CARBON DIOXIDE STRIPPING: -Fundamentals -Computer Design Model

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The title of this presentation is “Carbon Dioxide Stripping: Fundamentals and Computer Design Model”. This material is a compilation of a few years of work and has had multiple contributors including Steven Summerfelt, Raul Piedrahita of UC Davis, Mike Timmons, and Barnaby Watten of the USGS.

In this presentation I will cover some of the basics of carbon dioxide in aquaculture, starting with CO_2 production and CO_2 toxicity. Then I will cover the carbonate system and how CO_2 acts as a component of the carbonate system. I will also discuss some basics of gas transfer and the stripping of CO_2 from aquaculture waters. After getting through those concepts we will start on a few of the CO_2 stripping options commonly used in aquaculture.

OVERVIEW

- Basic Design Parameters
- Design Example
  - Two Methods
- Facility Considerations
- Computer Design Model
- Model Results

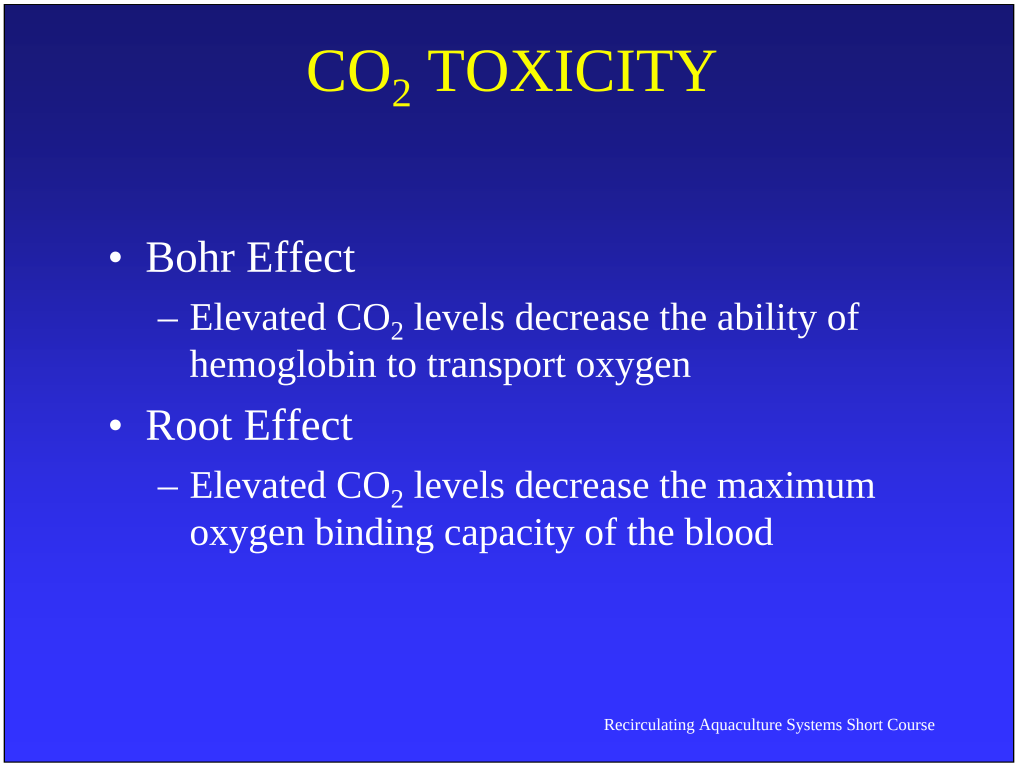
Recirculating Aquaculture Systems Short Course

For each of the CO_2 stripping options I will cover some of the basic design parameters that you need to think about when considering each option. After the CO_2 stripping options we'll go through a design example for sizing a stripping tower and we'll use two methods of calculation for the same example and compare the methods. I will also discuss some of the facility considerations concerning CO_2 that are very important in indoor aquaculture operations. We will then start in on the computer model that is available for the design of CO_2 control in intensive aquaculture operations and cover some model simulation results.

CO_2 PRODUCTION

- Molar basis
  - 1 mole of CO_2 is produced for every 1 mole O_2 consumed
- Mass basis
  - 1.38 g of CO_2 is produced for every 1 g O_2 consumed

Production – on a molar basis 1 mole of carbon dioxide is produced for every mole of oxygen consumed by fish. Converting to a mass basis this results in 1.38 grams of carbon dioxide being produced for every 1 gram of oxygen consumed by fish. What's important here is that carbon dioxide is produced by the fish at a greater rate than oxygen is consumed.



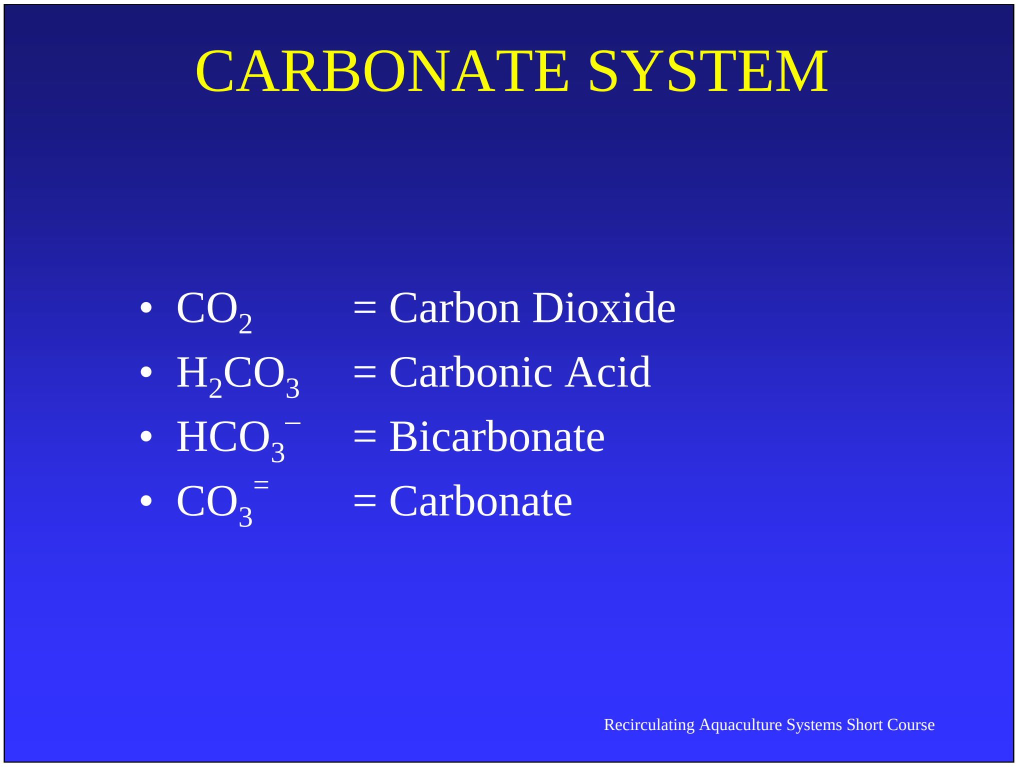
Toxicity – carbon dioxide is attributed to the Bohr and Root effects. The Bohr Effect is that elevated CO2 levels decrease the ability of a fish's hemoglobin to transport oxygen. The Root Effect is that elevated CO_2 levels decrease the maximum oxygen binding capacity of a fish's blood. Both effects indicate that high levels of CO_2 result in compromised fish respiration.

CO_2 TOXICITY

- Safe levels depend on species, developmental stage, and water quality:

Concentration (mg/L)	Fish Health Effect	Reference
60	Operational level for Tilapia	Timmons, unpublished data
60	Operational level for Striped Bass	Piedrahita, unpublished data
9–30	Safe level for Trout	Heinen et al., 1996

The safe or accepted level of carbon dioxide in water depend upon fish species, the developmental stage of the fish, and the water quality. For tilapia, Mike Timmons has data that suggest that 60 mg/L CO_2 is a safe operational level. For striped bass, Raul Piedrahita has data that suggest that 60 mg/L is also a safe operational level. In the case of trout, Heinen and others have reported that safe levels are much lower, from 9 to 30 mg/L.



Whenever talking about dissolved carbon dioxide it is important to note that it is part of an aqueous chemical system known as the carbonate system or carbonate carbon system. The carbonate system includes all species that have inorganic carbon. There are four such species: carbon dioxide (CO_2), carbonic acid (H_2CO_3), bicarbonate ion (HCO_3^-), and carbonate ion ($CO_3^=$).

CARBONATE SYSTEM

$CO_2 + H_2O \Leftrightarrow H_2CO_3$ $\qquad K_0$

$[H_2CO_3^*] = [CO_2] + [H_2CO_3]$

$H_2CO_3^* \Leftrightarrow HCO_3^- + H^+$ $\qquad K_1$

$HCO_3^- \Leftrightarrow CO_3^= + H^+$ $\qquad K_2$

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The carbonate system relates the different carbonate carbon species through a series of acid/base reactions. The first reaction is the hydration of aqueous carbon dioxide into carbonic acid. The equilibrium constant for this reaction is denoted here as K_O. Because it is very difficult to determine the difference between dissolved carbon dioxide and carbonic acid, the two species are often "lumped" together into the functional species H_2CO_3*. H_2CO_3* is simply known as dissolved CO_2. The second reaction is the acid/base reaction where carbon dioxide, H_2CO_3*, dissociates into bicarbonate ion, HCO_3^-, and a hydrogen ion, H^+. The equilibrium constant for this reaction is denoted here as K_1. The third reaction is the acid/base reaction where bicarbonate dissociates into carbonate ion, $CO_3^=$, and a hydrogen ion, H^+. The equilibrium constant for this reaction is denoted here as K_2.

CARBONATE SYSTEM

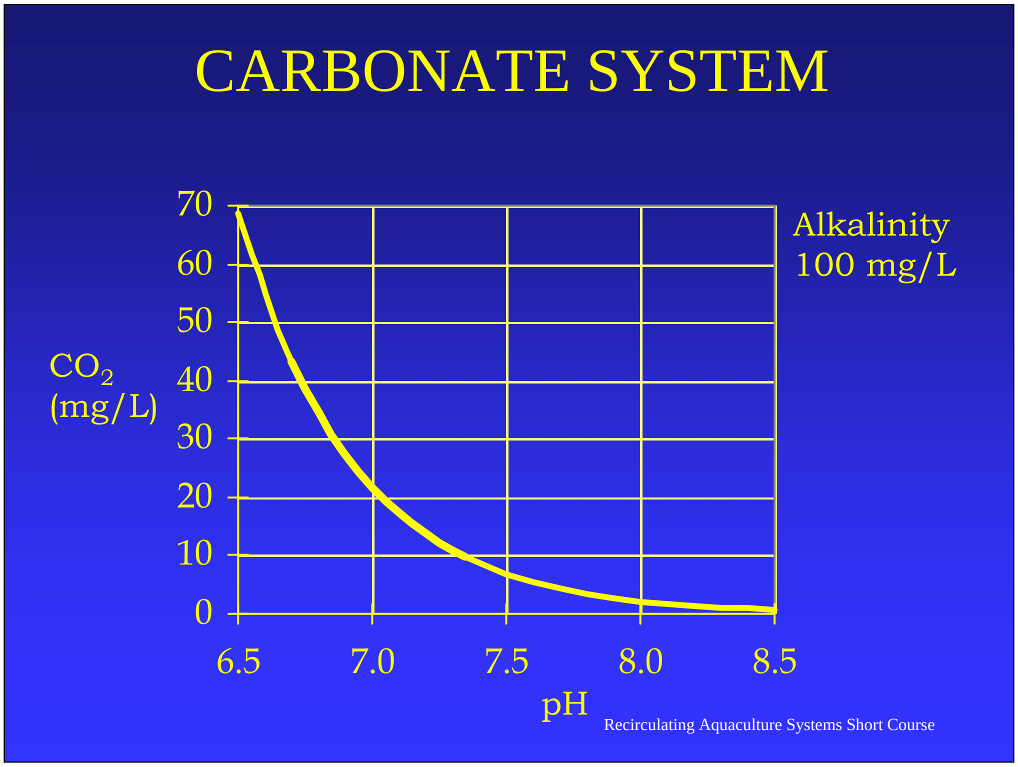
- Total Carbonate Carbon (mol/L)

$$C_T = [H_2CO_3^*] + [HCO_3^-] + [CO_3^=]$$

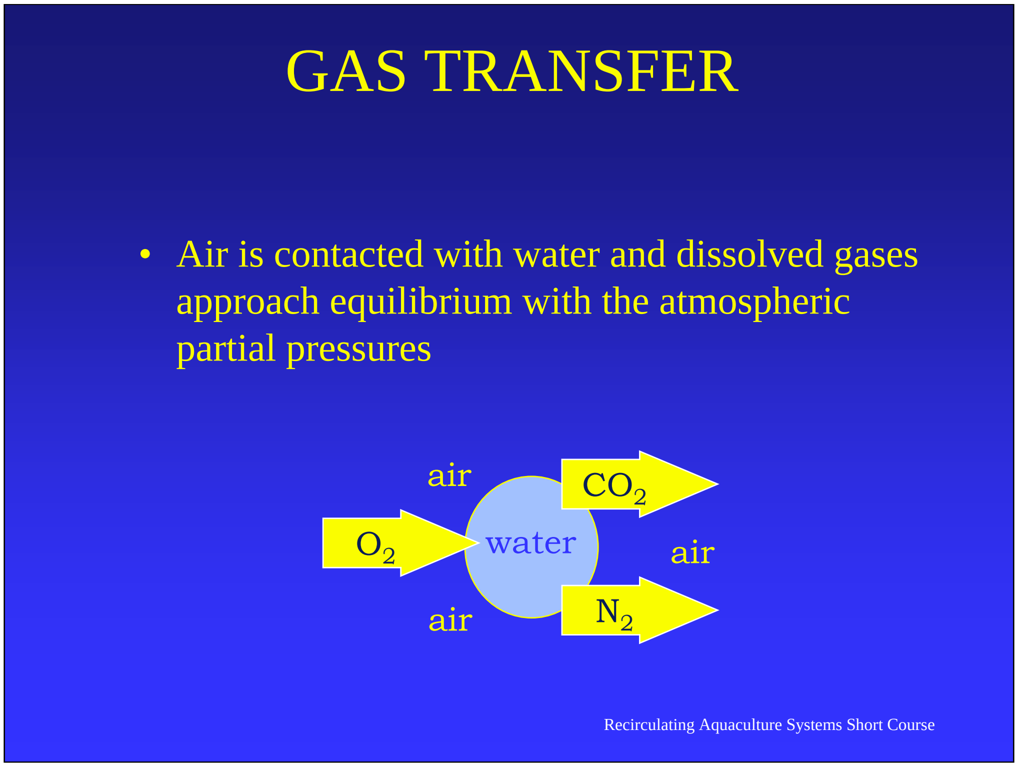
- Alkalinity (eqv/L)

$$Alk = [HCO_3^-] + 2[CO_3^=] + [OH^-] - [H^+]$$

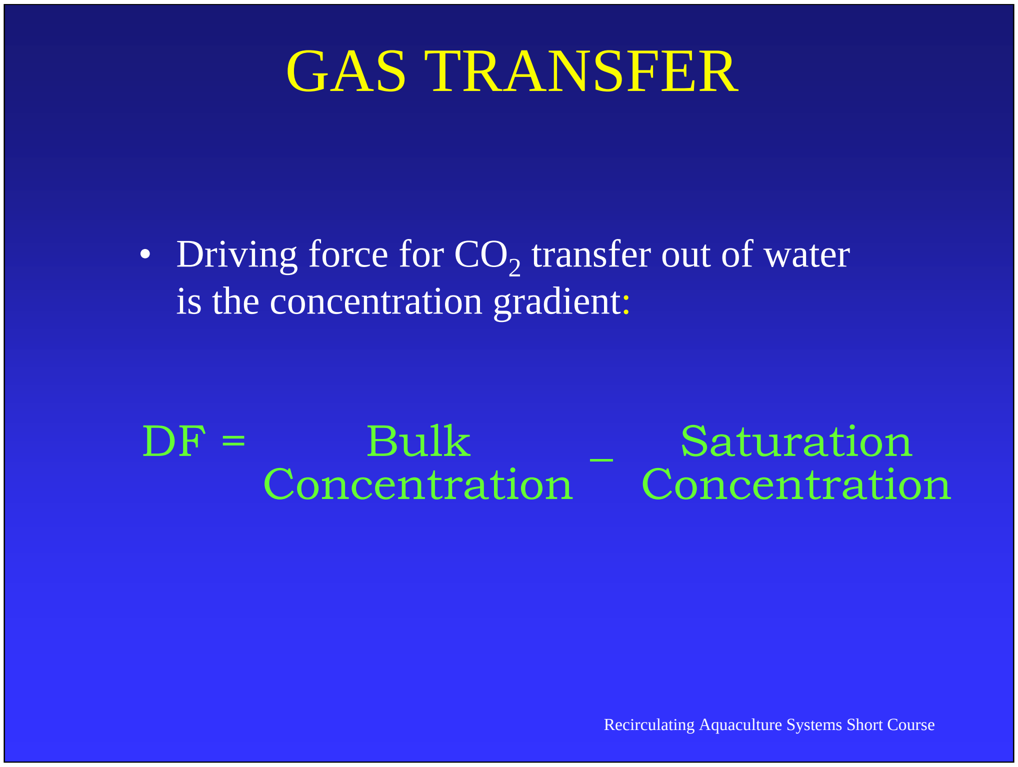
The carbonate system also has two important definitions: total carbonate carbon and alkalinity. The total carbonate carbon is the sum of all the inorganic carbon in the water expressed as moles of carbon per liter. Total carbonate carbon or C_T is the sum of carbon dioxide ($H_2CO_3^*$), plus bicarbonate (HCO_3^-), plus carbonate ($CO_3^=$), all individually expressed in moles per liter. The alkalinity of water is also known as the acid neutralizing capacity and is expressed in equivalents per liter. Alkalinity or Alk is the sum of bicarbonate (HCO_3^-), plus twice the carbonate ($CO_3^=$), plus hydroxyl ion (OH^-), minus hydrogen ion (H^+). Alkalinity is also commonly expressed in mg $CaCO_3$ per liter through the use of an equivalents conversion.



Just to give an example of how all this chemistry works together is this graph of dissolved carbon dioxide versus pH for a water with an alkalinity of 100 mg CaCO3 per liter. At lower pHs a larger proportion of the total carbonate carbon exists as CO2. But as the pH is increased less and less carbonate carbon exists as CO2, but shifts to bicarbonate. This is shown in the plot where at a pH of 6.5 the dissolved CO2 is approximately 70 mg/L, at a pH of 7.0 the dissolved CO2 is approximately 20 mg/L and at a pH of 8.0 the dissolved CO2 is approximately 3.0 mg/L. Please take note that this is for an alkalinity of 100 mg CaCO3/L. The same graph at a different alkalinity would have a similar shape but different values of CO2 at increasing pHs.



To shift gears a little lets move on to gas transfer. As air is contacted with water the dissolved gases approach equilibrium with atmospheric partial pressures. In this figure we’re trying to show that in a typical aquaculture water with low dissolved oxygen and high dissolved carbon dioxide and nitrogen that as water is exposed to atmospheric air the tendency to approach equilibrium will transfer oxygen in and carbon dioxide and nitrogen out of the water.



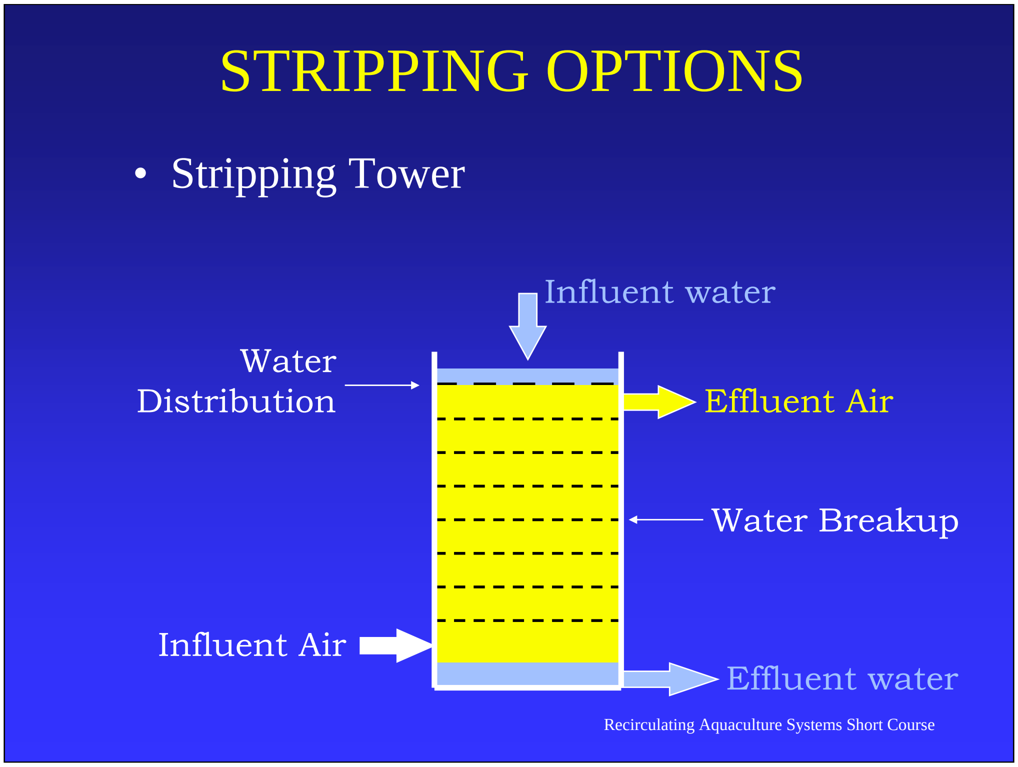
With this concept in mind, the driving force for CO_2 transfer out of water is the concentration gradient between the bulk dissolved CO_2 concentration and the saturation dissolved CO_2 concentration. Whenever possible you want to maximize this driving force and this can be accomplished by manipulating the saturation concentration with gas phase partial pressures. In the case of CO_2 you want to minimize the gas phase partial pressure for CO_2 removal.

GAS TRANSFER

- Dissolved Gas Solubility at 15^{o}C:

	Mole Fraction	Saturation (mg/L)	Mole Fraction	Saturation (mg/L)
CO_2	1	1,993	0.00035	0.69
N_2	1	21	0.78	16.4
O_2	1	48	0.21	10.1
Ar	1	66	0.0093	0.62

In a review of dissolved gas solubility, you can see the saturation concentration of the following gases in water. First, under pure environments of each gas we have the saturation concentrations. Then, at standard atmospheric conditions we have the saturation concentrations. The important point here is that CO_2 is much more soluble in water than nitrogen, oxygen, or argon.



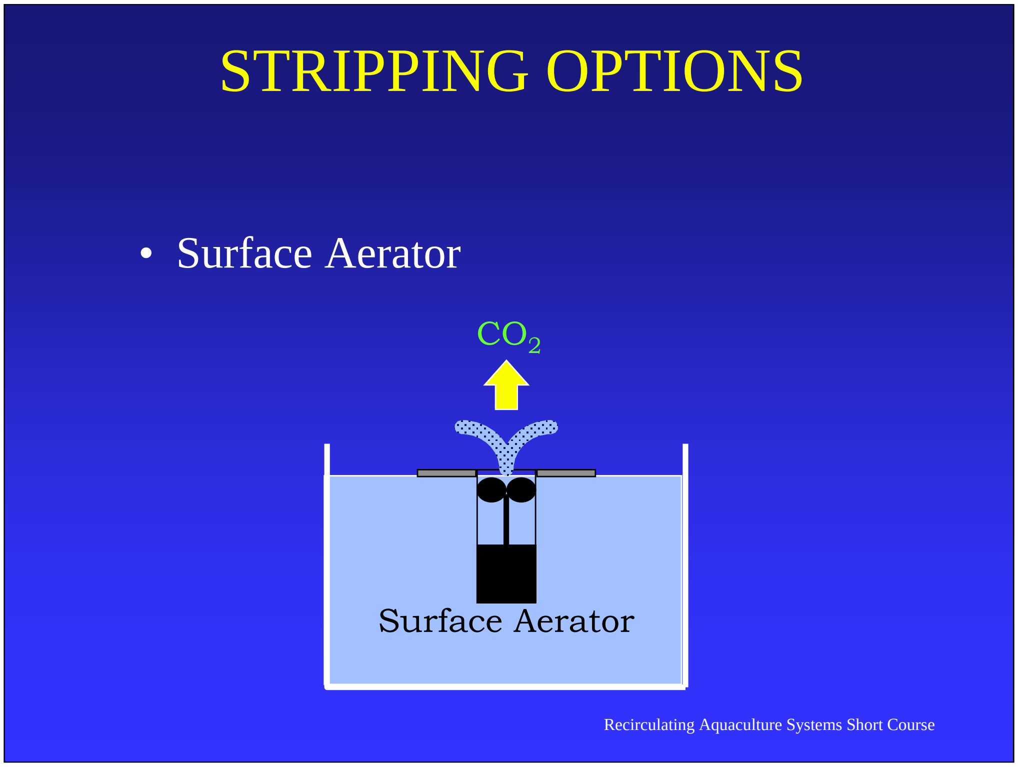
One of the most common ways to strip carbon dioxide out of the water is with a stripping tower. Here influent water from the culture tank with high CO_2 enters at the top of a tower and is distributed for uniform loading. The tower internals may have water breakup of some sort like plastic packing. As the water passes through the tower air is blown through the tower and it exits having picked up CO_2 from the water.

STRIPPING OPTIONS

- Stripping Tower Design Parameters:

	Low Range	High Range
Water Distribution	Drip Plate	Spray Nozzles
Hydraulic Loading	10 kg/m^2s	30 kg/m^2s
Water Breakup	Splash Screens	Random Packing
Tower Height	0.5 m	2 m
Volumetric G:L	1	20

Some of the basic parameters important in designing stripping towers are water distribution, hydraulic loading, water breakup, tower or packing height, and volumetric gas to liquid flowrate ratio. In the low range of distribution it is common to have just a flooded drip plate through which water flows. On the high end one could have spray nozzles that assure a very uniform water distribution. In the low range of hydraulic loading we have 10 kg of water per square meter of tower cross section per second. On the high end of hydraulic loading we have 30 kg/m^2-sec. For water breakup on the low end it is common to have splash screens or plates that breakup the water in big chunks and on the high end you would have random plastic packing that breaks up the water flow really well. Stripping tower height or height of the packing/water breakup can range from 0.5 m to 2 m. Finally, the volumetric gas:liquid ratio, which is the ratio of the air flowrate blown through the tower to the water flowrate through the tower ranges from 1 to 20.



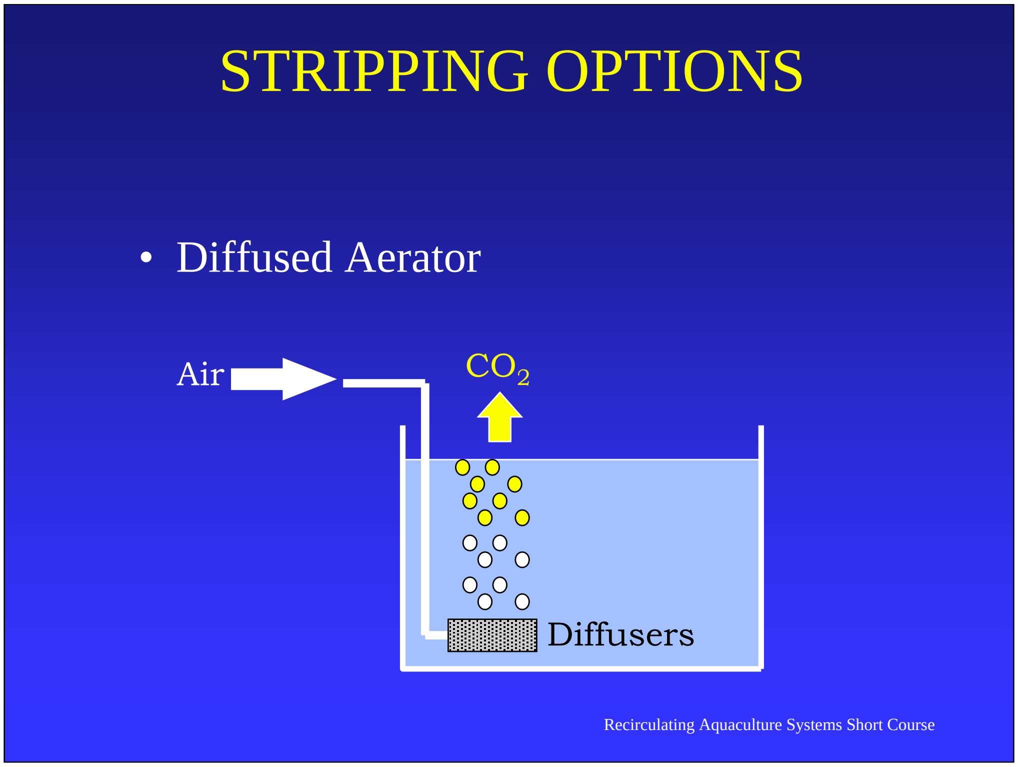
Another way to strip carbon dioxide in aquaculture operations is the surface aerator. Here a motor has a shaft attached to a propeller-type blade, all of which is suspended by a float on the surface of the water. The propeller churns up the water pumping it out through the top of the aerator. Commonly these are used as de-icers in marinas. However, they have applications in aquacultural carbon dioxide stripping as well and a few years back Mike Timmons had a student study the design and operation of this alternate stripping strategy in the lab in cooperation with a commercial partner.

STRIPPING OPTIONS

- Surface Aerator Design Parameters:

	Low Range	High Range
SAE	1.0 kg/kWh	3.0 kg/kWh
Motor Size	0.5 HP	2 HP
Spray Pattern	Boil	Fountain
Spray Height	0.5 m	2 m
Spray Diameter	1 m	4 m

Some of the basic design parameters important in designing/operating surface aerators are standard aeration efficiency (SAE), motor size, spray pattern, spray height and spray diameter. The low range for SAE would be 1 kg oxygen transferred per kilowatt hour and the high range would be 3 kg/kWh. SAE rates the entire aerator transfer efficiency and the values in the table do not correspond to each listed SAE. Aerators often have motors ranging from 0.5 to 2 horsepower. The spray pattern which may be a very important consideration from recent research can be just a foaming boil to a straight vertical fountain. Spray heights in the boil pattern may be as low as 0.5 m high and 1 m wide. Spray heights in the fountain pattern may be as high as 2 m and 4 m wide.



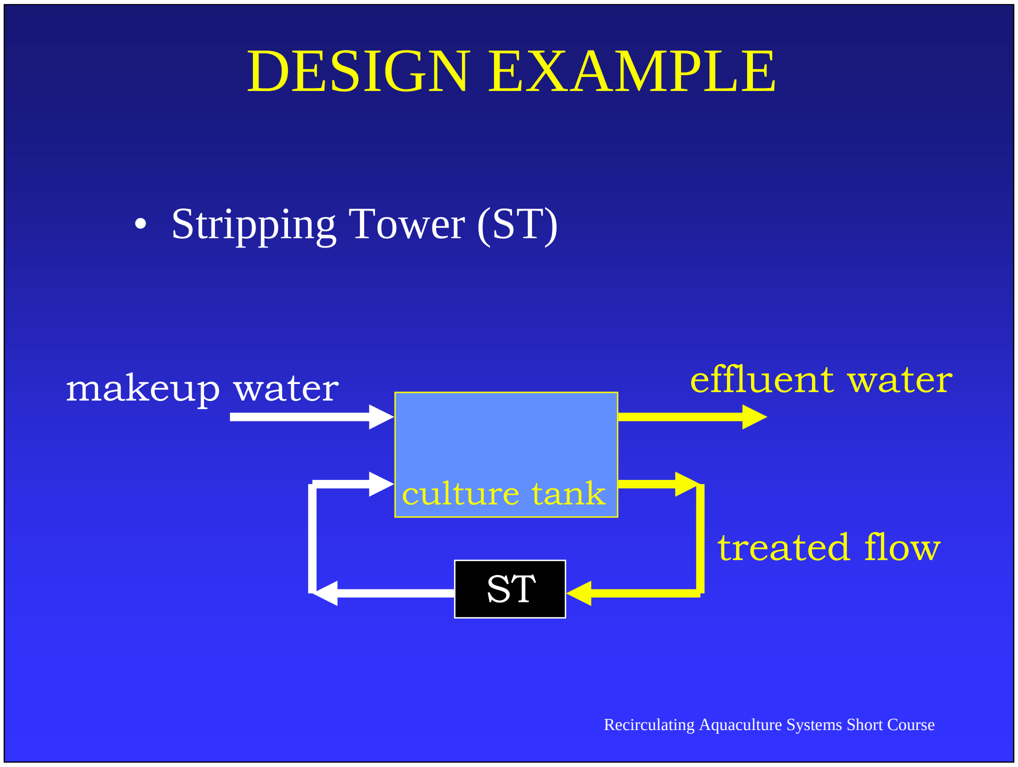
Another way to strip carbon dioxide in aquaculture operations is with diffused aerators. Here a blower or compressor is used to provide air flow to porous diffusers which deliver air bubbles through the water column. Commonly these are used as a way to add oxygen to water. However, in the stripping application they pick up CO_2 from the water column and vent it from the water as the bubbles reach the water surface.

STRIPPING OPTIONS

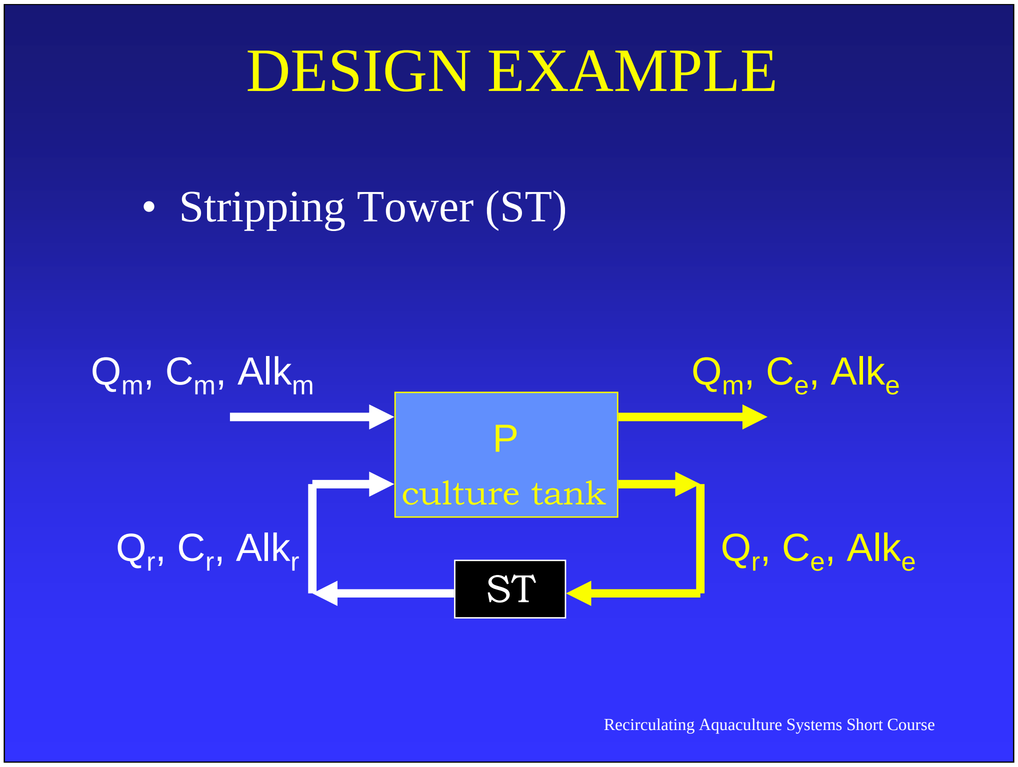
- Diffused Aerator Design Parameters:

	Low Range	High Range
SAE	0.5 kg/kWh	2.0 kg/kWh
Motor Size	0.25 HP	3 HP
Diffuser Depth	0.25 m	2 m
Bubbles	Fine	Coarse

Some of the basic parameters important in designing/operating diffused aerators are standard aeration efficiency (SAE), blower/compressor motor size, diffuser depth, and bubble type. The low range for SAE would be 0.5 kg oxygen transferred per kilowatt hour and the high range would be 2.0 kg/kWh. SAE rates the entire blower/diffuser package transfer efficiency and the values in the table do not correspond to each listed SAE. Diffused aerator packages often have motors ranging from 0.25 to 3 horsepower. The diffuser depths range from 0.25 m to 2 m and the bubble types go from fine, small bubbles to large, coarse bubbles.



Now using the stripping tower (ST) as the CO_2 stripping device let's go through a design example. We'll use the basic recirculating aquaculture flow-pattern with makeup water and treated water flow entering the culture tank, and effluent water both leaving the culture system and being directed through a series of unit processes for treatment.



Assigning some variables to define the system yields: Q_m for makeup flow, C_m for concentration of the constituent of interest in the makeup water, and ALK_m for alkalinity of the makeup water. On the effluent side we have the same Q_m for water flow wasted, C_e for effluent water concentration, and ALK_e for alkalinity of the effluent water. The treated flow will have a flowrate Q_r, and the same effluent C_e and ALK_e go through the treatment system. On the post treatment side we will again have Q_r, and now C_r for concentration in the treated flow and ALK_r for alkalinity of the treated flow. We will also assign a P term in the culture tank due to the fish. This set of notation may be used for a variety of constituents including oxygen, nitrogen, and solids; but here we will use the generic C for concentration of dissolved carbon dioxide and P as the production of carbon dioxide.

DESIGN EXAMPLE

- Culture Tank
  - Volume = 50,000 L
  - Q_m = 10% of the volume per day
  - Feed = 100 kg per day

Some important parameters for this example are that the culture tank is 50,000 liters or approximately 15,000 gallons. The makeup water flow, Q_m, is set to 10% of the volume per day and the feed fed to the fish is 100 kg per day. This approximates single tank RAS conditions at a commercial tilapia grower in NY.

DESIGN EXAMPLE

- Culture Tank Water Quality

  CO_2 = 40 mg/L

  Alkalinity = 100 mg/L

- Makeup Water Quality

  Q_m = 3.5 Lpm

  CO_2 = 5 mg/L

  Alkalinity = 100 mg/L

Also, we need to set some water quality parameters for the design of the CO_2 stripping tower. In this example we'll pick a culture tank dissolved CO_2 level of 40 mg/L and an alkalinity of 100 mg $CaCO_3$/L. The makeup water flow was set by the 10% volume exchange per day which converts to 3.5 liters per minute. The makeup water dissolved CO_2 will be set at 5 mg/L and the alkalinity as 100 mg $CaCO_3$/L.

DESIGN EXAMPLE

- CO_2 Mass Balance:

IN + PRODUCED = OUT + STRIPPED

$$Q_mC_m + P = Q_mC_e + Q_r(C_e – C_r)$$

$$Q_r = \{Q_m(C_m – C_e) + P\}/(C_e – C_r)$$

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After identifying the tank water quality the next thing we need to do is a steady-state mass balance for dissolved carbon dioxide on the culture tank. Doing that we have to account for the CO_2 that flows into the tank from the makeup water plus whatever CO_2 is produced by the fish being set equal to the CO_2 that flows out of the tank in the wasted effluent plus the CO_2 that is stripped from the stripping tower. Using the notation from before the CO_2 into the tank from the makeup water is Q_mC_m, the CO_2 produced by the fish is P, the CO_2 that flows out in the effluent is Q_mC_e, and the CO_2 that is stripped is Q_r times the change in CO_2 across the stripper, C_e - C_r. Solving the mass balance for Q_r will allow us to design the stripping tower later on in the example.

DESIGN EXAMPLE

- CO_2 Produced:

$$P = (F)(OCR)(CPR)$$

$$P = (100\ kg/day)(0.4)(1.38)$$

$$P = 55.2\ kg\ CO_2/day$$

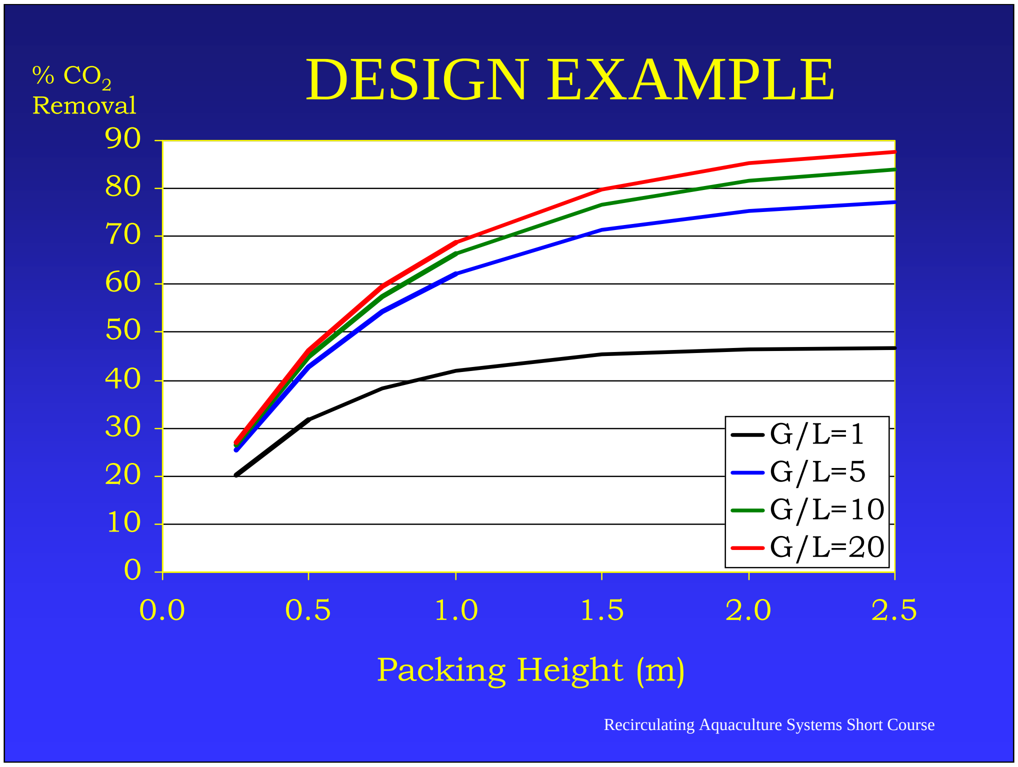
$$P = 38{,}333\ mg\ CO_2/min$$

The first item we will fill in for the mass balance is the CO_2 produced by the fish, P. We know the feeding rate F (100 kg/day), but now we need to know the oxygen consumed by the fish or oxygen consumption rate, OCR. This is a value that ranges from 0.25 to 0.5 kg of oxygen consumed per kg feed fed. For this example we'll select a value of 0.4. Finally we can use the mass basis CO_2 production rate, CPR, from earlier in the presentation of 1.38. Doing the math gives us 55.2 kg CO_2 produced per day. Converting this to mg/minute gives 38,333 mg CO_2 produced per minute.

DESIGN EXAMPLE

- Stripping Tower:
  - Hydraulic Loading = 20 kg/m^{2}s
  - 5.1 cm NORPAC Packing
  - Influent Stripping Gas CO_2 = 1,000 ppm
  - Influent CO_2 = 40 mg/L
  - Influent Alkalinity = 100 mg/L

Next we can look at the stripping tower design more closely. We first need a hydraulic loading and a packing type. In this example I selected a middle value for hydraulic loading of 20 kg/m2-sec and a commonly used commercial packing, 5.1 cm NORPAC plastic packing. We also need to set the CO_2 in the gas phase of the gas used for stripping in the tower. I selected 1,000 ppm CO_2 in this example but I'll come back to this issue later on. Also, recall that the CO_2 that leaves the tank and travels in the treatment loop will be the CO_2 in the tank, earlier we said that would be 40 mg/L and the same for alkalinity at 100 mg/L.



This graph will help us design our stripping tower. This is a plot of percent CO_2 removal versus tower/packing height for 4 gas to liquid ratios for our set parameters of 20 kg/m2-sec hydraulic loading, 5.1 cm NORPAC packing, 1,000 ppm CO_2 in the stripping gas, 40 mg/L influent CO_2 and 100 mg/L influent alkalinity. The plot shows that with increasing tower height the percent CO_2 removal increases. Also, with increasing G:L the percent CO_2 removed increases for the same packing height. What's interesting to note is that after about 1 m in height the removal rates start to flatten and we get into a diminishing returns situation. For our specific example let's select a packing height of 1 m and a G:L of 10. Following the curve on the graph and reading off the removal rate gives us about 66% CO_2 removal.

DESIGN EXAMPLE

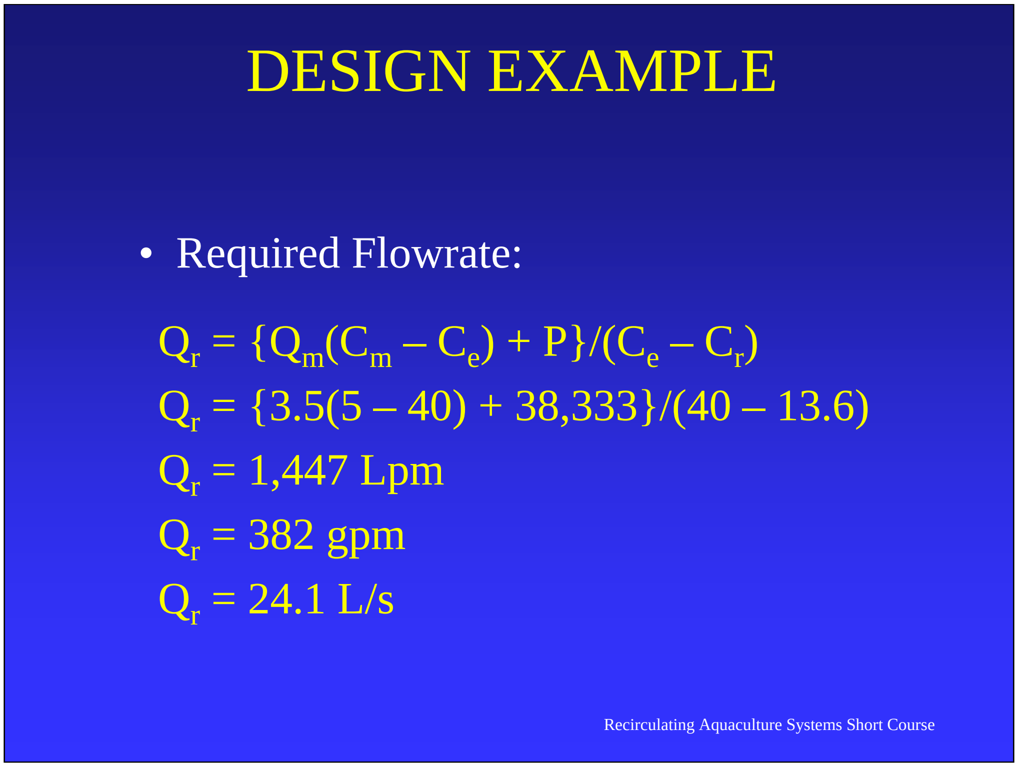
- Height = 1 m
- G:L = 10
- Removal Efficiency = 66%
- Effluent CO_2 from Stripper:

$$C_r = C_e(1 – \text{efficiency})$$

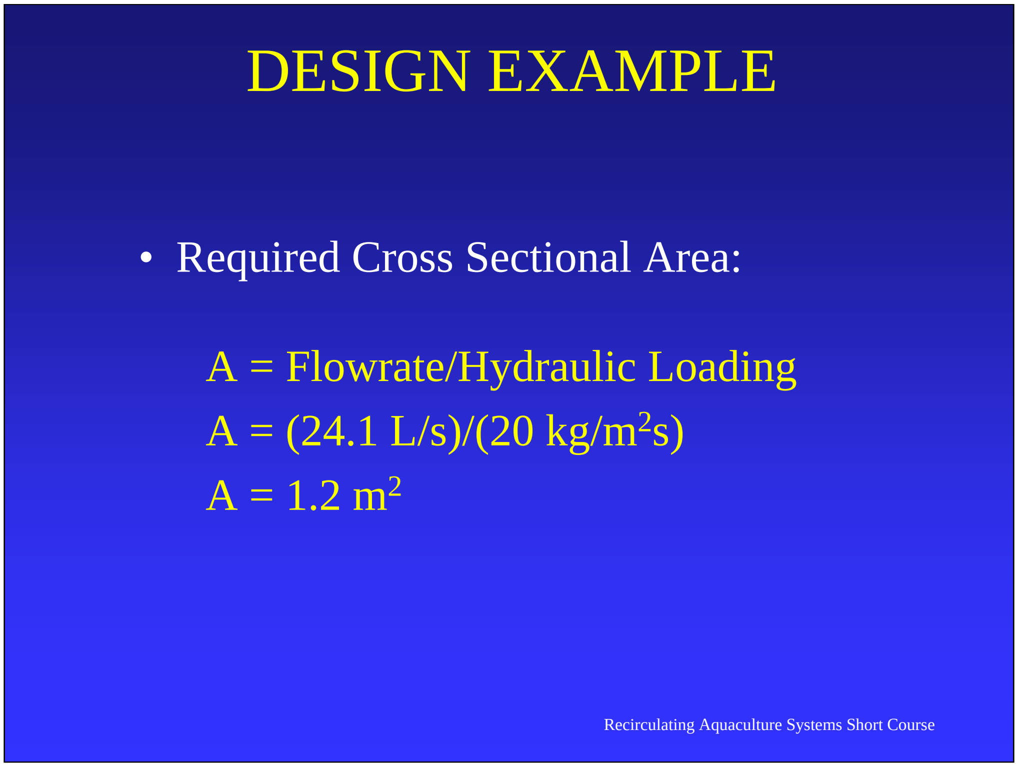
$$C_r = 40(1 – 0.66)$$

$$C_r = 13.6 \text{ mg/L}$$

So with our stripper at 1 m in height and a gas to liquid ratio of 10 we have a removal efficiency of 66%. To calculate the effluent CO_2 from the stripper we can use the following equation: treated flow CO_2, C_r, is equal to the tank CO_2, C_e times 1 minus the removal efficiency. Substituting the numbers: 40 times 1 minus 0.66 gives a C_r of 13.6 mg/L.



Now we can use the mass balance on CO_2 that gave us the equation for the required flowrate in the treatment loop. Substituting the numbers in: Q_r of 3.5 liters per minute, C_m of 5 mg/L, C_e of 40 mg/L, the production P of 38,333 mg/min, and the treated flow CO_2, C_r, of 13.6 mg/L. Doing the math gives us a Q_r of 1,447 liters per minute rounded to the nearest liter per minute. Converting this flow to gallons per minute rounded to the nearest gallon per minute gives 382 gallons per minute. Converting to liters per second gives 24.1 liters per second.



Now we have the critical design parameters for our stripping tower including height of packing, hydraulic loading and flowrate, but we don’t have how big in cross-sectional area the tower needs to be. To determine the required cross-sectional area we take the required flowrate and divide by the set hydraulic loading and incorporating the density of water. For our tower: the flowrate of 24.1 liters per second divided by the hydraulic loading of 20 kg/m^2-sec and using a water density of 1 kg/L gives the required cross-sectional area of the tower to be 1.2 m^2 to the nearest tenth of a square meter.

DESIGN EXAMPLE

- Stripping Column Parameters:

Tower Height	1 m
Cross Sectional Area	1.2 m^2
Hydraulic Loading	20 kg/m^2s
Water flow	1,447 Lpm
Water Breakup	5.1 cm NORPAC
G:L	10
Air flow	14,470 Lpm

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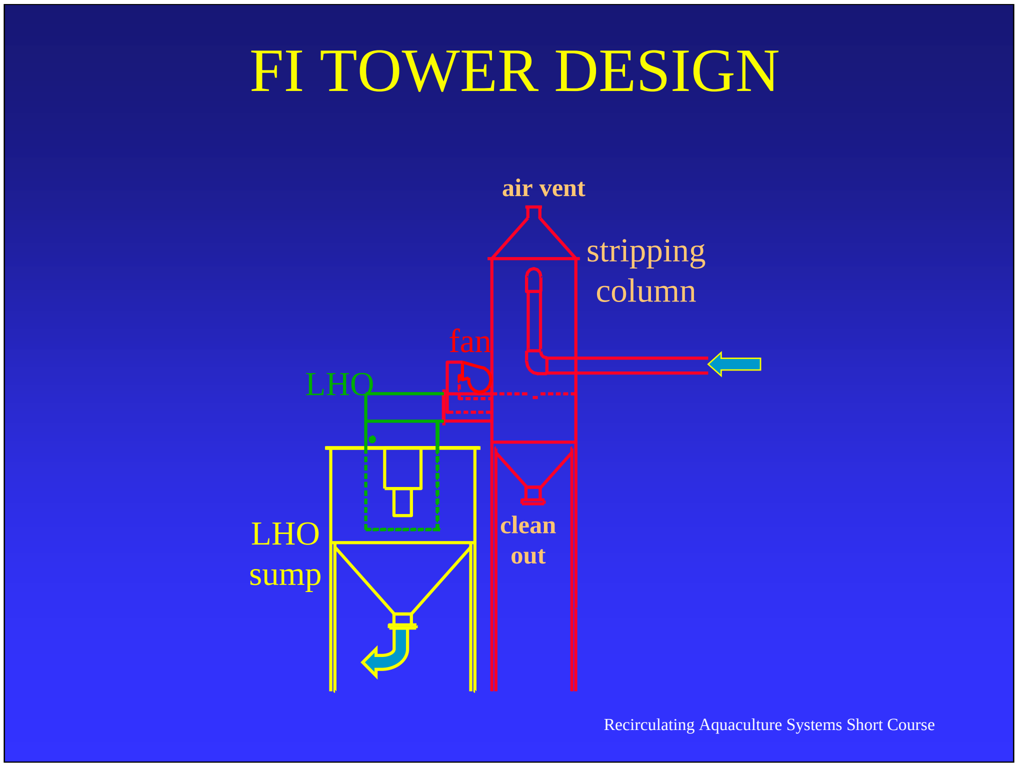
In summary the design of our stripping tower is as follows: The packing height is 1 m, the cross sectional area is 1.2 m^2, the hydraulic loading is 20 kg/m^2-sec, the water flow is 1,447 liters per minute, the water breakup is 5.1 cm NORPAC plastic packing, the gas to liquid ratio is 10 and the air flowrate through the tower is 14,470 liters per minute.



What does a CO_2 stripping tower like the one identified in the example look like? Well there is a very similar tower in use at the Freshwater Institute partial water reuse system. A schematic is shown here – water with high CO_2 enters the top through a spray nozzle and flows through 1 m of NORPAC plastic packing arranged vertically (not randomly packed). The fan provides the required airflow to move stripped CO_2 out of the tower to the air vent. After the water is stripped of CO_2 it flows to a low head oxygenator for pure oxygen addition and then flows to the culture tanks.

FI TOWER DESIGN

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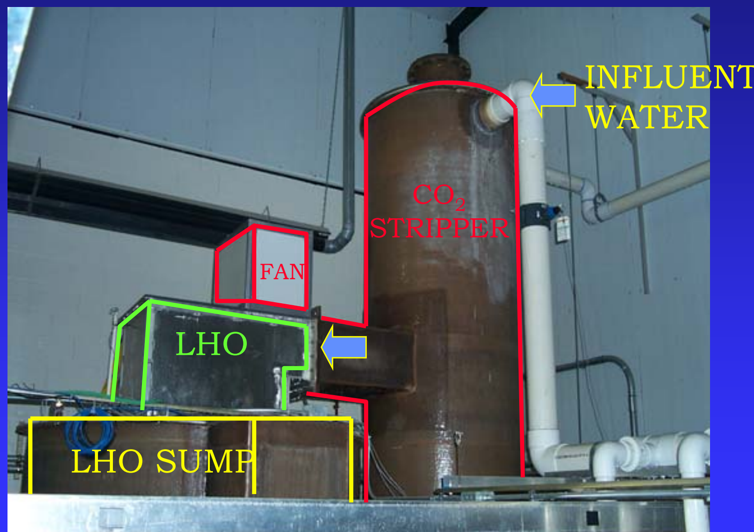
This is a picture of the tower which is constructed of fiberglass.

FI TOWER DESIGN



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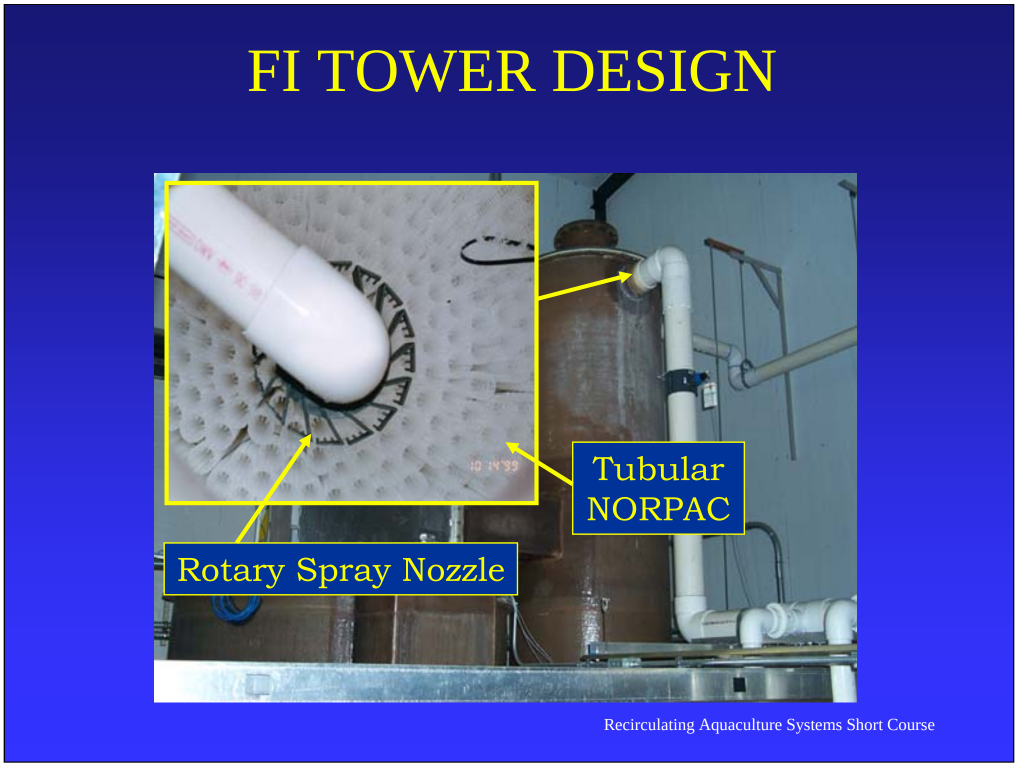
Outlining the components shows us that influent water is pumped in the top of the tower. The fan sits outside of the tower and provides air flow from the bottom to the top. The CO2 stripped water flows from the tower to a LHO and then into the LHO sump.



The water is distributed at the tower top with a rotary spray nozzle over the NORPAC packing which is arranged vertically. This vertical placement provides a continuous void space the length of the tower to avert any plugging due to solids or particulates.

The high air flow rates required are provided by a low pressure, high volume blower outside the tower. These are relatively low horsepower units that do an excellent job in CO_2 stripping tower applications.

DESIGN EXAMPLE

- Carbonate Carbon (C_T) Mass Balance:

IN + PRODUCED = OUT + STRIPPED

$$Q_m C_m + P = Q_m C_e + Q_r (C_e - C_r)$$

$$Q_r = \{Q_m (C_m - C_e) + P\}/(C_e - C_r)$$

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The second method for doing the example is to use a carbonate carbon mass balance. We will use the exact same mass balance equation, but we'll use it on carbonate carbon (C_T).

DESIGN EXAMPLE

- Carbonate Carbon (C_T) Produced:

  P = (F)(OCR)(CPR)

  P = (100 kg/day)(0.4)(1.38)

  P = 55.2 kg CO_2/day

  P = 38,333 mg CO_2/min

  P = 0.871212 mol C_T/min

The fish produce carbonate carbon when they produce carbon dioxide so we use the exact same relationship and numbers for P that we used before and we convert to carbonate carbon at the end. The 38,333 mg CO_2 per minute converts to 0.871212 moles C_T per minute using gram molecular weight relationships.

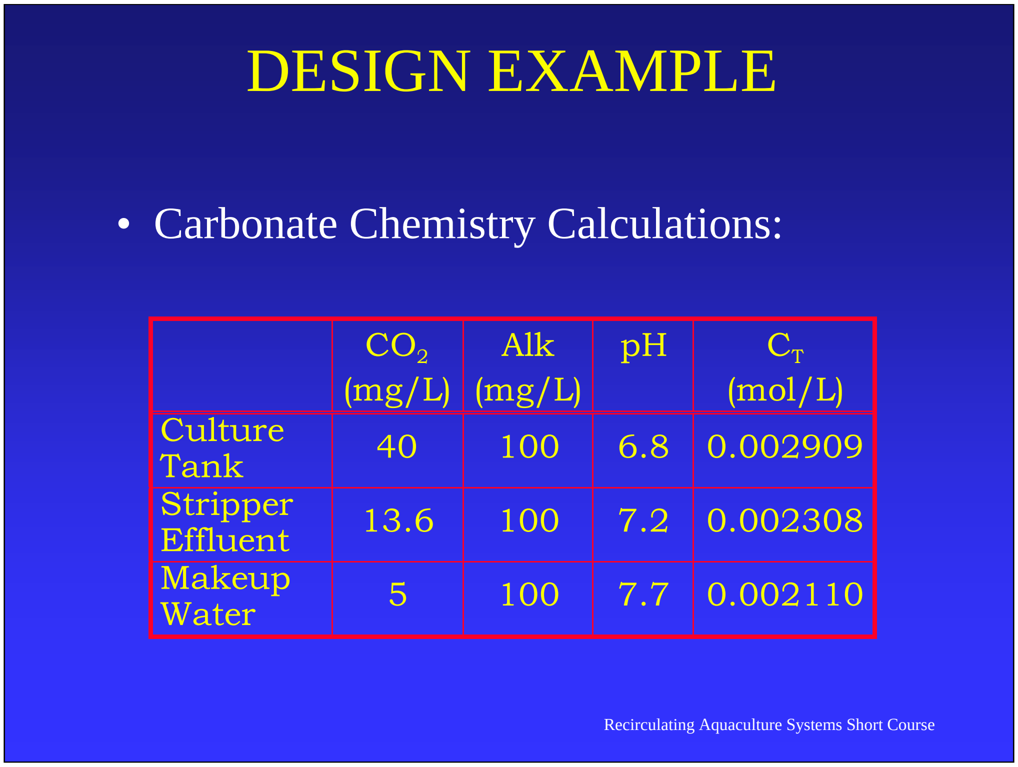
DESIGN EXAMPLE

$$[H_2CO_3^*] = \frac{1}{\frac{K_1}{[H^+]} + \frac{2K_1K_2}{[H^+]^2}}\left(Alk - \frac{K_w}{[H^+]} + [H^+]\right)$$

$$C_T = \frac{Alk - \frac{K_w}{[H^+]} + [H^+]}{\frac{1}{1 + \frac{[H^+]}{K_1} + \frac{K_2}{[H^+]}} + \frac{2}{1 + \frac{[H^+]}{K_2} + \frac{[H^+]^2}{K_1K_2}}}$$

Recirculating Aquaculture Systems Short Course

Now here is the real difference in the two approaches – when using the mass balance on carbonate carbon you have to use the carbonate system chemistry equations. These can be pretty complex equations. In this example I used two relationships, the first one for determining the pH of a water given its CO_2 or H_2CO_3* and its alkalinity; the second one for determining the carbonate carbon (C_T) of water given its pH and alkalinity. Part of what makes these calculations time consuming is that in this case the first equation must be solved by trial and error iteratively. There are no easy mathematical recipes for explicitly solving for pH.



	CO_2 (mg/L)	Alk (mg/L)	pH	C_T (mol/L)
Culture Tank	40	100	6.8	0.002909
Stripper Effluent	13.6	100	7.2	0.002308
Makeup Water	5	100	7.7	0.002110

Performing these calculations on the three waters gives the following results: for the culture tank water, C_e, which is also the influent to the CO_2 stripper we had set it to 40 mg/L CO_2 and 100 mg/L alkalinity - this gives a pH of 6.8 and a C_T of 0.002909 moles per liter. For the stripper effluent water, C_r, which is the treated flow concentration, we had an effluent of 13.6 mg/L CO_2 and we have to conserve alkalinity to know that its alkalinity is 100 mg/L – this gives a pH of 7.2 and a C_T of 0.002308 moles per liter. When I say conserve alkalinity I mean that no alkalinity is lost or gained across a device that only removes CO_2. This is so because alkalinity is not a function of CO_2. Finally, the makeup water, C_m, had a CO_2 of 5 mg/L and 100 mg/L alkalinity – this gives a pH of 7.7 and a C_T of 0.002110 moles per liter.

DESIGN EXAMPLE

- Required Flowrate:

$$Q_r = \{Q_m(C_m - C_e) + P\}/(C_e - C_r)$$

$$Q_r = \{3.5(0.002110 - 0.002909) + 0.871212\}/(0.002909 - 0.002308)$$

$$Q_r = 1{,}445 \text{ Lpm}$$

$$Q_r = 382 \text{ gpm}$$

$$Q_r = 24.1 \text{ L/s}$$

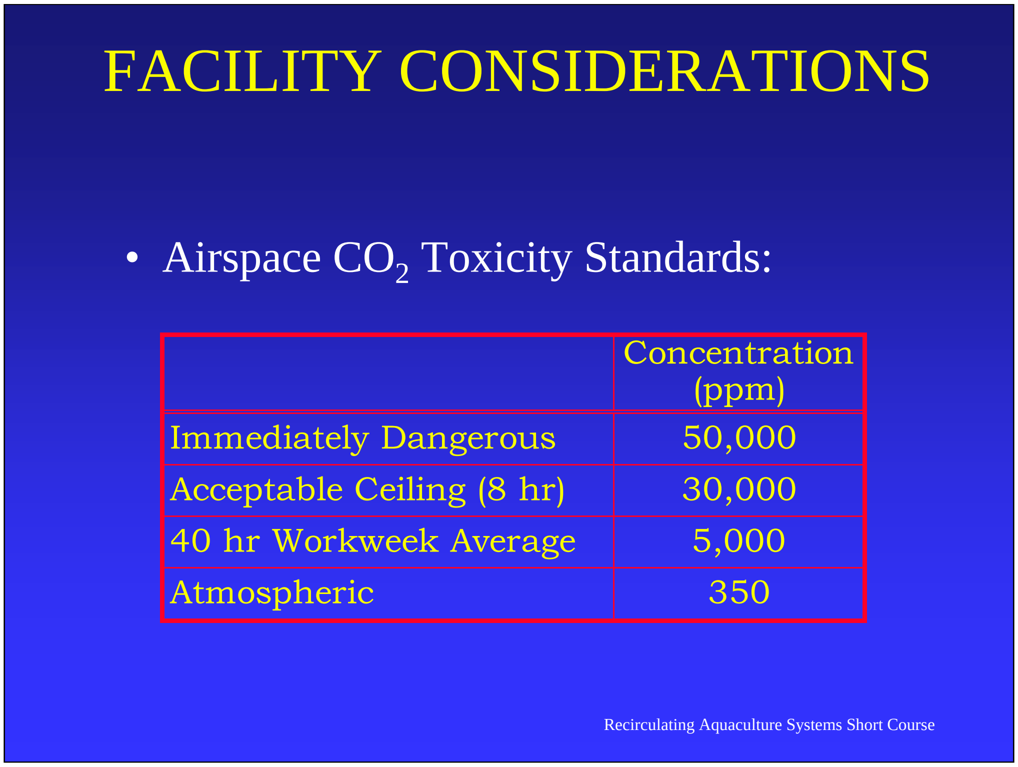
Now we can use the mass balance on C_T that gave us the equation for the required flowrate in the treatment loop. Substituting the numbers in: Q_m of 3.5 liters per minute, C_m of 0.002110 mol/L, C_e of 0.002909 mol/L, the production P of 0.871212 mol/minute, and the treated flow CO_2, C_r, of 0.002308 mol/L. Doing the math gives us a Q_r of 1445 liters per minute rounded to the nearest liter per minute. Converting this flow to gallons per minute rounded to the nearest gallon per minute gives 382 gallons per minute and converting to liters per second gives 24.1 liters per second.

DESIGN EXAMPLE

- Difference Between Methods:

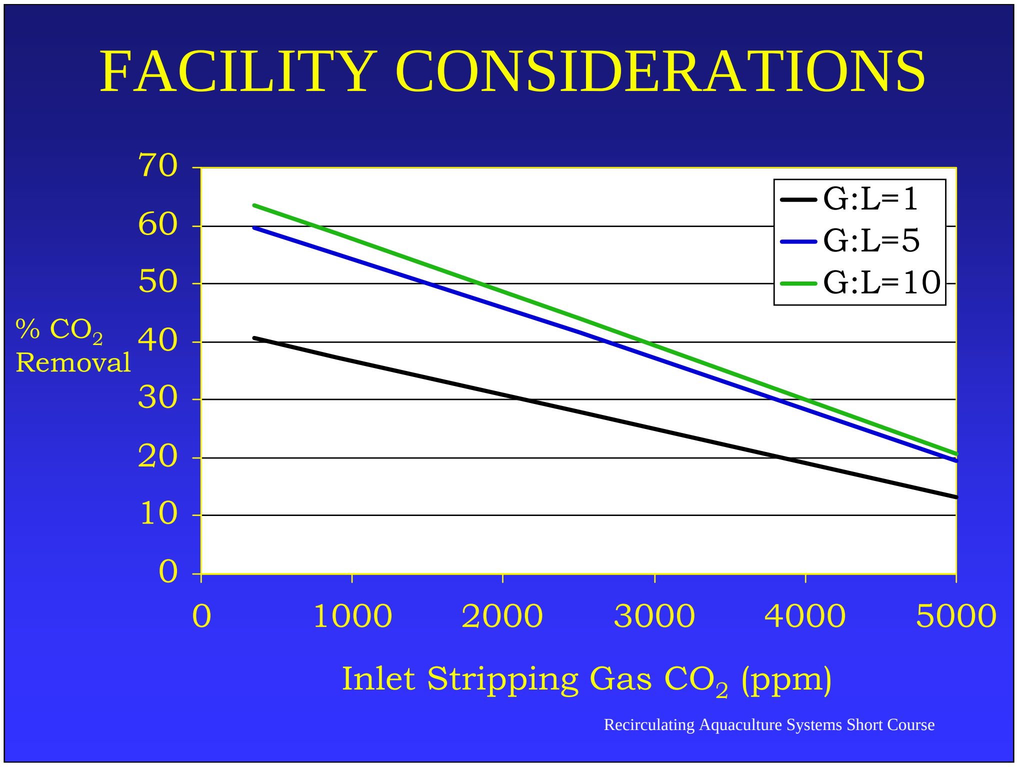
Method	Required Flowrate			Area
	Lpm	gpm	L/s	(m^2)
CO_2	1447	382	24.1	1.2
C_T	1445	382	24.1	1.2

We can compare the two methods and see that in this specific example the results are very close and using the same rounding they will result in almost the exact same design. But why do both methods and show the difference? It is acknowledged that the most correct way to design for CO_2 stripping is to use carbonate carbon mass balances and equations. However, because of the chemistry and complex equations many are put off by this approach. What we wanted to show was that in a typical situation just using a mass balance on CO_2 will use simple math and give a result within 0.2% of the correct answer. It will also be a conservative estimate, although increasing alkalinity will increase the error. It is also important to note that the computer model that allowed us to determine a treated effluent CO_2 concentration is based upon carbonate carbon mass balances and calculations and that is a factor in this comparison.

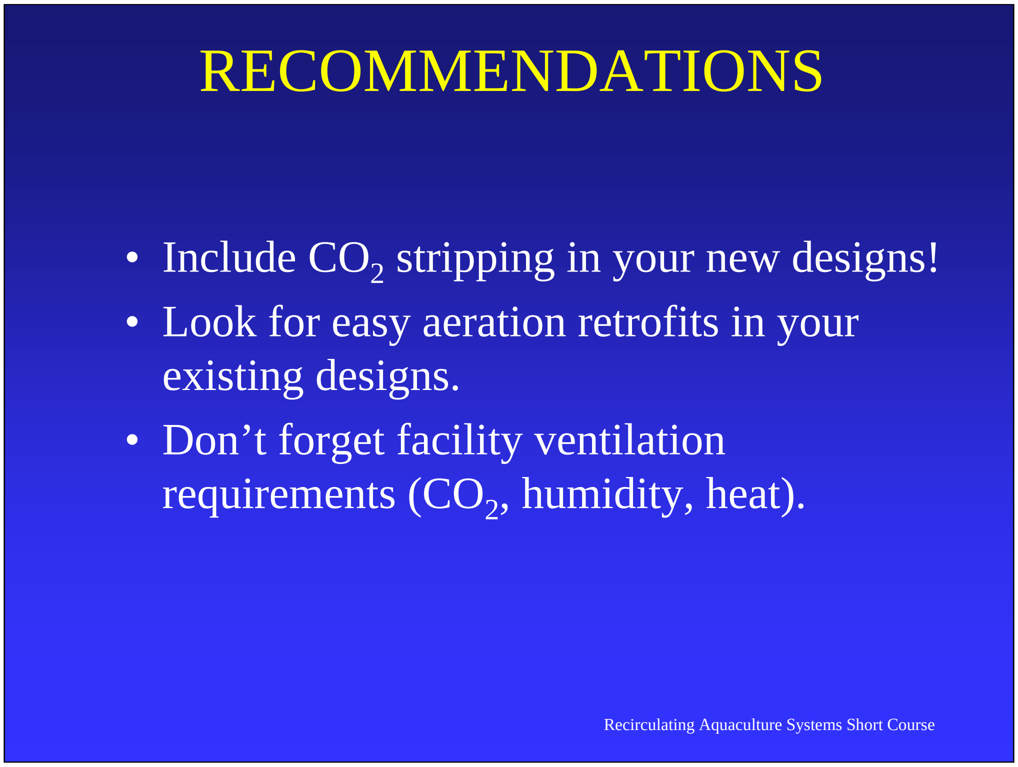


	Concentration (ppm)
Immediately Dangerous	50,000
Acceptable Ceiling (8 hr)	30,000
40 hr Workweek Average	5,000
Atmospheric	350

As aquaculture engineers we often focus on the engineering unit processes like CO_2 stripping but we must also consider the impacts such unit processes can have on the environment in which they operate. As CO_2 is removed from these systems it will end up in the surrounding air if not directly vented. This can cause unique problems for indoor aquaculture operations including high levels of CO_2 in the facility airspace which can be a hazard to the people in the building. This table summarizes the toxicity standards for carbon dioxide in the gas phase. Immediately dangerous to life and health is 50,000 ppm. The acceptable ceiling concentration in an 8 hour period is 30,000 ppm. The OSHA standard for a 40 hour workweek average is 5,000 ppm and atmospheric is 350 ppm.



However, while those managers here may see the OSHA standard is 5,000 ppm and decide to use that in the ventilation design – they must also consider other factors. There is a tradeoff between the inlet stripping gas CO_2 and the percent CO_2 removal as shown in this plot. This is for a 1 m tall stripping tower with an alkalinity around 200 mg/L and an influent CO_2 around 14 mg/L. As the stripping gas CO_2 ppm increases the percent CO_2 removal decreases. So while a CO_2 of 1,000 ppm gives a removal of 60% for a G:L of 10, the higher CO_2 of 5,000 ppm only gives a removal of 20%.

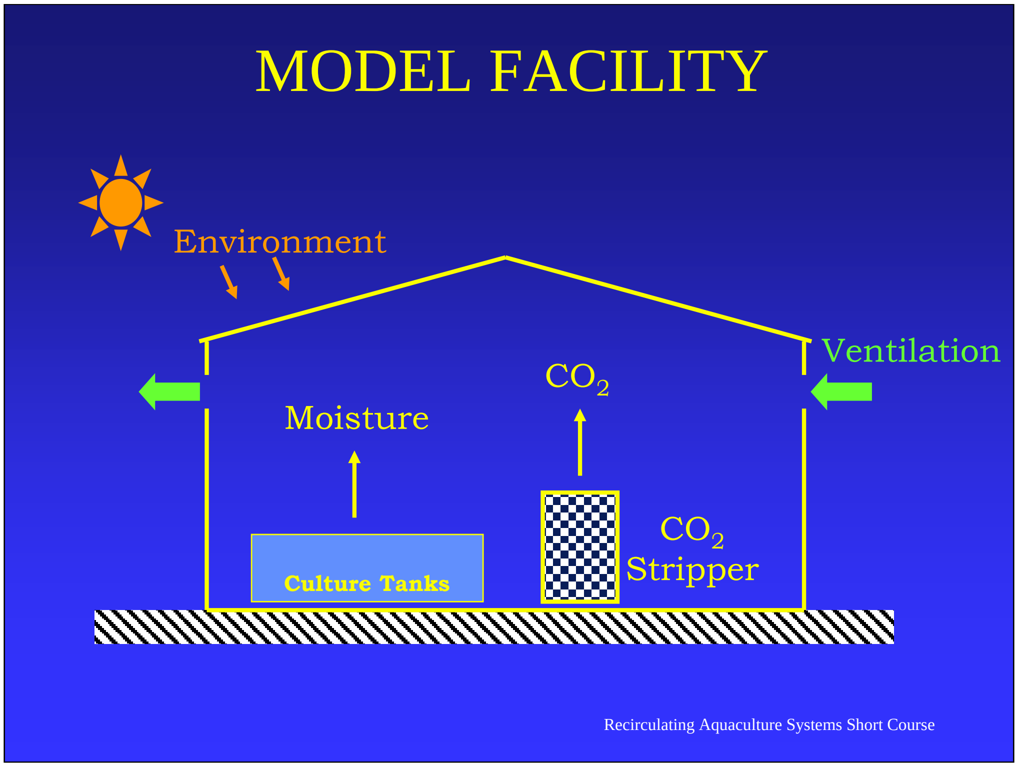


Some summary observations – include CO_2 stripping in your new designs - just about everyone is now talking about including CO_2 removal in their facilities. And if you think you may be having CO_2 problems look for easy aeration retrofits in your existing designs. Often there are some very simple things you can do including surface aerators and side-stream spray columns. Finally, don't forget facility ventilation requirements in indoor facilities. CO_2 problems can creep up on workers giving them headaches and vague symptoms.

COMPUTER DESIGN MODEL

- Vinci, B. J., Timmons, M. B., Summerfelt, S. T., & Watten, B. J. (1998). Carbon Dioxide Control in Intensive Aquaculture (Version 2.1) [Computer software]. Ithaca, NY: Natural Resource, Agriculture, and Engineering Service.

The CO_2 computer design tool used in this work was developed by myself, Mike Timmons, Steve Summerfelt and Barnaby Watten. It is currently available as part of this shortcourse or through NRAES at Cornell University. The next part of this presentation will cover the model in more detail so that you will be able to see what it can do for you during design or evaluation of an intensive aquaculture production facility.

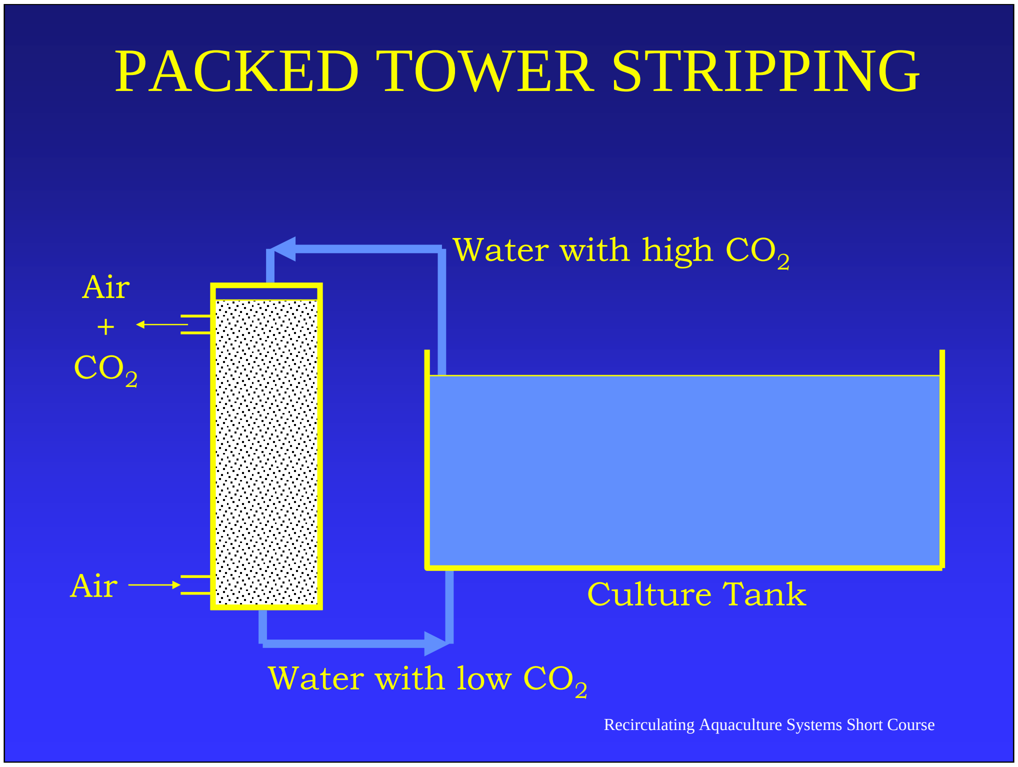


The model facility employed in the computer model is shown schematically here. The culture tanks are housed indoors and the CO2 removal device is venting directly to the airspace. The important process flows include carbon dioxide, moisture, and heat.

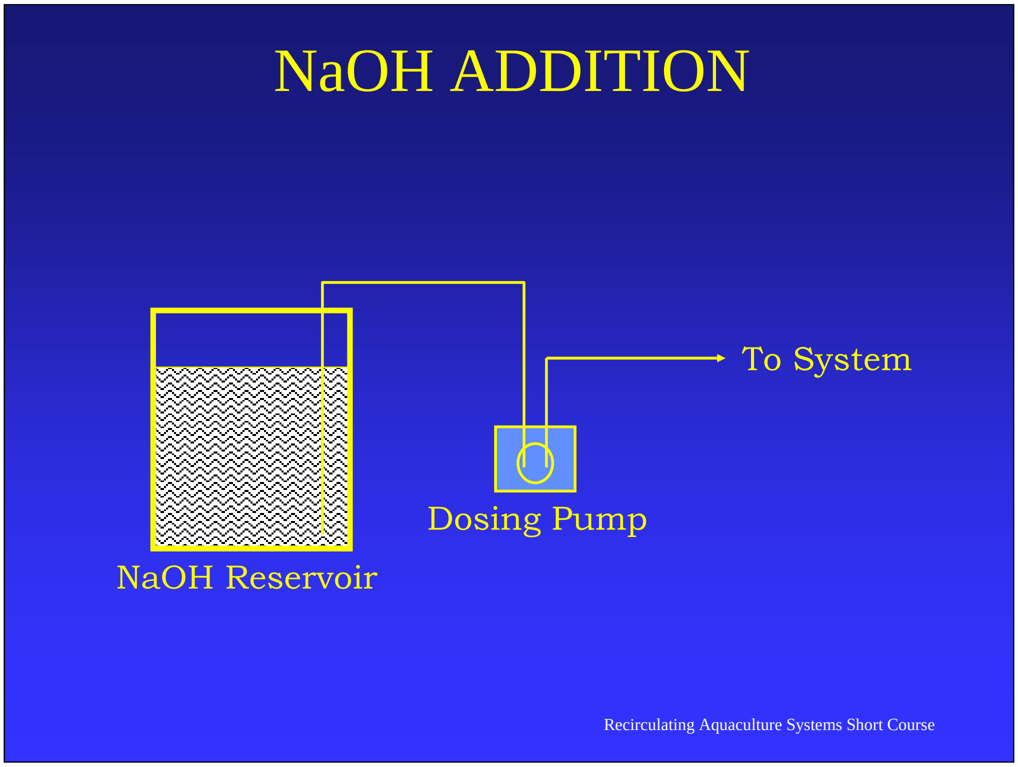
CONTROL OPTIONS

- Packed Tower Stripping
- Sodium Hydroxide Addition
- Water Exchange
- In-tank Surface Aeration
- Side-stream Surface Aeration
- In-tank Diffused Aeration
- Side-stream Diffused Aeration

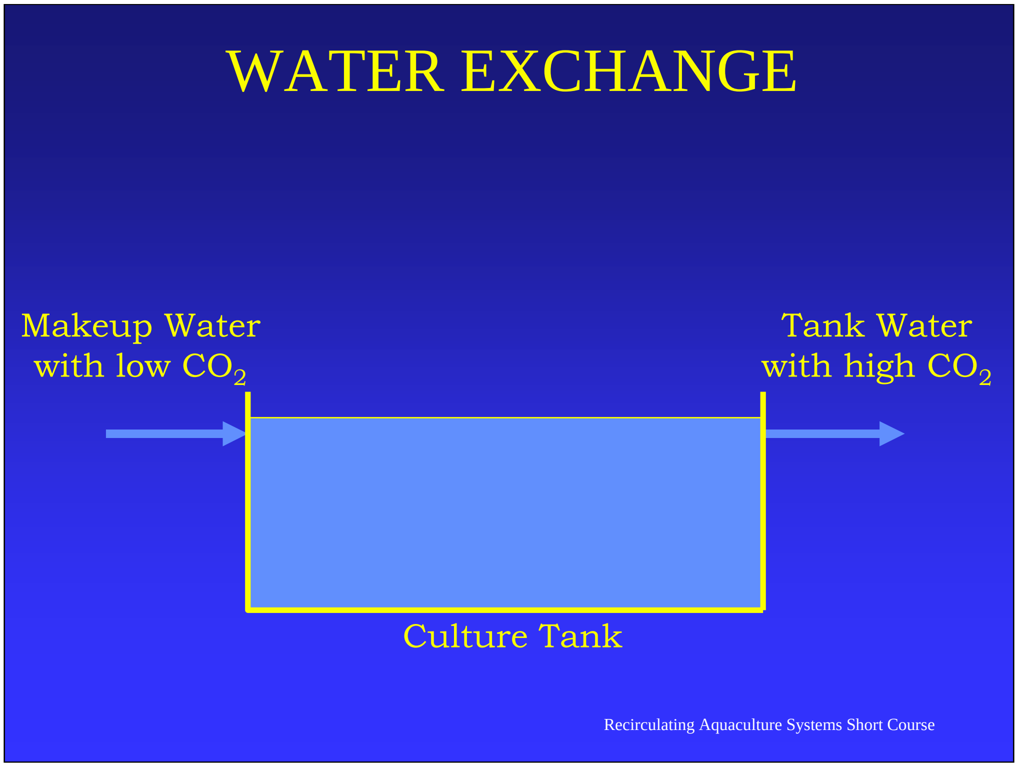
The carbon dioxide control options considered in the computer model include packed tower stripping, addition of sodium hydroxide, dilution through water exchange, in-tank and side-stream surface aeration, and in-tank and side-stream diffused aeration.



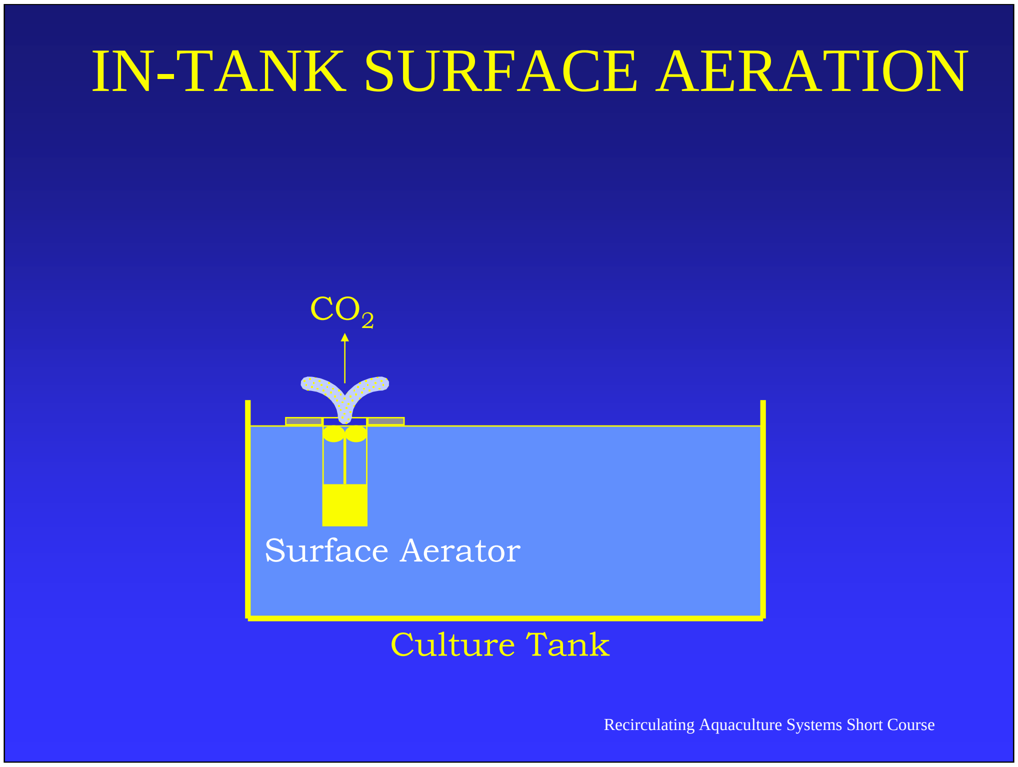
In packed tower stripping water with high CO_2 is pumped to a packed tower where ambient air is blown by the water in the tower, picking up carbon dioxide, leaving water with lower carbon dioxide levels to be returned to the culture tank. The stripping gas with higher carbon dioxide is returned to the airspace. As mentioned before, typical air volumes blown are five to ten times the water volume pumped through the tower.



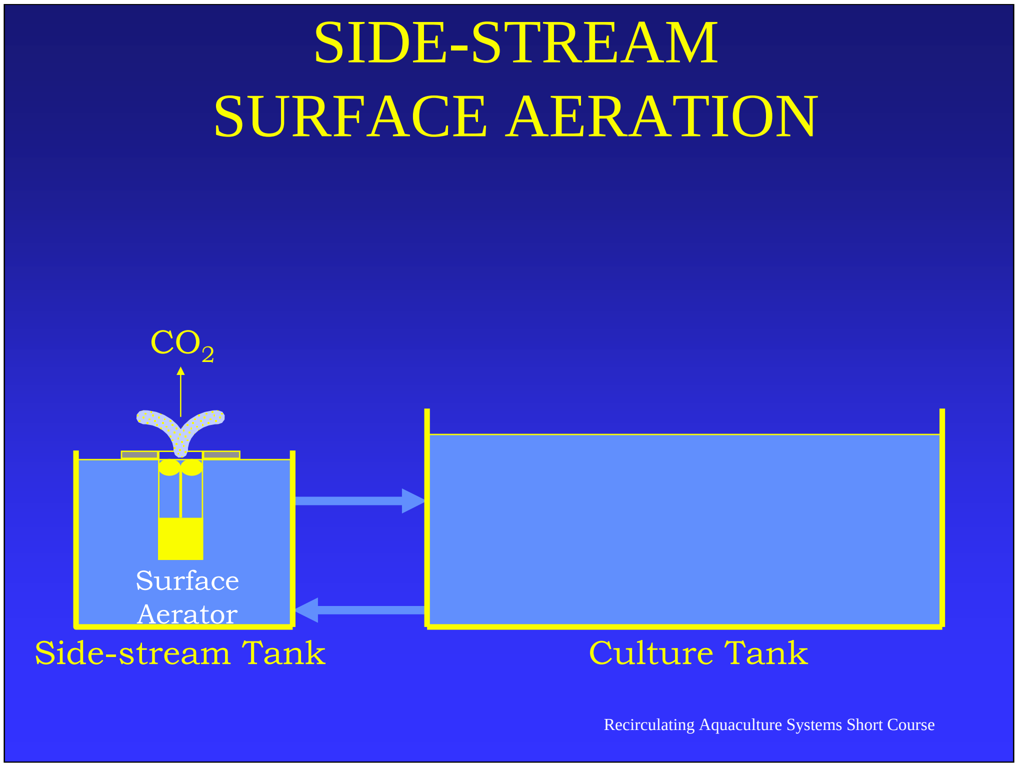
In sodium hydroxide addition, sodium hydroxide is delivered from a reservoir to the aquaculture system by a dosing pump or gravity feed, where it shifts the pH and the partitioning in the carbonate carbon system.



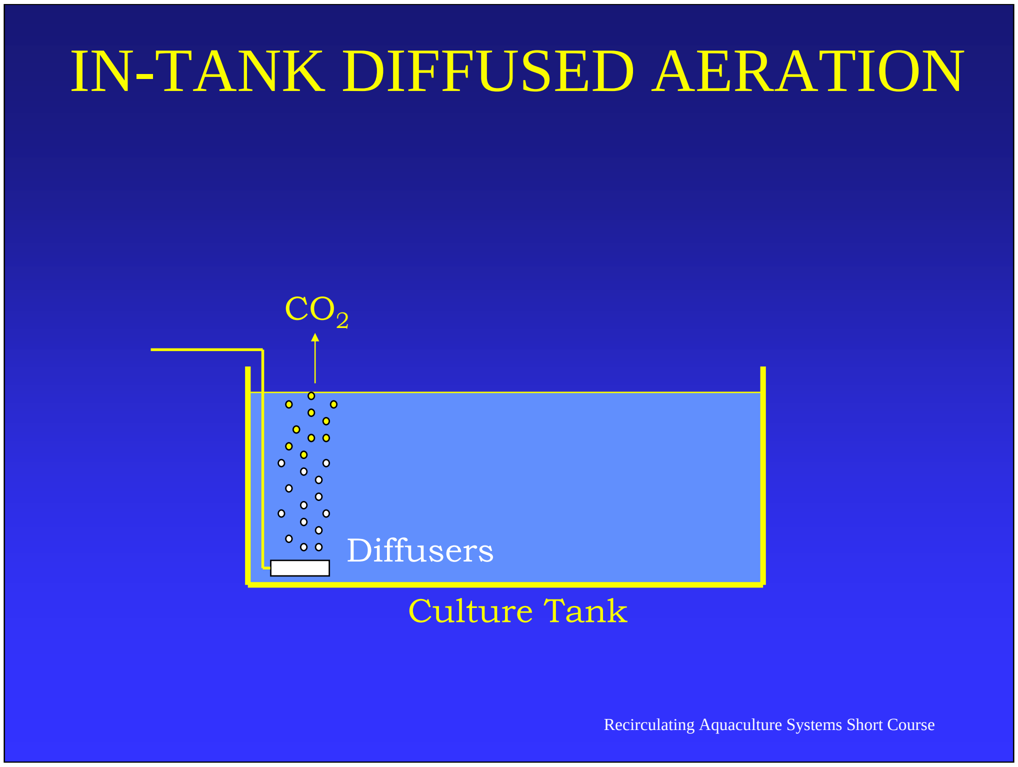
In water exchange makeup water having a low carbon dioxide concentration is pumped into the aquaculture system, replacing system water that has a high carbon dioxide concentration. This also replaces or flushes out other constituents such as ammonia or nitrite.



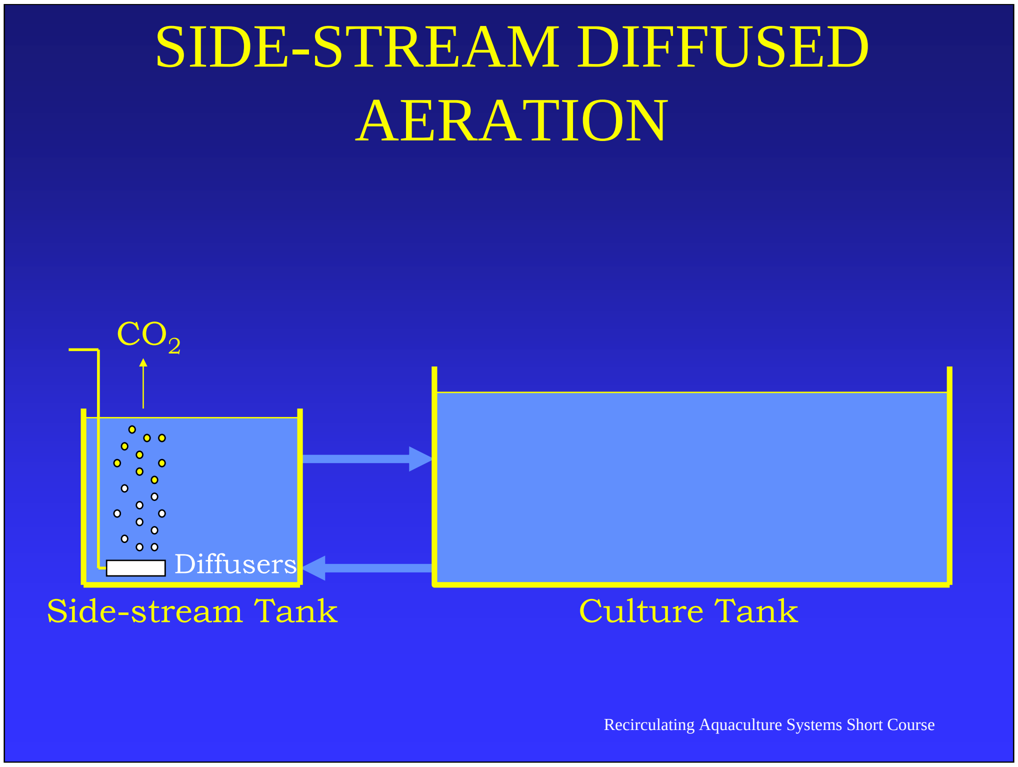
In in-tank surface aeration a surface aerator is placed in the culture tank where it aerates and agitates the culture water driving off dissolved carbon dioxide.



In side-stream surface aeration the surface aerator is placed in a side-stream tank and the water with high CO2 from the culture tank is pumped over to a side –stream basin, the carbon dioxide driven off and the water returned to the culture tank.



In in-tank diffused aeration, bubble diffusers are placed in the culture tank and ambient air blown through the diffusers picking up carbon dioxide from the culture water and driving it off to the airspace.

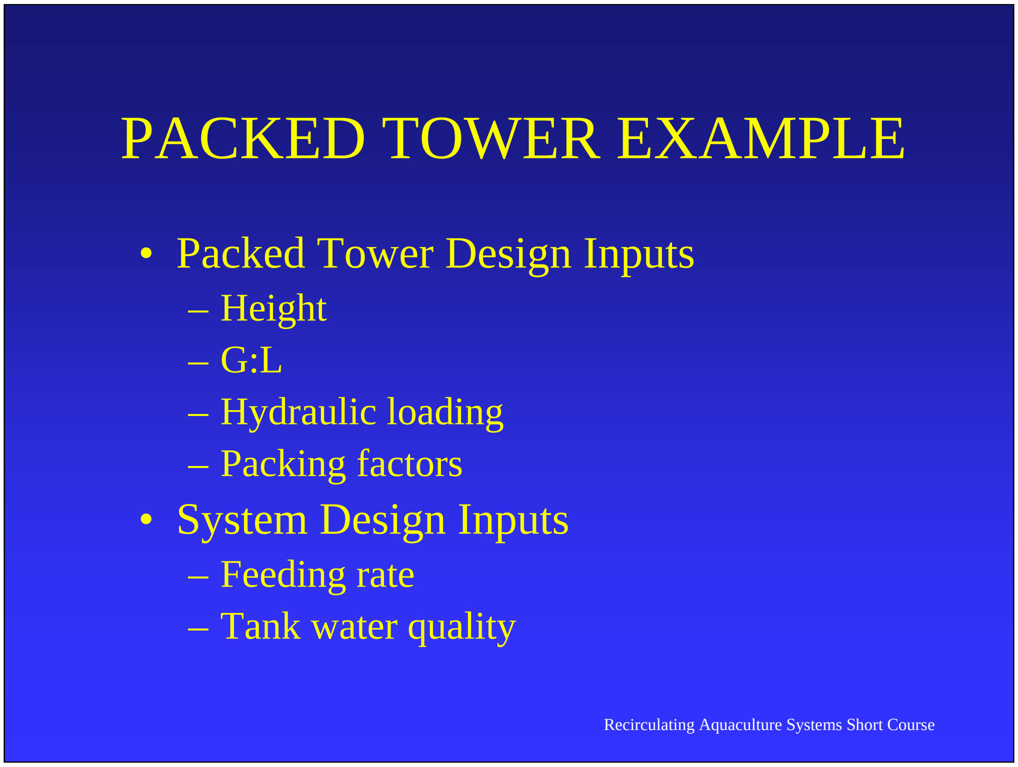


In side-stream diffused aeration the bubble diffusers are placed in a side-stream tank and the water with high carbon dioxide from the culture tank is pumped over to the side-stream basin, the carbon dioxide driven off and the water returned to the culture tank.

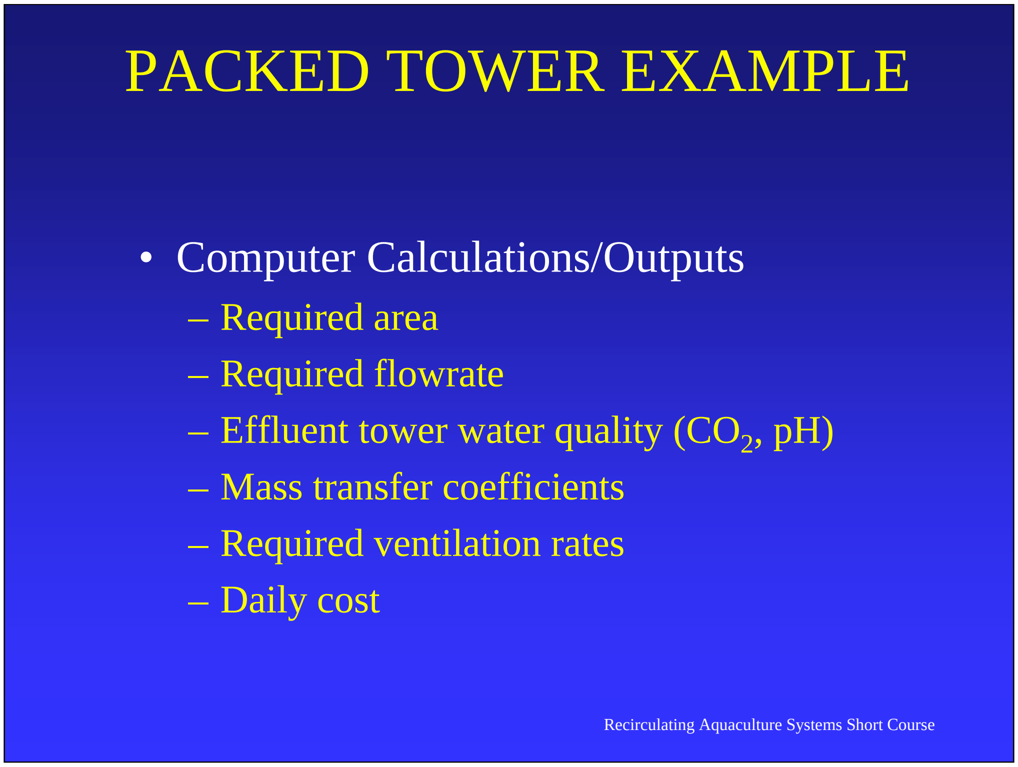
COMPUTER DESIGN TOOL

- Mathematical models for each option
- Carbonate carbon mass balance
- Weather simulation
- Facility heat balance
- Facility ventilation requirements
- Economics of control options
- Economics of heating and ventilating

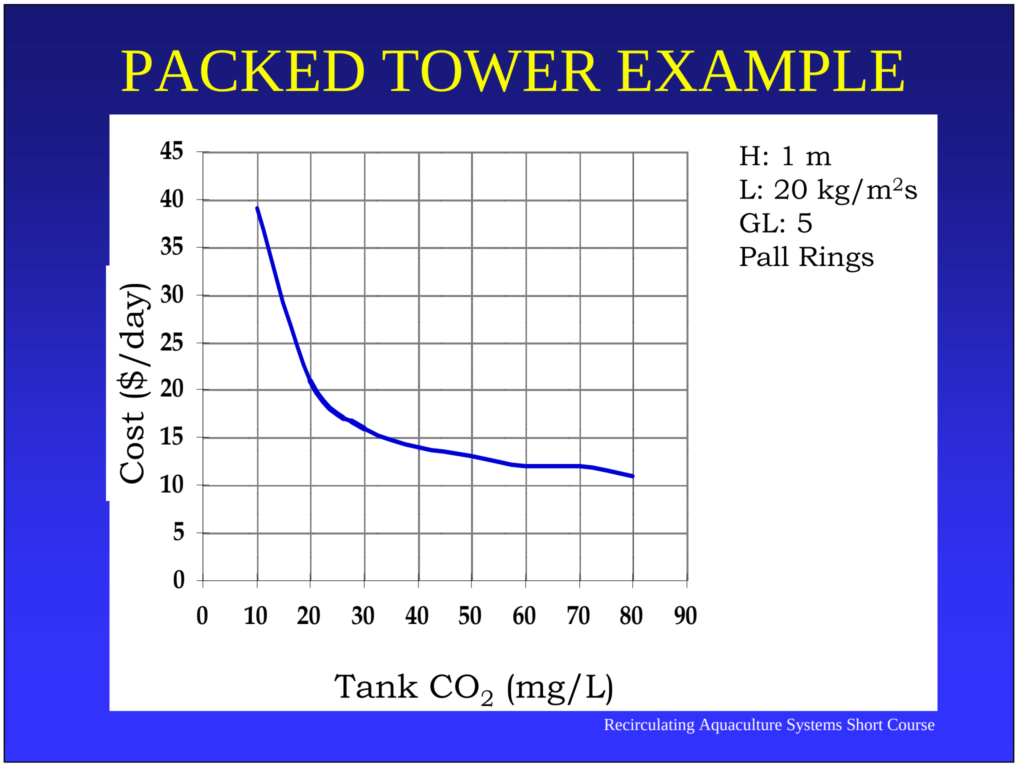
Using mathematical models for each option the interactive computer design tool was developed. Besides modeling the carbon dioxide mass transfer in each option, a carbonate carbon mass balance is employed along with an alkalinity mass balance. The overall model includes culture tanks inside a production facility and so a stochastic weather simulation is used, allowing for any geographic location to be modeled given typical weather data and elevation. The aquaculture facility, which is described with many inputs, is also modeled with a heat and moisture balance and controlling ventilation requirements (either for heat, moisture, CO2, or infiltration). The economics of the control options are included in the modeling as well as the economics for heating and ventilating the facility.



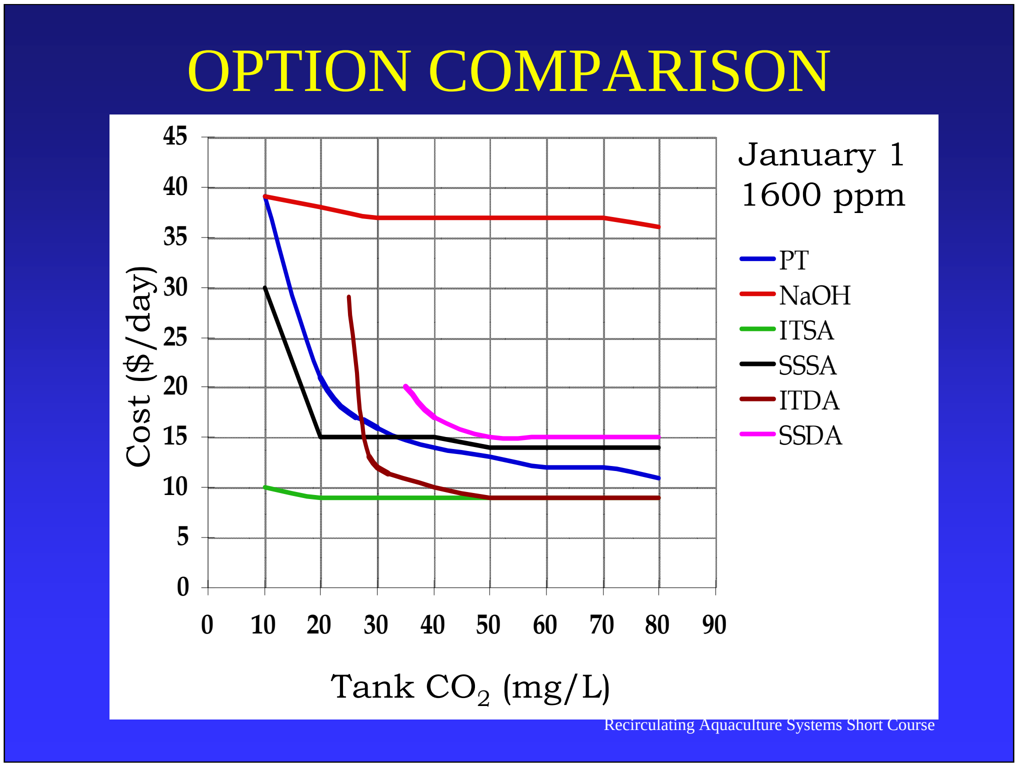
As an example of how the program works we will look at the packed tower. The design inputs are packed tower height, the volumetric gas to liquid ratio, the hydraulic loading, and factors describing the packing type and size. Of course there are many other inputs describing the facility, but most important are the fish feeding rate and tank water quality which includes the dissolved carbon dioxide concentration.



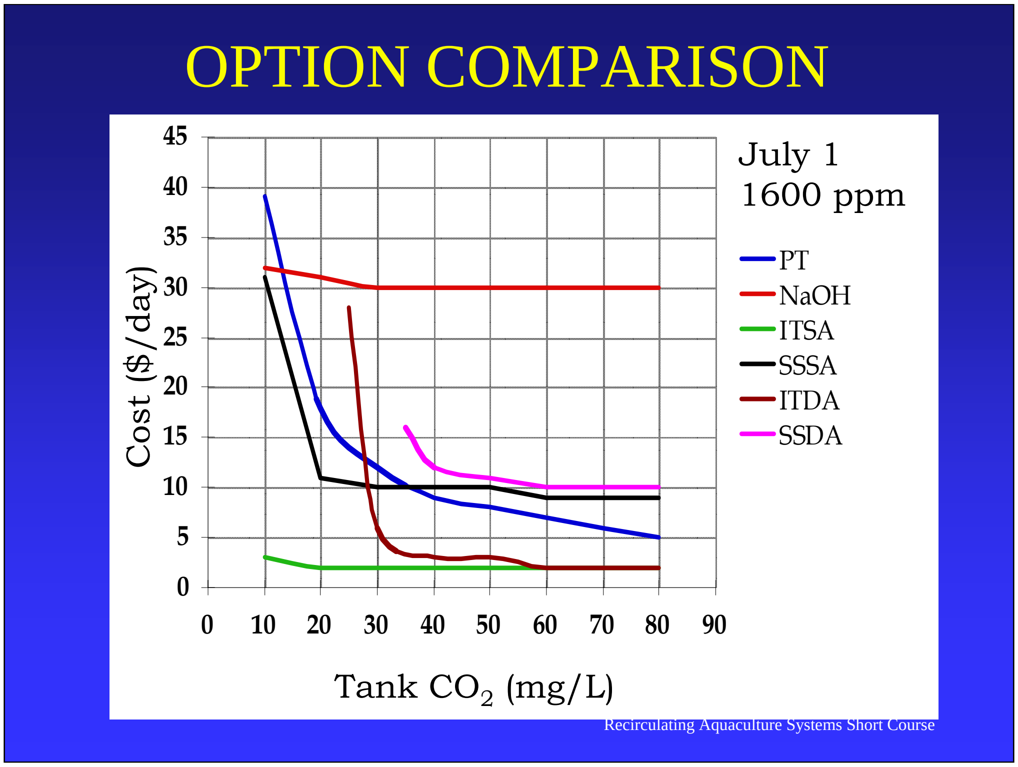
The computer model outputs for the packed tower option are the required cross sectional area, the required flowrate, effluent water quality (including CO_2 and pH), some mass transfer coefficients and costs for any length of simulation required.



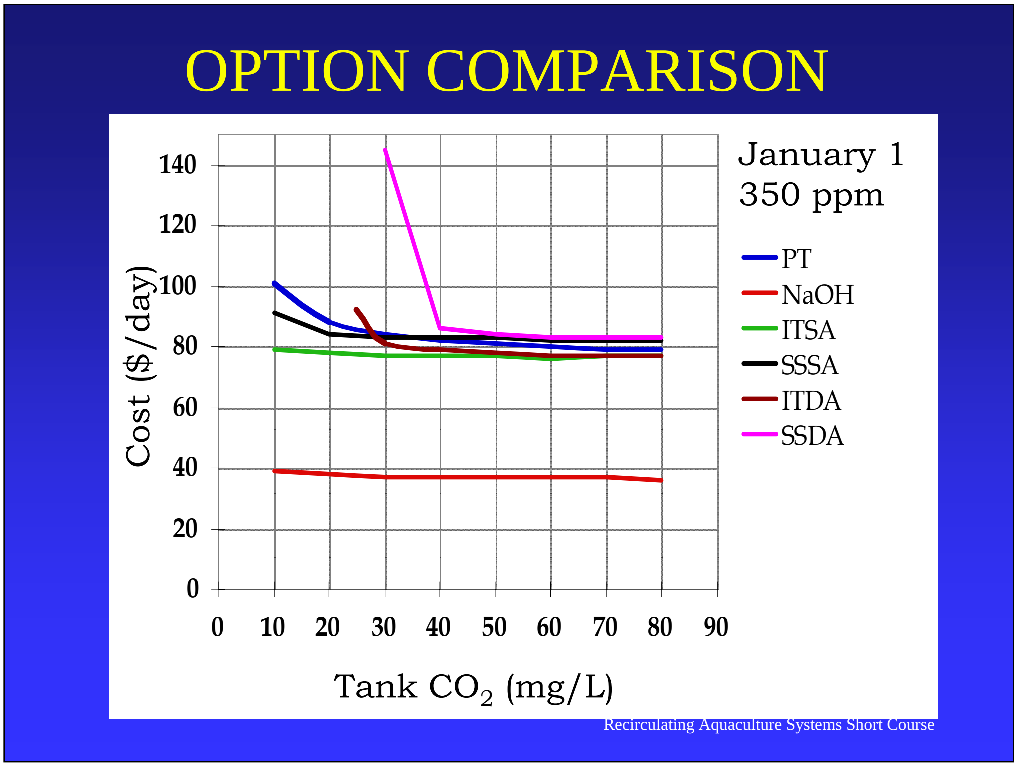
Choosing a production situation where you are feeding 200 pounds of feed per day in a 25,000 gallon culture tank in an indoor facility in the northeast US these are typical model results for a packed tower, 1 m in height, hydraulic loading of 20 kg/m^2-sec, a G:L ratio of 5 and using Pall rings as packing material. The cost in dollars per day decreases quickly at first as the tank design carbon dioxide level is increased, but then slowly decreases at higher carbon dioxide levels. These costs include water pumping, blowing air, and capital depreciation.



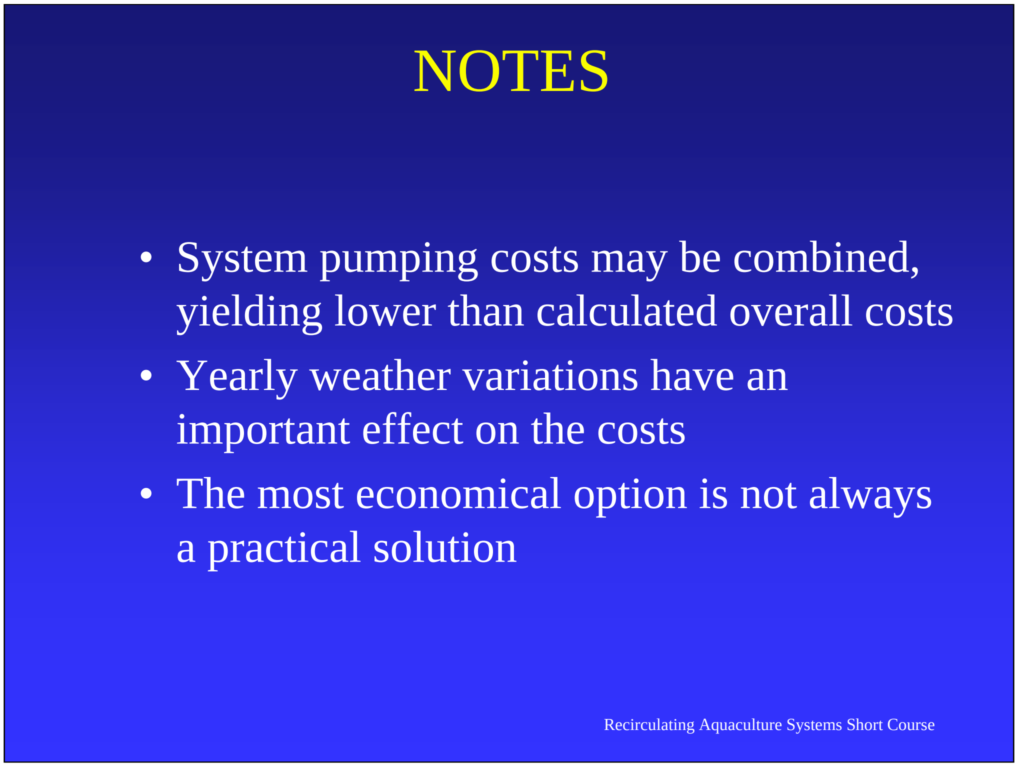
Now, putting all options on this same graph for a 25,000 gallon culture tank feeding at 200 pounds per day on January 1 and allowing for 1,600 ppm carbon dioxide in the facility airspace. We can see that many of the costs cross at different carbon dioxide levels with the diffused aeration options having a lower limit and the in-tank surface aeration option being the least expensive.



Looking at the same production situation but on July 1 we can see the costs have come down quite a bit. This is due to a decrease in the facility heating in the summer as opposed to the winter. The general trends of each option remain the same.



Finally, in the same production situation but with a strict constraint on the carbon dioxide in the airspace at 350 ppm the costs go up dramatically due to the high ventilation requirements to vent degassed carbon dioxide. The only option not effected is sodium hydroxide addition.



In conclusion we have a few observations – system pumping costs may be combined yielding lower than calculated overall costs for the packed tower and side-stream options. Yearly weather variations have an important effect on the costs and finally that the most economical option is not always a practical solution. This is especially true for the in-tank options which may cause problems with the tank hydraulics and fish rearing.