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THOUGHTS OF SELECTION AND DESIGN OF RESERVOIR AERATION DEVICES

BY

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ABSTRACT

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Alternative devices for reservoir aeration are briefly reviewed. It is noted that each device is best suited for particular applications and objectives. It is recommended that care be taken by the designer to select the appropriate device for the particular application. Advantages and disadvantages of the various devices are given along with representative destratification and oxygenation efficiencies. Design considerations are discussed including techniques for sizing units, the effects of inflows and releases, the effects of reservoir stratification, evaluation of aeration impact on the reservoir temperature regime, and the possible development of nitrogen supersaturation.

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DEVICE SELECTION

Many devices have been developed to aerate reservoir and lake water. This includes pneumatic (air) devices, mechanical devices, buoyant water devices, and molecular oxygen devices. However, in all cases, considerations in the selection of the appropriate device are the same. The appropriate device for use at any site is a function of the specific site with its characteristics and the objectives of the aeration treatment. Treatment devices may destratify or influence the temperature and water density distribution within a reservoir or they may not. Thus the influence of the various devices on both temperature and oxygen distribution should be considered. As an initial step, the characteristics of the reservoir to be treated should be noted. In particular, the following should be considered:

1. Reservoir volume and the volume of the oxygen-depleted reservoir to be treated. - This volume will influence the extent of the problem and thus the size of treatment system required. Typically, a larger reservoir will require a larger aeration system. An option, if the quality of release water is of particular interest and if the quality of reservoir water is less critical, is to treat only the portion of the reservoir around the outlet. This option, of course, yields treatment demands that are less

than required for the full reservoir and thus yields reduced system size and cost. Partial treatment also has, by its nature, limits on its potential effectiveness which are a function of discharge, treatment water quality objectives, and size of the treatment zone. Some devices such as wind driven aerators, hydraulic guns, and mechanical jetting destratifiers have limited influence and thus are specifically suited for smaller lakes or for partial treatment of larger lakes.

2. Oxygen demand and thus the hypoliminion oxygen decline rate. - Oxygen decline rate in conjunction with minimum allowable oxygen levels and in conjunction with the initial D.O. levels, is the other factor which predominantly influences the extent of the reaeration problem and thus the size of the treatment system required. Typically, the desired unit reaeration rate times the volume of the oxygen-depleted water of interest yields a bulk required reaeration or oxygenation rate. The reaeration system must then be sized to meet this bulk rate.

As discussed under volume, some devices are best suited for small applications and thus to meet relatively small oxygen demands. Consequently, total demand to be supplied may be a factor in device selection. In addition, the reaeration efficiency and effectiveness of some devices are functions of the initial, pretreatment dissolved gas levels within the water. For example, D.O. increases of 3 mg/l from an initial level of 0 mg/l can be relatively easily achieved using draft tube aeration. However, it is quite difficult to achieve the same increase using draft tube aeration from an initial level of say 3 mg/l. Higher initial D.O. levels reduce the oxygen deficit between the saturation level and existing level which reduces the driving force for gas transfer. In particular, this may be critical for devices for which the gas transfer occurs under relatively low pressure.

3. <u>Reservoir depth and the depth at which increased D.O. is required</u>. - Some devices such as mechanical surface aerators have a limited range of vertical influence. Likewise, some devices may be used over limited vertical ranges to push higher D.O. epilimnion water down into the hypolimnion (locally lower the thermocline). With these devices, for example, if the withdrawal outlet is at a shallow depth (say 50 feet or less below the epilimnion, water may be jetted down to the outlet and thus epilimnion water or a epilimnion-hypolimnion water mix is released. For deeper outlets, other treatment devices would be appropriate.

Reservoir depth or submergence depth on the device may also influence operating efficiency. For example, a pneumatic line diffuser which aerates by entraining hypolimnion water into a rising bubble and water column and bringing that water to the surface for mixing with epilimnion water, functions more efficiently with a long bubble plume path through the hypolimnion and thus substantial entrainment of hypolimnion water. In cases where the hypolimnion depth is small relative to the epilimnion depth (shallow stratified reservoirs), the bubble path through the hypolimnion is short. Consequently, entrainment of hypolimnion water is relatively minor and system efficiency is substantially reduced. Consequently, pneumatic diffusers are more efficient and economically more competitive in deeper reservoirs.

4. Reservoir flowthrough or the size, temperature, and D.O. levels of inflows and releases. - At some sites substantial flowthrough of low D.O. water occurs. In effect, devices may be required to aerate the flowthrough as well as the reservoir. Thus, substantially larger devices may be required than those indicated by the reservoir volume and oxygen demand. At other sites substantial high D.O. flowthrough may have a freshening effect and may reduce required hypolimnion aeration. The influence of flowthrough is a function of not only discharge and D.O. concentration, but is also a function of the stratified flow dynamics of the reservoir. If the inflow is warm and stays on the reservoir surface and if withdrawal is also from the surface, then a stagnant hypolimnion may result in which D.O. decline is maximized. On the other hand, if the inflow is cold and high in D.O. and if withdrawals are made from the bottom of the reservoir, then the inflows will tend to replace and freshen the hypolimnion waters and thus minimize oxygen decline.

Thus inflows and releases should be considered in selecting and sizing treatment systems. As can be seen, it is appropriate to use a hydrodynamic reservoir model to evaluate residence times, freshening effects, and thus to guide evaluation of expected hypolimnion oxygen decline rates. It should be noted that many reaeration devices also yield destratification. The degree and nature of this destratification are functions of the device type, method of device operation, and frequently of the strength and profile shape of the reservoir stratification itself. Somehow this device destratification should be incorporated in the hydrodynamic model if a clear picture is to be obtained. However, for many devices the destratification mechanics including destratification efficiency and resulting destratification circulation patterns are not known. Consequently, inclusion of the destratification in a hydrodynamic model is very approximate.

In addition, a treatment option other than partial or complete reservoir reaeration is to treat only the release water as it is being withdrawn from the reservoir. This is beyond the scope of this paper, but nevertheless should be considered with other treatment alternatives. For this case, the reservoir water quality would be allowed to deteriorate. Selective withdrawal, localized aeration of the withdrawal within the reservoir, aeration of the release flow as it passes through energy dissipators or other types of hydraulic structures, and/or turbine or draft tube aeration could then be used to increase the D.O. level in the release water. It should be recognized that with this option poor quality water that may limit recreational, fishery, or other uses of the reservoir may result. Likewise, substantially more treatment of the withdrawal than just aeration may be required to obtain acceptable water from a poor quality reservoir. The Metropolitan Water District of Southern California has reported that, in their case, it is more economically efficient to maintain good quality water within the reservoir through aeration than to treat poor quality water as it is withdrawn (Pearson et al., 1976). At other sites and in particular for hydroturbine power releases and stream releases, aeration of the release flow is a common technique.

As earlier noted, a final consideration is whether modification of the temperature structure of the reservoir can be tolerated. Many treatment devices function by mixing the low D.O. hypolimnion water with the high D.O. epilimnion water.

This tends to yield efficient aeration in that the large reservoir water surface becomes the primary oxygen transfer interface. This, however, yields warming of the hypolimnion and cooling of the epilimnion. It may be that due to the fishery, either in the reservoir or in the downstream channel, or due to some other consideration, these temperature changes cannot be tolerated. In these cases hypolimnion aerators that do not mix the reservoir are an option and may be used.

Table 1 contains an incomplete but representative list of reservoir reaeration treatment device options. Included are information on device efficiencies as reported in the literature, a brief description of the potential advantages and disadvantages of the various devices, and a list of useful references on the specific device. Figure 1 contains illustrations of the devices mentioned in table 1. In addition to the specific references cited in table 1, several more general references that are quite useful are available. They include King, 1970, Lorenzen and Fast, 1976, Pastorok et al., 1981, and Bohac et al., 1983.

DEVICE DESIGN

With the selection of a device or devices to be further considered, either feasibility or more detailed designs may be undertaken. As an initial step, the size or extent of the problems to be treated must be defined. To do this, the size of the impoundment to be treated and thus the volume of water to be treated should be evaluated. Likewise, the expected oxygen demand in the untreated impoundment and desired or acceptable oxygen decline rates in the treated reservoir should be defined. Expected oxygen demand in the untreated impoundment may be evaluated through observation of historical data for that impoundment, through observation of the oxygen response in similar impoundments, or through the use of D.O. prediction mathematical models such as the model of Ford et al., 1980. It should first be noted that oxygen demand observed from historical data or similar reservoirs' demand will vary over the short term, for example, due to the decay of algae blooms or due to flooding; and over the long term, for example, due to reservoir maturing or seasonal variations. A decision must be made as to whether reaeration system design should be based on typical expected oxygen decline rates or on some extreme value. Sizing a system based on an extreme decline rate will yield a system that is oversized for most cases and thus may have both excessive capital and operating costs. However, sizing a system based on a typical or mean decline rate will yield a system that is unable to meet all desired demands. The design D.O. reaeration rate selected is generally dependent on how critical the reaeration is.

It appears that historical data for the reservoir of interest may supply the best estimate of initial untreated D.O. Similar reservoirs can supply a good estimate of untreated conditions. However, care should be taken to ensure sufficient similarity. The comparison impoundment should be in the same vicinity as the impoundment of interest, should experience fairly similar climatic conditions, and should be of similar depth or at least deep enough to allow similar thermocline and hypolimnion development. The comparison reservoir should experience similar inflow and release discharges. The relative influence of the flowthrough should be similar and thus the relative magnitude of the discharges versus reservoir volume and the stratified flow response of the flows in the reservoirs should be similar. This also implies the need, where multiple release structures exist, to have similar release operating characteristics for the two sites.

Finally, for a good comparison of D.O. response, the oxygen demand of the two reservoir hypolimnions should be similar. This generally implies that the impoundments have similar nutrient characteristics, biological productivity, and that they are biologically managed in similar ways.

The final technique for determining the initial of untreated state of a reservoir is through the use of mathematical models. Numerous models are available for the prediction of temperature and dynamic response of a reservoir. Available models include those of Edinger and Buchak, 1979 and Norton et al., 1973. Likewise in recent years, models such as that of Ford et al., 1980, have been developed to obtain prediction of biological and chemical response including D.O. Use of the models requires substantial data bases and are best applied where sufficient data exist for verification. With limited input data and with no historic profiles to help fit the model, only approximate predictions and guidance can be obtained.

After it is established what the untreated D.O. state of the reservoir of interest is, the next step is to select a desired minimum acceptable D.O. state that could result when reaeration is used. The desired uses of the water and their implication on required D.O. levels should be identified. For example, if the objective is to prevent the development of anaerobic conditions, a level of 2 mg/l might be established. However, if the objective is to maintain a trout fishery, a minimum acceptable hypolimnion D.O. level of 5 mg/l might be established. Noting then that the epilimnion water will tend to be saturated in D.O., and considering the degree of destratification or variation away from a traditional two-layer density profile (discussed later in the paper) that would result, estimated minimum acceptable D.O. profiles can be obtained. These profiles are an epilimnion-hypolimnion composite with a transition between the two layers. Because hypolimnion D.O. levels will decline from their saturation value at the start of the stratification season to their minimum acceptable values just prior to fall turnover, the minimum acceptable profiles just developed represent the profiles that would exist prior to turnover. By comparing the total D.O. content of the reservoir for the saturated spring condition and for the minimal acceptable condition, an acceptable total D.O. mass decline is obtained. This acceptable total D.O. mass decline is then divided by the expected stratification season length to obtain an acceptable D.O. decline rate. For example, if it is found that an acceptable total D.O. mass decline of 5×10^5 kgO_2 could occur over the stratified season and if the expected stratified season length is 200 days, an acceptable total D.O. decline rate of 2500 kgO_2/day could be tolerated. It should be noted that if destratification accompanies the reaeration then the stratified season will be shorter than it would be in the untreated reservoir.

A similar computational process can be conducted for the untreated reservoir. The total D.O. mass content of the reservoir at the start of the stratified season can be computed. Likewise a total D.O. content at the end of the stratified season or when the hypolimnion goes anaerobic can also be computed. Note that once the hypolimnion goes anaerobic, the total oxygen decline rate that results in the reservoir declines simply because there is no oxygen left to be depleted. Again, by taking the difference between the total D.O. mass at the start of the season and the depleted total D.O. mass, the total D.O. mass decline that occurs in the untreated reservoir is found. When this is divided by the time period, the stratified season length, or the time length to an anaerobic hypolimnion, the total oxygen decline rate in the untreated reservoir is found (for example, 3700 kgO_2/day). The difference between the total D.O. decline rates (3700 to 2500 kgO_2/day) represents an oxygenation or reaeration rate that must be supplied by the device.

It should be noted that the untreated D.O. levels in the reservoirs which were obtained either from historic data, a similar reservoir, or mathematical models do include the influence of inflows and releases. One exception, however, is in cases where heavy flowthrough of oxygen-depleted water occurs. In these cases, it may be required to size the reaeration system to treat not only the reservoir, but the flowthrough as well. Noting flowthrough volumes and desired D.O. levels, estimates of required additional reaeration for the flowthrough can be obtained.

With a knowledge of the required total oxygenation or reaeration rate (1200 kgO_2/day for the example), the reaeration system may then be sized. Typically some sort of oxygenation efficiency data are available for the reaeration devices being considered. These efficiencies may take the form of a crude bracketing of observed efficiencies (as shown in table 1) or may take the form of more exact efficiencies such as shown on figure 3. The figure 3 efficiencies were obtained by the Bureau of Reclamation for straight line pneumatic diffusers submerged at a depth of 46 m (King et al., 1983). Knowing the required reaeration rate (1200 kgO_2/day) and knowing a device efficiency (for example, 1.5 kgO_2/kWh), a required energy consumption rate is obtained (1200/1.5 or 800 kWh per day). This may then be used in conjunction with available literature on the particular device of interest to size the required reaeration system. Note that this process contains substantial potential for error. The efficiencies reported in the literature for various devices show substantial scatter. Not only are device efficiencies a function of the hardware (the particular compressors, pumps, motor, and plumbing used), but they are likely also a function of the particular application geometry.

For example, diffused molecular oxygen or air can have very different efficiency characteristics depending on whether the gas is uniformly distributed or concentrated at local points. Stratification strength and reservoir depth and device submergence can also substantially affect resulting efficiencies. In most cases, there are no guidelines to be used in evaluation of the effect of these various parameters. Analytical techniques for calculating gas transfer, bubble plume flow entrainment, water jet flow entrainment, and the like are available and may be used to approximately adjust efficiencies to satisfy the geometries and flow conditions of a particular situation. Good general analytical references include Neilson, 1972, and Pastorok et al., 1981. Studies of specific devices may also give guidance.

With the system sized, hardware design as appropriate can be conducted. It is strongly recommended that the designer contact or visit field sites where the particular reaeration device type of interest is in use. There is much fabrication, operation, and maintenance knowledge that is obtained through experience.

Two final factors should be considered in reaeration system design. First, if destratification results due to system operation, a satisfactory reservoir temperature regime may or may not be obtained. Typically destratification results in cooling of the epilimnion and warming of the hypolimnion. If the reservoir is intended for a temperature dependent use, such as for a cold water fishery, then a conflict may result. Sufficient reaeration to yield the desired D.O. levels may produce unacceptable temperatures. For some devices, destratification efficiencies are available. Thus a technique similar to the one presented in this paper for reaeration may be followed to evaluate the destratification influence. Initial untreated temperature profiles can be determined, untreated reservoir stabilities computed, destratification influence on stability evaluated (using system size determined from the reaeration computations and appropriate destratification efficiencies), and the impact on temperature profiles found. If the temperature impact is unacceptable, a treatment device that would yield less or no destratification could be determined.

A final consideration is potential nitrogen supersaturation development within the reservoir. Supersaturation may develop either due to direct gas transfer from air bubbles or due to the warming of the water that results with destratification. Warming of the water lowers the stable saturation concentration. Thus warming can yield supersaturation even with no additional gas transfer. Fast and Hulquist, 1982, show the degree of supersaturation development to be a function of reaeration device influence, density stratification strength, and position of the reaeration device in the water column. In many cases, nitrogen supersaturation development does not pose a problem. Due to submergence, supersaturation levels within the reservoirs (with respect to atmospheric pressure) are typically well below saturation levels. Likewise high turbulence releases from the reservoirs cause stripping of the excess gas from the release water and alleviate the problem. Only where releases with no free interface (such as hydroturbine power releases) are made does the supersaturation pose a problem. Where supersaturation is a problem, hypolimnion injection of molecular oxygen may be required.

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Table 1. - Comparative reaeration device features

Device	Efficiencies	Advantages	Disadvantages	References
		Devices for in-reservoir reaeration through mixing or destratification		
Pneumatic diffusers or diffused air bubble plumes	Mixing 0-8 percent Aeration 0.6-3.9 kg/kWh	Proven suitable for deep reservoirs, relatively low capital and operating cost for deep reservoirs	May yield nitrogen supersaturation, may have clogging problems and require filtering of air	Johnson (1980) King et al. (1983) Davis (1980) AWWA (1971)
Diffused hydraulic buoyant water plumes	No field proven efficiencies, may be greater than pneumatic diffusers	May be used in deep reservoirs; potentially offers high efficiencies	Unproven, concept has not been field applied, may cause nitrogen supersaturation	Dortch (1979)
Mechanical pumping with free jets	Aeration less than 0.6 kg/kWh	Simple equipment, may push surface water down to intake - replaces selective withdrawal	Jetting effective only for shallow (less than 60 ft deep) applications and relatively small volumes	Garton et al. (1978) Toetz (1979a, b) Holland (1983)
Hydraulic guns	Aeration 1 kg/kWh	Efficient mixing of upwelled water with surface, may use small compressor	Moves relatively low volumes of water, little gas transfer from bubbles. Best for small applications	Hydraulic Research Station (1978)
		Devices for hypolimnion aeration with no reservoir mixing		
Air lift-limno (air or molecular oxygen driven)	Aeration 0.2-0.6 kg/kWh	Allows temperature stratification to remain undisturbed	Relatively low efficiency with relatively high capital cost, air-driven units may yield nitrogen supersaturation	Bernhardt (1974) Fast et al. (1975) Fast et al. (1976)
Molecular oxygen injection through fine bubble diffusers	Aeration 14-55 percent oxygen transfer 0.3-0.7 kg/kWh	Allows temperature stratification to remain undisturbed, no nitrogen supersaturation, high transfer efficiency	High operating and capital cost	Speece (1973, 1976)

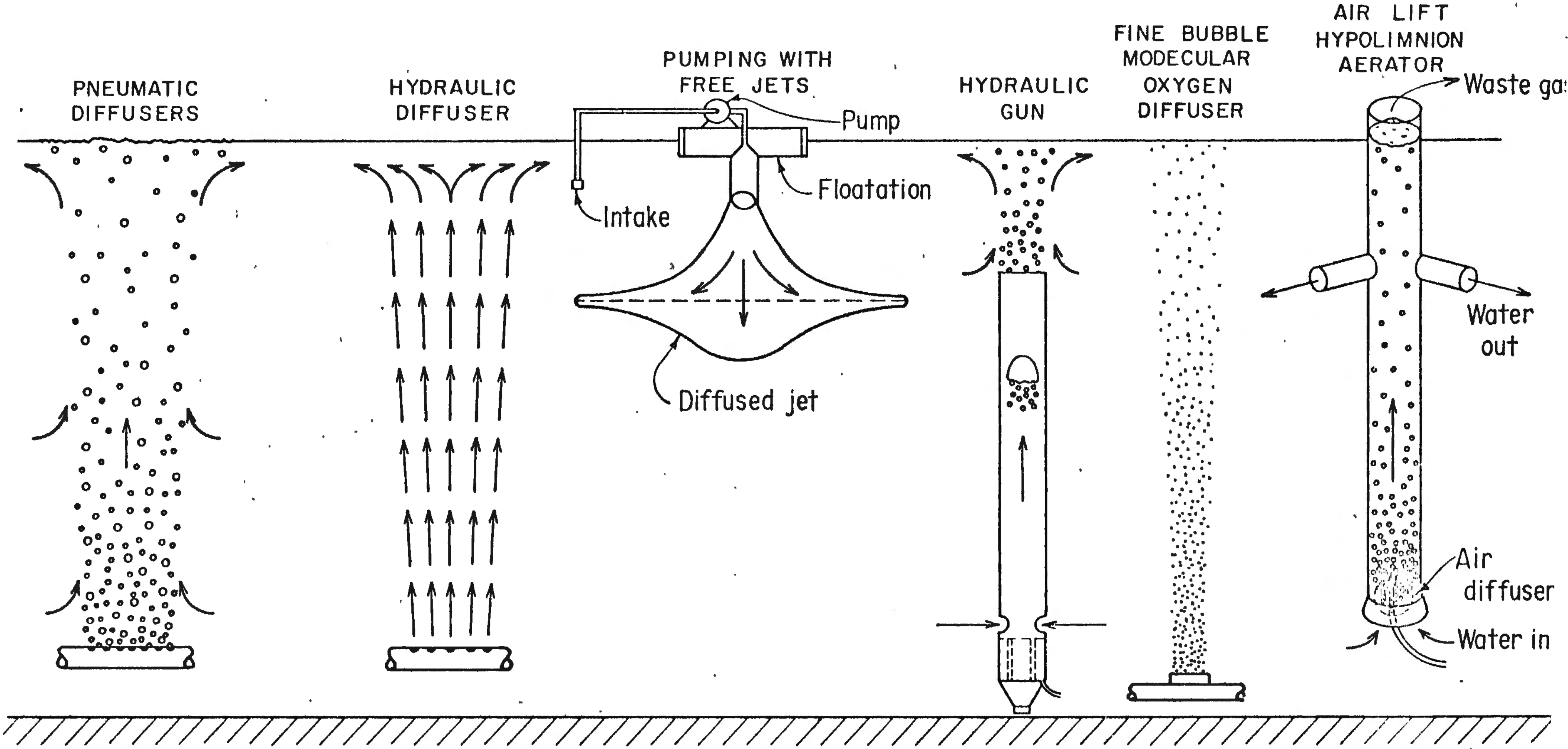

FIGURE I - AERATION DEVICES

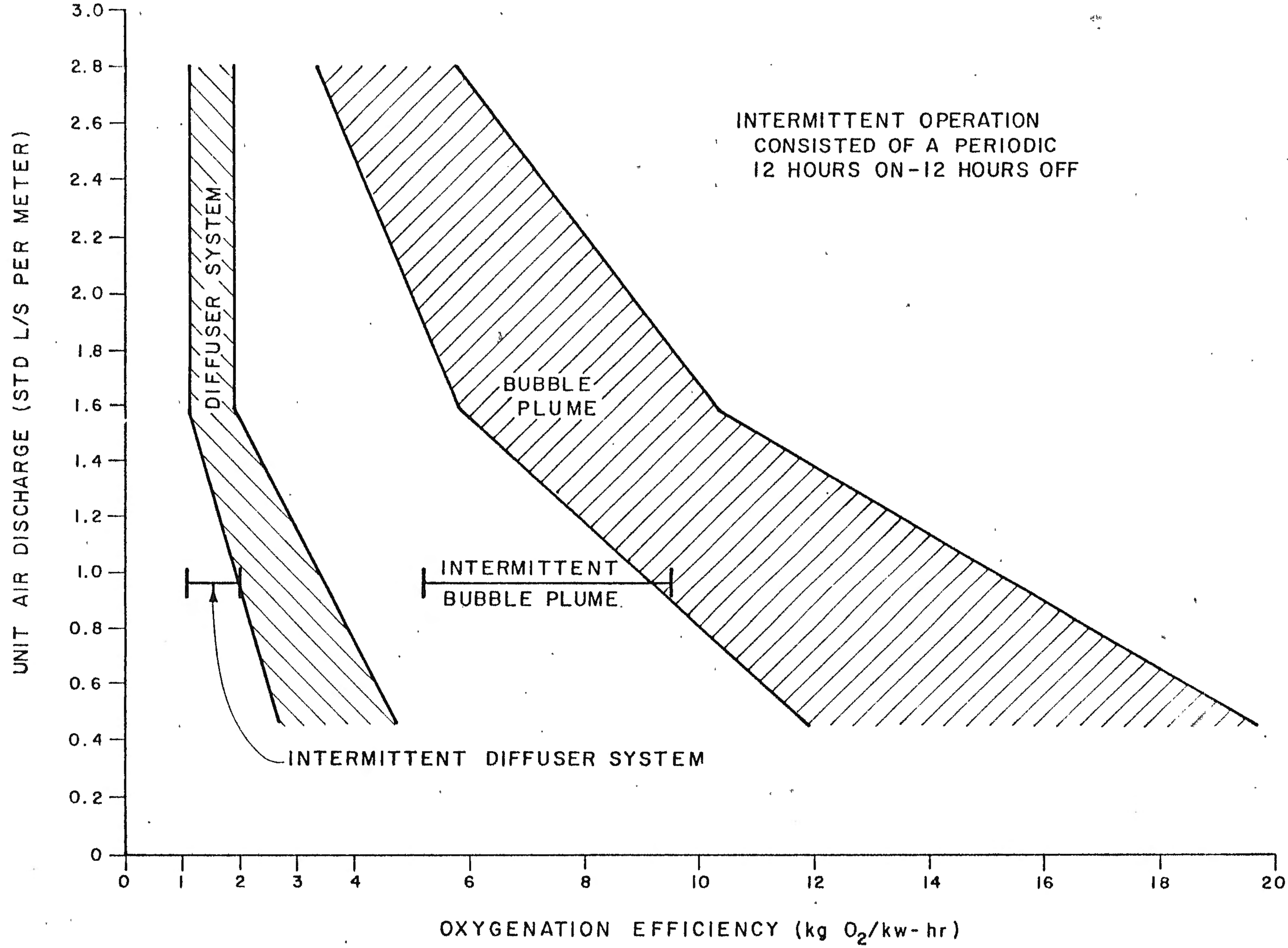

FIGURE 2 - PNEUMATIC DIFFUSER EFFICIENCY CURVES