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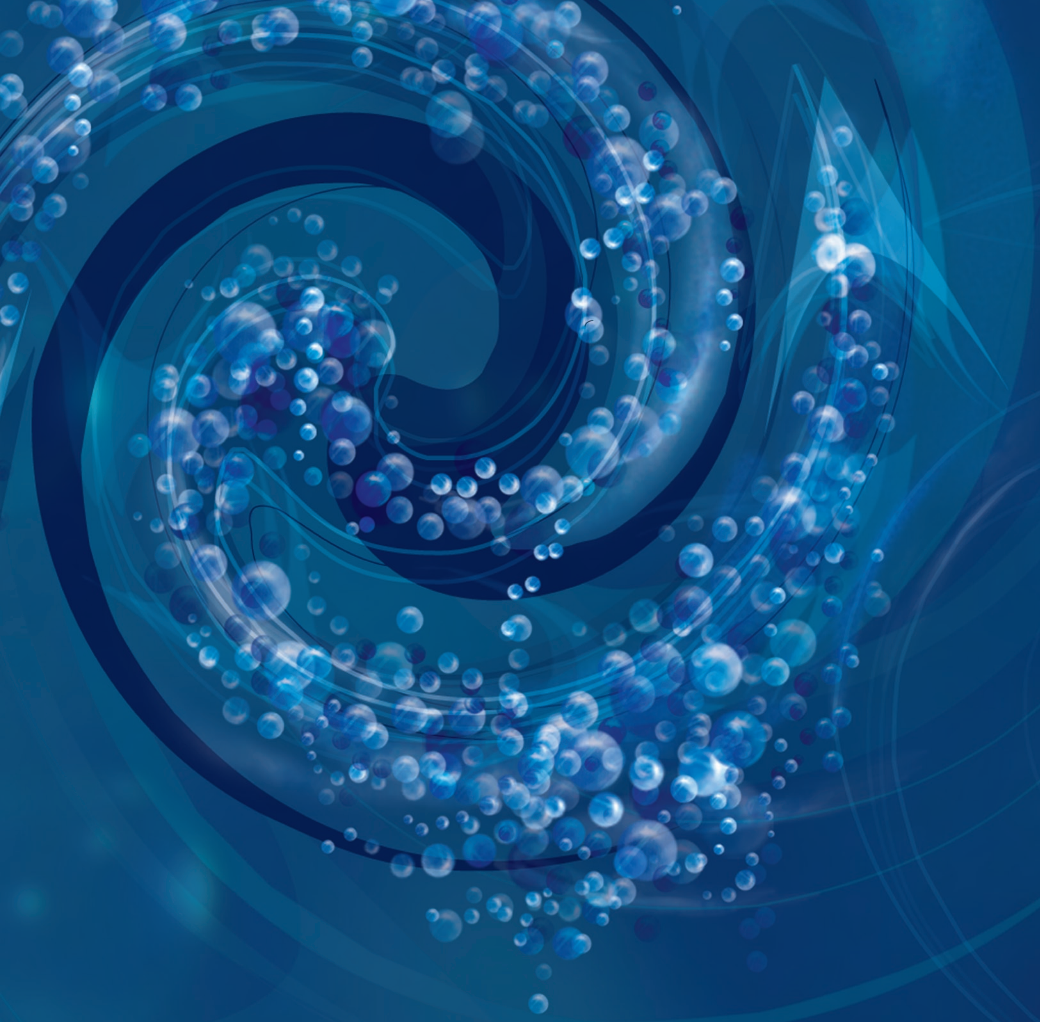

RECIRCULATING SYSTEMS NH_3

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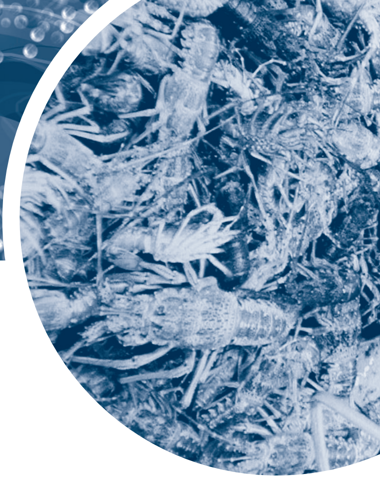
CONTENTS



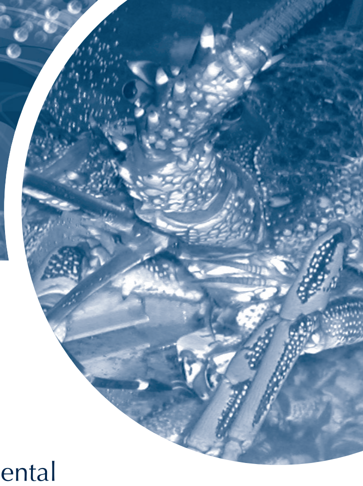
INTRODUCTION 1

Two main systems are currently being used for holding lobsters: flow-through and recirculating. In flow-through systems, the water that is pumped into a tank is only used once. After passing through a tank all the water goes to waste, meaning that waste products should not build up to high levels. In recirculating systems, the majority of the water is re-used after each pass through the tanks, first being treated to remove waste products before being returned to the tanks. As a result recirculating systems have a greatly reduced water demand.

Flow-through systems for holding lobsters are generally easy to design and operate, however, there is little control over the quality of the water. It is dependent on the point source and may not be of constant optimal quality. Even though initial set up costs may be higher, there is an increasing interest in and movement towards the use of recirculating holding systems. Experience has shown that lobsters can be successfully held in recirculating systems.

Recirculation systems have practical application to a range of situations, including: where seawater of optimal quality is not guaranteed (e.g. estuaries); where pumping costs from the sea are excessive (inshore holding facilities); where specific control over temperature or other environmental parameters is required; where lobsters are being held outside their normal geographical range; and where environmental controls are in place to reduce nutrients in effluent water. As lobsters are generally not fed whilst in captivity and as they possess a relatively good tolerance of poor water quality, the systems can be relatively simple.

This publication describes the principles of recirculating systems as they apply to the holding of rock lobsters. It covers all aspects of such systems, from design to daily operation. There are a number of reference manuals/books on recirculating systems, some of which deal in much more detail with aspects mentioned in this manual and the reader is referred to them if they require further information. This publication provides information specifically for lobster holding systems based on recently obtained data on ammonia excretion rates and ammonia tolerance of lobsters.



BASIC PRINCIPLES

2

Holding systems must provide a suitable environment for the lobsters. Critical environmental parameters include the concentrations of dissolved oxygen, ammonia, nitrite and carbon dioxide (Losordo et al., 1998). Nitrate concentration, pH, salinity and alkalinity levels within the system are also important. In flow-through systems the main limiting water quality parameter is dissolved oxygen. Sufficient water needs to be pumped through or the water needs to be aerated to ensure lobsters are supplied with sufficient oxygen. As the water is only used once and the turnover time is rapid then other water quality parameters should not reach toxic levels. That is assuming that the incoming water is of good quality in the first place.

In recirculating systems the main limiting factor is still dissolved oxygen, however the unionised ammonia (NH_3) concentration becomes increasingly important, and is probably the next limiting factor. Ammonia must be removed from the system at a rate equal to the rate of production to maintain a safe concentration (Losordo et al., 1998). Controlling the concentration of unionised ammonia in the tanks is the primary objective of recirculating treatment system design.

All effective recirculating systems need to remove waste solids, oxidise ammonia and nitrite, remove carbon dioxide, and aerate the water before returning it to the holding tanks. Waste solids are generally removed via some form of mechanical filtration, ammonia and nitrite via biological filtration, and carbon dioxide by the provision of an air/water interface. Aeration of the water is also achieved across the same air/water interface. In simple systems, such as glass aquaria, all these processes are done within the holding tank. In more complex systems, most if not all of the processes are undertaken external to the holding tank.

2.1 ADVANTAGES AND DISADVANTAGES OF RECIRCULATING SYSTEMS

2.1.1 ADVANTAGES

Low water requirements

A properly designed and operated recirculating system requires a minimum daily input of water, just enough to clean particulate waste filters and to replace water lost to evaporation. This permits the construction of holding systems at considerable distances from a seawater supply, thus allowing them to be situated in more convenient positions, such as close to airports and markets.

Control of water quality

The water quality in flow-through systems is largely dependent on the quality of the source water. At times that can be less than ideal: rain can cause decreased salinity, algal blooms can cause low oxygen levels, storms/wave action can cause increased sediment loads. Efficient recirculation systems largely overcome these problems.

Good water quality can be managed in recirculating systems through effective operation of the system components and by avoiding water exchanges / collection in poor water quality events.

Control of water temperature

Good control over the water temperature is one of the major advantages of recirculating systems. The optimal water temperature for holding can be much more easily and cheaply maintained in recirculating systems than in flow-through systems. Also species can be held in geographical areas outside their normal range e.g. temperate water lobsters can be marketed in tropical areas. The temperature is normally maintained towards the lower end of the temperature range that a particular species is able to tolerate. At lower temperatures lobsters are less active, and thus require less oxygen and excrete lower levels of waste products, and are less aggressive. Lobsters can also be chilled down within the holding tanks, meaning there is less need for handling of the lobsters (i.e. moving them to a separate chilling tank) just prior to transport. This may increase the ability of lobsters to handle transport conditions and thus extend the life of the lobsters during transit.

Increased ability to control biofouling

Biofouling, both within pipework and within the tanks, is a significant problem within seawater systems. Biofouling in the pipework will lead to decreased flows and higher pumping costs. The piping will need to be cleaned on a regular basis, which can be expensive. Biofouling in the tanks also needs to be removed on a regular basis; the cleaning process can result in damage to the tanks. As the amount of water entering recirculating systems is relatively small, it is easier to prevent the growth of biofouling organisms. Water can be treated either chemically (e.g. chorinate/dechlorinate a header or storage tank) or mechanically (filtration). Filtration to 100 µm will remove the larvae and eggs of most biofouling organisms, such as mussels and fan worms.

2.1.2 DISADVANTAGES

Increased complexity

Recirculating systems are an intricate balance of bacterial populations, engineering equipment and seawater. The system operator must understand how the balance is created, maintained and most importantly, what to do when that balance is upset. Experience in the management of recirculating systems is a key component of their operational success. This is probably one of the principal reasons why recirculation systems for holding lobsters are not more commonly used.

Higher set up costs

As more equipment is required the setup costs can be higher. However, in some instances the use of recirculating systems can be cost-effective. The costs of pumps and electricity to provide water for flow-through systems can be large and filtration equipment can be required to prevent the flow of debris (silt/sediment/sand) into the tanks. A key to the successful use of recirculating systems is the use of cost-effective water treatment system components (see Section 3).

3

SYSTEM COMPONENTS

The major components of a recirculating system are the water supply, holding tanks, solids filter, biological filter, temperature control system, oxygen and carbon dioxide control system and sump tank (Fig. 1). Other more sophisticated components, such as ozonation and ultraviolet filtration, can be added, but are generally not required in lobster holding systems. A reservoir of fresh seawater is also a necessity but not shown in Fig. 1.

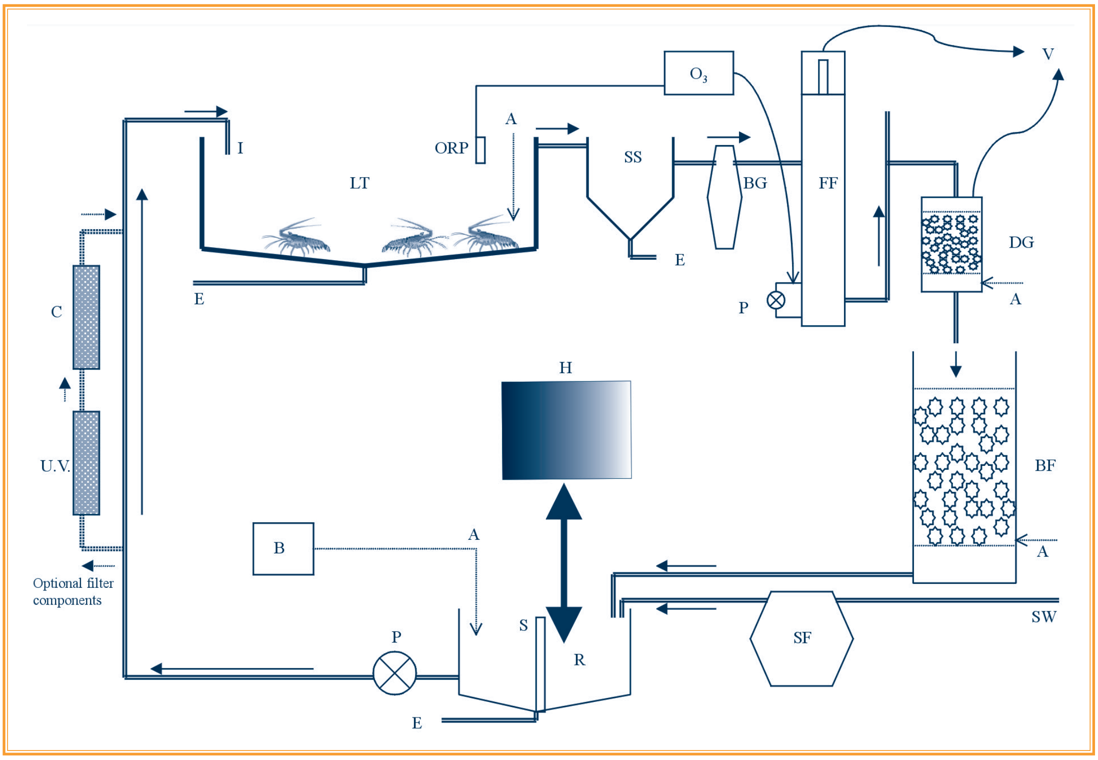


Figure 1. Schematic diagram of a recirculating system for holding lobsters showing all possible components. Abbreviations, A = Airline from blower (Note: not all connections to blower shown); B = Blower; BG = Bag filter; BF = Biofilter; C = carbon filter; DG = Degassing of residual ozone and CO_2 (in a packed column); E = Effluent discharge; FF = Foam fractionator; H = Heat-exchange unit; I = Inlet; LT = Lobster holding tank; O_3= Ozone generator; ORP = Redox probe (controls ozone generator); P = Pump; R = Reservoir (Sump tank); S = Standpipe; SF = Rapid sand filter; SS = Swirl separator (or other solids filter); SW = Fresh seawater supply; U.V. = Ultraviolet light steriliser; V = Venting off ozone gas and CO_2, outside of building.

3.1 WATER SUPPLY

3.1.1 INCOMING WATER

Water to add to the recirculating system would generally come either directly from the source (sea/estuary) via pipe or be transported to the system by truck. Either way it is important that it is obtained from a source of good quality water. If you are reliant on pumping from the sea/estuary you cannot always be sure that the water quality is going to be of suitable quality when it is required. It is because of this that a water reservoir (see Section 3.1.2) is an important component of a recirculating system.

3.1.2 WATER RESERVOIR

A reservoir of fresh seawater is a necessity. The reservoir provides backup if the quality of the water in the recirculating system decreases and a water exchange is necessary. It is not always possible to obtain suitable quality replacement water when it is required, especially if the holding system is situated a long way from a reliable seawater supply. It is also useful to have the ability to easily add water to the system to make up for losses associated with general day-to-day operations (backflushing, siphoning). Ideally the volume of water maintained as a reservoir should be similar to that in the system and it should be maintained at a similar temperature to that in the holding tanks.

3.2 HOLDING TANKS

Broadly, two methods are being used to hold lobsters: the tank or the stacked bin method. Each method offers advantages and disadvantages (adapted from Harvie, 1993).

	ADVANTAGE	DISADVANTAGE
TANK	Freedom of movement of lobsters Easy to see weak/dead lobsters	Take up a lot of space Extra handling of lobsters involved in transferring between tanks
STACKED BINS	Space efficient Reduced handling (especially just prior to live export)	Difficult to see weak/dead lobsters

A combination of the two methods may be the most appropriate. Tanks can be used for the initial stages of holding when the health of the lobsters needs to be regularly checked. Lobsters that are to be live exported can then be moved to the bin system in appropriate sized lots where they can be slowly chilled to the export temperature prior to packout. The major advantage of this system is that the lobsters do not undergo any handling stress just prior to the packout. Therefore, they should be in the optimal physiological condition to handle the stresses of live export. Tank systems can also be set up to achieve this advantage by having the ability to decrease the temperature in a tank where the correct number of lobsters have been previously stored in baskets. Extra chilling capacity may be required on the "live export preparation" tank to achieve this.

3.2.1 TANK DESIGN

There are two major design requirements for the holding of lobsters in tanks. First, they need to supply the lobsters with the appropriate conditions to maintain them in optimal condition. Second, to achieve an efficient processing operation the handling of lobsters, both into and out of the tanks, needs to be a simple process.

Commonly used tank designs include long narrow raceways or troughs, square or rectangular tanks, and circular tanks (Tetzlaff and Heidinger, 1990). Tank construction materials are usually constrained by budget. Common construction materials are concrete, block and mortar, fibreglass and plastic. Movable fibreglass or plastic tanks give some flexibility in the overall design of the holding system.

Raceways have many features that make them the most suitable tank design. If they are designed so that two baskets fit across the width of the raceways, the baskets can be easily accessed from the sides. Aeration would be required along the length of the raceway to ensure water quality, e.g. oxygen levels need to be maintained, and to ensure that no dead spots (areas of low flow) develop. There is likely to be some buildup of the ammonia level at the outlet end of the tank but it should not be excessive as long as there is a good water turnover rate. If the baskets used for holding lobsters are large and not easy to manually handle, some sort of mechanical lifting device (e.g. a gantry system) would need to be incorporated into the design of the system.

If lobsters are to be held in tanks they should be placed within baskets. Lobsters should be size-graded and selected when they first enter the holding system. Lobsters judged as being suitable for live holding should be placed into the storage baskets and these placed into the tanks as soon as possible after grading.

3.3 WASTE SOLIDS REMOVAL

Waste solids add significantly to the load on a recirculating system. The breaking down of the waste solids by bacteria results in the consumption of oxygen and generation of ammonia. This organic matter can also clog the biofilter, interfering with the flow of the water through, and the balance of, the biofilter. Thus, waste solids should be removed from the system as quickly as possible (Losordo et al., 1998). Numerous methods are available to remove this waste; an efficient system should remove as much of the waste as possible and concentrate it for easy removal, while using minimal amounts of water and energy (Tetzlaff and Heidinger, 1990). Waste solids can be classified into several categories: settleable, suspended (which includes floating) and dissolved. Specific methods are required to deal with each of the different forms.

3.3.1 SETTLEABLE SOLIDS

Large amounts of settleable solids material (faeces, regurgitated feed, seaweed, sand) enter the system when new lobsters are added. Due to the design of most holding tanks much of this waste settles out in the holding tanks. This should not be seen as a significant problem as it is better for the material to be in the holding tanks, where it can be more easily and regularly cleaned out, than for it to move into the biofilter. Lobsters should be separated from the waste material and the easiest way to achieve that is by keeping them in baskets supported off the floor of the tanks. Unless the tanks are specifically designed to allow easy removal of this waste material (e.g. V-shaped bottom) then regular siphoning of the tanks will be required. The loss of water associated with the siphoning can be substantial and it will need to be replaced or reused after the waste material is filtered from it. Another option would be to have the capacity to store the water from the recirculating system in a separate tank and then clean out the settled material approximately every week or after a tank is emptied of stock. To be able to easily clean a tank it is important that tanks have a good sized drain outlet at the bottom.

Another way of dealing with the large influx of waste solids is to have a flow-through settlement or purging tank, where lobsters are purged for 24 hours prior to being moved into the main recirculating tanks. Faecal production and high rates of ammonia excretion usually cease within 24 hours and thus most material will remain in the settlement tank when the lobsters are moved on. However, this method adds another handling step, adding further complexity to the process.

3.3.2 SUSPENDED SOLIDS

Other waste material does not settle out (suspended or floating solids) and specific mechanical filtration equipment is required to remove it. These filters catch and hold large and small particles from water flows for removal or *in situ* decay (Moe, 1992). The filtration is usually incorporated in the system between the tanks and the biofilter. This filtration can be as simple as the addition of mat filters placed over the top of the biofilter. Although they can serve a useful purpose, simple filtration units are not generally successful mainly because they are improperly designed. Also they tend to be awkward to clean, meaning cleaning is not undertaken as regularly as required. Poorly designed or cleaned filter mats result in water short circuiting the filter mats thus making them ineffective. Thus, it is important to have a properly designed mechanical filter in place.

There is a range of mechanical filters to choose from. The ones most applicable to lobster holding systems are filter sumps, sand filters, filter bags, canister type filters and microscreens:

- Filter sumps incorporate the material used for mat filters (as discussed above) into specially designed sumps, and waste is collected passively as the water flows through them.
- Pressurised sand filters are commonly used in many aquaculture applications. They consist of an enclosed vessel that is typically half to two thirds full with sand. Water is pumped into the top of the filter under pressure and is forced through the sand. The sand acts as the filter and the size of particle that can be filtered is largely dependent on the size of the sand grains. To clean sand filters the water flow is reversed and they are backflushed. Their limitations in recirculation systems are that, in addition to reasonably high operational costs, they use a lot of water for backflushing. If sand grain size is too fine, the requirement for backflushing increases
- Filter bags are cloth materials (usually nylon or polypropylene) in the shape of a bag (Huguenin and Colt, 2002) which are attached to the end of a pipe. The pipe usually discharges over or within an open tank and suspended solids are filtered out as the water passes through the bag. Head loss through the bags is small when they are clean. They need to be cleaned regularly. Filter bags are simple to set up and operate and are useful filters in the appropriate situation.
- Canister type filters are enclosed vessels designed for the removal of fine solids and operate under pressure. A filter material (e.g. mesh bag, cartridge) is inserted in the vessel and water passes from the inside to the outside. Filtration to less than 1 µm is possible with such filters although the cost of replacement of the filter material, and the cost of pumping is high. They require regular manual cleaning, usually once per day, but more frequently if the particulate content of the water is high.
- Microscreens are available in a wide variety of materials, configurations, and (Huguenin and Colt, 2002). Drum filters, disc filters, conveyer/belt filters are some of the different types. They are automatically cleaned filters where water jets are used to clean the screen. The screen material is constantly moving and is cleaned as it rotates. Such filters are capable of removing solids as small as 6 µm. These types of filters have not been used much in lobster holding facilities. They have the advantage that they have a very low head loss (typically 10-70 mm) which reduces the pumping costs in recirculation systems.

3.3.3 FINE AND DISSOLVED SOLIDS

Much of the waste material will be in the form of fine or dissolved solids (< 30 µm) which cannot be easily removed by sedimentation or mechanical filtration. Foam fractionation (see Section 3.7.1) is the most practical method of removing these waste materials, and thus foam fractionators are very important components of recirculating systems.

3.4 BIOLOGICAL FILTRATION

Ammonia exists in two forms in water – unionised (NH_3) and ionised (NH_4^+). Together these make up the total ammonia level which can be measured in water. NH_3 is much more toxic than NH_4^+. The percentage of ammonia present as NH_3 is dependent on the temperature and pH of the water, increasing with both parameters. At the temperature and pH normally found in lobster holding systems NH_3 represents 1-5% of the total ammonia. While the lethal concentration of ammonia has been established for many species, including lobsters, the sub-lethal effects of ammonia are relatively unknown. There are a number of methods of removing ammonia from the water and the most widely used method is biological filtration.

3.4.1 THE NITROGEN CYCLE AND BIOLOGICAL FILTRATION

Biological filtration is the most common method of preventing the build-up of toxic levels of ammonia in recirculating systems. Basically, a biofilter is simply a surface on which bacteria grow. These bacteria convert the toxic ammonia to the relatively non-toxic nitrate via the natural nitrogen cycle.

NH_3 (ammonia) > NO_2 (nitrite) > NO_3 (nitrate)

Ammonia is oxidised to nitrite by a group of chemautotrophic (chemotrophic = chemical eaters) bacteria, of which the *Nitrosomonas* bacteria are the most well known genus. They need a substrate to live on (the biofilter material) and a source of ammonia and oxygen in a damp or aquatic environment to grow and form colonies (Moe, 1992). Nitrite is oxidised to nitrate by another group of chemoautotrophic bacteria, of which the *Nitrobacter* bacteria are the most well known genus. These bacteria need a source of nitrate and similar environments to *Nitrosomonas* to grow and form colonies. Bacteria of both groups are present in soils, freshwater and marine waters throughout the world (Moe, 1992).

Nitrate accumulates in the system until it is removed; in most systems this is generally achieved via a water change. Other bacteria can convert the nitrate to nitrogen gas but this process is unlikely to happen in most recirculating systems.

3.5 AERATION AND DEGASSING

The addition of oxygen to water and the release of excess carbon dioxide can be achieved through a variety of devices such as air diffusers, spray bars or packed columns. Maintaining oxygen concentrations of greater than 80% saturation is highly recommended in rock lobster holding systems, therefore aeration into the tanks and into the biofilter is a necessity. Aeration methods for rock lobster holding systems are outlined in a companion guide to industry by Crear and Allen (2002). Generally, increases in carbon dioxide concentration are the primary reason for decreases in the pH of recirculating systems for holding lobsters. While spray bars and diffusers are effective in adding oxygen they can be ineffective for removing carbon dioxide. Packed columns (also referred to as degassers), which have a large air to water ratio, are a simple and efficient method of removing carbon dioxide from the water. Such columns are also very good at removing supersaturated gases, which can have a detrimental effect on the health of the lobsters, and thus provide a safety net within the system.

The use of pure oxygen is generally not necessary, as correctly designed aeration systems (i.e. adding air, which is 20% oxygen) should more than adequately meet most systems requirements.

3.6 TEMPERATURE CONTROL

Cooler temperatures tend to reduce activity, oxygen consumption, waste excretion and aggressive behaviour of lobsters. There are many sources of heat which act to increase the water temperature; pumps, aeration and external air temperature are the largest influences. Heat exchangers are the most common method of controlling the water temperature. Chilling units with titanium coils are the most suitable. Some units contain copper coils. Copper can be detrimental to the health of lobsters at even quite low concentrations. Although copper coils can be coated with plastic to prevent contact with the seawater, coatings are susceptable to failure and copper coils should not be used. The appropriate size unit for controlling temperature will be dependent on many factors, including the required water temperature, water volume and air temperature. Insulated tanks (e.g. foam sandwich fibreglass) will improve the efficiency of water temperature control.

Chilling of water is often achieved through chilling the air in the room. This is an inefficient way of chilling water, however there may need to be some sort of air temperature control maintained because if the air temperature is high the transfer of heat to the water may result in the heat exchangers have trouble maintaining the right temperature.

3.7 OTHER COMPONENTS

3.7.1 FOAM FRACTIONATOR

Foam fractionators (also referred to as protein skimmers) are used to remove fine and dissolved solids from the water. Foam fractionation is a process of introducing air bubbles at the bottom of a closed column of water. As the bubbles rise through the water column, solid particles attach to the bubbles' surfaces, forming the foam at the top of the column. The foam build-up is then channelled out of the fractionation unit to a waste collection tank. The process can be used to significantly reduce water turbidity and oxygen demand of the system (Losordo et al., 1998). Although they are not always incorporated into systems, correctly functioning foam fractionators are one of the most important components to include in a recirculating system. They can be purchased from aquaculture equipment suppliers, and are available in a range of sizes to suit the system demands. The size of fractionator is principally based on the total volume of water in the system.

3.7.2 OZONE

Ozone is a colourless gas (O_3) that is commonly used as a steriliser. Ozone is generated by passing oxygen (either as air or as pure oxygen) through an electric discharge. It is a very strong oxidising agent, highly toxic to all forms of life and corrosive to many materials. In recirculation systems ozone has several beneficial effects such as the breakdown (through oxidisation) of long chain molecules into simpler forms which can then be broken down further in the biological filter. It is through this process that ozone eliminates the yellow/brown colourations, that build up in recirculation systems. It is generally used in conjunction with a foam fractionator, with the ozone being introduced into the fractionating column via a venturi inlet. Control is essential, as over-dosing can result in concentrations harmful to both the lobsters in the tanks and to humans (through off-gassing of ozone into the air). The Redox level (which changes with the amount of ozone in the water) is the commonly used method of determining the amount of ozone in the water. Although a very useful tool in many situations, the use of ozone in recirculating systems for holding lobsters is usually unnecessary.

3.7.3 ACTIVATED CARBON

Activated carbon is available as a powder or in granular form, with the granular form being the most practical for commercial use. It has the ability to absorb organic and inorganic molecules to its surface. Carbon is often used in addition to a biofilter as a polishing stage. Again although a very useful tool in many situations, the use of activated carbon in recirculating systems for holding lobsters is usually unnecessary. However, it is an essential component if ozone is used as it removes toxic by-products.

3.7.4 ULTRAVIOLET DISINFECTION

Ultraviolet (or UV) light radiation is probably the most commonly used disinfection process with seawater. The effectiveness of the light depends on a number of factors including bulb wattage, age, cleanliness, the distance between the bulb and the organism you are trying to kill, the species you are trying to kill, the duration and intensity of light, and the clarity of the water. Although UV is a very useful tool in many situations, it is usually unnecessary in recirculating systems for holding lobsters.

3.7.5 LIGHTS

Lights generally need to be kept on 24 hours per day. Lobsters are naturally active at night, and the increased activity will lead to greater oxygen consumption and may result in lobsters crawling out of tanks. Only a low level of light is required to stop the activity. When work is undertaken the lights do not have to be bright, only sufficient to work safely and efficiently.

SETTING UP AND OPERATING BIOFILTERS

4

A biofilter is the heart of a recirculating system.

4.1 BIOFILTER DESIGN

The two most commonly used biofilter designs in lobster systems are the submerged bed biofilter and the packed column (or trickle) biofilter.

Submerged bed biofilters are characterised by having a fixed (non-moving) medium that is constantly under water; the water may flow either upward (up-flow) or downward (down-flow). The biofilter medium used in these filters is highly diverse and includes gravel (blue metal), calcareous gravel (e.g. oyster shell, crushed coral, dolomite), plastic beads and extruded or high surface area plastic media. The gravel substrates are low cost, buffer the seawater (at least the calcareous ones), however they have higher frictional head losses and are more prone to clogging with solids and short-circuiting than plastic media (Huguenin and Colt, 2002).

A packed column is basically a vessel, open to the atmosphere, containing a media, over which water falls by gravity. Packed columns are used for degassing, dechlorination and are the basis for trickle biological filters. In a properly designed trickling filter the water cascades over the medium in a thin film (Tetzlaff and Heidinger, 1990). This provides a large interface between the air and the water allowing the efficient transfer of gases into and out of the water. The media used in trickle filters is typically high surface area plastic with a large void space to minimise clogging. Air can be added to the base of the vessel to improve the efficiency of CO_2 removal. Constant aeration prevents CO_2 levels from increasing in the air inside the packed column.

4.2 BIOFILTER SIZE

The size of the biofilter required to service a holding system is largely dependent on two factors: the amount of ammonia being added to the system and the nitrifying capacity of the biofilter.

Most of the ammonia added to systems is excreted by the lobsters, although the bacterial degradation of organic material (e.g. uneaten and regurgitated feed, algae) would also add to the ammonia load. Lobsters also excrete some urea, which adds to the ammonia load. Data is now available on the ammonia output of lobsters under a range of conditions. Feeding has the greatest effect on the ammonia output of lobsters (Crear and Forteath, 2002). A flow-through purging tank (see Section 3.3.1) would minimise the influence of placing recently caught lobsters into a system, as the effect of feeding on ammonia excretion rate only lasts approximately 24 hours.

The nitrifying capacity of the biofilter is largely dependent on the water temperature and the surface area of the media. Nitrifying capacity increases with water temperature. Biofilter media with a large surface area to volume ratio will have a high capacity to undertake nitrification as higher numbers of bacteria can grow.

The following outlines the calculations to determine the appropriate volume of a biological filter in a recirculating system that will hold 1000 kg of *J. edwardsii* at 13°C. Lobsters are generally not fed when they are held in recirculating systems, therefore, the unfed rate of ammonia excretion was used. The ammonia excretion rate of a 500 g *J. edwardsii* at 13°C is 1 μg g^{-1} h^{-1} (i.e. for every gram of lobster, 1 microgram of ammonia is produced per hour), so a 500 g lobster will produce 500 μg (0.5 milligrams) per hour and 1000 kg of 500 g lobsters will excrete 24 g of ammonia per day (1000 kg x 1 μg g^{-1} h^{-1} x 24 h). The specific nitrification surface area (SSA) refers to the total exposed surface area of the substrate in the filter or the area on which the bacteria can grow. The SSA is calculated by the following formula:

SSA = TAN excretion rate / nitrification rate

TAN is the total ammonia nitrogen. The nitrification rates of biofilters used in aquaculture range from 0.15-1.0 g ammonia m^{-2} day^{-1} (Losordo and Hobbs, 2000). At 13°C, the rate would be expected to be towards the low end of that range. Therefore, a rate of 0.2 g ammonia m^{-2} day^{-1} is presumed. The SSA based on the above data is 120 m^{2} (i.e. 24/0.2). This allows the volume of substrate required to give the SSA to be calculated.

Required biofilter volume = SSA / Specific surface area of filter medium

It is assumed that the specific surface area of the filter medium is 200 m^{2} m^{-3}. Therefore, the required biofilter volume is 0.6 m^{3} (i.e. 120/200). However, this calculation does not take into account the contribution of urea to the ammonia nitrogen. If all of the urea was oxidised to ammonia then there would be ~ 20% more ammonia in the system. Thus, a biofilter of 0.72 m^{3} would be required. If the lobsters were to be fed in such a system the biofilter would be far too small to handle the ammonia load because of the large increase in ammonia excretion associated with feeding.

4.3 BIOFILTER CONDITIONING

Prior to adding lobsters to the tanks, it is necessary to condition the biofilter. That is, suitable populations of nitrifying bacteria must be encouraged to form a living film over the surface area of the filter media. These films of living bacteria consume and convert the ammonia produced by the lobsters. However, there is a lag period between the starting up of the recirculating system and the establishment of a suitable population of bacteria (Fig. 2). When starting up a biofilter it is important to constantly monitor the ammonia and nitrite concentrations. Under normal start up procedures the lag period can be several weeks. There are several ways to decrease the start up time.

- Bacterial cultures can be added to the system. Commercially concentrated bacteria are readily available. It is important that the bacteria used are grown in similar environmental conditions (e.g. temperature, seawater not freshwater) to that present in the biofilter.
- The system can be run at a slightly higher temperature than normal to increase the rate of bacterial growth.
- Add media from an already operating biofilter. It is suggested that 10-30 percent of the new biofilter volume should be made up from the operating biofilter material. It is important that both biofilters are operating under similar environmental conditions.

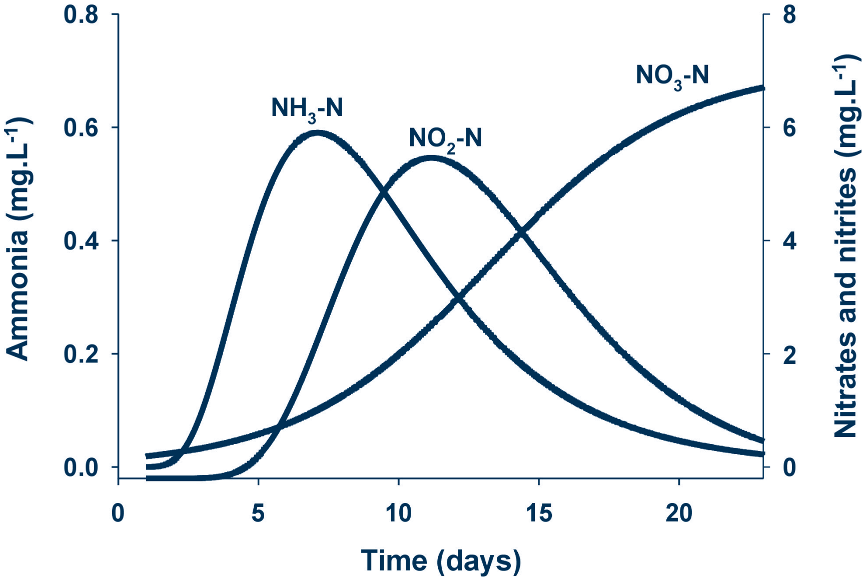


Figure 2. Representative diagram of biofilter start up over time.

4.4 SHOCK LOADING

Shock loading of a recirculating system occurs when there is a large increase in the ammonia load, resulting in an imbalance in the system. The bacterial population in the biofilter will take time to handle the extra ammonia load, meaning the ammonia levels will be maintained above the desirable level for a significant period of time. Success depends on the ability of the system to restabilise as quickly as possible (Harvie, 1993). The holding of lobsters is characterised by the rapid turnover of stock and thus variable stocking densities within tanks. The main cause of shock loading is the introduction of lobsters. The introduction of greater than 10% of the weight already stocked into the system is likely to result in significant increases in ammonia. There are a variety of methods used to overcome and/or prevent shock loading.

- Extra weight of lobsters (biomass) can be added slowly over a number of days. Unfortunately, this is unlikely to be possible in most cases as the time of delivery and quantity of lobsters coming into a holding system is generally variable.

- Extra water changes can be employed whilst the system is acclimating to the increased load. Large quantities of suitable quality water need to be available.

- The maximum biofiltration capacity of the system can be maintained by artificially feeding the bacteria in the filter during times of low stocking. Therefore, if a system can hold four tonnes of lobsters and only one tonne is in it, then ‘artificial’ ammonia equivalent to that produced by three tonnes of lobsters can be added to the system daily. This should be added slowly over the course of the day so that the addition of the artificial ammonia does not result in ammonia peaks. Ammonium chloride (NH_4Cl) is the most commonly used source of ammonia.

- Some biofilter material can be maintained fully operational (by artificial feeding with ammonia) in a separate system and moved into the biofilter for the stocked tanks as required.

- Appropriate quantities of bacterial cultures can be added to the biofilter when the extra stock is added to the system. Commercially concentrated bacteria are readily available.

- New stock can be spread out across a number of completely separate systems so that the load into any particular system is not large. This may make it difficult to trace stock.

It is under the conditions of shock loading that the experience of the operator becomes important. Shock loading does not necessarily need any action at all. Lobsters are reasonably tolerant of ammonia and if all other water quality parameters are kept optimal then they can handle moderate levels of ammonia for a couple of days. It is essential that the operator is able to determine when action is required to ensure that both the lobsters and the biofilter are maintained in optimal condition.

5

WATER QUALITY PARAMETERS AND MONITORING

Once a recirculating system is operating it is important that the appropriate water quality parameters are monitored regularly. Operators need to be trained in water quality management and need to understand the physiological needs of the organisms, which include those in the biological filter. This Section outlines the important parameters to measure and the frequency that they need to be monitored.

To be able to accurately measure the parameters suitable sampling equipment needs to be available. This section also outlines some of the sampling equipment choices. Sampling equipment can be expensive, but considering the risks they are a necessary outlay. Sampling equipment is varied but can be basically broken into two groups: a) test kits or b) meters. Each has their advantages and disadvantages.

a) Test kits are typically simple to use. While each test is usually less accurate than can be obtained with meters, test kits are adequate for most applications. Although they are generally relatively cheap compared to meters, they tend to be more expensive per sample. If a lot of testing were to be undertaken it would usually be cheaper to buy a meter.

b) Meters on the other hand are generally more difficult to use, requiring some technical knowledge about their operation and maintenance. They also generally require a larger initial capital outlay. Most importantly, they require calibration on a regular basis to ensure that accurate results are obtained. Some meters are capable of measuring more than one parameter e.g. oxygen, salinity, pH and temperature.

Tolerance limits for various water quality parameters for the southern rock lobster (SRL) and the western rock lobster (WRL) (modified from Crear and Allen, 2002)

PARAMETER	TOLERANCE LIMITS
Temperature	SRL: 8 to 23°C (OHT[A] 9-13°C)
	WRL: 12 to 31°C (OHT 17-23°C)
Dissolved Oxygen (% saturation)	Min. 70%, preferably >80%
Salinity (g kg^{-1} or ppt)	30 to 38
Ammonia (mg L^{-1})	< 2
Nitrite (mg L^{-1})	< 5
Nitrate (mg L^{-1})	< 100
pH	7.8 to 8.4
Redox (mV)	200 - 350
Hardness (ppm)	100 - 200

[A] OHT – Optimum Holding Temperature

5.1 DISSOLVED GAS

5.1.1 OXYGEN

Monitor weekly or after system changes

The oxygen concentration in new systems should be checked regularly (every 2-3 h) for a few days to ensure that there is a good understanding of the normal oxygen concentrations, over a range of stocking densities. Provided appropriate stocking densities, flow rates and aeration are maintained the oxygen concentration should not vary greatly. Thus, in the longer term it is probably only necessary to measure the oxygen concentration on a weekly basis. If there were changes to the system (e.g. temperature change, increased stocking density, pump or aeration problems) then regular checking of the oxygen concentration is vital. It is also important to get an understanding of the oxygen concentrations at a range of points throughout the system e.g. at the influent and effluent of the biofilter, and at the top and the bottom of the tanks.

Oxygen meters are an expensive capital outlay, varying from just under $1000 to many thousands of dollars for highly complex integrated systems. Oxygen test kits, which generally cost several hundred dollars and do around 100 tests, are also available. Oxygen probes that provide a permanent display and alarm capability are available, and would be worthwhile considering in some systems.

5.1.2 CARBON DIOXIDE

Carbon dioxide (CO_2) is a by-product of lobster and bacteria respiration and it can accumulate within recirculating systems. Although carbon dioxide itself may not be toxic to lobsters at the concentrations normally found in holding systems, increased levels of carbon dioxide result in a lowering of the water pH.

It is reasonably easy to determine if a drop in pH is due to an accumulation of CO_2. Take a sample (500 mL or greater is best) of the tank water and place it into a container. Measure the pH and then place an airstone into the container and aerate the water vigorously. The water in the container should be maintained at the same temperature, therefore place the container in the main tank and use it as a water bath. After 1 hour check the pH again. If the pH has increased noticeably (>0.1 of a pH point) then CO_2 is accumulating and an increase in the degassing ability of the system is necessary.

5.2 TEMPERATURE

Monitor continuously

Temperature monitoring is relatively easy, and cheap, with many types of thermometers to choose from. It is up to individual preference whether a glass thermometer or a thermocouple with digital readout. Prices range from a few dollars to several hundred dollars. Potential contamination of lobsters from mercury and broken glass are an important consideration against the use of glass and mercury thermometers. A reasonably good quality digital thermometer should be able to be purchased for less than $50. A thermocouple thermometer placed in the tank with a permanent digital display that is clearly visible is the best option. Ideally the system should be set up so that an alarm is activated if the temperature moves outside the optimal set range.

5.3 pH

Monitor weekly or if system changes

pH is the measure of how acidic or alkaline a product is and is usually measured between 0 and 14. Seawater is always slightly alkaline with a pH between 7.8 and 8.4. As lobsters are marine animals, they require their holding water to be of the same pH range. In partial or full recirculation systems, pH should be tested in conjunction with water hardness. If there are changes to the system (e.g. temperature change, increased stocking density, pump or aeration problems) then checking the effect on pH is vital. If you find that the pH of your holding system is below the normal parameters for seawater then you must take action to buffer the water (using calcium carbonate and/or sodium bicarbonate, see Section 5.6.1) or make more regular water exchanges. CO_2 build-up causes a decrease in pH, therefore it is necessary to ensure the CO_2 is removed either by strong aeration, partial water change or via a device that creates a large air/water interface e.g. trickle filter or packed column.

To determine the level of pH in your holding system you can use a pH meter (most accurate method) or test strips (give a general estimate). pH meters range in cost from around $150 to several thousand dollars. Test kits can be purchased for around $20 to $100 and will generally do between 50 and 300 tests. pH probes that provide a permanent display and alarm capability are available, and would be worthwhile considering in some systems.

5.4 SALINITY

Monitor weekly

Salinity is the term used for the measurement of the total amount of salts in seawater. It can be measured with a refractometer, hydrometer or salinity meter. Seawater generally has a salinity of 33 to 35 g kg^{-1} (g L^{-1}). Levels outside this range occur as the result of factors such as rainfall, ocean currents and evaporation. As seawater is heavier than fresh water, water for topping up recirculating systems should be sourced from well below the water surface. It is preferable that water is sourced from as oceanic a site as possible (i.e. not from an estuary). Even so, the salinity of the water should be checked prior to it being added to the recirculating system.

Evaporation, resulting in elevated salinity levels, can be a problem in recirculating systems. Freshwater should be used to decrease the salinity. This needs to be done very carefully as a forgotten freshwater hose running into a recirculating system can lead to disastrous consequences. Add the freshwater in small amounts and check the salinity regularly. If a system contains 10 tonnes of water and the salinity is 40 g L^{-1}, to reduce the salinity to 35 g L^{-1} the calculation of the amount of freshwater to add is; the required salinity drop of 5 g L^{-1} (40-35) divided by the original salinity (40 g L^{-1}) multiplied by the system volume (10000 L), to give 1250 L freshwater (5/40 x 10000 = 1250). This should be added in 3-4 batches (over 2-3 days), ensuring the water is well mixed between each addition.

A refractometer measures the degree to which the path of light is changed (refracted) as it passes through a thin layer of water. The amount of refraction is directly proportional to the amount of salt in the water, the more refraction the more saline the water. Refractometers can be purchased for around $200 to $300.

A hydrometer is used to determine the specific gravity (SG) of water and consists of a glass bulb with a weight at one end and a closed thin tube at the other. The greater the salinity the higher in the water the hydrometer will float. It is simply a matter of reading the salinity off the scale printed on the side of the tube (or converting the SG to g kg^{-1}). A reasonable quality hydrometer should not cost more than $50.

A salinity meter measures conductivity: the amount of electrical current that can be carried by seawater. The capacity of the water to conduct electricity is directly proportional to the level of salt in the water, the greater the current the more saline the water. Salinity or conductivity meters can be purchased for between $500 and $1000.

5.5 NITROGEN - AMMONIA, NITRITE AND NITRATE

Monitor daily

5.5.1 AMMONIA

Ammonia results from the normal metabolic processes of lobsters and from the bacterial decomposition of faeces, bait and dead animals. The unionised form of ammonia is the toxic part, and its concentration is dependent on the pH and temperature of the water. Ammonia will build up rapidly if lobsters are fed or if the biofilter's nitrifying bacteria *Nitrosomonas* are not adequately conditioned to handle a shock loading.

5.5.2 NITRITE

Nitrite is the intermediate step in the nitrification process. An increase in nitrite indicates that the *Nitrobacter* populations are not functioning well. Common causes of high nitrite are low oxygen in the biofilter and a surge of high ammonia (e.g. shock loading) (Tetzlaff and Heidinger, 1990).

5.5.3 NITRATE

Nitrate is the end product of the nitrification process and is generally regarded as having very low toxicity, thus it does not need to be monitored daily and weekly sampling is sufficient.

There is a wide range of kits available on the market to test these parameters, the choice of which to use is up to individual preference. Most have simple to follow instructions and can be completed within a matter of minutes. Generally a water sample is treated with reagents to produce a colour, which is then compared against colour standards. They are usually available for under $50 and will perform between 25 and 200 tests.

5.6 ALKALINITY AND HARDNESS

Monitor weekly or if system changes

5.6.1 ALKALINITY

Alkalinity (or carbonate hardness) of seawater gives an indication of its' buffering capacity i.e. the ability to prevent fluctuations in pH. It is a measure of the capacity of the water to accept acidity. Alkalinity is usually measured as either mg L^{-1} (milligrams per litre) $CaCO_3$ (calcium carbonate) or meq L^{-1} (milli-equivalents per litre), 1 meq L^{-1} = 50 mg L^{-1} $CaCO_3$. Ideally alkalinity should be greater than 100 mg L^{-1}. Commonly, calcareous biofilter materials such as coral gravel or oyster shells are used as a carbonate source. Even with such material the alkalinity can still decrease and it needs to be maintained with the addition of bases. Some bases commonly used, include hydrated lime or calcium hydroxide ($Ca(OH)_2$), quick or slaked lime (CaO), sodium bicarbonate ($NaHCO_3$), sodium carbonate (Na_2CO_3), calcium carbonate ($CaCO_3$), magnesium carbonate ($MgCO_3$). A 6:1 mix of sodium bicarbonate (*baking soda*) and sodium carbonate (*soda ash*) is added to increase the buffering capacity of the system and to control the pH within the desired range.

5.6.2 HARDNESS

Hardness is a general term to describe the total amount of cations of the earth metals (mainly calcium and magnesium) in the water. In most waters, the hardness is similar to that of alkalinity, as calcium and magnesium are usually bound to the main alkalinity bases (bicarbonate and carbonate). Alkalinity tends to be used more as a measurement than hardness.

There is a wide range of kits available on the market to test these parameters, similar to those used for nitrogen, the choice of which to use is up to individual preference. Most have simple to follow instructions and cost and perform in a similar manner to nitrogen kits.

5.7 REDOX POTENTIAL or ORP

Redox is a word derived from a combination of the words Reduction and Oxidation. The redox potential or ORP (oxidation reduction potential) is a measure of the potential of the water for oxidation or reduction processes. The higher the reading, the higher the availability of oxidising agents in the water. Optimum levels of oxidising and reduction agents occur at around 300 mV and this is regarded to be the approximate ORP level of very good quality water. ORP levels in excess of 500 mV may prove toxic to life over prolonged periods, and ORP levels of over 600 mV are often maintained in systems where oxidising agents (such as ozone) are used to disinfect water. A low ORP level is a sign of poor water quality as the amount of oxidising compounds in the water is low, which limits the breakdown of organic matter.

The measurement of ORP is usually undertaken in recirculating systems when ozone is being used in the system. ORP meters are available for about $200. ORP controllers measure and control the ORP to within desired levels by regulating the input of ozone into the system. ORP controllers are available for about $500.

APPENDIX 6

The calculation of the water flow rate required to ensure ammonia levels are maintained at an acceptable level in a flow-through system is largely dependent on two factors: the amount of ammonia being added to the system and the specified safe level of ammonia to be maintained. It is assumed that aeration is in place and thus the only requirement of the flow-through water is to ensure ammonia levels do not get too high. It is also assumed that the incoming seawater is good quality, with negligible ammonia.

As discussed under Biofilter size (Section 4.2), lobsters excrete most of the ammonia added to systems, although the bacterial degradation of organic material (e.g. uneaten and regurgitated feed, algae) would also add to the ammonia load. We have used the data available on the ammonia output of lobsters under a range of conditions (Crear and Forteath, 2002) and recent experiments to calculate flow rates required for unfed and for fed or purging lobsters. The example used is a flow-through system that will hold 1000 kg of *J. edwardsii* at 13°C.

The required flow rate (FR) is calculated by the following formula:

FR (L h^{-1}) = TAN excretion rate (g h^{-1}) / Specified “safe” level TAN (g L^{-1})

The safe level of ammonia for holding lobsters is <2 mg L^{-1}

UNFED LOBSTERS

The ammonia excretion rate of an unfed 500 g *J. edwardsii* at 13°C is 1 μg g^{-1} h^{-1}; 1000 kg of lobsters will excrete 1 g of ammonia per hour and 24 g per day. If you have larger animals the amount of ammonia excreted per unit weight of lobster decreases; *J. edwardsii* of around 700 g excrete 0.63 μg g^{-1} h^{-1}.

For 1000 kg of 500 g lobsters FR (L h^{-1}) = 1 g h^{-1} / 0.002 g L^{-1}
= 500 L h^{-1}

For 1000 kg of 700 g lobsters FR (L h^{-1}) = 0.63 g h^{-1} / 0.002 g L^{-1}
= 320 L h^{-1}

If lobsters are stocked at 100 kg m^{-3} of water (total water volume = 10 m^3), then this flow rate equates to a water turnover rate of once every 20 to 30 hours. This shows that the water flow does not need to be very high to ensure ammonia build-up is kept under control.

FED OR PURGING LOBSTERS

The maximum ammonia excretion rate of a fed 500 g *J. edwardsii* at 13°C is 7.5 µg g^{-1} h^{-1}; 1000 kg of 500 g fed lobsters will excrete 7.5 g of ammonia per hour and 180 g per day.

$$\begin{aligned} \text{FR } (\text{L h}^{-1}) &= 7.5 \text{ g h}^{-1} / 0.002 \text{ g L}^{-1} \\ &= 3750 \text{ L h}^{-1} \end{aligned}$$

These calculations do not take into account the contribution of urea to the ammonia nitrogen. If all of the urea was oxidised to ammonia then there would be ~ 20% more ammonia in the system, and a 20% increase in flow rate is required, i.e. 600 L h^{-1} for unfed and 4500 L h^{-1} for fed 500 g animals.

The basal level of ammonia excretion in a 500 g unfed *P. cygnus* at 23°C, is around 2 µg g^{-1} h^{-1}, which is double that for *J. edwardsii* at 13°C, although the peak in ammonia excretion following feeding is the same at 7.5 µg g^{-1} h^{-1}. More recent trials at lower temperatures of 19 to 20ºC found that 442 g *P. cygnus* had excretion rates of 0.97 µg g^{-1} h^{-1}. In general, flow rate calculations must be adjusted according to the species held, size of animals, and holding temperature.

NB. IT IS IMPORTANT TO ENSURE OXYGEN REQUIREMENTS OF THE LOBSTERS ARE MET. SIGNIFICANTLY HIGHER FLOW RATES THAN THOSE CALCULATED HERE WILL BE REQUIRED IF AERATION IS NOT PROVIDED (SEE CREAR AND ALLEN, 2002).

GLOSSARY

AERATION	The act of providing an air supply to water in order to increase the oxygen content of that water.
AMMONIA	Ammonia is the major end product of protein metabolism in most aquatic animals. Ammonia is toxic to lobsters and therefore must be prevented from building up in holding systems. Ammonia is present in two forms in water (ionised – NH_4^+ and unionised – NH_3), the higher the pH and temperature, the higher the percentage of the toxic fraction (unionised).
ALKALINITY	Alkalinity is basically a measure of the carbonate content of water. It gives a measure of the capacity of the water to accept acidity (i.e. its buffering capacity). Alkalinity is usually measured as either $mg\ L^{-1}$ (milligrams per litre) $CaCO_3$ (calcium carbonate) or meq (milli-equivalents). $1\ meq = 50\ mg\ L^{-1}\ CaCO_3$.
BIOLOGICAL FILTER (BIOFILTER)	A filter providing a large surface area on which denitrifying bacteria grow; used to remove waste (particularly ammonia and nitirite) from recirculating systems.
BIOMASS	Total weight (kilograms) of organisms in a system.
FLOW-THROUGH	Single use water. Water enters a system, passes through the system and goes to waste.
NITRATE	Formed as a result of the breakdown of ammonia to nitrite and then to nitrate by bacteria in biofilters. Generally not toxic at the levels found in recirculating systems. Chemical symbol: NO_3.
NITRITE	Toxic chemical formed during the oxidation of ammonia to nitrate by bacteria in a biofilter. Most of the nitrite is converted to nitrate before the water exits the biofilter, therefore it is not generally found at toxic concentrations. Chemical symbol: NO_2.
OXYGENATION	The addition of pure or very high purity oxygen to water in order to increase the dissolved oxygen concentration of the water.
pH	A measure of acidity of a solution. It is in effect a measure of the amount of hydrogen ions. The normal pH of seawater ranges from 7.8-8.4.
RECIRCULATION	The process of taking water from a holding system which would otherwise be discarded from the system and reintroducing it to the same system. Prior to being reintroduced, the water is often treated to remove some of the wastes so that the water quality is maintained at a sufficient high level that it remains suitable for the held animals. Recirculation systems can be operated as 100% recirculation (no new water added) or may have partial replacement water added.

REDOX	Redox is a word derived from a combination of the words reduction and oxidation. The redox potential or ORP (oxidation reduction potential) is a measure of the potential of the water for oxidation or reduction processes.
SALINITY	The term used for the measurement of the total amount of dissolved salts in the water. Full strength seawater has salinity in the region of 33-35 g kg^{-1} (grams per kilogram).
TAN	The term given to total ammonia nitrogen, which is all nitrogen involved in the equilibrium between unionised ammonia and ammonium ions, as follows: $NH_3 + H^+ \leftrightarrow NH_4^+$
VENTURI EFFECT	The act of drawing air into a water system via a small tube or crack in a pipe. As the water passes through a restriction in a pipe, it forms a vacuum at the end of the restriction. A hole bored into the pipe at the point where this vacuum occurs will cause air to be drawn into the main flow. Although efficient at mixing chemicals and gasses into water, the operational costs of a venturi is high due to the cost of the increased pumping pressure required for the unit to operate. Venturis have their applications in some systems where there is more pressure available than is required by the rest of the system components.
WATER HARDNESS	The amount of cations of the earth metals (mainly calcium and magnesium) in the water. In most waters, the hardness is similar to that of alkalinity, as calcium and magnesium are usually bound to the main alkalinity bases (bicarbonate and carbonate). Alkalinity tends to be used more as a measurement than hardness.

LIST OF SYMBOLS

WEIGHT

μg	microgram	10^{-6} grams; 1,000,000 μg = 1 g
mg	milligram	10^{-3} grams; 1,000 mg = 1 g
g	gram	
kg	kilogram	1000 grams; 1 kg = 1000 g

LENGTH

μm	micrometre (also called microns)	10^{-6} metres; 1,000,000 μm = 1 m
mm	millimetre	10^{-3} metres; 1,000 mm = 1 m

VOLUME

mL	millilitre	10^{-3} litres; 1,000 mL = 1 L
L	litre	
m^3	cubic metre	1 m^3 = 1,000 L

TIME

h	hour

TEMPERATURE

°C	degrees Celsius

ELECTRIC POTENTIAL

mV	millivolts

DERIVED UNITS

	Defined in the context of this booklet
g h^{-1}	grams per hour
μg g^{-1} h^{-1}	micrograms (of ammonia) per gram (of lobsters) per hour = ammonia excretion rate
g ammonia m^{-2} day^{-1}	grams of ammonia per square metre per day
m^2 m^{-3}	square metres (surface area) per cubic metre (filter medium)
g L^{-1}	grams per litre
mg L^{-1}	milligrams per litre
L h^{-1}	litres per hour = flow rate
kg m^{-3}	kilograms per cubic metre = lobster stocking density
ppm	parts per million

SALINITY

g kg^{-1}	grams (salts) per kilogram (water)
equivalent to g L^{-1}	grams (salts) per litre (water)
equivalent to ppt	parts (salts) per thousand parts (water)

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RECIRCULATING SYSTEMS

NH_3

GUIDE FOR THE ROCK LOBSTER INDUSTRY No 2