The use of the zero-exchange systems has become a viable alternative to traditional pond methods of intensive aquaculture production. Recently, the concept of zero-exchange systems has been applied to indoor tank based production systems for marine shrimp, *Penaeus vannamei*. In these systems, ammonia-nitrogen is controlled by the manipulation of the carbon/nitrogen ratio in such a way as to promote the growth of heterotrophic bacteria (Avnimelech, 1999, McIntosh, 2001). As a result, the ammonia-nitrogen is removed from the system through assimilation into microbial biomass. As a bonus, for some aquaculture species (marine shrimp and tilapia), this bacterial biomass produced in the intensive zero-exchange systems can be an important source of feed protein, reducing the cost of production and thus improving the overall economics (Moss, 2002).
The United States appears to have an almost insatiable demand for seafood; most of which is imported from overseas. In 2003, the U.S., imported over $11.1 billion of seafood, $974 million more than in 2002 (Fisheries Statistics & Economics Division, NOAA. The total trade deficit related to seafood trade is $8.0 billion (US Department of Commerce), of which $3.8 billion was for imported shrimp. In addition, consumption of shrimp in 2003 reached 4.0 lb per capita, 26% higher than in 2001 (Aquaculture Outlook, LDP-AQS-19, March 12, 2004). Shrimp production accounts for 1/3 of the total economic value of all seafood sold in the US. The shrimp production worldwide totaled 4,168,400 tons in 2000, up slightly from 4,118,900 tons in 1999 (www.foodmarketexchange.com). Production from aquaculture is estimated at 855,500 tons in 2001. This was a 10% increase over the previous year's production but not enough to keep up with the world's growing demand for shrimp. The US wild harvest of shrimp was 158,500 tons in 2002 (2002 is the most recent year that wild domestic harvest data is available). However, the U.S. shrimp catch has remained essentially constant (ignoring annual fluctuations) over the period (1970-1995). The domestic farm-raised shrimp industry (ponds) has been increasing, but price drops have reduced the incentives for new farmers to enter the industry (Aquaculture Outlook, LDP-AQS-19, March 12, 2004).

In the US, marine aquaculture currently accounts for about 1/3 of commercial aquaculture production. However, growth has been constrained due to a variety of reasons, with environmental concerns, permitting processes, and low market prices being dominant. The environmental constraint naturally raises the advantages of recirculating aquaculture system technology, as recirculating systems can eliminate potentially any negative environmental impact from the production operation. Recirculating systems also conserve water, eliminates escapement of cultured animals, and can be site independent. The recycling nature of these systems also permits culture of marine or freshwater species and allows the farms to be located primarily for the benefit of market proximity, as opposed to being sited, based upon the availability of natural resources, such as high volume water (fresh or saline) or open ocean sites. The capability of recirculating systems to be located near markets is a key attribute, as shrimp raised in intensive recirculating systems will need to achieve premium pricing to be economically viable.

For traditional marine aquaculture to increase production, more coastal sites must be found. Appropriate sites are those located in protected areas with abundant access to unpolluted water. However, these same-type sites are also used for other high-profile activities, such as recreational fishing, wildlife protection, and aesthetic enjoyment. As an example, Alaska has prohibited the use of its coastal shoreline for aquaculture, in order to protect their native salmon populations and the associated industries that they support. More and more, other communities and states are following this example. In attempts to circumvent these restrictions, there is considerable interest in developing what is referred to as "off-shore" sites, which are within the 3 to 200 miles offshore zone controlled by the US government. This is a difficult environment, however, and aquaculture in such areas will be subjected to higher capitalization and operating costs, which makes the production of commodity type seafood all but impossible on an economical basis. The practical alternative to these problems is the development of "in-shore" or land based marine aquaculture systems.
Raceways have been used for years for the production of salmonids and other species by federal and state agencies for stocking purposes and commercial growers. Where there are large ground water resources, raceways are the most common rearing tank design being used to grow the majority of rainbow trout produced in the USA. One significant advantage of raceways is their better utilization of floor space and easier handling and sorting of fish as compared to circular tanks. Their primary disadvantages are the large volume of water required for maintaining water quality and their limited self-cleaning ability (Timmons et al. 1998). Water enters the raceway at one end and flows through the raceway in a plug-flow manner. As a result, the best water quality is found at the head of the raceway where the water first enters and then it deteriorates steadily towards the raceway outlet. Because of the low velocities through the raceway (2-4 cm/s), removal efficiency of settled solids is very poor, requiring frequent cleaning and maintenance tasks (Timmons et al. 1998). This is due to the hydraulic design being based on oxygen design requirements, rather than cleaning requirements, that result in the much lower velocities. In practical terms, raceways are incapable of producing the optimum water velocities recommended for fish health, muscle tone, and respiration (Timmons et al. 2002). Even using lower exchange rates and lower velocities, use of raceways is being severely limited due to the unavailability of large quantities of high quality water, increased concern about their environmental impacts on receiving waters, and the difficulty in treating the large flows producing a large effluent discharge.
Quite the opposite is the case of circular tanks, where hydraulic behavior approximates that of a mixed-flow reactor (MFR). These characteristics have been well established in traditional circular tanks (Watten and Beck, 1987) and in more recent studies on the Cornell circular dual-drain tank (Davidson and Summerfelt, 2004), especially at high fish densities (> 80 kg/m³). Circular tanks also exhibit good self-cleaning and the capability to maintain optimal velocities for fish health and conditioning (Davidson and Summerfelt, 2004), which ultimately leads to improved growth rates and food conversion efficiencies (Timmons et al., 1998, 2002). Unfortunately, not only husbandry tasks are more difficult to achieve in circular tanks as compared to linear raceways, but are less efficient in utilizing the footprint space.
Introduction

Application of engineering principles for economically sustainable production

Mixed-cell Raceway

- Efficient footprint utilizations
- Efficient and easy handling & sorting
- Good self cleaning velocities
- Optimal velocities for fish

The mixed-cell raceway (MCR) was developed by Watt et al. (2000) to combine the best characteristics of circular tanks and linear raceways in a single vessel design, e.g., uniform water quality, rapid solids removal, and easier husbandry and maintenance. Vertical discharge manifolds along the sidewalls of an MCR allows converting linear raceways into a series of hydraulically independent mixed-cells, each having a counter-rotating hydraulic flow pattern to the next cell and a bottom-center drain that forces each cell to behave as an individual circular tank.
“New Paradigm”

Sustainable Engineering

- Zero-exchange Production Systems
- Mixed-cell raceways
  - Design and Construction
  - Hydraulic Characterization
  - Water Quality
  - Solids Management
  - Production Systems Options

We are seeing a new “Paradigm” in aquaculture production, combining the use of heterotrophic bacteria for waste management and the mixed-cell raceway as an efficient production system.
The basic design concept of the mixed-cell raceway is to operate it as a series of adjacent counter rotating square/octagonal tanks, each having a center drain for continuous removal of solids and sludge, Fig. 2. Early research on mixed-cell raceways by Watten et al. (2000) examined their use in retrofitting existing raceways at federal and state hatcheries and was reflected in the overall small systems size, 22.7 m³. In contrast, our research started with the design of a small commercial production system, 108 m³. In addition, Timmons, et al. (1998) recommended tank diameter to depth ratios for good self-cleaning capability from 5:1 to 10:1, compared to 3.7 for Watten et al. 2000 vs. 5.5 in this current study.

The mixed-cell raceway acts as a series of hydraulically separated round tanks. The basic design concept of the mixed-cell raceway (Watten, et al., 2000) is to operate it as a series of adjacent counter rotating square/octagonal tanks, each having a center drain for continuous removal of solids and sludge, Figure 1. A prototype raceway was constructed in one bay of an existing greenhouse at The Conservation Fund's Freshwater Institute with approximated dimensions of 16.3 m x 5.44 m x 1.22 m (54 ft x 18 ft x 4 ft), which created three mixed-cells. Each cell received water from four vertical manifolds (downlegs) extending to the raceway floor and located in the corners of each cell and at the intersection between adjacent cells (Figure 2); four of the manifolds supply water to two cells concurrently. Water is pumped through several orifice discharges (or jet ports) from each of the downleg pipes to establish rotary circulation in the cell, with adjacent cells rotating in opposite directions. Each cell had a bottom drain located at the center of the cell connected to a drain line, which discharged solids and sludge to a settling sump. A small fraction of the total recirculated flow, e.g., 10 to 20%, is withdrawn from this sump and returned to the raceway, creating a “Cornell” dual drain system.
A prototype raceway was constructed in an existing greenhouse with approximated dimensions of 16.3 m x 5.44 m x 1.22 m (54 ft x 18 ft x 4 ft), which created three mixed-cells (Ebeling, et al. 2005). The basic design concept was to operate the raceway as a series of square/octagonal tanks, each having a center drain for continuous removal of solids and sludge. Each cell received water from four vertical manifolds (downlegs) extending to the raceway floor and located in the corners of each cell and at the intersection between adjacent cells (Fig. 3); four of the manifolds supply water to two cells concurrently. Water is pumped through several orifice discharges (or jet ports) from each of the downleg pipes to establish rotary circulation in the cell, with adjacent cells rotating in opposite directions. Each cell had a bottom drain located at the center of the cell connected to a drain line, which discharged solids and sludge to a settling sump.
Due to construction limitations imposed by the greenhouse, the mixed cell raceway was constructed as an above ground tank the width of one bay, with approximate dimensions of 16.3 m x 5.44 m x 1.22 m (18 ft x 56 ft x 4 ft). Sidewall modules (1.22m x 2.44m) were prefabricated of 2x6 construction studs on 24” spacing and covered with ½” plywood sheeting. These sidewall modules were then supported on a 6x6 treated wood beam ‘foundation’ and connected together with ½” lag bolts. In addition, a top plate was used to provide additional rigidity to the sidewall modules. Normally such a tank would be constructed below grade, allowing for structural support of the walls with backfill material. To provide this structural support, a series of polypropylene-impregnated wire rope were run across the top of the tank at five equally spaced intervals and also below the tank. In addition, a single cable was strung the length of the tank top and a second one below the insulated floor. These cables were secured into the sidewall top plates and the 6x6 treated wood beam foundation with eyebolts and forged galvanized steel hook and eye turnbuckles to allow adjusting and tightening. These proved quite adequate, but only after several failed attempts with lighter gauge materials. The message here is to never underestimate the structural requirements and the large pressures exerted by a tank of water.

The tank was lined with a 20 ml high density cross laminated polyethylene (HDPE) raceway liner from Permalon, Reef Industries, Inc. The floor of the raceway was covered with approximately 5 cm of fine sand and graded to provide a slight slope to the three center drains. To minimize heat loss through the sidewalls, these were insulated with 2.54cm x 1.22m x 2.44m foam insulation board. To minimize heat loss through the ground, the outside perimeter of the floor was covered with 5.0cm x 1.22m x 2.44m insulation board and the center strip of the floor with 2.54cm x 1.22m x 2.44m insulation board. The tank was lined with a 20 ml high density cross laminated polyethylene (HDPE) raceway liner from Permalon, Reef Industries, Inc.
A 15.24 cm (6 in) drainline with three discharge drains (tee fittings) centered on each of the three cells was buried along the longitudinal axis of the tank. A standard flange socket fitting was modified by boring out the center to allow either standpipe or screened inlet and installed on each of the three tee fittings. A concentric ring of PVC sheet materials was used to secure the liner to the flange flat surface to provide a water tight seal at the three drains. The three drains discharged into a 1.83m x 1.83m x 1.83m (6 ft x 6 ft x 6 ft) fiberglass sump tank. The sump tank had both a standpipe for water level control and a drainline to flush the system. The sump tank was intended to fulfill several roles, including solids management by acting as a solids settling basin, water level set point with the standpipe and harvesting basin by flushing the production tank through a screened harvesting cage.

Eight 0.75 kW pumps (1hp) were installed along the outside walls on platforms and discharged into a 10cm (4 in) schedule 40 PVC manifold that encircled the raceway. These pumps were used as a cost saving measure, since they were free. Although in retrospect, they simulated a dual-drain system, where most of the recycled water is removed from the top sides of a tank and only a small fraction is removed from the center drains. Two of the pumps were located on the sump collection tank, while the remaining six were placed equal distant along the length of the tank outside walls. The suction lines with check valves were located approximately at mid-depth in the tanks. The pump discharges were connected to the manifold with a 5.08cm (2 in) flexible hose with a bronze gate valve to control flow and a clear plastic manometer to measure downleg back pressure.
Eight 0.75 kW pumps (1hp) were installed along the outside walls on platforms and discharged into a 10cm (4 in) schedule 40 PVC manifold that encircled the raceway. These pumps were used as a cost saving measure, since they were free. Although in retrospect, they simulated a dual-drain system, where most of the recycled water is removed from the top sides of a tank and only a small fraction is removed from the center drains. Two of the pumps were located on the sump collection tank, while the remaining six were placed equal distant along the length of the tank outside walls. The suction lines with check valves were located approximately at mid-depth in the tanks. The pump discharges were connected to the manifold with a 5.08cm (2 in) flexible hose with a bronze gate valve to control flow and a clear plastic manometer to measure downleg back pressure.

Each hydraulically separated cell created within the tank measured approximately 5.44 m x 5.44m (18ft x 18ft) as determined by the downleg placements. Four 5.08cm (2 in) downlegs with seven orifices were placed in the four corners of the tank and four 7.62cm (3 in) discharge pipes were located along the sidewalls, dividing the tank into three equal cells. Two of the 7.62cm (3 in) downlegs had 14 orifices; seven discharging along each edge of the wall and the other two discharge downlegs had 7 orifices each. The downlegs were constructed of either 5.0 cm (2 in) or 7.62 cm (3 in) PVC schedule 40 pipe. The orifice opening were constructed by welding a threaded bushing 3.18 cm by 2.54 cm (1 ¼ x 1 in), allowing a 2.54 cm (1 in) threaded plug to be inserted. This allowed for easy modifications of the orifice sizes and plugging of unused orifice openings.

Temperature was maintained using a standard swimming pool propane heater and three aluminum heat exchangers located in the tank. A small circulation pump forced water around a closed loop from the heater to the heat exchangers. A simple thermostat control on the propane heater was used to maintain temperature at a set point of 86 Degrees F.

A monitoring and control system has been designed, constructed, and installed as shown above. The system monitors tank water level, pressure (flow) in the injection manifold, air pressure for the air stones, and flow in the heating system. In addition, it monitors sound level in the immediate area, production water temperature, greenhouse temperature, and power. It can call out to four phone numbers, which currently are my office, my home and a pager that I carry with me at all times. There is also a temperature controller for the propane heating system that will control the production tank temperature. The large enclosure contains a Campbell Scientific data acquisition system that could be used to monitoring water quality parameters and system environmental parameters at various locations in the production system, greenhouse, and other locations.
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The rotational flow in the mixed-cells of the MCR is created by the action of submerged water jets directed either tangentially or perpendicularly to the tank wall (Ebeling et al., 2005; Labatut et al., 2005a). Water jets create a momentum flux that breaks the inertial state of the flow field ahead of the jet, accelerating the fluid and creating a turbulent mixing layer at the jet boundary. This mixing layer entrains some of the surrounding liquid and creates the swirl pattern that leads to mixing of the contents (Patwardhan, 2002).

Although in a jet-forced circulation vessel, such as the MCR, rotational velocities are affected by a number of variables (Labatut et al., 2005a), they are mostly controlled by the inlet flux of momentum, which is a function of both the nozzle discharge velocity (jet velocity) and the nozzle diameter. Past studies, however, have considered the inlet jet velocity as a single controlling design parameter to achieve specific rotational velocities (Paul et al., 1991), while the nozzle diameter has been disregarded. Yet, when the objective is to determine the liquid mixing time of jet-mixed tanks, the nozzle diameter has been extensively considered (Fossett, 1951; Fox and Gex, 1956; Lehrer, 1981; Lane and Rice, 1982; Simon and Fonade, 1993; Orfaniotis et al., 1996; Grenville and Tilton, 1996).
Labatut et al. (2006) conducted a series of experimental trials to evaluate the effect of nozzle diameter and the rate of bottom-center drain discharge on both the magnitude and uniformity of rotational velocities in the mixed-cell. Three nozzle diameters, 10, 15, and 20 mm, and three bottom-center flows, 0, 15, and 20%, were evaluated. Measurements of rotational velocities in the mixed-cell were made at 5 cm from the bottom of the tank. While the nozzle diameter was found to have a highly significant influence (p < 0.01) on the magnitude of the rotational velocities, the percentage of bottom flow did not (p > 0.05). Also, results suggested that uniformity of rotational velocities in terms of the radial-wise profile is not affected by either the nozzle diameter or the percentage of bottom flow.
Velocity measurements were made by using a SonTek Argonaut-ADV ultrasonic velocity meter (San Diego, CA). The SonTek velocity meter is a single-point, 3D Doppler current meter designed for shallow water flow monitoring. It measures velocities within a range of 0.001 to 6 m/s with a resolution of ± 0.0001 m/s and an accuracy of ± 1% of measured velocity (± 0.001 m/s). The Argonaut-ADV probe transmitter generates a short pulse of sound at a known frequency that is reflected by fine and dissolved particles suspended in the water current. The reflected pulse is received by three acoustic receivers that measure the Doppler shift and convert the signal into Cartesian velocities. The instrument reports the magnitude of the x, y and z velocity components and the resultant velocity magnitude and direction in the x-y plane. Velocities were measured 5 cm from the bottom, i.e., 1.1 m depth, of mixed-cell 1, over a 0.5 m x 0.5 m horizontal grid (Fig. 5).
Hydraulic Characterization

Grid Layout for one cell

0.5 m grid lines
one sample/sec
20 sec average

Velocities of only one half of cell 1 were measured, since rotational velocities were assumed to be symmetric on the x-y horizontal plane based on the results obtained previously by the authors (Labatut et al., 2005a). Thus, a total of 89 sampling points on the horizontal grid of cell 1 were measured for each of the nine operating conditions. The Argonaut-ADV was mounted on an aluminum transport system and placed over the tank to allow moving the probe in both vertical and horizontal directions across the grid. The Argonaut-ADV probe samples 10 times per second and produces an average measurement of velocity magnitude and direction within a user-defined time interval. The interval was set at 20 seconds for our trials; therefore, in each and every sampling point of the grid the measurement reported was the average of a total of 80 samplings. Experimental data were downloaded into MS Excel® (Microsoft Corp) for processing, plotting, and analysis. Rotational velocities for each diameter and bottom flow were averaged at radial distances from the center to the wall. Velocities in the corners of cells, located outside the outer most ring, but inside the cell, were also averaged. Plots of the results were created for each diameter and bottom flow. Multiple regression analyses were conducted to correlate the nozzle diameters and bottom flows to the rotational velocities found in the mixed-cell. A two-way analysis of variance (ANOVA) was performed to test data differences between the nozzle diameters and bottom flows used. All statistical analyses were conducted with Minitab® release 4 statistical software (Minitab Inc.).
Labatut et al. (2006) also showed that the flux of momentum is the driving force controlling rotational velocities in a jet-forced circulation vessel and therefore jet velocity and nozzle diameter become the main variables to control. He found that the linear influence of the jet velocity on rotational velocities reported in previous studies remained valid provided that the nozzle diameter was maintained constant. Results of the study indicated that rotational velocities in mixed-cells follow a logarithmic trend as a function of the nozzle diameter for a constant jet velocity. The linear and logarithmic models were combined to construct a set of iso-curves to predict rotational velocities as a function of jet velocity and nozzle diameter (Fig. 4). The iso-curves can be used to facilitate the design of a MCR where particular rotational velocities are desired.

Iso-curves for predicting mean rotational velocities for different nozzle diameters and discharge jet velocities.
Piezometric head required in the vertical manifolds as a function of the inlet jet velocity.

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In a zero-exchange system, ammonia-nitrogen is removed via the growth of heterotrophic bacteria, stocking densities are low (5 to 10 kg /m³) and oxygen requirements are modest, so high tank exchange rates through biofilters and oxygenators are not necessary. At an exchange rate of approximately 0.5 tank volume/hr, a flow rate of only 0.74 m3/min (250 gpm) is required for the raceway in this example. This was accomplished using two 0.95 kW (1 hp) pumps which removed water at the two ends of the raceway and injected it into a 7.5 cm (3 in) manifold that circled the top of the raceway. Water was withdrawn either from a 5 cm (2 in) PVC pipe inlet located approximately 25 cm below the surface at one end or an end sidewall discharge drain at the other. Approximately 15% of the flow 0.13 m3/min (35 gpm) was from the three bottom drains, using a smaller 0.375 kW (1/2 hp) submersible pump in the sump drain.

Little is know about the optimal tank rotational velocities for marine shrimp. A mean tank velocity of 10 cm/s was chosen to insure adequate rotational velocities to move waste particles and uneaten food to the center drains. From Fig. 3, the required discharge jet velocity for a tank mean rotational velocity of 10 cm/s is approximately 4 m/s. The required piezometric head to achieve this jet velocity is computed from the equation described by Brater and King (1976):
A SonTek Argonaut Acoustic Doppler Velocimeter from Yellow Springs Instruments (1725 Brannum Lane, Yellow Springs, OH 45378 USA) was utilized in this study to measure speed and direction within the hydraulically separated cells. The SonTek velocity meter is a single-point, 3D Doppler current meter that measures water velocity via the Doppler shift in frequency of sound from a moving object, in this case small particulate matter in water current. The SonTek probe assembly was mounted on a rigid aluminum beam supported above the width of the raceway, which allowed the probe to be moved across the raceway width in a repeatable fashion. The probe was lowered into the raceway to specified depths of 5 cm off the bottom, mid-depth, and 10 cm below the water surface, along a 0.5 m horizontal-squared-grid measuring system. Measurements were taken for a 20 seconds averaging interval at each of grid points and the values averaged for a numerical value used to plot the results. The data collected form the SonTek system was downloaded into Microsoft Excel for processing and contour graphing of the velocities was created with Sigma Plot.
Figure 5 shows the contour plot for cell #3 (end cell) at velocity intervals of 5 cm/sec, approximately 5 cm off the bottom. The pressure head was approximately 1.00 m gauge (1.5 psi). As can be seen in this figure, relatively high scouring velocities are found at the outside perimeter of the cell (20 to 24 cm/sec), lower velocities near the center (10 to 6 cm/sec) and very low velocities at the center of the cell. The velocity profiles shown in Figure 6 were created by averaging the velocities at each grid point in an annular ring 0.5 m wide starting at the center at each of the three depths. This graph shows the almost linear velocity profile as a function of distance from the center drain and significant cleaning velocities in the corners of the cell. The velocities in the z-direction were very small, just above the drain values of -2.2 to 2.8 cm/s was measured. The mean tank rotational velocity was estimated from the average of all measurements taken as 10.5 cm/s, consistent with both the initial assumption and Fig. 4.
The systems was stocked with marine shrimp, *Penaeus vannamei* and managed as a zero-exchange low salinity production system for several months. Research was conducted into new methods of maintaining or controlling the dynamics of the water quality of the system through the addition of carbon to stimulate heterotrophic bacterial production. In addition, suspended solids concentration in the production tank was maintained at acceptable levels by controlling the amount and frequency of discharge from the settling tank. Basic water quality parameters were routinely measured, including temperature, dissolved oxygen, ammonia-nitrogen, nitrite-nitrogen, nitrate-nitrogen, alkalinity, total suspended solids (TSS), and volatile suspended solids (TVS).
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6th International Conference on Recirculating Aquaculture
Water Quality

Mixed-cell Raceway Production Tank NO₂-N

No Sugar!


NO₂ - N (mg/L)
Water Quality

Mixed-cell Raceway Production Tank TSS


TSS (mg/L)
“New Paradigm”

Sustainable Engineering

- Zero-exchange Production Systems
- Mixed-cell raceways
  - Design and Construction
  - Water Quality
  - Solids Management
  - Production Systems Options

The basic design concept was to operate the raceway as a series of square/octagonal tanks, each having a center drain for continuous removal of solids and sludge. A series of vertical discharge pipes were placed along the raceway sidewalls that directed recycle water through orifice discharges tangentially to the walls to establish the desired rotary circulation. This was then combined with the concept of the ‘Cornell double drain system’, where 10% to 20% of the total flow into a tank was removed from a center bottom drains and 80 to 90% of the flow was removed from the side drains.

Settable wastes and sludge were then removed from the center drains and collected in a settling sump. The systems was stocked with marine shrimp, *Penaeus vannamei* and managed as a zero-exchange low salinity production system for several months. Research was conducted into new methods of maintaining or controlling the dynamics of the water quality of the system through the addition of carbon to stimulate heterotrophic bacterial production. In addition, suspended solids concentration in the production tank was maintained at acceptable levels by controlling the amount and frequency of discharge from the settling tank. Basic water quality parameters were routinely measured, including temperature, dissolved oxygen, ammonia-nitrogen, nitrite-nitrogen, nitrate-nitrogen, alkalinity, total suspended solids (TSS), and volatile suspended solids (TVS).
Settling Basins

Sedimentation: Advantages
- Simplest technologies
- Little energy input
- Relatively inexpensive to install and operate
- No specialized operational skills
- Easily incorporated into new or existing facilities

Sedimentation: Disadvantages
- Low hydraulic loading rates
- Poor removal of small suspended solids
- Large floor space requirements
- Resuspension of solids and leaching

Settling basins are very effective if properly configured and operated. Sedimentation, i.e., gravity separation, is one of the simplest of technologies available to control particulate solids in process water and wastewater. Sedimentation basins require little energy input, are relatively inexpensive to install and operate, require no specialized operational skills, and can be easily incorporated into both new and existing facilities.

The disadvantages of sedimentation are low hydraulic loading rates and poor removal efficiency of small suspended solids (<100 µm). Also, they require additional floor space for their incorporation in comparison to microscreen filters. Innovative uses of vertical space over the settling bed or placing the settling bed in less expensive space can reduce this cost considerably.

Another potentially serious disadvantage is that settled manure remains in the system until the settling basin is cleaned. This condition is one of the major concerns in their use. Dissolution of nutrients and the resuspension of solids that have settled and collected on the bottom of settling basins can markedly reduce the expected performance of these clarifiers (Cripps and Kelly, 1996). Henderson and Bromage (1988) estimated that settling ponds could capture an estimated 97% of their solids loading if resuspension of settled solids was not a factor. They suggest that settling basins are not effective in removing TSS when inlet concentrations are <10 mg/L or attaining effluent concentrations of <6 mg/L. Eliminating resuspension of TSS is difficult at best in most settling basins. Thus, settling basins will generally require further TSS treatment to meet the stringent removal criteria necessary to achieve mandated levels of TSS.
All continuous flow settling basins are conceptually divided into four zones according to function, see above. The inlet zone serves to uniformly distribute the suspension over the entire cross-section of the basin. Sedimentation occurs in the settling zone and, upon removal from the water column, the solids accumulate in the sludge zone. The clarified liquid is generally collected over the entire cross-section of the basin at the outlet zone and is discharged. Under ideal conditions (no mixing or turbulence), required retention time is the time required for a particle that starts at the top of the inlet zone and settles to the floor of the basin at or before the junction of the outlet zone. The key parameter for the design of settling basins is the volumetric flow of water per unit surface area of the basin or overflow rate ($V_o$).

Any particle with a settling velocity ($V_s$) greater than the overflow rate ($V_o$) will settle out of suspension. Other particles, for which $V_s < V_o$, will be removed in the ratio $V_s/V_o$, depending upon their vertical position in the tank at the inlet.
Settling Basins

6 ft x 6 ft x 6 ft fiberglass tank
Several management strategies were tried out on the settling basin for removing accumulated wastes either in the center drainline or accumulated in the sump itself. Return water from the settling sump was taken from only a few inches below the surface. This allowed very low upward flow velocities in the settling sump, which provided for excellent removal of heavy biofloc and any uneaten food particles (although rarely seen). The above figure shows the solids removed in kg, calculated by taking the mean Total Suspended Solids from three gab samples and multiplying by the volume of water flushed from the settling basin. The standard protocol that developed was to first turn off the return pump, isolate the sump from the production tank with a knife valve and allow the solids in the sump to settle for about half-hour. The second pump was then used to lower the water level so that only about 225 gallons of water remained. The remaining water was then mixed, sampled and pumped to an aerobic lagoon located next to the greenhouse. This procedure worked very well and required very little staff time. In theory, it could be automated, although at some expense.
The above figure shows the cumulative solids removed by the settling sump and the model of solids production based on heterotrophic conversion of the ammonia-nitrogen produced by the feed. The model starts at day 40 because the system took that long to come to equilibrium and develop a robust heterotrophic bacterial bloom. Maximum daily feed was approximately 5 kg (11 lbs).
The above figure shows the cumulative solids removed by the settling sump and the model of solids production based on heterotrophic conversion of the ammonia-nitrogen produced by the feed. The model starts at day 40 because the system took that long to come to equilibrium and develop a robust heterotrophic bacterial bloom. Maximum daily feed was approximately 5 kg (11 lbs).
The basic design concept was to operate the raceway as a series of square/octagonal tanks, each having a center drain for continuous removal of solids and sludge. A series of vertical discharge pipes were placed along the raceway sidewalls that directed recycle water through orifice discharges tangentially to the walls to establish the desired rotary circulation. This was then combined with the concept of the ‘Cornell double drain system’, where 10% to 20% of the total flow into a tank was removed from a center bottom drains and 80 to 90% of the flow was removed from the side drains.

Settable wastes and sludge were then removed from the center drains and collected in a settling sump. The systems was stocked with marine shrimp, *Penaeus vannamei* and managed as a zero-exchange low salinity production system for several months. Research was conducted into new methods of maintaining or controlling the dynamics of the water quality of the system through the addition of carbon to stimulate heterotrophic bacterial production. In addition, suspended solids concentration in the production tank was maintained at acceptable levels by controlling the amount and frequency of discharge from the settling tank. Basic water quality parameters were routinely measured, including temperature, dissolved oxygen, ammonia-nitrogen, nitrite-nitrogen, nitrate-nitrogen, alkalinity, total suspended solids (TSS), and volatile suspended solids (TVS).
Production Systems - Trays

Four – four tiered trays – PVC / screen material – 4 ft x 8 ft
Production Systems - Trays

Mixed-Cell Mean Velocity Profile Cell #3
10 mm Orifices Bottom (corresponding data sets)

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Production Systems - Trays

Mixed-Cell Mean Velocity Profile Cell #3
10 mm Orifices  Mid-depth  (corresponding data sets)

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Conclusions

• Mixed-cell raceways have significant potential as growout and production systems

• Velocity profiles suggest that systems can be designed with both low and high exchange rates

• Solids management is straightforward and easy

• Construction costs are moderate

• Space utilization is maximized
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Opinions, conclusions, and recommendations are of the authors and do not necessarily reflect the view of the USDA.

All experimental protocols involving live animals were in compliance with Animal Welfare Act (9CFR) and have been approved by the Freshwater Institute Animal Care and Use Committee.
Questions