

To the Graduate Council:

I am submitting herewith a thesis written by Azarina Mohd Jalil entitled “LIMESTONE CONTACTORS AS A CORROSION CONTROL TECHNOLOGY FOR SMALL PUBLIC WATER SYSTEMS: An Educational Module for Drinking Water Professionals.” I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Environmental Engineering.

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LIMESTONE CONTACTORS
AS A CORROSION CONTROL TECHNOLOGY
FOR SMALL PUBLIC WATER SYSTEMS:
An Educational Module for Drinking Water Professionals

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ABSTRACT

This thesis includes a review of literature of the limestone contactors technology for small water systems and discusses the process and methodology involved in developing the educational module on limestone contactors. It includes most of the narrative texts presented in the module. Both this thesis and the module are intended to be used as an educational tool by small public water system operators, owners, regulators, and engineers of limestone contactors as a corrosion control method to meet the lead and copper action level stated in the U.S. EPA's Lead and Copper Rule. This module includes the description of the processes involved in a limestone contactor, the criteria used in the design, operational and maintenance procedure, and performance data, as well as multimedia tools such as photos and interactive process diagrams to further explain the process and components involved in a limestone contactor. Data and information presented are based on limestone contactors designed in U.S., Germany and South Africa. The module is the fourth in a series of water treatment technology educational modules created by the University of Tennessee and the University of New Hampshire and the first to be available on the web.

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LIST OF SYMBOLS AND ABBREVIATIONS

Ca^{2+}	Calcium ion
$CaCO_3$	Calcium carbonate or calcite
$CaMg(CO_3)_2$	Dolomite
CO_2	Carbon dioxide
CO_3^{2-}	Carbonate ion
CND\$	Canadian Dollar
$C_{T,Ca}$	Total calcium concentration
C_{T,CO_3}	Total carbonate concentration
DIC	Dissolved Inorganic Carbon
DVGW	German Technical and Scientific Association on Gas and Water
Fe(II)	Ferrous iron
H^+	Hydrogen ion
$H_2CO_3^*$	Carbonic acid
L.I.	Langelier Index
LCR	Lead and Copper Rule
NHDES	New Hampshire Department of Environmental Services
NPDWR	National Primary Drinking Water Regulations
OH^-	Hydroxide ion
SDWA	Safe Drinking Water Act
SSP	Sidestream Stabilization Process

(list of symbols and abbreviations continued)

US\$ US Dollar

U.S. EPA U.S. Environmental Protection Agency

ZAR South African Rand

CHAPTER I

INTRODUCTION

1.1. BACKGROUND

Limestone contactors are one of the oldest treatment methods to stabilize the pH of water in order to control corrosion in drinking water distribution systems. Limestone contactors have been used for corrosion control since as early as 1908 in Germany (Cox, 1930), in the 1930's in the United States (Cox, 1930; Glace, 1937 and Ryon, 1935), in 1912 in Egypt (Cox, 1930) and in the 1960's in South Africa (Spencer, 2000).

Limestone contactors have recently become a technology of interest in the United States (U.S.) since it is easier and safer to operate and maintain, reduces operating cost, self adjusts the water pH without overdose of chemicals, requires minimal operator skills and does not require continuous feed of chemicals compared to the other corrosion control methods (Benjamin et al., 1992; Letterman, 1995; Spencer, 1998; and De Souza et al., 2000). Due to these attributes, limestone contactors are suitable for a small water treatment system due to their limited number of operators and financial resources.

The main driving force behind stabilization of pH for corrosion control in the U.S. is the Lead and Copper Rule. Implemented by the U.S. Environmental Protection Agency (U.S. EPA) in 1991, this rule requires that the lead and copper in the drinking water not exceed certain levels. There are two lead and copper goals that were established by the U.S. EPA to control the lead and copper levels in drinking water. The first goal is non-enforceable and is called the Maximum Contaminant Level Goal (MCLG). It requires a

water system to supply water without lead and with less than 1.3 mg/L of copper. The second goal called the Lead and Copper Action Level is enforceable and must not be exceeded by the drinking water system. The action level is 0.015 mg/L of lead and 1.3 mg/L of copper. A water system that exceeds one or both of the lead and copper action levels must carry out several treatment requirements including installation of corrosion control treatment. Other driving forces include pipe leakage, lost of water and high cost of pipe repair due to corrosion of the plumbing system (Mackintosh, De Souza and De Villiers, 2003a).

As years have passed, limestone contactors have not only been used solely to stabilize pH of water for corrosion control but also used in promoting flocculation (Benjamin et al., 1992), used in combination with aeration and slow sand filtration to assist in the iron and manganese removal present naturally in the groundwater (Mackintosh et al., 2003b; Aziz et al., 1996 and Smith et al., 1993), used in combination with membrane filtration to assist in aluminum removal (Kettunen and Keskitalo, 2000) and to remove copper from wastewater (Aziz et al., 2001). To date, limestone contactors are not limited to stabilizing drinking water, but are also used for acid mine drainage (Cravotta et al., 1999 and Menendez et al., 2000), acidic wastes (Pearson and McDonnell, 1975a and Santoro et al., 1987), wastewater (Du Plessis et al., 1994 and Maree et al., 1992) and surface water (Vaillancourt, 1981).

Conventional limestone contactors become too large for application in large systems but stabilization of pH using limestone contactors has also been made possible for large water treatment systems and small-scale iron or manganese laden groundwater treatment systems using innovative system designs. The Sidestream Stabilization Process

(SSP) proposes using a limestone contactor in a manner suitable for large water treatment systems (De Souza et al., 2002). A similar process to SSP was also developed by the German Technical and Scientific Association on Gas and Water (DVGW) in the 1980s (Stauder, 2003). The process is called 'Reinerzauer Verfahren', where 'Reinerzauer' is the name of the plant where the process was first implemented in Germany in 1988. The Spraystab is a combination of several treatment processes that enables limestone contactor to be used for treating groundwater with or without the presence of iron and manganese.

1.2. PROBLEM STATEMENT

Most small water systems find it difficult to comply with new environmental regulations because they cannot afford the necessary equipment or staff for treatment due to the small number of customers in their area (USEPA, 1999). The educational modules produced by the University of New Hampshire Water Treatment Technology Assistance Center and the University of Tennessee promote technology options that are easy, economical and require minimal maintenance and supervision to the small water systems in order to comply with environmental regulations and serves as a guide for them to implement the technology. In this project, the educational module serves to introduce limestone contactors as one of the options for corrosion control treatment to control the levels of lead and copper in drinking water as required by the Lead and Copper Rule.

Even though stabilization of pH using limestone contactors has been widely used since the beginning of the 19th century, there has not been a documented guideline available in the U.S. for designing, operating and maintaining a limestone contactor.

There is also limited amount of published literature available discussing the limestone contactors in the U.S. Lack of the design, operational and maintenance guidelines not only may result in incorrectly designed limestone contactors but also in improperly maintained contactors. Even though limestone contactors have proven to be operationally cost effective, improperly designed and maintained limestone contactors may result in contactor fouling and high cost of repairing the problems resulting from improperly designed and maintained limestone contactors.

This document aims to provide guidance to the state and federal regulators, practicing engineers and small water system managers and operators on the design, operation and maintenance of limestone contactors. It is intended to educate the targeted audience on the factors that they need to be aware of before designing a contactor, the typical components of a contactor, the required operator skills, the required maintenance procedure and the design approach used not only in the U.S. but also in other countries where limestone contactors have been successfully designed for both small and large water systems and ferruginous groundwater such as Germany and South Africa.

1.3. PROJECT OBJECTIVE

The objective of this project is to develop a web based educational module on limestone contactors specifically for drinking water professionals such as state and federal regulators, practicing engineers and small water system managers and operators. The module includes description of the processes involved in a limestone contactor, required operator skills and maintenance procedures, capital and operational costs, and design criteria of a limestone contactor. In order to help the targeted audience to better

understand the components and processes, this module also includes interactive process diagrams, photos, downloadable computer software and charts for limestone contactor design, sample problems on using some of the computer software, example plans and specifications, and interactive links to published papers on limestone contactors. The targeted audience will also be able to see the similarities and differences between the limestone contactors in U.S., Germany and South Africa from this module.

CHAPTER II

REVIEW OF THE LITERATURE

2.1. HEALTH IMPACTS OF LEAD AND COPPER

Lead is highly toxic to humans. Its level of toxicity is directly proportional to the period of exposures since lead has a potential to build up in the body over a long time (USEPA, 2000). Even after diminished exposures, lead may still cause adverse effects due to its ability to stay in the body. Lead gradually accumulates and is stored in the soft tissues and skeleton upon repeated exposures. It then moves to the blood and causes a temporary effect in the blood's capacity in carrying oxygen as well as other effects. Based on studies, lead exposure cannot exceed 60 ppb for infants and 500 ppb for adults over a short-term period (USEPA, 2000). The concentration is lower for infants because they have a higher capacity for absorbing lead from the gastrointestinal track.

Short term effects of lead at relatively low levels of exposure include interference with the red blood cells' chemistry, delays in the normal physical and mental development in babies and children, slight interference with attention span, hearing and learning abilities of children and slight increase in the blood pressure of some adults (USEPA Technical Fact Sheet on Lead). A lifetime exposure to lead may cause damage to the central and peripheral nervous system and kidneys, cancer and stroke.

Short-term exposure to high levels of copper may cause gastrointestinal disturbance including nausea and vomiting (USEPA Consumer Factsheet on Copper). A

long-term exposure to copper may cause stomach and intestinal distress, liver and kidney damage and anemia.

2.2. REGULATION TO CONTROL LEAD AND COPPER IN DRINKING WATER

The Safe Drinking Water Act (SDWA) passed in 1974 requires the U.S. EPA to determine the safe levels of chemicals (that do or may cause health problems) that can be present in drinking water. In response to the SDWA, the U.S. EPA set the Maximum Contaminant Level Goal (MCLG) and the Action Level for lead and copper. The MCLG is a non-enforceable goal and is based on possible health risks and exposure. The MCLG for lead is 0 mg/L and for copper is 1.3 mg/L. The Action Level is the level at which water systems may be required to control the concentration of either lead or copper in the drinking water at the consumers' taps. The Action Level for lead is 0.015 mg/L and for copper is 1.3 mg/L.

The U.S. EPA later developed the Lead and Copper Rule (LCR) in 1991. The LCR is intended to control the levels of lead and copper in drinking water in order to minimize the health effects associated with the metals. It is also one of the driving forces for installing corrosion control treatment in a water system.

The LCR requires all community water systems (CWSs) and non-transient non-community water systems (NTNCWSs) to conduct tap monitoring to determine whether the water system exceeds the lead and copper action levels. If more than 10% of the lead and copper samples collected at the consumers' taps exceed either the lead action level of 0.015 mg/L and/or the copper action level of 1.3 mg/L, the LCR requires the water

system to carry out steps to control corrosion in their distribution system. These corrosion control steps may include corrosion control treatment, source water treatment, public education and/or lead service line replacement (USEPA, 2002). The U.S. EPA proposed minor revisions to the LCR in 1996. The purposes of these revisions were to streamline and reduce the regulatory burden without affecting the level of protection of the public health and the environment but did not change the rules listed above (USEPA, 2000).

2.3. FACTORS FOR PRESENCE OF LEAD AND COPPER IN DRINKING WATER

Lead and copper rarely occur at high concentrations in the water that a system provides to its customers (USEPA, 2003). They primarily occur in the drinking water due to corrosion of plumbing materials or piping fixtures containing lead and copper. Another source of these metals are from older submersible water pumps used in wells (NHDES, 1998).

Since corrosion is by far the greatest factor for the presence of lead and copper in drinking water, it is interesting to know what causes the water to corrode the metals from the plumbing and piping fixtures. All water is corrosive towards lead and copper to some extent including water that is termed non-corrosive or water that is treated to make it less corrosive (Schock, 1999b).

The water quality characteristics that have the greatest effect on lead and copper corrosion are pH, dissolved inorganic carbon (DIC), orthophosphate concentration, alkalinity and buffer intensity (USEPA, 2003). Dissolved oxygen and/or chlorine residual specifically affect copper corrosion. However, the corrosive potential of water is mainly

determined by the pH and alkalinity of the water. Generally, a water with a pH of greater than 7.8 and with alkalinity between 30 and 100 mg/L CaCO_3 is not corrosive (USEPA, 2003). The following guidance was prepared by the New Hampshire Department of Environmental Services in estimating the degree of corrosiveness of water assuming that alkalinity is greater than 30 mg/L (NHDES, 1998):

- pH less than 6.0 : Water is normally highly corrosive.
- pH between 6.0 to 6.9 : Water is somewhat corrosive.
- pH between 7 and 7.5 : Water is possibly not excessively corrosive.
- pH above 7.6 : Water should not be particularly corrosive to metal plumbing.

2.4. LIMESTONE CONTACTORS FOR pH STABILIZATION TO CONTROL CORROSION

Altering the water quality characteristics, mainly by pH or alkalinity adjustment, can control lead and copper corrosion. Depending on the suitability of the water quality characteristics, limestone contactors can be used to alter the water quality and thus control corrosion of lead and copper in the water.

2.4.1. Description of Process Involved in Limestone Contactors

In a limestone contactor, water flows through a bed of crushed sieved limestone in a similar way as it would flow through a sand filter (Spencer, 2000). The process and design of limestone contactors is similar to a sand filter except its loading rate is less than 1 gpm/ft², which is less than the typical filtration loading rate (Spencer, 2000). The low

loading rate ensures adequate time for water to dissolve calcium carbonate ($CaCO_{3(s)}$) from limestone. The pH of water that flows through the limestone bed will be adjusted until it nears equilibrium with $CaCO_{3(s)}$.

There are two types of contactors: (i) open and (ii) closed system contactors. The former is exposed to the atmosphere and the latter is covered from the atmosphere. Some of the closed system contactors are built in pressurized vessels (Stauder, 2002).

Limestone contactors are typically located at the end of the treatment train – after filtration, primary disinfection and chlorine contact (Spencer, 2000 and Benjamin et al., 1992). According to Spencer (2000) and Benjamin et al. (1992), placing the contactor after chlorination gives a lower pH and hence more effective chlorination. However, there are also contactors that are located after filtration and before chlorine addition (Stauder, 2002). Most of these contactors are located in Germany. The reason for placing the contactor before chlorine addition is because disinfection is not required in most limestone contactor plants in Germany especially if the plants are treating high quality deep spring water with very low turbidity (less than 0.1 NTU) and no or very low number of coliforms (Stauder, 2003).

The SSP process which as stated earlier is intended for large systems, takes a side stream of unstabilized water and doses it with carbon dioxide (De Souza et al., 2000). The acidified CO_2 -dosed side-stream then contacts a limestone bed, which will dissolve a considerable amount of $CaCO_3$, increasing alkalinity and calcium concentration in the water. Much of the remaining CO_2 is recovered by stripping with air and reused in the process and the stabilized side-stream blends with the main stream for full stabilization.

The Simplified SSP is similar to the SSP but excludes CO₂ recovery. In this process, there are two options that can be carried out after the acidified CO₂-dosed sidestream contacts the limestone bed: (1) strip CO₂ from the sidestream with no recovery, or (2) blend the sidestream and mainstream without stripping (De Souza et al., 2000).

The Spraystab I is intended for small groundwater systems that need to remove iron or manganese. It combines aeration, limestone stabilization and filtration in one tank (Mackintosh, De Souza and De Villiers, 2003b). The raw groundwater is first aerated to strip excess carbon dioxide from water and dissolve oxygen into the water to oxidize iron and manganese. The aerated water then flows downward through the limestone bed to be stabilized. Finally, the water flows through a dual media filter (top layer of hydroanthracite and lower layer of filter sand). In the filter, the limestone fines and other insoluble matter such as iron and manganese flocs are removed.

The Spraystab II is intended for small groundwater systems that do not need to remove iron or manganese. It is similar to Spraystab I but excludes multi-media filtration and the water flows in the contactor in an upward direction (Mackintosh, De Souza and De Villiers, 2003b). The raw groundwater is first aerated and then flows downward through a tube to the base of the limestone stabilization unit. Sludge will be collected at the base of the unit. Then, the water is uniformly distributed by a slotted pipe manifold system through the limestone bed in an upward direction to be stabilized.

2.4.2. Typical Components of a Limestone Contactor

A limestone contactor typically consists of a structure used to hold a limestone bed, maximum limestone level mark, limestone refill level mark, outlet for treated water, flush outlet, limestone bed, supporting media, distribution system, access lid (for closed

contactors only) and overflow line. A ladder may also be necessary if the access hatch for the limestone contactor is not at the ground level. [Figure B1](#) (Click on the link for Figures B1 to B2) shows the typical components of a limestone contactor in detail.

The maximum level mark indicates the maximum amount of limestone that needs to be filled in a limestone contactor. It can be determined using empty bed contact time (EBCT) and superficial flow rate by using the worst-case of influent water chemistry such as lowest water temperature (Cox, 1930) and pH (Spencer, 2002). Computer models such as DESCON (Letterman and Kothari, 1995) and STASOFT (De Souza et al., 2000 and De Souza et al., 2002) or design curves from DVGW (1998) can be used to aid in determination of this level.

The refill or recharge level is the minimum amount of limestone that can be present in a contactor and still achieve adequate water stabilization. When the level of the media reaches this level, additional media must be added to avoid reduction in the performance of the contactor and treated water quality.

The piping on the limestone contactor includes the inlet, outlet, flush outlet and the overflow pipe. The inlet pipe allows water to flow into the contactor and the outlet pipe allows water to flow out of the contactor. The flush outlet is used to discharge the dirty water resulting from the backwashing or cleaning process.

An access lid is used to cover a contactor from exposure to the atmosphere. It minimizes dissolution of carbon dioxide gas into the water and prevents contamination in outside installation. It also provides access for maintenance or cleaning work.

The limestone contactor media consists of a layer of limestone on the top and a layer of supporting media on the bottom. The height of the limestone bed in a contactor

depends on the required contact time and superficial flow rate. According to Stauder (2002), the height of the limestone bed should be in the range of 4 to 10 feet (1 to 3 meters). This should yield an EBCT of 15 to 60 minutes, which is an optimum range for contactor design. The supporting media usually consists of gravels or garnet. In Figure B1, there is a slotted pipe in the supporting media layer to distribute the water uniformly throughout the limestone bed. Since the inlet of the contactor is located at the bottom of the contactor, the distribution system is also located at the bottom and the water flows upward through the limestone bed. There are also contactors in which water flows downward through the limestone bed, for example the limestone contactor in Mars Hill Blaine Water Co. Filter Plant, Maine. In this plant, a wall with submerged weir is used as the distribution system since it was retrofitted into an existing clear well (Kearney, 2003).

Figure B2 shows the schematic of the Sidestream Stabilization Process. The components of the SSP process include flow splitting, a limestone contactor, addition of CO_2 , recovery of CO_2 , recycling of CO_2 and flow blending. The components and the process involved in the limestone contactor in Figure B2 are the same as in Figure B1.

Figure B3 shows the schematic of the Simplified Sidestream Stabilization Process. The components of a Simplified SSP include flow splitting, a limestone contactor, addition of CO_2 , stripping of CO_2 or addition of lime and flow blending.

Figure B4 shows the typical components of a Spraystab I unit. Spraystab I is a combination of three treatment processes; aeration, stabilization using limestone contactor, and filtration.

- The aeration unit consists of the spray nozzles, aeration ducts and ventilation holes (Mackintosh, Engel and De Villiers, 1997). It is located inside the lid of the Spraystab system. Air is drawn in through the air ducts to aerate the water. The purpose of aeration is to strip excess carbon dioxide from the water and dissolve oxygen into the water. This will assist in the oxidation of iron and manganese. Water flows directly from the borehole pump to the spray nozzles. The nozzles are designed such that they would provide sufficient spray action. The air ducts in the lid are covered with mesh screen and allow air that is drawn into the system to escape. A feed control valve and a rotameter may be installed in the feed line for additional control, but are not necessary.
- The stabilization unit consists of a limestone bed supported by a 10 mm wire mesh screen (Mackintosh, Engel and De Villiers, 1997). The limestone bed is approximately 800 mm deep and is granular porous graded limestone with a grading of $-15 \text{ mm} + 12 \text{ mm}$. The aerated water from the aeration unit flows downward through the limestone bed resulting in an increase in pH and total alkalinity. The iron and manganese will oxidize and precipitate to form insoluble flocs. The iron and manganese flocs, limestone fines and insoluble silica will flow through the support screen to the filtration unit to be removed.
- The filtration unit is divided into two compartments; each with a slotted pipe underdrain (Mackintosh, Engel and De Villiers, 1997). The water from the slotted pipe feeds into a common manifold fitted with a raised outlet to control the water level in the filter. The filter media consists of an upper layer of 1.0 to 1.5 mm hydro-anthracite and a lower layer of 0.3 to 0.5 mm filter sand to a depth of 300

mm above the underdrain. The filter bed is divided in two by a splitter to allow backwashing of half the filter area using the low volume supply to the aeration unit. The filtration unit removes limestone fines and iron and manganese flocs. Spraystab II unit consists of an access lid with ventilation holes, inlet, spray nozzles, “settling tubes”, limestone bed, supporting media, slotted pipe manifold, drain valve and outlet to storage tank as shown in [Figure B5](#).

2.4.3. Chemical Reactions Involved in Limestone Dissolution

In order to understand the reactions involved in a limestone contactor, one must understand the basic principles governing the carbonate system in natural water and its equilibrium with limestone. Natural water contains carbonate species such as aqueous or dissolved carbon dioxide ($CO_{2(aq)}$), carbonic acid ($H_2CO_3^*$), bicarbonate (HCO_3^-) and carbonate (CO_3^{2-}) (Snoeyink and Jenkins, 1980). In a limestone contactor, the concentrations of the dissolved carbonate species are driven toward chemical equilibrium with $CaCO_3$ by dissolving limestone. It is the interaction of these species that controls the pH in natural water (De Souza et. al., 2000) and can be undersaturated, in equilibrium or oversaturated with $CaCO_3$ although lower pH and lower alkalinity waters of interest here are undersaturated with $CaCO_3$.

The degree of $CaCO_3$ saturation of water is commonly calculated using the Langelier Index (L.I.). L.I. is the difference between the actual pH and hypothetical pH at equilibrium. Undersaturated water is represented by a negative value of L.I. and tends to dissolve $CaCO_3$ whereas oversaturated water is represented by a positive value of L.I.

and tends to precipitate $CaCO_3$. Other procedures that can be used to determine the state of saturation of $CaCO_3$ include evaluating the Calcium Carbonate Dissolution Potential, Ryznar (Saturation) Index, general saturation index also known as disequilibrium index and Larson's Ratio (Schock, 1999b). The Marble Test and the carbonate saturometer device can also be used and both operate on the same principle (Schock, 1999b).

If one assumes that the only aqueous species are H^+ , OH^- , calcium and carbonate species, then Equations 1 to 7 take place when unstabilized water dissolves limestone in a closed system and reaches equilibrium.

Equation 1. Dissociation of Water



Equation 2. Dissolution of $CaCO_3$ from Limestone



Equation 3. Formation of HCO_3^-



Equation 4. Formation of $H_2CO_3^*$



Equation 5. Formation of $CaCO_3^0$ Complex:



Equation 6. Formation of CaOH^+ Complex:**Equation 7. Formation of CaHCO_3^+ Complex:**

In Equations 1 to 7, activities rather than concentrations are used in expressing the corresponding equilibrium constants. This is due to increased electrostatic interactions between ions as concentration of ions in solution increases (Snoeyink and Jenkins, 1980). As a result, the activity of ions becomes less than their measured or analytical concentration. Several mass balances must also be met as follows:

Equation 8. Total Calcium Concentration

$$C_{T,\text{Ca}} = [\text{Ca}^{2+}] + [\text{CaHCO}_3^+] + [\text{CaCO}_3^0] + [\text{CaOH}^+]$$

Equation 9. Total Carbonate Concentration

$$C_{T,\text{CO}_3} = [\text{H}_2\text{CO}_3^*] + [\text{HCO}_3^-] + [\text{CaHCO}_3^+] + [\text{CaCO}_3^0] + [\text{CO}_3^{2-}]$$

Equation 10. Charge Balance

$$2[\text{Ca}^{2+}] + [\text{CaHCO}_3^+] + [\text{CaOH}^+] + [\text{H}^+] = [\text{HCO}_3^-] + 2[\text{CO}_3^{2-}] + [\text{OH}^-]$$

Equation 11. Concentration Balance

$$C_{T,\text{Ca}} = C_{T,\text{CO}_3}$$

Calculations for real waters soon become more complicated because of the presence of other species but the principles are the same. In practice, computer software such as AQUACHEM, MINEQL, MINTEQA, STASOFT or custom programs are used.

Both Letterman and Kothari (1995) and Schott (2003) have developed programs specifically for solving dissolution of limestone in contactors as discussed in [Section 2.5](#).

2.4.4. Factors Affecting Limestone Dissolution

Dissolution of limestone increases pH, alkalinity and dissolved inorganic carbon (DIC) of water and depletes the amount of limestone in a bed (Haddad, 1986). As the amount of limestone lessens over time, the bed depth and contact time will also be reduced. In a poorly designed contactor, dissolution takes less time for the limestone to reach the recharge level and it needs to be refilled more frequently. This will not only affect the contactor performance but also the operating cost. Therefore, it is important to know the factors affecting dissolution rate of limestone before designing a contactor in order to ensure its long-term performance. Generally, the dissolution rate of limestone is affected by the physical and chemical properties of water and limestone as discussed below.

- **Physical and Chemical Properties of Water:**

- a. **Extent of CaCO_3 undersaturation:**

Water can only dissolve limestone if it is undersaturated with respect to CaCO_3 . Higher dissolution rates occur with waters that are more undersaturated (Van Tonder et. al., 1997; Striebel et. al., 2002).

- b. **DIC content:**

DIC is the sum of all carbonate containing species. It is represented by C_{T,CO_3} as shown in [Equation 9](#). If complexes are negligible, DIC is the sum of H_2CO_3^* , HCO_3^- and CO_3^{2-} concentrations. DIC content governs the equilibrium

of the carbonate system and the level of CaCO_3 saturation. It affects the dissolution rate because it affects the extent of CaCO_3 undersaturation.

c. Temperature:

Limestone dissolution rate increases as the temperature of water increases (Cox, 1930; Letterman, 1995; Spencer, 2000). Rickard and Sjöberg (1983) also found that the overall dissolution rate constant is a complex function of temperature.

d. Ionic strength:

Rickard and Sjöberg (1983) found that calcite dissolution rates are dependent on ionic strength. In general, solubility of salts increases with increasing ionic strength (Snoeyink and Jenkins, 1980). Since ionic strength is used to calculate the activity coefficients of each carbonate species in water, it also affects the activities of species in equilibrium and dissolution kinetic equations.

e. Iron content:

A study conducted by Maree et. al. (1992) on using limestone in neutralizing acid mine water showed that the efficiency of the CaCO_3 stabilization process is strongly influenced by the acid mine water's iron content. They found that Fe(II) inhibits the dissolution rate due to precipitation of Fe(II) on the limestone surface. However, this may not necessarily occur with surface waters since typical iron content in surface waters is much lower and the pH is much higher than in acid mine water.

- **Physical and Chemical Properties of Limestone:**

- a. **Limestone content:**

There are several types of minerals that can be considered as limestone and used as a media in a contactor. These include calcite ($CaCO_3$) and dolomite ($CaMg(CO_3)_2$). In Germany, half-burnt dolomite ($CaCO_3 \cdot MgO$) and porous calcium carbonate ($CaCO_3$) are used (Stauder, 2003). According to Letterman (1995), media with the highest calcite and lowest dolomite content has the highest initial rates of dissolution. When dolomite was used, he found that the calcium carbonate component of the dolomite dissolved faster than the magnesium carbonate component. A similar result was reported by Plummer and Busenberg (1982) (Letterman, 1995). Laboratory tests conducted by Menendez et. al. (2000) using limestone to neutralize acidic mine drainage also showed that the higher the $CaCO_3$ content in the stone, the higher the dissolution rate. The same result was also obtained in a study conducted by Letterman (1995) where the overall dissolution rate constant decreased by approximately 60% as the calcite content decreased from 0.92 to 0.09 g $CaCO_3$ per gram stone.

- b. **Particle size:**

According to Rickard and Sjoberg (1983), Erga and Terjesen found that the rate of calcite dissolution is proportional to the surface area per unit volume of media. Smaller media sizes have a larger surface area exposed to the water, resulting in higher dissolution rates compared to the larger media sizes (Cox,

1930; Santoro et al., 1987; Maree et al. 1992; Du Plessis et al., 1994; Menendez et al., 2000).

c. Presence of impurities:

Benjamin et al. (1992) recommended that the type of limestone to be used in a contactor should be of high calcium limestone with minimum impurities.

Impurities in limestone include iron, aluminum and silica. According to Letterman (1995), presence of silica only reduced the effective surface area of limestone but did not appear to cause a reduction in the dissolution rate of the calcite surface. However, aluminum and iron content of the stone reduced the overall dissolution rate.

Haddad (1986) also found that as limestone dissolved from the stone, the rate of dissolution decreased because a residue layer consisting of insoluble impurities (such as silica, alumino-silicates and aluminum and iron oxides/hydroxides) is formed and remains on the surface. As the layer thickness increases, the rate of transport of calcium ion from $CaCO_3$ surface to the bulk solution decreases (Letterman, 1995).

2.4.5. Modeling Limestone Dissolution

As $CaCO_3$ dissolves from the limestone contactor media, particle size, bed depth, flow velocity and pressure drop change with time. It is important to make design choices for these variables since they affect the dissolution rate and recharge frequency. Letterman and Kothari (1995) and Haddad (1986) developed models of limestone dissolution rate that are sensitive to these variables and can be used for design.

Haddad (1986) used Equations 12 and 13 below to model the limestone dissolution process in a contactor operating at steady state.

Equation 12. Calcium Carbonate Dissolution Rate, r

$$r = k_o a (C_{eq} - C)$$

where:

r = Calcium carbonate dissolution rate (moles/cm².s).

C_{eq} = Equilibrium calcium ion concentration, moles/L.

C = Bulk calcium concentration, moles/L.

a = Area of $CaCO_3$ per unit volume of fluid, cm⁻¹.

k_o = Overall dissolution rate constant, cm/s.

Equation 13. Continuity Equation

$$N_D \frac{d^2 C}{dZ^2} - \varepsilon \frac{dC}{dZ} + r\theta = 0$$

where:

N_D = Axial dispersion number, dimensionless.

Z = Depth, dimensionless.

ε = Porosity of limestone particles, dimensionless.

θ = Mean fluid residence time, sec.

Using Equations 12 and 13, Letterman, Haddad and Driscoll (1991) developed a steady-state model that relates the depth of limestone required in the contactor to the desired effluent water chemistry, influent water chemistry, limestone particle size and shape, bed porosity, water temperature and superficial velocity as shown in Equation 14.

Equation 14. Substitution of Equation 12 into 13

$$\frac{C_{eq} - C_{bL}}{C_{eq} - C_{bo}} = \exp \left\{ -\frac{k_o a L \varepsilon}{U_s} + \left(\frac{k_o a L \varepsilon}{U_s} \right)^2 N_D \right\}$$

where:

C_{bo} = Calcium concentration in the influent of a contactor, moles/L.

C_{bL} = Calcium concentration in the effluent of a contactor, moles/L.

L = Overall depth of a contactor, cm.

U_s = Superficial velocity of fluid, cm/s.

N_D = Axial dispersion number, dimensionless.

This model assumes that the rate of dissolution is controlled by two resistances that act in series: a surface reaction that controls the release of calcium from the solid and a mass transfer resistance that controls the rate of calcium transport between the solid surface and the bulk solution (Letterman and Kothari, 1995). Based on this kinetic model, Letterman and Kothari (1995) developed a computer program called DESCON used to facilitate the design of limestone contactors.

2.5. DESIGN APPROACH

A limestone contactor designer must be aware of the factors affecting limestone dissolution as discussed in [Section 2.4.4](#) before designing a limestone contactor to ensure its optimal performance. [Table 1](#) shows the general design criteria for limestone contactors in the U.S., Germany and South Africa.

Table 1. General Criteria for Limestone Contactor Design

Design Criteria	U.S.	Germany	South Africa
Location in the Treatment Train	Limestone contactors are typically placed after filtration, primary disinfection and chlorination (Spencer, 2000). There was also a pilot study conducted in British Columbia (Benjamin et al., 1992) that used a limestone contactor before the flocculation process 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., 1996). The USEPA(2003) prepared a flow diagram as shown in Figure B6 to determine whether a limestone contactor would be a feasible option for a water system. The decision would be	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	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)

Table 1. Continued

Design Criteria	U.S.	Germany	South Africa
Water Quality Characteristics – continued	based on assessing the water quality parameters of the system. In summary, a water system should have a pH of less than 7.2, calcium less than 60 mg/L and alkalinity less than 100 mg/L. A special contactor design is required if the iron content is more than 0.2 mg/L and manganese content is more than 0.05 mg/L. This is due to the possibility of 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. In the Spraystab unit, the water is first aerated, then stabilized by contacting limestone and finally filtered through a sand filter. The values in Figure B6 are	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 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, pH_c 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,	See previous page.

Table 1. Continued

Design Criteria	U.S.	Germany	South Africa
Water Quality Characteristics – continued	similar to those given by Spencer (2000) except that alkalinity was given as less than 50 mg/L and hardness less than 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.	manganese, or aluminum removal may be required ahead of the limestone contactor (DVGW, 1998).	See previous page.
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 to 0.75 hour), depending on the CO_2 and HCO_3^- contents in the raw water (Stauder, 2002).	EBCT is typically 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).	Typical loading rate is 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	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).

Table 1. Continued

Design Criteria	U.S.	Germany	South Africa
Flow Requirements – continued	See previous page.	30% (DVGW, 1998) to avoid the water from becoming oversaturated with respect to $CaCO_3$ and precipitating in the contactor (Stauder, 2003)	See previous page.
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 as discussed in the design aids section of Table 1 .	The limestone bed depth can be determined using the appropriate Figures B8 to B13 and the equations discussed in the design aids section of Table 1 . 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 fluctuations.	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). The weighted sum of aluminum and iron in the limestone media must not exceed 10 mg/g of stone (Letterman, 1995). Testing of constituents of the limestone media must adhere to	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 of Table 1). The following shows the water quality characteristics that are applicable for each type of the limestone media (DVGW, 1998):	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.

Table 1. Continued

Design Criteria	U.S.	Germany	South Africa
Limestone Characteristics - continued	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 imparted to the water as the limestone dissolves.	a) Dense Calcium Carbonate: i. Target pH=8 $K_{S,4.3} + 2K_{B,8.2} \leq 1.5 \text{ mol/m}^3$ $[Ca] \leq 0.75 \text{ mol/m}^3$ ii. Target pH=saturation pH $K_{S,4.3} + 2K_{B,8.2} \leq 1.0 \text{ mol/m}^3$ $[Ca] \leq 0.75 \text{ mol/m}^3$ a) Porous Calcium Carbonate: $K_{S,4.3} + 2K_{B,8.2} \leq 1.5 \text{ mol/m}^3$ $[Ca] \leq 0.75 \text{ mol/m}^3$ b) Half-Burnt Dolomite: $K_{S,4.3} + 2K_{B,8.2} \leq 2.5 \text{ mol/m}^3$ 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 Standard available from http://www.techstreet.com/info/bsi.html: • 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).	See previous page.

Table 1. Continued

Design Criteria	U.S.	Germany	South Africa
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 reactivity of the media for the size range between 0.7-3.0 mm (Stauder, 2003).	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).
Supporting Media	Supporting media used is based on the AWWA Standards for Filtering and Support Media (Spencer, 2003). The size of the support media used should be larger than the limestone size (Spencer, 2003).	Supporting media consists of 0.2 to 0.3 m in depth of inert materials (DVGW, 1998).	Supporting media consists of 150 mm deep, 25 mm diameter granite aggregate.

Table 1. Continued

Design Criteria	U.S.	Germany	South Africa
Design Aids	The DESCON model was developed by Letterman and Kothari (1995) to aid in the design of a limestone contactor. This computer program has been used by Spencer (2002) to design the limestone contactor facility in Mars Hill Blaine Water Co. Filter Plant, 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 B7 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.	A guideline for designing a limestone contactor is available (W 214/II: Entsauerung von Wasser Teil 2: Grundsätze für Planung, Betrieb und Unterhaltung von Filteranlagen) from DVGW (1998). However, this guideline is based on empirical correlations (Stauder, 2003). 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 B8 to B13 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	$CaCO_3$ 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 (De Souza et al., 2000) is used to determine the $CaCO_3$ saturation and degree of stabilization of water using $CaCO_3$.

Table 1. Continued

Design Criteria	U.S.	Germany	South Africa
Design Aids - continued	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. 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	size ranges between 1.0 – 2.0 mm and a target pH value of either 8 or pHc. (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 B13 is used for temperature correction. Using Figures B8 to B13, the minimum volume of the limestone media required can be calculated as follows (DVGW, 1998): (i) Minimum volume of Limestone, V_M: $V_M = Q \times t_f \times f \times 1/60$ where: V_M = minimum volume of media, m^3 chosen using the appropriate Figure B8 to B13 (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.	See previous page.

Table 1. Continued

Design Criteria	U.S.	Germany	South Africa
Design Aids – continued	calculated using this program include pH, total alkalinity, CO_2 concentration, DIC, calcium content and copper content from the initial to equilibrium condition. The program is available in the design criteria section of the educational module and can be run from module.	Therefore, 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 B13) 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): <u>Estimation of V_B:</u>	See previous page.

Table 1. Continued

Design Criteria	U.S.	Germany	South Africa
Design Aids – continued	See previous page.	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: $V_F = \text{filter bed volume, m}^3$ $V_B = \text{consumption volume, m}^3$ Refer to Appendix C to view an example	See previous page.

Table 1. Continued

Design Criteria	U.S.	Germany	South Africa
Influent Distribution Systems	No information found.	on using Figures B8 to B13 . 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	No information found.	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).	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,

Table 1. Continued

Design Criteria	U.S.	Germany	South Africa
Contactors Configuration – continued	See previous page.	However, the configuration depends on the amount of water to treat and the benefit of keeping the pressure (Stauder, 2003).	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	No information found.	Concrete is usually used for open filters and stainless steel is typically used for closed filters (Stauder, 2003).	Cement-concrete or fiberglass (Mackintosh, De Souza and De Villiers, 2003a).
Contactors Wall Protection	No information found.	For open filters, the wall can be protected from corrosion using ceramic tiles while in the closed filters, 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).
Backwash Requirements	No information found.	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	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 Villiers, 2003a).

Table 1. Continued

Design Criteria	U.S.	Germany	South Africa																									
Backwash Requirements – continued	See previous page.	backwash practice in Germany (DVGW, 1998): <table><tr><th colspan="2">Backwash Step</th><th>Period (min)</th><th colspan="2">Backwash Rate (m/hr)</th></tr><tr><th colspan="2"></th><th></th><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 ^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-burnt dolomite 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.	Backwash Step		Period (min)	Backwash Rate (m/hr)					Air	Water	1	Air	3 – 5	60	None	2	Air/ Water	5 – 10	60	10–12	3	Water	None ^a	None	12–25	See previous page.
Backwash Step		Period (min)	Backwash Rate (m/hr)																									
			Air	Water																								
1	Air	3 – 5	60	None																								
2	Air/ Water	5 – 10	60	10–12																								
3	Water	None ^a	None	12–25																								
Water Quality Monitoring Requirements	No information found.	Limestone contactors must be equipped with water quality monitoring taps before and after stabilization (DVGW, 1998). The most important parameter to measure is the pH of the effluent from the contactor especially if a contactor uses dolomite as a media.	Sample taps for water quality monitoring before and after stabilization must be provided. (Mackintosh, De Souza and De Villiers, 2003a). Two piezometers must be provided																									

Table 1. Continued

Design Criteria	U.S.	Germany	South Africa
Water Quality Monitoring Requirements – continued	See previous page.	Limestone contactors should have visible indicator showing the level for media refilling (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).	on each contactor to measure pressure loss across the limestone bed (Mackintosh, De 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	No information found.	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, 2003a). 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).

[Table A1](#) shows the treatment objectives and [Table A2](#) 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 (Click on the link for Tables A1 to A17). [Table A3](#) shows the general design criteria of the Spraystab I unit. [Table A4](#) shows the design criteria of the Spraystab II system used to stabilize water in small-scale groundwater systems without iron and manganese present.

2.6. LIMESTONE CONTACTORS PERFORMANCE DATA

The following shows the performance of limestone contactors in stabilizing water by presenting data taken before and after limestone contactors were installed in Mars Hill, Maine; New Hampshire; Bredasdorp, South Africa and Stellenbosch, South Africa.

2.6.1. Performance Data From Mars Hill, Maine

Prior to installation of a limestone contactor in October 1998, Mars Hill Blaine Water Co. Filter Plant, Maine exceeded the Lead and Copper Rule (Spencer, 2000). The 90th percentile lead level was 0.017 mg/L and copper level was 1.30 mg/L. Part of the cause was believed to be low pH. Installing a limestone contactor raised the pH and significantly reduced the lead and copper level. After limestone contactor was installed in the plant, the pH of treated water in Mars Hill increased as shown in [Figure B14](#).

[Figure B15](#) shows that limestone stabilization decreased the 90th percentile lead level from 0.017 mg/L in Fall 1996 to 0.008 mg/L in Spring and 0.006 mg/L in Fall 1999. [Figure B16](#) shows that the 90th percentile copper concentration was reduced from 1.3 mg/L in Fall 1998 to 0.5 mg/L in Spring and 0.65 mg/L in Fall 1999.

2.6.2. Performance Data From Various Sites in New Hampshire

There are several water systems in New Hampshire that use limestone contactors for corrosion control (Lucey, 2003). These systems include community water systems and non-transient community water systems (Thayer, 2001). Most of these water systems obtain their raw water sources from bedrock wells. Others obtain their raw water sources from either gravel well or surface water (Thayer, 2001). [Table A5](#) shows the summary of treatment performance of the limestone contactors in New Hampshire.

2.6.3. Performance Data From Stellenbosch and Bredasdorp, South Africa

In Bredasdorp, problems of “blue” and “red” water were common prior to limestone stabilization in 1996 (Daniels et al., 2002). Blue and red water are caused by high levels of iron and copper. [Table A6](#) shows the effectiveness of limestone contactor by comparing the water quality before (in 1996) and after stabilization (in 2001). The treated water quality was monitored at various sampling points within the Bredasdorp drinking water distribution network. After limestone stabilization, the treated water characteristics within the network were improved. The Calcium Carbonate Dissolution Potentials (CCDP) were low and the pH values were generally greater than 8.3 (Daniels et al., 2002).

According to the AWWA guidelines for copper corrosion mitigation, the bulk water pH must be in the range of 7.1 to 8.0 (Daniels et al., 2002). [Figure B17](#) shows the relationship between copper and pH levels at various sampling points in the Bredasdorp pipe network after limestone stabilization. [Figure B17](#) shows that the copper level remains fairly consistent throughout the pH range except for three samples. All these three samples had a pH value below 7.1. Similar results were obtained in a study on the

effectiveness of a limestone contactor on copper reduction in Stellenbosch, South Africa as shown in [Figure B18](#). Based on [Figures B17](#) and [B18](#), Daniels et al. (2002) concluded that copper corrosion is not expected at pH above 7.1 consistent with the AWWA guidelines mentioned above.

The effectiveness of a limestone contactor on copper reduction was also studied in Stellenbosch, South Africa by collecting pH and copper data at a household sampling point. According to Daniels et al. (2002), the limestone contactor was operated at a loading rate 50% greater than its design capacity due to increased water requirements in Stellenbosch. The author implied that this overloading caused the pH to be lower than desired and led to higher copper concentrations. The author further implied that expanding the limestone contactor increased the pH and decreased the copper level as shown in [Figure B19](#).

2.6.4. Performance Data of Spraystab Unit

[Table A7](#) shows the typical performance of the Spraystab I unit in stabilizing groundwater containing iron and manganese.

2.7. COST DATA

This section presents cost data for limestone contactor installations in British Columbia, Maine and South Africa.

2.7.1. Example of Construction Costs: Case Study at Port Simpson, British Columbia

[Table A8](#) shows cost estimates of two limestone contactors built in Port Simpson, British Columbia for flocculation and corrosion control purposes. The total cost to

construct both of these contactors was CND\$ 140,000 in 1992 (US\$ 105,717 in 2002) (Based on Bank of Canada inflation calculator and exchange rate: CND\$1 = US\$ 0.63 on Dec 31, 2002). The high total cost was due to the facility being remote from large towns causing increased cost in transporting construction materials. It was estimated that 90% of the limestone cost was for transportation. The total cost would be approximately 50% lower if the facility were close to large towns.

The cost for the two contactors at Port Simpson was estimated based on the design basis listed in [Table A9](#). The limestone contactor used for flocculation used different design criteria than the limestone contactor used for corrosion control. This may be due to higher requirement on the pH and alkalinity content of the water treated used for corrosion control. Therefore, it is designed to have a contact time lower than that of the contactor used for flocculation.

2.7.2. Cost Comparison Between Limestone Contactor and Other Treatment Options: Case Study at Mars Hill Plant, Maine and Makwane Plant, South Africa

A cost comparison was made between a limestone contactor and soda ash for treating an average of 1.1 MLD of water (1.6 MLD maximum) at the Mars Hill, Maine water treatment facility. It showed that the capital costs between the two options were similar, in the range of US\$ 40,000 (Spencer, 2000). De Souza et al. (2000) found that the capital cost for limestone contactor installation is much higher than adding lime and soda ash for treating 6 MLD water at Makwane Treatment Plant in South Africa. Refer to [Table A10](#) for cost comparison.

Even though the capital cost for limestone contactor is high, it is less expensive to operate and maintain compared to feeding soda ash and lime (Spencer, 2000 and De

Souza et al., 2000). It was estimated that the yearly cost of limestone replacement at Mars Hill, Maine is US\$ 200 compared to US\$ 2,500 for soda ash (Spencer, 2000). [Figure B20](#) and [Table A11](#) shows comparison of cumulative cost between limestone, lime and sodium carbonate over a 10-year period for the Makwane Plant in South Africa. [Figure B20](#) and [Table A11](#) demonstrate a significant savings when using limestone contactor over lime and sodium carbonate that more than offset higher capital costs.

2.7.3. Comparison of Operational Costs Between Simplified SSP Variation and Conventional Stabilization: Case Study at Lesotho Highlands Scheme, South Africa

Comparison of operating costs was made (i) between the Simplified SSP and conventional stabilization (based on achieving the same final water quality) as shown in [Table A12](#) and (ii) between each Simplified SSP variation as shown in [Figure B21](#). The operating costs in [Figure B21](#) were determined using the chemical dosages and chemical costs required to treat the raw water quality characteristics as shown in [Table A12](#) until a final alkalinity of 50 mg/L and a CCPP of zero were achieved. The chemical prices were based on the current cost at Stellenbosch, South Africa in November 1999 shown in [Table A13](#). [Figure B21](#) shows that the use of a 20% sidestream in the SSP leads to a 50% chemical cost saving (De Souza et al., 2002). In the case of a 100 ML/day treatment plant using the SSP, this is equivalent in a savings of ZAR 78,900 (US\$ 12,624) per month and ZAR 959,950 (US\$ 153,592) per year (De Souza et al., 2002) (Exchange Rate: ZAR 1 = US\$ 0.16 based on Bank of Canada Exchange Rates Schedule on Dec 31, 1999). The treatment cost using conventional lime/ CO_2 shows a constant trend throughout the range of the percent sidestream. Cost comparison also shows that it was financially attractive to do any of the following:

- a) Strip the excess CO_2 after blending the sidestream and mainstream instead of before blending the sidestream and mainstream.
- b) Accompany the partial stripping of the mainstream by adding lime.
- c) Not strip the CO_2 from the mainstream.

Cost analysis was carried out to investigate the viability of the Simplified SSP to stabilize the raw water of the Lesotho Highlands Scheme, South Africa. Financial evaluation of SSP was conducted by comparing its cost with the conventional methods (lime and carbon dioxide stabilization) treating the raw water from Katse Dam, South Africa as shown in [Table A14](#). The viability of the SSP was assessed using a computer model developed using JAVA and by pilot plant operation. [Table A15](#) shows the cost comparison between SSP and conventional stabilization. The cost comparison in [Table A15](#) and financial model in [Table A16](#) were based on utilizing a “high” percentage sidestream (10%) combined with “low” percentage CO_2 recovery and re-use (10%), and an airstrip of the blended stream.

Based on the data shown in [Table A15](#) and [Table A16](#), even using assumptions that are detrimental to SSP (such as lifespan of 10 years, raised electricity costs for SSP, risk discount factor of 30% per annum, minimum required return of investment of 10% per annum and low percentage CO_2 recovery), SSP still provides a significant cost advantage over conventional lime/ CO_2 stabilization with a project payback period of 4.3 years compared to the typical payback period of 15 years for municipal systems (De Souza et al., 2002). The Net Present Value is greater than required which is ZAR 2.7

million (US\$ 0.4 million) with an associated Internal Rate of Return of 52% (De Souza et al., 2002).

2.8. REQUIREMENTS AND PROCEDURE FOR OPERATION AND MAINTENANCE

A limestone contactor requires minimal operator attention and maintenance provided that it is correctly designed to treat the maximum flow of the plant and it is properly situated in the treatment train (Spencer, 2000). A limestone contactor operator must have the skills to carry out the operation and maintenance procedures listed in [Table A17](#).

The operator must also maintain a record of all operations, regular inspections, water quality parameters monitored and maintenance of the contactor in a limestone contactor log book (Mackintosh, De Souza and De Villiers, 2003a).

2.9. ADVANTAGES AND DISADVANTAGES OF LIMESTONE CONTACTORS

Limestone contactors effectively reduce the dissolution of corrosion products; such as lead, copper and zinc from piping surfaces (Letterman et al., 1987; Letterman, 1995) by using a simple, safe and cost-effective process. Limestone contactors have been proven to be suitable for small public water treatment plants since it eliminates the common problems associated with using chemical dosing equipment including eliminating the risk of chemical overdose since limestone contactors do not require chemical feed.

Limestone contactors are also cost competitive compared to traditional corrosion control treatment technologies since minimal operation and maintenance effort are required (Spencer, 1998). Limestone contactors only require backwashing, media refilling and media replacement as required maintenance.

If regular maintenance is carried out, a successfully designed limestone contactor will last for a long period of time between media replacement. According to Stauder (2002) and Spencer (2002), a limestone contactor is expected to operate for 10 years before it needs complete media replacement. Benjamin et al. (1992) predicted the operational period of a limestone contactor in their study to last 20 years until it needs complete media replacement.

Limestone contactors do have a few limitations (Stepp, 2002). Since stabilization in a limestone contactor only involves contact of water with the limestone bed, direct control of the stabilization process is not possible. Limestone contactors depend highly on the quality of raw water (such as iron, manganese, aluminum and turbidity content) to successfully stabilize it. Refer to [Table 1](#) for complete list of water quality characteristics that must be taken into consideration before designing a limestone contactor. As discussed in [Section 2.7.2](#), the capital cost of a limestone contactor may be significant compared to chemical feed systems especially as water systems get larger, the footprint required for a limestone contactor can be substantial.

CHAPTER III

METHODS AND PROCEDURE FOR PREPARATION OF EDUCATIONAL MODULE

3.1. EDUCATIONAL MODULE DEVELOPMENT APPROACH

The first step in the development of the educational module was creating a general outline of the contents, elements and specifications of the module as shown in [Appendix D](#) and [Appendix E](#). The outline explains briefly the contents in the main sections and sub sections of the module. The search button contained in the outline has been replaced with a print button. The print button allows a user to print each of the individual section in the module. The main sections of the module are similar to the main sections contained in the previous WTTAC educational module created by Dr. Robin Collins and Dr. Bruce Robinson on slow sand filtration technology for small drinking water systems. Upon approval of the outline from the reviewers, the draft of the web page templates of the module were created as seen in [Appendix F](#).

This educational module is to be made available on the web. The web pages of the module are created primarily using Macromedia[®] Dreamweaver[®] MX and partly using Adobe PDF Maker 5.0 through Microsoft[®] Word. Macromedia[®] Dreamweaver[®] MX is a user-friendly HTML developer and capable of producing interactive images and slides using Java script. Adobe[®] PDF Maker 5.0 was used to create hypertext links for the file used in the design criteria section of the module. Since most of the sections in the module contain interactive images, the internet browser used to view the module must be capable

of running Java script. It is best to view the module using the latest versions of internet browsers such as Netscape[®] 7.0 and Microsoft[®] Internet Explorer 6.0.

It may be possible to distribute the educational module in a CD-ROM if internet connections are not available to some users. If the educational module is distributed using CD-ROMs, it is still possible to view the module as long as internet browsers capable of running Java script are available in the user's computer. Users should navigate from the main page of the module. The file name of the main page is *default.html*.

3.2. INSTRUMENTS AND SOFTWARE

The following tools and software were used in creating the educational module:

Preparation of Buttons:

- Microsoft[®] Powerpoint
- Microsoft[®] Photodraw
- Macromedia[®] Dreamweaver[®] MX
- Gateway Computer
- Adobe[®] Photoshop

Preparation of Web Templates of Educational Module:

- Macromedia[®] Dreamweaver[®] MX
- Gateway Computer

Preparation of Interactive Slides

- Microsoft[®] Powerpoint
- Microsoft[®] Photodraw
- Gateway Computer

Preparation of Photos, Drawings and Images:

- Olympus Camedia Digital Camera (1.3 Megapixel)
- 4 Megabytes Smart Media Card
- 16 Megabytes Smart Media Card

- Canon CanoScan D1250 U2F Scanner
- Gateway Computer

Preparation of Text:

- Microsoft® Word

3.3. PROCEDURE FOR CREATING WEB FILES AND ICONS

The following shows the procedure used to prepare the web files and icons in the educational module:

3.3.1. Preparation of Buttons

All the buttons in the module were created using Microsoft® Photodraw. The general procedure for creating the buttons in Microsoft® Photodraw is as follows:

- Select the shape of the button desired from the *autosshapes* function.
- Insert text using the *text* tool.
- Draw the shape that corresponds to the function of the button if necessary using the *line* or *autosshapes* tool.
- Apply color to the text, the background of the button and the edge of the button by using the *fill* or *edge* tool and selecting color from the color palette.
- Resize the button as necessary using the *resize* tool.
- Save the button as a Joint Photographic Experts Group (JPEG) file.

In order to make the background of the button transparent, the following procedure was followed using Adobe® Photoshop:

- Open and save the button as a Graphic Interchange Format (GIF) file.
- Select the *magic wand tool* from the toolbar.
- Click on all the background area on the button that needs to be transparent by holding the *shift* button on the keyboard.
- Click on the *help* tab and select *export transparent image*.
- Check *online* in the next window.
- Save the button as a GIF file.

3.3.2. Preparation of Web Pages of Educational Module

The approach used in creating the web pages was to create templates of the pages that share common purposes such as all the pages for the photos use the same template. There were six templates created for this module as listed in [Appendix F](#). The templates were created using Macromedia[®] Dreamweaver[®] MX. The general procedure for applying a template to a page in Macromedia[®] Dreamweaver[®] is as follows:

- Click on the *modify* tab.
- Select *apply template*.
- Select the filename of the template desired.

Some parts of the templates were made editable to include the texts, photos, figures, tables and equations by including editable regions in the template. The back and next buttons in all the templates are also editable regions. These editable regions are shown as boxes with green borders with the names of the regions as can be seen in [Figure F2](#).

All the templates except for [Figures F1](#) and [F2](#) have a close button that closes the current window when users click on the button. The following Java script code was placed as a hyperlink for the close button to enable the interactive behavior:

```
"javascript:self.close();">close_button.jpg</a>
```

The pop-up windows in this module were created by placing the following Java script code in the body of [Figures F1](#) and [F2](#).

```
<script language="JavaScript" type="text/javascript">  
    leftPos = 200  
</script>  
  
<script language="JavaScript" type="text/javascript">  
    function newWindow(popuplink)  
    { popupWindow = window.open  
      (popuplink,"linkWin","scrollbars=yes,width=800,height=570,  
      left="+leftPos+",top=80,left=80,")  
      popupWindow.focus() }  
</script>
```

The following HTML code was used in the body of [Figures F3 to F6](#) to create pop up windows in the module:

```
<a href="#" onclick=  
"window.open('filename','file  
description','menubar=no,location=no,height=400,width=600,align=center,  
top=170,left=180,scrollbars=yes'); return false;">
```

3.3.3. Preparation of Interactive Slides

The interactive slides as seen in the typical contactor section of the module were created in Microsoft® Powerpoint®. After selecting full-view of the slides, they were then

copied into Microsoft® Photodraw® using screen capture to be resized to fit into the module's editable template region called 'Limestone Contents'.

The hot spots on the slides that are active links to the appropriate web pages are highlighted. A slide with highlight on the hot spot is only visible when users place their mouse on the hot spot. The slides with the highlights are individual images and are separate from the image of the slide when the mouse is not placed on any hotspots.

The general procedure for creating the hotspots on the slide using Macromedia® Dreamweaver® MX is as follows:

- Click on the slide.
- Draw the shape of the hotspot by selecting either the rectangular, oval or the polygon tool from the *properties* tab.
- Click on the hotspot.
- Enter the path of the filename, which the hotspot links to in the *links* space in the *properties* tab.

The procedures for highlighting the hotspots on the slide are as follows:

(i) In Microsoft® Powerpoint®:

- Apply a yellow color to the edge of a hotspot on a slide using Microsoft® Powerpoint®. Copy the slide into Microsoft® Photodraw®.
- Save the slide as a Joint Photographic Experts Group (JPEG) file. Repeat this procedure for each hotspot.

(ii) In Macromedia® Dreamweaver® MX:

- Click on a hotspot.

- Click on the *design* tab, *behaviors* tab and *plus* tab.
- Select *swap image* from the drop down toolbars.
- Select the slide with the hotspot highlighted that was created in [Section 3.3.3 part \(i\)](#) by clicking on the *browse* button.
- Save the slide as a Hyper Text Markup Language (HTML) file.

3.3.4. Preparation of Photos, Drawings and Images

Some of the photos in the module were courtesies of Dr. Ray Letterman of Syracuse University, New York, Mr. Stefan Stauder of DVGW, Germany, Mr. Grant Mackintosh of CSIR, South Africa and Dr. Manuel Hernandez of the Canary Islands Water Center, Spain. The photos taken by Tracey Hiltunen and myself during the visit to the Mars Hill, Maine limestone contactor site were captured using an Olympus Camedia Digital Camera. The photos were stored in a 16 MB and a 4 MB smart cards. The photos were touched-up accordingly by adjusting the brightness and contrast of the photos in Microsoft® Photodraw®.

The limestone contactor drawings are courtesies of Dr. Ray Letterman of Syracuse University, New York and Wright-Pierce. The drawing received from Wright-Pierce was scanned using the Canon scanner and then saved as an image file. The drawings from Dr. Ray Letterman were received and included in the module as image files.

Other images contained in the module are either tables or charts. Most of the tables were created in Microsoft® Word then screen-captured and copied onto Microsoft® Photodraw® and saved as image files. All the photos, drawings and images were inserted

in the module by following the procedure in Macromedia® Dreamweaver® MX as listed below:

- Click on the *insert* tab.
- Select *images*.
- Select the filename of the image.

3.4. SITE VISIT

One of the purposes of the development of this educational module is to include photos of limestone contactors to help users to better understand the process involved in a limestone contactor. The process involved in arranging a site visit include communications through telephone and email with engineers, state and federal environmental agencies involved with previous design or studies of limestone contactors to identify the location and contact information for the sites. After identifying the contact information, a letter of request for permission to visit the site and permission to use the photos taken at the site were sent to the superintendent of the plant. A sample of letter for requesting a site visit is shown in [Appendix I](#) and a sample of permission- to-use letter is shown in [Appendix J](#).

During the course of the project, it was found that there are several limestone contactor sites in New Hampshire, Maine and Washington. However, only the site in Maine is a municipal water system, which is the aim for this project. The site in Maine is located in Mars Hill. The facility is classified as a small water system and serves water to more than 500 people and less than 3,000 people. Most of the sites identified in New

Hampshire and Washington are either non-transient non-community water systems that serve water to schools, office buildings and factories or very small community water systems that serve water to small residential areas.

The site visited in Maine is called Mars Hill and Blaine Co. Filter Plant in Mars Hill. It was visited on August 11, 2003. The plant obtains raw water from Young's Lake. It was originally built with treatment processes such as micro filtration, slow sand filters, disinfection and sodium fluoride addition in 1993. The limestone contactor was not built until 1998 when there were problems in the slow sand filters. Prior to 1998, the pH of the water was stabilized naturally by contacting the concrete basins and the under layer gravels containing limestone materials in the filter beds. When the filters were having problems, some modifications had to be done to the filter beds including replacing the limestone gravels with new non-limestone gravels and lining the concrete basins with a hypalon liner (Spencer, 2000). Due to the modifications, the water was no longer stabilized in the filter beds and the plant exceeded the Lead and Copper Rule in its first sampling event in 1996, requiring them to install a corrosion control treatment.

A limestone contactor was chosen for pH adjustment in this plant since it was operationally cost attractive. The limestone contactor is located in the existing clear water well. Part of the clear water well was modified to accommodate the limestone contactor. A wall was constructed to separate the clear water well from the limestone contactor and acts as a weir. The limestone contactor is rectangular with approximately 16 ft x 19 ft (4.9 m x 5.8 m) in dimension (Spencer, 2000). It is filled with 4 feet of limestone obtained from Graymont NB Inc., New Brunswick, Canada and 1 foot of supporting gravel.

CHAPTER IV

RESULTS: LIMESTONE CONTACTORS EDUCATIONAL MODULE

[Appendix G](#) shows the first page of each major section in the limestone contactor module. Although the module is intended to be available on the web, but it may be incorporated onto a CD-ROM for users who do not have an internet connection. An instruction on how to properly view the module from a CD-ROM and on the web is shown in [Appendix H](#).

The module has also been made available as an attachment in the [Limestone Contactors Educational Module](#) to accompany this thesis. In order to view the module, click on limestone contactors button. The screen resolution must be set to 1024 X 768 pixels for the module to be displayed correctly. For instruction on setting a screen resolution, refer to Appendix H. The module is also temporarily accessible on the web at:

http://www.engr.utk.edu/~brobinso/WTTAC_Water_Tech_Guide_Vol2

It will later reside permanently on the University of New Hampshire's Water Treatment Technology Assistance Center's website at <http://www.unh.edu/erg/wttac>.

CHAPTER V

CONCLUSIONS

Small water systems need a technology that is simple, easy and economical to operate. Based on the treatment performance data presented in [Figures B15](#) and [B16](#), limestone contactors are able to raise pH of water such that the lead and copper are reduced to concentrations below the Action Levels. The 90th percentile lead concentration in Mars Hill, Maine decreased to 0.006 mg/L after limestone stabilization from 0.017 mg/L before limestone stabilization. The 90th percentile copper concentrations also decreased to 0.65 mg/L after limestone stabilization from 1.3 mg/L before limestone stabilization. Based on the cost comparison presented in [Table A11](#), limestone contactors are also cheaper to operate than lime or soda ash. The cumulative cost of 10 years of operation for the limestone contactor is ZAR 333,745 (US\$ 50,062) compared to ZAR 1,056,659 (US\$ 158,499) for lime and ZAR 4,154,215 (US\$ 623,132) for soda ash (Exchange Rate: ZAR1 = US\$0.15 based on Bank of Canada Exchange Rates Schedule on Jun 30, 2000). This results in a savings of ZAR 722,913 (US\$ 108,437) when using a limestone contactor over lime and ZAR 3,820,469 (US\$ 573,070) when using a limestone contactor over soda ash. The stabilization operation is simple and safe, only involves contact of water with the limestone bed with no risk of chemical overdose. Based on [Table A17](#), the daily maintenance required is only pH monitoring, flow monitoring and flow adjustment if necessary. The frequency of other maintenance works required are weekly, biweekly or yearly. Due to the simplicity of the operation, viability for corrosion

control and cost effectiveness, limestone contactors are suitable for small water systems due to their limited number of personnel and financial resources.

There are similarities and differences in the design approach to limestone contactors between the U.S., South Africa and Germany.

The following are the similarities in the design approach:

- *Location in the Treatment Train:* Limestone contactors should be placed after disinfection.
- *Water Quality Characteristics:* Considerations should be made to the water quality characteristics before designing a limestone contactor. These include pH, alkalinity, hardness, iron, manganese and aluminum content.
- *EBCT:* The empty bed contact times (EBCT) used are in the range of 20 to 45 minutes.
- *Flow Requirements:* The flow to the contactors must not exceed the maximum design capacity.
- *Piping Requirements:* Limestone contactors must have drain to allow maintenance.
- *Configuration:* Both rectangular and cylindrical shaped contactors are possible.

The following are the differences in the design approach:

- *Design Guidelines:* Design guidelines are available in South Africa and Germany, but not in the U.S.

- *Loading Rate:* Based on the information found, the loading rate is higher in Germany (4-8 m/hr) and South Africa (10 m/hr) than in the U.S. (2.4 m/hr).
- *Design Aids:* Computer software is used to aid in the design of the limestone contactors in the U.S. and South Africa such as DESCON (Letterman and Kothari, 1995), Limestone Bed Contactor: Corrosion Control and Treatment Analysis Program Version 1.02 (Schott, 2002) and STASOFT (De Souza et al., 2000). In Germany, design curves from DVGW (1998) are used to aid in the design although according to Stauder (2003), computer software that can determine CaCO_3 saturation is useful.
- *Limestone Characteristics:* Limestone media used in the U.S. should conform to the ASTM standard C51-02 (Spencer, 2000). In Germany, several media options can be used such as dense calcium carbonate, dense calcium carbonate and half-burnt dolomite. These media must conform to the British Standard EN 1018:1998 and EN 1017:1998 (DVGW, 1998). In South Africa, the media used to date is the commercially available limestone pebbles from Bredasdorp, South Africa (De Souza et al., 2000).
- *Limestone Size:* The size of media used in U.S. is in the range of 11 to 14 mm (Spencer 2000). In Germany, there are several grain sizes available depending on the type of media used but the common size is 1.0-2.0 mm (Stauder, 2003). The size of media that produces optimal results in South Africa is 12 mm (Spencer, 2000).

- *Supporting Media:* In U.S., the supporting media used must conform to the AWWA Standards for Filtering and Support Media (Spencer, 2003). Supporting media used in Germany are 0.2 to 0.3 m of inert materials (DVGW, 1998) and in South Africa are 0.15 m of granite aggregate (Mackintosh et al., 2003a).

Although the educational module is targeted towards small water systems, large water systems may find this educational module to be equally useful. Limestone contactor application has been limited in the past to systems less than 30 MLD (De Souza et al., 2002). As discussed in the earlier section of this thesis, limestone contactors may be uneconomical for large water systems due to the massive footprint that may be required. However, the SSP developed by CSIR, South Africa enable the use of limestone contactors in large water systems. Currently, CSIR is constructing a 100 MLD limestone contactor in the Free State province of South Africa (Mackintosh et al., 2003a). The use of limestone contactors in large water systems has also been successful in Germany using a process similar to the SSP. Based on cost analysis prepared by the CSIR on the SSP for the Lesotho Highlands Scheme, the SSP offers a significant cost advantage over conventional lime/ CO_2 . The project payback period for the Lesotho Highlands Scheme using SSP is 4.3 years compared to the typical payback period of 15 years for municipal systems (De Souza et al., 2002). The Net Present Value is also higher than required which is ZAR2.7 million (US\$0.4 million) with an associated Internal Rate of Return of 52% (De Souza et al., 2002).

The educational module discusses treatment processes that can be used in combination with limestone contactors. For example, the Spraystab I unit is a

combination of aeration, limestone contactor and filtration. A study has also been conducted on the use of limestone in slow sand filters such as in Contoocook Village Precinct, New Hampshire (Lucey, 2003). In this study, a layer of limestone was placed in the slow sand filter for stabilization. The slow sand filter with limestone layer is currently under operation in the Contoocook Village Precinct's plant.

During the course of the project, it was found that there were a limited number of limestone contactor facilities for small municipal water systems in the U.S. One of the reasons for the small number of systems using limestone contactors may be because the technology is not widely known. Encouraging more publishing of studies, creating a design manual and promoting design tools should promote this technology. The educational module is also one way to promote this technology. The module is a very comprehensive document available on limestone contactors and can be viewed by anyone in the world.

CHAPTER VI

RECOMMENDATIONS

Future studies should be conducted on using alternative media, such as dolomite, in a limestone contactor. In Germany, dolomite is listed as one of the media options in a limestone contactor (DVGW, 1998). The document outlining the requirements for using dolomite for water treatment is available from British Standard Online (EN 1017:1998 : Chemicals used for treatment of water intended for human consumption – half-burnt dolomite) but no documentation on the kinetics of dolomite and its effect on limestone contactor performance could be found. The paper written by Letterman (1995) thoroughly discusses the effect of impurities, media composition and temperature on the kinetics of calcium carbonate dissolution in limestone contactors. Similar research should be conducted on dolomite that considers all of these factors studied by Letterman (1995). The study conducted by Rooklidge and Ketchum Jr. (2002) on the limestone contactor performance from a dolomite amended slow sand filter could be a starting point.

The educational module discusses treatment processes that can be used in combination with limestone contactors. For example, the Spraystab I unit is a combination of aeration, limestone contactor and filtration. A study has also been conducted on the use of limestone in slow sand filters such as in Contoocook Village Precinct, New Hampshire (Lucey, 2003). In this study, a layer of limestone was placed in the slow sand filter for stabilization. The slow sand filter with the limestone layer is currently under operation in the Contoocook Village Precinct's plant. Researchers should

consider the use of limestone contactors in combination with other treatment processes in the future.

Future guidance manuals should consider other design tools in addition to DESCONE for designing a limestone contactor such as the Limestone Bed Contactor: Corrosion Control and Treatment Analysis Program Version 1.02 (Schott, 2003), the DVGW (1998) design curves and calcium carbonate equilibrium software (i.e. STASOFT, MINEQL, MINTEQA2).

It is important that a limestone contactor be correctly designed and maintained. Therefore, a guidance manual for design, operation and maintenance of limestone contactors should be developed in the future. A guidance manual will not only assist engineers in designing limestone contactors but also assist small water system operators in operating and maintaining a limestone contactor. Small water system operators should also be able to refer to the manual if any problems occur in the limestone contactor.

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APPENDICES

APPENDIX A

TABLES DISCUSSED IN THE LITERATURE REVIEW SECTION

Table A1. Treatment Objectives of Spraystab I Unit (Based on 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.

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Table A2. Installation and Operation Requirements of Spraystab I Unit (Based on 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.

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Table A3. General Design Criteria of Spraystab I Unit (Based on 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° 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.

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Table A4. General Design Criteria of Spraystab II Unit (Based on 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 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 must 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 “settling 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 layer 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.

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Table A5. Treatment Performance of Calcite Contactors in New Hampshire (Based on Thayer, 2001)

Water Quality Parameters		Before Treatment	After Treatment
<i>Community Water Systems</i>			
pH	Average	6.21	7.41
	Range	5.9 – 6.6	7.1 – 8.8
Alkalinity (mg/L)	Average	< 15	42
	Range	3 – 37	23 – 73
<i>Non-Transient Non-Community Water Systems</i>			
pH	Average	5.97	7.61
	Range	5.8 – 6.2	7.1 – 8.1
Alkalinity (mg/L)	Average	22	76
	Range	15 – 41	32 – 111

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Table A6. Water Quality Before and After Limestone Stabilization (Based on Daniels, Manxodidi, De Souza and Mackintosh, 2002)

Typical Results	Before Limestone Stabilization in 1996		After Limestone Stabilization in 2001			
	<i>After Treatment</i>	<i>Hotel Sample</i>	<i>After Limestone</i>	<i>Network Sample 1</i>	<i>Network Sample 2</i>	<i>Network Sample 3</i>
Alkalinity as CaCO ₃ (mg/L)	0.8	N/A	13.8	14.3	14	14
pH	5.1	N/A	8.6	8.6	8.5	7.6
Copper as Cu (mg/L)	< 0.02	2.5	< 0.05	< 0.05	< 0.05	0.09
N/A: Not Analyzed						

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Table A7. Typical Water Quality Treated by Spraystab I Unit (Based on Mackintosh, De Souza and De Villiers, 2003b)

Water Quality Parameters	Site A		Site B	
	Raw	Treated	Raw	Treated
pH	6.0	8.5	4.7	8.2
Calcium (mg/L as CaCO ₃)	6.5	26.3	0	40.0
Alkalinity (mg/L as CaCO ₃)	19.0	39.0	6.0	39.8
Calcium Carbonate Dissolution Potential (CCDP) (mg/L as CaCO ₃)	80.3	1.4	332.0	1.6
Iron (mg/L)	< 0.05	< 0.05	1.55	0.05

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Table A8. Estimated Cost of Limestone Contactors in Port Simpson, British Columbia (Based on Benjamin et al., 1992)

Item	1992 Estimated Cost (CND\$ ^a)	2002 Estimated Cost (CND\$)	2002 Estimated Cost ^c (US\$)
Construction (concrete)	90,000	107,874	67,961
Limestone media ^d	35,000	41,951	26,429
Engineering	15,000	17,979	11,327
<i>Total</i>	140,000	167,804	105,717

^a Canadian Dollar

^b Based on Bank of Canada inflation calculator (http://www.bankofcanada.ca/en/inflation_calc.htm)

^c Based on Dec 31, 2002 exchange rate (CND\$1 = US\$0.63) from Bank of Canada Exchange Rates Schedule (<http://www.bank-banque-canada.ca>)

^d 90% of limestone cost is for transportation

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Table A9. Design Basis of Limestone Contactors in Port Simpson, British Columbia (Based on Benjamin et al., 1992)

Design Basis	Contactors for Water Conditioning Prior to Coagulation/Flocculation	Contactors for Corrosion Control
Population	1000	1000
Design Flow Rate (m ³ /day) ^a	600	950
Contact Time (hours)	0.5	1
Volume (m ³)	29	92

^a Contactors for water conditioning designed for maximum day flow.

Contactors for corrosion control designed for peak 10-minute flow.

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Table A10. Comparison of Capital Costs for Stabilization in Makwane WTP, South Africa (Based on De Souza, Jason and Manxodidi, 2000)

Treatment Technologies	2000 Cost (ZAR^a)	2000 Cost^b (US\$)	2002 Cost^c (US\$)
Limestone Contactor	500,000	75,000	78,354
Lime Doser	200,000	30,000	31,341
Sodium Carbonate Doser	140,000	21,000	21,939

^a South African Rand

^b Based on Jun 30, 2000 exchange rate (ZAR 1 = US\$ 0.15) from Bank of Canada Exchange Rates Schedule (<http://www.bank-banque-canada.ca>)

^c Based on Federal Reserve Bank of Minneapolis inflation calculator (<http://minneapolisfed.org/Research/data/us/calc/>)

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Table A11. Cumulative Cost Comparison Between Lime, Soda Ash and Limestone (Based on De Souza, Jason and Manxodidi, 2000)

	Lime	Sodium Carbonate	Limestone
CHEMICAL COST			
2000 prices	R 1,260/ton	R 2,500/ton	R 370/ton
Escalation p.a.	8%	8%	4%
Cumulative Cost	R 450,512	R 3,842,818	R 222,384
Carbonation cost	N/A	N/A	N/A
Total Cumulative Cost	R 450,512	R 3,842,818	R 222,384
LABOUR			
2000 salary	R 50,000	R 50,000	R 50,000
Salary increment p.a.	5%	5%	5%
ROUTINE OPERATING			
Total time per week	2 days	1 day	0.25 days
Cumulative Cost	R 202,398	R 101,199	R 25,300
PREVENTIVE AND LINE MAINTENANCE			
Total WTP maintenance % annual salary cost	20%	20%	20%
% of WTP maint for stab unit maintenance	50%	25%	2%
Cumulative Cost	R 70,839	R 35,420	R 2,834
EQUIPMENT MAINTENANCE			
Capital costs stab unit (1997)	R 200,000	R 140,000	R 500,000
Equipment cost escalation	10% p.a.	10% p.a.	10% p.a.
% maintenance of capital cost	7.5% p.a.	5% p.a.	1% p.a.
Cumulative Cost	R 332,910	R 174,778	R 83,227
TOTAL CUMULATIVE COSTS	R 1,056,659	R 4,154,215	R 333,745
TOTAL CUMULATIVE SAVINGS			
Limestone over lime	R 722,913		
Limestone over sodium carbonate	R 3,820,469		

* Exchange Rate on Jun 30, 2000 is ZAR 1 = US\$ 0.15 (Bank of Canada Exchange Rates Schedule - <http://bank-banque-canada.ca>)

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Table A12. Typical Raw Water Characteristics of Stellenbosch, South Africa (Based on De Souza et al., 2002)

Raw Water Characteristics	Value
Temperature (°C)	20
Conductivity (mS/m)	6
Dissolved Calcium (mg/L as Ca)	2
pH	6.3
Alkalinity (mg/L as CaCO ₃)	5

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Table A13. Cost of Chemicals Used in the Simplified SSP (Based on De Souza et al., 2002)

Chemical	Description of Chemical	Purity (%)	1999 Cost (ZAR ^a /ton)	1999 Cost ^b (US\$/ton)	2002 Cost ^c (US\$/ton)
Limestone	Aquastab Pebbles, Bredasdorp	95	140	22	24
Lime	Local lime with 65% CaO	85.9	750	120	130
Carbon Dioxide	Not specified	100	730	117	126
Sodium Hydroxide	In flake form in bags	100	2500	400	432
Soda Ash	Dense soda ash	95	1700	272	294

^a South African Rand

^b Based on Dec 31, 1999 exchange rate (ZAR1 = US\$0.16) from Bank of Canada Exchange Rates Schedule (<http://www.bank-banque-canada.ca>)

^c Based on Federal Reserve Bank of Minneapolis inflation calculator (<http://minneapolisfed.org/Research/data/us/calc/>)

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Table A14. Typical Raw Water Characteristics of Katse Dam, South Africa (Based on De Souza et al., 2002)

Raw Water Characteristics	Value
Hardness (mg/L CaCO ₃)	41.75
Conductivity (mS/m)	8.1
Dissolved Calcium (mg/L as Ca)	9.25
pH	7.27
Alkalinity (mg/L as CaCO ₃)	35.55
Magnesium (mg/L as Mg)	4.13
Sodium (mg/L as Na)	3.3

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Table A15. Cost Comparison Between SSP and Lime/CO₂ (Based on De Souza et al., 2002)

	Conventional (Lime/CO₂)	SSP
Capacity of Plant (MLD)	2000	2000
TIC Cost	ZAR 77 million (US\$ 12.3 million)	ZAR 99 million (US\$ 15.8 million)
Project Lifespan	10 years	10 years
Operating Days (days/year)	350	350
Carbon Dioxide Dose (mg/L)	26.0	38.0
Carbon Dioxide Cost	ZAR 700/ton (US \$112/ton)	ZAR 700/ton (US\$ 112/ton)
Chemical Dose	35 mg/L lime	46.1
Chemical Cost	ZAR 1400/ton (US\$ 224/ton)	ZAR 370/ton (US\$ 59)

Currency conversion is based on Dec 31, 1999 exchange rate (ZAR 1 = US\$ 0.16) from Bank of Canada Exchange Rates Schedule (<http://www.bank-banque-canada.ca>)

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Table A16. Cost Analysis of SSP vs. Conventional Stabilization (Based on De Souza et al., 2002)

Cost Analysis	Conventional (Lime/CO₂)	SSP
Capital Cost	ZAR 77 million (US\$ 12.3 million)	ZAR 99 million (US\$ 15.8 million)
Payback period (corrected for inflation and risk)	Not indicated	4.3 years
Discount rate:		
Average inflation	7%	7%
Required real return	10%	10%
Estimated risk	0%	30%
Internal Rate of Return (IRR)	Not indicated	52%
Net Present Value (NPV)	Not indicated	ZAR 2.7 million (US\$ 0.4 million)

Currency conversion is based on Dec 31, 1999 exchange rate (ZAR 1 = US\$ 0.16) from Bank of Canada Exchange Rates Schedule (<http://www.bank-banque-canada.ca>)

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Table A17. Operation and Maintenance Requirements

Procedure	Frequency	Reference
Inspection of the tank	Weekly	Benjamin et al. (1992)
pH monitoring to ensure target pH values are met	Periodically	Spencer (2000)
Flow adjustment to maintain constant contact time	Periodically	Spencer (2000)
Backwashing of the media	Biweekly	Stauder (2002)
Limestone bed scraping/cleaning and refilling	6 – 8 weeks	Stauder (2002)
Complete media replacement	Once in 10 years	Spencer (2002)
Monitor the flow rate to ensure it is within the permissible value.	Regularly.	DVGW (1998)
Headloss inspection.	Weekly.	DVGW (1998)
Monitor the height of the limestone media.	At least once a month.	DVGW (1998)
Ensure no precipitates on the media surface.	Regularly.	DVGW (1998)
Monitor the raw and treated water quality parameters to ensure that the water is required for stabilization.	At least once a year.	DVGW (1998)

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APPENDIX B

FIGURES DISCUSSED IN THE LITERATURE REVIEW SECTION

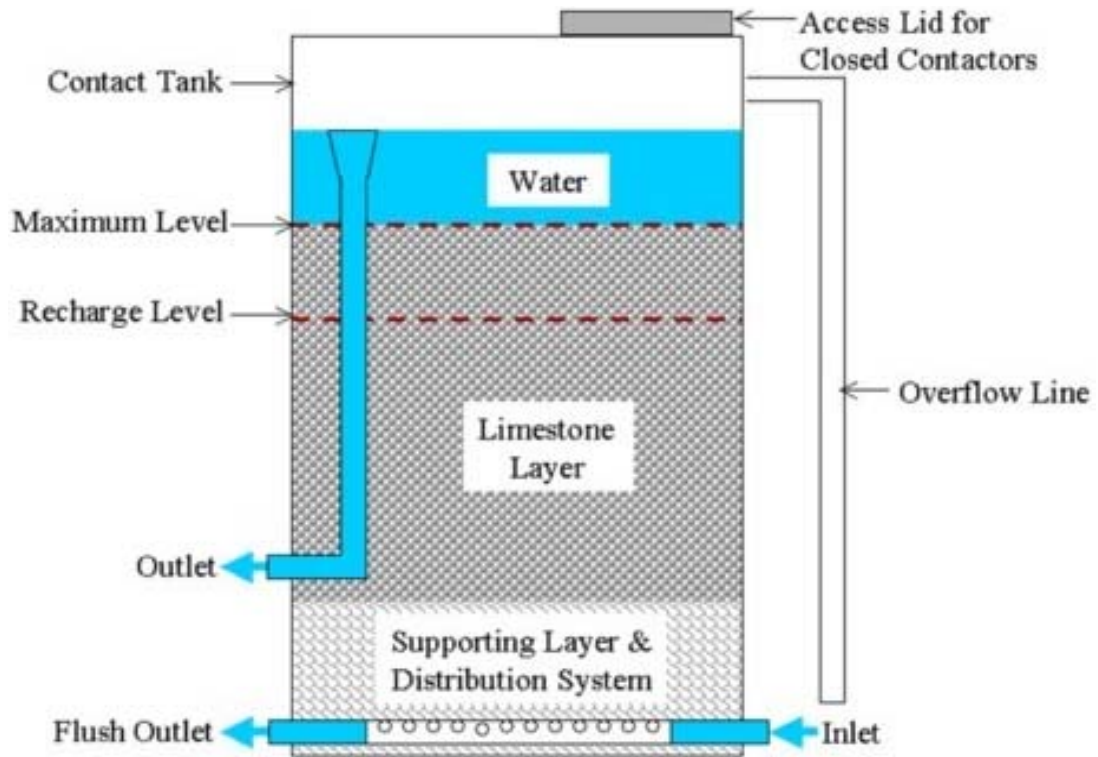


Figure B1. Typical Components of a Limestone Contactor (Based on De Souza, Jason and Manxodidi, 2002)

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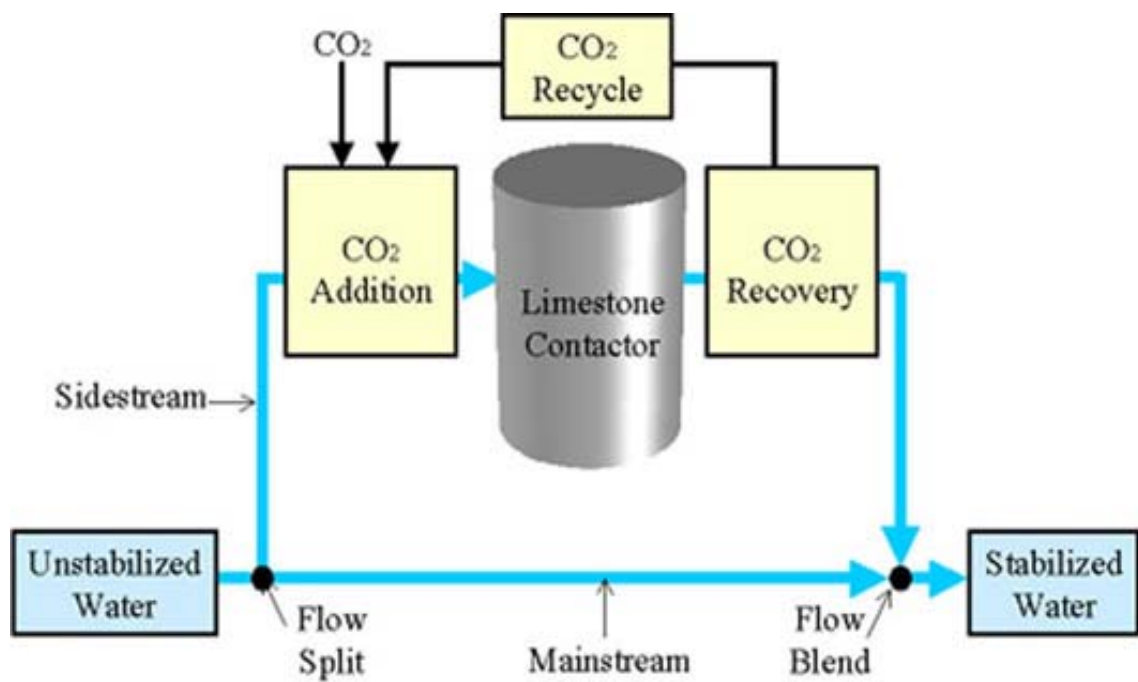


Figure B2. Schematic of Sidestream Stabilization Process (Based on De Souza, Du Plessis and Mackintosh, 2002)

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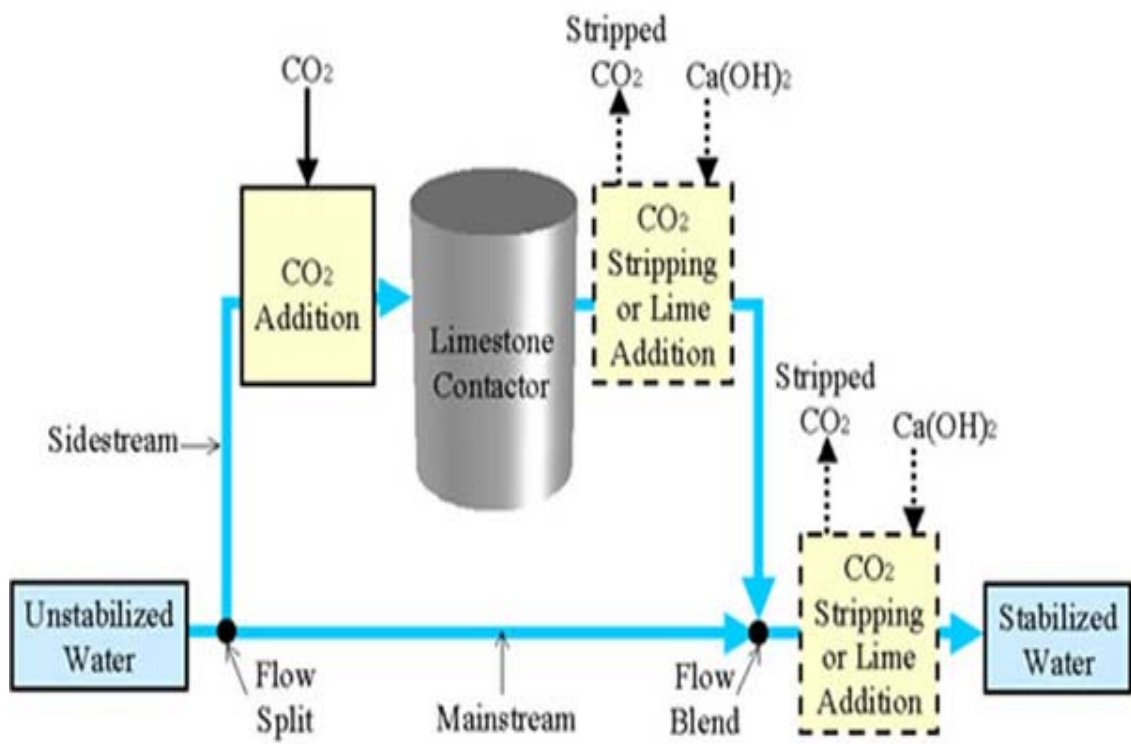


Figure B3. Schematic of Simplified Sidestream Stabilization Process (Based on De Souza, Du Plessis and Mackintosh, 2002)

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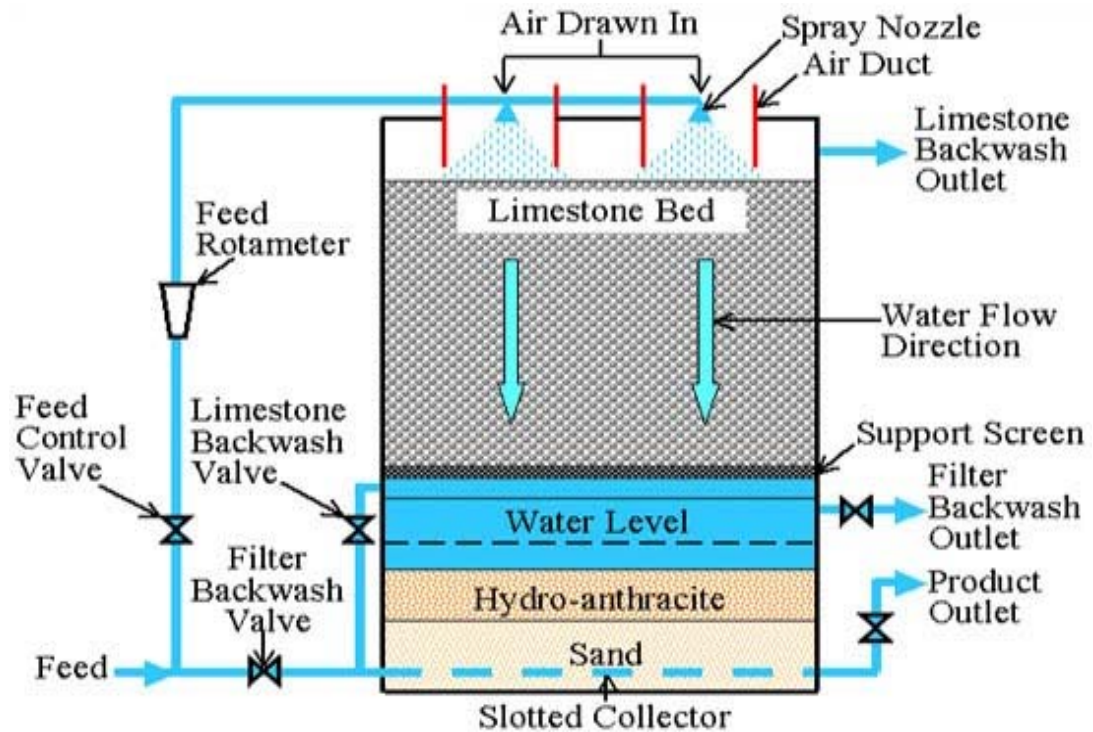


Figure B4. Typical Components of a Spraystab I Unit (Based on Mackintosh, De Souza, and De Villiers, H.A., 2003b)

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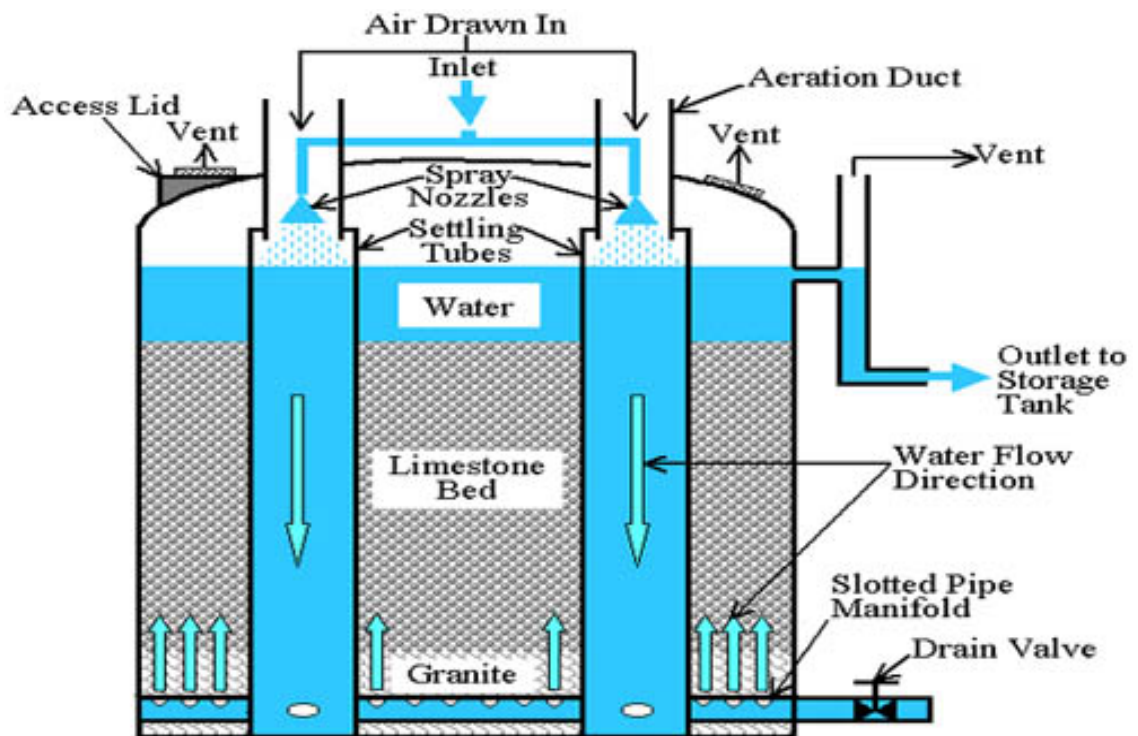


Figure B5. Typical Components of a Spraystab II Unit (Based on Mackintosh et al., 2003b)

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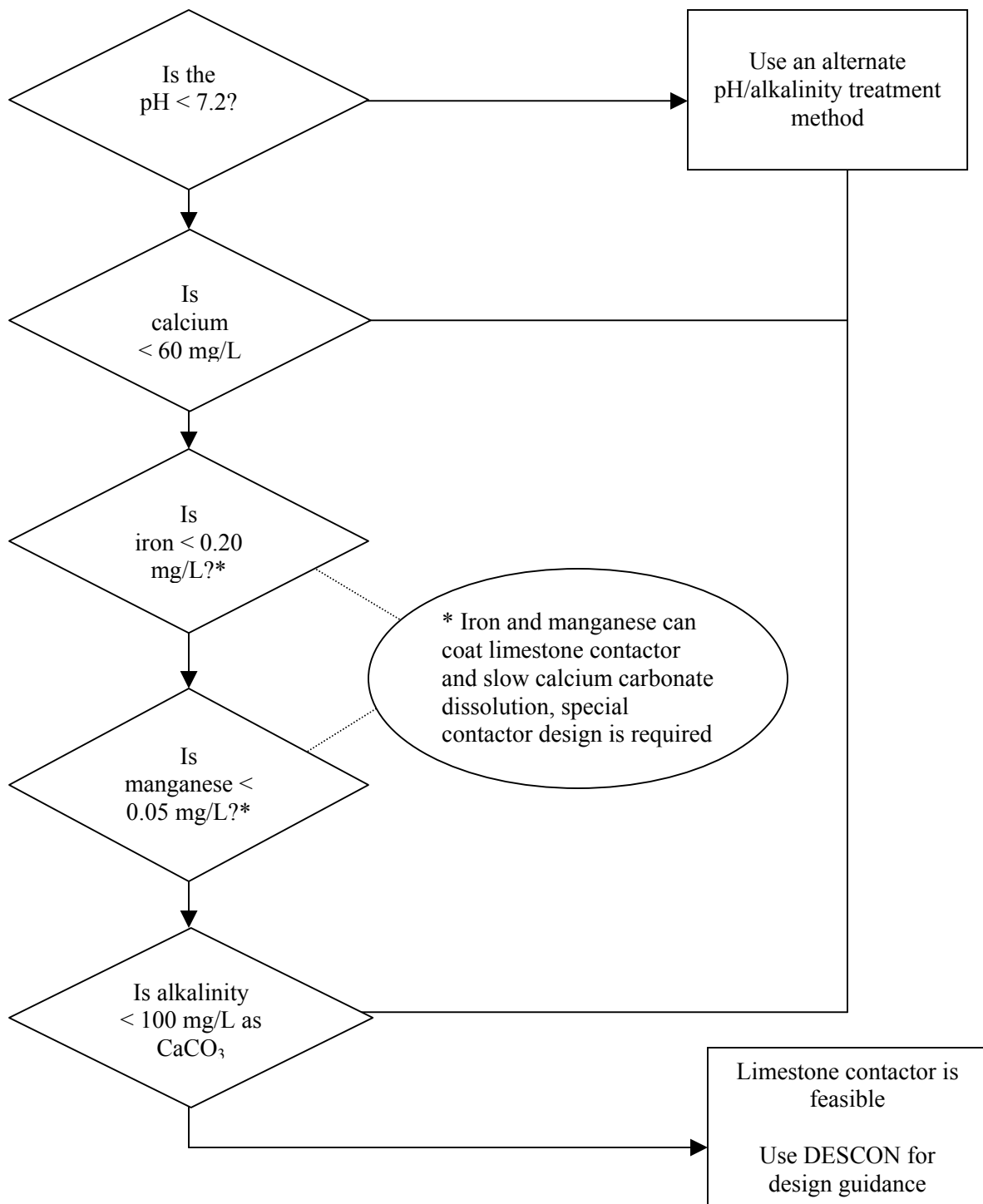


Figure B6. Limestone Contactor Decision Tree (USEPA, 2002)

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Small Public Water System Technology Guide - Limestone Contactor Educational Module - Netscape 6

C:\unzipped\DESCON-1\Descon.exe

```
INPUT PARAMETERS
Influent pH                      6.88
Influent Calcium, ngCa/L        18.88
Influent Alkalinity, meq/L      8.34
Ionic Strength, mMols/L        188.88
Influent Temperature, Celsius   28.88
Superficial Velocity, gpm/sq.ft. 1.88
Limestone Particle Diameter, cm 1.28
Limestone CaCO3 Content, mass% 98.88
Target pH                       8.58

OUTPUT
Equilibrium pH                   8.82
Calcium Concentration at Equilibrium, ngCa/L 15.63
Calcium Concentration at Target pH, ngCa/L 14.74
Calculated Influent DIC, ngC/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) 1.48
```

Figure B7. DESCON Output Using the Typical Western Water System Data as Input

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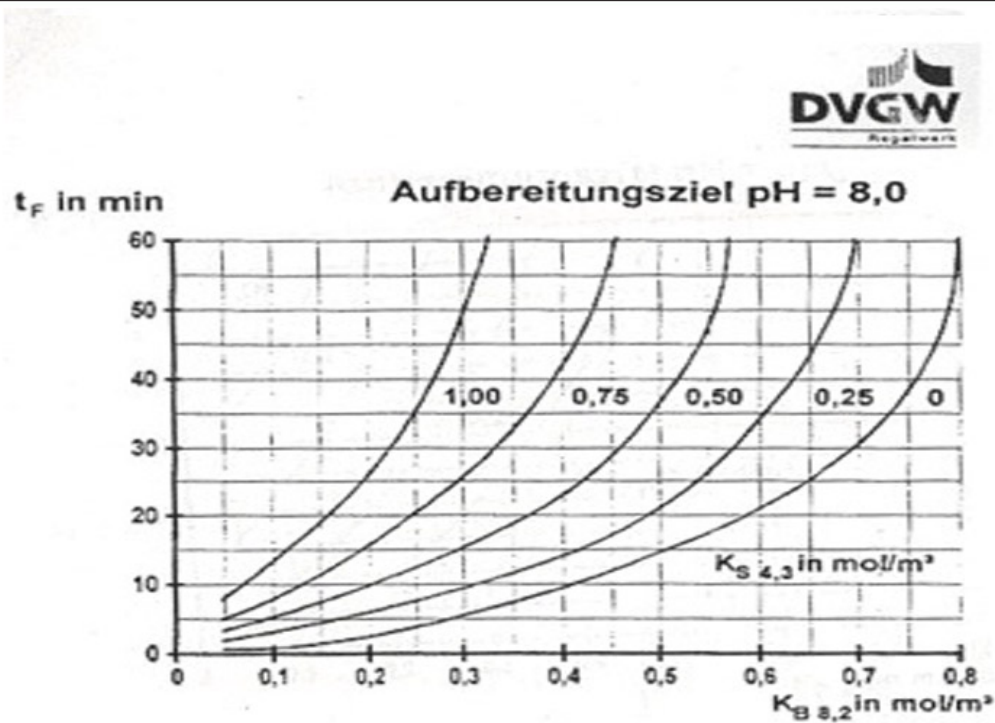


Figure B8. Contact Time as a function of Base Consumption ($K_{B,8,2}$) and Acid Consumption ($K_{S,4,3}$) for Dense Calcium Carbonate (Grain Size 1.0-2.0 mm). Temperature: 10°C, Processing Goal pH=8.0 (DVGW, 1998)

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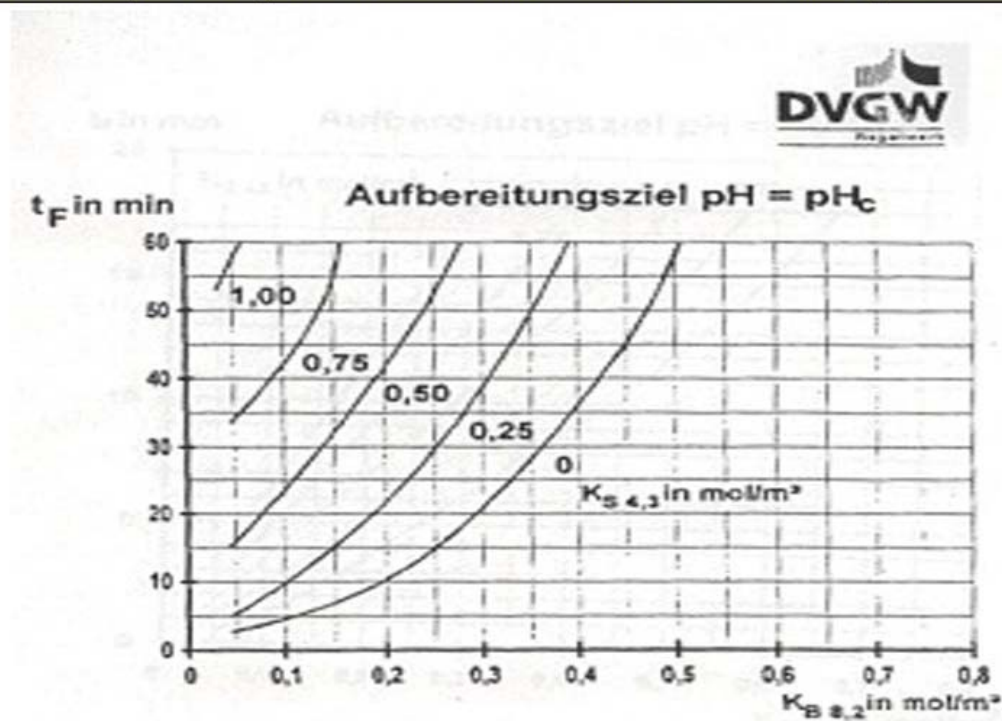


Figure B9. Contact Time as a function of Base Consumption ($K_{B,8,2}$) and Acid Consumption ($K_{S,4,3}$) for Dense Calcium Carbonate (Grain Size 1.0-2.0 mm). Temperature: 10°C, Processing Goal pH=pH_c (DVGW, 1998)

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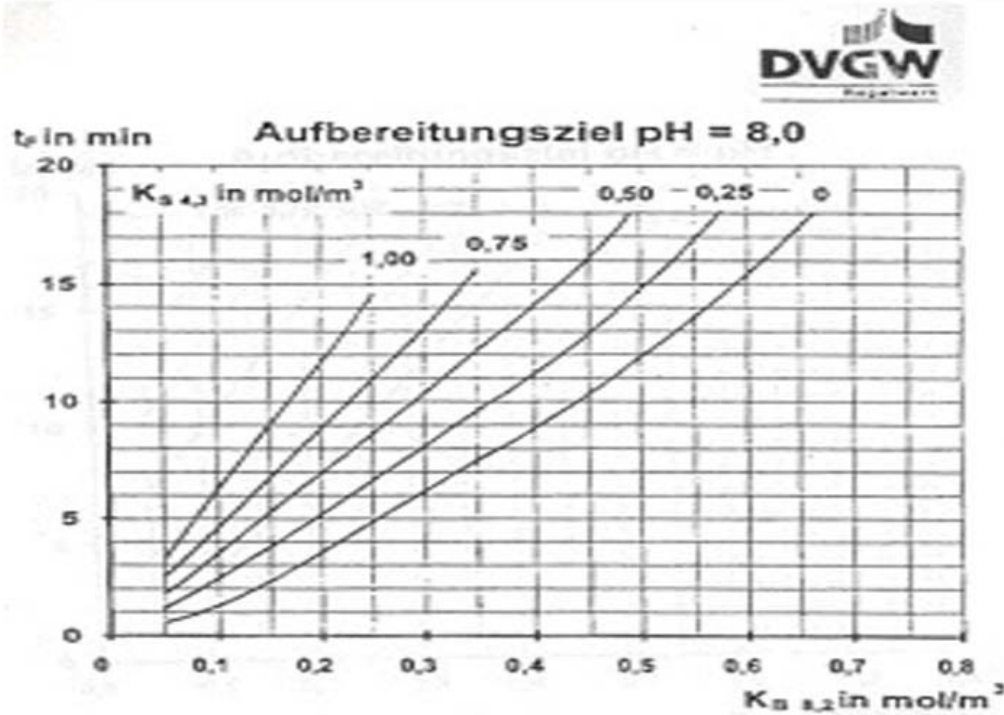


Figure B10. Contact Time as a function of Base Consumption ($K_{B,8.2}$) and Acid Consumption ($K_{S,4.3}$) for Porous Calcium Carbonate (Grain Size 1.0-3.0 mm). Temperature: 10°C, Processing Goal pH=8.0 (DVGW, 1998)

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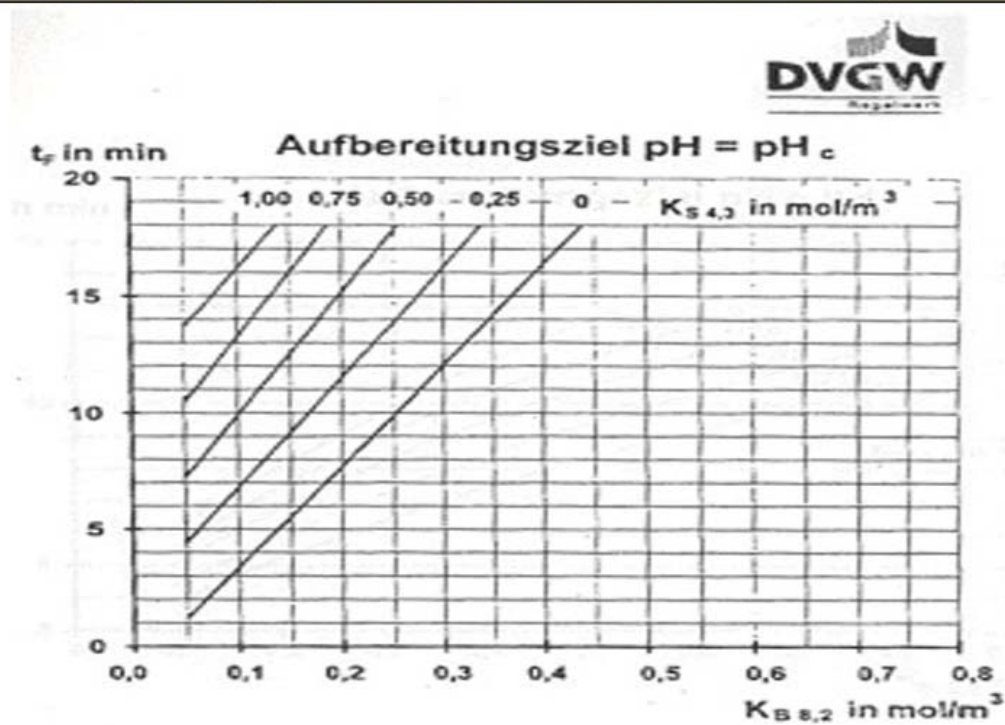


Figure B11. Contact Time as a function of Base Consumption ($K_{B,8,2}$) and Acid Consumption ($K_{S,4,3}$) for Porous Calcium Carbonate (Grain Size 1.0-3.0 mm). Temperature: 10°C, Processing Goal pH=pH_c (DVGW, 1998)

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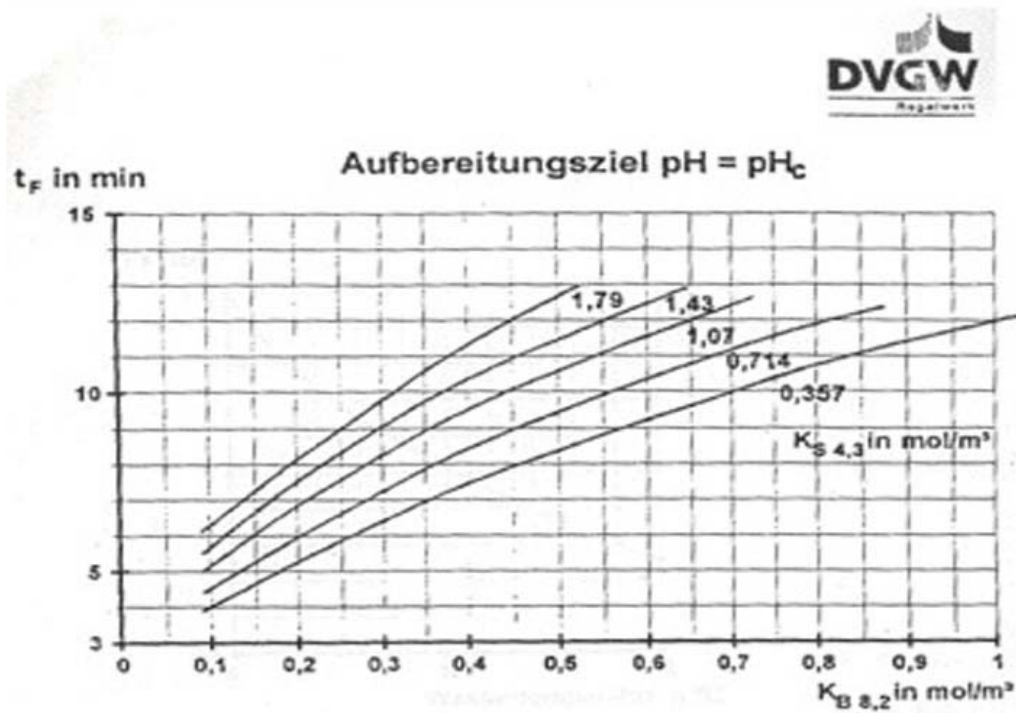


Figure B12. Contact Time as a function of Base Capacity ($K_{B,8,2}$) and Acid Capacity ($K_{S,4,3}$) for Half-Burnt Dolomite (Grain Size 0.5-2.5 mm). Temperature: 10°C, Processing Goal pH=pH_c (DVGW, 1998)

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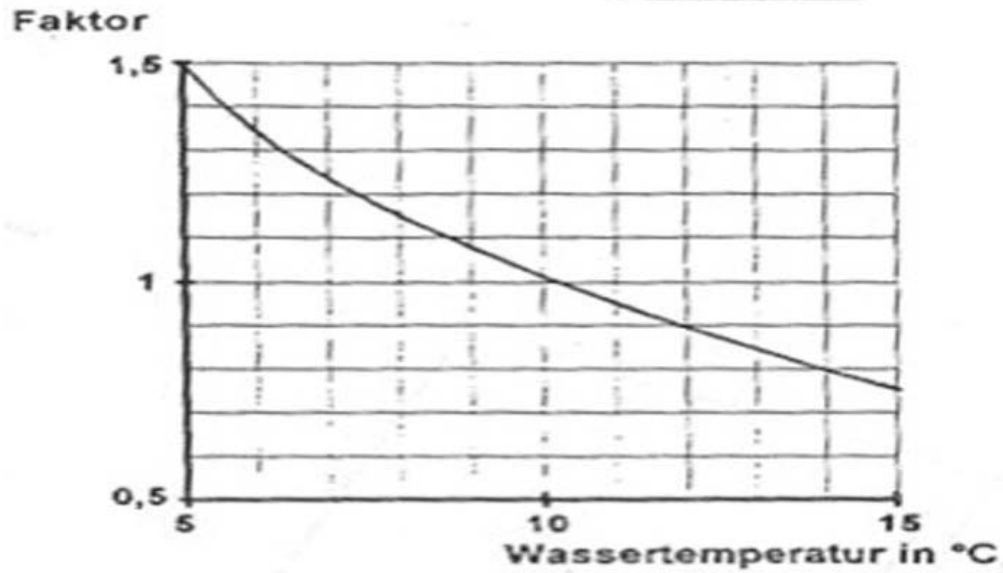


Figure B13. Correction Factor as a Function of Water Temperature (DVGW, 1998)

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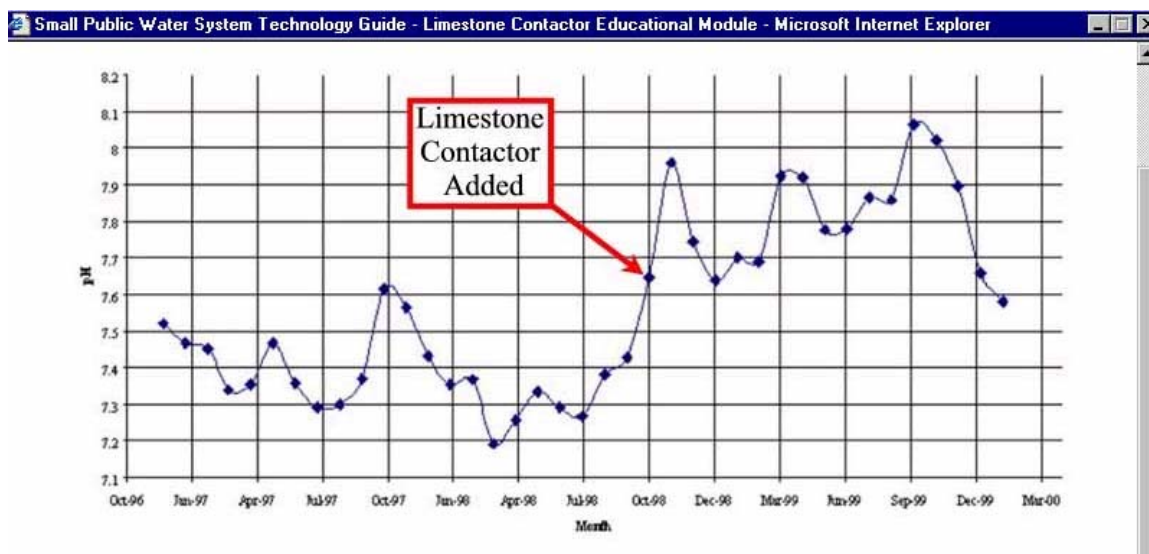


Figure B14. pH of Mars Hill Finished Water Before and After Limestone Stabilization (Spencer, 2000)

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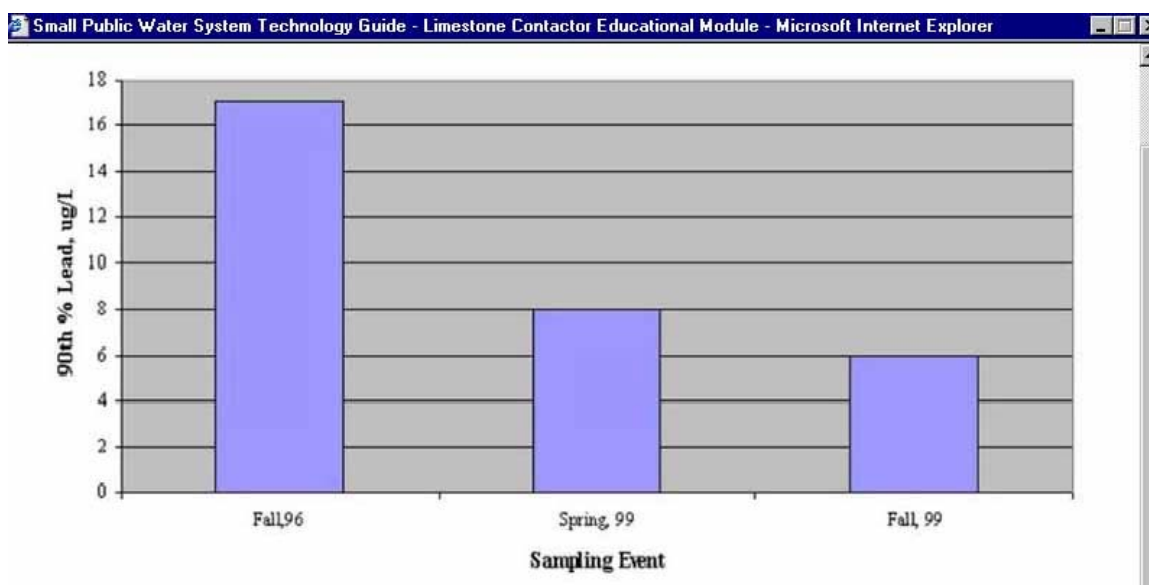


Figure B15. 90th Percentile Lead Level in Mars Hill Finished Water (Spencer, 2000)

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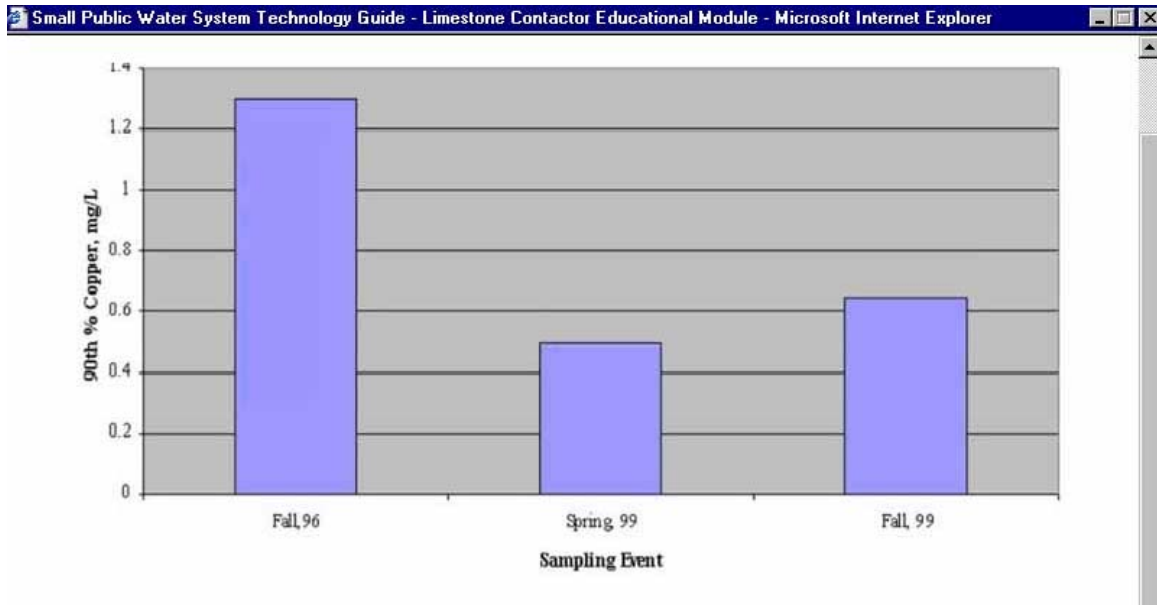


Figure B16. 90th Percentile Copper Level in Mars Hill Finished Water (Spencer, 2000)

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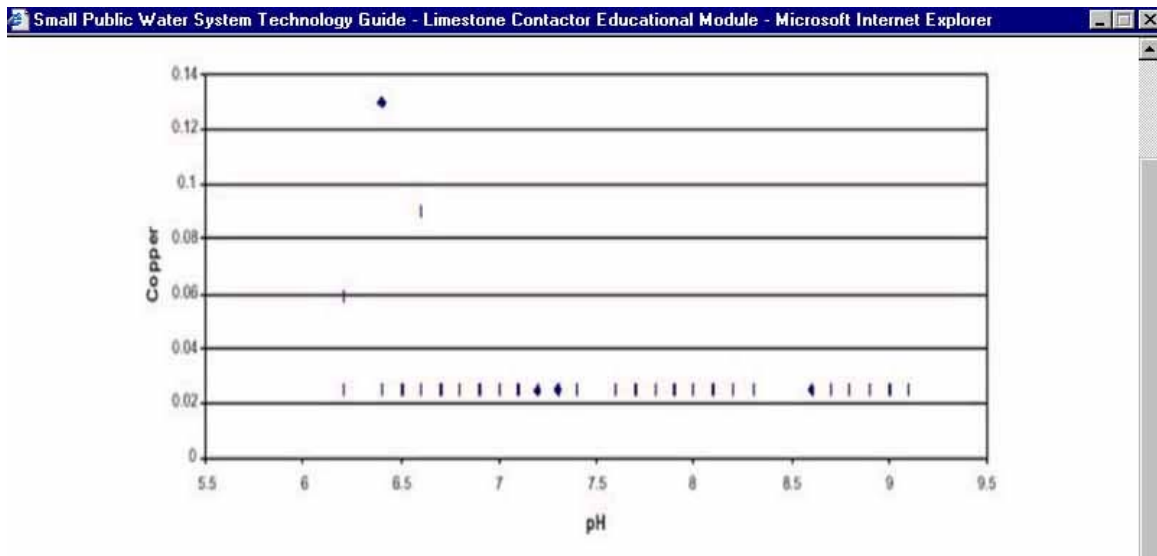


Figure B17. Scattergram of Copper vs. pH Levels in Bredasdorp Network (Daniels, Manxodidi, De Souza and Mackintosh, 2002)

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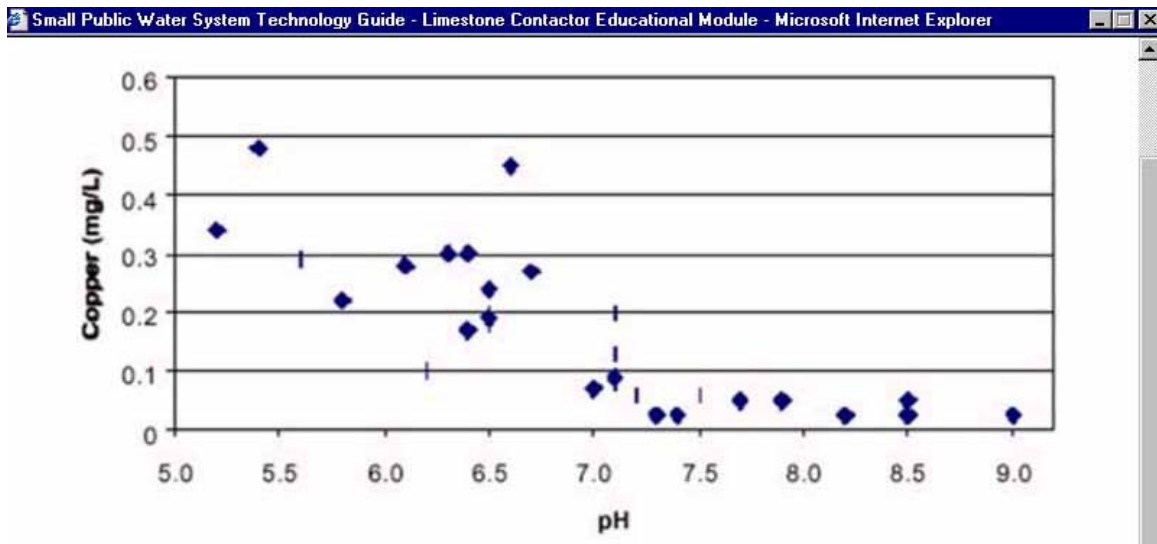


Figure B18. Copper versus pH at Stellenbosch Network Sampling Point (Daniels, Manxodidi, De Souza and Mackintosh, 2002)

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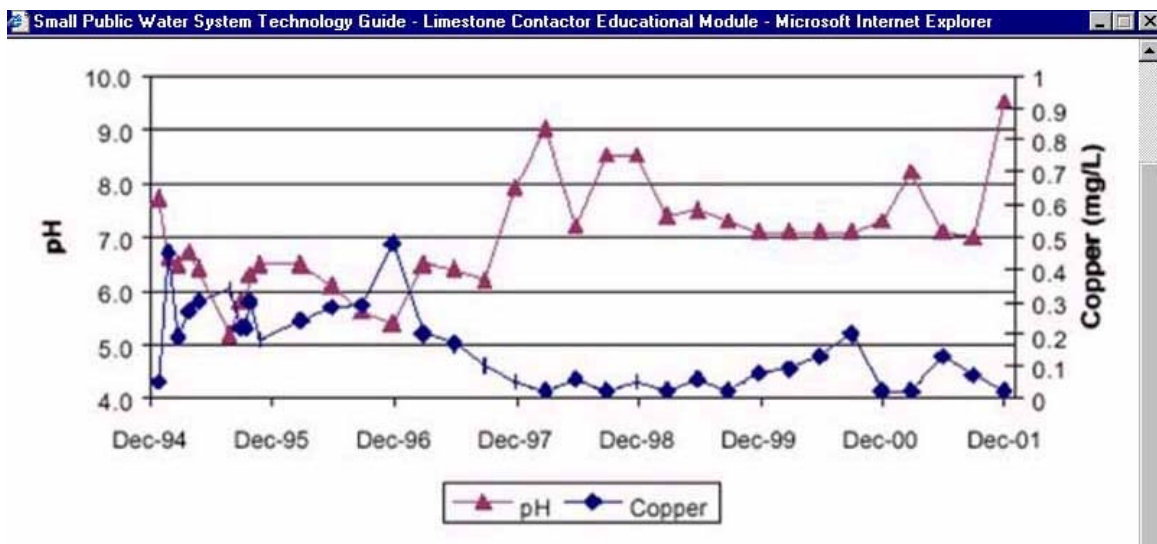


Figure B19. pH and Copper Levels at a Household Sampling Point in Stellenbosch (Daniels, Manxodidi, De Souza and Mackintosh, 2002)

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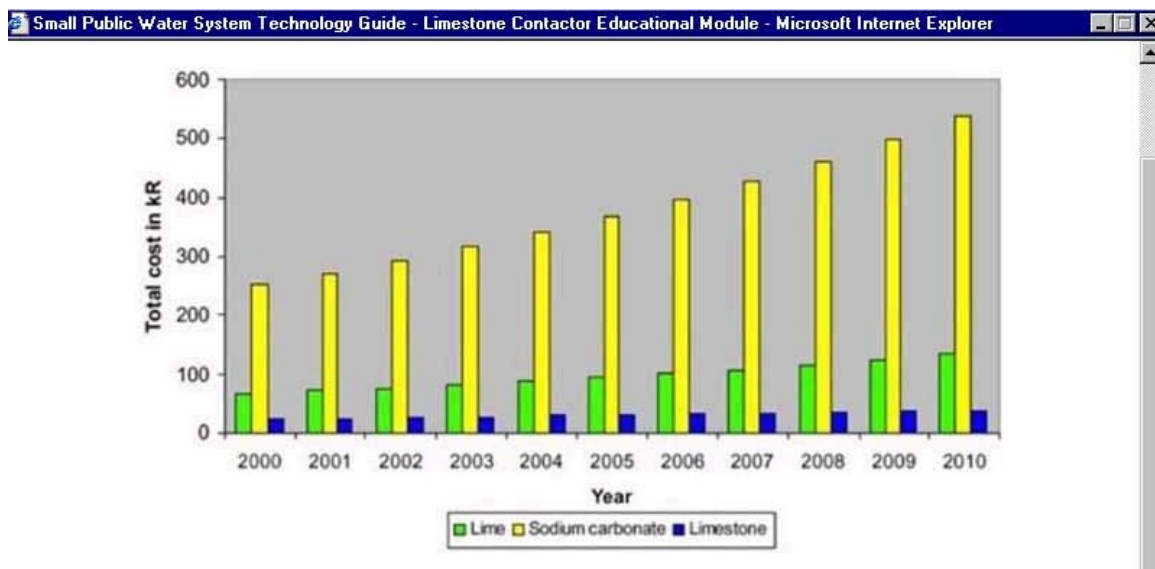


Figure B20. Comparison of Cost Between Limestone, Lime and Sodium (De Souza, Jason and Manxodidi, 2000)

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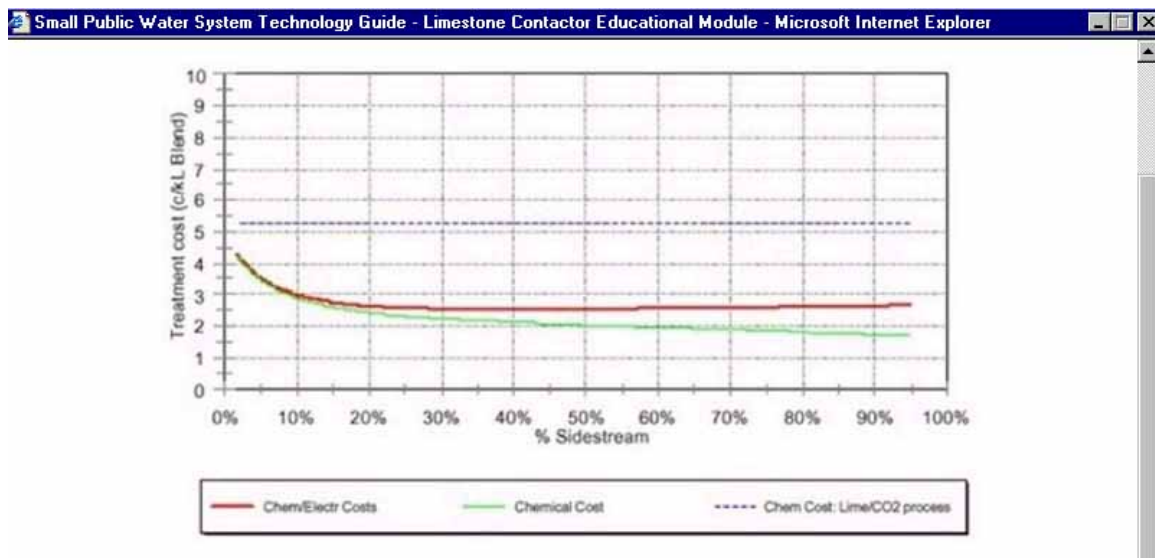


Figure B21. Chemical and Running Costs for Simplified SSP Configuration with Nominal Lime Dosage after Blending, for a Final Alkalinity of 50 mg/L (De Souza, Jason and Manxodidi, 2000)

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APPENDIX C

SAMPLE PROBLEM ON USING FIGURES B8 TO B13

This example shows how to design a limestone contactor by using Figures B8 to B13. A 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 CaCO₃

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 CaCO₃

Most of the alkalinity source at pH = 7.18 is from HCO₃⁻:

$$K_{S,4.3} = [\text{HCO}_3^-] = \frac{45 \text{ mg}}{\text{L}} \times \frac{1 \text{ meq}}{50 \text{ mg}} \times \frac{1 \text{ mmol HCO}_3^-}{1 \text{ meq HCO}_3^-} \times \frac{1 \text{ mol}}{10^3 \text{ mmol}} \times \frac{10^3 \text{ L}}{1 \text{ m}^3} = \mathbf{0.9 \frac{\text{mol}}{\text{m}^3}}$$

Assume the lowest temperature, T = 5 °C,

Therefore pK_{a1} = 6.52 at T = 5 °C (Snoeyink and Jenkins, 1980). Assume CO₂ = H₂CO₃* and ignoring activity coefficients:

$$K_{B,8.2} = [\text{CO}_2] = [\text{H}_2\text{CO}_3^*]$$

$$\frac{[\text{HCO}_3^-][\text{H}^+]}{[\text{H}_2\text{CO}_3^*]} = 10^{-\text{pK}_{a1}}$$

$$K_{B,8.2} = [\text{CO}_2] = [\text{H}_2\text{CO}_3^*] = \frac{(0.9 \times 10^{-3})(10^{-7.18})}{(10^{-6.52})} \frac{\text{mol}}{\text{L}} \times \frac{10^3 \text{ L}}{\text{m}^3} = \mathbf{0.2 \frac{\text{mol}}{\text{m}^3}}$$

DETERMINATION OF MEDIA TYPE:

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

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

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 B8 is applicable.
- Porous Calcium Carbonate, Target Goal pH=8 or pH=pH_c. Figure B10 is applicable.
- Dolomite, Target Goal pH=pH_c. Figure B12 is applicable.

Applicability of Design Figures:

Figures B8, B10 and B12 in this thesis) can be used to determine the contact time based on $K_{S,4.3}$ and $K_{B,8.2}$. Figure B13 is used for temperature correction.

Design Method:

Maximum flow rate, $Q = 1600 \text{ m}^3/\text{day}$ (430,000 gallons/day) (Spencer, 2000)

Loading Rate = 2.4 m/hr (1 gpm/ft^2) (Spencer, 2000)

Assume lowest temperature, $T = 5^\circ\text{C}$.

(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 B8, $t_F = 25 \text{ min}$ and from Figure B13, $f = 1.5$.

$$\begin{aligned}\text{Minimum bed volume, } V_M &= t_F \times f \times Q \times 1/60 \text{ min} \\ &= 25 \text{ min} \times 1.5 \times 1600 \text{ m}^3/\text{day} \times 1 \text{ day}/24\text{hr} \\ &\quad \times 1 \text{ hr}/60 \text{ min} \\ &= \mathbf{42 \text{ m}^3}\end{aligned}$$

$$\begin{aligned}\text{Depth of limestone bed} &= t_F \times f \times \text{Loading Rate} \\ &= 25 \text{ min} \times 1.5 \times 2.4 \text{ m/hr} \times 1 \text{ hr}/60 \text{ min} \\ &= \mathbf{1.5 \text{ m (5 ft)}}\end{aligned}$$

$$\text{Surface area of the contactor} = 1600 \text{ m}^3/\text{day} \times 2.4 \text{ m/hr} \times 1 \text{ day}/24 \text{ hr} = \mathbf{28 \text{ m}^2}$$

Determination Whether V_B is Needed in the Design

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/m³). The following calculations show the amount of CaCO_3 dissolved daily, weekly, monthly and yearly based on the result obtained using MINTEQ.

$$\begin{aligned}\text{The daily consumption of } \text{CaCO}_3 &= 1600 \text{ m}^3/\text{day} \times 0.1988 \text{ mol/m}^3 \times 100 \text{ g/mol} \\ &\quad \times 10^{-3} \text{ kg/g} \\ &= \mathbf{32 \text{ kg/day}}\end{aligned}$$

$$\begin{aligned}\text{Weekly consumption of } \text{CaCO}_3 &= 31.8 \text{ kg/day} \times 7 \text{ days/week} \\ &= \mathbf{223 \text{ kg/week}}\end{aligned}$$

$$\begin{aligned}\text{Monthly consumption of } \text{CaCO}_3 &= 31.8 \text{ kg/day} \times 30 \text{ days/month} = \\ &= \mathbf{954 \text{ kg/month}}\end{aligned}$$

$$\begin{aligned}\text{Yearly consumption of } \text{CaCO}_3 &= 31.8 \text{ kg/day} \times 365 \text{ days/yr} \\ &= \mathbf{11,607 \text{ kg/year}}\end{aligned}$$

Using the density of dense CaCO_3 of 1500 kg/m³ (DVGW, 1998), the weight of CaCO_3 can be calculated. Based on Figures B8 and B13, 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.

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

$$V_F = 42 \text{ m}^3 + 5 \text{ m}^3 = 47 \text{ m}^3$$

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

(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 B10, $t_F = 11.5 \text{ min}$ and from Figure B13, $f = 1.5$.

$$\begin{aligned} \text{Minimum bed volume, } V_M &= t_F \times f \times Q \times 1/60 \text{ min} \\ &= 11.5 \text{ min} \times 1.5 \times 1600 \text{ m}^3/\text{day} \times 1 \text{ day}/24\text{hr} \\ &\quad \times 1 \text{ hr}/60 \text{ min} \\ &= \mathbf{19.2 \text{ m}^3} \end{aligned}$$

$$\begin{aligned} \text{Depth of limestone bed} &= t_F \times f \times \text{Loading Rate} \\ &= 11.5 \text{ min} \times 1.5 \times 2.4 \text{ m/hr} \times 1 \text{ hr}/60 \text{ min} \\ &= \mathbf{0.7 \text{ m (2.2 ft)}} \end{aligned}$$

$$\text{Surface area of the contactor} = 1600 \text{ m}^3/\text{day} \times 2.4 \text{ m/hr} \times 1 \text{ day}/24 \text{ hr} = \mathbf{28 \text{ m}^2}$$

(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 B12, $t_F = 7.8 \text{ min}$ and from Figure B13, $f = 1.5$.

$$\begin{aligned} \text{Minimum bed volume, } V_M &= t_F \times f \times Q \times 1/60 \text{ min} \\ &= 7.8 \text{ min} \times 1.5 \times 1600 \text{ m}^3/\text{day} \times 1 \text{ day}/24\text{hr} \\ &\quad \times 1 \text{ hr}/60 \text{ min} \\ &= \mathbf{11 \text{ m}^3} \end{aligned}$$

$$\begin{aligned} \text{Depth of limestone bed} &= t_F \times f \times \text{Loading Rate} \\ &= 7.8 \text{ min} \times 1.5 \times 2.4 \text{ m/hr} \times 1 \text{ hr}/60 \text{ min} \\ &= \mathbf{0.5 \text{ m (1.5 ft)}} \end{aligned}$$

$$\text{Surface area of the contactor} = 1600 \text{ m}^3/\text{day} \times 2.4 \text{ m/hr} \times 1 \text{ day}/24 \text{ hr} = \mathbf{28 \text{ m}^2}$$

[**Click to Return to the Source Page**](#)

APPENDIX D

ELEMENTS AND SPECIFICATIONS OF EDUCATIONAL MODULE

The educational module will discuss two types of technologies (MAIN TOPIC):

- i. Limestone contactor
- ii. Ultraviolet disinfection

The educational elements for each technology are as follows (SUB-TOPIC):

- i. Introduction
- ii. Process description
- iii. Interactive typical process diagram
- iv. Design criteria
- v. Examples of plans and specifications
- vi. Treatment performance
- vii. Operational skills
- viii. Automation potential
- ix. Advantages
- x. Limitations and concerns
- xi. Pilot plant objectives
- xii. Costs
- xiii. References
- xiv. Contacts and facilities

The following are the specifications for the multimedia presentation:

a. *Main page 'HOME' :*

Main page will have title of the educational module, buttons or links to the technologies that will be discussed and the authors of each module. There will be buttons that link the main page to the 'about the water technology guide series', 'help' and 'search' webpages. The following logos; WTTAC, UNH and UT logo will also be included and the user will be able to click on the logos for information on each organization and a link to their respective websites. Users can click on the name of the authors for contact information.

b. *SUB-TOPICS (i.e. Introduction, Process Description, Design criteria, etc.) will contain the following specifications:*

(i) SUB-TOPIC (i.e. Introduction, Process Description etc.) to let user know where they are in the module.

(ii) NAVIGATIONAL SIDE BAR which list the contents of each of the technology discussion (i.e. Introduction, Process Description, etc.). The contents listed will be linked to the respective webpage and user can click on it to arrive to the webpage.

(iii) Interactive links to the WTTAC, UNH and UT websites.

(iv) TOP BUTTONS/LINKS will consist of 'LIMESTONE CONTACTOR', 'ULTRAVIOLET DISINFECTION' and 'CORROSION CONTROL'.

(v) BOTTOM BUTTONS/LINKS (EXCEPT THE MAIN PAGE):

a. Back and forward buttons – User can click on these buttons to move backward or forward in the module.

b. Help – User can click on help button to find out about tips on how to use the module. Users will be prompt to set their screen resolution to 1024 X 768 in order to maximize the viewing capabilities (the webpage will be designed in a way that the module will fit into all monitor screen sizes so that the user does not have to scroll and 1024 X 768 (maximum resolution for 15" monitor) is chosen to be the resolution for this module).

c. Search – User can click on search button to search for topic of interest by entering topic keyword(s). There will be a built-in search function in the HTML program that will automatically search for the entered keyword(s).

d. Email – User can email the webmaster to send feedback, comments, questions or anything related to the website. There will be a form for the user to fill in and a submit button to submit the email to the webmaster.

e. Glossary – User can find definition of the technical words used in the module by clicking on glossary button. The HTML search function may be used in the glossary webpage.

(vi) PAGE NUMBER (i.e. Sheet 1 of 20)

(vii) BACKGROUND IMAGE use photo of contactor, uv-reactor and etc. for each of the technology's module.

c. *HELP, SEARCH, EMAIL AND GLOSSARY PAGES:*

These webpages will contain the same specifications as in Part 2 except for the navigational side bar.

d. *OTHER SPECIFICATIONS:*

i. Main HTML tags used:

TABLE (td, tr, col span, row span) : the entire website will be constructed with HTML table formatting.

To insert LINK : `<a href="www.*.com">Description</a>`

To insert PHOTOS : ``

Use `<blockquote>` to center the texts vertically and horizontally in the contents' section.

- ii. Set the table border=5. Table in all pages will consist of 7 columns. Use `<COLSPAN="7">` tag to specify number of columns. For the banner in sub-topic pages, the WTTAC, UNH and UT logos are inserted as image links and lined up in a row using `<ROWSPAN=3>` (3 rows). Set column width=200.
- iii. The navigational side bar took up two columns (`COLSPAN="2">`). Therefore, there are 5 columns remaining to insert the navigational top 'image' buttons/links and page number `<COLSPAN="5">`.
- iv. Font type : Times New Roman.
- v. Font size : Title (+2), Sub-title (+1), Content (do not specify size, use default size).
- vi. Navigational side 'text' buttons : Grey background and white font (Not images, they are only links created using HTML).
- vi. Navigational top 'image' buttons : Grey background and white font (Using Photodraw, set image width=90px and image height=26px).
- vii. Navigational bottom 'image' buttons : Image created using Photodraw. Using Photodraw, set the Border color=grey, Image width=90px, Image height=90px.

[Click to Return to the Source Page](#)

APPENDIX E

GENERAL CONTENTS OF LIMESTONE CONTACTORS EDUCATIONAL MODULE

Website Homepage:

- i. Title page screen/Main page ('HOME'):**
 - a. Graphic background
 - b. Authors
 - c. Acknowledgments
 - d. Interactive links to WTTAC, UNH and UTK websites

Limestone Contactor Educational Module (List of Pages):

- ii. Introduction :**
 - a. Brief overview of the technology and its application in the U.S.
- iii. Process Description :**
 - a. Summary description of process
 - b. Chemistry of calcium carbonate dissolution:
 - Mathematical model of calcite dissolution
 - Calcium carbonate dissolution rate equations
 - Benefits of calcite dissolution (increase in pH and alkalinity)
 - Factors affecting dissolution rate: temperature, water quality, limestone characteristics (size of crushed limestone, stone composition and crystallography and aluminum and iron content in the stone), empty bed contact time and location in the treatment process and aging.
- iv. Typical Contactor :**
 - a. Actual photos of contactor equipment.
 - b. Videos of contactor in operation (videos will be available only if UT personnel visit sites and will only be used if appropriate).
 - c. Frequency of maintenance and cleaning
 - d. Frequency of limestone bed's replacement
 - e. Interactive flow diagram of contactor
 - User can click on each process unit in the flow diagram and there will be a brief description of the process
 - User can click on the 'media' in the flow diagram and there will be a discussion on the typical limestones used :
 - i. Most often type of limestone used in contactor
 - ii. Composition of chemicals contained in the limestone and how to determine which limestone to use based on weighted sum

[less than 10mg/g of the aluminum (mg Al/g) and 0.3 X iron content (mg Fe/g)] and limestones defined in the ASTM Standard C51 containing no more than 0 to 5% magnesium carbonate

- iii. Effects of stone composition on the dissolution kinetics
- iv. Photos of limestones

v. Design Criteria :

- a. There is no codified design criteria for limestone contactor however let the readers know that design of contactor is made using the DESCON model created by Dr. Ray Letterman and based on the slow sand filtration design.
- b. Brief discussion on how the DESCON model is developed, the assumptions used and a link to Dr. Ray Letterman's DESCON website.
- c. What the designer should be aware of before designing a contactor: include a link to 'factors affecting calcite dissolution rate' under process description.
- d. Typical design parameters used for some existing contactors

vi. Examples of Plans and Specifications :

- a. Include examples of plans and design specifications of the contactor in Mars Hill, Maine Water Treatment Facility designed by Wright Pierce.

vii. Treatment Performance :

- a. Include a table/graph that shows influent and effluent water quality to and from the contactor. Data to be used may be obtained from the Mars Hill, Maine water treatment facility. Examples of water quality data include turbidity, temperature, pH and alkalinity, calcium content and conductivity.

viii. Operation and Maintenance :

- a. State the skills that are necessary for the operators to have in order to operate the contactor.
- b. Cleaning/backwashing
- c. Media addition/replacement

ix. Automation Potential :

- a. If the treatment plant is automated then the contactor will run automatically too.

x. Advantages :

- a. Simple and low cost device
- b. Possibly generate cost comparison between contactor and other corrosion control methods to determine whether contactor is the least expensive method.
- c. Usually require minimal maintenance.

- xi. Limitations and concerns :**
 - a. List disadvantages of limestone contactor.
 - b. Types of water amenable to process.
- xii. Pilot plant objectives :**
 - a. Most common questions to answer in pilot plant study.
- xiii. Costs :**
 - a. Cost of construction, operation and maintenance of Mars Hill, Main contactor.
 - b. Cost of other facilities is still being sought.
- xiv. References :**
 - a. List of references.
- xv. Contacts and Facilities :**
 - a. List of contacts (individuals, agencies, and companies)

[**Click to Return to the Source Page**](#)

APPENDIX F

WEB TEMPLATES OF EDUCATIONAL MODULE

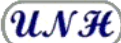
SMALL PUBLIC WATER SYSTEM TECHNOLOGY GUIDE VOLUME II		
  	LIMESTONE CONTACTOR by ULTRAVIOLET DISINFECTION by	  
Developed by the University of New Hampshire Water Treatment Technology Assistance Center, The University of New Hampshire, and The University of Tennessee-Knoxville Funded by the United States Environmental Protection Agency Grant Number © COPYRIGHT 2002 University of Tennessee		

Figure F1. Template for the Main Page of the Educational Module
([Click to Return to the Source Page](#))

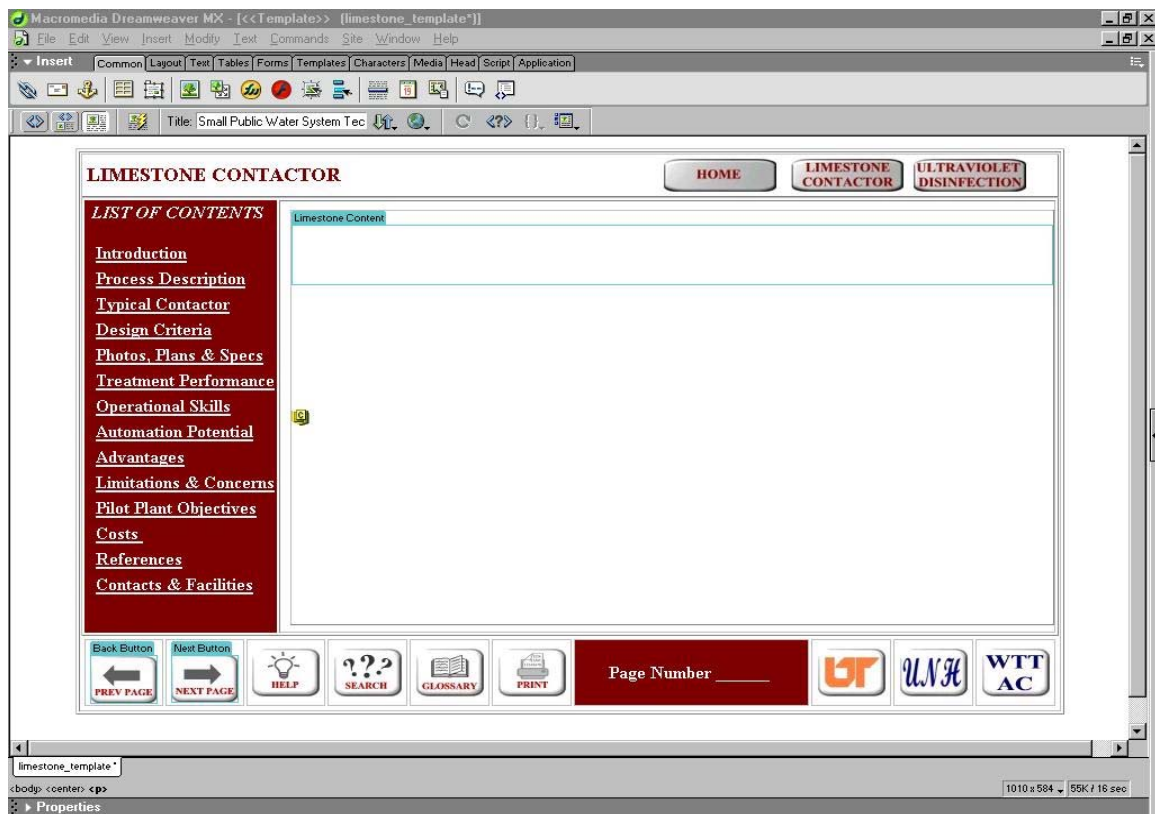


Figure F2. Template for Front Page of the Individual Section in Educational Module (Click to Return to the Source Page)

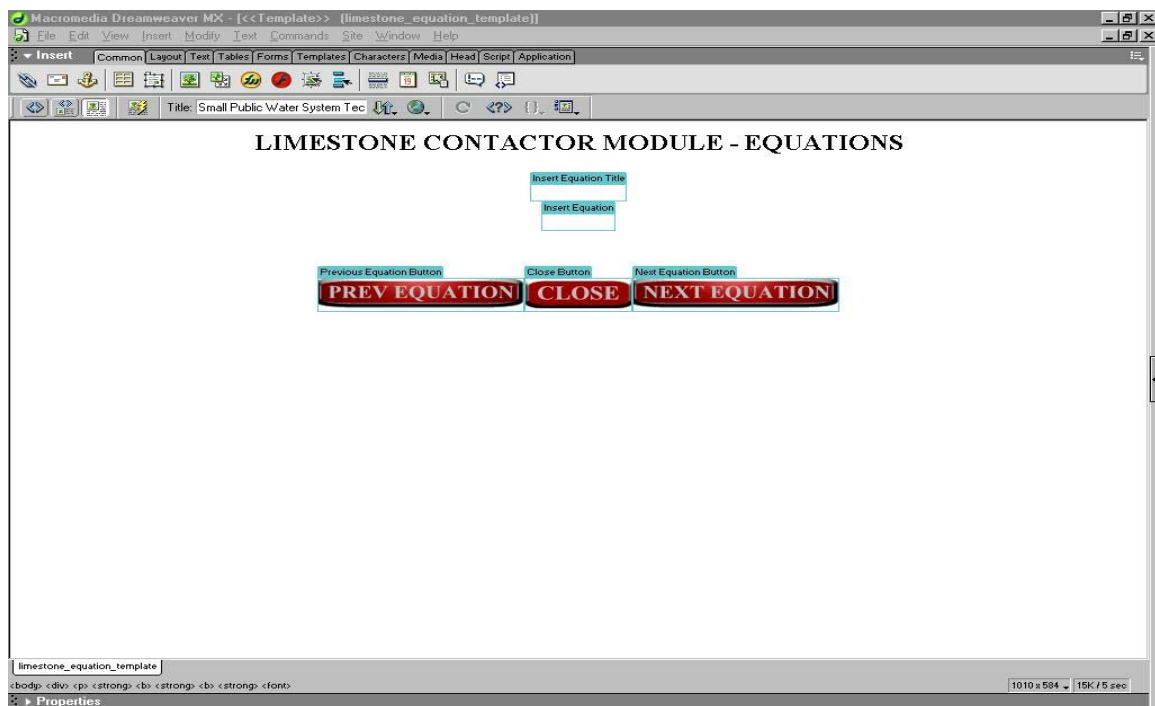


Figure F3. Template for Equation (Click to Return to the Source Page)

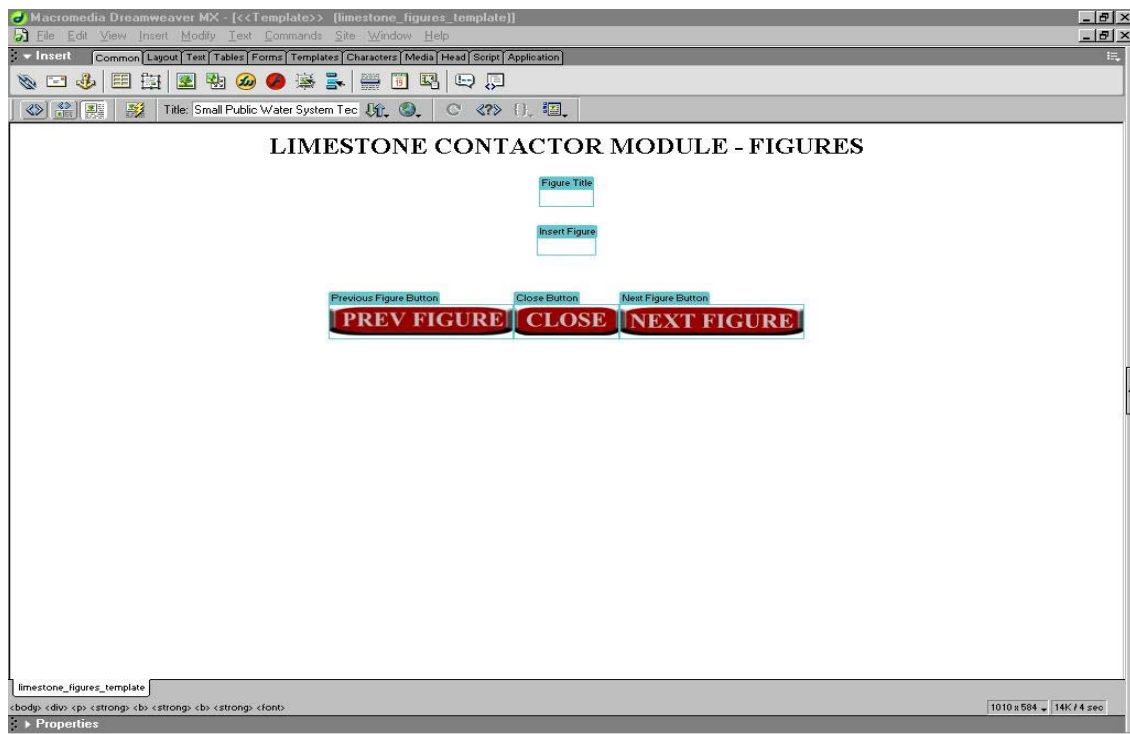


Figure F4. Template for Figures ([Click to Return to the Source Page](#))

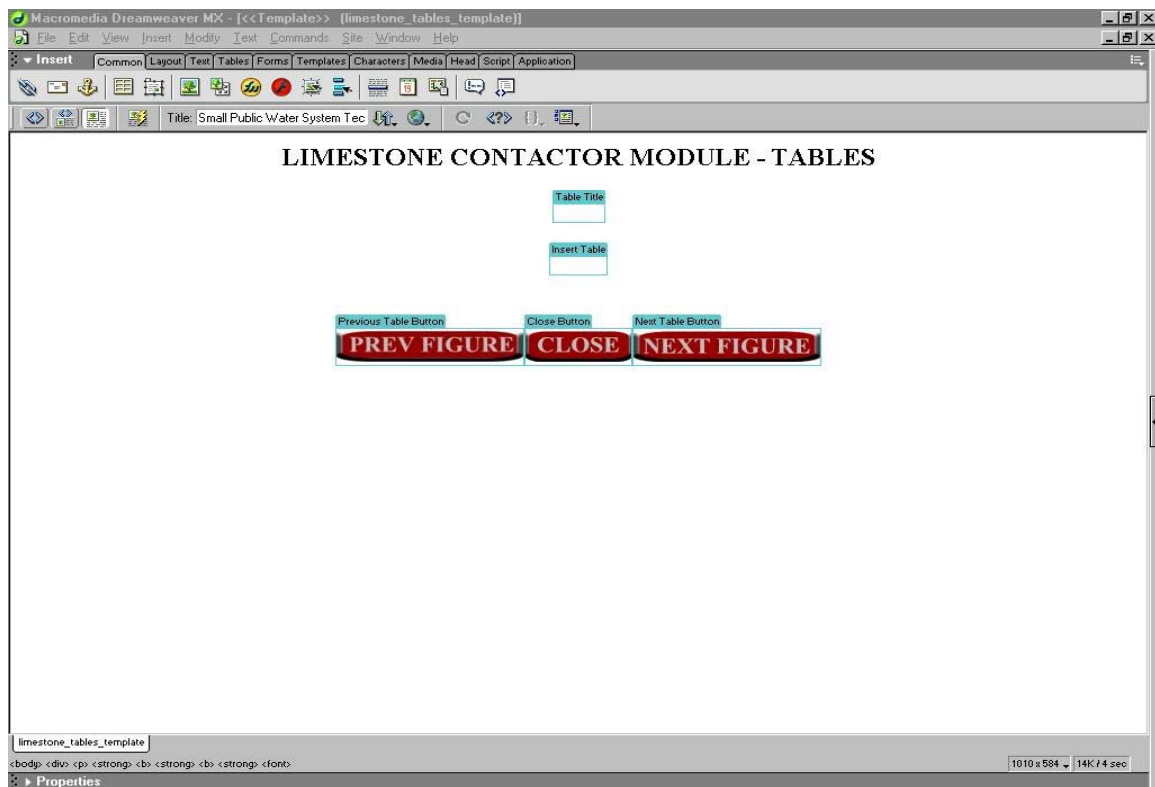


Figure F5. Template for Tables ([Click to Return to the Source Page](#))

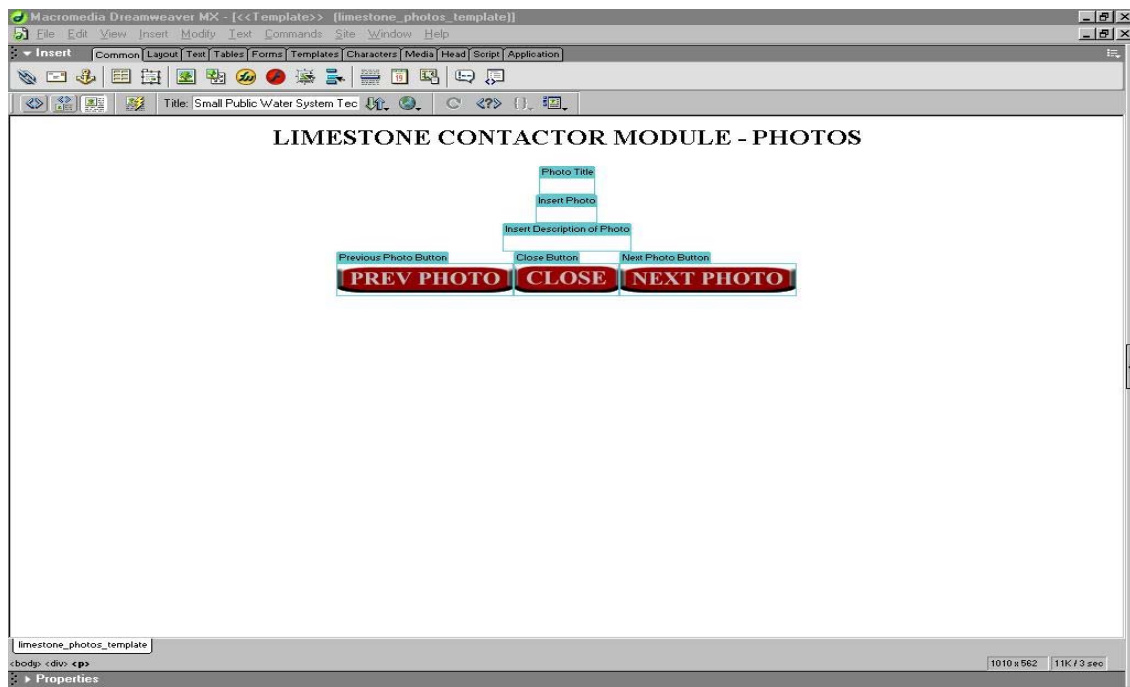


Figure F6. Template for Photos ([Click to Return to the Source Page](#))

APPENDIX G

SAMPLE OF EDUCATIONAL MODULE SCREENS

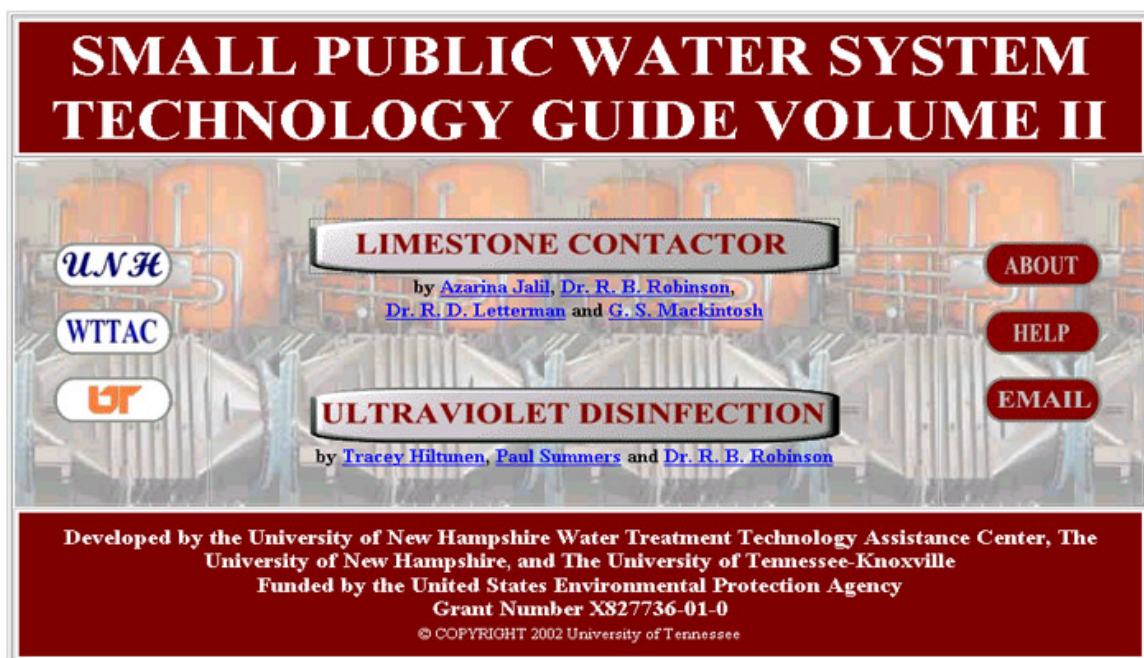


Figure G1. Main Page Screen ([Click to Return to the Source Page](#))

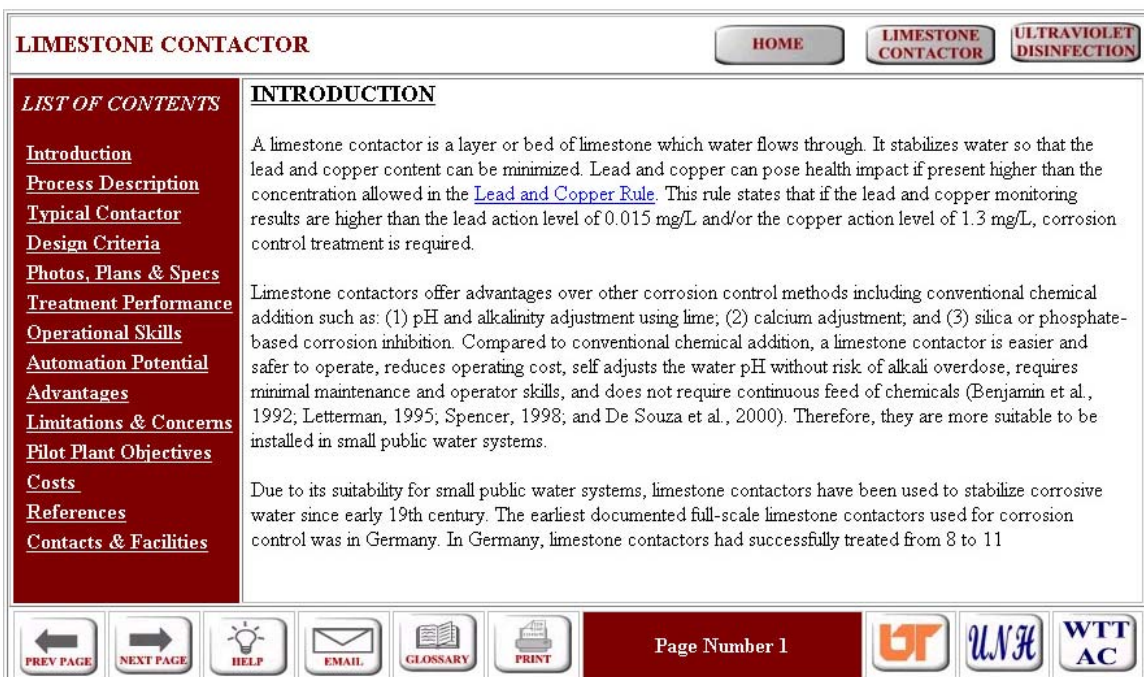


Figure G2. Introduction Screen ([Click to Return to the Source Page](#))

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PROCESS DESCRIPTION

In a limestone contactor, water flows through a bed of crushed sieved limestone in a similar way as it would flow through a sand filter (Spencer, 2000). The process and design of limestone contactor is almost similar to a sand filter except its overflow loading rate is less than 1 gpm/ft², which is less than the typical filtration flow rate (Spencer, 2000). The slow flow rate ensures adequate time for water to dissolve calcium carbonate from limestone. The pH of water that flows through the limestone bed will be adjusted until it nears equilibrium with calcium carbonate (CaCO₃(s)). The components of a contactor include a contact tank, limestone bed, inlet line, outlet line, overflow line, access lid (for closed system contactor only) and a flush outlet line (DeSouza et al., 2000).

There are two types of contactors: (i) open and (ii) closed system contactor. The former is exposed to the atmosphere and the latter is covered from the atmosphere. There are also contactors that are built in pressurized vessels (Stauder, 2002).

Limestone contactors are typically located at the end of the treatment train – after filtration, primary disinfection and chlorine contact (Spencer, 2000 and Benjamin et al., 1992). According to Spencer (2000) and Benjamin et al. (1992), by placing a contactor this way ensures the pH is maintained at a low level for effective chlorination. However, there are also contactors that are located after filtration and before chlorine addition (Stauder, 2002).

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Figure G3. Process Description Screen ([Click to Return to the Source Page](#))

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TYPICAL CONTACTOR

Based on: On-site Assessment of the Suitability of Limestone Mediated Stabilisation at Makwane Water Treatment Plant (De Souza, Jason and Manxodidi, 2002).

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Figure G4. Typical Contactor Screen ([Click to Return to the Source Page](#))

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DESIGN CRITERIA

(A) General Design Criteria for 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. Click [here](#) to see the common design criteria and approaches used in U.S., Germany and South Africa for designing limestone contactors (Note: [Adobe Acrobat Reader](#) (Version 5.0 or higher) is required to view the file. It may take several minutes to load the file depending on the speed of your internet connection).

(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** 3 shows the design criteria of the Spraystab I unit.

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Figure G5. Design Criteria Screen ([Click to Return to the Source Page](#))

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PHOTOS, PLANS AND SPECIFICATIONS

(A) PHOTOS

i. Photos of Limestone Contactor in U.S.:

a) Limestone contactors installed at a resort in the Adirondack Mountains, New York:

The following photos show a column-type contactor and a box-type contactor installed at a resort in the Adirondack Mountains, New York (on Big Moose Lake). The owner of the resort had problems with corrosion especially pin-holes in copper pipe.

- [Covewood Lodge](#)
- [Column-type limestone contactor being carried into a Covewood Lodge cabin](#)
- [Installation of a column-type limestone contactor in the basement of a Covewood Lodge cabin](#)
- [Box-type limestone contactor in the mountain side springs at the Covewood Lodge](#)
- [Installation of the cover on the spring where the box-type limestone contactor was installed](#)

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Figure G6. Photos, Plans and Specifications Screen ([Click to Return to the Source Page](#))

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TREATMENT PERFORMANCE

The performance of limestone contactor in stabilizing water is discussed below by presenting data taken before and after limestone contactors were installed in Mars Hill, Maine, Bredasdorp and Stellenbosch, South Africa.

(A) Limestone Contactor Performance in Mars Hill, Maine:

Prior to installation of limestone contactor in October 1998, Mars Hill, Maine exceeded the Lead and Copper Rule (Spencer, 2000). The 90th percentile lead level was 0.017 mg/L and copper level was 1.3 mg/L. Part of the cause was believed to be low pH. Installing a limestone contactor raised the pH and significantly reduced the lead and copper level.

FIGURE 10 shows that the pH of treated water in Mars Hill increased after stabilization using limestone contactor.

FIGURE 11 shows that limestone stabilization decreased the 90th percentile lead level from 0.017 mg/L in Fall 1996 to 0.008 mg/L in Spring and 0.006 mg/L in Fall 1999.

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Figure G7. Treatment Performance Screen ([Click to Return to the Source Page](#))

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TYPICAL OPERATOR SKILL REQUIREMENTS

A limestone contactor requires minimal operator attention and maintenance provided that it is correctly designed to treat the maximum flow of the plant and it is properly situated in the treatment train (Spencer, 2000). A limestone contactor operator must have the skills to carry out the operation and maintenance procedures listed in

TABLE 8. The operator must also maintain a record of all operations, regular inspections, water quality parameters monitored and maintenance of the contactor in a limestone contactor log book (Mackintosh, De Souza and De Villiers, 2003).

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Figure G8. Typical Operator Skills Requirement Screen ([Click to Return to the Source Page](#))

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Automation Potential

Water flows automatically through the limestone contactors in automated water treatment plants. Typically, the flow of water to the contactors is the same as the plant throughput (Spencer, 2003). The most important design parameter in a limestone contactor is the contact time, but trying to independently control the flow of the influent and effluent water of the contactor is problematic. Doing so may cause a reduction in the treated water production. Even if sufficient storage of treated water is available, it may also complicate the monitoring process and cause the monitoring to be costly (Stauder, 2003). Therefore, it is important to design a limestone contactor so that it will stabilize water at the worst conditions so that control of flow of water to the contactor is not necessary.

Limestone contactors are cleaned periodically by backwashing the media but backwash is generally manually initiated. Media replacement is not automated but is done manually and is discussed further in the operation and maintenance section.

Limestone contactor performance can be observed by monitoring the pH. The pH can be monitored either manually or by a sensor which feeds the data into a computer data management system.

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Figure G9. Automation Potential Screen ([Click to Return to the Source Page](#))

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Limitations and Concerns

Limestone contactors have a few limitations as listed below (Stepp, 2002):

1. There is no direct control of the treatment process.
2. Depending on the quality of the raw water, limestone contactors may not be able to raise pH very much.
3. Capital costs can be significant compared to chemical feed systems.
4. As water systems get larger, the footprint required for the contactors can be substantial.

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Figure G10. Limitations and Concerns Screen ([Click to Return to the Source Page](#))

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PILOT PLANT OBJECTIVES

The objective of a pilot limestone contactor plant study is to determine whether it is suitable as a stabilization treatment by assessing the cost, performance and feasibility of the process. The suitability of the limestone contactor is mainly dependent on raw water characteristics such as pH, alkalinity and temperature. These along with using correct choices of design and operating variables will determine the success of a limestone contactor operation. These variables are determined from pilot study.

Engineering Design Variables:

1. Media size
2. Chemical constituents / purity of media
3. Filtration rate
4. Maximum flow rate
5. Contact time
6. Limestone bed depth
7. Recharge level
8. Location in the treatment train

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Figure G11. Pilot Plant Objectives Screen ([Click to Return to the Source Page](#))

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EXAMPLE OF CONSTRUCTION AND O&M COSTS

TABLE 9 shows cost estimates of limestone contactors built in Port Simpson, British Columbia for flocculation and corrosion control purposes. The total cost to construct both of these contactors was \$CND 140,000. The high total cost was due to the facility being remote from large towns causing increased cost in transporting construction materials. It was estimated that 90% of the limestone cost was for transportation. The total cost would be approximately 50% lower if the facility were close to large towns.

The cost for the two contactors was estimated based on the design criteria listed in **TABLE 10**. Different design criteria were used for these contactors. This may be due to higher requirement on the pH and alkalinity content of the water treated used for corrosion control. Therefore, it is designed to have a contact time slower than that of the contactor used for flocculation.

A cost comparison was made between a limestone contactor and soda ash for treating an average of 1.1 MLD of water (1.6 MLD maximum) at the Mars Hill, Maine water treatment facility. It showed that the capital costs between the two options were similar, in the range of US\$ 40,000 (Spencer, 2000). De Souza et al. (2000) found that the capital cost for limestone contactor installation is much higher than adding lime and carbonate for treating 6 MLD water at Makwane Treatment Plant in South Africa. Refer to **TABLE 11** for cost comparison.

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Figure G12. Example of Construction and O&M Costs Screen ([Click to Return to the Source Page](#))

LIMESTONE CONTACTOR		HOME	LIMESTONE CONTACTOR	ULTRAVIOLET DISINFECTION
LIST OF CONTENTS Introduction Process Description Typical Contactor Design Criteria Photos, Plans & Specs Treatment Performance Operational Skills Automation Potential Advantages Limitations & Concerns Pilot Plant Objectives Costs References Contacts & Facilities	REFERENCES 1. Alkattan, M., Oelkers, E.P., Dandurand J.L., Schott J. (1998). "An experimental study of calcite and limestone dissolution rates as a function of pH from 1 to 3 and temperature from 25 to 80 degrees C". <i>Chemical Geology</i>. 151:1-4:199-214. 2. Aziz, H.A. et. al. (2001). "Removal of copper from water using limestone filtration technique. Determination of mechanism of removal". <i>Environment International</i>. 26:5-6:395-399. 3. Aziz, H.A. and Smith, P.G. (1996). "Removal of manganese from water using crushed dolomite filtration technique". <i>Water Research</i>. 30:2:489-492. 4. Baldauf G., Henkel M. (1991). "Moglichkeiten und Grenzen der Marmorentsauerung vor dem Hintergrund der neuen Trinkwasserverordnung". <i>Wasser/Abwasser</i>. 132:3:132-140. 5. Beforth, H. (2003). Personal Communication. <i>Consultant for Water Technology and Chemistry, Germany</i>. 6. Benjamin, L. et. al. (May 1992). "Pilot testing a limestone contactor in British Columbia". <i>Journal AWWA</i>, pp 70-79.			
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Figure G13. References Screen ([Click to Return to the Source Page](#))

LIMESTONE CONTACTOR		HOME	LIMESTONE CONTACTOR	ULTRAVIOLET DISINFECTION
LIST OF CONTENTS Introduction Process Description Typical Contactor Design Criteria Photos, Plans & Specs Treatment Performance Operational Skills Automation Potential Advantages Limitations & Concerns Pilot Plant Objectives Costs References Contacts & Facilities	CONTACTS AND FACILITIES 1. Dr. Michael Schock Principal Research Environmental Lab USEPA Cincinnati, OH Tel: (513) 569-7412 Email: Schock.Michael@epamail.epa.gov 2. Catherine M. Spencer, P.E. Water Quality Engineer Black & Veatch ME Tel: (207) 688-4234 Email: SpencerCM@bv.com 3. Bernie Lucey New Hampshire Department of Environmental Services Email: blucey@des.state.nh.us URL: http://www.des.state.nh.us			
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Figure G14. Contacts and Facilities Screen ([Click to Return to the Source Page](#))

APPENDIX H

INSTRUCTIONS FOR VIEWING THE EDUCATIONAL MODULE

A. Instruction for viewing the educational module from a CD-ROM:

1. Place the CD-ROM in the CD-ROM drive.
2. Click on *My Computer*.
2. Click on the CD-ROM drive icon.
3. Click on the folder inside the CD-ROM drive.
4. Click on *default.html*. Then, click on *limestone contactors* button.
5. Follow the procedure below (Appendix G Part B) for setting the screen resolution and browser and software requirements. Note: If the module is viewed from a CD-ROM, internet browser is still required to open the module.

B. Instruction for viewing the educational module on the web:

1. This website is best viewed with a display setting of 1024 x 768 pixels. Follow the instructions below to change your computer's display settings to this resolution.

a) Click on 'Start', 'Settings' and Control Panel as shown in Figure H1.



Figure H1. Setting the Screen Resolution Step 1

b) On the 'Control Panel' menu, double click on the 'Display' icon as shown in Figure H2.

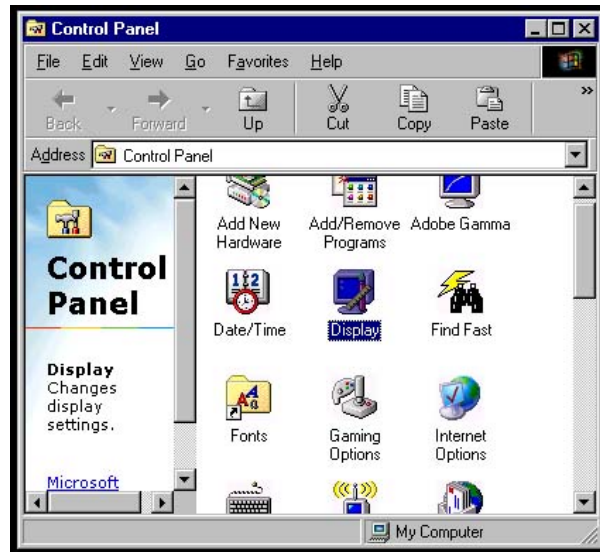


Figure H2. Setting the Screen Resolution Step 2

c) Click on the 'Settings' tab on the 'Display Properties' menu. Move the notch on the 'screen area' to 1024 x 768 pixels as shown in Figure H3. Then, click 'OK'.

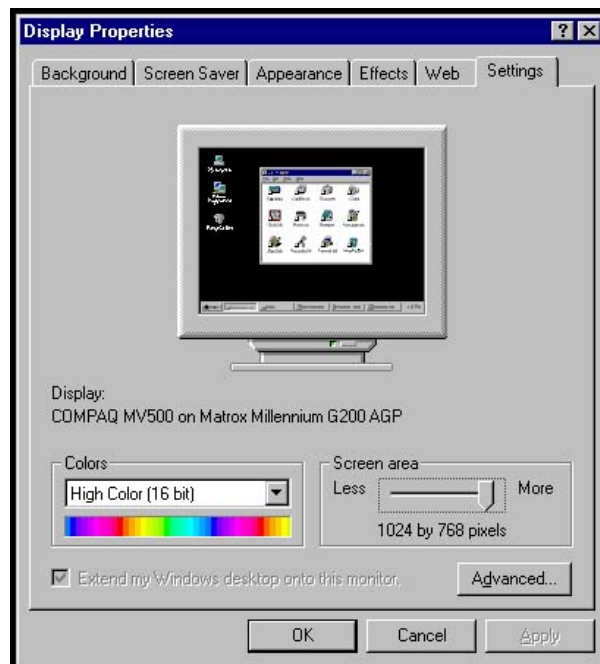


Figure H3. Setting the Screen Resolution Step 3

2. The web educational module is partly designed using JAVA script in order to make it user-interactive. Therefore, it is required that your browser is enabled to run JAVA. If this error message: "the file animate.js could not be found" appears on the computer screen when you enter the URL address of this website, JAVA may have been disabled on your browser or your browser does not support JAVA. This is true for all versions of Netscape prior to 5.0 and Internet Explorer (I.E.) prior to 6.0. In order to know the version of Netscape or I.E. you are using, click on the 'Help' tab on your browser menu.

If your browser has a problem running JAVA, you can try one of the following options:

- For Netscape 3.0 user:
 - a) Click on 'Options'
 - b) Select 'Network Preferences'
 - c) Click on the 'Languages' tab
 - d) Check the box next to 'Enable JAVA'
 - e) Click 'OK'
- For Netscape 4.0 user:
 - a) Click on the 'Edit' tab on the browser menu
 - b) Select 'Preferences'
 - c) On the 'Preferences' menu, click on 'Advanced'
 - d) Check the box next to 'Enable JAVA'
 - e) Click 'OK'
- For Internet Explorer 4.0 and 5.0 user:
 - a) Click on 'View' on the browser menu
 - b) Select 'Internet Options'
 - c) Click on the 'Security' tab
 - d) Click the radio button next to 'Custom'
 - e) Click the 'Settings' button
 - f) Enable 'Scripting/Active Scripting' in the 'Settings' options list
 - g) Click 'OK'

If the same error message reappears after trying one of the above options, your browser does not support JAVA. Therefore, you may have to upgrade your browser to higher versions. For Netscape user, visit the Netscape Smart Update website at <http://www.netscape.com> to upgrade your browser. For Internet explorer user, visit the Microsoft Download Center at <http://www.microsoft.com> to upgrade your browser.

2. The *.pdf files that are on the web educational module may not be displayed correctly if you are using Adobe Acrobat Reader 3.0. If you have an error message while you are trying to load the *.pdf files, you may need to upgrade your Adobe Acrobat Reader to a higher version downloading the Adobe Acrobat Reader at <http://www.adobe.com>

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APPENDIX I

SAMPLE CORRESPONDENCE WITH WATER TREATMENT FACILITY'S OWNERS

**THE UNIVERSITY OF TENNESSEE
KNOXVILLE**

College of Engineering
Department of Civil and Environmental Engineering
223 Perkins Hall Knoxville, Tennessee 37996-2010
Phone: 865/974-2503
FAX: 865/974-2669

June 30, 2003

Mr. Frank Kearney
Mars Hill Water Treatment Facility
P.O. Box 342
Mars Hill, ME 04758

Dear Mr. Kearney,

I believe that Azarina Jalil, who is working for me on a project, talked with you about visiting the Mars Hill Water Treatment Facility. Our purpose for visiting is to take photos and video of the facility. The photos and video will be incorporated into an educational module on limestone contactors for small water treatment systems. This project is funded by E.P.A. through the New Hampshire Water Treatment Technology Assistance Center (WTTAC), which is managed by Dr. Robin Collins. The educational module will be available on the web. Its aim is to provide guidance to the state and federal regulators, engineers, water treatment plant owners and operators on small water treatment technologies. Currently, the module temporarily resides with the University of Tennessee's domain, but the finished product will later remain permanently with the WTTAC's website. You are welcome to visit the module that is currently under construction at <http://www.engr.utk.edu/~brobinso/watertechtrial>.

We are very grateful to you for allowing us to visit your facility and we are very excited to include the photos and video of your facility in the module. I believe that Azarina Jalil and her partner in this project plan to visit your facility in the second week of August, probably on Monday August 11th or Tuesday August 12th, if these dates are suitable for you and the facility. She will make final arrangements with you in the next few weeks. She hopes to capture the photos and video of the limestone contactor in your facility; if possible including the type of limestone used, the backwashing process, the tank structure

and all the piping connected to the contactor. If permitted, we would also hope to take the photos and video of the other treatment processes in the facility.

We would also be happy if you or any of your treatment personnel would like to be included in the photos or video or provide narration of the process involved in the limestone contactor in the video that we are going to take. If you or any of your treatment personnel wish to do so, we will request world rights to include you or them in the photo or video. A copy of the permission-to-use form is attached with this letter. Azarina will bring the original copy to your facility when she visits.

I appreciate your permission to let us visit your facility and I would like to thank you in advance for your assistance in the duration of our visit.

Sincerely,

R. Bruce Robinson, Ph.D., P.E.
Professor of Civil and Environmental Engineering
Office: 865-974-7730
FAX: 865-974-2669
E-mail: rbr@utk.edu

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APPENDIX J

SAMPLE PERMISSION-TO-USE LETTER

THE UNIVERSITY OF TENNESSEE
KNOXVILLE

College of Engineering
Department of Civil and Environmental Engineering
223 Perkins Hall Knoxville, Tennessee 37996-2010
Phone: 865/974-2503
FAX: 865/974-2669

DATE

NAME

ADDRESS LINE 1

ADDRESS LINE 2

Dear XXX:

We are in the process of creating a web based educational module on limestone contactors for small water supplies through a grant to the University of Tennessee (UT) provided by the University of New Hampshire's Water Treatment Technology Assistance Center which is a new center funded by the U.S. Environmental Protection Agency. It is possible that the web educational module may be incorporated onto a CD-ROM for some users.

We would like permission to use the attached figures, drawings, specifications, and text. The source of this material is as follows:

SELECT RELEVANT CHOICES:

a) the slides and video that we took while visiting your plant and/or the slides and video that you provided us,

b) the attached figure, drawing, specifications, or text. The source of this material is as follows:

list figure or drawing number(s) or other reference, author, text name or other source, publisher, city, date or copyright date, and page number.

We are requesting world rights to use the above-mentioned material in the web site and CD-ROM(s) and any future versions of the web site and CD-ROM(s). These rights would be non-exclusive rights for figures, drawings, text, photos, and video provided by you and the copyright for these materials remains with you.

Unless you would like an alternative credit, the material will include a citation as listed below which will appear after the title of the figure, drawing, photo, or video or as a footnote for text

material and specifications:

Courtesy of *NAME*

If you are willing to grant UT the requested permission for use in the educational website and/or CD-ROM(s), please return a copy of this letter with the agreement block signed below, or send me your own signed agreement form. If you do not control these rights, please refer me to the proper source. I will provide you the URL address of the finished web site and of any CD-ROM(s) produced incorporating this material upon completion. You can view a draft of the website at <http://www.engr.utk.edu/~brobinso/watertechtrial>.

I would like to thank you in advance for your willingness to provide permission to use this material in our web site and/or CD-ROM(s) which should be a valuable resource for regulators, engineers, and water utilities.

Sincerely,

R. Bruce Robinson, Ph.D., P.E.
Professor of Civil and Environmental Engineering

Agreement

I hereby grant the above requested permission for use in the educational web site and CD-ROM(s) as discussed herein.

Date: _____ Signature: _____

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VITA

Azarina Jalil was born in Kota Kinabalu, Sabah, Malaysia on November 22, 1976. She went to Tanjung Aru School, Kota Kinabalu for primary school and Sabah Fully Residential School for high school. She graduated high school in December 1993 and was offered a scholarship from the Malaysian Government to further her studies in the United States through a Twinning Degree Program with one of the colleges in Malaysia. She accepted the offer and went to Mara Community College in Kuantan, Pahang in August 1994. She graduated with an Associate Degree in Chemical Engineering from that college in May 1996. From there, she went to the University of Tennessee, Knoxville and received a Bachelor of Science in Chemical Engineering in May 1999.

Azarina worked as an environmental consultant with ERM Borneo for several months after she graduated. Then, she continued to work for the Sabah Water Department as a Water Treatment Plant Engineer in Beaufort District for two years. From there, she went back to the University of Tennessee, Knoxville for the Master's program. She received the Master's degree in December 2003.