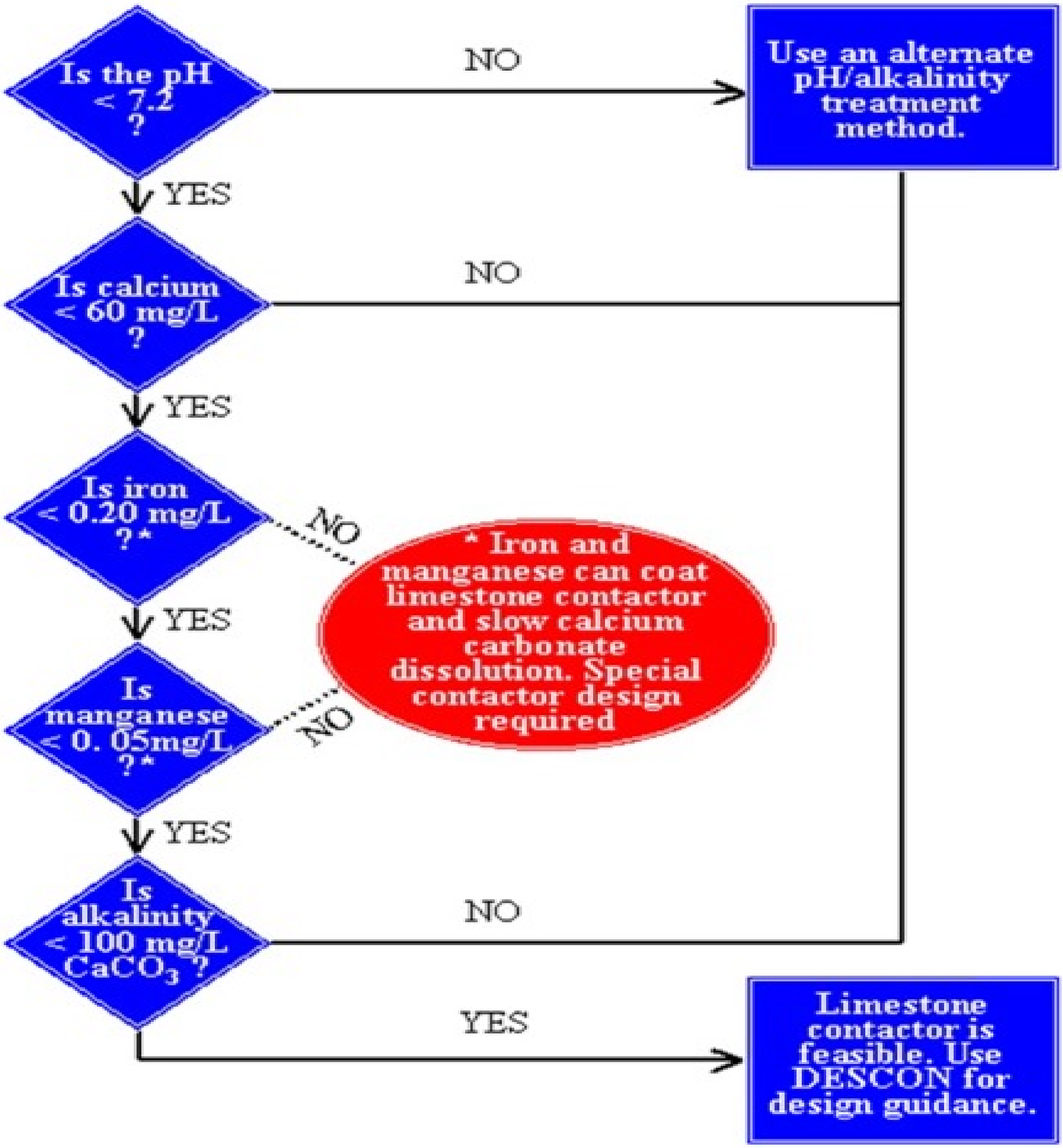
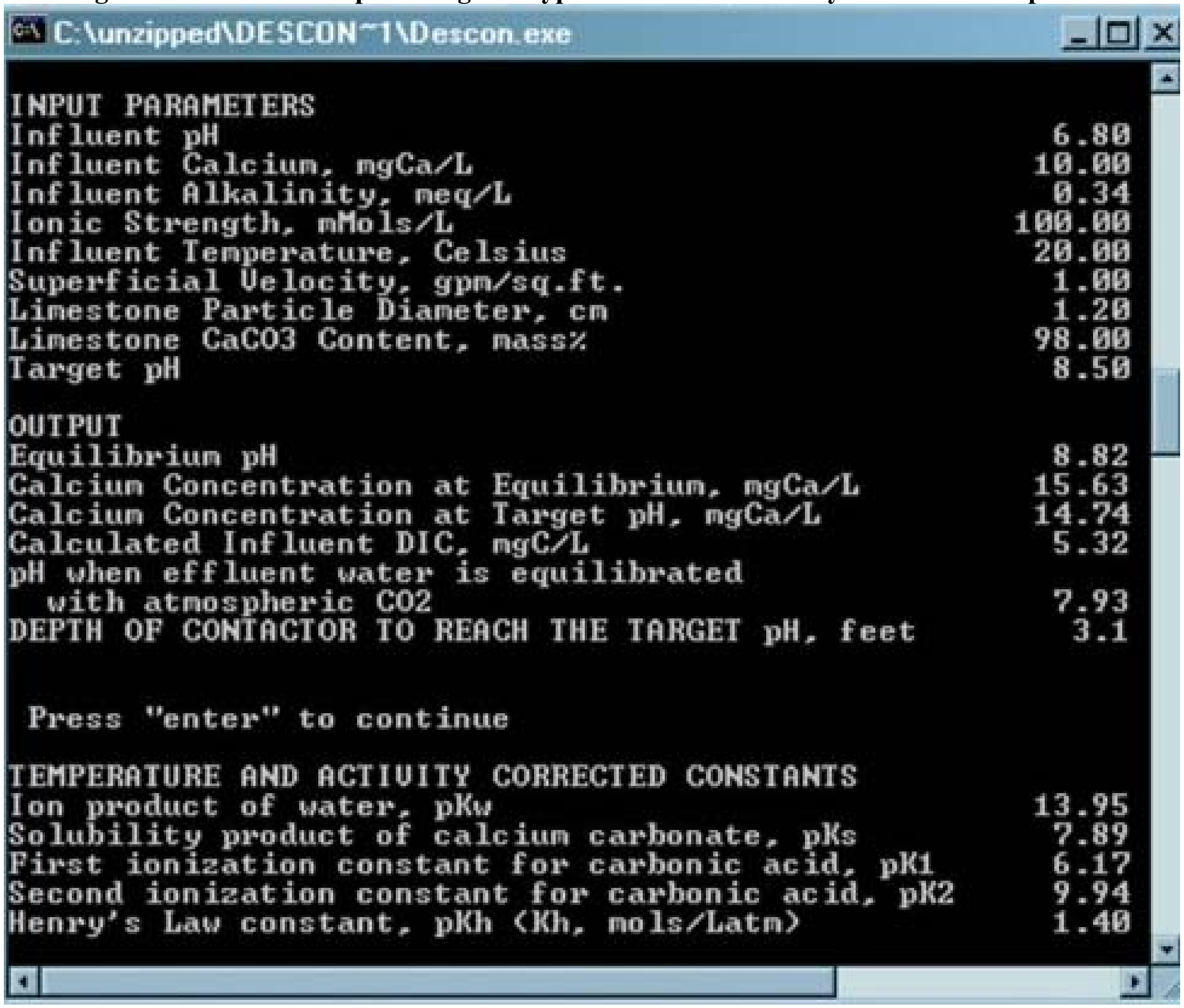


Figure 2. DESCON Output Using the Typical Western Water System Data as Input



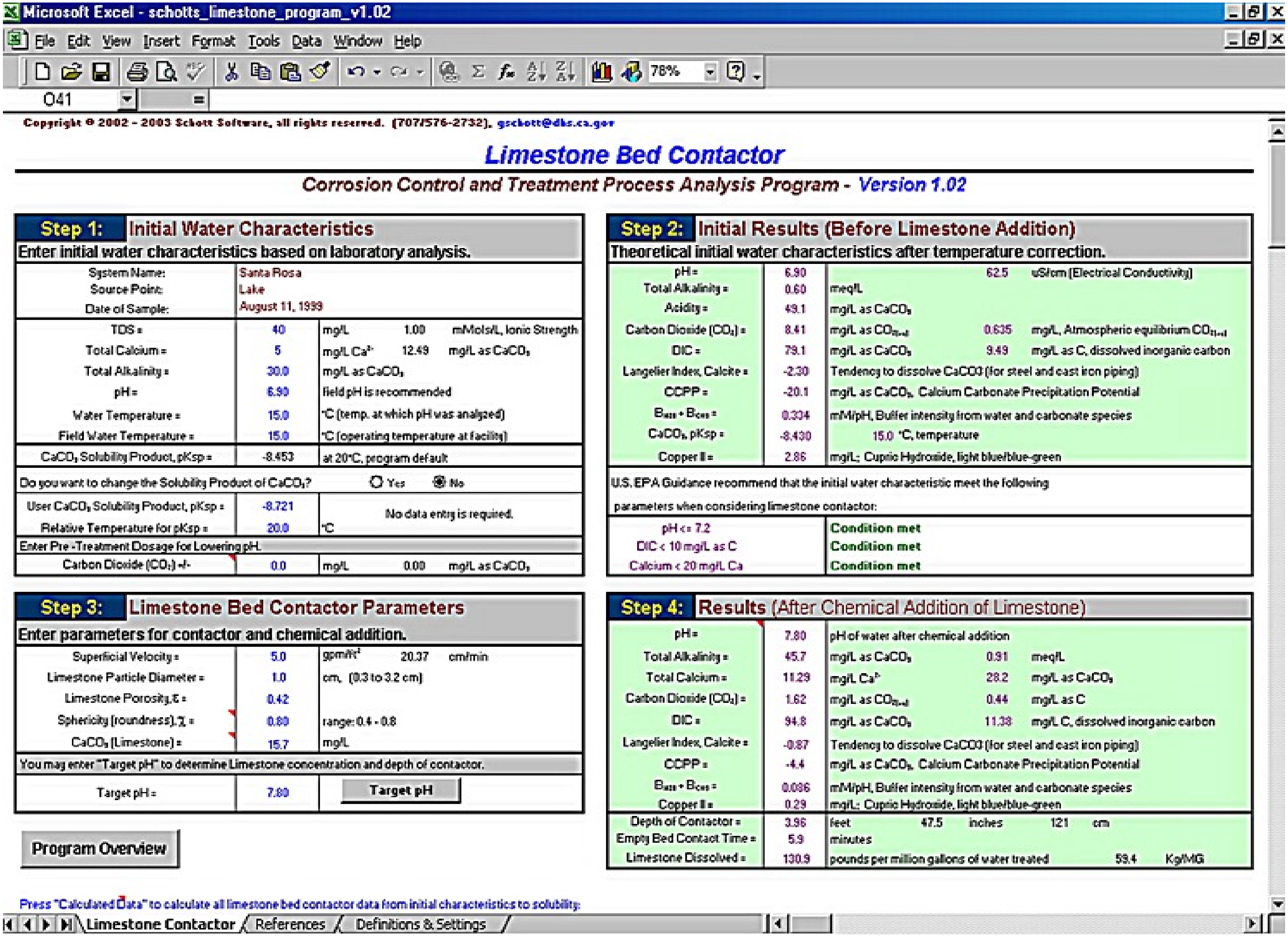
```
INPUT PARAMETERS
Influent pH                                                     6.80
Influent Calcium, mgCa/L                                       10.00
Influent Alkalinity, meq/L                                      0.34
Ionic Strength, mMols/L                                       100.00
Influent Temperature, Celsius                                  20.00
Superficial Velocity, gpm/sq.ft.                                1.00
Limestone Particle Diameter, cm                                 1.20
Limestone CaCO3 Content, mass%                                 98.00
Target pH                                                       8.50

OUTPUT
Equilibrium pH                                                  8.82
Calcium Concentration at Equilibrium, mgCa/L                   15.63
Calcium Concentration at Target pH, mgCa/L                     14.74
Calculated Influent DIC, mgC/L                                  5.32
pH when effluent water is equilibrated
  with atmospheric CO2                                          7.93
DEPTH OF CONTACTOR TO REACH THE TARGET pH, feet                  3.1


 Press "enter" to continue

TEMPERATURE AND ACTIVITY CORRECTED CONSTANTS
Ion product of water, pKw                                      13.95
Solubility product of calcium carbonate, pKs                    7.89
First ionization constant for carbonic acid, pK1                6.17
Second ionization constant for carbonic acid, pK2               9.94
Henry's Law constant, pKh (Kh, mols/Latm)                       1.40
```

Figure 3. Limestone Bed Contactor Corrosion Control and Treatment Analysis Program Version 1.02 (Schott, 2003)



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Limestone Bed Contactor

Corrosion Control and Treatment Process Analysis Program - Version 1.02

Step 1: Initial Water Characteristics

Enter initial water characteristics based on laboratory analysis.

System Name:	Santa Rosa			
Source Point:	Lake			
Date of Sample:	August 11, 1999			
TDS =	40	mg/L	1.00	mMols/L, Ionic Strength
Total Calcium =	5	mg/L Ca^{2+}	12.49	mg/L as $CaCO_3$
Total Alkalinity =	30.0	mg/L as $CaCO_3$		
pH =	6.90	field pH is recommended		
Water Temperature =	15.0	°C (temp. at which pH was analyzed)		
Field Water Temperature =	15.0	°C (operating temperature at facility)		
$CaCO_3$ Solubility Product, pKsp =	-8.453	at 20°C, program default		

Do you want to change the Solubility Product of $CaCO_3$? ○ Yes ● No

User $CaCO_3$ Solubility Product, pKsp =	-8.721	No data entry is required.
Relative Temperature for pKsp =	20.0	°C

Enter Pre-Treatment Dosage for Lowering pH.

Carbon Dioxide (CO_2) +/-	0.0	mg/L	0.00	mg/L as $CaCO_3$

Step 2: Initial Results (Before Limestone Addition)

Theoretical initial water characteristics after temperature correction.

pH =	6.90		62.5	uS/cm (Electrical Conductivity)
Total Alkalinity =	0.60	meq/L		
Acidity =	49.1	mg/L as $CaCO_3$		
Carbon Dioxide (CO_2) =	8.41	mg/L as $CO_{2(aq)}$	0.635	mg/L, Atmospheric equilibrium $CO_{2(aq)}$
DIC =	79.1	mg/L as $CaCO_3$	9.49	mg/L as C, dissolved inorganic carbon
Langelier Index, Calcite =	-2.30	Tendency to dissolve CaCO3 (for steel and cast iron piping)		
CCPP =	-20.1	mg/L as $CaCO_3$, Calcium Carbonate Precipitation Potential		
$B_{H2O} + B_{CO3}$ =	0.304	mM/pH, Buffer intensity from water and carbonate species		
$CaCO_3$, pKsp =	-8.430	15.0 °C, temperature		
Copper II =	2.86	mg/L; Cupric Hydroxide, light blue/blue-green		

U.S. EPA Guidance recommend that the initial water characteristic meet the following parameters when considering limestone contactor:

pH <= 7.2	Condition met
DIC < 10 mg/L as C	Condition met
Calcium < 20 mg/L Ca	Condition met

Step 3: Limestone Bed Contactor Parameters

Enter parameters for contactor and chemical addition.

Superficial Velocity =	5.0	gpm/ft^2	20.37	cm/min
Limestone Particle Diameter =	1.0	cm, (0.3 to 3.2 cm)		
Limestone Porosity, ε =	0.42			
Sphericity (roundness), χ =	0.80	range: 0.4 - 0.8		
$CaCO_3$ (Limestone) =	15.7	mg/L		

You may enter "Target pH" to determine Limestone concentration and depth of contactor.

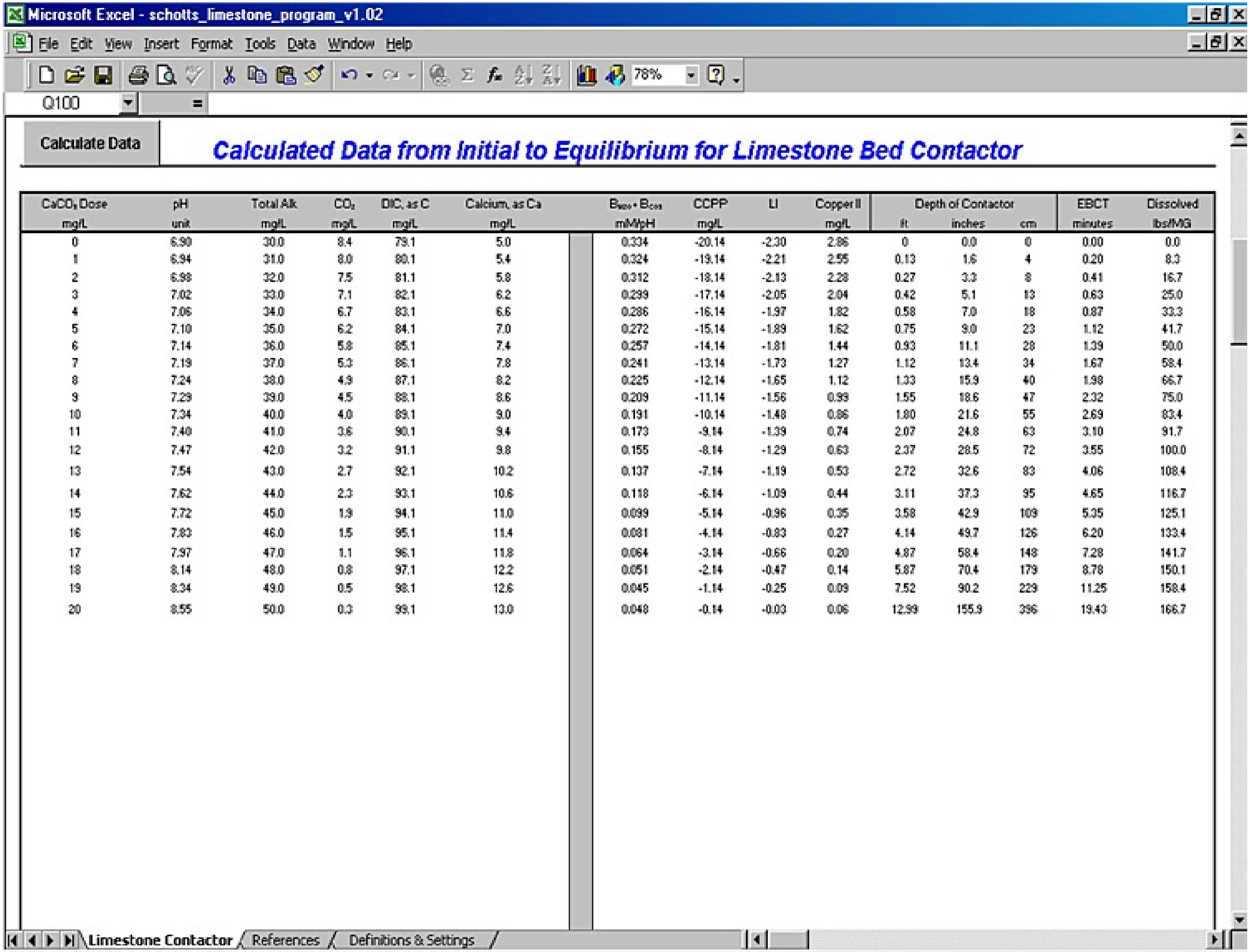
Target pH =	7.80	Target pH

Program Overview

Step 4: Results (After Chemical Addition of Limestone)

pH =	7.80	pH of water after chemical addition				
Total Alkalinity =	45.7	mg/L as $CaCO_3$	0.91	meq/L		
Total Calcium =	11.29	mg/L Ca^{2+}	28.2	mg/L as $CaCO_3$		
Carbon Dioxide (CO_2) =	1.62	mg/L as $CO_{2(aq)}$	0.44	mg/L as C		
DIC =	94.8	mg/L as $CaCO_3$	11.38	mg/L C, dissolved inorganic carbon		
Langelier Index, Calcite =	-0.87	Tendency to dissolve CaCO3 (for steel and cast iron piping)				
CCPP =	-4.4	mg/L as $CaCO_3$, Calcium Carbonate Precipitation Potential				
$B_{H2O} + B_{CO3}$ =	0.086	mM/pH, Buffer intensity from water and carbonate species				
Copper II =	0.29	mg/L; Cupric Hydroxide, light blue/blue-green				
Depth of Contactor =	3.96	feet	47.5	inches	121	cm
Empty Bed Contact Time =	5.9	minutes				
Limestone Dissolved =	130.9	pounds per million gallons of water treated	59.4	Kg/MG		

Press "Calculated Data" to calculate all limestone bed contactor data from initial characteristics to solubility.



Calculated Data from Initial to Equilibrium for Limestone Bed Contactor

CaCO₃ Dose	pH	Total Alk	CO₂	DIC, as C	Calcium, as Ca	B[illegible] - B[illegible]	CCPP	LI	Copper II	Depth of Contactor			EBCT	Dissolved
mg/L	unit	mg/L	mg/L	mg/L	mg/L	mM/pH	mg/L		mg/L	ft	inches	cm	minutes	lbs/MG
0	6.90	30.0	8.4	79.1	5.0	0.334	-20.14	-2.30	2.86	0	0.0	0	0.00	0.0
1	6.94	31.0	8.0	80.1	5.4	0.324	-19.14	-2.21	2.55	0.13	1.6	4	0.20	8.3
2	6.98	32.0	7.5	81.1	5.8	0.312	-18.14	-2.13	2.28	0.27	3.3	8	0.41	16.7
3	7.02	33.0	7.1	82.1	6.2	0.299	-17.14	-2.05	2.04	0.42	5.1	13	0.63	25.0
4	7.06	34.0	6.7	83.1	6.6	0.286	-16.14	-1.97	1.82	0.58	7.0	18	0.87	33.3
5	7.10	35.0	6.2	84.1	7.0	0.272	-15.14	-1.89	1.62	0.75	9.0	23	1.12	41.7
6	7.14	36.0	5.8	85.1	7.4	0.257	-14.14	-1.81	1.44	0.93	11.1	28	1.39	50.0
7	7.19	37.0	5.3	86.1	7.8	0.241	-13.14	-1.73	1.27	1.12	13.4	34	1.67	58.4
8	7.24	38.0	4.9	87.1	8.2	0.225	-12.14	-1.65	1.12	1.33	15.9	40	1.98	66.7
9	7.29	39.0	4.5	88.1	8.6	0.209	-11.14	-1.56	0.99	1.55	18.6	47	2.32	75.0
10	7.34	40.0	4.0	89.1	9.0	0.191	-10.14	-1.48	0.86	1.80	21.6	55	2.69	83.4
11	7.40	41.0	3.6	90.1	9.4	0.173	-9.14	-1.39	0.74	2.07	24.8	63	3.10	91.7
12	7.47	42.0	3.2	91.1	9.8	0.155	-8.14	-1.29	0.63	2.37	28.5	72	3.55	100.0
13	7.54	43.0	2.7	92.1	10.2	0.137	-7.14	-1.19	0.53	2.72	32.6	83	4.06	108.4
14	7.62	44.0	2.3	93.1	10.6	0.118	-6.14	-1.09	0.44	3.11	37.3	95	4.65	116.7
15	7.72	45.0	1.9	94.1	11.0	0.099	-5.14	-0.96	0.35	3.58	42.9	109	5.35	125.1
16	7.83	46.0	1.5	95.1	11.4	0.081	-4.14	-0.83	0.27	4.14	49.7	126	6.20	133.4
17	7.97	47.0	1.1	96.1	11.8	0.064	-3.14	-0.66	0.20	4.87	58.4	148	7.28	141.7
18	8.14	48.0	0.8	97.1	12.2	0.051	-2.14	-0.47	0.14	5.87	70.4	179	8.78	150.1
19	8.34	49.0	0.5	98.1	12.6	0.045	-1.14	-0.25	0.09	7.52	90.2	229	11.25	158.4
20	8.55	50.0	0.3	99.1	13.0	0.048	-0.14	-0.03	0.06	12.99	155.9	396	19.43	166.7

Figure 4. Contact Time as a function of Base Consumption ($K_{B,8.2}$) and Acid Consumption ($K_{S,4.3}$) for Dense Calcium Carbonate (Grain Size 1.0-2.0 mm). Temperature: 10°C, Processing Goal pH=8.0. (DVGW, 1998)

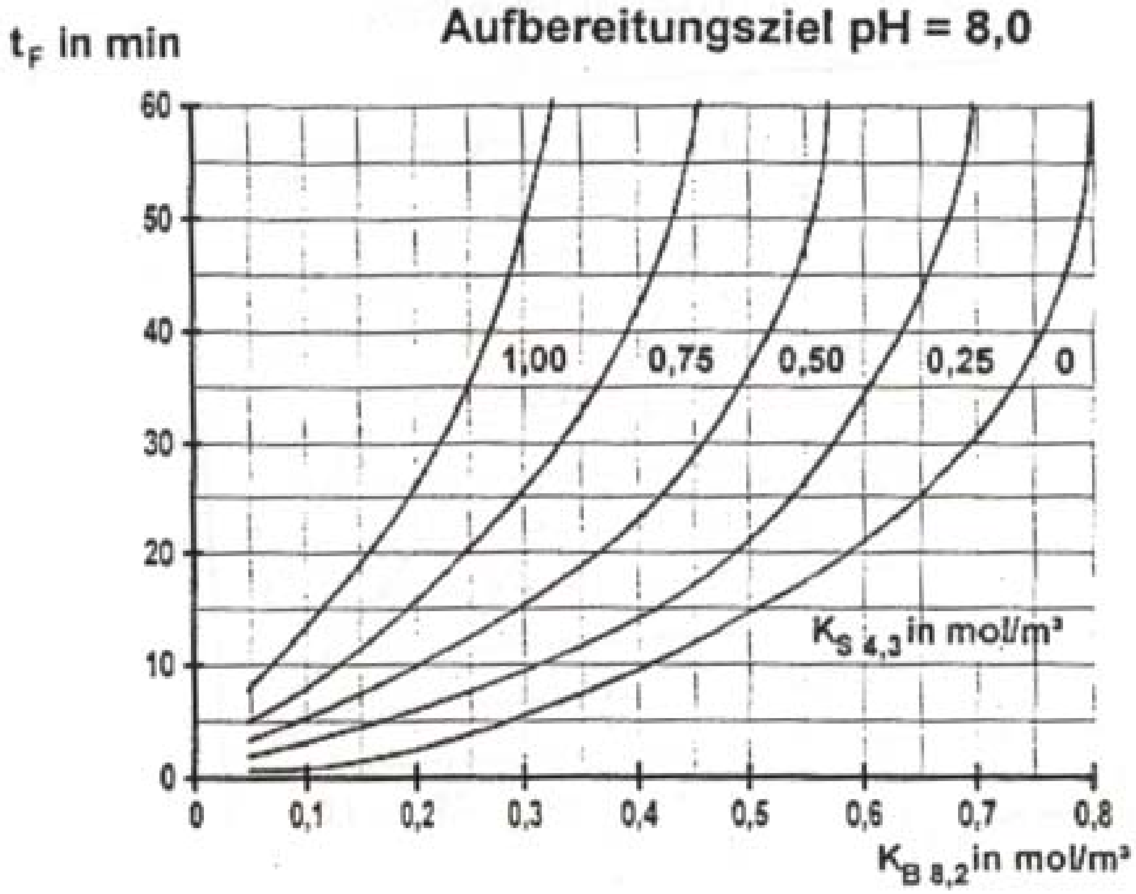


Figure 5. Contact Time as a function of Base Consumption ($K_{B,8.2}$) and Acid Consumption ($K_{S,4.3}$) for Dense Calcium Carbonate (Grain Size 1.0-2.0 mm). Temperature: 10°C, Processing Goal pH=pHc. (DVGW, 1998)

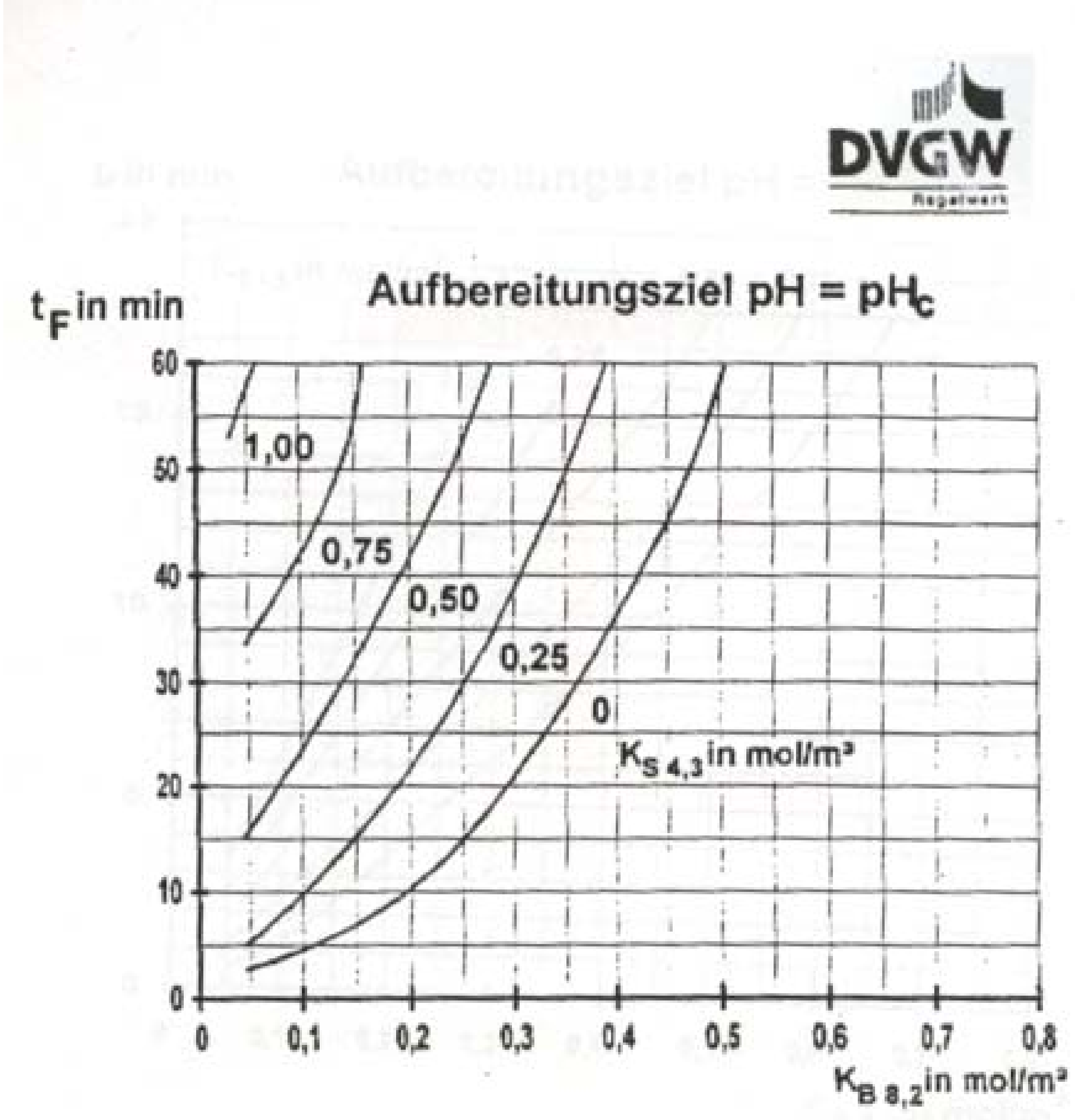


Figure 6. Contact Time as a function of Base Consumption ($K_{B,8.2}$) and Acid Consumption ($K_{S,4.3}$) for Porous Calcium Carbonate (Grain Size 1.0-3.0 mm). Temperature: 10°C, Processing Goal pH=8.0. (DVGW, 1998)

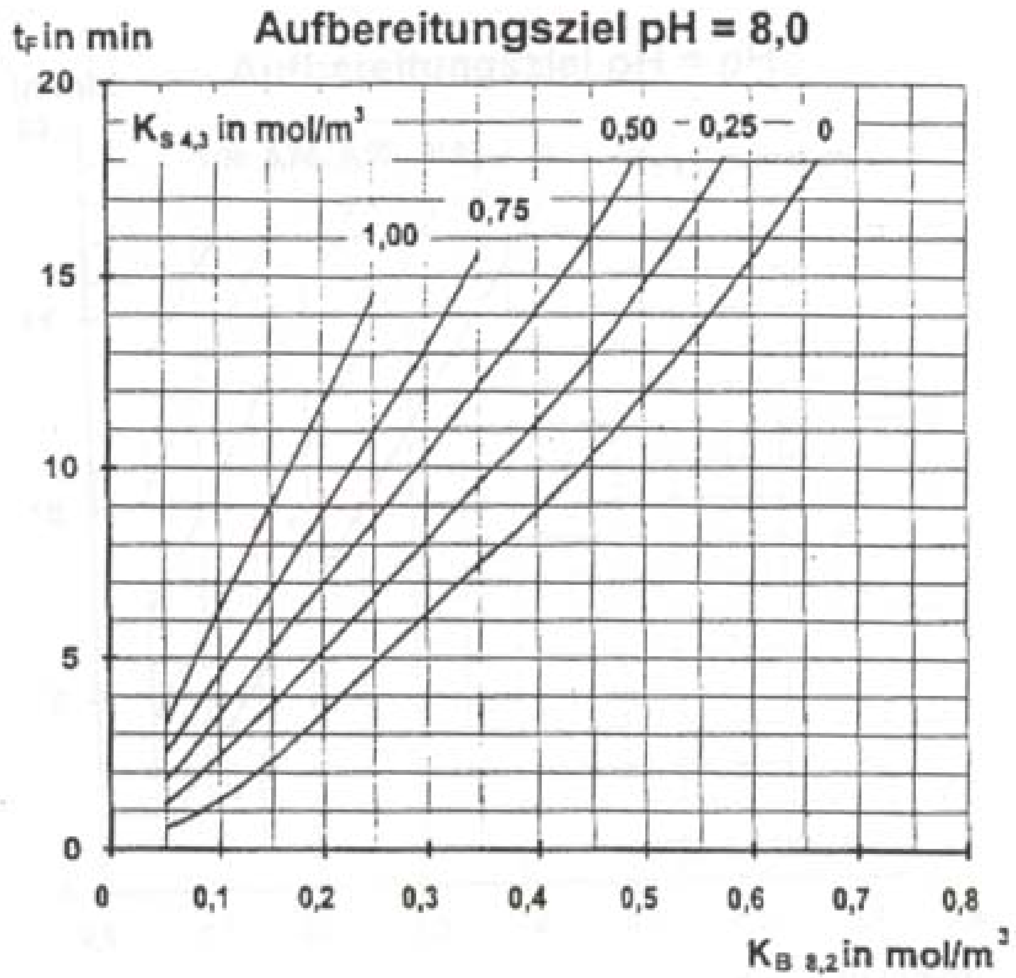


Figure 7. Contact Time as a function of Base Consumption ($K_{B,8.2}$) and Acid Consumption ($K_{S,4.3}$) for Porous Calcium Carbonate (Grain Size 1.0-3.0 mm). Temperature: 10°C, Processing Goal pH=pHc. (DVGW, 1998)

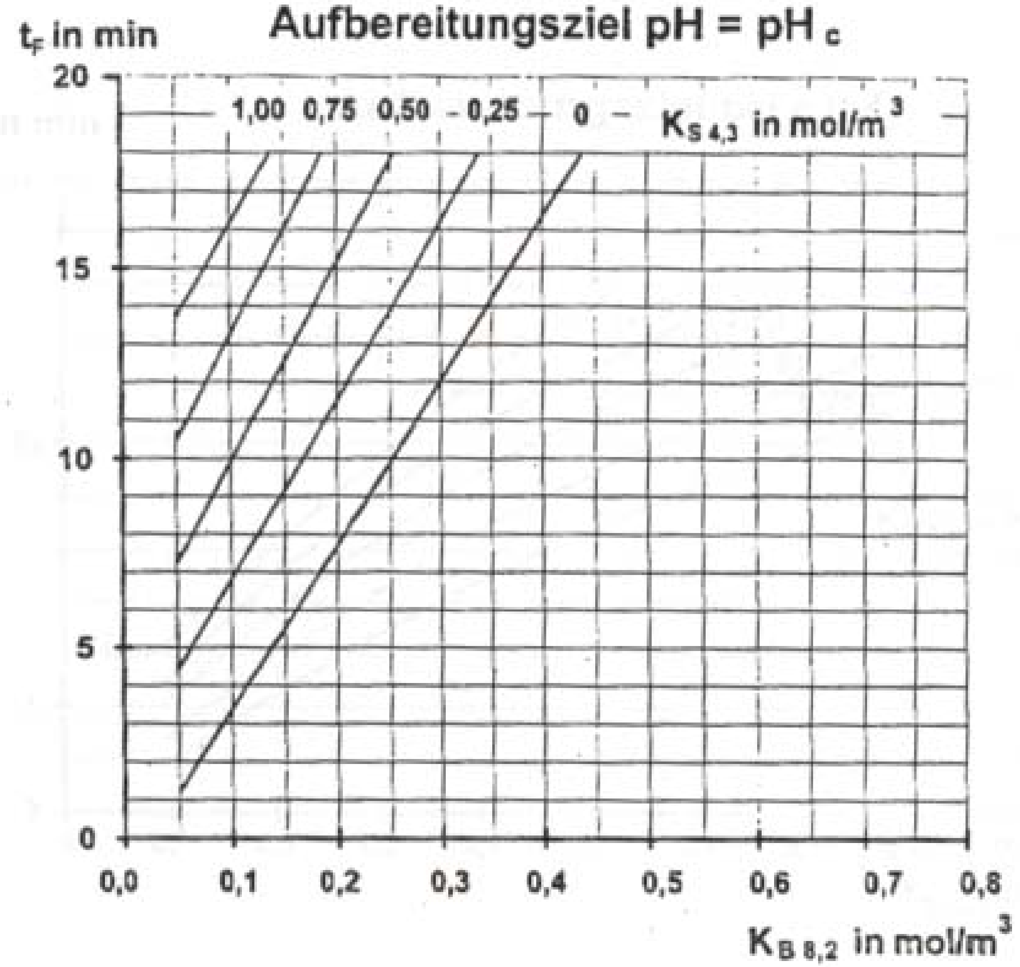


Figure 8. Contact Time as a function of Base Capacity ($K_{B,8.2}$) and Acid Capacity ($K_{S,4.3}$) for Half-Calcine Dolomitic Lime (Grain Size 0.5-2.5 mm). Temperature: 10°C, Processing Goal pH=pHc. (DVGW, 1998)

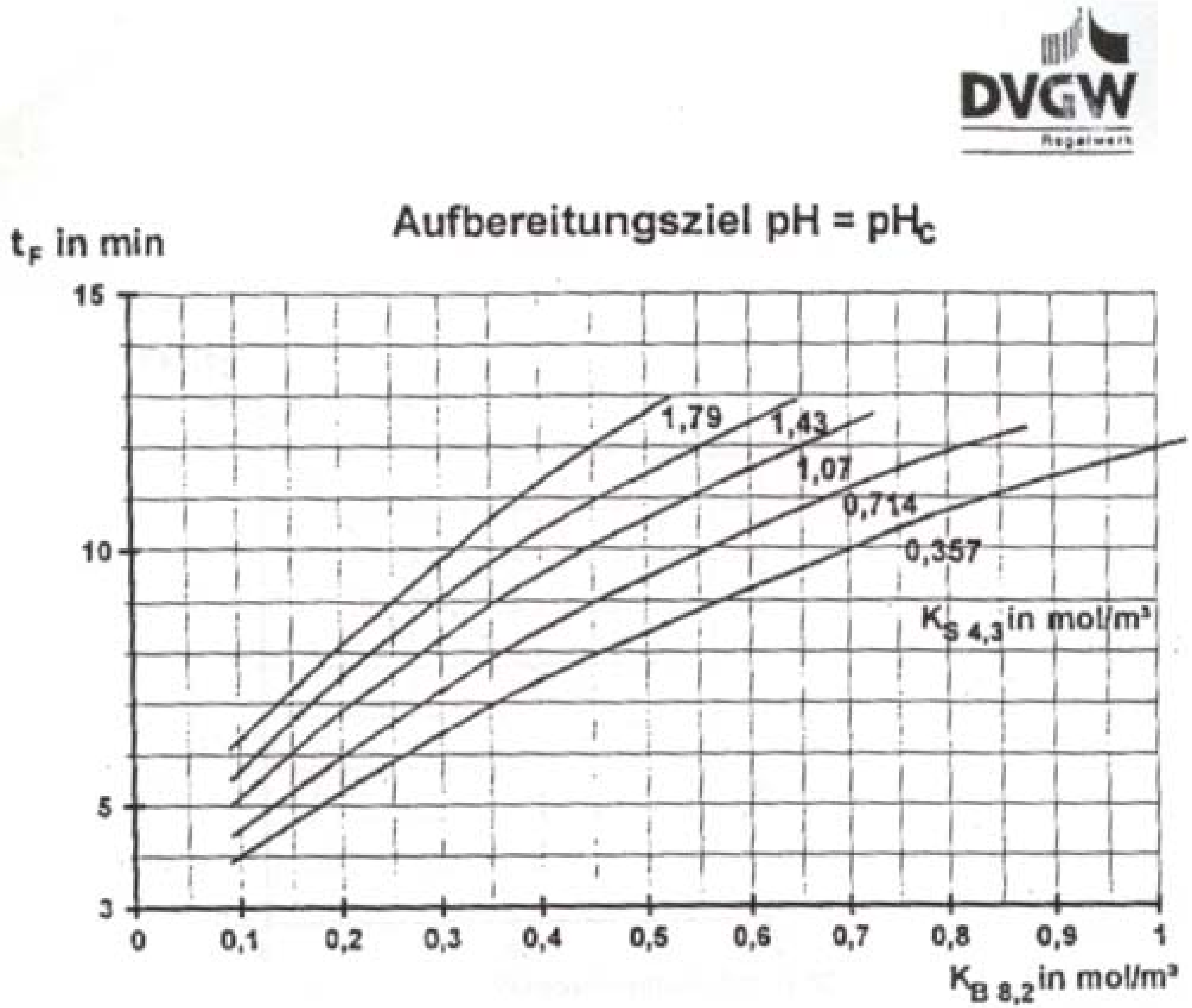
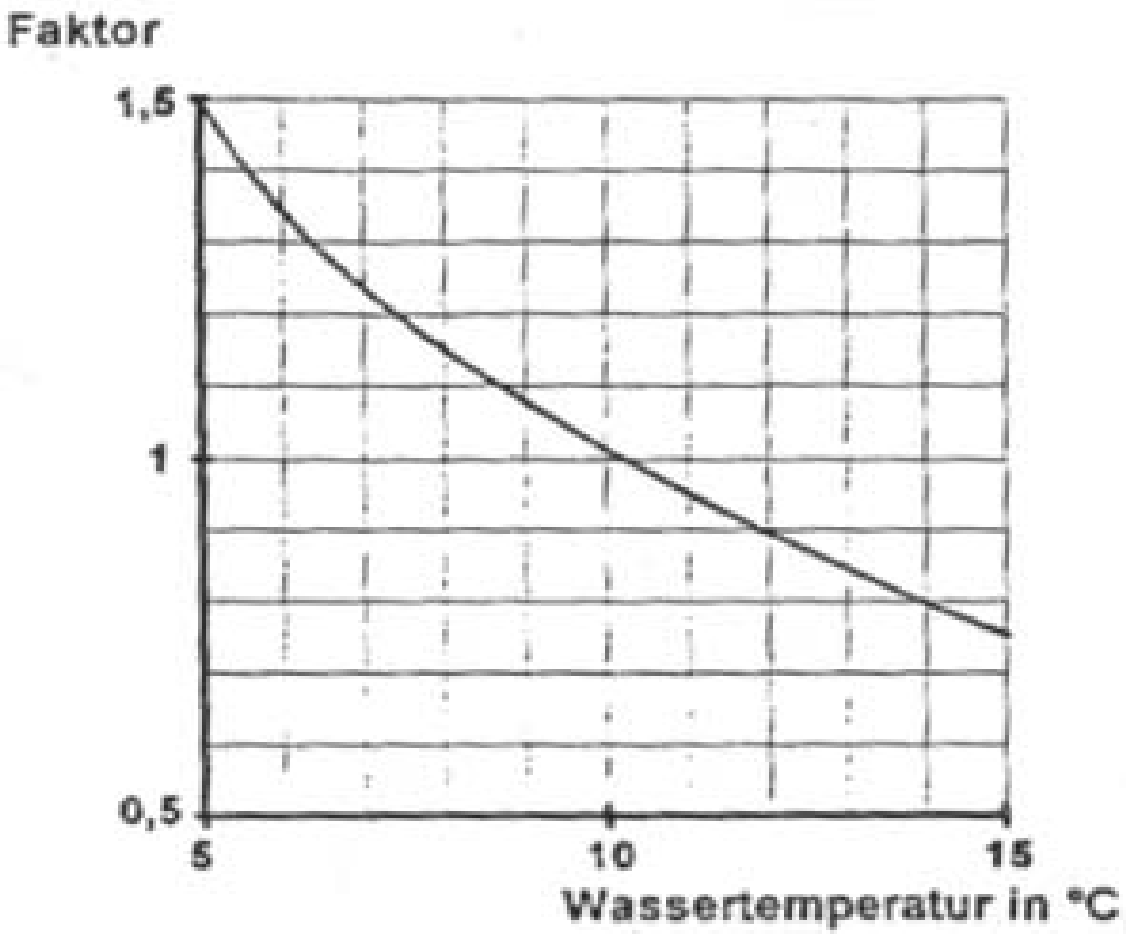


Figure 9. Correction Factor as a Function of Water Temperature. (DVGW, 1998)



SAMPLE PROBLEM

Sample on how to use Figure 1 to 6 in W214/11 (DVGW, 1998):

This example shows how to design a limestone contactor by using figure 1 to 6 in W214/11 (DVGW, 1998). Limestone contactor will be used to treat the following raw water:

Raw Water Treated by Mars Hill, Maine Water Treatment Plant (Spencer, 2000):*

Surface Water Source: Young's Lake
Lowest pH of influent to the limestone contactor = 7.18
Alkalinity in the raw water = 45 – 83 mg/L as $CaCO_3$
Calcium in the raw water = 19 – 34 mg Ca/L
**Note: These water quality parameters were obtained in 1996, before the limestone contactor was installed in the plant.*

Determination of $K_{S,4.3}$ and $K_{B,8.2}$:

Use the worst case condition, pH = 7.18 and alkalinity of 45 mg/L as $CaCO_3$

Most of the alkalinity source at pH = 7.18 is from HCO_3^-:

$$K_{S,4.3} = [HCO_3^-] = \frac{45\text{ mg}}{\text{L}} \times \frac{1\text{ meq}}{50\text{mg}} \times \frac{1\text{ mmol }HCO_3^-}{1\text{ meq }HCO_3^-} \times \frac{1\text{ mol}}{10^3\text{ mmol}} \times \frac{10^3\text{ L}}{1\text{ m}^3} = 0.9\ \frac{\text{mol}}{\text{m}^3}$$

Assume the lowest temperature, T = 5 ^{o}C,

Therefore $pKa_1 = 6.52$ at T = 5 ^{o}C (Snoeyink and Jenkins, 1980). Assume $CO_2 = H_2CO_3^*$ and ignoring activity coefficients:

$$K_{B,8.2} = [CO_2] = [H_2CO_3^*]$$

$$\frac{[HCO_3^-][H^+]}{[H_2CO_3^*]} = 10^{-pKa1}$$

$$K_{B,8.2} = [CO_2] = [H_2CO_3^*] = \frac{(0.9 \times 10^{-3})(10^{-7.18})}{(10^{-6.52})}\ \frac{\text{mol}}{\text{L}} \times \frac{10^3\text{ L}}{\text{m}^3} = 0.2\ \frac{\text{mol}}{\text{m}^3}$$

Determination of Media Type:

$K_{S,4.3} + 2K_{B,8.2} = 0.9 + 2(0.2) = 1.3\text{ mol/m}^3$

$$[Ca] = 19\ \frac{\text{mg}}{\text{L}} \times \frac{\text{mmol}}{40.08\text{ mg}} \times \frac{\text{mol}}{10^3\text{ mmol}} \times \frac{10^3\text{ L}}{\text{m}^3} = 0.47\text{ mol/m}^3$$

Based on the total amount of $K_{S,4.3}$ + $2K_{B,8.2}$, the calcium content and the requirement listed in Part 3.2 of W 214/11 (1998), the following media can be used:

- Dense Calcium Carbonate, Target Goal pH=8. Figure 1 of W214/11 is applicable.
- Porous Calcium Carbonate, Target Goal pH=8 or pH=pHc. Figure 3 of W214/11 is applicable.
- Dolomite, Target Goal pH=pHc. Figure 5 of W214/11 is applicable.

Applicability of Design Figures:

Figure 1, 3 and 5 of W214/11 (or Figure 4,6 and 8 in this module) can be used to determine the contact time based on $K_{S,4.3}$ and $K_{B,8.2}$. Figure 6 of W214/11 (or Figure 9 in this module) is used for temperature correction.

Design Method:

Maximum flow rate, Q = 1600 m^3/day (430,000 gallons/day) (Spencer, 2000)
Loading Rate = 2.4 m/hr (1 gpm/ft^2) (Spencer, 2000)
Assume lowest temperature, T = 5 °C.

(i) If using Dense Calcium Carbonate and the desired target pH=8:

Assume size of media = 1.0 – 2.0 mm
Target pH = 8

From Figure 1, t_F = 25 min and from Figure 6, f = 1.5.

Minimum bed volume, V_M = t_F x f x Q x 1/60 min
= 25 min x 1.5 x 1600 m^3/day x 1 day/24hr x 1 hr/60 min
= 42 m^3

Depth of limestone bed = t_F x f x Loading Rate
= 25 min x 1.5 x 2.4 m/hr x 1 hr/60 min
= **1.5 m (5 ft)**

Surface area of the contactor = 1600 m^3/day x 2.4 m/hr x 1 day/24 hr = **28 m^2**

Figure 1. Contact Time as a function of Base Consumption ($K_{B,8.2}$) and Acid Consumption ($K_{S,4.3}$) for Dense Calcium Carbonate (Grain Size 1.0-2.0 mm). Temperature: 10°C, Processing Goal pH=8.0. (DVGW, 1998)

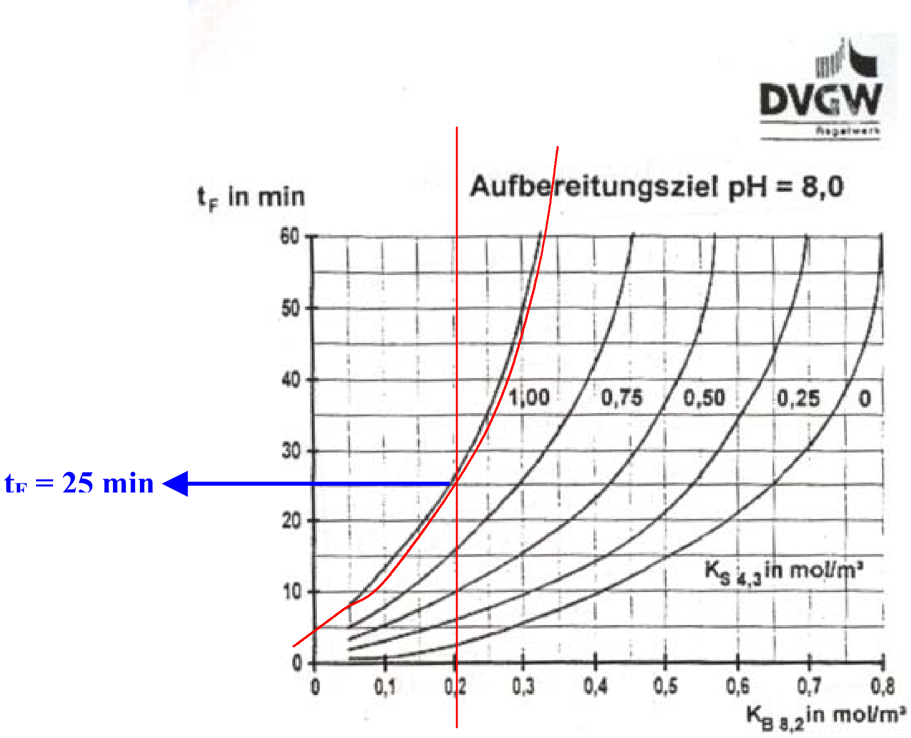
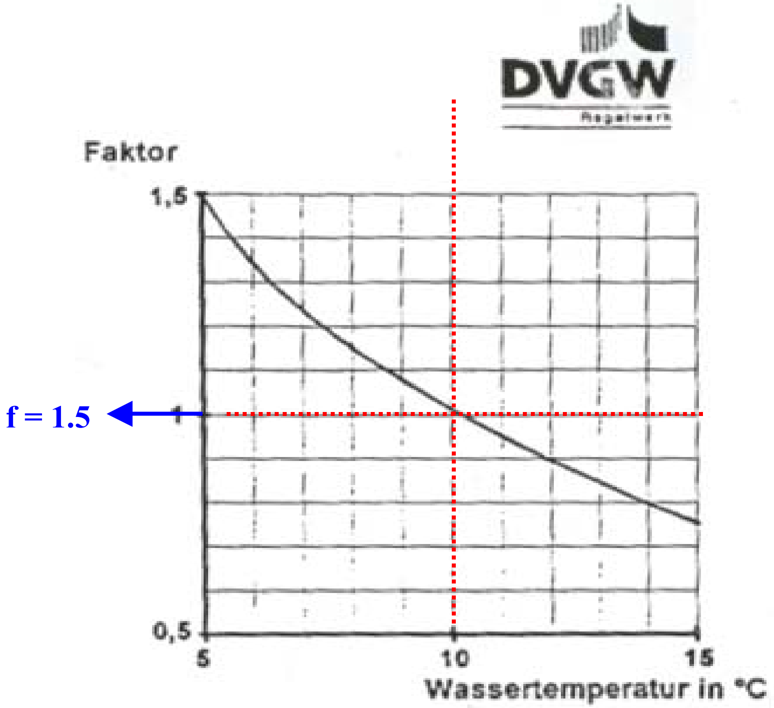


Figure 6. Correction Factor as a Function of Water Temperature. (DVGW, 1998)



<u>Determination Whether V_B is Needed in the Design</u>

If the dissolution rate of the limestone is very slow, then a consumption volume, V_B is not needed (Stauder, 2003). The need to include V_B in the design of a limestone contactor is up to the designer. The choice depends much on the frequency of media refilling. Additional factors include the capacity of the limestone supplier truck and the capacity of the silo used to store the limestone (Stauder, 2003). If the capacity of the truck and the silo is small, it may limit the amount of limestone that can be refilled each time, therefore, the refill frequency must be chosen by taking these factors into account. The amount of $CaCO_3$ dissolved for several options of media refills frequency is shown in this example.

A run using MINTEQ reveals that at saturation, this water dissolves 0.008 g/L of Ca^{2+} (0.1988 mol/m^3). The following calculations show the amount of $CaCO_3$ dissolved daily, weekly, monthly and yearly based on the result obtained using MINTEQ.

The daily consumption of $CaCO_3$ $= 1600\ m^3/day \times 0.1988\ mol/m^3 \times 100\ g/mol \times 10^{-3}\ kg/g$
= **32 kg/day**

Weekly consumption of $CaCO_3$ = 31.8 kg/day x 7 days/week = **223 kg/week**

Monthly consumption of $CaCO_3$= 31.8 kg/day x 30 days/month **= 954 kg/month**

Yearly consumption of $CaCO_3$ = 31.8 kg/day x 365 days/yr **= 11,607 kg/year**

Using the density of dense $CaCO_3$ of 1500 kg/m³ (Table 1 in W214, DVGW 1998), the weight of $CaCO_3$ can be calculated. Based on Figure 1 and 6, the minimum volume, V_M of limestone needed to stabilize this water is 42 m³. This corresponds to 63,000 kg of $CaCO_3$. The following table shows the percent of $CaCO_3$ dissolved daily, weekly, monthly and yearly.

No.	Frequency of Media Refilling	Amount of $CaCO_3$ Dissolved	Percent of $CaCO_3$ Dissolved (%)
1	Daily	32 kg/day	0.05
2	Weekly	223 kg/week	0.35
3	Monthly	954 kg/month	1.51
4	**Yearly**	11,607 kg/year	18.42

The above table shows that if the designer decides to refill the limestone either daily or weekly, the percent of $CaCO_3$ dissolved between media refilling is very small (less than 1%). Since the amount dissolved is very small, the designer may exclude V_B in the design if he/she decides to have the limestone refilled daily or weekly. Thus, the total contactor bed volume should only include the minimum volume of limestone required, V_M. However, if a designer decides to have the limestone refilled monthly or yearly, then V_B must be included in the design since a significant amount of limestone will be dissolved between media refilling.

The amount of V_B can be calculated based on the amount of $CaCO_3$ dissolved as calculated above (954 kg for monthly refill and 11,607 kg for yearly refills) with the addition of 10% to account for losses of media due to backwashing. The following shows an example to calculate V_B, the total contactor bed volume, V_F and the total height of contactor for monthly media refills.

$V_B = 954\ kg / 1500\ kg/m^3 + 0.10\ (42\ m^3 + 954 / 1500\ kg/m^3) = 5\ m^3$

$V_F = 42\ m^3 + 5\ m^3 = 47\ m^3$

Total Height of Contactor = $47\ m^3 / 28\ m^2 = 1.7\ m$ (5.6 ft)

(ii) If using Porous Calcium Carbonate and the desired target pH = 8:

Assume size of media = 1.0 – 3.0 mm
Target pH = 8

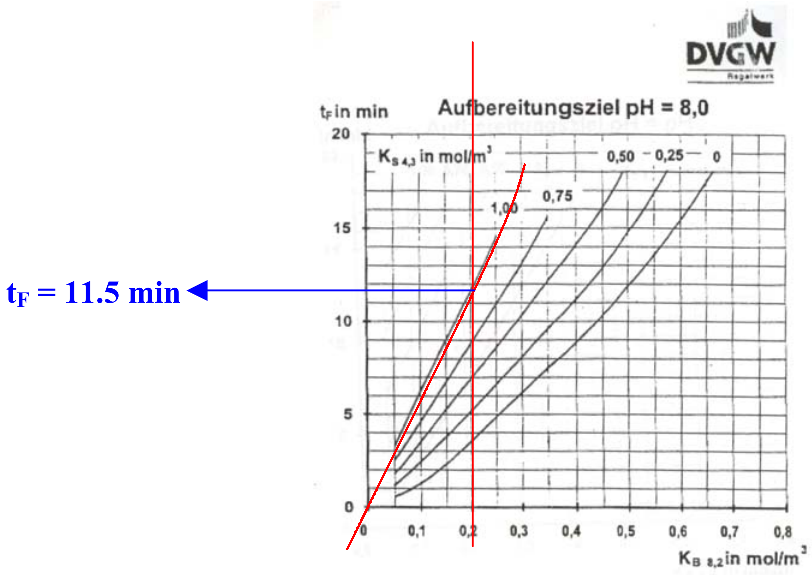
From Figure 3, t_F = 11.5 min and from Figure 6, f = 1.5.

Minimum bed volume, V_M = t_F x f x Q x 1/60 min
= 11.5 min x 1.5 x 1600 m^3/day x 1 day/24hr x 1 hr/60 min
= 19.2 m^3

Depth of limestone bed = t_F x f x Loading Rate
= 11.5 min x 1.5 x 2.4 m/hr x 1 hr/60 min
= **0.7 m (2.2 ft)**

Surface area of the contactor = 1600 m^3/day x 2.4 m/hr x 1 day/24 hr = **28 m^2**

Figure 3. Contact Time as a function of Base Consumption ($K_{B,8.2}$) and Acid Consumption ($K_{S,4.3}$) for Porous Calcium Carbonate (Grain Size 1.0-3.0 mm). Temperature: 10°C, Processing Goal pH=8.0. (DVGW, 1998)



t_F = 11.5 min

(iii) If using Dolomite and the desired target pH = pHc

Assume size of media = 0.5 – 2.5 mm
Target pH = saturation pH = pHc

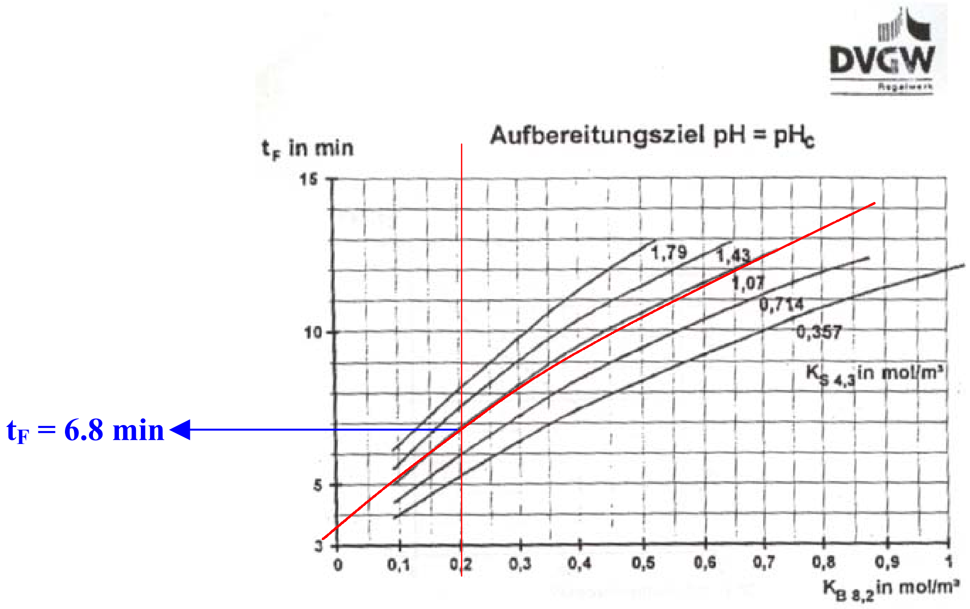
From Figure 5, t_F = 7.8 min and from Figure 6, f = 1.5.

Minimum bed volume, V_M = t_F x f x Q x 1/60 min
= 6.8 min x 1.5 x 1600 m^3/day x 1 day/24hr x 1 hr/60 min
= 11 m^3

Depth of limestone bed = t_F x f x Loading Rate
= 6.8 min x 1.5 x 2.4 m/hr x 1 hr/60 min
= **0.4 m (1.5 ft)**

Surface area of the contactor = 1600 m^3/day x 2.4 m/hr x 1 day/24 hr = **28 m^2**

Figure 5. Contact Time as a function of Base Consumption ($K_{B,8.2}$) and Acid Consumption ($K_{S,4.3}$) for Porous Calcium Carbonate (Grain Size 1.0-3.0 mm). Temperature: 10°C, Processing Goal pH=pHc. (DVGW, 1998)



(B) Design Criteria Specifically for Small Groundwater Systems with Iron and Manganese Present

Table 1 shows the treatment objectives and Table 2 shows the installation and operation requirements applicable for the Spraystab I unit used to stabilize water in small-scale groundwater systems containing iron and manganese in South Africa.

Table 1. Treatment Objectives of Spraystab I Unit (Mackintosh, Engel and De Villiers 1997)

No.	Treatment Objectives
1.	The unit should achieve an appreciable level of pH adjustment and stabilization.
2.	The unit should be able to remove iron such that the iron level in the treated water is no more than 1 mg/L and preferably less than 0.3 mg/L.
3.	The unit should be able to remove manganese such that the manganese level in the treated water is no more than 1 mg/L and preferably less than 0.1 mg/L.
4.	The unit should be able to filter the water.
5.	The unit should be able to treat between 25 and 50 m^3/day.

Table 2. Installation and Operation Requirements of Spraystab I Unit (Mackintosh, Engel and De Villiers, 1997)

No.	Installation and Operation Requirements
1.	All components of the unit are easily handled by two people and easily transported.
2.	The materials and equipment needed should result in a low cost and easy construction and repair.
3.	The unit requires minimum operator attention and skills.
4.	The unit utilizes minimum chemical dosing. If dosing is required, it should be self-regulating.
5.	The unit should not require dosing pumps.
6.	The unit should not require water pumps other than the well pump.
7.	The unit must be robust and reliable.
8.	The unit is independent of electrical control or operating systems.

Table 3 shows the design criteria of the Spraystab I unit.

Table 3. General Design Criteria of Spraystab I System (Mackintosh, De Souza and De Villiers, 2003b)

No.	Components	Functions
1.	Access Lid	An access lid must be provided on a closed contactor to allow access for maintenance or cleaning work, prevent contamination from outside materials such as leaves and twigs, prevent the beds from algal/bacterial growth and minimize dissolution of carbon dioxide into the water.
2.	Spray Nozzles	The 60^o full cone spray nozzles are located at the center of the aeration ducts. The well pumps feeds directly to the spray nozzles. The nozzle height above the aeration duct is designed such that the air flowing into the aeration duct is at the maximum.
3.	Aeration Ducts	The aeration ducts are located on the access lid and covered with coarse stainless steel wire mesh screens.
4.	Vent Ducts	The vent ducts are covered with coarse stainless steel wire mesh screens.
5.	Limestone Media	The limestone contact unit consists of a bed of approximately 800 mm in depth of limestone with a grading of –15mm +12mm. The bed rests on top of the support grid.
6.	Support Grid	The support grid is located at the lower end of the limestone contactor unit of a Spraystab I unit. There is a 10 mm wire mesh screen placed on the support grid.
7.	Slotted Pipe Underdrain	Each compartment in the filtration unit of a Spraystab I unit is equipped with a slotted pipe underdrain. The slotted pipe feeds into a common manifold fitted with a raised outlet used to control the water level in the filtration unit.
8.	Filtration Media	There are two media used in the filtration unit. The lower layer of the filtration unit consists of 0.3 to 0.5 mm graded filter sand to a depth of 300 mm above the underdrain. The upper layer of the filtration unit consists of 1.0 to 1.5 mm graded hydro-anthracite media.

(C) General Design Criteria Specifically for Small Groundwater Systems without Iron and Manganese Present

Table 4 shows the design criteria of the Spraystab II system used to stabilize water in small-scale groundwater systems without iron and manganese present.

Table 4. General Design Criteria of Spraystab II System (Mackintosh, De Souza and De Villers, 2003b)

No.	Components	Functions
1.	Access Lid	An access lid must be provided on a closed contactor to allow access for maintenance or cleaning work, prevent contamination from outside materials such as leaves and twigs, prevent the beds from algal/bacterial growth and minimize dissolution of carbon dioxide into the water.
2.	Spray Nozzles	The type of material used for spray nozzles is important. The full cone HH stainless steel spray nozzles are more effective in aerating water and durable compared to PVC/plastic spray nozzles. In addition, PVC/plastic spray nozzles are also more prone to clogging resulting in poor performance in aeration.
3.	Aeration Ducts	Each limestone contactor unit is required to have two aeration ducts (i.e. air inlets). Each duct have a diameter of 250 mm. The ducts must be covered with a stainless steel mesh to avoid leaves, twigs and other outside materials from building up on the surface of the limestone beds.
4.	Vent Ducts	Each limestone contactor unit is required to have two vent ducts, one on the access lid and the other on the roof of the tank. Each vent duct should have a diameter of 300 mm. Similar to the aeration ducts, the vent ducts mush also be covered with a stainless steel mesh.
5.	“Settling Tubes”	The “settling tubes” must be connected to the aeration ducts to allow the water from the aeration ducts to flow to the slotted pipe. The top of the “settling tubes” must be above the treated water level to vent the air between the aeration duct and the “setting tubes”.
6.	Slotted Pipe	Slotted pipe manifold system results in uniform distribution of water in a small limestone contactor unit.
7.	Granite Layer	A 150 mm deep later of 25 mm diameter granite aggregate is required between the limestone bed and the manifold system. The granite used must be appropriate for water treatment.
8.	Drain/Flush Valves	At least two drain/flush valves are required for each limestone contactor unit, but four valves are preferred.
9.	Treated Water	The limestone contactor must be designed such that the treated water level is always less than the height of the “settling tubes” and is 200 mm above the limestone bed. A fully enclosed pipeline must be used to collect and transport the treated water to the storage tank to prevent contamination.
10.	Treated Water Outlet Pipe	The pipe must be positioned such that the treated water level is 200 mm above the limestone bed.
11.	Loading Rate	Loading rate must be less than 10 m/hr. Higher loading rates will result in increased water turbidity.