Gas supersaturation and gas bubble trauma in fish downstream from a moderately-sized reservoir

by

Donna Schulze Lutz

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ABSTRACT

Dissolved gas data were collected downstream from a moderately-sized midwestern reservoir over a period of nine years. From 255 observations the average total gas pressure was 116% of saturation under an average discharge of 222.9 m^3/s (7,870 ft^3/s). Periodic examinations of live fish and fish collected from fish kills documented the occurrence of chronic and acute gas bubble trauma in aquatic organisms downstream from the dam. The occurrence of periodic gas supersaturation-induced fish kills was tied to continued high gas pressures during periods when the discharge from the reservoir was substantially decreased. Less discharge decreased river depth and lowered compensating hydrostatic pressure leaving uncompensated gas pressure in excess of atmospheric pressure. The occurrence of gas supersaturation at this reservoir is of interest because of the potential for gas supersaturation at other moderately-sized reservoirs where gas supersaturation might not be predicted.

INTRODUCTION

Gas supersaturation and it's effects on aquatic organisms inhabiting waters supersaturated with atmospheric gases have been studied off and on for nearly ninety years. Marsh and Gorham (1905) first described the occurrence of waters supersaturated with atmospheric gases and the effects of this excess pressure on aquatic organisms were termed "gas bubble disease". [Recently, this phenomenon has been termed "gas bubble trauma" because it is the result of a physical process not an infectious disease.] The greatest interest in researching gas supersaturation and its effects on aquatic animals occurred in the late 1960's and 1970's when the occurrence of gas supersaturation was documented downstream from large dams on the Columbia and Snake rivers (Ebel 1969; Meekin 1971). Meekin and Allen (1974) estimated that 6% to 60% of the adult salmonids in the middle region of the Columbia River died between 1965 and 1970. Carcasses of adult salmon were found when nitrogen gas supersaturation reached 120% of saturation or higher. May (1973) found that along the upper reaches of the Columbia River most fish showed signs of gas bubble trauma in an area where the total gas pressure was 130% of saturation, whereas, fish collected downstream where the total gas pressure was 105% to 118% of saturation, showed no signs of gas bubble trauma. Levels of gas supersaturation in the Des Moines River, as described herein, are equally as great in magnitude and duration as levels reported in the Columbia and Snake rivers.

The physics of gas supersaturation

The circumstances that result in gas bubble trauma can be described by the physical conditions that determine gas concentrations in water. Dissolved gas data, as percent of saturation, are the measurements of a gas in solution with respect to its solubility in air-equilibrated water at the test temperature and barometric pressure (Harvey 1975). A recent trend to standardize data reporting has been to report the gas pressure that is in excess of barometric pressure, which is then reported as ΔP. This parameter has the advantage of being independent of barometric pressure and elevation and so it is easier to compare data from different locations. Colt (1983) contributed to the field by publishing standardized formulae and terminology to quantify and describe gas supersaturated conditions.

The solubility of a gas in solution depends on the nature of the gas and liquid and on the pressure and temperature. The two most important environmental factors affecting solubility of atmospheric gases are pressure and temperature. As the pressure on a volume of water increases, the capacity of that water to hold dissolved gas also increases. Pressure is the most important factor affecting gas solubility, as stated in Henry's Law: "the mass of gas dissolved by a given volume of solvent, for a constant temperature, is proportional to the pressure of the gas with which it is in equilibrium" (Harvey 1975). Hydrostatic pressure increases rapidly with depth, greatly increasing the ability of deeper water to hold gases in solution.

Temperature also affects the solubility of gases in water. For nitrogen and oxygen, gas solubilities decrease with increased water temperature. Therefore, it is possible for water that is saturated to become supersaturated upon heating (APHA et al. 1989).

The partial pressure of a gas is defined as the pressure of each gas in a mixture of gases as if it alone occupied the total volume. [The pressure of a single gas is commonly called tension when in the liquid phase and partial pressure when in the gas phase.] According to Dalton's Law the total gas pressure is equal to the sum of the individual gas pressures. For air in water, the total gas pressure is equal to the sum of the partial pressures of the constituent gases plus the vapor pressure at that particular temperature. In the past many researchers had failed to include water vapor pressure.

For dry air at one atmosphere the fractional composition of the major gases are, according to Colt (1984):

Nitrogen	0.78084
Oxygen	0.20946
Argon	0.00934
CO_2	0.00032

The concentration of a gas in solution is related to it's partial pressure and it's solubility. Each gas has a unique solubility in water so the number of molecules of different gases in water at the same equilibrium pressure is different and depends on the Bunsen solubility coefficient. The Bunsen coefficient is the volume of gas, reduced to standard temperature and pressure (STP), which is absorbed by a unit volume of solvent at the temperature of measurement and a gas pressure of 1 atmosphere (Macdonald and Wong 1975). The relationship of a gas at equilibrium is described by the following equation (D'Aoust and Clark 1980):

$$C = P \times B$$

where C equals the concentration of the gas

P equals the partial pressure of the gas

and B equals the bunsen coefficient

Therefore, oxygen, which is only ¼ as plentiful as nitrogen in the atmosphere becomes ½ as plentiful in water because it is twice as soluble (Harvey 1975). Generally, in gas supersaturation research, nitrogen and argon gases are combined as atmospheric nitrogen for simplicity. The ratio of nitrogen to oxygen gas appears to play a role in tolerance to gas supersaturation. In water in equilibrium with the air, the ratio of the partial pressure of nitrogen gas to the partial pressure of oxygen gas is 3.77 (APHA et al. 1989).

There has been much confusion over the effect of depth on gas solubility. According to Bouck (1980) the hydrostatic pressure at a specific depth must be considered as a compensating pressure. Thus, gas bubbles can only form in a fish if the difference between the total gas pressure and the compensating gas pressures is positive. Since hydrostatic pressure increases with depth, the capacity of deeper water to hold gas in solution increases. This is described in Boyle's Law which states that a volume of gas changes inversely with pressure. Thus, if you halve the pressure the volume doubles. So at a greater depth the hydrostatic pressure (due to the weight of the water) keeps gases in solution, however, when the fish surfaces to a lower pressure the excess gases come out of solution and form gas bubbles. This is why the river depth, or the capacity of the fish to sound to a depth deeper than the compensation depth, is so important. The compensation depth is the depth where the compensating pressures (barometric plus hydrostatic pressure) equal the cavitation pressures (sum of the dissolved gas pressures). Gas bubble trauma can only occur when the cavitation pressure exceeds the compensation pressure (Bouck 1980).

Water that is supersaturated with dissolved gases, in the absence of vigorous surface turbulence, requires a long time to re-equilibrate to the normal saturation level (Knittel et al. 1980). The upward diffusion of the excess gases is generally small and does not warrant attention unless anaerobic systems are involved or an extended time frame, as in mass transport studies (Klots 1961).

Computation of gas pressure data

In membrane-diffusion methods the differential pressure between barometric pressure and total dissolved gas pressure is directly measured and is equal to ΔP in mmHg. This value will be negative in undersaturated conditions and positive in supersaturated conditions. A total gas meter reading in air should equal zero, therefore, a ΔP of zero in water indicates that it is in equilibrium with the atmosphere. Dissolved gas levels are conventionally computed as % of saturation rather than % supersaturation. For example, 112% of saturation is only 20% supersaturated. The recommended formula for determining total gas pressure as a percent of saturation includes water vapor pressure. It is calculated as the sum of the barometric pressure and ΔP divided by the barometric pressure, multiplied by 100 to result in a percent (Colt 1983). Total gas pressure is normally computed relative to the surface barometric pressure. However, to assess exposure in natural systems it is desirable to compute gas pressures at depth. The total gas pressure at equilibrium at a given depth is equal to the barometric pressure plus the density of water, the acceleration due to gravity and the depth (Colt 1983). This is often referred to as the ambient barometric pressure. Percent total dissolved gas pressure at depth can be determined by substituting ambient barometric pressure for the denominator. This is referred to as the uncompensated total gas pressure. For example, a ΔP of 76 mmHg corresponds to a percentage total gas pressure of 110% of saturation with respect to the surface. At a depth of 1 meter the uncompensated total gas pressure is 100.4% of saturation. In calculating uncompensated gas pressure the assumption is made that the temperature and dissolved oxygen levels are uniform with depth. This assumption is probably valid for streams but would not be in lakes and reservoirs. The preferable method of reporting total gas pressure is in terms of ΔP because initial bubble formation is dependent on it (Colt 1983; APHA et al. 1989). At the surface the total dissolved gas pressure equals ΔP plus the barometric pressure. Assuming that the water column is uniformly mixed the uncompensated ΔP decreases about 73 mmHg for each meter of depth (Colt 1983).

Generally, only the component gases nitrogen, oxygen and argon are considered in gas pressure research. The partial pressure of carbon dioxide is usually small enough to be neglected because high concentrations on a mg/l basis represent small pressures (Colt 1983). Supersaturation of a component gas will not cause gas bubble trauma unless the total gas pressure exceeds 100%. Nitrogen and argon gases are measured together in membrane-diffusion methods. The conventional computation of oxygen saturation is with respect to moist air. Thus, it is preferable to determine nitrogen plus argon saturation in the same manner. The reporting of component gas pressure as a percent of saturation is misleading because a given percentage can represent significantly different pressures and changes with barometric pressure and elevation (Colt 1983). The preferable method of reporting component gases is in terms of partial pressures or excess pressures (ie. ΔP N_2 is the part of the ΔP that is a result of nitrogen gas, it is the excess pressure as a result of nitrogen gas pressure).

Causes of gas supersaturation

Four mechanisms by which water may be supersaturated were discussed by Lindroth (1957). These processes either cause an increase in the amount of air dissolved or they reduce the amount of air that water will hold. First, water containing dissolved gas from a gas mixture containing more of that gas than found in air. This mechanism is probably found only experimentally. Second, water may contain a dissolved gas at a temperature that is lower than ambient temperature. This mechanism can occur as water is heated for aquaculture (Embody 1934), as water is cooled at power plants (Adair and Hains 1974; DeMont and Miller 1972), and as a result of natural geothermal heating (Bouck 1976). Third, two bodies of water at different temperatures are mixed. This may cause supersaturation but probably at only low levels. And fourth, water may contain gas that was dissolved under a pressure higher than atmospheric pressure. This mechanism is probably the most common cause of gas supersaturated waters. It occurs at some dams (Ebel 1969; Blahm 1974). When bubbles are carried down into the water or gas and water are present together at elevated pressures, gas supersaturation can be produced. [For example, at 20°C the equilibrium concentration of oxygen at 4.0 meters is 12.67 mg/l, compared to 9.08 mg/l at the surface. If the ambient concentration of dissolved oxygen is less than 12.67 mg/l at 4.0 m, oxygen will be transferred into the water from the bubble (Colt 1984).] The dissolved gas concentration resulting from bubble entrainment depends on the depth of submergence, the amount of air entrained and the degree of mixing and turbulence (Colt 1985). Also, this mechanism is possible at air injector locations in aquaculture (Harvey and Smith 1961) and in lakes with artificial aeration (Fast 1979). It can also occur at natural springs (Marsh 1910), rapids (Jarnefelt 1948) and waterfalls (Harvey and Cooper 1962). In addition, it can occur with air injection to prevent "water hammer" in turbines and sluiceways (Bouck et al. 1976). [Water hammer is a term for vibration caused by pressure differences occurring in plumbing and artificial water systems.] White et al. (1986) found sluice gate openings were closely correlated with total gas pressure and gas bubble trauma in fish.

In addition to these four mechanisms discussed by Lindroth, photosynthesis may generate oxygen gas to a pressure higher than atmospheric pressure (Woodbury 1941; Renfro 1963; and Supplee and Lightner 1976). However, this mechanism results in temporal gas supersaturation and may not be as significant.

Several approaches have been demonstrated to reduce gas supersaturation in laboratory and hatchery situations. Embody (1934) was able to pass water over a series of baffles at the head of a trough to reduce supersaturation. Harvey and Cooper (1962) used a splash tower with 12 sets of baffles. Recently, research has focused on using packed columns (Bouck et al. 1984;

Colt and Bouck 1984), vacuum systems (Marking et al. 1983; Fuss 1983) or screen decks (Hartman 1983) to lower gas supersaturation.

Pathology of gas bubble trauma

Descriptions of the acute and chronic gas bubble trauma and clarification of the situations that must occur to result in gas bubble trauma were well described by Bouck (1980). Stroud et al. (1975) presented an excellent discussion of the pathology of acute and chronic gas bubble trauma. Gas bubble disease is defined as a non-infectious, physically-induced process caused by uncompensated, hyperbaric total dissolved gas pressure, which produces primary lesions in the blood (emboli) and in tissues (emphysema) and subsequent physiological dysfunctions (Bouck 1980). [Please note that this phenomena will be described here as gas bubble trauma rather than disease as it is the result of a physical occurrence not an infectious disease.] The pathology of gas bubble trauma in fish has been described by several researchers as the external appearance of emphysema under the skin, between fin rays, in scale pockets, along the lateral line, and on the head (Meekin and Turner 1974; Stroud et al. 1975; Sneisko and Axelrod 1976; Weitkamp 1976). These gas bubbles increase in size as the time of exposure to supersaturated water increases (Marsh and Gorham 1905). Also, petechial hemorrhages, small, round, non-raised hemorrhages in the skin or membrane, frequently accompany emphysema in chronic gas bubble trauma. The petechial hemorrhages usually occur following the appearance of external emphysema and seem to indicate an advanced stage of the phenomenon (Weitkamp and Katz 1980). Exophthalmia (pop-eye), which is a protrusion of the eyeball from the orbit, is a sign commonly associated with gas bubble trauma (Marsh and Gorham 1905; Harvey 1975), but exophthalmia may be present or absent in only a few fish suffering from gas bubble trauma (Meekin and Turner 1974). It is believed that exophthalmia is more closely related to chronic gas bubble trauma (Weitkamp and Katz 1980). Also, exophthalmia can have other causes such as kidney disease or physical damage (Weitkamp 1976). Research has shown that not all fish will show external signs of gas bubble trauma but that external signs are pathognomonic, diagnostically specific (Bouck 1980). Evidence of former external lesions appear as circular depressions, for example on the skin, on fins and in the buccal cavity (Crunkilton et al. 1980).

Internal signs of gas bubble trauma has been documented as emphysema in the buccal cavity, in the gut, in gill arches and gas emboli in the circulatory system (D'Aoust and Smith 1974; Stroud et al. 1975; Beyer et al. 1976; Smith 1988). Bubbles along the lateral line can occur, reducing the ability of the sensory units to respond to stimuli (Schiewe and Weber 1976). The most conclusive sign of gas bubble trauma is the appearance of gas emboli in gill blood vessels and in the rest of the vascular system. The cause of death due to gas bubble trauma has been established as the occurrence of gas emboli in the bloodstream that prevents the movement of oxygenated blood in the organism and results in death by anoxia (Stroud et al. 1975; Pauley and Nakatani 1967). Marsh and Gorham (1905) found gas completely filled and distended the bulbus of the heart, preventing movement of the blood even though the heart continued to beat. Lesser amounts of gas may form emboli only in the gills leading to blood stasis in the gill arterioles (Dawley et al. 1976). Bouck (1980) describes three stages in acute gas bubble trauma induced in a laboratory setting. During the first stage the fish's body gains dissolved gas pressure toward the ΔP, hyperbaric pressure, of the water. This process is aided by the blood-water countercurrent flow arrangement in the gills. [Efficient exchange of dissolved gases in fish with gills depends on bringing the blood and water into close apposition on either side of a thin membrane through which the dissolved gases can diffuse. This works best if the blood and water flow opposite to one another. The structure of the gills of bony fish maximizes the surface area exposed by having hundreds of gill filaments, each filament carries an abundance of lamellae at right angles. The lamellae are held so that the water must pass through the lamellae channels not just over the gill filaments. Coordinated muscular action of the buccal cavity (mouth) and operculum (gill cover) produces a continuous flow of water across the gills (Bond 1979).] When the exposure persists and compensatory pressures are inadequate, small bubbles form in the blood. Affected fish often become restless or erratic and may jump out of the water. Emphysema may begin in organs, muscle or skin. The second stage begins with mortality caused by hemostasis. Mortality is linear until the median mortality. In stage three, after half of the fish have died, the remaining fish are increasingly more tolerant, thus, 100% mortality is not observed without long exposure. Protracted exposure to ΔP allows the development of emphysemas. Thus, in gas bubble trauma there appears to be a latent stage where gas equilibrium occurs and gas emboli form before mortality occurs.

In addition, substantial research continues to yield information on the causes of gas supersaturation and the effects of both chronic and acute levels of gas supersaturation on many different species of aquatic organisms: fish, crustaceans, amphibians, zooplankton and other invertebrates. *Daphnia spp.* were shown to develop massive air bubbles in the gut and under the carapace in the brood pouch (Nebeker et al. 1976). Crayfish became immobilized (Nebeker et al. 1976). Stoneflies developed bubbles at the base of legs and in gills (Nebeker et al. 1976). The lethal thresholds for the zooplankton *Daphnia magna* and the crayfish *Pascifastacus leniusculus* were reported as 111% and 127% of saturation, respectively (Nebeker 1976). In general, with the exception of daphnia, most freshwater invertebrates appear to be less sensitive to gas supersaturation than fish, although they will succumb if the pressure is great enough. This greater tolerance may be a result of the more open, simpler circulatory system of invertebrates (Nebeker et al. 1976). Exposure of tadpoles to supersaturation exhibited similar signs with accumulation of gas in the gut and positively buoyant animals (Colt et al. 1984). Maulof et al. (1972) observed gas bubble trauma in adult oysters and clams. The clams exhibited gas-filled conchiolin blisters. Bubbles of gas were observed in the gill filaments of the oysters and clams and in the mantle tissue of the oysters.

Differing effects on different life stages are also apparent. In larval fish the phenomena appears differently than in juvenile and adult fish. Larval fish often develop gas bubbles in the digestive system, or on the surface of the fry and cause them to rise to the water surface (Henly 1952; Stroud et al 1975). Death of larvae and fry often occurs when the yolk membrane ruptures. Cornacchia and Colt (1984) found clinical signs of gas bubble trauma in 10-day old larval striped bass, *Morone saxatilis*, exposed to ΔPs as low as 22 mmHg (103% of saturation). Commonly the larvae floated belly-up at the surface.

Behavior

Behavior may prove to be an important factor in the occurrence of gas bubble trauma. Several researchers (Gray et al. 1983; Bouck et al. 1976) have found increased vulnerability to gas supersaturation in more active fish. Gray et al. (1983) found that black bullhead (*Ictalurus melas*) were more susceptible to gas bubble trauma under lotic (flowing water, forced swimming) conditions versus lentic (still water, nonforced swimming) conditions. Testing under conditions of flowing water would be more representative of riverine environments. It has been shown that muscle contractions during swimming can contribute to the formation of gas emboli in the bloodstream (McDonough and Hemmingsen 1985). Crunkilton et al. (1980) hypothesized that pelagic fish and those associated with shallow, near shore waters were most adversely affected by gas bubble trauma. These fish would include gizzard shad (*Dorosoma cepedianum*), white bass (*Morone chrysops*), crappie (*Pomoxis spp.*), bluegill (*Lepomis macrochirus*), green sunfish (*Lepomis cyanellus*) and largemouth bass (*Micropterus salmoides*). Abnormal behavior is an obvious but nonspecific sign of gas bubble trauma. Wyatt and Beiningen (1971) described behavior in fish exposed to rapidly lethal level of supersaturation (150%) as fish suddenly lost the ability to swim against a current, were unable to avoid obstacles, soon lost equilibrium, moved to the surface without an apparent sense of direction and then exhibited violent writhing movements interspersed with inactivity. Stroud et al. (1975) reported that prior to death in juvenile fish signs included loss of equilibrium, abnormal buoyancy, violent head shaking, terminal convulsions and finally death. Decreased response to external stimuli was observed probably as a result of gas accumulation in the lateral line. Fish were frequently observed to die with mouth open and gills and opercula flared, a sign frequently observed in fish dying of anoxia. Dawley and Ebel (1975) reported behavioral changes and reduced growth in juvenile chinook salmon (*Oncorhynchus tschawytscha*) exposed to 115% total gas pressure. Bouck et al (1976) found adult chinook salmon swam aimlessly, were unresponsive and exhibited coughing as they approached death. In addition, some fish species seem to be able to sense the presence of gas supersaturated water and avoid these conditions by swimming at greater depths where hydrostatic pressure would compensate for the excess gas pressure (Bentley et al. 1976; Meekin and Turner 1974; and Weitkamp 1976). This may allow periodically sounding fish to spend a portion of the day near the surface without producing substantial effects of gas bubble trauma. However, as the fish do not eliminate the gas when they sound, the tissues will again be supersaturated on return to the surface. In addition, not all fish appear able to sense supersaturated conditions. Gray et al. (1983) found that the common carp (*Cyprinus carpio*) and the black bullhead avoided excessively high gas saturations (>140% of saturation) but did not avoid saturation levels near the threshold levels as measured by their 96-hr LC_{50} values of 122% of saturation and 114% of saturation, respectively. Chamberlain et al. (1980) found gas supersaturation caused swim bladders of Atlantic croakers (*Micropogon undulatus*), an estuarine physoclist, to inflate, resulting in first an upward drift and then downward swimming to restore neutral buoyancy. Inflation of the swim bladder may provide physoclistous fishes a direct mechanism for avoiding gas bubble trauma by stimulating the fish to descend to a compensation depth. Bouck et al. (1976) found that one of the greatest factors influencing tolerance to gas bubble trauma was the difference in tolerance between fish families. It was found that trout and salmon, which are physostomous, were generally more sensitive to gas supersaturation than bass, which are physoclistous. [Physostomous fish have an gas bladder that connects with the alimentary canal allowing some direct elimination of gas; physoclistous fish have a closed gas bladder and rely solely on special structures that can secrete or absorb gas (Bond 1979).] Bouck hypothesized that the physoclistous bass were more tolerant because of concurrent and compensatory increase of intrabody pressure. Evidence of high intrabody pressure was indicated in necropsy examinations. When punctured, the heart and swim bladder emitted an audible release. High intrabody pressure would keep gases in solution within vital organs of the area adjacent to the body cavity and thus protect the fish. However, sudden release of gas (from physostomous fish) would tend to sharply diminish intrabody pressure and promote cavitation of gas and the growth of emboli. Physostomus fish include catfish, carp, salmonids (salmon and trout), herrings (gizzard shad) and suckers. Physoclistous fish include bass, perch and crappie. Bowser et al. (1983) found that exposure of juvenile channel catfish, *Ictalurus punctatus*, to gas supersaturation resulted in abdominal distention presumably due to the accumulation of intrabody gas. Cornacchia and Colt (1984) found that larval striped bass exposed to gas supersaturation exhibited over-inflation of the gas bladder and accumulation of gas in the gut.

Recovery

Since the earliest research it has been known that fish can recover from gas bubble trauma. Several researchers have found that fish can rapidly recover from sublethal signs of gas bubble trauma, such as emphysema and exophthalmia, when the gas level is decreased, some after only two hours.

The rate of equilibrium between a fish's blood and the surrounding water is very rapid (Harvey 1975). This explains why fish can move relatively rapidly through waters of varying gas saturation without developing signs of gas bubble trauma and why intermittent exposure increases the level of supersaturation that fish are able to tolerate. [This also illustrates the difference between gas bubble trauma in fish and the bends in humans.] Intermittent exposure may increase the level of gas pressure that fish can tolerate because the time over which a specific exposure accumulates increases and there is some recovery occurring between exposures (Weitkamp and Katz 1980). Beyer et al. (1976) and Bouck (1980) have reported that the equilibrium of fish tissues to any saturation is fast, thus, the time lag often seen with chronic gas supersaturation is caused by other factors. Research has shown that recovery of fish from gas bubble trauma is possible using equilibrated water, hydrostatic pressure and artificially produced pressure. Henly (1952) and Weitkamp (1976) used hydrostatic pressure to alleviate signs of gas bubble trauma. Temperature also influences tolerance to gas bubble trauma and some species are inherently more susceptible than are others.

Ratio of oxygen to nitrogen gas

The ratio of oxygen gas to nitrogen gas pressure has been shown to affect the occurrence of gas bubble trauma. Bubbles formed in water have nitrogen gas and oxygen gas present in the same ratio as found in air. Thus, gas bubble trauma has been found to be caused by supersaturation of atmospheric gases and not by nitrogen gas alone as was earlier thought. Earlier it was assumed that nitrogen, being biologically inert, was the causative agent, as oxygen supersaturation would be regulated or reduced by biological processes. Nebeker et al. (1976) found a significant decrease in mortality when the ratio of oxygen to nitrogen gas was increased while holding the total percent of saturation constant. Rucker (1976) also reported an increased tolerance to supersaturation when the ratio of oxygen to nitrogen gas was increased. Lower gas pressure levels may be encountered during parts of the day since dissolved oxygen concentrations, and thus oxygen gas pressure, vary diurnally as a result of photosynthetic production of oxygen and biological respiratory depletion of oxygen (Nebeker et al. 1979).

Secondary effects

Sublethal, secondary effects of gas bubble trauma include blindness, stress, and decreased lateral line sensitivity. These sublethal effects can indirectly led to death. Gas bubble trauma can increase susceptibility to other diseases. Weitkamp (1976) found that fish that were not able to recover from gas bubble trauma under saturated conditions apparently died as a result of secondary fungal infections. Jensen (1974) found that white bass showed a high incidence of fungal infections that may have secondarily invaded lesions from gas bubble trauma. Large gas bubbles in the buccal cavity (mouth) can lead to the inability to feed. In addition, chronic gases may decrease peristaltic movement of food in the intestinal tract leading to a buildup of gas, toxic products, bacteria and heat (Stroud and Nebeker 1976). Several researchers reported that fish recovering from exophthalmia suffered permanent eye damage (Miller 1974; Marsh 1903). In addition, Crunkilton et al. (1980) reported that they observed progressive degeneration of tissue between the fin margins, particularly the caudal fin, caused by the trauma of gas bubble formation and subsequent infection, which resulted in the complete loss of fin structure and of the entire fin of fishes observed from a major fish kill at the Lake of the Ozarks.

Ecological significance

The ecological significance of the effects of gas supersaturation induced gas bubble trauma on naturally occurring populations is one area that requires additional study. Egusa (1959) stated that lethal nitrogen limits varied considerably among species. He found a median tolerance limit of 120% for adult common carp and felt that most fish could survive indefinitely below 115%. Bouck et al. (1976) found that at 10°C and at a gas pressure of 130% the median time to death for adult largemouth bass was 130 hours (or over five days). Although they exhibited external signs of gas bubble trauma largemouth bass survived prolonged exposure, at 120% of saturation (157 mmHg) which killed salmon and trout. Fickeisen et al. (1973) found that bluegill and common carp were more tolerant than smallmouth bass (*Micropterus dolomieui*) at 130% saturation. Thus, it appears that nonsalmonid fish may be able to tolerate higher gas supersaturation or (more accurately) tolerate positive hyperbaric pressures for a longer period of time. In addition, if the exposure is intermittent (the degree of saturation or hyperbaric pressure changes or the fish sounds) then the fish may be able to tolerate high levels even longer. Crunkilton et al. (1980) found that optimum conditions for supersaturation did not necessarily coincide with massive fish mortality but that mortality was more likely a result of a combination of physical conditions and fish behavior. Fickeisen et al. (1973) reported a narrow range between lethal and nonlethal saturation levels. Colt et al. (1985) found that the mortality of juvenile channel catfish varied from one percent to 54 percent at uncompensated hyperbaric gas pressures of 76 mmHg (110% of saturation) and 117 mmHg (115% of saturation), respectively. At 117 mmHg initial mortality was followed by a period of steady mortality. Bouck et al. (1976) reported that tolerance to gas bubble trauma appears to involve different biological factors at high versus low levels of supersaturation. In acutely lethal conditions survival may be influenced by the ability of a fish to tolerate changes in vascular dynamics. But survival at long-term subacute levels may be more dependent on complex alterations of physiological functions such as immune responses, infectious agents or adaptive behavior.

All of these factors illustrate the complex nature of gas bubble trauma in aquatic organisms. So what level of gas pressure is hazardous or ecologically significant in the real world, in natural systems? The answer to this question is difficult because the effects of gas supersaturation-induced gas bubble trauma vary according to fish species, size, age, and condition, as well as varying with temperature, depth distribution and gas ratios as discussed above. A few early studies indicated that 110% total gas saturation was the critical level for young salmonids held in shallow water. Thus, this value was adopted as a water quality standard by several states and the National Academy of Sciences and it is the maximum level recommended by the Environmental Protection Agency (EPA 1986). Other studies (Bouck 1980; Rulifson and Pine 1976) suggest that this is just the minimum level that can be safely tolerated by fish. However, Alderice and Jensen (1985) deduced from the literature that the initial lower level of chronic gas trauma begins at a hyperbaric pressure of only 28 mmHg to 35 mmHg (104% to 105% of saturation) and that acute gas bubble trauma begins at 60 mmHg to 76 mmHg (108% to 110% of saturation) above ambient pressure. Jensen et al. (1986) used a multivariate dose-response model to examine the response of salmonids to gas supersaturation and reported the safe levels of total gas pressure ranged from 104% to 115% of saturation depending on water depth and fish size. Alderice and Jensen (1985) concluded that total gas pressure should be maintained below 104% - 105% to prevent gas bubble trauma in streams. The EPA guideline for total gas pressure of 110% saturation equals an excess pressure of 76 mmHg and is viewed as too high to protect hatchery fish from chronic effects of gas bubble trauma (Krise and Mead 1988). So what pressure produces gas bubble trauma that is ecologically significant in natural systems? There is no clear consensus.

The following work will illustrate that gas supersaturation is not only associated with large dams having deep plunge basins but that substantially high levels of gas supersaturation can exist below a moderately-sized midwestern reservoir under both crest Tainter gate and sluice-gate release operations. In addition, field studies through collection of live fish and examination of fish kills provide evidence of both chronic and acute trauma to several species of fish.

STUDY AREA

This study took place at Red Rock Reservoir - a moderately-sized reservoir in south-central Iowa on the Des Moines River (Figure 1). It is located 230 kilometers (142.9 miles) above its junction with the Mississippi River and has a drainage basin of 31,916 square kilometers (12,323 square miles) (U.S. Army Corps of Engineers 1988). This research was conducted as part of a larger more generalized water quality monitoring effort that was conducted by Iowa State University's Engineering Research Institute under contract with the U.S. Army Corps of Engineers, Rock Island District.

Red Rock Reservoir became operational in March 1969 and is primarily operated for the purposes of flood control and low flow augmentation with secondary conservation and recreational benefits. The fishery below the dam is a popular natural resource.

Red Rock Dam is a rolled earthfill dam with a total length of 1,730 meters (5,676 feet) and height of 33.5 meters (110 feet) with a concrete spill-way. There are two release works - a gated spillway and outlet structures. The gated spillway consists of a series of five Tainter crest gates. The Tainter crest gates measure 12.5 meters by 13.7 meters (41 feet by 45 feet) on a concrete ogee crest at 224.3 meters (736 feet) above National Geodetic Vertical Datum (NGVD). The outlet structure consists of a series of 14 sluice gates. The 14

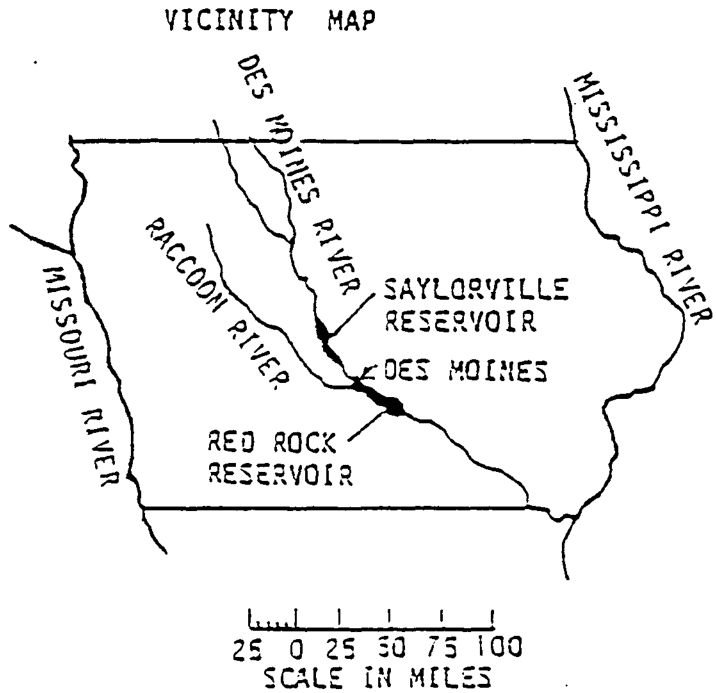

Figure 1. Vicinity map for gas supersaturation study.

sluice outlets measure 1.5 meters by 2.7 meters (5 feet by 9 feet) and extend through the concrete ogee spillway section into the stilling basin. The exit portals are completely below minimum tailwater. The inlet invert elevation is at 210.3 meters (690 feet) NVGD. The stilling basin is approximately 73.4 meters by 54.9 meters (241 feet by 180 feet) with a floor elevation at 199.3 meters (654 feet) NGVD. The basin is a hydraulic jump in which the jump height curve is below the tailwater rating curve at low discharges and above at high discharges. Baffle piers are in two rows, staggered, each 3.6 meters (12 feet) high, 4.8 meters (16 feet) long and 2.4 meters (8 feet) wide, spaced 3.0 meters (10 feet) apart in each row (Army Corps of Engineers 1988). The end sill is 3.0 meters (10 feet) high with top elevation at 202.4 meters (664 feet) NVGD. The tailwater elevation ranges from an elevation of 209.0 meters (685.6 feet) NVGD at a discharge of 8.5 m^3/s (300 ft^3/s) to an elevation of 213.4 meters (700.0 feet) NGVD at a discharge of 1,132.8 m^3/s (40,000 ft^3/s). Thus, the depths in the stilling basin would range from 9.6 meters (31.6 feet) to 14.0 meters (46.0 feet) under these flow regimes. At the average discharge of 223.1 m^3/s (7,879 ft^3/s) during this study the average depth of water in the stilling basin would be 11.1 meters (36.4 feet). Figures 2 and 3 illustrate the release structures at Red Rock Dam.

The reservoir is currently operated at a conservation pool level of 226.1 meters (742 feet) NVGD. Since the beginning of this study the conservation pool level has been raised periodically to offset sedimentation, with the

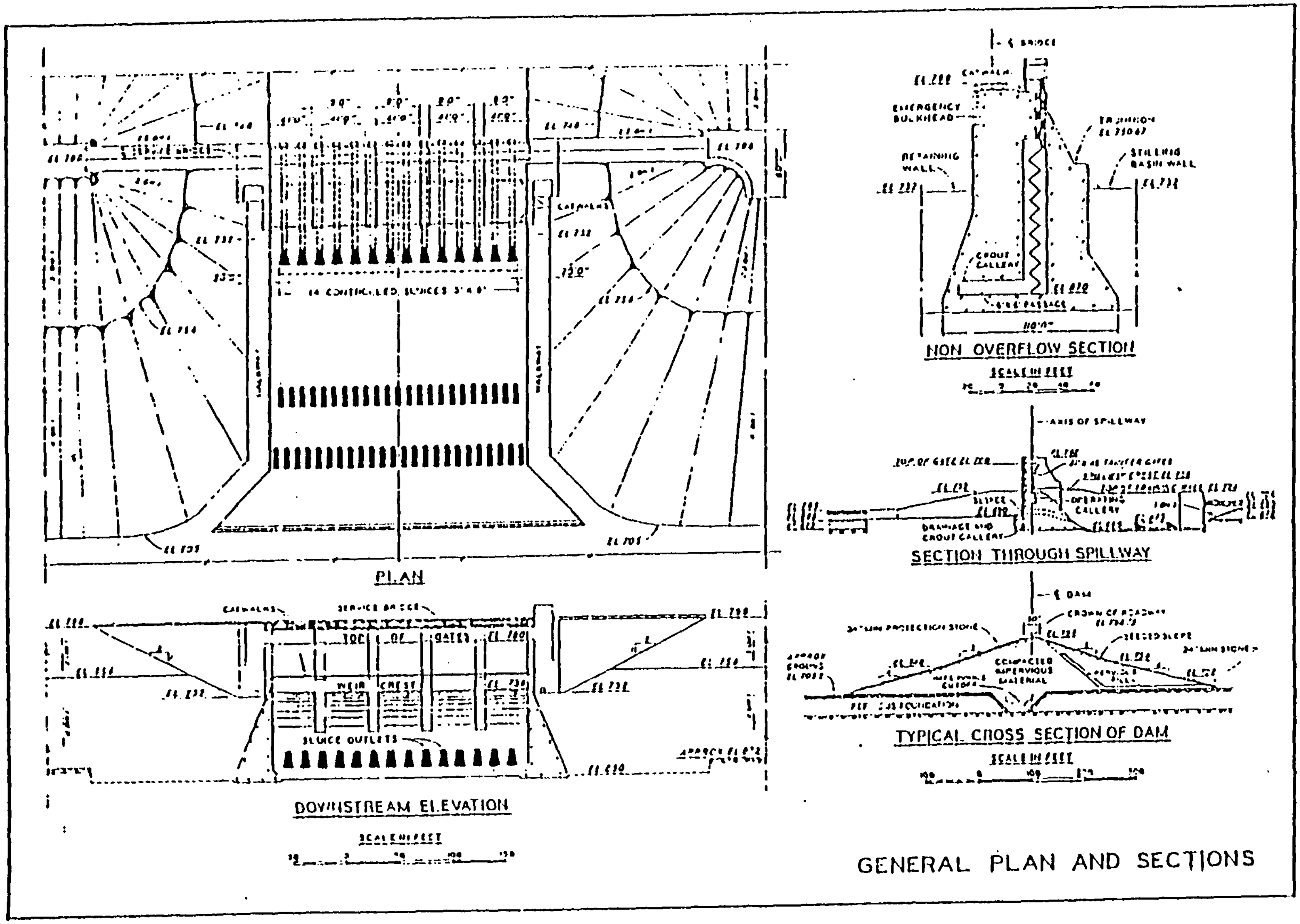

Figure 2. Red Rock Dam detail. General plan, from Bucci and Murphy, 1965.

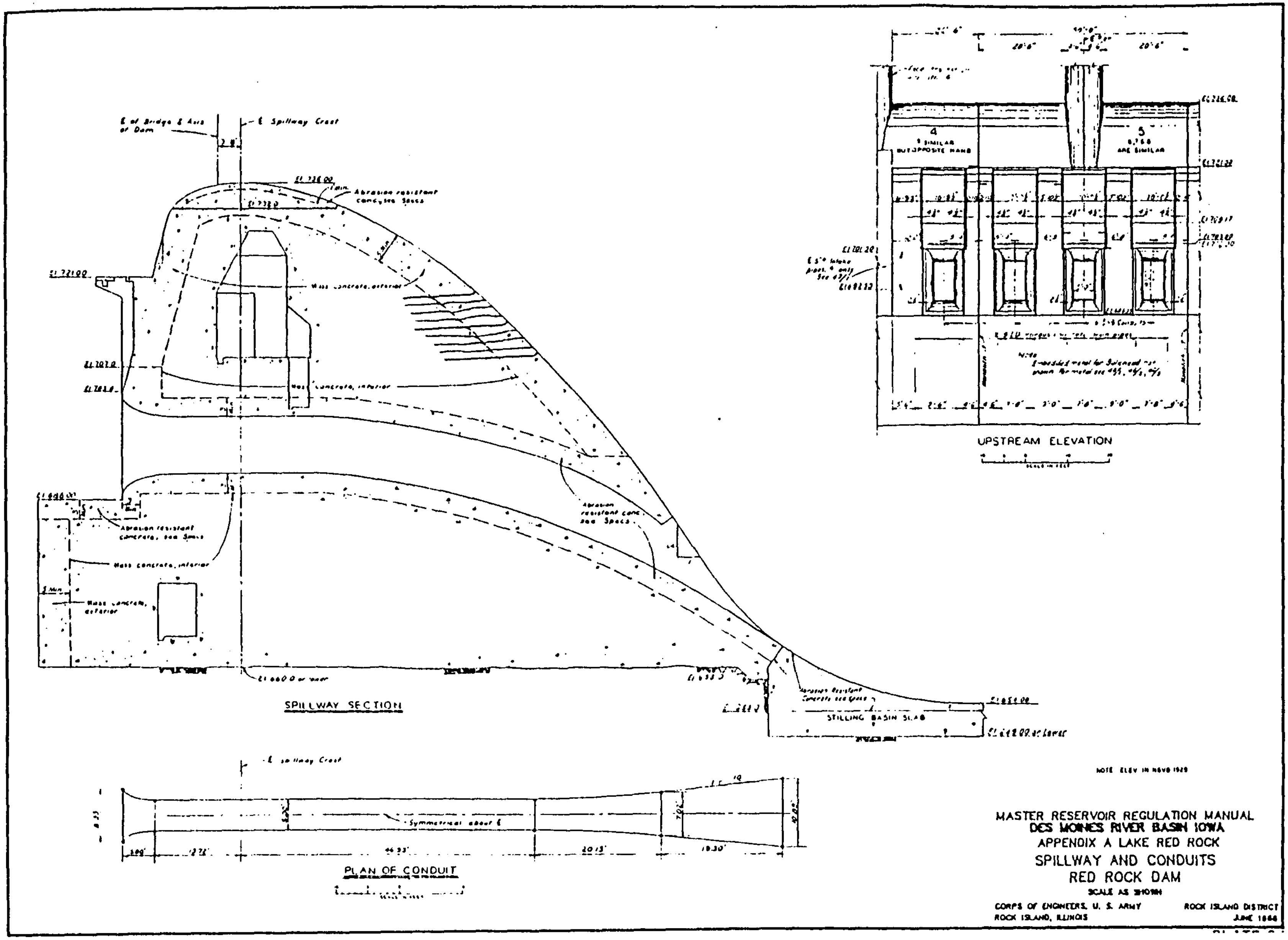

Figure 3. Red Rock Dam detail. Spillway and conduits, from U.S. Corps of Engineers, 1988.

conservation pool rising from 221.9 meters (728 feet) NVGD to 223.7 meters (734 feet) NVGD in December 1988, and rising to 226.1 meters (742 feet) NVGD in April 1992.

At its current conservation pool level the reservoir covers 77.3 square kilometers (19,100 acres) and its storage capacity is 327 million cubic meters (265,500 acre-feet). The maximum flood control pool is at 237.7 meters (780 feet) NVGD covering 265 square kilometers (65,500 acres), with a storage capacity of 2,208 million cubic meters (1,790,000 acre-feet). Normal release from the reservoir is constrained to a minimum of 8.5 m^3/s (300 ft^3/s) and a maximum release of 849.6 m^3/s (30,000 ft^3/s) during the nongrowing season. The maximum discharge recorded during the study period was 1,133 m^3/s (40,000 ft^3/s) which occurred in June 1984.

Water samples were collected and gas pressure readings were conducted at the same location, approximately 1,067 meters (3,500 feet) downstream from the dam. Samples were collected off of a fishing jetty on the northeastern river bank. Electrofish collection and examination of fish generally occurred within 2.4 kilometers (1.5 miles) of the dam. Examinations of dead fish from fish kills were conducted on fish observed within 305 meters (1,000 feet) of the sampling location.

Beginning in April 1988 and continuing through October 1992 gas pressure readings and water samples for Winkler determination of dissolved oxygen content were also collected in the main basin area of Red Rock Reservoir. Beginning in December 1990 total gas pressure readings and Winkler determination of dissolved oxygen content were also collected below Saylorville Reservoir which is located approximately 114 kilometers (71 miles) upstream from Red Rock Reservoir on the Des Moines River.

METHODS

Gas pressure in the river below Red Rock Dam was determined by the use of a saturometer and a dissolved gas meter. These instruments were constructed from gas permeable Silastic© tubing (dimethyl silicone rubber tubing) connected to a pressure gauge. Both instruments measure ΔP directly, the difference in the pressure of dissolved gases in the river as compared to atmospheric pressure. All pressure readings were taken about one half meter below the river surface.

Gas pressure data were taken from August 3, 1983 through August 1, 1989 with a Weiss saturometer (model ES) that was periodically checked for positive and negative pressure leaks. No leaks were ever found. The pressure gauge ranged from -100 to +400 mmHg with an accuracy of +/- 1%. Time to equilibration was approximately 20 minutes, varying with the degree of supersaturation. Care was taken to be assured that the saturometer had reached equilibration with the water. A final reading was not recorded until there had been no change in pressure over a two minute time period. An assurance check with a Common Sensing total gas meter on March 14, 1989, yielded similar results (Total gas pressure as percent of saturation: Weiss saturometer 99.2% versus Common Sensing total gas meter 100.0%). From August 3, 1983 through August 1, 1989, barometric pressure was determined from the barometric pressure at a meteorological station at the Des Moines International Airport correcting for the elevation difference between the two sites.

Gas pressure readings beginning in October 1989 were conducted using a Common Sensing gas meter model TB-L. With the Common Sensing gas meter the time to equilibration ranged from 10 to 15 minutes, depending on the level of supersaturation. Care was taken to be assured that the Common Sensing gas meter had reached equilibration with the water. A final reading was not recorded until there had been no change in pressure over a two minute time period. Patency checks of the Common Sensing gas meter were performed periodically according to the manufacturers instructions with no problems ever detected. From October 1989 barometric pressure was recorded from the barometer contained in the Common Sensing gas meter which was frequently checked against a mercury barometer.

Dissolved oxygen content of the water was determined in replicate samples collected in a sewage sampler by the azide modification of the idometric Winkler method according to Standard Methods for the Examination of Water and Wastewater, 17th edition (1989). The average absolute difference between replicates was 0.01 mg/l and the average absolute percent difference was 0.1%. The standard deviation of the difference between replicates was 0.18 mg/l.

Temperature readings were taken with two models of Fisher Scientific digital thermometers with thermistor sensors having accuracies of 0.2°C and resolution to 0.1°C. These thermometers were certified traceable to National Institute of Standards and Technology standards. Periodically the ice point was checked.

Nearly all gas pressure readings and water sample collections from the locations in the main basin of Red Rock Reservoir and below Red Rock Dam were collected between 1500 and 1700 Central Standard Time/Central Daylight Savings Time (CST/CDT). Gas pressure readings and water sample collections below Saylorville Reservoir were collected about 1100 CST/CDT.

Total gas meter readings were taken from the main basin of Red Rock Reservoir from a motorboat. These readings were taken just below the surface. Total gas meter readings were taken in the river reach just below Red Rock Dam off the fishing jetty on the northeast bank. This location is about 1.1 kilometers (0.7 mile) downstream from the dam. Several investigations showed that the total gas pressure at this bank location was equivalent to total gas pressure in the mid-channel of the river (accessed by motorboat). Due to time constraints total gas pressure below the dam was determined from the jetty location. The location below Saylorville Reservoir was about 2.4 kilometers (1.5 miles) downstream from the dam.

Total gas pressure (TGP) equals the sum of the partial pressures of the dissolved gases plus water vapor pressure. Total gas pressure data were calculated and expressed in two ways. First, as a percent of local barometric pressure (% of saturation) and second, as ΔP, the difference between total gas pressure in mmHg and local barometric pressure (mmHg). Nitrogen gas and oxygen gas pressure were expressed as a percentage of saturation defined as a percent of the partial pressure of the respective gas in air (N_2P % of saturation; O_2P % of saturation). Also, ΔP values for nitrogen and oxygen were calculated as the difference in partial pressure between air and water for the respective gas ($\Delta P\ N_2$; $\Delta P\ O_2$). The actual pressure that an aquatic organism experiences at a particular depth is called uncompensated gas pressure. The effect of changing river depth was evaluated by calculating the uncompensated total gas pressure as a percent of saturation at the maximum river depth at the time of the pressure reading. Likewise, uncompensated ΔP was calculated as the ΔP that aquatic organisms would encounter at the maximum river depth at the time of the pressure reading. Compensation depth was calculated as the depth necessary for hydrostatic pressure to equal barometric pressure plus water vapor pressure. These depth calculations assume that both ΔP and temperature are uniform with depth, assumptions that may not be valid for other studies in lakes or reservoirs. All calculations were done as recommended by Colt (1984). The equations used in these calculations are listed in Table 1.

Table 1. Equations used in the calculation of dissolved gas pressure data. Based on Colt (1974).

Equation 1: Total gas pressure (TGP), in percent of saturation

$$\text{Total gas pressure (\%)} = \frac{P_{bar} + \Delta P}{P_{bar}} \times 100$$

Equation 2: Nitrogen gas pressure (N_2P), in percent of saturation

$$\text{Nitrogen gas pressure (\%)} = \frac{(P_{bar} + \Delta P) - \left(\frac{[O_2]_m}{\beta} \times 0.532\right) - P_{H_2O}}{(P_{bar} - P_{H_2O})\,(0.7902)} \times 100$$

Equation 3: Oxygen gas pressure (O_2P), in percent of saturation

$$\text{Oxygen gas pressure (\%)} = \frac{\left(\frac{[O_2]_m}{\beta} \times 0.532\right)}{(P_{bar} - P_{H_2O})\,(0.2095)} \times 100$$

Equation 4 (a, b, c): Delta P pressure, in mmHg

(a) $\Delta P\ (mmHg) = P_{meter}$

(b) $\Delta P_{N_2}\ (mmHg) = (P_{bar} + \Delta P) - \left(\frac{[O_2]_m}{\beta} \times 0.532\right) - P_{H_2O} - \left[(P_{bar} - P_{H_2O}) \times 0.7905\right]$

$$(c)\quad \Delta P_{O_2} = \left(\frac{[O_2]_m}{\beta} \times 0.532\right) - \left[(P_{bar} - P_{H_2O}) \times 0.2095\right]$$

Equation 5 (a,b): Uncompensated pressure, the effect of depth

$$(a)\quad \Delta P_{uncompensated} = \Delta P - pgZ$$

$$(b)\quad TGP_{uncompensated} = \left[\frac{P_{bar} + \Delta P}{P_{bar} + pgZ}\right] \times 100$$

P_{bar}	=	barometric pressure (mmHg)
P_{H2O}	=	water vapor pressure (mmHg)
ΔP	=	Saturometer or total gas meter reading (mmHg)
$[O_2]_m$	=	dissolved oxygen concentration by Winkler method
β	=	Bunsen coefficient of oxygen solubility
0.532	=	a correction factor, to convert β to mg/l
0.7902	=	the fractional composition of nitrogen (plus argon) in air
0.2095	=	the fractional composition of oxygen in air
p	=	density of water
g	=	acceleration due to gravity, 9.80665 m/s^2
Z	=	depth, m

RESULTS

Evidence of the occurrence of gas supersaturation and associated gas bubble trauma in fish in the Des Moines River below Red Rock Dam has accumulated from over nine years of gas pressure data, 14 fish kill reports and several examinations of recently expired and live fish (Baumann et al. 1985; Baumann and Lutz 1986; Baumann and Lutz 1987; Baumann et al. 1988; Baumann et al. 1989; Lutz et al. 1990; Lutz and Baumann 1991; Lutz 1992; Lutz 1993). The evidence of gas supersaturation and associated gas bubble trauma at this location can be summarized in four arguments. These consist of:

- the occurrence of unusual fish kills,
- the phenomenon of elevated gas pressure,
- the confirmation of chronic gas bubble trauma in live fish and acute gas bubble trauma in dead fish from fish kill events
- comparison of dissolved gas pressure below the dam with dissolved gas pressure in the main basin of the reservoir

Unusual fish kills

Prior to this study, several fish kills were noted below the dam in which no known cause was established. These fish kills did not seem to have a sudden onset and many different species and size ranges were affected.

Thermal stress, dissolved oxygen depletion and point-source pollution were eliminated as possible causes. [Thermal stress-related fish kills of yearling gizzard shad were not uncommon in the fall, however these kills were easily distinguishable. Shad are susceptible to temperature fluctuations in the 4°C to 6°C range and to rapid temperature changes (Chittenden 1972).] Reports of fish kill events listed time, air and water temperature, river flow, dissolved oxygen content, severity of kill (how many fish floating downstream per minute as well as a tally of fish present on river banks), species of fish, approximate range in fish lengths per species and any observations of live fish. An example of a fish kill report is shown in Appendix A. The 14 fish kill events are summarized in Appendix B.

High total gas pressure

Gas pressure data indicated that the river below the dam was consistently supersaturated with dissolved atmospheric gases. Total gas pressure data are given as both a percent of local barometric pressure (% of saturation) and as ΔP (the difference in pressure between total gas pressure and local barometric pressure). Positive values of ΔP are often referred to as hyperbaric pressure. Of 255 gas meter readings taken over more than a nine year period, only one indicated an undersaturated condition. Values of total gas pressure ranged from 99% of saturation to 132% of saturation with a mean of 116% of saturation and a standard deviation of 7%. Expressed as ΔP, values ranged from -10 mmHg to 237 mmHg with a mean pressure of 120 mmHg and a standard deviation of 50 mmHg. From these 255 pressure readings, 79 percent equalled or exceeded the EPA criteria for dissolved gases of 110% of saturation, 40 percent equalled or exceeded 115% of saturation, 32 percent equalled or exceeded 120% of saturation and 10 percent of the readings equalled or exceeded 125% of saturation. Figure 4 illustrates the total gas pressure results in a time series. The dark horizontal line in this figure represents the EPA criterion value of 110% of saturation. Thus, the EPA criterion of 110% was exceeded during most of the study period. Expressed as ΔP, 68 percent of the readings equalled or exceeded 100 mmHg, 31 percent equalled or exceeded 150 mmHg and four percent of the readings exceeded 200 mmHg. The EPA criterion expressed as ΔP equals 76 mmHg and 78 percent of the readings equalled or exceeded this value. Figure 5 illustrates the ΔP results in a time series. Summary statistics of the 255 dissolved gas values and related parameters from below Red Rock Dam are listed in Table 2. The complete gas pressure data set is contained in Appendix C.

The gas pressures exerted by nitrogen gas and oxygen gas were also calculated as a percent of saturation and as the hyperbaric pressure contributed by these respective gases. The nitrogen gas pressure ranged from 100% of saturation to 138% of saturation, with an average of 119% of saturation and a standard deviation of 7%. The oxygen gas pressure ranged from 71% of

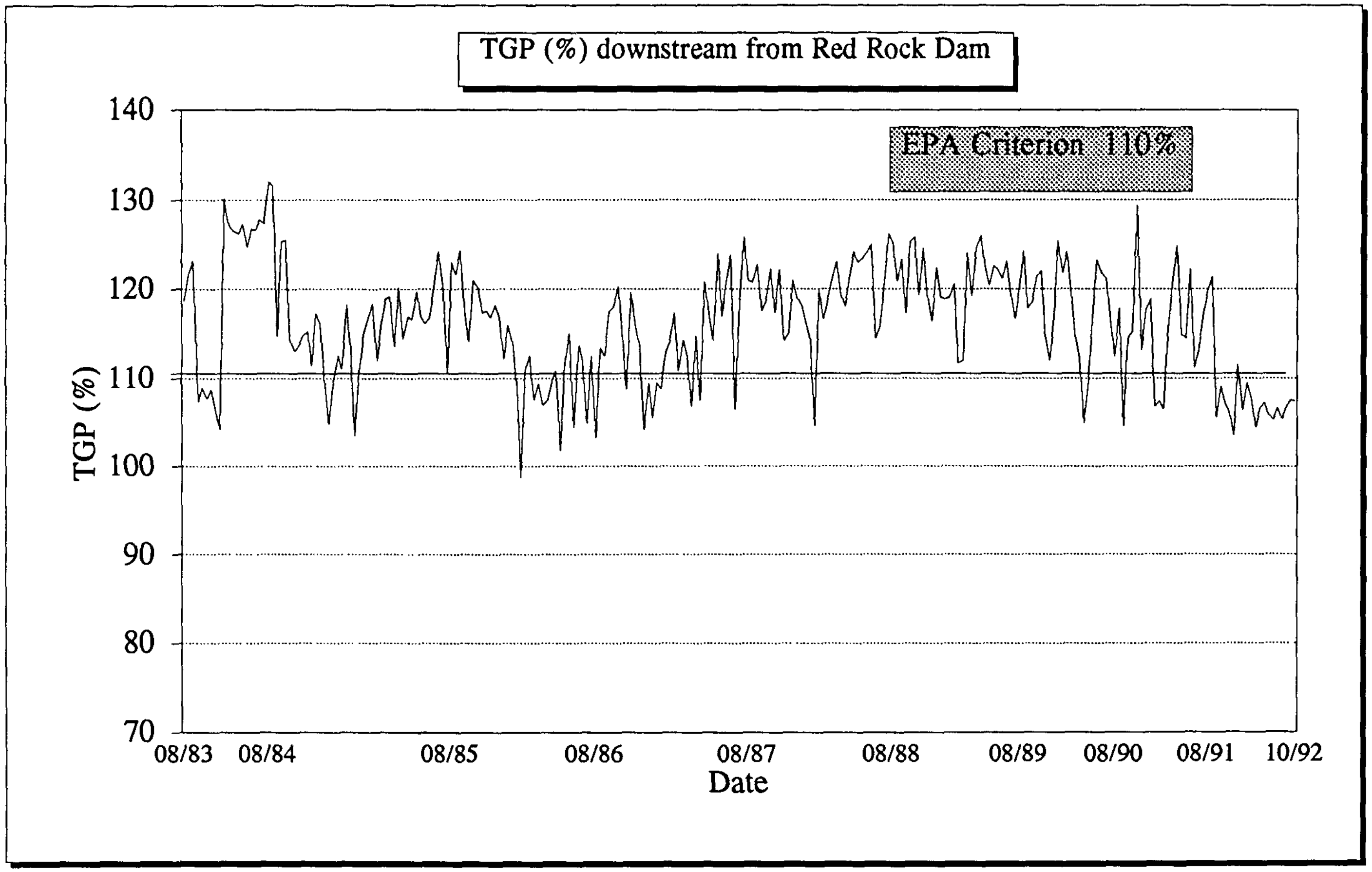

Figure 4. Time series of total gas pressure (% of saturation) downstream from Red Rock Dam.

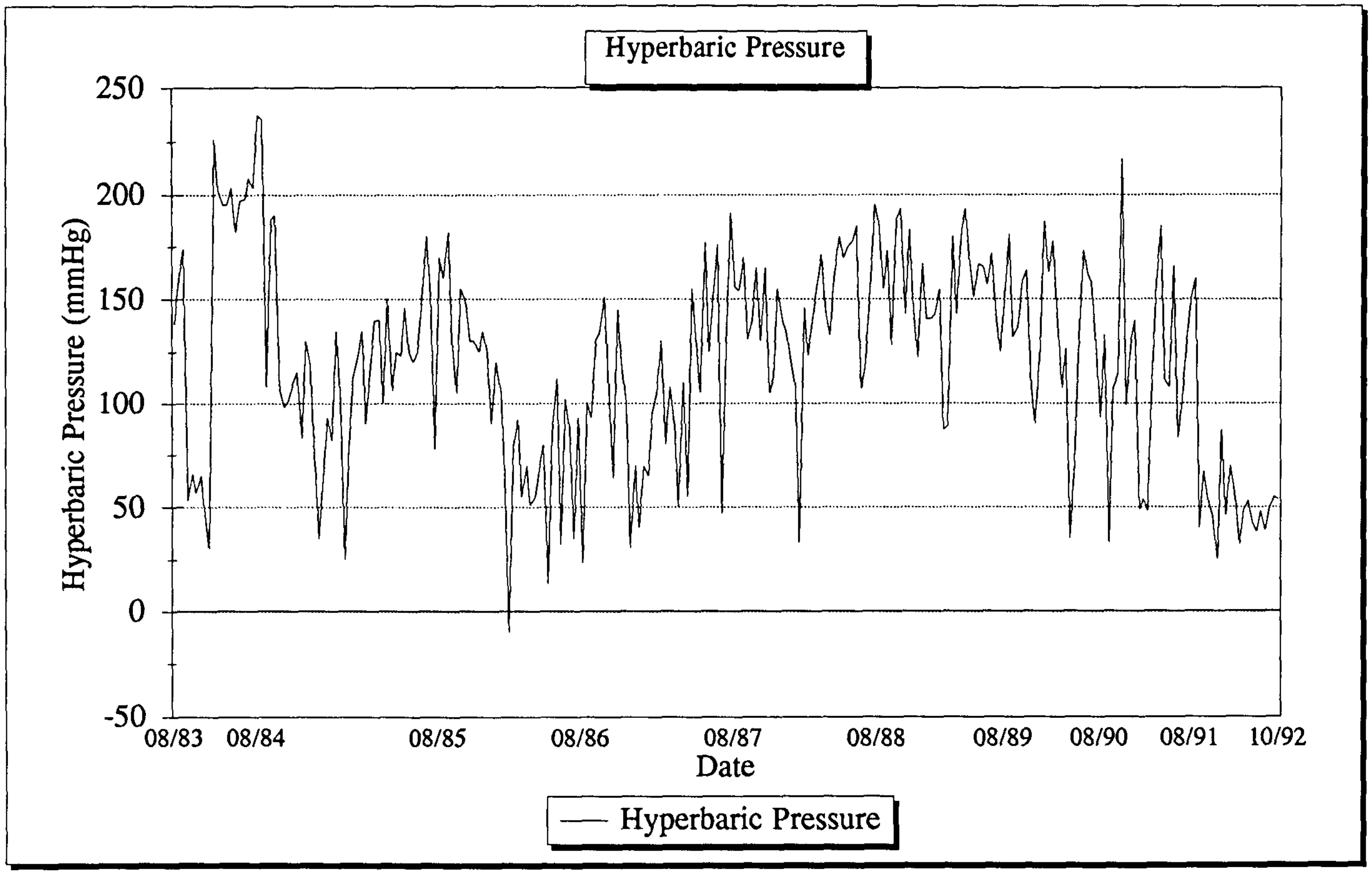

Figure 5. Time series of ΔP or hyperbaric pressure (mmHg) downstream from Red Rock Dam.

Table 2. Summary statistics of dissolved gas data and related parameters downstream from Red Rock Reservoir, Iowa. This data set includes 255 observations.

Parameter	Minimum	Maximum	Mean	Standard deviation
Discharge (m^3/s)	8.5	1133	222.9	228.4
Discharge (ft^3/s)	300	40000	7870	8065
Temperature (°C)	0.0	31.4	16.4	9.1
Dissolved oxygen (mg/l)	5.6	17.5	10.8	2.7
Barometric pressure (mmHg)	727.6	755.0	742.9	4.6
Total gas pressure (%)	98.7	132.1	116.1	6.6
Nitrogen gas pressure (%)	99.9	138.4	118.6	7.1
Oxygen gas pressure (%)	70.6	184.8	108.8	16.7
ΔP (mmHg)	-10	237	120	49.2
ΔP N_2 (mmHg)	-0.5	217.2	106.5	40.2
ΔP O_2 (mmHg)	-44.2	125.7	13.4	25.4
Maximum depth (m)	0.5	4.2	2.0	1.1
Compensation depth (m)	-0.1	3.2	1.6	0.7
Uncompensated total gas pressure at the maximum depth (%)	74.7	120.3	97.9	11.6
Uncompensated ΔP at the maximum depth (mmHg)	-262.1	158.4	-27.4	106.5

saturation to 185% of saturation, with a mean of 109% of saturation and a standard deviation of 17%. The ratio of nitrogen gas pressure as a percent of saturation versus oxygen gas pressure as a percent of saturation ranged from 0.6 to 1.7, with a mean value of 1.1 and a standard deviation of 0.2. The ΔP contributed by nitrogen gas ranged from 0.5 mmHg to 217.2 mmHg, with a mean of 106.5 mmHg and a standard deviation of 7.1. The ΔP contributed by oxygen gas ranged from -44.2 mmHg to 125.7 mmHg, with a mean of 13.4 mmHg and a standard deviation of 25.4. Figures 6 and 7 illustrate the time series of nitrogen gas pressure (% of saturation) and oxygen gas pressure (% of saturation), respectively. It should be noted that there was more variance in oxygen gas pressure data as a result of oxygen demand and diurnal fluctuations of oxygen production by algae. The highest maximum values (as % of saturation) were also of oxygen gas, however, the average nitrogen gas pressure was greater.

Visual evidence of gas bubble trauma in fish

Visual external evidence of gas bubble trauma, mainly emphysema (gas bubbles in organs or tissue), exophthalmia (pop-eye) and petechial hemorrhages (just under the epidermis), was observed in recently expired fish and in live fish collected by electrofishing or found hugging the river bank. Often, these

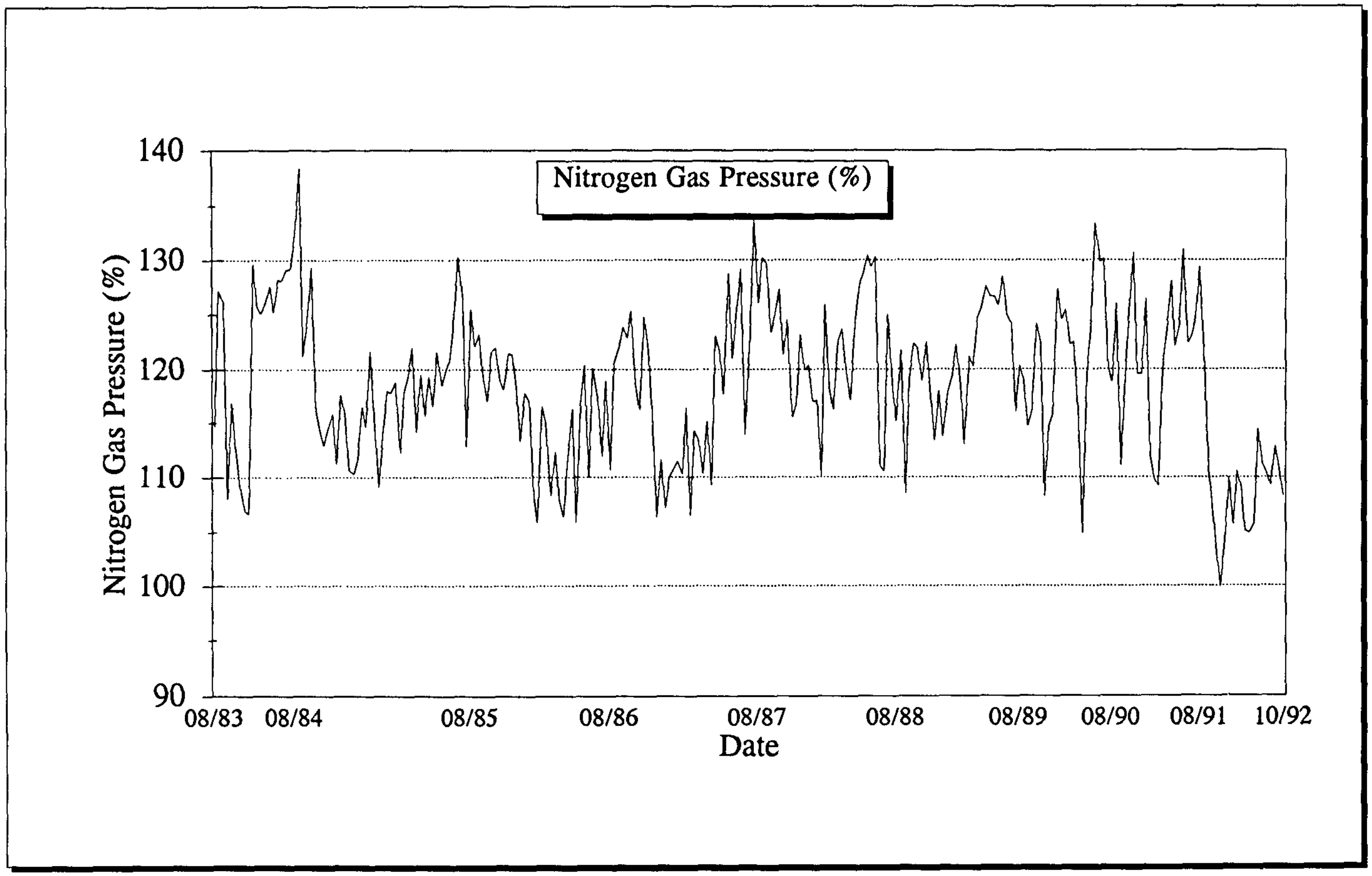

Figure 6. Times series of nitrogen gas pressure (% of saturation) downstream from Red Rock Dam.

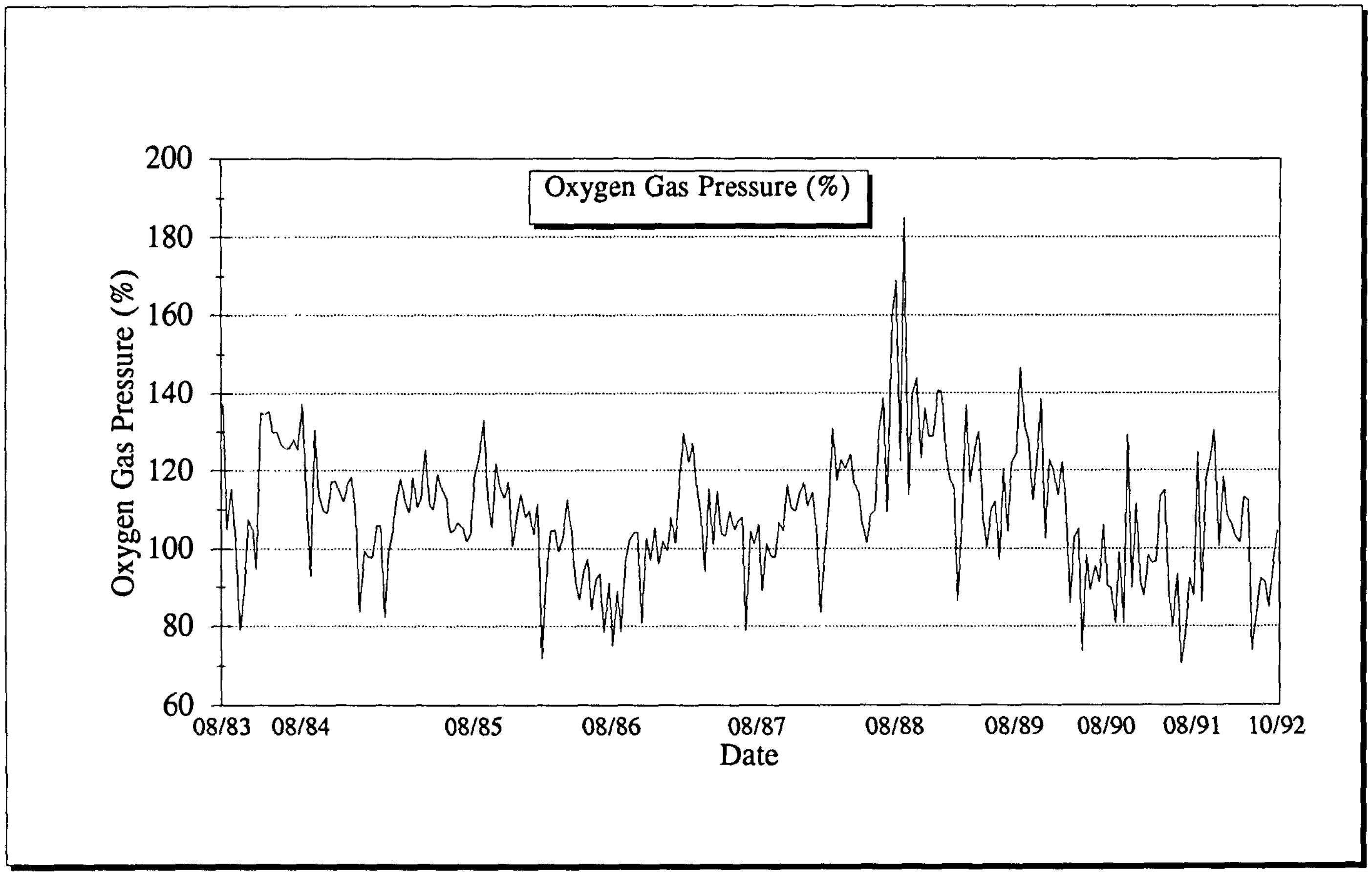

Figure 7. Time series of oxygen gas pressure (% of saturation) downstream from Red Rock Dam.

visual indications were not present in dead fish that were discovered after the fish kill event was over, as gas bubbles present in tissues of dead organisms or in organisms removed from supersaturated conditions disappear over time. Thus, visual indications of gas bubble trauma would not be expected in fish from fish kills that occurred several days before they were discovered either floating or washed up on the river bank. Both emboli and emphysema disappear because the heart has stopped supplying hyperbaric gases for continued inflation (Bouck 1980). Coutant and Genoway (1968) reported that external signs of gas bubble trauma disappeared rapidly after death, nearly all signs were lost after 24 hours.

Acute gas bubble trauma

The first visual confirmation of the occurrence of gas bubble trauma in fish below Red Rock Dam came during a fish kill on September 6, 1983. Since then, 14 other fish kill events were studied in which gas supersaturation appeared be the causative agent. Table 3 lists gas pressure data and related parameters during these 14 fish kills believed to be related to gas bubble trauma. Table 4 summarizes the gas pressure data and tallies fish kill events by water year. Each fish kill event is summarized in Appendix B.

The first fish kill event in which recently expired fish could be examined came on September 16, 1986. Thirty dead fish were collected at

Table 3. Summary statistics of dissolved gas data and related parameters during 14 fish kill events downstream from Red Rock Reservoir, Iowa.

Parameter	Minimum	Maximum	Mean	Standard deviation
Discharge (m^3/s)	8.5	104.8	45.8	37.3
Discharge (ft^3/s)	300	3700	1618	1317
Temperature (°C)	1.8	29.0	20.7	11.1
Dissolved oxygen (mg/l)	7.9	12.4	9.9	1.9
Barometric pressure (mmHg)	739.2	748.9	742.7	3.5
Total gas pressure (%)	109.0	126.2	120.2	6.5
Nitrogen gas pressure (%)	107.2	130.3	123.2	7.9
Oxygen gas pressure (%)	89.7	159.3	111.8	20.8
ΔP (mmHg)	67	195	150	48
ΔP N_2 (mmHg)	40.7	171.9	132.2	44.8
ΔP O_2 (mmHg)	-16.1	88.7	17.6	31.4
Maximum depth (m)	0.5	1.9	1.1	0.5
Compensation depth (m)	0.9	2.7	2.0	0.7
Uncompensated total gas pressure at the maximum depth (%)	97.8	120.3	108.9	8.1
Uncompensated ΔP at the maximum depth (mmHg)	-19.0	158.4	71.1	64.1

Table 4. Summary of gas supersaturation data below Red Rock Reservoirs for water years 1984-1992.

	Water Year (Oct-Sep)								
	1984	1985	1986	1987	1988	1989	1990	1991	1992
No. of Observations	19	46	36	34	33	22	27	21	15
TGP≥110%	13	44	23	26	32	22	24	14	1
TGP≥115%	12	28	12	19	29	20	18	10	0
TGP≥120%	12	11	1	10	18	12	10	5	0
Range									
TGP(%)	104-132	103-126	99-120	105-126	104-126	112-126	104-129	105-125	103-112
N_2P(%)	107-138	109-130	106-125	106-134	108-130	113-128	105-133	100-131	104-113
O_2P(%)	79-137	82-133	72-117	79-130	83-185	86-141	74-146	71-130	74-11
Mean Flow									
(m^3/s)	586	123	322	235	64	34	237	419	289
(ft^3/s)	20685	4345	1385	8,294	2,258	1,190	8,370	14,810	10,200
Fish Kills									
Thermal Stress	0	3	0	2	1	1	0	0	0
Gas Bubble Trauma	0	3	2	1	2	1	0	3	0

random from fish floating downstream. Of the 30 fish, 18 were freshwater drum, *Aplodinotus grunniens*, six were black crappies, *Pomoxis nigromaculatus*, four were white crappies, *Pomoxis annularis*, and two were channel catfish. More than 70% of the freshwater drum showed obvious signs of gas bubble trauma (emphysema and/or exophthalmia), whereas only half of the crappie exhibited any signs of gas bubble trauma and the two channel catfish showed no external signs of gas bubble trauma. Many of the gas blisters (which occurred in the buccal cavity, between fin rays or in the orbitals) were 0.5 cm and larger, and many fish had numerous (five to 20) gas blisters.

Table 3 lists the summary statistics of dissolved gas data and related parameters during these 14 fish kill events. The total gas pressure during these fish kills ranged from 109% of saturation to 126% of saturation with a mean of 120% of saturation. From the data set excluding the fish kill events (see Table 5) the total gas pressure ranged from 99% of saturation to 132% of saturation with a mean of 116% of saturation. Thus, it is obvious that the event of the highest total gas pressure observed, 132% of saturation, did not result in a fish kill. As will be discussed again later, this was because of the effect of river depth. During the period of maximum total gas pressure observed, the release from the reservoir was 623 m^3/s (22,000 ft^3/s) which resulted in a river depth of 3.6 meters, a depth greater than the required compensation depth of 3.2 meters. Thus, although the total gas pressure was extreme there was still

Table 5. Summary statistics of dissolved gas data and related parameters downstream from Red Rock Reservoir, Iowa. Data from fish kill events has been excised from the data set. This data set includes 240 observations.

Parameter	Minimum	Maximum	Mean	Standard deviation
Discharge (m^3/s)	8.5	1133	234.0	230.8
Discharge (ft^3/s)	300	40000	8264	8148
Temperature (°C)	0.0	30.9	16.0	9.1
Dissolved oxygen (mg/l)	5.6	17.5	10.8	2.7
Barometric pressure (mmHg)	727.6	755.0	742.9	4.7
Total gas pressure (%)	98.7	132.1	115.8	6.6
Nitrogen gas pressure (%)	99.9	138.4	118.3	7.0
Oxygen gas pressure (%)	70.6	169.1	108.2	15.9
ΔP (mmHg)	-10	237	118	49.0
ΔP N_2 (mmHg)	-0.5	217.2	105.1	39.8
ΔP O_2 (mmHg)	-44.2	102.5	12.6	24.2
Maximum depth (m)	0.5	4.2	2.1	1.1
Compensation depth (m)	-0.1	3.2	1.6	0.7
Uncompensated total gas pressure at the maximum depth (%)	74.7	120.0	97.2	11.4
Uncompensated ΔP at the maximum depth (mmHg)	-262.1	158.3	-34.1	105.3

11% of the water column in which the uncompensated total gas pressure was below 100% of saturation.

In fact, the greatest differences between the fish kill data set and the data set without fish kill events was in parameters related to flow and river depth. During the fish kill events, the average river flow was only 45.8 m^3/s (1,618 ft^3/s), as compared to 234.0 m^3/s (8,264 ft^3/s) for the rest of the data set. Thus, the maximum river depth was much less during fish kill events. The maximum river depth during fish kill events ranged from 0.5 meter to 1.9 meters with a mean of 1.1 meters. For all but one event, the compensation depth required to offset the total gas pressure exceeded the maximum river depth observed. Thus, during these events, aquatic organisms would be continually subjected to hyperbaric pressures at any depth. The uncompensated total gas pressure at the maximum river depth averaged 109% of saturation during the fish kill events and 97% of saturation for the rest of the data set. The uncompensated ΔP at the maximum river depth averaged 71.1 mmHg during the fish kill events and -34.1 mmHg for the rest of the data set. Studies in hyperbaric physiology have shown that initial gas bubble formation is dependent on ΔP (D'Aoust and Clark 1980; Bouck 1980). Gas bubble trauma can only exist when the sum of the dissolved gas pressures (barometric pressure plus ΔP) exceeds the sum of the hydrostatic pressure. During 13 of the 14 fish kills attributed to gas bubble trauma, the uncompensated ΔP at the maximum river depth was not only positive but in half of the cases it was over 100 mmHg.

Examinations of fish during another fish kill event resulted in positive confirmation that gas bubble trauma was indeed the cause of death. Positive confirmation of acute gas bubble trauma requires both the confirmation of hyperbaric dissolved gas pressure, the cause, and confirmation of emboli in the vascular system, the effect (Bouck 1980).

On December 13, 1990, an ongoing fish kill event was discovered. The fish kill included gizzard shad, freshwater drum and white bass. All observed freshwater drum exhibited external emphysema on their heads in the occiput region (Figure 8) and between fin rays. Many exhibited exophthalmia with gas bubbles visually apparent (Figure 9). Half of the white bass observed were still alive but had lost equilibrium, were oriented upside down, and were hugging the river bank. Both the dead and live white bass exhibited no obvious external signs of gas bubble trauma. Dissection of a few freshwater drum specimens showed that there were gas emboli in the vascular system, including the heart, indicating that gas bubble trauma was in fact the cause of death (Figure 10). In the two white bass specimens dissected, emphysema were noted in the mesenteries (Figure 11) and in the lateral line (Figure 12). In addition, the body cavity seemed to be pressurized with excess gas, which escaped when the body cavity was opened. This excess gas could account for the upside down orientation of the fish as their bellies became more buoyant. There did not appear to be any gas bubbles in the vascular system of the white bass.

Figure 8. Microphotograph of the head region of a freshwater drum (*Aplodinotus grunniens*) with many emphysema (gas bubbles). Collected from a fish kill downstream from Red Rock Dam on December 13, 1990.

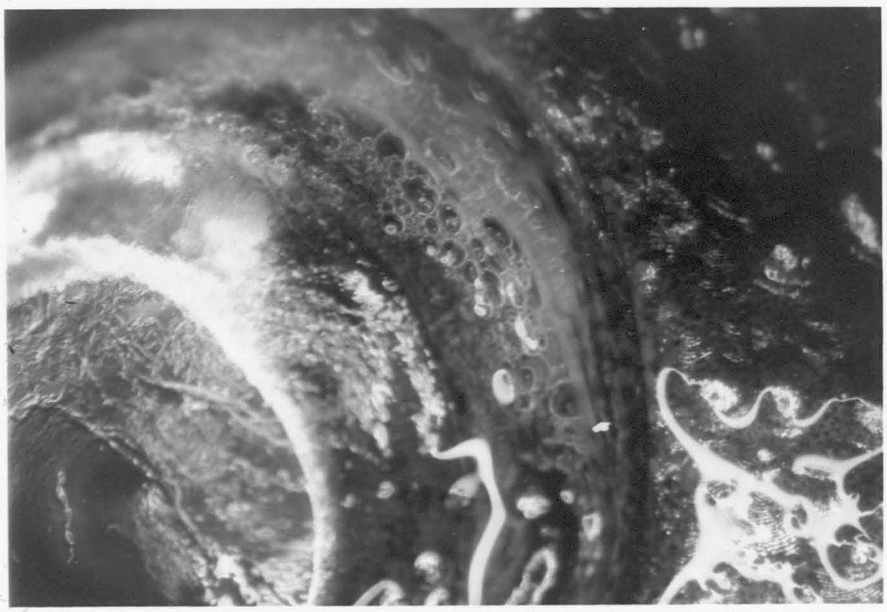

Figure 9. Microphotograph of the eye of a freshwater drum (*Aplodinotus grunniens*) exhibiting exophthalmia. Gas bubbles are clearly evident. Collected from a fish kill downstream from Red Rock Dam on December 13, 1990.

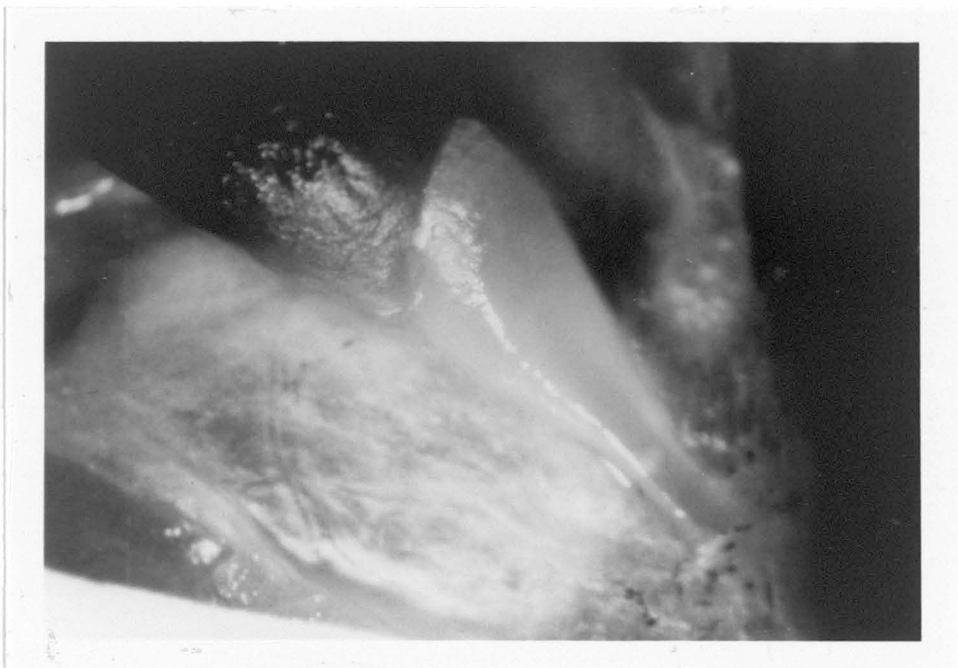

Figure 10. Microphotograph of gas emboli present in the heart of a white bass (*Morone chrysops*) confirming that the cause of death was acute gas bubble trauma. Collected from a fish kill downstream from Red Rock Dam on December 13, 1990.

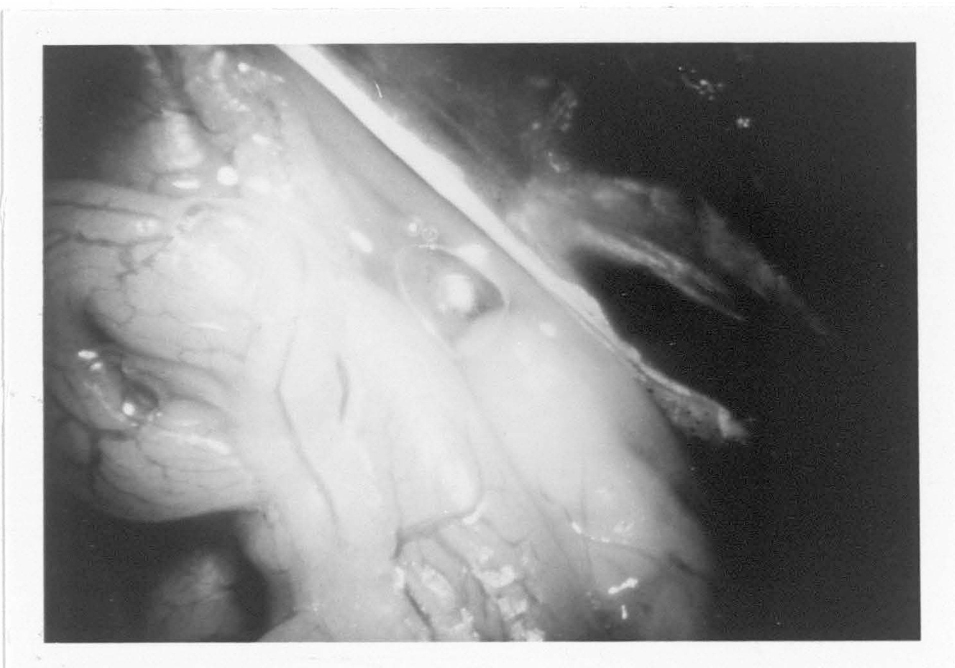

Figure 11. Microphotograph of gas bubbles present in the mesenteries of a white bass (*Morone chrysops*). Collected from a fish kill down stream from Red Rock Dam on December 13, 1990.

Figure 12. Microphotograph of gas bubbles present in the lateral line of a white bass *(Morone chrysops)*. Collected from a fish kill downstream from Red Rock Dam on December 13, 1990.

The largest fish kill that occurred during this nine year study period appeared to occur between August 27 and August 29, 1991. Unfortunately, this researcher was not notified of the fish kill. The first observation was made on a routine monitoring trip on September 3, 1991. However, the Iowa State Conservation Commission did investigate and estimated the number of dead fish at 5,000. On September 3, 1991, it was observed that there were still about 10 dead fish floating downstream per minute, with 10 dead fish seen per 30 meters (100 feet) of river bank. Approximately 60% of the observed dead fish were white bass, 10% channel catfish, 10% freshwater drum, 5% largemouth bass, 5% bluegill, 5% gizzard shad, and a few walleye (*Stizostedion vitreum*). One dead paddlefish (*Polyodon spathula*) was observed. Many live fish were also observed. There were several green sunfish that were alive but were hugging the river bank. Upon closer examination it was noticed that these fish exhibited severe exophthalmia and emphysema were present in their fin tissue (Figure 13). Most of the dead fish that were examined (many were too decayed to reveal much) exhibited some sign of gas bubble trauma. On this date, September 3, 1991, the total gas pressure was 109% of saturation (ΔP of 67 mmHg) with nitrogen gas and oxygen gas pressures of 107% of saturation (ΔP of 41 mmHg) and 117% of saturation (ΔP of 26 mmHg), respectively. The uncompensated gas pressure at the maximum river depth was 101% of saturation while the uncompensated ΔP at the maximum river depth was 8 mmHg.

Figure 13. Photograph of a live green sunfish (*Lepomis cyanellus*) with extreme exophthalmia and difficulty maintaining orientation. Collected downstream from Red Rock Reservoir on September 3, 1991.

This was the first time since February 13, 1991 (which also triggered a fish kill) that the uncompensated ΔP at the maximum river depth was positive. Previous to the September 3 fish kill, the outflow from Red Rock Reservoir was decreased substantially. The last previous monitoring event was on August 20, 1991, when the outflow was 365.3 m^3/s (12,900 ft^3/s), the total gas pressure was 105% of saturation (ΔP of 40 mmHg), and the uncompensated gas pressure at the maximum river depth was 98% of saturation (ΔP of -19 mmHg). By September 3 the outflow had decreased to 28.6 m^3/s (1,010 ft^3/s). This decrease in river flow, which decreased the river depth, triggered a fish kill as uncompensated dissolved gas pressures became hyperbaric throughout the water column.

Chronic gas bubble trauma

Live fish exhibited signs of chronic gas bubble trauma. The occurrence of elevated gas pressure and occasional fish mortality, along with the casual observation of gas blisters in live fish collected during electrofishing activities for a related project in May 1988, led to attempts to externally examine live fish collected in May 1989. Common carp were collected from four locations in central Iowa in May 1989. These locations corresponded to the main basin of Saylorville Reservoir [which is located about 114 kilometers (71 miles) upstream from Red Rock Dam on the Des Moines River], just downstream from Saylorville Reservoir, the main basin area of Red Rock Reservoir and just downstream from Red Rock Dam. Common carp were collected by electrofishing until twenty-plus fish were obtained at each location in the target length range. Common carp obtained from Saylorville Reservoir and below Saylorville Dam were casually examined during fish processing (which took place within hours of collection). Closer examinations were conducted on fish collected at Red Rock Reservoir with records kept of any abnormal external signs. During the electrofishing collection trip below Red Rock Dam additional fish species were collected for examination for external signs of gas bubble trauma. In the beginning, all catchable shocked fish were examined. When this became cumbersome, only additional (so far unsampled) species or those considered gamefish were collected. Very few gamefish were seen during the collection trip below Red Rock Dam. Fish were identified, measured, and examined for external signs of gas bubble trauma. A log sheet, detailing the presence or absence of emphysema, exophthalmia, and secondary infections, was completed for each fish. (A completed examination sheet is contained in Appendix D). The general degree of external chronic gas bubble trauma observed for each fish was classified:

- minimal - if only a few small to moderate (pinpoint to 2 mm) sized gas blisters were present
- moderate - if medium to large (2 mm to 5 mm) gas blisters were present in several locations; secondary infection and/or fin erosion may have been present

- severe - if large to extremely large (>5 mm) gas bubbles were present at several locations and fin erosion and/or secondary infection was present, or bubbles appeared to interfere with function (ie., swimming, feeding)

In total 47 fish were examined from nine species groups in addition to the 26 common carp collected below Red Rock Dam on May 25, 1989. It must be noted that this was an incidental survey and was not intended to be a population study. However, it was estimated that 90% of the fish observed while electrofishing below Red Rock Dam were either common carp, carpsuckers *(Carpiodes spp.)*, buffalo (*Ictiobus spp.*), or freshwater drum. The release from the reservoir on May 25, 1989, was relatively low at 83.5 m^3/s (2,950 ft^3/s). The total gas pressure at 1030 CDT, just before electrofishing was initiated below Red Rock Dam, was 114% of saturation (ΔP of 103 mmHg). Total gas pressure for the previous three weeks averaged 123% of saturation (average ΔP of 173 mmHg) at about 1530 CDT at this location. In addition, late afternoon total gas pressure in the main basin of Red Rock Reservoir was 97% of saturation (ΔP of -20 mmHg) on May 9, 1989, and 98% of saturation (ΔP of -11 mmHg) on May 30, 1989. Electrofishing took place in Red Rock Reservoir on May 24, 1989.

The twenty common carp collected in the main basin of Saylorville Reservoir were examined during processing for external signs of gas bubble trauma. The fish were examined within six hours of capture and had been kept on ice. No gas bubbles were present and there were no incidences of exophthalmia. Seventy percent (14 of 20) of the common carp appeared completely healthy. The remaining 30% (6 of 20) exhibited some minor secondary infection of the fin or minor fin erosion.

Common carp results from below Red Rock Dam will be discussed first so that they may be compared to results from fish collected in the reservoir. Twenty-six common carp were examined in the field, of which 85% (22 of 26) exhibited some external sign of gas bubble trauma, typically numerous emphysema in fin tissue or between scale pockets. In addition, 73% (19 of 26) of the common carp exhibited some degree of secondary infection of the fins and/or fin erosion. Furthermore, of the fish that exhibited no direct external sign of gas bubble trauma, the majority (3 of 4) exhibited secondary infections. Of the carp examined, 35% (9 of 26) were classified as minimally affected, 31% (8 of 26) as moderately affected and 19% (5 of 26) as severely affected by chronic external gas bubble trauma. The most common external signs of gas bubble trauma in common carp were emphysema in fin tissue; 73% (19 of 26) of the common carp examined had emphysema present in one or more fins. The incidence of gas bubbles was greatest in the pelvic fins. The incidence of emphysema in the dorsal, caudal, anal, pelvic, and pectoral fins was 35%, 35%, 46%, 54%, and 46%, respectively. Emphysema of the body, usually present in the scale pockets, was present in eight of the common carp, normally with those most severely affected. Several fish were referred to as "popping" in the field notes as the fish's body, when handled, felt like the plastic-bubble-inflated packing material often used to ship fragile parcels. Exophthalmia was displayed in 27% (7 of 26) of the common carp although no gas accumulation was visible from unaided observation.

The opportunity was taken to examine other species. In all, 47 fish of nine species groups were examined with 35 fish (or 74%) showing some direct external sign of gas bubble trauma. Overall, 21% (10 of 47) of the fish displayed external signs that were classified as minimal, 38% (18 of 47) as moderate, and 15% (7 of 47) as severe (Table 6). Fish from six of the nine species groups were classified as displaying moderate to severe external signs of gas bubble trauma. Three species groups - green sunfish, walleye, and crappie - were not found to exhibit substantial external signs of gas bubble trauma, however, only a few fish were collected in each group and they were all small fish (<250 mm). It is believed by several researchers that gas bubble trauma affects larger, fattier fish to a greater extent (Weitkamp and Katz 1980; Crunkilton et al. 1980; DeMont and Miller 1972; Egusa 1959; Marsh and Gorham 1905). No ictalurids (bullhead, catfish) were seen while electrofishing, so, unfortunately, none could be examined. [Earlier in May a fish kill comprised of mainly channel catfish and flathead catfish (*Pylodictis olivaris*) was reported by the public. It was also reported that some catfish were exhibiting unusual behavior by jumping up and skimming the water surface with their sides.]

Table 6. Summary of external examinations of live fish collected below Red Rock Dam on May 24, 1989 for signs of gas bubble trauma.

Fish Species	Length (mm)	No. Examined	No GBT[a] No 2° Infection	No GBT[a] 2° Infection	Minor GBT	Moderate GBT	Severe GBT
From Red Rock Reservoir (main basin)							
Common carp	316-359	20	14	6	—	—	—
From below Red Rock Dam							
Common carp	283-358	26	1	3	9	8	5
Carpsucker	290-418	17	---	1	2	11	3
Buffalo	285-550	8	1	2	2	2	1
Freshwater drum	240-420	8	—	—	3	3	2
Bluegill	113-162	5	2	—	2	1	—
Gar	510-710	3	1	—	—	1	1
Green sunfish	114-152	2	2	—	—	—	—
Crappie	205-250	2	2	—	—	—	—
Walleye	222-250	2	1	—	1	—	—

[a] GBT - gas bubble trauma

The most common signs of gas bubble trauma in the various species were emphysema in fin tissue, emphysema in the head region (which included the occiput, nuchal region, buccal cavity and operculum), emphysema in the body or scale pockets, exophthalmia, edema, petechial hemorrhages, and evidence of former lesions. Indirect indications of stress, probably enhanced by chronic gas bubble trauma, included secondary infections, fin erosion, and the presence of ectoparasites. Rates of incidence of various signs of gas bubble trauma varied by species, is seen in Table 7. River carpsuckers, *Carpiodes carpio*, of which 14 were examined, experienced emphysema primarily in the head region (43%) and the body area (79%), generally in the scale pockets, and characteristically on the belly between the pelvic fins. Petechial hemorrhages were present in 71% of the river carpsuckers, with secondary infection or fin erosion apparent to some degree in all the river carpsuckers examined. Exophthalmia was evident in 43% of the river carpsuckers with many exhibiting visible gas bubbles in orbital cavities. Quillback carpsuckers, *Carpiodes cyprinus*, of which only three were examined, exhibited similar emphysema on the belly and in scale pockets, as well as other signs. Buffalo, of which eight were examined, generally exhibited emphysema in the body region or scale pockets (50%) and in fin tissue (38%). Several affected buffalo suffered from innumerable gas blisters which covered the entire fish, as well as extensive petechial hemorrhaging and secondary infection (Figure 14). Buffalo did not appear to develop the

Table 7. Summary of the incidence rates of various external signs of gas bubble trauma in live fish collected downstream from Red Rock Dam on May 24, 1989.

	Common carp	Carpsucker	Buffalo	Freshwater drum	Bluegill	Shortnose Gar	Walleye
Total Number	26	17	8	8	5	3	2
Length (mm)	283-358	290-418	285-550	240-420	113-162	510-710	222-250
2° infection or fin erosion	19 (73%)	17 (100%)	6 (75%)	3 (38%)	0	2 (67%)	0
Emphysema							
any fin	7 (50%)	10 (59%)	3 (38%)	8 (100%)	3 (60%)	2 (67%)	1(50%)
dorsal fin	9 (35%)	6 (35%)	2 (25%)	5 (62%)	1 (20%)	1 (33%)	0
caudal fin	9 (35%)	5 (29%)	3 (38%)	5 (62%)	3 (60%)	2 (67%)	0
anal fin	12 (46%)	2 (12%)	2 (25%)	4 (50%)	0	1 (33%)	1 (50%)
pelvic fin	14 (54%)	2 (12%)	2 (25%)	3 (38%)	1 (20%)	1 (33%)	0
pectoral fin	12 (46%)	2 (12%)	2 (25%)	5 (62%)	1 (20%)	1 (33%)	0
head region	1 (4%)	6 (35%)	2 (25%)	5 (62%)	0	0	0
body	8 (31%)	14 (82%)	4 (50%)	4 (50%)	0	0	1 (50%)
Exophthalmia							
w/ emphysema	0	2 (12%)	0	1 (12%)	0	0	0
w/o emphysema	7 (27%)	4 (24%)	1 (12%)	1 (12%)	0	0	0
Petechial hemor-rhages	5 (19%)	12 (70%)	2 (25%)	1 (12%)	2 (25%)	1 (33%)	0

Figure 14. Photograph of a large buffalo (*Ictiobus* spp.) exhibiting innumerable emphysema directly under the epidermis with petechial hemorrhag ing and secondary infection. Collected downstream from Red Rock Reservoir on September 3, 1991.

bulging scale pockets exhibited in some other species, rather, emphysema appeared to be just under the epidermis and filling but not extending the scale pockets. Freshwater drum, of which eight were examined, exhibited emphysema in the fins of all fish, while 62% had emphysema present in the head region and 50% on the body or in scale pockets. In the more affected fish, scale pockets bulged as was described earlier as "popping" (Figure 15).

Casual observations of fish collected during electrofishing in May 1990 and June 1992, and closer observations in May 1990, did not detect substantial external signs of gas bubble trauma. (It can be seen from Table 4 that examinations in 1989 were conducted during the lowest flow water year of the study period.) However, many fish below Red Rock Dam exhibited secondary infections, body scars and lesions that were not noticed to such a degree at the other three locations where electrofishing activities were conducted. On May 21, 1991, 35 fish of nine species groups (ten fish were common carp) were collected during electrofishing activities and examined according to the procedures followed in 1989. These collections occurred under high reservoir releases of 574.9 m^3/s (20,300 ft^3/s). The total gas pressure below Red Rock Dam on May 13, 1991 and May 28, 1991 was 125% of saturation (ΔP of 185 mmHg) and 115% of saturation (ΔP of 111 mmHg), respectively. During the time of the fish collection, the maximum river depth was nearly twice the required compensation depth. Only three of the fish exhibited any direct

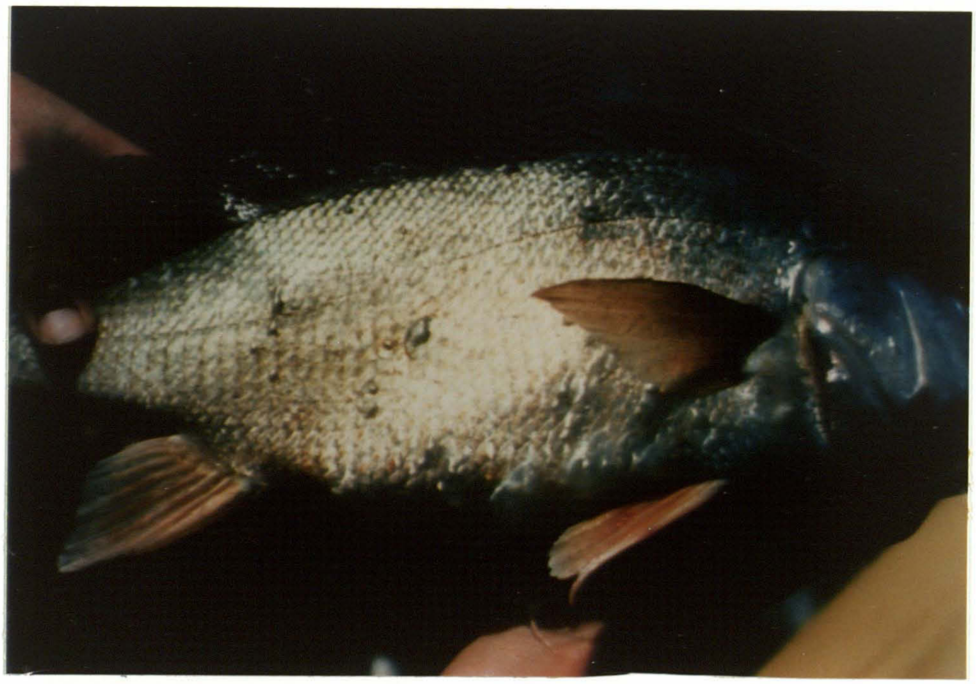

Figure 15. Photograph of a freshwater drum (*Aplodinotus grunniens*) exhibiting severe exophthalmia. Note the bulging scale pockets along the belly and midsection; there is some involvement of the lateral line. This fish was described as "popping". Collected downstream from Red Rock Reservoir on September 3, 1991.

external signs of gas bubble trauma. These fish (a largemouth bass, a buffalo, and a bluegill) exhibited minimal gas bubble trauma (few small gas bubbles in fin tissue). However, there was evidence of stress in many of the fish. Fifty-one percent (18 of 35) of the fish exhibited some degree of fin erosion, 31% (11 of 35) of the fish had external lesions and/or secondary infections and 23% (8 of 35) of the fish had some degree of petechial hemorrhaging. In addition, three fish displayed patches of missing scales and three fish had ectoparasites. Table 8 summarizes the examinations of live fish collected below Red Rock Dam in May 1991.

Effect of the dam

The fourth argument for a causal relationship between the gas super-saturated conditions in the river below the dam and the dam itself comes from comparing total gas pressure in the reservoir with total gas pressure in the river below. Also, the effect of different release operations (ie., Tainter gate versus sluice-gate release) was examined.

TGP in the river below versus the reservoir

In order to confirm that elevated dissolved gas pressure in the river below Red Rock Dam was actually an artifact of the dam itself, either the dam structure, its outlet or operations, total gas pressure readings were taken in the

Table 8. Summary of examinations for external signs of gas bubble trauma in live fish collected below Red Rock Reservoir on May 21, 1991.

	Total examined	Fin erosion	Secondary infection and/or lesions	Emphysema	Petechial hemor-rhages	Ectoparasites
Common carp	10	8	3	0	1	1
Carpsucker	8	7	5	0	5	2
Largemouth bass	5	0	2	2	0	0
Buffalo	4	2	1	2	2	0
Shortnose gar	3	0	0	0	0	0
Freshwater drum	2	0	0	0	0	0
White bass	1	0	0	0	0	0
Bluegill	1	0	0	1	0	0
White crappie	1	0	0	0	0	0
TOTAL	36	17 (47%)	11 (30%)	5 (14%)	8 (22%)	3 (8%)

main basin of Red Rock Reservoir. Since readings were initiated in April 1988, a total of 74 readings of gas pressure have been made in the main basin of Red Rock Reservoir. Interestingly, there have been periods of high gas pressure in the reservoir itself. The maximum total gas pressure in the main basin (132% of saturation) equalled the maximum total gas pressure recorded below the dam (132% of saturation) for the entire period of record. In fact, when looking at the pressure data as ΔP, the highest ΔP was recorded in the main basin (241 mmHg versus 237 mmHg). However, when comparing readings below Red Rock Dam for the same 74 dates it is obvious that chronic gas supersaturation is only a problem below the dam. From these 74 events, total gas pressure in the main basin averaged 103% of saturation while the total gas pressure below the dam averaged 116% of saturation. The main basin total gas pressure equalled or exceeded 110% on ten occasions (14% of readings) as compared to total gas pressure below the dam which equalled or exceeded 110% on 56 occasions (76% of the readings). Readings equalled or exceeded 120% of saturation on only two occasions in the main basin of the reservoir and on 33 occasions (44% of the readings) in the river below the dam. In fact, in the main basin the periods of elevated gas pressure were short-term events that could be correlated to intense primary productivity. The chlorophyll *a* (corrected for pheophytin) concentrations during the two peak gas pressure events (124% of saturation and 132% of saturation) in the main basin on July 31, 1990 and August 13, 1991 were 103 mg/m^3 and 114 mg/m^3, respectively, which is extreme for this location. The impact of primary productivity (diel fluctuations) can be seen in oxygen gas pressure data at the reservoir. In the main basin the oxygen gas pressure ranged from 52% of saturation to 238% of saturation with a mean of 101% of saturation. Below the dam the oxygen gas pressure ranged from 71% of saturation to 185% of saturation with a mean of 111% of saturation. Interestingly, there were a few events in the reservoir where nitrogen gas pressure exceeded 110%. These events occurred when oxygen gas pressure was well below saturation. Thus, it seems, that as oxygen was utilized and the gas tension reduced, atmospheric gases were entering the water and, since the atmospheric gases are about 80% nitrogen, the nitrogen concentration increased above saturation. Table 9 lists the total gas pressure, as well as nitrogen and oxygen gas pressure, in percent of saturation, for both locations. Figure 16 illustrates the total gas pressure at the main basin as compared to the river downstream from the dam.

Effect of Tainter gate operation

Early in the study period the effect of Tainter gate operations was monitored. It was suspected that operation of the Tainter gates could entrain air as the water cascaded over the dam and plunged into the

Table 9. Total gas pressure, as well as nitrogen and oxygen gas pressure, in percent of saturation, in the main basin of Red Rock Reservoir and below Red Rock Dam.

	Red Rock Reservoir Main Basin			Below Red Rock Dam		
Date	TGP (%)	N2P (%)	O2P (%)	TGP (%)	N2P (%)	O2P (%)
05Apr88	106	105	111	121	123	117
19Apr88	101	102	99	123	124	123
03May88	108	101	133	119	120	120
17May88	104	104	105	122	124	117
31May88	103	101	112	124	128	114
14Jun88	101	101	101	124	130	101
21Jun88	104	103	108	124	129	108
05Jul88	97	109	52	114	111	130
12Jul88	101	105	85	116	110	139
19Jul88	107	99	141	121	125	109
26Jul88	118	107	166	126	119	159
02Aug88	101	100	105	125	115	169
09Aug88	95	102	67	121	122	122
16Aug88	101	102	101	123	108	185
06Sep88	101	103	92	125	122	140
13Sep88	102	102	104	126	122	144
20Sep88	98	101	87	119	119	123
27Sep88	97	102	79	125	122	136
11Oct88	98	102	86	119	117	129
08Nov88	101	103	92	122	118	141
09May89	97	102	79	125	125	126
30May89	98	105	74	123	128	107
06Jun89	101	106	83	120	127	100
13Jun89	98	105	79	123	127	110
20Jun89	97	105	67	122	126	112
27Jun89	100	105	83	121	128	97
11Jul89	118	101	187	123	125	120
18Jul89	97	107	59	119	124	104
25Jul89	96	103	71	117	116	122
01Aug89	107	100	137	120	120	125
24Oct89	106	99	130	124	119	146
07Nov89	99	102	89	118	115	131
27Mar90	100	102	89	112	115	102
10Apr90	101	102	96	117	116	123

Table 9. Continued.

Date	Red Rock Reservoir Main Basin TGP (%)	N2P (%)	O2P (%)	Below Red Rock Dam TGP (%)	N2P (%)	O2P (%)
24Apr90	106	105	109	125	127	120
01May90	99	101	92	122	124	114
08May90	104	104	107	124	125	122
15May90	102	103	100	119	122	110
29May90	119	106	168	114	122	86
05Jun90	98	102	84	112	115	103
12Jun90	104	105	101	105	105	105
19Jun90	96	105	58	110	120	74
26Jun90	102	108	80	118	124	98
10Jul90	100	107	79	123	133	89
24Jul90	105	103	117	121	130	91
31Jul90	124	96	237	117	120	106
07Aug90	105	105	106	112	119	90
21Aug90	100	104	85	104	111	81
11Sep90	95	101	71	115	125	81
24Sep90	103	104	99	129	131	129
01Apr91	103	104	97	106	109	96
15Apr91	101	103	93	115	120	96
05Jun91	100	105	82	114	124	80
18Jun91	112	103	148	122	131	93
09Jul91	103	102	107	111	122	71
16Jul91	102	105	94	113	123	78
30Jul91	118	123	105	117	125	92
06Aug91	94	102	64	120	129	88
13Aug91	132	106	238	121	122	124
20Aug91	102	107	83	105	111	86
03Sep91	104	110	80	109	107	117
17Sep91	102	109	77	107	103	123
08Oct91	102	106	91	106	100	130
17Mar92	105	105	106	106	106	109
14Apr92	104	106	94	108	109	103
05May92	102	104	98	106	105	113
09Jun92	104	104	103	106	114	74
23Jun92	104	111	80	105	111	83

Table 9. Continued.

Date	Red Rock Reservoir Main Basin TGP (%)	N2P (%)	O2P (%)	Below Red Rock Dam TGP (%)	N2P (%)	O2P (%)
30Jun92	110	117	86	106	110	92
07Jul92	102	112	66	105	109	91
21Jul92	110	116	90	107	113	85
28Jul92	113	104	152	107	111	96
13Oct92	103			107	108	105
COUNT	73	72	72	73	73	73
MINIMUM	94	96	52	104	100	71
MAXIMU	132	123	238	129	133	185
MEAN	103	104	101	117	119	111

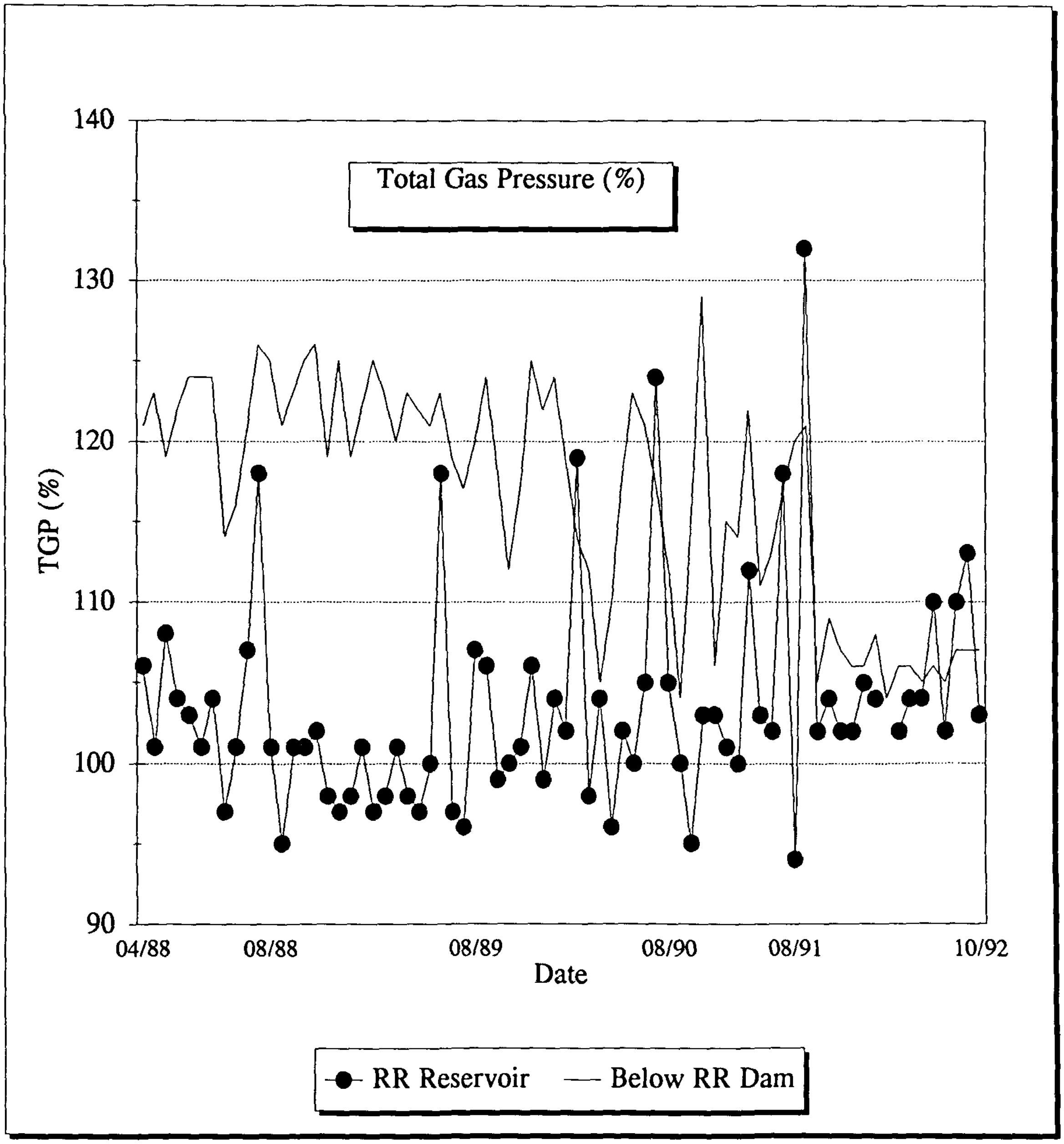

Figure 16. Total gas pressure, in percent of saturation, in the main basin of Red Rock Reservoir and below Red Rock Dam.

stilling basin. At the depth conditions in the stilling basin, the entrained air could be dissolved. As discussed before, this is the mechanism in which gas supersaturation has been shown to occur at other larger dams. However, because of the size of Red Rock Dam and the depth of the tailwater, gas supersaturation was not believed to be of concern at Red Rock Reservoir. Before September 1984, the Tainter gates were operated under conditions which required large releases (>425 m^3/s or 15,000 ft^3/s) and during a local tourist attraction in May (Pella Tulip Festival). As a result of the preliminary results of this study, which showed a substantial increase in total gas pressure during Tainter gate operation, the Tainter gates have not been operated at Red Rock Reservoir since August 1984, except when the gates needed to be opened for higher releases or for maintenance (in August 1991). During this study period (August 3, 1983-October 1992) the Tainter gates were only in use on August 3, 1983 (and for several months previous) and from May 14, 1984 to August 18, 1984. Also, one of the five tainter gates was in operation from May 6, 1986 to June 10, 1986. Fish kills were observed on September 13, 1983, October 3, 1984, and August 26, 1986, as dam discharges were substantially dropped, allowing the uncompensated ΔP at the maximum river depth to become positive.

During the study period two attempts were made to define the effects that Tainter gate operation had on total gas pressure below Red

Rock Dam. The first study took place on May 8, 1984 when total dissolved gas readings were taken just before the Tainter gates were opened and several times over the next 22 hours. The total gas pressure just before the Tainter gates were opened was 103% of saturation at 1045 CDT. Immediately following this reading the Tainter gates were opened. The reservoir outflow, both before and after the Tainter gates were operated, was about 453 m^3/s (16,000 ft^3/s). A reading taken at 1330 CDT showed that the total gas pressure had jumped to 125% of saturation. Thus, there was a substantial increase under Tainter gate operation and the effect was relatively rapid. Readings continued to be taken at 1600 CDT and 1830 CDT on May 8, 1984, and 0840 CDT on May 9, 1984, with the maximum pressure obtained being 126% of saturation. In addition, a reading was taken at 1115 CDT on May 9, 1984, about 19.3 kilometers (12 miles) below the dam at Highway 92. Even at this location, the total gas pressure was elevated (123% of saturation). (Another longitudinal study was conducted that will be discussed below.)

The second study was on August 9, 1991 when for the first time in over four years the Tainter gates were utilized as part of a planned maintenance operation. On August 9, the Tainter gates were opened in succession. It was expected that the total gas pressure would increase, but it was unknown to what degree and how rapidly. For comparison, dissolved gas readings were taken in the late afternoon of August 8 and in the early morning of August 9 before the gates were operated. At this time the outflow was 509.8 m^3/s (18,000 ft^3/s) ,as it had been since the middle of May. The initial total gas pressure was 117% of saturation (ΔP of 127 mmHg) at 1735 CDT August 8 and 119% of saturation (ΔP of 45 mmHg) at 0710 CDT on August 9. Tainter gate operation was expected to continue for an extended time, however, a malfunction (which was later found to be unrelated to the Tainter gates) prompted the Tainter gates to be closed at 1830 on August 9. Thus, the Tainter gates were in operation for a total of only 10 hours.

The first gate, the second gate from the left looking upstream, opened at 0830 CDT and a gas reading at 0846 CDT showed the total gas pressure had increased to 121% of saturation. A further increase of 2% total gas pressure was accomplished in only two minutes. At 0900 CDT the gate third from the left was operated, with the fourth and fifth gates being opened at 0910 and 0920, respectively. The river level fell 0.6 to 0.9 meter (two to three feet) during this time as a result of gate changes. (Also, a large amount of debris passed through with the first gate openings. Removal of floating debris was one of the benefits of using the Tainter gates.) A total gas meter reading at 0930 CDT showed that the pressure had increased 10% or 71 mmHg as a result of Tainter gate operation. The last gate (farthest left) was operated at 0955 and the gate settings appeared final at 1020. At this time the total gas pressure was 132% of saturation or 237 mmHg. A check of total gas pressure nearer the dam (next to the end of the stilling basin wall) showed a slightly higher total gas pressure of 134% of saturation (257 mmHg). Dissolved gas pressure stabilized quickly after the final gate settings with little difference in the pressure readings taken at 1143 CDT and 1410 CDT.

In all, the total gas pressure increased from 119% of saturation to 133% of saturation, or, as ΔP, from 145 mmHg to 244 mmHg, as a result of Tainter gate operation. Nitrogen gas pressure increased from 128% of saturation (ΔP of 158 mmHg) to 139% of saturation (ΔP of 225 mmHg) under Tainter gate operation. [This nitrogen gas pressure exceeds the maximum nitrogen gas pressure (138% of saturation or ΔP of 217 mmHg) seen during the 255 routine monitoring events downstream from the dam.] Oxygen gas pressure increased from 91% of saturation (ΔP of -13 mmHg) to 112% of saturation (ΔP of 19 mmHg) as a result of using the Tainter gates. As a result of the relatively high outflow of 509.8 m^3/s (18,000 ft^3/s), the uncompensated total gas pressure at the maximum river depth never exceeded 100% of saturation or 0 mmHg because of the compensating effects of hydrostatic pressure. However, the total gas pressure calculated for the maximum depth did increase from 86% to 97% as a result of Tainter gate operation. A few dead fish were observed, however, no significant adverse effects on fish were obvious from casual observation. According to hyperbaric theory a fish kill would not be expected until the outflow decreased, decreasing river depth. [In fact, this is what happened as a fish kill was observed on September 3, 1991 as the flow decreased to only 28.6 m^3/s (1,010 ft^3/s) and the uncompensated gas pressure as ΔP became positive for the first time since February 13, 1991, when a previous fish kill had occurred.]

The conclusion drawn from the Tainter gate studies was that the Tainter gates should not be used unless necessary because their use increases total gas pressure. However, it was obvious that elevated total dissolved gas pressures also occurred under sluice-gate release operations. The total gas pressure under sluice-gate operation may not be as extreme as it is under Tainter gate operation, but it is of sufficient magnitude to cause chronic and acute gas bubble trauma, especially at lower outflows, as was discussed above.

DISCUSSION

Predictable occurrence of acute gas bubble trauma

In general, gas bubble trauma-induced fatalities in fish from gas supersaturated waters downstream from Red Rock Dam seem rather predictable from gas pressure data. In the nine-year study period high gas pressures have triggered gas bubble trauma-associated fish kills when:

- high total gas pressure levels (>120% of saturation) occurred that steadily increased over several weeks
- uncompensated total gas pressures as ΔP became positive at the maximum river depth
- outflow from the reservoir decreased substantially over a relatively short period of time

In fact, the effect of decreasing reservoir outflow and the related occurrence of positive uncompensated pressure at the river bottom appears to explain the occurrence of most of the fish kill events. Figure 17 illustrates the total gas pressure as a percent of saturation (TGP at the surface) and the uncompensated total gas pressure at the maximum depth (TGP at the bottom). As illustrated all 14 fish kill events occurred

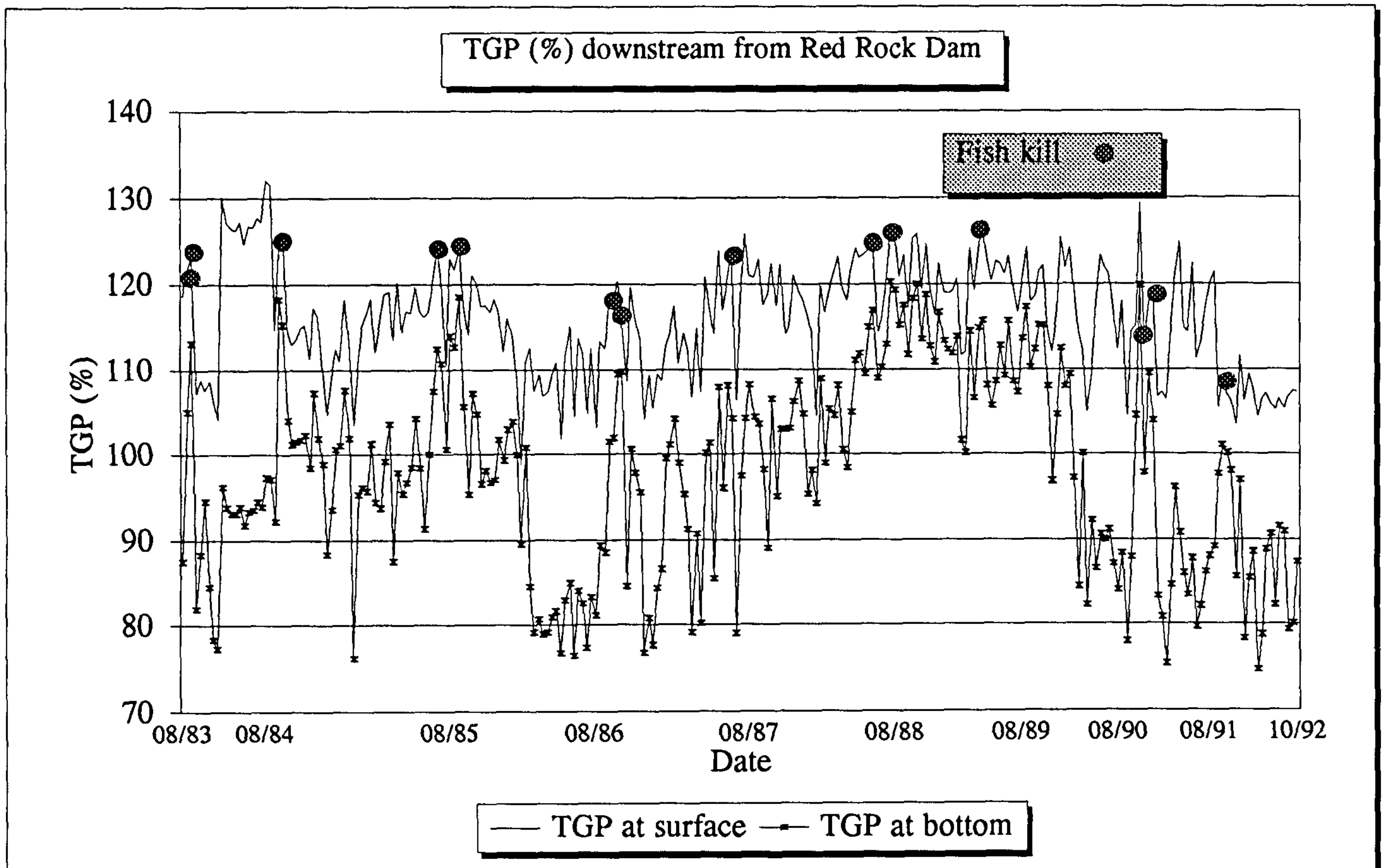

Figure 17. Total gas pressure, in percent of saturation, at the surface and uncompensated total gas pressure, in percent of saturation, at the maximum river depth below Red Rock Dam. Fish kill events are shown.

when the uncompensated total gas pressure neared or exceeded 110% of saturation. Figure 18 illustrates ΔP or hyperbaric pressure at the surface and at the maximum river depth. As illustrated, fish kill events occurred during the periods of greatest hyperbaric pressure at the maximum depth. In these instances aquatic organisms would be continually subjected to hyperbaric pressures and could not sound (inhabit deeper waters) to avoid high gas pressure. The effect of discharge and river depth is illustrated in Figures 19 and 20. In Figure 19 it is obvious that the fish kill events were associated with relatively rapid decreases in river flow as a result of decreases in discharge from the reservoir. The most extensive fish kills (September 1983, October 1984 and September 1991) appeared to be related to the greatest decreases in discharge, especially as Tainter gates were closed (September 1983 and October 1984). Figure 20 illustrates the maximum river depth observed versus the required compensation depth at the existing total gas pressure. In all but one case, the fish kills occurred when the compensation depth required in to offset total gas pressure was greater than the existing maximum depth. The one fish kill on December 13, 1990, probably occurred earlier. No routine monitoring was conducted during a three month period between September 25 and December 13, 1990. Thus, the first time the dead fish were observed was December 13 but the fish had actually succumbed earlier.

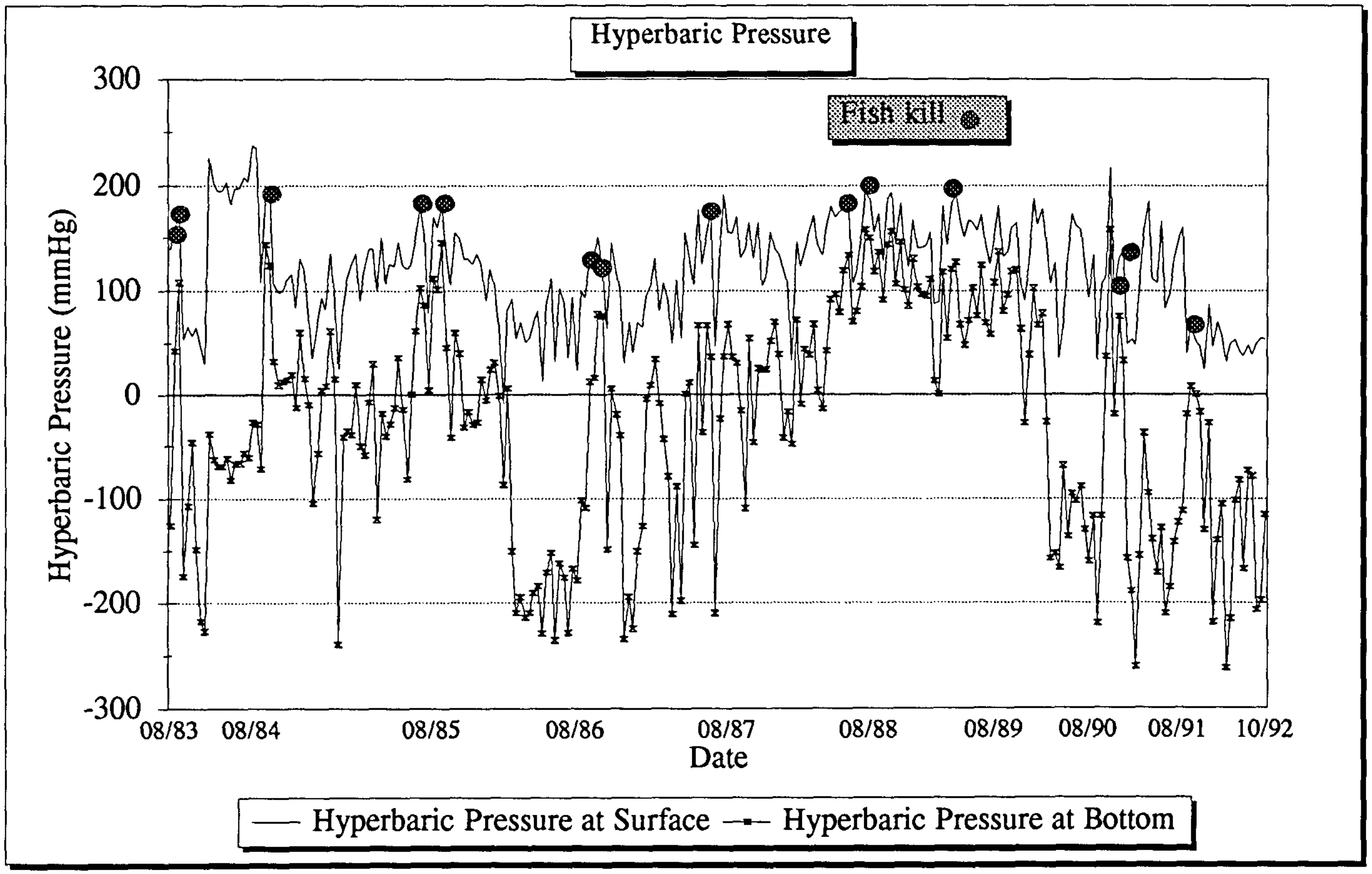

Figure 18. Hyperbaric pressure (or ΔP), in mmHg, at the surface and uncompensated hyperbaric gas pressure (or ΔP), in mmHg, at the maximum river depth below Red Rock Dam. Fish kill events are shown.

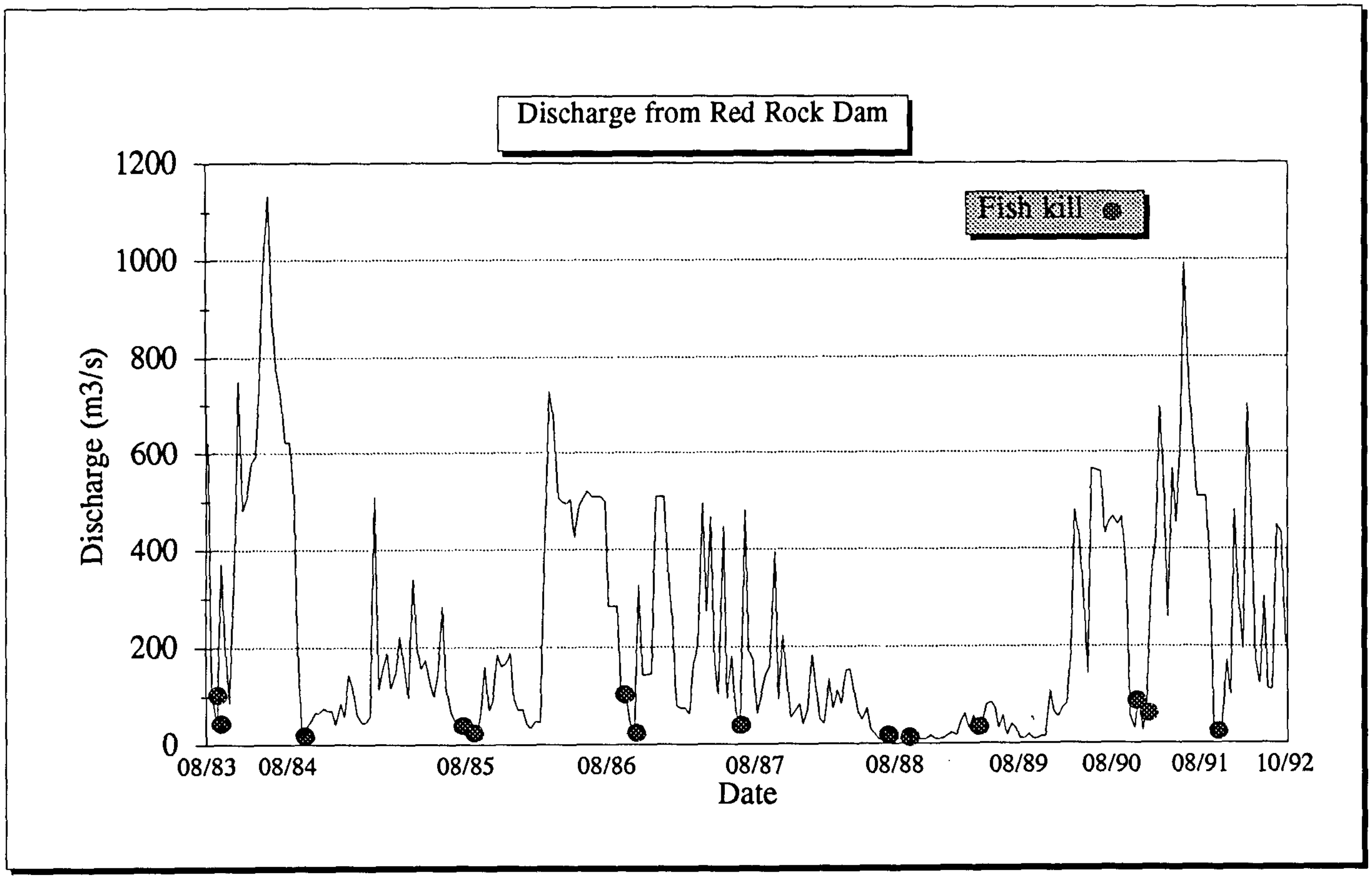

Figure 19. Discharge from Red Rock Dam illustrating the effect of river depth. Fish kill events are shown.

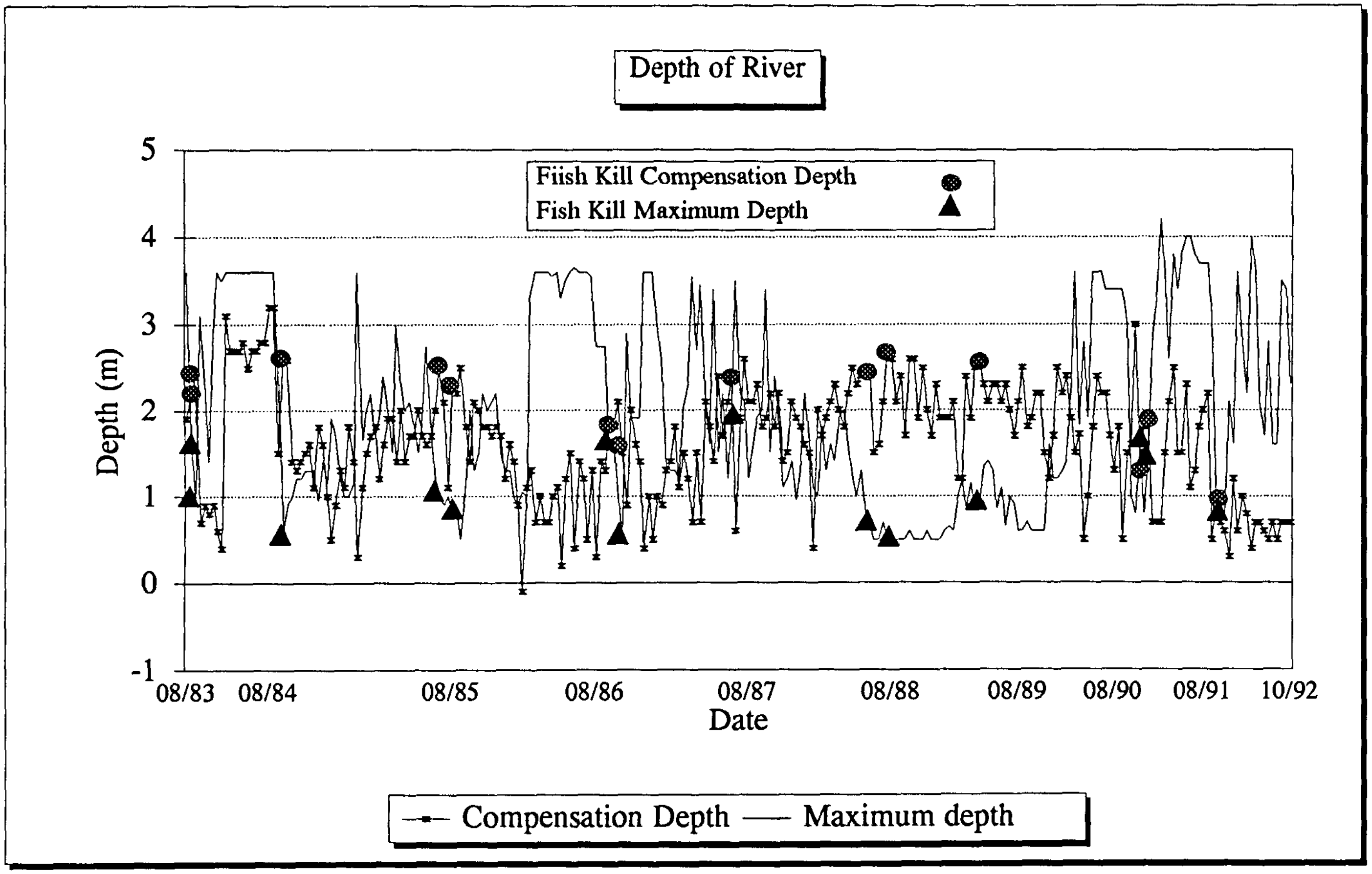

Figure 20. Maximum river depth observed below Red Rock Reservoir and compensation depth required to compensate for total gas pressure. Fish kills are shown.

Mitigating factors

Interestingly, there were also several instances when pressure data indicated that a fish kill event was probable and no such event was recorded. It appears that the reason for this lies in the rather complex nature of gas bubble trauma. There were at least five such occasions as shown by arrows in Figures 21 and 22. Basically, there appear to be three factors that mitigated gas pressure effects on fish during these occasions. First, as shown by the first and last arrows, there were occasions when the total gas pressure was extreme (approximately 130% of saturation) and yet no fish kill events occurred. This is easily explained by the mitigating effects of large flows which allowed compensation depths to be realized. Second, there was a period of time where uncompensated total gas pressure was excessive and yet no mortality occurred. The mitigating effect during this period may have been the ratio of nitrogen gas pressure to oxygen gas pressure. During these periods the ratio of nitrogen gas pressure (as % of saturation) to oxygen gas pressure (as % of saturation) was less than 1.0. In fact, the lowest ratio observed (0.6) was observed during this first period. In addition, since dissolved oxygen concentrations fluctuate during the day, lower gas pressure levels may have been encountered during parts of the day, decreasing periods of exposure to extreme levels. Intermittent

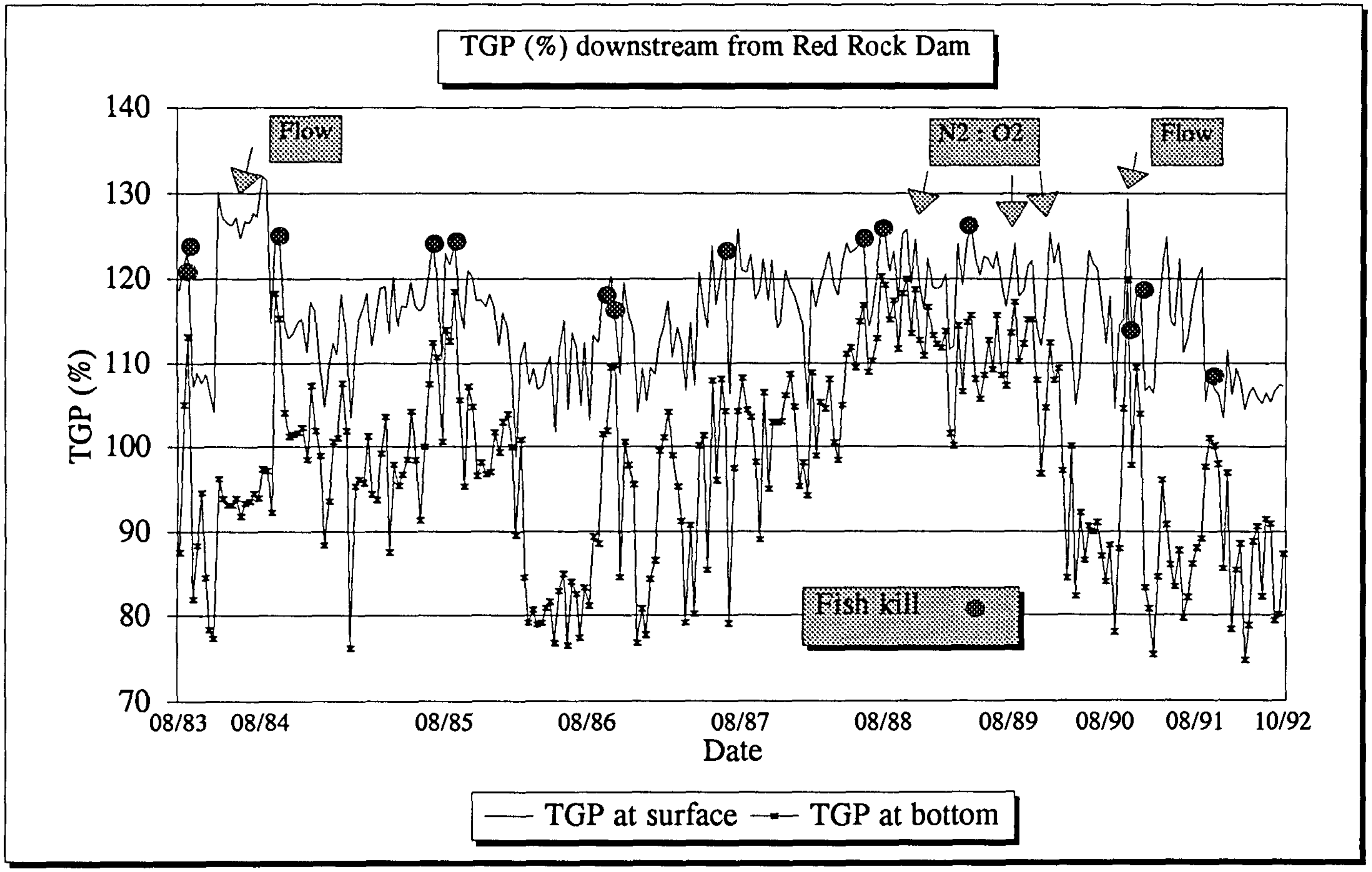

Figure 21. Total gas pressure, in percent of saturation, at the surface and uncompensated gas pressure, in percent of saturation, at the maximum river depth below Red Rock Dam. Fish kill events are shown. Arrows indicate when large outflow or lower nitrogen gas to oxygen gas ratios appeared to mitigate the effects of gas supersaturation.

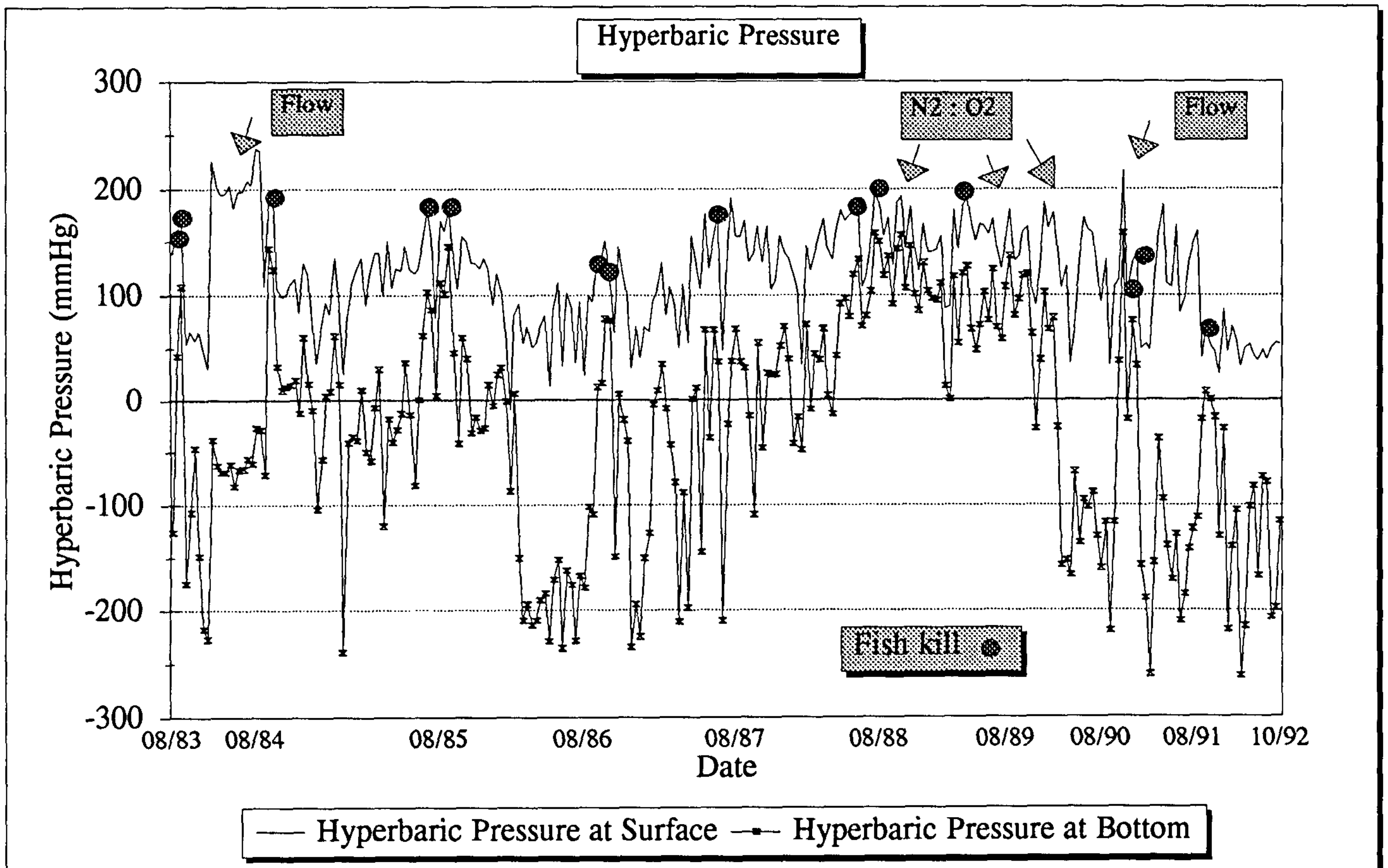

Figure 22. Hyperbaric gas pressure (or ΔP), in mmHg, at the surface and uncompensated hyperbaric gas pressure (or ΔP), in mmHg, at the maximum river depth below Red Rock Dam. Fish kill events are shown. Arrows indicate when large outflows or lower nitrogen gas to oxygen gas ratios appeared to mitigate the effects if gas supersaturation.

exposure to elevated gas pressure has been shown to increase resistance to gas bubble trauma (Meekin and Turner 1974; Blahm et al. 1976). In nature, intermittent exposure is probably the rule thus permitting higher tolerance than indicated by laboratory data (Bouck et al. 1976). Fluctuations in oxygen gas pressure would be greatest under conditions of intense primary productivity (Nebeker et al.1979).

Occurrence of chronic gas bubble trauma

The occurrence of chronic gas bubble trauma was much harder to observe. Casual examinations of fish during yearly electroshocking activities had documented the occurrence of chronic gas bubble trauma, however, on many occasions only secondary effects were observable. Obviously there were many more periods of chronic gas bubble trauma that were not directly observable. Recurring chronic gas bubble trauma may have an adverse effect on the fishery downstream from Red Rock Dam.

Ecosystem effects

It is possible that chronic gas bubble trauma may not lead to substantial mortality unless a lethal threshold is reached but there may be consequences of ecological significance with even sublethal conditions. Many fish food organisms - mollusks, shrimp, crayfish, stoneflies and daphnids - are adversely affected by gas bubble trauma (Marsh and Gorham 1905; Maulof et al. 1972; Nebeker 1976). Some research has found that zooplankton, in particular *Daphnia magna*, are more sensitive to gas supersaturation than are many fishes. The lethal threshold for *Daphnia magna* in a laboratory setting has been reported as a total gas pressure of 111% of saturation (Nebeker 1976). Also, early life stages of fishes (larvae, and fry) are more susceptible to gas bubble trauma than are later life stages. Cornacchia and Colt (1984) found increased mortality of larval striped bass at a total gas pressure of 103% of saturation. Besides the primary affect of mortality, gas bubbles can buoy fishes at younger life stages to the surface where they would be easy prey to predators. A similar problem has been shown to occur in zooplankton and other invertebrates (Nebeker 1976). Also, the degree of detrimental effects at a given pressure differs widely among species, with many popular gamefish being the most sensitive. Gray et al. (1982) found the acute threshold (96hr LC_{50}) was between 107% of saturation and 117% of saturation for black bullhead, and between 123% of saturation and 128% of saturation for common carp. Behavioral effects of chronic gas bubble trauma may increase mortality indirectly because of adverse effects on feeding (ie., by slowing digestion, emphysema obstructing the esophagus), predation (by affecting swimming ability or the ability to maintain orientation), and social behavior.

The overall ecosystem effect of the stress associated with gas bubble trauma may be to restrict the area to more tolerant species, thus decreasing species diversity. There is evidence to suggest that elevated gas pressure could extend quite a distance downstream of Red Rock Dam. Similar results were reported by D'Aoust and Clark (1980). Relatively slow dissipation of supersaturation was observed along the Columbia River. Data indicated that total gas pressure decreased only 1% of saturation between a distance of 50 kilometers. Additionally, the Columbia River dams when taken in series successively increased gas supersaturation. Crunkilton et al. (1980) stated that free water spillage over dams can adversely affect aquatic faunas over great distances in near-lentic (standing water) systems.

Two attempts were made to assess the downstream reach of elevated gas supersaturation. The first study was discussed earlier under the section about Tainter gate operation. From this study (performed on May 9, 1984, under high outflows through the Tainter gates) it was determined that the total gas pressure about 10 miles downstream from the dam (at Highway 92) was 123% of saturation as compared to 126% of saturation just below the dam. Thus, it would appear that gas supersaturation could persist for quite a distance downstream.

A second study took place on August 3, 1989, under low flow (400 ft^3/s) releases through the sluice gates. At this time the total gas pressure just below the dam was 120% of saturation, while the total gas pressure at downstream locations 4.8 kilometers (3 miles), 19.3 kilometers (12 miles) and 32.1 kilometers (20 miles) below the dam were 114% of saturation, 109% of saturation and 108% of saturation, respectively. Low flow conditions dominated this period and this led to increases in lotic (running water) algal populations. As a result of intense primary productivity the oxygen gas pressure at locations 19.3 kilometers and 32.1 kilometers downstream were 123% of saturation and 140% of saturation, as compared to 102% of saturation just below the dam. There may have been some diel effect as the readings directly below the dam were taken at 1145 CDT and the readings taken 4.8 kilometers, 19.3 kilometers and 32.1 kilometers downstream were taken at 1220 CDT, 1300 CDT and 1410 CDT, respectively. From this study it appears that under low flow conditions gas supersaturation may not extend as far downstream as under high outflow conditions. However, because the downstream reach of gas supersaturation can be substantial, the extent of area affected may be of concern.

Fish kills earlier in study

Although total gas pressure data below Red Rock Dam are not available prior to August 1983, dissolved oxygen pressure data are available from observed concentrations of dissolved oxygen, water temperature and solubility tables. These data, along with written accounts of observed fish kills, leads to the conclusion that gas supersaturation and associated fish kills have been a prevailing fact since the reservoir began to operate. Prior to August 1983, there were six other written accounts of fish kills in which gas bubble trauma is now suspected to have played a major role. Tainter gate use or reductions in flow were involved with all of them. Thus, the occurrence of gas supersaturation and associated fish kills is not of recent origin.

Gas supersaturation at other moderately-sized reservoirs

Recent monitoring of dissolved gas pressure downstream of Saylorville Reservoir, which is located about 114.2 kilometers (71 miles) upstream from Red Rock Reservoir on the Des Moines River, has shown that gas supersaturation may also be of some concern at this location. From 35 readings of total gas pressure taken approximately 2.4 kilometers (1.5 miles) downstream from Saylorville Reservoir, all equalled or exceeded saturation. Total gas pressure below Saylorville Reservoir ranged from 100% of saturation to 121% of saturation with an average of 110% of saturation. However, evidence of acute or chronic gas bubble trauma is not as abundant at this location. There was only one fish kill event below Saylorville Reservoir over the nine years of this study in which gas bubble trauma was suspected to have played a role. The total gas pressure during this event, which occurred on July 16, 1991, was 111% of saturation. Of greatest interest is the fact that during the previous two weeks the river flow had been decreased from about 424.8 m^3/s (15,000 ft^3/s) to a flow of 115.0 m^3/s (4,060 ft^3/s). Thus, other moderately-sized reservoirs may have similar problems with gas super-saturation below their dams.

CONCLUSION AND RECOMMENDATION

It is apparent from this study that gas supersaturation and associated gas bubble trauma-induced fish kills do indeed occur below Red Rock Reservoir. In addition, gas supersaturation may be occurring below Saylorville Reservoir. Thus, there may be potential for gas supersaturation below other moderately-sized reservoirs where it was previously believed that gas supersaturation could not occur. The source of excess atmospheric gases is unknown, however, from this study gas supersaturation below Red Rock Dam has been shown to be directly related to the release of water from Red Rock Reservoir.

It is strongly advised that the Corps of Engineers monitor total gas pressure at other moderately-sized reservoirs to determine how widespread is the problem of gas supersaturation. In addition, attention needs to be directed at: identifying the source and mechanism that results in the observed gas supersaturation below Red Rock Dam; evaluating whether similar circumstances exist elsewhere; and contriving design or operation alternatives to mitigate the gas supersaturation problem.

At Red Rock Dam, it is strongly recommended that river depth and its affect on uncompensated gas pressure at the predicted maximum depth be used to make decisions regarding reservoir releases. More gradual changes in lowering reservoir outflows may help to mitigate the problems associated with acute gas bubble trauma. Identification of the source and mechanism that results in the observed gas supersaturation is greatly needed. Only then can steps be taken to mitigate chronic effects from gas bubble trauma.

Additional information is needed to assess the impact of gas supersaturation on the aquatic ecosystem below Red Rock Dam and possibly below other moderately-sized reservoirs. At Red Rock, fish kill investigations should be continued with a monetary valuation of the fish lost. Examinations of live fish should be expanded. Documentation of diurnal trends in total gas pressure is needed. Comparison of species density and composition below Red Rock Dam and another similar reach would be essential to determining the effects on the ecosystem. Additionally, for comparative purposes, dissolved gas pressure data should also be collected from an uncontrolled location on the Des Moines River.

REFERENCES CITED

Adair, W.D. and J.J. Hains. 1974. Saturation values of dissolved gases associated with the occurrence of gas-bubble disease in fish in a heated effluent. Pages 59-77 in Gibbons, J.W. and R.R. Sharitz. Thermal Ecology. United States Atomic Energy Commission Contract 030505, Washington, D.C.

Alderdice, D.F. and J.O.T. Jensen. 1985. Assessment of the influence of gas supersaturation on salmonids in the Nechako River in relation to Kemano completion. Canadian Technical Report Fisheries and Aquatic Sciences. No. 1386.

APHA (American Public Health Association), American Water Works Association and Water Pollution Control Federation. 1989. Standard Methods for the Examination of Water and Wastewater. American Public Health Association, Washington, D.C.

Baumann, E.R., D.S. Lutz, and D.E. Harrold. 1985. Annual report, Water quality studies-Red Rock and Saylorville reservoirs, Des Moines River, Iowa. Engineering Research Institute, ISU-ERI-Ames-85180, Iowa State University, Ames, Iowa.

Baumann, E.R. and D.S. Lutz. 1986. Annual report, Water quality studies-Red Rock and Saylorville reservoirs, Des Moines River, Iowa. Engineering Research Institute, ISU-ERI-Ames-86283. Iowa State University, Ames, Iowa.

Baumann, E.R. and D.S. Lutz. 1987. Annual report, Water quality studies-Red Rock and Saylorville reservoirs, Des Moines River, Iowa. Engineering Research Institute, ISU-ERI-Ames 87185, Iowa State University, Ames, Iowa.

Baumann, E.R., D.S. Lutz and T.K. Yager. 1988. Annual report, Water quality studies-Red Rock and Saylorville reservoirs, Des Moines River, Iowa. Engineering Research Institute, ISU-ERI-Ames-88219, Iowa State University, Ames, Iowa.

Baumann, E.R., D.S. Lutz and T.K. Yager. 1989. Annual report, Water quality studies-Red Rock and Saylorville reservoirs, Des Moines River, Iowa. Engineering Research Institute, ISU-ERI-Ames-89196, Iowa State University, Ames, Iowa.

Bentley, W.W. and E.M. Dawley. 1981. Effects of supersaturated dissolved atmospheric gases on northern squawfish (*Ptychocheilus oregonensis*). Northwest Science 55:50-61.

Beyer, D., B.G. D'Aoust and L. Smith. 1976. Responses of coho salmon (*Oncorhynchus kisutch*) to supersaturation at one atmosphere. Pages 47-50 *in* Fickeisen, D.H. and M.J. Schneider, editors. Gas bubble disease. CONF-741033, Technical Information Center, Energy Research and Development Administration, Oak Ridge, Tennessee.

Blahm, T.H. 1974. Report to Corps of Engineers, gas supersaturation research. Prescott Facility-1974. National Marine Fisheries Service, Northwest Fisheries Center, Seattle, Washington.

Blahm, T.H., B. McConnell, G.R. Snyder. 1976. Gas supersaturation research at the National Marine Fisheries Service Prescott Facility, 1971-1974, Pages 11-19 *in* Fickeisen, D.H. and M.J. Schneider, editors. Gas bubble disease. CONF-741033, Technical Information Center, Energy Research and Development Administration, Oak Ridge, Tennessee.

Bond, C.E. 1979. Biology of fishes. Saunders College Publishing, Philadelphia, Pennsylvania.

Bouck, G.R. 1976. Supersaturation and fishery observations in selected alpine Oregon streams. Pages 37-40 *in* Fickeisen, D.H. and M.J. Schneider, editors. Gas bubble disease. CONF-741033, Technical Information Center, Energy Research and Development Administration, Oak Ridge, Tennessee.

Bouck, G.R., A.V. Nebeker and D.G. Stevens. 1976. Mortality, Saltwater adaption and reproduction of fish during gas supersaturation. EPA-600/3-76-050.

Bouck, G.R. 1980. Etiology of gas bubble disease. Transactions of the American Fisheries Society 109:703-707.

Bouck, G.R., R.E. King, and G. Bouck-Schmidt. 1984. Comparative removal of gas supersaturation by plunges, screens and packed columns. Icicleture Engineering 3:159-176.

Bowser, P.R., R. Toal, H.R. Robinette and M.W. Brunson. 1983. Coelomic distension in channel catfish fingerlings. Progressive Fish-Culturist 45:208-209.

Bucci D.R. and T.E. Murphy. 1965. Spillway and sluices, Red Rock Dam, Des Moines River, Iowa. U.S. Army Corps of Engineers Technical Report No. 2-673.

Chamberlain, G.W., W.H. Neill, P.A. Romanowsky, and K. Strawn. 1980. Vertical responses of Atlantic croaker to gas supersaturation and temperature change. Transactions of the American Fisheries Society 109:737-750.

Chittenden, Jr., M.E. 1972. Responses of young American shad, *Alosa sapidissima*, to low temperatures. Transactions of the American Fisheries Society 102:680-685.

Colt, J. 1983. The computation and reporting of dissolved gas levels. Water Research 17: 841-849.

Colt, J. 1984. Computation of dissolved gas concentrations in water as functions of temperature, salinity and pressure. American Fisheries Society Special Publication 14. Bethesda, Maryland.

Colt. J. and G. Bouck. 1984. Design of packed columns for degassing. Aquaculture Engineering 3:251-273.

Colt, J., K. Orwicz, and D. Brooks. 1984. Effects of gas-supersaturated water on *Rana catesbeiana* tadpoles. Aquaculture 38:127-136.

Colt, J., K. Orwicz, and D. Brooks. 1985. Impact of gas supersaturation on the growth of juvenile channel catfish, *Ictalurus punctatus*. Aquaculture 50:153-160.

Cornacchia, J.W. and J.E. Colt. 1984. The effects of dissolved gas supersaturation on larval striped bass (*Morone saxatilis*). Journal of Fish Diseases 7:15-27.

Coutant, C.C. and R.G. Genoway. 1968. Final report on an exploratory study of interaction of increased temperature and nitrogen supersaturation on mortality of adult salmonids. A report to the United States Bureau of Commercial Fisheries, Seattle, Washington. Battelle Memorial Institute, Pacific Northwest Laboratories, Richland, Washington.

Crunkilton, R.L., J.M. Czarnezki, and L. Trial. 1980. Severe gas bubble disease in the midwestern United States. Transactions of the American Fish Society 109:725-733.

D'Aoust, B.G. and L.S. Smith. 1974. Bends in fish. Comparative Biochemistry and Physiology, A, Comparative Physiology 49:311-321.

D'Aoust, B.G. and M.J.R. Clark. 1980. Analysis of supersaturated air in natural waters and reservoirs. Transactions of the American Fisheries Society 109:708-724.

Dawley, E.M. and W.J. Ebel. 1975. Effects of various concentrations of dissolved atmospheric gas on juvenile chinook salmon and steelhead trout. United States National Marine Fisheries Center, Seattle, Washington.

DeMont, J.D. and R.W. Miller. 1972. First reported incidences of gas bubble disease in the heated effluent of a steam electric generating station. Proceedings of the Annual Conference, Southeastern Association of Game and Fish Commissioners 25: 392-399.

Ebel, W.J. 1969. Supersaturation of nitrogen in the Columbia River and its effect on salmon and steelhead trout. United States National Marine Fisheries Service Fishery Bulletin 68:1-11.

Egusa, S. 1959. The gas bubble disease of fish due to excess of nitrogen. Animal Husbandry, Hiroshima University 2:157-182.

Embody, G.C. 1934. Relation of temperature to the incubation period of eggs of four species of trout. Transactions of the American Fisheries Society 64:281-292.

EPA (Environmental Protection Agency). 1986. Quality criteria for water. Office of Water Regulations and Standards, Washington, D.C. EPA 440/5-86-001.

Fast, A.W. 1979. Nitrogen gas supersaturation during artificial aeration of Lake Casitas, California. The Progressive Fish-Culturist 41:153-155.

Fickeisen, D.H. and M.J. Schneider, editors. Gas bubble disease. CONF-741033, Technical Information Center, Energy Research and Development Administration, Oak Ridge, Tennessee.

Fickeisen, D.H., J.C. Montegomery and M.J. Schneider. 1973. Tolerance of selected fish species to atmospheric gas supersaturation. 103rd meeting of the American Fisheries Society, September 10-12, 1973. Orlando, Florida. BNWL-SA-4794.

Fuss, J.T. 1983. Effective flow-through vacuum degasser for fish hatcheries. Aquaculture Engineering 2:301-307.

Gray, R.H., T.L. Page and M.G. Saroglia. 1983. Behavioral response of carp, *Cyprinus carpio*, and black bullhead, *Ictalurus melas*, from Italy to gas supersaturated water. Environmental Biology of Fishes 8:163-167.

Hartman, J. 1983. Performance and operation of Alaska Department of Fish and Game screen decks. Pages 9/1-9/7 *in* Gas supersaturation in hatcheries-causes, effects and solutions, Bio-technology Sections, American Fisheries Society, Milwaukee, Wisconsin.

Harvey, H.H. 1975. Gas disease in fishes - a review. Pages 450-485 *in* Adams, W.A., editor. Chemistry and physics of aqueous gas solutions. The Electrochemical Society, Princeton, New Jersey.

Harvey, H.H. and A.C. Cooper. 1962. Origin and treatment of supersaturated river water. Progress Report 9, International Pacific Salmon Fisheries Commission, Vancouver, Canada.

Harvey, H.H. and S.B. Smith. 1961. Supersaturation of the water supply and occurrence of gas bubble disease at Cultus Lake Trout Hatchery. Canadian Fish Culturist 30:39-46.

Henly, E. 1952. The influence of the gas content of sea-water on fish and fish-larvae. Rapports et Proces-verbaux des Reunions, Conseil International pour l'Exploration de la Mer 131(3):24-27.

Jarnefelt, V.H. 1948. Der Einfluss der Stromschnellen auf den Sauerstoff und Kohlensauregehalt und das pH des Wassers im Flusse Vuoski. International Association of Theoretical and Applied Limnological Proceedings 10:210-215.

Jensen, L.D. 1974. Environmental response to thermal discharges from Marshall Steam Station, Lake Norman, North Carolina. Report to Electric Power Research Institute and Duke Power Company, Raleigh, North Carolina.

Jensen, J.O.T., J. Schnute and D.F. Alderice. 1986. Assessing juvenile salmonid response to gas supersaturation using a general multivariate dose-response model. Canadian Journal of Fisheries and Aquatic Sciences 43:1694-1709.

Klots, C.E. 1980. Effects of hydrostatic pressure upon the solubility of gases. 1961. Limnology and Oceanography 6:365-366.

Knittel, M.D., G.A. Chapman and R.R. Garton. 1980. Effects of hydrostatic pressure on steelhead survival in air supersaturated water. Transactions of the American Fisheries Society 109:755-759.

Krise, W.F. and J.W. Meade. 1988. Effects of low level gas supersaturation on lake trout (*Salvelinus namaycush*). Canadian Journal of Fisheries and Aquatic Sciences 43:1694-1709.

Lindroth, A. 1957. Abiogenic gas supersaturation of river water. Archiv fur Hydrobiologie 53:589-597.

Lutz, D.S., E.R. Baumann and T.K. Yager. 1990. Annual report, Water quality studies-Red Rock and Saylorville reservoirs, Des Moines River, Iowa. Engineering Research Institute, ISU-ERI-Ames-90166, Iowa State University, Ames, Iowa.

Lutz, D.S. and E.R. Baumann. 1991. Annual report, Water quality studies-Red Rock and Saylorville reservoirs, Des Moines River, Iowa. Engineering Research Institute, ISU-ERI-Ames-91192, Iowa State University, Ames, Iowa.

Lutz, D.S. 1992. Annual report, Water quality studies-Red Rock and Saylorville reservoirs, Des Moines River, Iowa. Engineering Research Institute, ISU-ERI-Ames-92161, Iowa State University, Ames, Iowa.

Lutz, D.S. 1993. Annual report, Water quality studies-Red Rock and Saylorville reservoirs, Des Moines River, Iowa. Engineering Research Institute, ISU-ERI-Ames-93092, Iowa State University, Ames, Iowa.

MacDonald, R.W. and C.S. Wong. 1975. Factors influencing the degree of saturation of gases in seawater. Pages 214-223 *in* Adams, W.A.,editor. Chemistry and physics of aqueous gas solutions. The Electrochemical Society, Princeton, New Jersey.

Malouf, R., R. Keck, D. Maurer and C. Epifanio. 1972. Occurrence of gas-bubble-disease in three species of bivalve mollusks. Journal of the Fisheries Research Board of Canada 29:588-589.

Marking, L.L., V.K. Dawson and J.R. Crowther. 1983. Comparison of column aerators and a vacuum degasser for treating supersaturated culture water. Progressive Fish-Culturist 45:81-83.

Marsh, M.C. 1903. A fatality among fishes in water containing an excess of dissolved air. Transactions of the American Fisheries Society 32:192-193.

Marsh, M.C. and F.P. Gorham. 1905. The gas disease in fishes. Report of the United States Bureau of Fisheries (1904):343-376.

Marsh, M. C. 1910. Notes on the dissolved content of water in its effect upon fishes. Bulletin of the United States Bureau of Fisheries (1908) 28:891-906.

May, B. 1973. Evaluation on the effects of gas bubble disease on fish populations in the Kootenai River below Libbey Dam. Proceedings of the 53rd Annual Conference, Western Association of State Fish and Game Commissioners: 525-540.

McDonough, P.M. and E.A. Hemmingsen. 1985. Swimming movements initiate bubble formation in fish decompressed from elevated gas pressures. Comparative Biochemistry and Physiology 81(A):209-212.

Meekin, T.K. 1971. Levels of nitrogen supersaturation at Chief Joesph Dam under various spill conditions, phase 1. Report to United States Army Corps of Engineers, Contract NPSSU-71-796, Washington Department of Fisheries, Olympia, Washington.

Meekin, T.K. and B.K. Turner. 1974. Tolerance of salmonid eggs, juveniles and squawfish to supersaturated nitrogen. Washington Department of Fisheries Technical Report 12:127-153.

Meekin, T.K. and R.L. Allen. 1974. Nitrogen gas levels in the mid-Columbia River , 1965-1971. Washington Department of Fisheries Technical Report 12:32-77.

Miller, R.W. 1974. Incidence and cause of gas bubble disease. Pages 79-93 *in* J.W. Gibbons and R.R. Sharitz, editors. Thermal ecology. CONF-730505, United States Environmental Protection Agency, Washington D.C., District of Columbia.

Nebeker, A.V. 1976. Survival of *Daphnia*, crayfish and stoneflies in air supersaturated water. Journal of the Fisheries Research Board of Canada 33:1208-1212.

Nebeker, A.V., D.G. Stevens and J.R. Brett. 1976. Effects of gas supersaturated water on freshwater aquatic invertebrates. Pages 51-65 *in* Fickeisen, D.H. and M.J. Schneider, editors. Gas bubble disease. CONF-741033, Technical Information Center, Energy Research and Development Administration, Oak Ridge, Tennessee.

Nebeker, A.V., A.K. Hauck and F.D. Baker. 1979. Temperature and oxygen-nitrogen gas ratios affect fish survival in air-supersaturated water. Water Research 13:299-303.

Pauley, G.B. and R.E. Nakatani. 1967. Histopathology of "gas bubble" disease in salmon fingerlings. Journal of the Fisheries Research Board of Canada 24:867-871.

Renfro, W.C. 1963. Gas-bubble mortality of fishes in Galveston Bay, Texas. Transactions of the American Fisheries Society 92:320-322.

Rucker, R.R. 1976. Gas bubble disease of coho salmon (*Oncorhynchus kisutch*) in water with constant total gas pressure and different oxygen-nitrogen gas ratios. U.S. National Marine Fisheries Service, Fisheries Bulletin 73:915-918.

Rulifson, R.L. and R. Pine. 1976. Water quality standards. Pages 120- *in* Fickeisen, D.H. and M.J. Schneider, editors. Gas bubble disease. CONF-741033, Technical Information Center, Energy Research and Development Administration, Oak Ridge, Tennessee.

Schiewe, M.H. and D.D. Weber. 1976. Effect of gas bubble disease on lateral line function in juvenile steelhead trout. Pages *in* Fickeisen, D.H. and M.J. Schneider, editors. Gas bubble disease. CONF-741033, Technical Information Center, Energy Research and Development Administration, Oak Ridge, Tennessee.

Smith, C.E. 1988. Histopathology of gas bubble disease in juvenile rainbow trout. Progressive Fish-Culturist 50:98-103.

Snieszko, S.F. and H.R. Axelrod. 1976. Section D: Dissolved gases (gas bubble disease) *in* Salia, S.B., editor. Environmental stress and fish diseases. T.F.H. Publications Inc. Ltd.

Stroud, R.K., G.R. Bouck and A.V. Nebeker. 1975. Pathology of acute and chronic exposure of salmonid fishes to supersaturated water. Pages 435-449 *in* Adams, W.A., editor. 1975. Chemistry and physics of aqueous gas solutions. The Electrochemical Society, Princeton, New Jersey.

Stroud, R.K. and A.V. Nebeker. 1976. A study of the pathogenics of gas bubble disease in steelhead trout (*Salmo gairdneri*). Pages 66-71*in* Fickeisen, D.H. and M.J. Schneider, editors. Gas bubble disease. CONF-741033, Technical Information Center, Energy Research and Development Administration, Oak Ridge, Tennessee.

Supplee, V.C. and D.V. Lightner. 1976. Gas bubble disease due to oxygen supersaturation in raceway-reared california brown shrimp. Progressive Fish-Culturist 38:158-159.

U.S. Army Corps of Engineers. 1988. Upper Mississippi River Basin, Des Moines River, Iowa and Minnesota, Appendix A, Master Reservoir Regulation Manual. Rock Island District, Rock Island, Illinois.

Weitkamp, D.E. 1976. Dissolved gas supersaturation: live cage bioassays at Rock Island Dam, Washington. Pages *in* Fickeisen, D.H. and M.J. Schneider, editors. Gas bubble disease. CONF-741033, Technical Information Center, Energy Research and Development Administration, Oak Ridge, Tennessee.

Weitkamp, D.E. and M. Katz. 1980. A review of dissolved gas supersaturation literature. Transactions of the American Fisheries Society 109:659-702.

White, R.G, G. Phillips, G. Liknes and S. Sanford. 1986. The effects of supersaturation of dissolved gases on the fishery of the Bighorn River downstream from the Yellowtail Dam. 1985 Annual Report, Bureau of Reclamation, Missouri Basin, Montana Cooperative Fisheries Research Unit, Montana State University, Bozeman, Montana.

Woodbury, L.A. 1941. A sudden mortality of fishes accompanying a supersat-uration of oxygen in Lake Waubesa, Wisconsin. Transactions of the American Fisheries Society 71:112-117.

Wyatt, E.J. and K.T. Beiningen. 1971. Nitrogen gas bubble disease related to a hatchery water supply from the forebay of a high head regulating dam. Research Reports of the Fish Commission of Oregon 3:3-12.

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In closing, I want to wish that everyone may come close to a place like I have been with the Des Moines River. My weekly excursions along it have challenged me and enriched my life.

APPENDIX A: AN EXAMPLE OF A FISH KILL REPORT

Des Moines River Water Quality Network

Report of Fish Kill

Week #: 1048 Date: 03Sep91

LOCATION Downstream from Red Rock Dam
(at Station 9)

(River reach, county, nearest town, etc.)

SEVERITY large kill
10 fish floating downstream/minute
w/ hundreds on bank; ~10 fish/10 feet bank

(Estimate of number killed; number floating past a certain point in a given period of time and number washed up ~~on~~ banks. Minor <50, small 50-100, moderate 100-500, and large (>500))

FISH IDENTIFICATION White bass 6-12" (60%)
gizzard shad (5%) channel catfish (12"-20") (10%)
walleye (various) largemouth bass 4-18" (5%)
green sunfish (a few) freshwater drum (various) (10%)
paddlefish (one) ~~bluegill various~~ (various) (5%)
(Type of fish; bass, bluegill, buffalo, bullhead, catfish, carp, crapple, drum, minnow, redhorse, shad, sunfish, etc. and size distribution.)

CLIMATIC CONDITIONS Today moderately hot (85°F) and humid
TGP(%) = 109% D.O. = 9.51 mg/l.
Outflow from Red Rock Dam has decreased from 12,900 ft³/s on last sampling (Aug 20) to only 1,010 ft³/s today.
(Air and water temperatures, horizontal or vertical profile, ice cover, cloud cover, weather trends, etc.)

ADDITIONAL COMMENTS According to news reports fish kill was extensive on Sat Aug 31 with 5,000 fish killed. However we were unaware of it until today.
Observations - Many live fish were observed with severe exophthalmia and most dead fish observed (that were not too decayed) exhibited gas bubbles in fins, under scales and pop-eye
(Observations as to possible sources of pollution, symptoms displayed by fish, whether observed any live fish, etc.)
Cause of death most probably gas bubble trauma prompted by drop in river depth.
(Photo of green sunfish live w/ severe exophthalmia.)

APPENDIX B: SUMMARIES OF THE 14 FISH KILL EVENTS

SUMMARIES OF THE 14 FISH KILL EVENTS

Event 1: September 6, 1983

A moderate fish kill was discovered on this day with approximately 40 dead fish floating downstream per minute. There were about six to 10 dead fish per 4.5 meters (15 feet) of bank. Most (80%) of the fish were freshwater drum (*Aplodinotus grunniens*), 7 cm to 30 cm in length. Crappie (*Pomoxis spp.*) 7 cm to 18 cm in length, made up about 15% of the kill. The other 5% was mostly made up of black bullhead (*Ictalurus melas*), 7 cm to 10 cm in length. Fish were examined by Dr. Nickum, Iowa State University Professor of Animal Ecology. Preliminary examination determined there were some signs of gas bubble trauma, mostly as exophthalmia. There were no other distinguishable diseases or damage.

Air temperature on this date was 24°C (75°F) and the water temperature was 25.5°C (77.9°F). There had been extremely hot weather but there was a cooling trend recently. The total gas pressure was 122% of saturation with nitrogen gas and oxygen gas pressures at 127% of saturation and 105% of saturation, respectively. The ΔP was 160 mmHg. From April to August 1983 reservoir water release had been through the Tainter gates and the outflow was as high as 556.4 m^3/s (20,000 ft^3/s). However, the release had recently been through the sluice gates and the outflow on September 3 was 107.6 m^3/s (3,800

ft^3/s). The uncompensated ΔP at the maximum depth was 43 mmHg. During the most recent monitoring on August 3, the uncompensated ΔP at the maximum depth had been -126 mmHg.

Event 2: September 13, 1983

This event was a continuance of the first event. The fish kill was classified as minor at this time with about 28 dead fish floating downstream per minute. There were many dead fish on the river banks but most appeared to have been there over a week. Species involved included freshwater drum, crappie and gizzard shad (*Dorosoma cepedianum*) of various sizes. Observations noted were of a freshwater drum with gaping mouth and flared gills, and crappie with internal hemorrhaging around caudal peduncle. Also observed large school of live bullheads (about 9 cm in length).

Total gas pressure was 123% of saturation, with nitrogen gas and oxygen gas pressures of 125% of saturation and 115% of saturation, respectively. The ΔP observed was 174 mmHg. The outflow had to declined to 35.4 m^3/s (1,250 ft^3/s). The uncompensated ΔP at the maximum depth was 108 mmHg.

Event 3: October 3, 1984

There was a scattering of dead fish along the bank. There were no fish floating downstream. On this day the total gas pressure was 125% of saturation (ΔP of 188 mmHg). The uncompensated total gas pressure was 118% of saturation (ΔP of 144 mmHg). The reservoir outflow was extremely low at only 11.3 m^3/s (400 ft^3/s). Dissolved oxygen concentrations were more than adequate as the oxygen gas pressure was 130% of saturation. The most recent monitoring event was August 28 when the total gas pressure was 115% of saturation (ΔP of 108 mmHg) and the uncompensated total gas pressure was 92% of saturation (ΔP of -72 mmHg). On August 28 the outflow had been 226.6 m^3/s (8,000 ft^3/s).

Event 4: July 16, 1985

This fish kill was classified as moderate. There were no fish floating downstream but there were about 300 dead fish per 30 meters (about 100 feet) of bank. It was estimated that 95% or more of the kill consisted of channel catfish (*Ictalurus punctatus*), 13 cm to 25 cm, although some large catfish were also observed. Also observed were largemouth bass (*Micropterus salmoides*), crappie, walleye (*Stizostedion vitreum*), buffalo (*Ictiobus spp.*) and freshwater drum. The dead fish were at least a few days old and had begun to decay. Exophthalmia was observed in some of the dead fish. Live common carp (*Cyprinus carpio*) and channel catfish were observed near the surface.

Weather conditions had been hot and humid. The high air temperature on this day was 27°C (81°F). The river flow has diminished over the last month. The total gas pressure was 124% of saturation with nitrogen gas and oxygen gas pressures of 130% of saturation and 105% of saturation, respectively. The ΔP was 180 mmHg with an estimated ΔP at the maximum depth of 103 mmHg. The uncompensated ΔP at the maximum depth for the last two monitoring events on July 9 and July 2 were 62 mmHg and 0 mmHg, respectively.

Event 5: August 6, 1985

There were several dead fish reported. Species composition not recorded. The total gas pressure was 123% of saturation, with nitrogen gas and oxygen gas pressures of 123% of saturation and 126% of saturation. The uncompensated ΔP at the maximum depth was 111 mmHg, as compared to 5 mmHg on July 30, 1985. The outflow was only 24.3 m^3/s (860 ft^3/s).

Event 6: August 26, 1986

This fish kill was classified as small. There were about 100 dead fish per 45 meters (about 150 feet) of bank. There were no fish observed floating downstream. A majority (85%) of the fish were small (<8 cm) freshwater drum and small channel catfish (<15 cm). There were also a few larger specimens observed. The rest of the kill consisted of crappie of various sizes and a few large common carp. There were many live fish observed in the shallows. No other unusual conditions were noted.

The outflow at this time was 102.0 m^3/s (3,600 ft^3/s), down from 283.2 m^3/s (10,000 ft^3/s) on the previous monitoring event on August 19. This was the first time since February 1986 that the outflow had been below 283.2 m^3/s. One of the Tainter gates had been in operation from early May to mid-June. The total gas pressure on August 26 was 117% of saturation. The uncompensated ΔP at the maximum depth was 13 mmHg as compared to -109 mmHg on the previous monitoring day.

Event 7: September 15, 1986

This minor fish kill event occurred during a planned decrease in outflow for maintenance reasons. There were just a few fish observed floating down-stream per minute with a scattering of fish along the banks. Most of the kill (80%) consisted of small freshwater drum, with small crappie and various sizes of channel catfish also observed. There were several severely exophthalmic fish along the waters edge but they were still able to swim.

The water temperature was 20°C (68°F). The total gas pressure at 1245 CDT was 123% of saturation (ΔP of 170) when the outflow was 36.8 m^3/s (1,300 ft^3/s). The uncompensated gas pressure at the maximum river depth was 112% of saturation (ΔP of 97 mmHg). At 1430 CDT, after the outflow was dropped to 8.5 m^3/s (300 ft^3/s), the total gas pressure was 124% of saturation

(ΔP of 183 mmHg). The total gas pressure at the lower maximum river depth was 118% of saturation (ΔP of 139 mmHg).

Event 8: July 7, 1987

A minor fish kill. There was six dead fish floating downstream per minute and about 100 dead fish washed up along 30 meters (about 100 feet) of river bank. Most (95%) of the fish were channel catfish of various sizes (7 cm to 50 cm) with the rest of the kill comprised of various sizes of freshwater drum. The weather had been hot and humid. There was a recent decrease in river flow. There were many common carp observed at the surface. The water temperature was 26°C (79°F) and the dissolved oxygen content was 8.4 mg/l.

The outflow at this time was 38.5 m^3/s (1,360 ft^3/s). The total gas pressure was 124% of saturation (ΔP of 176 mmHg) with nitrogen and oxygen gas pressures of 129% of saturation and 108% of saturation, respectively. The uncompensated gas pressure at the maximum depth was 104% of saturation (ΔP of 37 mmHg). Thus, aquatic organisms were continually exposed to excess gas pressures between 37 mmHg and 176 mmHg. The uncompensated gas pressure was also positive (ΔP of 67 mmHg) during the previous monitoring on June 30, 1987.

Event 9: June 28, 1988

On this day a small fish kill was discovered. Bait shop owners reported that the kill had been off and on for about two weeks. There were about 100 dead fish observed on the river bank (10 to 20 dead fish per 30 meters). There were no dead fish observed floating downstream. Most of the kill was comprised of freshwater drum (80%), with catfish (15%) and common carp (5%). Most of the fish ranged from 15 cm to 50 cm in length.

Weather conditions had been hot and dry. River flow had dropped over the last two weeks from 72.5 m^3/s to 19.0 m^3/s (2,560 ft^3/s to 670 ft^3/s). The total gas pressure exceeded 120% of saturation for the last six weeks. The total gas pressure on this day was 125% of saturation (ΔP of 185 mmHg) with an uncompensated gas pressure at the maximum depth of 117% of saturation (ΔP of 134 mmHg).

Event 10: July 26, 1988

A minor kill was discovered on this day. There was only four or five fish floating downstream per minute and there were about five dead fish per 30 meters (about 100 feet) of river bank. One-half of the fish were common carp (25 cm length) and the rest were various sizes of freshwater drum. Weather conditions were clear and hot (90°F).

Some externally examined fish exhibited emphysema in the head region and exophthalmia. The total gas pressure was 126% of saturation (ΔP of 195 mmHg). The uncompensated gas pressure was 120% of saturation (ΔP of 158 mmHg), which was the maximum uncompensated gas pressure observed in this study.

Event 11: May 16, 1989

This fish kill was reported by private citizens who voiced concern. No evidence of the kill was noted at the time of the gas monitoring as river flow had increased and washed carcasses downstream. The kill was reported to be comprised of various sizes of catfish and was reported to extend downstream to the town of Harvey. The event was reported to have occurred over several weeks. The severity and species composition could not be confirmed.

The total gas pressure had exceeded 119% of saturation (ΔP of 140 mmHg) for the last month. The uncompensated gas pressure as ΔP at the maximum depth exceeded 100 mmHg for the last two weeks when the river flow was approximately 34.0 m^3/s (1,200 ft^3/s).

Event 12: December 13, 1990

There were fish floating downstream but an estimation of how many was not recorded. The kill was classified as moderate with about 50 fish observed per 4.5 meters (15 feet) of river bank. There were hundreds of eight to 10 cm gizzard shad, with 12 to 30 cm freshwater drum and 20 to 25 cm white bass (*Morone chrysops*) also observed. Weather conditions had been moderately cold. The water temperature was 2.8°C (37°F). A gizzard shad kill was also noted below Saylorville Reservoir on this day. The gizzard shad probably succumbed to thermal stress.

All observed freshwater drum had many emphysema in the head region and in fin tissue. About half the white bass observed were still alive but were swimming upside down. Some of the white bass exhibited small whitish dots scattered over their bodies that appeared to be a bacterial or fungal infection. Dissection of a few freshwater drum exhibited gas bubbles in the vascular system. Microphotographs were taken.

The total gas pressure at this time was 113% of saturation (ΔP of 99 mmHg) and nitrogen and oxygen gas pressure was 120% of saturation and 90% of saturation. The uncompensated gas pressure at the maximum depth was negative. This is baffling since gas bubbles were present in the vascular system. It is possible that gas pressures were fluctuating as the water appeared visibly green indicating intense primary productivity. The total gas pressure during the previous monitoring event on September 25, 1990 was 129% of saturation (ΔP of 217 mmHg) with a uncompensated total gas pressure of 120% of saturation (ΔP of 158 mmHg). There had been a break in monitoring events due to contractual lapses.

Event 13: February 13, 1991

A small fish kill was observed downstream from Red Rock Dam on this day. There were about 17 fish floating downstream per minute. The majority of the fish (90%) were white bass with gizzard shad (5%) and crappie (5%) also present. There were many white bass that were still alive but were oriented upside down. Fishermen indicated that these conditions had existed for at least a few days. Air temperatures were moderate at -1.1°C (30°F). The water temperature was 1.8°C (35°F). The total gas pressure was 119% of saturation (ΔP of 140 mmHg) and an uncompensated gas pressure of 104% of saturation (ΔP of 33 mmHg).

Dissection of a few white bass showed that their body cavity was pressurized. No gas bubbles were observed in the vascular system. The stomachs of all dissected fish were empty.

Event 14: September 3, 1991

The largest fish kill during this nine-year study period occurred between August 27 and August 29, 1991. Unfortunately, this researcher was not notified of the fish kill. The first observation was made on a routine monitoring trip on

September 3, 1991. However, the Iowa State Conservation Commission did investigate and estimated the number of dead fish at 5,000. On September 3, 1991, it was observed that there were still about 10 dead fish floating downstream per minute, with 10 dead fish seen per 30 meters (about 100 feet) of river bank. Approximately 60% of the observed dead fish were white bass, 10% channel catfish, 10% freshwater drum, 5% largemouth bass, 5% bluegill (*Lepomis macrochirus*), 5% gizzard shad, and a few were walleye. One dead paddlefish (*Polyodon spathula*) was observed. Many live fish were also observed. There were several green sunfish that were alive but were hugging the river bank. Upon closer examination it was noticed that these fish exhibited severe exophthalmia and emphysema were present in their fin tissue (Figure 13). Most of the dead fish that were examined (many were too decayed to reveal much) exhibited some sign of gas bubble trauma. On this date, September 3, 1991, the total gas pressure was 109% of saturation (ΔP of 67 mmHg) with nitrogen gas and oxygen gas pressures of 107% of saturation (ΔP of 41 mmHg) and 117% of saturation (ΔP of 26 mmHg), respectively. The uncompensated gas pressure at the maximum river depth was 101% of saturation while the uncompensated ΔP at the maximum river depth was 8 mmHg. This was the first time since February 13, 1991 (which also triggered a fish kill) that the uncompensated ΔP at the maximum river depth was positive. Outflow from Red Rock Reservoir had decreased substantially prior to the September 3 fish kill. The previous monitoring event was on August 20, 1991, when the outflow was 365.3 m^3/s (12,900 ft^3/s), the total gas pressure was 105% of saturation (ΔP of 40 mmHg), and the uncompensated gas pressure at the maximum river depth was 98% of saturation (ΔP of -19 mmHg). By September 3 the outflow had decreased to 28.6 m^3/s (1,010 ft^3/s). This decrease in river flow which decreased the river depth triggered a fish kill as uncompensated dissolved gas pressures became hyperbaric throughout the water column.

APPENDIX C: GAS PRESSURE DATA FROM BELOW RED ROCK DAM

	Date	Flow (m3/s)	Temp (C)	D.O. (mg/l)	P bar (mmHg	Total gas pressure (%) TGP (%)	N2P (%)	O2P (%)	(%) N2/O2 Ratio	Delta P (mmHg)	Delta N2 (mmHg	Delta O2 (mmHg	Max Depth (m)	Comp Depth (m)	TGP (%)	TGPun (%)	Delta P (mmHg)	Punc (mmHg	Partial Pressure PP N2	PP O2	N2/O2
1	03Aug83	623.0	27.9	10.5	742.6	118.6	114.6	137.2	0.8	138	82.3	55.7	3.6	1.9	118.6	87.5	138	-125.9	647.0	205.4	3.1
2	06Sep83	107.6	25.5	8.3	738.3	121.7	127.2	104.7	1.2	160	153.0	7.0	1.6	2.2	121.7	105.0	160	42.7	717.2	156.6	4.6
3	*13Sep83	35.4	22.1	9.9	750.0	123.2	126.2	115.2	1.1	174	150.8	23.2	0.9	2.4	123.2	113.2	174	107.9	727.9	176.1	4.1
4	21Nov83	371.0	7.9	12.1	735.7	107.2	108.0	104.9	1.0	53	45.6	7.4	3.1	0.7	107.2	81.9	53	-174.9	620.8	159.9	3.9
5	12Dec83	209.6	0.1	11.3	743.1	108.9	116.9	78.9	1.5	66	98.6	-32.6	2.4	0.9	108.9	88.3	66	-106.8	682.3	122.1	5.6
6	10Jan84	85.0	0.0	12.9	754.5	107.6	112.6	89.0	1.3	57	74.3	-17.3	1.4	0.8	107.6	94.6	57	-46.0	667.1	139.8	4.8
7	06Mar84	325.7	2.1	14.6	744.9	108.7	109.1	107.7	1.0	65	53.1	11.9	2.9	0.9	108.7	84.5	65	-148.3	637.7	166.8	3.8
8	17Apr84	750.5	10.1	11.5	739.3	106.4	106.9	105.0	1.0	47	39.4	7.6	3.6	0.6	106.4	78.3	47	-217.6	616.5	160.6	3.8
9	08May84	481.4	11.3	10.2	744.6	104.0	106.6	94.6	1.1	30	38.3	-8.3	3.5	0.4	104.0	77.3	30	-227.3	619.0	145.5	4.3
10	14May84	509.8	15.3	13.3	749.4	130.2	129.6	134.9	1.0	226	172.2	53.8	3.6	3.1	130.2	96.2	226	-38.6	754.3	208.1	3.6
11	23May84	580.6	17.2	12.7	746.2	127.1	125.9	134.4	0.9	202	149.3	52.7	3.6	2.7	127.1	93.8	202	-62.6	727.5	206.0	3.5
12	05Jun84	594.7	20.2	11.8	734.5	126.5	125.1	135.3	0.9	195	142.0	53.0	3.6	2.7	126.5	93.1	195	-69.2	708.6	203.2	3.5
13	13Jun84	736.3	21.7	11.2	744.4	126.2	126.2	129.8	1.0	195	149.8	45.2	3.6	2.7	126.2	93.1	195	-69.2	722.9	197.1	3.7
14	19Jun84	991.2	23.0	10.9	744.1	127.3	127.6	130.0	1.0	203	157.6	45.4	3.6	2.8	127.3	93.9	203	-61.2	729.1	196.9	3.7
15	26Jun84	1132.8	23.6	10.4	736.2	124.7	125.2	126.8	1.0	182	141.9	40.1	3.6	2.5	124.7	91.8	182	-82.2	706.6	189.8	3.7
16	10Jul84	892.1	25.5	10.0	737.8	126.7	128.2	125.6	1.0	197	158.7	38.3	3.6	2.7	126.7	93.3	197	-66.9	722.6	187.7	3.8
17	18Jul84	764.6	26.2	9.9	743.6	126.6	128.1	125.9	1.0	198	159.1	38.9	3.6	2.7	126.6	93.5	198	-65.9	726.7	189.3	3.8
18	24Jul84	722.2	26.5	10.1	747.2	127.8	129.1	127.9	1.0	208	165.8	42.2	3.6	2.8	127.8	94.5	208	-55.9	735.9	193.3	3.8
19	31Jul84	623.0	26.0	9.9	742.3	127.3	129.2	125.2	1.0	203	165.1	37.9	3.6	2.8	127.3	93.9	203	-60.9	732.0	188.1	3.9
20	08Aug84	623.0	28.0	10.4	738.5	132.1	132.4	137.2	1.0	237	181.6	55.4	3.6	3.2	132.1	97.3	237	-26.9	743.0	204.2	3.6
21	14Aug84	509.8	27.7	8.6	743.9	131.6	138.4	111.9	1.2	235	217.2	17.8	3.6	3.2	131.6	97.1	235	-28.9	783.2	167.8	4.7
22	28Aug84	226.6	26.5	7.2	736.5	114.7	121.2	92.6	1.3	108	119.1	-11.1	2.5	1.5	114.7	92.2	108	-71.6	680.7	137.8	4.9
23	*03Oct84	11.3	17.0	12.1	743.1	125.3	124.6	130.4	1.0	188	141.7	46.3	0.6	2.6	125.3	118.3	188	143.9	717.6	199.0	3.6
24	09Oct84	36.2	16.9	10.8	745.3	125.5	129.3	113.7	1.1	190	169.0	21.0	0.9	2.6	125.5	115.3	190	123.9	746.8	174.1	4.3
25	16Oct84	47.3	17.0	10.1	734.5	114.4	116.1	109.7	1.1	106	91.3	14.7	1.0	1.4	114.4	104.0	106	32.5	660.4	165.5	4.0
26	23Oct84	65.1	12.5	11.5	752.0	113.0	114.4	109.0	1.0	98	84.1	13.9	1.2	1.3	113.0	101.2	98	9.8	670.0	169.2	4.0
27	06Nov84	65.1	10.6	12.8	744.8	113.6	112.9	117.1	1.0	101	74.6	26.4	1.2	1.4	113.6	101.5	101	12.8	655.8	180.4	3.6
28	13Nov84	75.0	8.5	13.4	744.1	114.8	114.4	117.1	1.0	110	83.7	26.3	1.3	1.5	114.8	101.7	110	14.5	665.3	180.5	3.7
29	19Nov84	70.8	5.8	14.2	751.2	115.3	115.8	114.4	1.0	115	92.5	22.5	1.3	1.6	115.3	102.3	115	19.4	680.9	178.4	3.8
30	27Nov84	70.8	4.0	14.2	736.2	111.3	111.2	112.0	1.0	83	64.7	18.3	1.3	1.1	111.3	98.5	83	-12.6	641.8	171.3	3.7
31	04Dec84	39.6	2.3	15.9	752.8	117.3	117.7	116.6	1.0	130	104.1	25.9	1.0	1.8	117.3	107.3	130	60.1	694.9	182.5	3.8
32	11Dec84	85.0	3.1	15.3	732.9	116.2	115.9	118.2	1.0	119	91.3	27.7	1.4	1.6	116.2	101.9	119	16.0	666.1	180.1	3.7
33	18Dec84	56.6	1.0	15.1	748.9	110.0	110.7	108.0	1.0	75	62.6	12.4	1.2	1.0	110.0	98.9	75	-9.6	650.7	168.3	3.9
34	02Jan85	141.6	0.1	12.1	754.3	104.6	110.3	83.5	1.3	35	60.9	-25.9	1.9	0.5	104.6	88.3	35	-104.7	653.5	131.2	5.0
35	08Jan85	118.9	0.6	14.1	750.2	109.1	111.7	99.4	1.1	68	68.9	-0.9	1.7	0.9	109.1	93.5	68	-57.0	658.1	155.3	4.2
36	15Jan85	62.3	0.2	14.0	745.9	112.5	116.5	97.9	1.2	93	96.2	-3.2	1.2	1.3	112.5	100.6	93	4.7	682.2	152.1	4.5
37	22Jan85	45.3	2.0	13.3	748.4	111.0	114.6	97.7	1.2	82	85.5	-3.5	1.0	1.1	111.0	101.0	82	8.5	672.9	152.2	4.4
38	29Jan85	45.3	1.9	14.3	740.0	118.2	121.7	105.9	1.1	135	125.9	9.1	1.0	1.8	118.2	107.6	135	61.5	706.7	163.0	4.3
39	19Feb85	59.5	2.1	14.4	746.7	113.4	115.5	105.9	1.1	100	90.8	9.2	1.2	1.4	113.4	101.9	100	15.4	676.8	164.5	4.1
40	25Feb85	509.8	2.2	11.0	743.6	103.4	109.1	82.1	1.3	25	52.6	-27.6	3.6	0.3	103.4	76.2	25	-239.8	636.2	127.0	5.0
41	05Mar85	113.3	2.1	13.5	751.0	110.7	113.9	98.9	1.2	80	81.7	-1.7	1.7	1.1	110.7	95.3	80	-41.4	671.1	154.6	4.3
42	12Mar85	155.8	4.8	13.2	745.4	115.0	118.0	104.6	1.1	112	104.9	7.1	2.0	1.5	115.0	96.1	112	-35.1	689.0	161.9	4.3

	Date	Flow (m3/s)	Temp (C)	D.O. (mg/l)	P bar (mmHg	Total gas pressure (%) TGP (%)	N2P (%)	O2P (%)	(%) N2/O2 Ratio	Delta P (mmHg)	Delta N2 (mmHg	Delta O2 (mmHg	Max Depth (m)	Comp Depth (m)	TGP (%)	TGPun (%)	Delta P (mmHg)	Punc (mmHg	Partial Pressure PP N2	PP O2	N2/O2
43	19Mar85	186.9	9.2	12.7	741.6	116.6	117.8	113.1	1.0	123	102.8	20.2	2.2	1.7	116.6	95.7	123	-38.7	682.2	173.7	3.9
44	26Mar85	115.5	9.8	13.0	737.8	118.3	118.8	117.8	1.0	135	107.8	27.2	1.7	1.8	118.3	101.2	135	10.1	683.9	179.8	3.8
45	02Apr85	147.3	9.3	12.7	749.2	112.0	112.2	112.1	1.0	90	71.3	18.7	1.9	1.2	112.0	94.4	90	-49.7	656.6	173.9	3.8
46	09Apr85	220.9	9.3	12.4	749.2	115.8	117.8	109.2	1.1	118	103.8	14.2	2.4	1.6	115.8	93.7	118	-58.4	689.1	169.3	4.1
47	15Apr85	161.4	14.8	11.7	742.6	118.9	119.5	118.3	1.0	140	112.0	28.0	2.0	1.9	118.9	99.2	140	-7.0	689.0	180.9	3.8
48	23Apr85	96.3	19.0	9.9	732.9	119.1	122.0	110.5	1.1	140	124.3	15.7	1.5	1.9	119.1	103.5	140	29.9	690.6	165.8	4.2
49	30Apr85	339.8	18.5	10.3	741.1	113.5	114.1	112.9	1.0	100	80.5	19.5	3.0	1.4	113.5	87.5	100	-120.2	653.7	171.4	3.8
50	07May85	198.2	20.6	11.0	743.1	120.2	119.5	125.3	1.0	150	111.6	38.4	2.3	2.0	120.2	97.9	150	-18.8	684.6	190.3	3.6
51	15May85	155.8	17.9	10.2	737.5	114.4	115.6	111.3	1.0	106	89.0	17.0	2.0	1.4	114.4	95.4	106	-40.8	659.8	168.3	3.9
52	28May85	172.8	22.5	9.3	740.8	116.9	119.3	110.1	1.1	125	109.7	15.3	2.1	1.7	116.9	96.7	125	-29.1	679.1	166.2	4.1
53	04Jun85	135.9	20.8	10.4	742.8	116.6	116.5	119.1	1.0	123	93.9	29.1	1.9	1.7	116.6	98.5	123	-12.8	666.6	180.8	3.7
54	11Jun85	99.1	21.5	9.9	741.3	119.7	121.6	115.1	1.1	146	123.2	22.8	1.5	2.0	119.7	104.2	146	35.9	694.0	174.0	4.0
55	18Jun85	141.6	21.0	9.8	740.3	116.9	118.5	113.1	1.0	125	105.2	19.8	1.9	1.7	116.9	98.4	125	-14.5	675.7	170.9	4.0
56	25Jun85	283.2	24.0	8.5	740.6	116.2	120.1	104.0	1.2	120	114.0	6.0	2.8	1.6	116.2	91.3	120	-81.9	681.7	156.5	4.4
57	02Jul85	118.9	25.8	8.4	743.1	116.8	120.7	105.1	1.1	125	117.4	7.6	1.7	1.7	116.8	100.0	125	0.4	685.1	158.1	4.3
58	09Jul85	66.6	27.0	8.2	738.8	120.3	124.9	106.7	1.2	150	140.0	10.0	1.2	2.0	120.3	107.5	150	62.0	702.8	159.2	4.4
59	*16Jul85	48.1	27.0	8.2	745.1	124.2	130.3	105.4	1.2	180	171.9	8.1	1.1	2.5	124.2	112.5	180	103.0	739.7	158.6	4.7
60	23Jul85	36.8	26.7	8.0	741.3	120.5	126.4	101.9	1.2	152	149.1	2.9	0.9	2.1	120.5	110.7	152	86.0	714.3	152.7	4.7
61	30Jul85	42.5	27.2	8.0	742.1	110.5	112.8	104.0	1.1	78	72.1	5.9	1.0	1.1	110.5	100.6	78	4.7	637.3	155.7	4.1
62	*06Aug85	24.4	27.7	9.0	739.2	123.0	125.5	118.1	1.1	170	143.0	27.0	0.8	2.3	123.0	114.0	170	111.4	705.3	176.0	4.0
63	13Aug85	24.4	26.3	9.7	741.1	121.6	122.1	123.6	1.0	160	124.6	35.4	0.8	2.2	121.6	112.7	160	101.4	690.2	185.2	3.7
64	27Aug85	9.9	26.0	10.6	748.2	124.3	123.3	133.0	0.9	182	132.1	49.9	0.5	2.5	124.3	118.5	182	145.4	703.6	201.4	3.5
65	03Sep85	56.6	25.2	9.1	738.3	117.6	119.5	113.3	1.1	130	110.1	19.9	1.2	1.8	117.6	105.6	130	45.7	674.7	169.5	4.0
66	10Sep85	158.6	24.5	8.6	746.2	114.1	117.0	105.5	1.1	105	96.7	8.3	2.0	1.4	114.1	95.3	105	-41.8	668.3	159.8	4.2
67	17Sep85	70.8	22.3	10.3	737.5	121.0	121.6	121.8	1.0	155	122.3	32.7	1.3	2.1	121.0	107.2	155	59.6	689.3	183.0	3.8
68	24Sep85	90.6	18.0	10.7	744.2	120.2	122.0	115.3	1.1	150	126.7	23.3	1.5	2.0	120.2	104.7	150	39.9	702.8	176.0	4.0
69	01Oct85	184.1	13.7	11.5	746.4	117.4	119.0	112.9	1.1	130	110.1	19.9	2.2	1.8	117.4	96.5	130	-31.7	690.8	173.8	4.0
70	08Oct85	158.6	12.8	12.1	739.3	117.6	118.1	117.0	1.0	130	104.0	26.0	2.0	1.8	117.6	98.1	130	-17.0	679.6	178.6	3.8
71	15Oct85	167.1	12.7	10.4	742.8	116.8	121.5	100.5	1.2	125	124.2	0.8	2.1	1.7	116.8	96.7	125	-29.4	702.7	154.1	4.6
72	22Oct85	187.5	14.3	10.8	740.4	118.2	121.4	108.0	1.1	135	122.7	12.3	2.2	1.8	118.2	97.0	135	-26.7	698.4	164.8	4.2
73	29Oct85	93.5	13.7	11.6	745.9	116.8	117.9	114.0	1.0	125	103.5	21.5	1.5	1.7	116.8	101.7	125	14.8	683.8	175.3	3.9
74	26Nov85	70.8	1.8	14.7	742.8	112.1	113.3	108.1	1.0	90	77.4	12.6	1.3	1.2	112.1	99.3	90	-5.6	660.5	167.1	4.0
75	10Dec85	73.3	1.0	15.4	749.7	116.0	117.8	109.8	1.1	120	104.6	15.4	1.3	1.6	116.0	102.9	120	24.4	693.4	171.4	4.0
76	14Jan86	42.2	2.0	14.0	745.4	114.1	117.1	103.5	1.1	105	99.5	5.5	1.0	1.4	114.1	103.8	105	31.5	684.6	160.5	4.3
77	23Jan86	34.0	2.0	14.9	734.5	108.8	108.3	111.4	1.0	65	47.5	17.5	0.9	0.9	108.8	99.9	65	-1.2	624.0	170.2	3.7
78	11Feb86	48.1	1.0	10.1	749.8	98.7	105.8	71.7	1.5	-10	34.2	-44.2	1.1	-0.1	98.7	89.5	-10	-87.2	623.0	111.9	5.6
79	18Feb86	45.3	1.5	12.2	733.2	110.9	116.5	90.2	1.3	80	95.0	-15.0	1.0	1.1	110.9	100.8	80	6.5	670.5	137.6	4.9
80	18Mar86	424.8	5.0	12.8	727.6	112.6	115.0	104.4	1.1	92	85.3	6.7	3.3	1.3	112.6	84.5	92	-150.7	655.3	157.7	4.2
81	25Mar86	727.8	10.0	11.5	740.6	107.4	108.3	104.8	1.0	55	47.7	7.3	3.6	0.7	107.4	79.1	55	-209.6	625.8	160.6	3.9
82	08Apr86	676.8	13.7	10.1	746.2	109.4	112.3	99.2	1.1	70	71.2	-1.2	3.6	1.0	109.4	80.7	70	-194.6	651.8	152.6	4.3
83	22Apr86	506.9	11.0	11.1	746.2	106.8	108.0	102.9	1.0	51	46.5	4.5	3.6	0.7	106.8	78.9	51	-213.6	628.6	158.7	4.0
84	29Apr86	498.4	17.3	10.5	738.5	107.4	106.4	112.5	0.9	55	36.1	18.9	3.6	0.7	107.4	79.1	55	-209.6	608.2	170.5	3.6
85	06May86	495.6	18.2	9.5	736.8	109.5	111.2	104.3	1.1	70	63.6	6.4	3.6	1.0	109.5	80.9	70	-190.6	633.7	157.4	4.0

	Date	Flow (m3/s)	Temp (C)	D.O. (mg/l)	P bar (mmHg	Total gas pressure (%) TGP (%)	N2P (%)	O2P (%)	(%) N2/O2 Ratio	Delta P (mmHg)	Delta N2 (mmHg	Delta O2 (mmHg	Max Depth (m)	Comp Depth (m)	TGP (%)	TGPun (%)	Delta P (mmHg)	Punc (mmHg	Partial Pressure PP N2	PP O2	N2/O2
86	13May86	504.1	17.7	8.5	737.5	110.8	116.3	91.6	1.3	80	92.8	-12.8	3.6	1.1	110.8	81.6	80	-184.2	664.5	138.7	4.8
87	20May86	424.8	18.3	8.0	744.6	101.7	105.8	86.6	1.2	13	33.4	-20.4	3.3	0.2	101.7	76.8	13	-229.2	609.6	132.3	4.6
88	27May86	489.9	18.3	8.6	740.8	111.6	116.6	94.1	1.2	86	95.0	-9.0	3.5	1.2	111.6	82.9	86	-170.9	668.2	142.9	4.7
89	03Jun86	509.8	21.2	8.4	742.3	115.1	120.4	97.2	1.2	112	116.2	-4.2	3.6	1.5	115.1	84.9	112	-152.2	688.1	147.4	4.7
90	10Jun86	521.1	24.0	6.8	736.1	104.3	110.0	84.0	1.3	32	56.0	-24.0	3.7	0.4	104.3	76.5	32	-235.5	620.2	125.5	4.9
91	24Jun86	509.8	26.8	7.2	746.0	113.7	120.1	92.1	1.3	102	114.0	-12.0	3.6	1.4	113.7	84.0	102	-161.9	682.8	138.8	4.9
92	08Jul86	509.8	27.0	7.2	741.6	111.9	117.4	93.3	1.3	88	98.1	-10.1	3.6	1.2	111.9	82.5	88	-175.9	663.2	139.7	4.7
93	22Jul86	509.8	28.1	6.0	746.9	104.7	111.9	78.5	1.4	35	67.3	-32.3	3.6	0.5	104.7	77.4	35	-228.9	635.2	118.2	5.4
94	29Jul86	498.4	28.9	6.8	741.9	112.5	118.9	91.1	1.3	93	106.3	-13.3	3.6	1.3	112.5	83.3	93	-167.2	669.1	135.9	4.9
95	05Aug86	283.2	24.0	6.2	742.1	103.1	110.7	75.1	1.5	23	60.6	-37.6	2.8	0.3	103.1	81.1	23	-178.9	629.5	113.2	5.6
96	12Aug86	283.2	22.8	7.5	746.2	113.4	120.4	89.0	1.4	100	116.7	-16.7	2.8	1.4	113.4	89.3	100	-101.9	690.1	135.3	5.1
97	19Aug86	283.2	24.0	6.5	745.1	112.5	122.0	78.4	1.6	93	125.7	-32.7	2.8	1.3	112.5	88.5	93	-108.9	697.0	118.7	5.9
98	*26Aug86	102.0	24.2	7.9	741.6	117.5	123.9	96.3	1.3	130	135.6	-5.6	1.6	1.8	117.5	101.5	130	12.6	704.1	145.0	4.9
99	02Sep86	107.0	22.0	8.7	743.3	118.0	122.9	102.1	1.2	134	130.8	3.2	1.6	1.8	118.0	101.9	134	16.6	702.7	154.8	4.5
100	09Sep86	43.3	20.7	9.1	743.4	120.3	125.3	104.1	1.2	151	144.7	6.3	1.0	2.1	120.3	109.5	151	77.6	717.9	158.2	4.5
101	*16Sep86	8.5	20.1	9.2	739.8	115.3	118.7	104.1	1.1	113	106.7	6.3	0.5	1.5	115.3	109.8	113	76.3	677.6	157.5	4.3
102	23Sep86	325.7	21.2	7.1	748.2	108.6	116.2	80.7	1.4	64	93.4	-29.4	2.9	0.9	108.6	84.5	64	-148.9	669.9	123.4	5.4
103	30Sep86	141.6	20.8	8.9	738.5	119.6	124.8	102.6	1.2	145	141.1	3.9	1.9	2.0	119.6	100.6	145	5.5	710.3	154.7	4.6
104	07Oct86	141.6	18.2	8.9	741.3	116.2	121.8	97.0	1.3	120	124.5	-4.5	1.9	1.6	116.2	97.8	120	-19.5	698.1	147.5	4.7
105	14Oct86	145.0	13.8	10.7	742.6	113.5	115.9	105.4	1.1	100	91.7	8.3	1.9	1.4	113.5	95.5	100	-39.7	669.4	161.4	4.1
106	21Oct86	509.8	13.9	9.7	746.9	104.0	106.3	95.8	1.1	30	36.5	-6.5	3.6	0.4	104.0	76.8	30	-234.6	617.6	147.4	4.2
107	04Nov86	509.8	10.9	11.1	747.0	109.4	111.6	101.8	1.1	70	67.3	2.7	3.6	1.0	109.4	80.8	70	-194.6	650.0	157.2	4.1
108	18Nov86	509.8	3.0	13.1	744.9	105.4	107.1	99.3	1.1	40	41.0	-1.0	3.6	0.5	105.4	77.7	40	-224.8	625.4	153.8	4.1
109	02Dec86	339.8	2.7	14.3	740.3	109.5	110.0	108.0	1.0	70	57.7	12.3	3.0	1.0	109.5	84.3	70	-150.7	638.5	166.3	3.8
110	09Dec86	255.4	2.6	14.2	746.2	108.7	110.8	101.2	1.1	65	63.1	1.9	2.6	0.9	108.7	86.5	65	-126.2	649.2	157.2	4.1
111	13Jan87	79.6	3.8	15.2	738.3	112.9	111.5	118.9	0.9	95	66.0	29.0	1.4	1.3	112.9	99.5	95	-4.3	644.9	182.4	3.5
112	27Jan87	74.8	2.1	17.4	740.8	114.2	110.3	129.5	0.9	105	59.6	45.4	1.3	1.4	114.2	101.1	105	9.4	641.0	199.5	3.2
113	03Feb87	74.5	3.0	16.1	745.6	117.4	116.4	122.0	1.0	130	95.9	34.1	1.3	1.8	117.4	104.1	130	34.4	680.8	189.1	3.6
114	17Feb87	60.9	3.0	16.8	745.6	110.7	106.5	127.1	0.8	80	38.0	42.0	1.2	1.1	110.7	99.0	80	-8.3	622.9	197.1	3.2
115	03Mar87	164.3	4.0	15.0	752.8	114.3	114.3	115.3	1.0	108	84.1	23.9	2.1	1.5	114.3	95.3	108	-42.8	674.4	180.3	3.7
116	24Mar87	201.1	10.0	11.8	728.6	112.4	113.5	109.0	1.0	90	76.4	13.6	2.3	1.2	112.4	91.2	90	-79.1	645.1	164.3	3.9
117	21Apr87	495.6	15.0	9.3	746.4	106.7	110.3	93.7	1.2	50	59.6	-9.6	3.6	0.7	106.7	79.1	50	-210.9	639.6	144.0	4.4
118	28Apr87	269.9	17.9	10.7	745.1	114.8	115.1	115.3	1.0	110	86.6	23.4	2.7	1.5	114.8	90.7	110	-88.2	663.5	176.2	3.8
119	05May87	467.3	17.6	9.5	749.2	107.3	109.3	100.9	1.1	55	53.6	1.4	3.5	0.7	107.3	80.2	55	-198.2	633.9	155.2	4.1
120	12May87	167.1	20.5	10.1	745.0	120.8	123.1	114.8	1.1	155	132.5	22.5	2.1	2.1	120.8	100.1	155	0.9	707.1	174.8	4.0
121	26May87	102.0	21.6	8.9	740.0	117.4	121.7	103.8	1.2	129	123.2	5.8	1.6	1.8	117.4	101.3	129	11.6	692.9	156.8	4.4
122	02Jun87	447.5	24.0	8.4	741.6	114.2	117.7	103.1	1.1	105	100.3	4.7	3.4	1.4	114.2	85.4	105	-144.6	668.9	155.4	4.3
123	16Jun87	93.5	25.0	8.8	740.6	123.9	128.8	109.5	1.2	177	162.7	14.3	1.5	2.4	123.9	107.9	177	67.1	729.4	164.5	4.4
124	23Jun87	181.2	28.0	8.0	740.9	116.9	121.0	104.7	1.2	125	118.0	7.0	2.2	1.7	116.9	96.0	125	-36.3	681.3	156.3	4.4
125	30Jun87	68.0	25.8	8.5	743.6	120.8	125.5	106.9	1.2	155	144.6	10.4	1.2	2.1	120.8	108.1	155	67.0	712.8	160.9	4.4
126	*07Jul87	38.5	26.3	8.4	740.0	123.8	129.1	107.9	1.2	176	164.1	11.9	1.9	2.4	123.8	104.2	176	36.7	728.8	161.5	4.5
127	14Jul87	481.4	23.7	6.5	743.1	106.3	113.9	78.7	1.4	47	79.2	-32.2	3.5	0.6	106.3	79.0	47	-209.9	649.3	118.8	5.5
128	21Jul87	192.6	28.1	8.0	746.7	118.5	123.2	104.5	1.2	138	131.2	6.8	2.2	1.9	118.5	97.4	138	-23.3	698.9	157.2	4.4

	Date	Flow (m3/s)	Temp (C)	D.O. (mg/l)	P bar (mmHg	Total gas pressure (%) TGP (%)	N2P (%)	O2P (%)	(%) N2/O2 Ratio	Delta P (mmHg)	Delta N2 (mmHg	Delta O2 (mmHg	Max Depth (m)	Comp Depth (m)	TGP (%)	TGPun (%)	Delta P (mmHg)	Punc (mmHg	Partial Pressure PP N2	PP O2	N2/O2
129	28Jul87	172.2	30.4	7.4	741.1	125.8	133.9	101.0	1.3	191	189.6	1.4	2.1	2.6	125.8	104.2	191	37.3	749.7	149.9	5.0
130	04Aug87	61.7	29.1	8.0	743.1	121.0	126.1	106.1	1.2	156	146.9	9.1	1.2	2.1	121.0	108.2	156	68.0	710.5	158.4	4.5
131	11Aug87	104.8	26.3	7.0	740.6	120.8	130.2	88.9	1.5	154	170.6	-16.6	1.6	2.1	120.8	104.3	154	36.7	735.7	133.2	5.5
132	18Aug87	141.6	27.6	7.8	744.2	122.8	129.7	101.3	1.3	170	168.1	1.9	1.9	2.3	122.8	103.5	170	30.7	734.5	152.0	4.8
133	25Aug87	158.6	21.1	8.5	744.1	117.6	123.4	98.1	1.3	131	133.9	-2.9	2.0	1.8	117.6	98.2	131	-15.8	707.2	149.1	4.7
134	08Sep87	393.6	21.9	8.4	743.1	118.8	125.1	97.7	1.3	140	143.5	-3.5	3.4	1.9	118.8	89.0	140	-109.6	715.3	148.1	4.8
135	15Sep87	90.6	21.2	9.2	739.0	122.3	127.3	106.7	1.2	165	154.9	10.1	1.5	2.2	122.3	106.5	165	54.9	724.1	161.0	4.5
136	22Sep87	220.9	18.1	9.7	748.4	117.4	121.3	104.4	1.2	130	123.3	6.7	2.4	1.8	117.4	95.0	130	-46.2	702.6	160.3	4.4
137	29Sep87	138.2	19.4	10.5	744.0	122.2	124.5	116.2	1.1	165	140.3	24.7	1.9	2.2	122.2	102.9	165	25.5	715.1	177.1	4.0
138	06Oct87	53.8	14.5	11.0	741.1	114.2	115.5	110.3	1.0	105	89.3	15.7	1.1	1.4	114.2	102.9	105	24.2	665.4	168.4	4.0
139	20Oct87	67.7	9.5	12.3	747.9	115.1	116.9	109.5	1.1	113	98.3	14.7	1.2	1.5	115.1	103.0	113	24.8	682.5	169.5	4.0
140	03Nov87	82.1	12.2	11.9	739.7	121.0	123.2	114.2	1.1	155	133.3	21.7	1.4	2.1	121.0	106.2	155	52.1	709.6	174.4	4.1
141	17Nov87	39.6	8.2	13.3	736.6	119.0	119.9	116.8	1.0	140	114.4	25.6	1.0	1.9	119.0	108.7	140	70.2	690.3	178.2	3.9
142	01Dec87	70.8	3.6	14.3	740.3	118.2	120.4	110.9	1.1	135	118.3	16.7	1.3	1.8	118.2	104.7	135	39.4	698.8	170.6	4.1
143	08Dec87	182.1	4.5	14.3	735.4	116.3	117.0	114.5	1.0	120	97.9	22.1	2.2	1.6	116.3	95.3	120	-41.8	674.2	174.9	3.9
144	16Dec87	113.3	0.3	15.0	749.2	114.4	117.0	105.3	1.1	108	99.7	8.3	1.7	1.5	114.4	98.1	108	-17.0	688.2	164.3	4.2
145	26Jan88	49.3	0.8	11.7	750.2	104.4	110.1	83.2	1.3	33	59.3	-26.3	1.1	0.4	104.4	94.2	33	-47.9	648.4	129.9	5.0
146	16Feb88	40.5	1.9	13.1	737.5	119.8	125.9	97.6	1.3	146	149.7	-3.7	1.0	2.0	119.8	108.9	146	72.5	728.6	149.7	4.9
147	08Mar88	133.1	4.7	14.0	738.8	116.6	118.3	111.4	1.1	123	105.4	17.6	1.8	1.7	116.6	98.9	123	-9.4	684.4	171.0	4.0
148	22Mar88	71.6	8.2	15.0	737.5	119.0	116.2	130.8	0.9	140	93.0	47.0	1.3	1.9	119.0	105.3	140	44.5	669.5	199.8	3.4
149	05Apr88	111.3	11.4	12.4	735.7	121.2	122.7	117.2	1.0	156	129.9	26.1	1.6	2.1	121.2	104.5	156	38.4	703.4	178.1	3.9
150	19Apr88	82.1	13.1	12.6	740.0	123.1	123.7	122.8	1.0	171	136.1	34.9	1.4	2.3	123.1	108.1	171	68.1	712.2	187.5	3.8
151	03May88	150.9	15.8	11.6	740.6	119.4	119.7	120.4	1.0	144	112.9	31.1	1.9	2.0	119.4	100.5	144	4.4	687.7	183.4	3.7
152	09May88	152.9	21.1	10.7	734.2	118.1	117.1	124.3	0.9	133	96.5	36.5	2.0	1.8	118.1	98.4	133	-13.8	662.1	186.4	3.6
153	17May88	107.0	20.7	10.2	743.4	121.5	123.5	116.9	1.1	160	134.4	25.6	1.6	2.2	121.5	104.9	160	42.6	707.6	177.5	4.0
154	31May88	66.3	21.9	9.8	743.4	124.2	127.7	114.4	1.1	180	158.2	21.8	1.2	2.5	124.2	111.1	180	91.9	730.3	173.4	4.2
155	07Jun88	49.0	27.5	8.1	739.0	123.0	128.6	106.2	1.2	170	160.8	9.2	1.0	2.3	123.0	111.9	170	96.7	723.2	158.2	4.6
156	14Jun88	72.5	24.3	8.3	745.4	123.5	130.4	101.2	1.3	175	173.3	1.7	1.3	2.4	123.5	109.5	175	79.6	744.5	153.1	4.9
157	21Jun88	29.7	26.8	8.4	739.5	124.1	129.4	108.5	1.2	178	165.3	12.7	0.8	2.4	124.1	115.0	178	119.4	729.0	162.1	4.5
158	*28Jun88	19.0	27.7	8.4	739.5	125.0	130.3	109.8	1.2	185	170.4	14.6	0.7	2.5	125.0	116.9	185	133.7	732.9	163.7	4.5
159	05Jul88	8.6	28.2	9.9	744.9	114.4	111.1	129.6	0.9	107	62.6	44.4	0.5	1.5	114.4	109.0	107	70.4	628.7	194.5	3.2
160	12Jul88	8.6	27.0	10.7	741.1	115.8	110.5	138.7	0.8	117	59.1	57.9	0.5	1.6	115.8	110.3	117	80.4	623.8	207.6	3.0
161	19Jul88	17.0	27.5	8.4	744.1	120.8	125.0	109.2	1.1	155	141.2	13.8	0.7	2.1	120.8	113.0	155	103.7	707.7	163.9	4.3
162	*26Jul88	9.3	29.0	12.0	744.9	126.2	118.8	159.3	0.7	195	106.3	88.7	0.5	2.7	126.2	120.3	195	158.4	671.4	238.5	2.8
163	02Aug88	9.9	30.9	12.3	741.8	125.2	115.1	169.1	0.7	187	84.5	102.5	0.5	2.6	125.2	119.3	187	150.4	644.4	250.9	2.6
164	09Aug88	8.6	28.8	9.2	742.1	120.9	121.7	122.2	1.0	155	121.8	33.2	0.5	2.1	120.9	115.2	155	118.4	685.0	182.4	3.8
165	16Aug88	8.6	31.4	13.3	741.8	123.3	108.5	184.8	0.6	173	47.3	125.7	0.5	2.4	123.3	117.5	173	136.4	606.5	273.8	2.2
166	23Aug88	8.5	27.7	8.8	741.8	117.3	119.1	113.5	1.0	128	107.8	20.2	0.5	1.7	117.3	111.7	128	91.4	672.8	169.9	4.0
167	06Sep88	14.7	22.7	11.8	743.4	125.3	122.4	139.7	0.9	188	127.9	60.1	0.6	2.6	125.3	118.3	188	144.0	699.2	211.5	3.3
168	13Sep88	8.5	21.8	12.4	746.7	125.8	122.0	143.9	0.8	193	126.2	66.8	0.5	2.6	125.8	120.0	193	156.3	700.9	219.2	3.2
169	20Sep88	8.5	20.8	10.7	742.6	119.3	118.9	123.0	1.0	143	108.2	34.8	0.5	1.9	119.3	113.6	143	106.3	680.6	186.5	3.6
170	27Sep88	8.5	21.8	11.7	743.9	124.6	122.5	136.0	0.9	183	128.3	54.7	0.5	2.5	124.6	118.7	183	146.3	700.9	206.4	3.4
171	11Oct88	15.9	15.2	12.7	747.2	119.4	117.4	128.7	0.9	145	100.8	44.2	0.6	2.0	119.4	112.8	145	100.9	681.3	198.0	3.4

	Date	Flow (m3/s)	Temp (C)	D.O. (mg/l)	P bar (mmHg	Total gas pressure (%) TGP (%)	N2P (%)	O2P (%)	(%) N2/O2 Ratio	Delta P (mmHg)	Delta N2 (mmHg	Delta O2 (mmHg	Max Depth (m)	Comp Depth (m)	TGP (%)	TGPun (%)	Delta P (mmHg)	Punc (mmHg	Partial Pressure PP N2	PP O2	N2/O2
172	25Oct88	11.0	10.3	14.1	742.8	116.4	113.4	129.0	0.9	122	77.4	44.6	0.5	1.7	116.4	110.9	122	85.3	657.2	198.2	3.3
173	08Nov88	8.5	7.9	16.4	744.1	122.4	117.9	140.7	0.8	167	104.2	62.8	0.5	2.3	122.4	116.7	167	130.2	686.1	217.0	3.2
174	06Dec88	9.9	4.8	17.5	741.0	119.0	113.7	140.2	0.8	141	79.1	61.9	0.5	1.9	119.0	113.4	141	104.2	659.8	215.8	3.1
175	10Jan89	17.3	1.8	16.9	746.0	118.9	117.8	123.9	1.0	141	102.9	38.1	0.6	1.9	118.9	112.3	141	96.9	684.5	192.3	3.6
176	14Feb89	21.8	1.5	16.3	749.7	119.1	119.5	118.1	1.0	143	114.8	28.2	0.7	1.9	119.1	111.9	143	95.2	703.4	184.2	3.8
177	07Mar89	16.7	2.4	15.6	751.0	120.6	122.3	115.1	1.1	155	131.3	23.7	0.6	2.1	120.6	113.9	155	110.9	720.7	179.8	4.0
178	21Mar89	44.5	3.6	11.3	751.2	111.6	118.5	86.2	1.4	87	108.5	-21.5	1.0	1.2	111.6	101.6	87	13.5	697.7	134.6	5.2
179	04Apr89	60.9	7.9	12.6	739.5	112.0	113.0	109.2	1.0	89	74.8	14.2	1.2	1.2	112.0	100.1	89	0.8	653.1	167.4	3.9
180	18Apr89	31.2	11.6	14.6	746.2	124.1	121.2	136.8	0.9	180	123.3	56.7	0.9	2.4	124.1	114.5	180	117.5	705.0	210.9	3.3
181	02May89	56.6	15.6	11.4	745.9	119.2	120.2	116.9	1.0	143	117.0	26.0	1.2	1.9	119.2	106.6	143	54.8	696.1	179.5	3.9
182	09May89	31.7	15.3	12.4	744.6	124.6	124.7	126.3	1.0	183	142.7	40.3	0.9	2.5	124.6	114.9	183	120.5	721.0	193.6	3.7
183	*16May89	34.6	16.5	12.4	742.1	126.0	125.6	130.0	1.0	193	147.2	45.8	0.9	2.6	126.0	115.7	193	126.9	722.7	198.3	3.6
184	30May89	79.3	22.1	9.0	736.0	122.7	127.6	107.3	1.2	167	156.1	10.9	1.4	2.3	122.7	108.1	167	67.9	722.1	160.9	4.5
185	06Jun89	85.0	23.9	8.2	738.5	120.4	126.7	100.2	1.3	151	150.7	0.3	1.4	2.1	120.4	105.7	151	48.2	716.9	150.4	4.8
186	13Jun89	72.5	21.7	9.4	738.8	122.6	126.7	110.2	1.1	167	151.6	15.4	1.3	2.3	122.6	108.6	167	71.6	720.2	166.1	4.3
187	20Jun89	31.2	21.6	9.6	741.3	122.3	125.8	112.1	1.1	165	146.7	18.3	0.9	2.3	122.3	112.8	165	102.7	717.4	169.5	4.2
188	27Jun89	56.6	23.7	8.0	740.9	121.2	128.5	97.0	1.3	157	161.6	-4.6	1.1	2.1	121.2	109.3	157	76.2	729.9	146.0	5.0
189	11Jul89	15.6	26.5	9.4	742.7	123.2	125.1	120.3	1.0	172	142.0	30.0	0.7	2.3	123.2	115.7	172	124.4	708.6	180.1	3.9
190	18Jul89	39.6	25.4	8.3	738.3	119.4	124.3	104.2	1.2	143	136.7	6.3	1.0	2.0	119.4	108.6	143	69.7	701.0	155.9	4.5
191	25Jul89	29.7	24.8	9.9	747.9	116.7	116.0	122.1	1.0	125	91.5	33.5	0.9	1.7	116.7	107.3	125	59.0	664.2	185.3	3.6
192	01Aug89	9.3	26.6	9.8	745.6	120.4	120.3	124.6	1.0	152	115.0	37.0	0.6	2.1	120.4	113.7	152	108.0	683.7	187.8	3.6
193	24Oct89	9.1	14.1	14.8	746.4	124.2	118.9	146.5	0.8	181	109.4	71.6	0.6	2.5	124.2	117.3	181	136.9	689.9	225.4	3.1
194	07Nov89	17.8	10.1	14.3	737.3	117.9	114.7	131.2	0.9	132	84.4	47.6	0.7	1.8	117.9	110.2	132	80.6	659.9	200.1	3.3
195	05Dec89	8.8	2.8	16.8	737.3	118.6	116.2	128.2	0.9	137	93.7	43.3	0.6	1.9	118.6	112.4	137	96.5	672.1	196.6	3.4
196	16Jan90	8.8	4.0	14.3	740.6	121.5	124.2	112.2	1.1	159	140.2	18.8	0.6	2.2	121.5	115.2	159	118.5	720.8	172.6	4.2
197	06Feb90	13.3	3.8	15.7	742.3	122.1	122.4	121.8	1.0	164	130.3	33.7	0.6	2.2	122.1	115.2	164	119.9	712.4	188.0	3.8
198	06Mar90	13.6	5.4	17.3	751.2	114.4	108.2	138.4	0.8	108	48.1	59.9	0.6	1.5	114.4	108.0	108	63.9	636.7	215.8	3.0
199	27Mar90	107.9	6.1	12.6	750.2	112.0	114.7	102.5	1.1	90	86.1	3.9	1.6	1.2	112.0	96.8	90	-27.7	673.5	159.6	4.2
200	10Apr90	66.3	8.0	14.2	745.6	117.0	115.8	122.7	0.9	127	91.9	35.1	1.2	1.7	117.0	104.6	127	38.7	675.0	189.6	3.6
201	24Apr90	53.8	11.8	12.6	736.8	125.4	127.3	120.0	1.1	187	156.6	30.4	1.2	2.5	125.4	112.5	187	102.5	730.8	182.6	4.0
202	01May90	73.6	14.8	11.3	746.7	121.8	124.5	113.7	1.1	163	141.9	21.1	1.3	2.2	121.8	108.0	163	67.5	722.2	174.9	4.1
203	08May90	80.7	16.0	11.6	736.0	124.2	125.4	122.1	1.0	178	144.5	33.5	1.4	2.4	124.2	109.4	178	78.8	715.6	184.8	3.9
204	15May90	188.9	15.0	10.8	735.7	119.4	122.3	110.5	1.1	143	127.1	15.9	2.3	1.9	119.4	97.1	143	-26.0	698.6	167.4	4.2
205	29May90	481.4	18.1	8.4	742.2	114.4	122.5	85.7	1.4	107	128.7	-21.7	3.6	1.5	114.4	84.4	107	-157.4	703.2	130.5	5.4
206	05Jun90	424.8	17.6	9.5	736.8	112.2	115.1	102.8	1.1	126	111.6	18.2	1.8	1.7	112.2	100.1	126	-152.4	656.3	155.3	4.2
207	12Jun90	308.7	22.4	8.8	736.2	104.8	104.8	105.2	1.0	35	27.2	7.8	2.8	0.5	104.8	82.2	35	-166.8	593.1	157.8	3.8
208	19Jun90	141.6	22.5	6.2	737.8	109.6	119.5	73.7	1.6	71	110.5	-39.5	1.9	1.0	109.6	92.2	71	-68.4	677.5	110.8	6.1
209	26Jun90	566.4	24.9	7.9	741.8	117.8	123.7	98.4	1.3	132	134.4	-2.4	3.6	1.8	117.8	86.6	132	-135.7	702.1	148.1	4.7
210	10Jul90	563.6	25.9	7.1	744.1	123.3	133.3	89.2	1.5	173	189.3	-16.3	3.6	2.4	123.3	90.6	173	-94.6	757.7	134.4	5.6
211	17Jul90	557.9	25.8	7.6	743.4	121.8	129.8	95.4	1.4	162	168.9	-6.9	3.6	2.2	121.8	89.9	162	-102.0	736.8	143.7	5.1
212	24Jul90	430.5	25.0	7.4	743.9	121.2	130.1	91.3	1.4	158	171.2	-13.2	3.4	2.2	121.2	91.1	158	-87.7	740.4	137.7	5.4
213	31Jul90	456.0	24.8	8.6	746.8	116.6	120.1	106.0	1.1	124	114.9	9.1	3.4	1.7	116.6	87.1	124	-129.0	686.6	160.7	4.3
214	07Aug90	467.3	24.7	7.4	748.8	112.4	118.8	90.3	1.3	93	107.8	-14.8	3.4	1.3	112.4	84.0	93	-160.0	681.3	137.2	5.0

	Date	Flow (m3/s)	Temp (C)	D.O. (mg/l)	P bar (mmHg	Total gas pressure (%) TGP (%)	N2P (%)	O2P (%)	(%) N2/O2 Ratio	Delta P (mmHg)	Delta N2 (mmHg	Delta O2 (mmHg	Max Depth (m)	Comp Depth (m)	TGP (%)	TGPun (%)	Delta P (mmHg)	Punc (mmHg	Partial Pressure PP N2	PP O2	N2/O2
215	14Aug90	450.3	24.3	7.4	744.9	117.9	126.0	89.8	1.4	133	148.4	-15.4	3.4	1.8	117.9	88.3	133	-116.4	719.2	135.9	5.3
216	21Aug90	467.3	25.5	6.5	746.4	104.4	111.0	80.6	1.4	33	62.4	-29.4	3.4	0.5	104.4	78.0	33	-220.0	633.1	121.8	5.2
217	28Aug90	356.8	27.7	7.6	739.5	114.5	119.3	99.0	1.2	107	108.4	-1.4	3.0	1.5	114.5	87.9	107	-116.5	671.0	147.6	4.5
218	11Sep90	55.5	26.8	6.3	744.9	115.3	125.3	80.6	1.6	114	143.2	-29.2	1.0	1.6	115.3	104.5	114	37.0	711.1	121.3	5.9
219	25Sep90	29.5	23.0	10.7	737.1	129.4	130.6	129.3	1.0	217	173.0	44.0	0.8	3.0	129.4	119.9	217	158.3	739.0	194.0	3.8
220	*13Dec90	104.8	2.8	12.0	748.9	113.2	119.6	89.7	1.3	99	115.1	-16.1	1.6	1.3	113.2	97.8	99	-18.7	702.6	139.7	5.0
221	21Jan91	25.2	2.1	15.0	741	117.7	119.5	111.6	1.1	131	113.1	17.9	0.8	1.8	117.7	109.5	131	75.8	694.6	172.1	4.0
222	*13Feb91	86.4	1.8	12.4	741	118.9	126.4	91.5	1.4	140	153.0	-13.0	1.4	1.9	118.9	103.9	140	33.4	734.7	141.1	5.2
223	06Mar91	334.2	3.2	11.3	734	106.7	111.9	87.5	1.3	49	68.1	-19.1	2.8	0.7	106.7	83.3	49	-156.9	643.8	133.4	4.8
224	18Mar91	424.8	4.3	12.4	741	107.3	109.8	98.3	1.1	54	56.7	-2.7	3.3	0.7	107.3	80.8	54	-188.7	637.5	151.3	4.2
225	01Apr91	693.8	9.1	11.0	750	106.4	109.2	96.3	1.1	48	53.8	-5.8	4.2	0.7	106.4	75.4	48	-260.7	639.8	149.5	4.3
226	15Apr91	538.1	10.3	10.6	742	114.8	120.0	96.5	1.2	110	115.4	-5.4	3.6	1.5	114.8	84.6	110	-154.7	694.5	148.1	4.7
227	06May91	257.7	13.1	11.7	746	121.2	123.7	113.5	1.1	158	137.2	20.8	2.6	2.1	121.2	96.1	158	-36.8	718.0	174.7	4.1
228	13May91	566.4	15.3	11.2	743	124.9	128.1	115.0	1.1	185	162.0	23.0	3.8	2.5	124.9	90.8	185	-94.3	739.0	175.9	4.2
229	28May91	453.1	20.5	7.9	744	114.9	122.1	89.8	1.4	111	126.4	-15.4	3.4	1.5	114.9	86.0	111	-138.6	700.3	136.6	5.1
230	05Jun91	623.0	19.9	7.2	749	114.4	124.1	79.8	1.6	108	139.0	-31.0	3.8	1.5	114.4	83.4	108	-171.1	717.3	122.3	5.9
231	18Jun91	991.2	24.3	7.6	746	122.3	130.9	93.3	1.4	166	176.1	-10.1	4.0	2.3	122.3	87.7	166	-127.6	747.8	141.4	5.3
232	09Jul91	736.3	25.4	5.6	743	111.2	122.4	70.6	1.7	83	127.2	-44.2	4.0	1.1	111.2	79.7	83	-210.4	695.3	106.4	6.5
233	16Jul91	623.0	25.3	6.3	748	113.1	123.0	78.1	1.6	98	131.2	-33.2	3.8	1.3	113.1	82.1	98	-184.4	703.4	118.4	5.9
234	30Jul91	509.8	25.5	7.4	746	117.4	124.9	92.3	1.4	130	141.6	-11.6	3.7	1.8	117.4	86.1	130	-141.4	712.0	139.6	5.1
235	06Aug91	509.8	24.3	7.2	747	119.9	129.3	87.7	1.5	149	167.6	-18.6	3.7	2.0	119.9	88.0	149	-122.4	740.1	133.1	5.6
236	13Aug91	509.8	25.1	10.0	747	121.4	121.8	124.7	1.0	160	124.2	35.8	3.7	2.2	121.4	89.1	160	-111.4	695.8	187.3	3.7
237	20Aug91	365.3	24.3	7.0	745	105.4	110.7	86.1	1.3	40	61.0	-21.0	3.1	0.5	105.4	97.7	40	-18.7	631.9	130.3	4.8
238	*03Sep91	28.6	25.1	9.5	748	109.0	107.2	117.3	0.9	67	40.7	26.3	0.8	0.9	109.0	101.0	67	8.3	613.1	178.0	3.4
239	17Sep91	21.2	24.1	10.1	744	107.0	103.0	123.1	0.8	52	17.0	35.0	0.7	0.7	107.0	100.1	52	0.6	587.4	186.1	3.2
240	08Oct91	31.7	14.2	13.1	742	106.2	99.9	130.4	0.8	46	-0.5	46.5	0.8	0.6	106.2	98.0	46	-16.5	576.4	199.4	2.9
241	16Jan92	169.9	0.8	13.9	736	103.4	104.2	100.5	1.0	25	24.2	0.8	2.1	0.3	103.4	85.5	25	-129.4	602.2	154.0	3.9
242	11Feb92	99.1	2.7	15.9	755	111.5	109.9	118.3	0.9	87	58.3	28.7	1.6	1.2	111.5	96.9	87	-27.0	650.7	185.7	3.5
243	17Mar92	481.4	5.1	13.6	745	106.2	105.6	108.8	1.0	46	32.3	13.7	3.6	0.6	106.2	78.3	46	-218.8	616.0	168.4	3.7
244	31Mar92	303.0	7.8	12.4	745	109.4	110.5	106.0	1.0	70	60.7	9.3	2.8	1.0	109.4	85.4	70	-139.6	643.4	163.7	3.9
245	14Apr92	192.6	10.1	11.4	746	107.6	109.0	102.9	1.1	57	52.5	4.5	2.2	0.8	107.6	88.5	57	-104.8	634.8	158.9	4.0
246	28Apr92	699.5	10.0	11.2	743	104.3	105.1	101.6	1.0	32	29.6	2.4	4.0	0.4	104.3	74.7	32	-262.1	609.6	156.1	3.9
247	05May92	489.9	15.0	11.3	751	106.5	104.9	113.3	0.9	49	28.5	20.5	3.6	0.7	106.5	78.8	49	-215.6	612.1	175.2	3.5
248	26May92	169.9	18.5	10.4	748	107.1	105.9	112.4	0.9	53	34.0	19.0	2.1	0.7	107.1	88.8	53	-101.2	612.6	172.4	3.6
249	09Jun92	123.2	19.0	6.7	745	105.8	114.4	73.8	1.6	43	82.9	-39.9	1.7	0.6	105.8	90.6	43	-81.8	658.8	112.7	5.8
250	23Jun92	300.2	23.5	6.8	737	105.2	111.2	83.1	1.3	38	63.3	-25.3	2.8	0.5	105.2	82.2	38	-167.5	628.7	124.6	5.0
251	30Jun92	113.3	23.2	7.7	739	106.5	110.5	92.4	1.2	48	59.4	-11.4	1.6	0.7	106.5	91.5	48	-73.1	626.7	139.0	4.5
252	07Jul92	110.2	24.0	7.5	741	105.3	109.3	91.2	1.2	39	52.3	-13.3	1.6	0.5	105.3	90.9	39	-78.4	620.4	137.2	4.5
253	21Jul92	450.3	23.5	7.0	747	106.7	112.8	84.6	1.3	50	73.4	-23.4	3.5	0.7	106.7	79.4	50	-206.8	646.7	128.6	5.0
254	28Jul92	433.3	24.0	7.9	744	107.4	110.7	96.3	1.1	55	60.7	-5.7	3.4	0.7	107.4	80.1	55	-198.1	631.1	145.5	4.3
255	13Oct92	203.9	15.4	10.2	739	107.3	108.2	104.6	1.0	54	47.0	7.0	2.3	0.7	107.3	87.3	54	-115.1	620.8	159.1	3.9

Date	Flow (m3/s)	Temp (C)	D.O. (mg/l)	P bar (mmHg	Total gas pressure (%) TGP (%)	N2P (%)	O2P (%)	(%) N2/O2 Ratio	Delta P (mmHg)	Delta N2 (mmHg	Delta O2 (mmHg	Max Depth (m)	Comp Depth (m)	TGP (%)	TGPun (%)	Delta P (mmHg)	Punc (mmHg	Partial Pressure PP N2	PP O2	N2/O2
SUMMARY STATISTICS																				
COUNT	255	255	255	255	255	255	255	255	255	255	255	255	255.0	255	255	255	255	255	255	255
MINIMUM	8.5	0.0	5.6	727.6	98.7	99.9	70.6	0.6	-10	-0.5	-44.2	0.5	-0.1	98.7	74.7	-10	-262.1	576.4	106.4	2.2
MAXIMU	1132.8	31.4	17.5	755.0	132.1	138.4	184.8	1.7	237	217.2	125.7	4.2	3.2	132.1	120.3	237	158.4	783.2	273.8	6.5
MEAN	222.9	16.4	10.8	742.9	116.1	118.6	108.8	1.1	120	106.5	13.4	2.0	1.6	116.1	97.9	120	-27.4	681.1	165.6	4.2
STD DEV	228.4	9.1	2.7	4.6	6.6	7.1	16.7	0.2	49.2	40.2	25.4	1.1	0.7	6.6	11.6	49.2	106.5	37.8	25.3	0.7

P bar - barometric pressure at Des Moines corrected for elevation
TGP - total gas pressure, in percent of saturation
N2P - nitrogen gas pressure, in percent of saturation
O2P - oxygen gas pressure, in percent of saturation

* indicates fish kill events associated with gas bubble disease

APPENDIX D: AN EXAMPLE OF A COMPLETED EXAMINATION DATA SHEET USED TO COLLECT INFORMATION ON CHRONIC GAS BUBBLE TRAUMA

INDIVIDUAL FISH EXAMINATION FOR EVIDENCE OF GAS BUBBLE DISEASE

Station 9 Fish Number 3 Date Collected 25 May 89 Inititals DSL

Location collected ______ Time ______ Time examined ______

Fish species Buffalo spp.

1. Total length 320 mm (12.6")

2. Presence of emphysema (gas blisters in tissue) and petechial hemorrhages

a. Emphysema: (Yes) NO	Hemorrhages: YES NO	Severity mild moderate severe

b. Location, size • ∞ •=A; o - O = B; O··O=C; > O=D, and number

X buccal cavity (mouth) hemorrhages roof of mouth ______

-- premaxilla (upper lip) ______ mandible (lower lip) ______

-- isthmus ______ preopercule ______

X operculum 10A-B each side hemorrh. cheek ______ nuchal region ______

X head 1B near eye snout ______ occiput ______

X fins: X caudal 5A dorsal hemorrhages

X pelvic 3A X anal 10A X pectoral 3A

-- scale pockets ______ lateral line ______

-- caudal peduncle ______

X body 5C-D between pelvic fins breast ______

-- belly ______

-- between pectoral fins ______

-- other ______ describe ______

3. X Exophthalmia ("pop-eye")

a. X (yes) ______ none apparent ______

b. right ______ (left) ______ both ______

c. missing eye ______ blind or damaged ______

d. gas blisters present no

4. X Secondary infection

a. fin erosion YES what fin caudal, anal, dorsal

b. degree of degeneration: (mild), (moderate), severe

5a. X Evidence of former lesions yes (pocked appearance)

a. location caudal fin

b. degree of severity - (mild), moderate or severe

6 General degree of external signs of gas bubble disease

a. minor - only a few small to moderate bubbles

b. (moderate) - moderate to large bubbles in several locations, secondary infection or fin erosion may be present

c. severe - large to extremely large bubbles are present at several locations, fin erosion and/or secondary infection is present, bubbles may be interfering with fish function (ie. equilbrium, feeding, fin function, etc.)

5b. Presence of ectoparasites: YES NO if yes, how many ______ where ______

APPENDIX E: GAS SUPERSATURATION AND GAS BUBBLE TRAUMA LITERATURE

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Adair, W.D. and J.J. Hains. 1974. Saturation values of dissolved gases associated with the occurrence of gas-bubble disease in fish in a heated effluent. Pages 59-77 in Gibbons, J.W. and R.R. Sharitz. Thermal Ecology. United States Atomic Energy Commission Contract 030505, Washington, D.C.

Adams, W.A., editor. 1975. Chemistry and physics of aqueous gas solutions. The Electrochemical Society, Princeton, New Jersey.

Alderdice, D.F. and J.O.T. Jensen. 1985. Assessment of the influence of gas supersaturation on salmonids in the Nechako River in relation to Kemano completion. Canadian Technical Report Fisheries and Aquatic Sciences. No. 1386.

Alderdice, D.F. and J.O.T. Jensen. 1985. An explanation for the high resistance of incubating salmonid eggs to atmospheric gas supersaturation of water. Aquaculture 49:85-88.

(APHA) American Public Health Association, American Water Works Association and Water Pollution Control Federation. 1989. Section 2810: Dissolved gas supersaturation *in* Standard Methods for the Examination of Water and Wastewater. American Public Health Association, Washington, D.C.

American Public Health Association, American Water Works Association and Water Pollution Control Federation. 1989. Section 4500-O: Oxygen (Dissolved) *in* Standard Methods for the Examination of Water and Wastewater. American Public Health Association, Washington, D.C.

Bagarinao, T. and P. Kungvankji. 1986. An incidence of swimbladder stress syndrome in hatchery-reared sea bass (*Lates calcarifer*) larvae. Aquaculture 51:181-188.

Baath, C., Bauer, K., Weikel, J., Wiedemann, H. and Wizigmann, G. 1989. Influence of gas supersaturation of water on infectious diseases of rainbow trout. *in* Lillelund, K. and H. Rosenthal, editors. Fish health protection strategies. Bundesministerium Forshung und Technologie, Bonn, West Germany.

Beck, A.P., G.V. Poje, and W.T. Waller. 1975. A laboratory study on the effects of the exposure of some entrainable Hudson River biota to hydrostatic pressure regimes calculated for the proposed Cornwall pumped-storage plant. Pages 167-172 *in* S.B. Salia, editor. 1975. Fisheries and energy production: A symposium. Lexington Books, D.C. Heath and Company, Lexington, Massachussets.

Beiningen, K.T. 1983. A manual for measuring dissolved oxygen and nitrogen gas concentrations in water with the Van Slyke-Neill apparatus. Fish Commission of Oregon, Portland, Oregon.

Benson, B.B. and D. Krause, Jr. 1984. The concentration and isotopic fractionation of oxygen dissolved in freshwater and seawater in equilibrium with the atmosphere. Limnology and Oceanography 29(3):620-632.

Bentley, W.W., E.M. Dawley and T.W. Newcomb. 1976. Some effects of excess dissolved gas on squawfish (*Ptychocheilus oregonensis* Richardson). Pages 41-46 *in* Fickeisen, D.H. and M.J. Schneider, editors. 1976. Gas bubble disease. CONF-741033, Technical Information Center, Energy Research and Development Administration, Oak Ridge, Tennessee.

Bell, T.G., A.L. Trapp, J.P. Machado, and D.L. Garling, Jr. 1985. A method for rapid fixation for preservation of tissue emphysema: diagnosis of gas bubble disease in hatchery reared rainbow trout. Proceedings of the annual meeting, American Association of Veterinary Laboratory Diagnosticians 28:81-85.

Bensen, B.B. and D. Krause. 1984. The concentration and isotopic fractionation of oxygen dissolved in freshwater and seawater in equilibrium with the atmosphere. Limnology and Oceanography 29:620-632.

Bentley, W.W. and E.M. Dawley. 1981. Effects of supersaturated dissolved atmospheric gases on northern squawfish (*Ptychocheilus oregonensis*). Northwest Science 55:50-61.

Beyer, D., B.G. D'Aoust and L. Smith. 1976. Responses of coho salmon (*Oncorhynchus kisutch*) to supersaturation at one atmosphere. Pages 47-50 *in* Fickeisen, D.H. and M.J. Schneider, editors. 1976. Gas bubble disease. CONF-741033, Technical Information Center, Energy Research and Development Administration, Oak Ridge, Tennessee.

Bisker, R. and M. Castagna. 1987. The effect of air-supersaturated sea-water on *Argopecten irradians* (Lamarck) and *Crassostrea virginica* (Gmelin) with reference to gas bubble trauma. Journal of Shellfish Research 7:150.

Blahm, T.H. 1974. Report to Corps of Engineers, gas supersaturation research. Prescott Facility-1974. National Marine Fisheries Service, Northwest Fisheries Center, Seattle, Washington.

Blahm, T.H., B. McConnell, G.R. Snyder. 1976. Gas supersaturation research at the National Marine Fisheries Service Prescott Facility, 1971-1974, Pages 11-19 *in* Fickeisen, D.H. and M.J. Schneider, editors. 1976. Gas bubble disease. CONF-741033, Technical Information Center, Energy Research and Development Administration, Oak Ridge, Tennessee.

Bouck, G.R. 1976. Supersaturation and fishery observations in selected alpine Oregon streams. Pages 37-40 *in* Fickeisen, D.H. and M.J. Schneider, editors. 1976. Gas bubble disease. CONF-741033, Technical Information Center, Energy Research and Development Administration, Oak Ridge, Tennessee.

Bouck, G.R., G.A. Chapman, P.W. Schneider, Jr. and D.G. Stevens. 1976. Observations on gas bubble disease among wild adult Columbia River fishes. Transactions of the American Fisheries Society 105:114-115.

Bouck, G.R., A.V. Nebeker, and D.G. Stevens. 1976. Mortality, saltwater adaption, and reproduction of fish during gas supersaturation. United States Environmental Protection Agency Technical Report, EPA 600/3-76-050.

Bouck, G.R. 1979. A synopsis of effects of supersaturation on fish. Pages 2-3 *in* Proceedings, Symposium on Reaeration Research, American Society of Civil Engineers.

Bouck, G.R. 1980. Etiology of gas bubble disease. Transactions of the American Fisheries Society 109:703-707.

Bouck, G.R., B. D'Aoust, W.J. Ebel and R. Rulifson. 1980. Atmospheric gas supersaturation: educational and research needs. Transactions of the American Fisheries Society 109:769-771.

Bouck, G.R. 1982. Gasometer: an inexpensive device for continuous monitoring of dissolved gases and supersaturation. Transactions of the American Fisheries Society 111:505-516.

Bouck, G.R. and R.E. King. 1983. Tolerance to gas supersaturation in fresh water and sea water by steelhead trout (*Salmo gairdneri* Richardson). Journal of Fish Biology 23(3):293-300.

Bouck, G.R. 1984. Annual variation of gas supersaturation in four spring-fed Oregon streams. Progressive Fish-Culturist 46(2):139-140.

Bouck, G.R., R.E. King, and G. Bouck-Schmidt. 1984. Comparative removal of gas supersaturation by plunges, screens and packed columns. Icicleture Engineering 3:159-176.

Bowser, P.R., R. Toal, H.R. Robinette and M.W. Brunson. 1983. Coelomic distension in channel catfish fingerlings. Progressive Fish-Culturist 45:208-209.

Bratby, J. and G.V.R. Marais. 1975. Saturator performance in dissolved-air (pressure) flotation. Water Research 9: 929-936.

Brisson, S. 1985. Gas-bubble disease observed in pink shrimp, Penaeus brasiliensis and Penaeus paulensis. Aquaculture 47:97-99.

Chamberlain, G.W., W.H. Neill, P.A. Romanowsky, and K. Strawn. 1980. Vertical responses of Atlantic croaker to gas supersaturation and temperature change. Transactions of the American Fisheries Society 109:737-750.

Clay, A., A. Baker, S. Testaverde, R. Marcello and G.C. McLeod. 1976. Observations on the effects of gas embolism in captured adult menhaden. Pages 81-84 *in* Fickeisen, D.H. and M.J. Schneider, editors. 1976. Gas bubble disease. CONF-741033, Technical Information Center, Energy Research and Development Administration, Oak Ridge, Tennessee.

Colt, J. 1983. The computation and reporting of dissolved gas levels. Water Research 17:841-849.

Colt, J. 1984. Computation of dissolved gas concentrations in water as functions of temperature, salinity and pressure. American Fisheries Society Special Publication 14. Bethesda, Maryland.

Colt, J. 1984. Seasonal changes in dissolved gas supersaturation in the Sacramento River and possible effects on the striped bass. Transactions of the American Fisheries Society 113:655-665.

Colt, J. 1991. Gas supersaturation in the American River. California Fish and Game 77:41-51.

Colt, J. and H. Westers. 1982. Production of gas supersaturation by aeration. Transactions of the American Fisheries Society 111:342-360.

Colt. J. and G. Bouck. 1984. Design of packed columns for degassing. Aquaculture Engineering 3:251-273.

Colt, J., K. Orwicz, and D. Brooks. 1984. Effects of gas-supersaturated water on *Rana catesbeiana* tadpoles. Aquaculture 38:127-136.

Colt, J., K. Orwicz and D. Brooks. 1984. Gas bubble disease in African clawed frog (*Xenopus laevis*). Journal of Herpetology 18:131-137

Colt, J., K. Orwicz, and D. Brooks. 1985. Impact of gas supersaturation on the growth of juvenile channel catfish, *Ictalurus punctatus.* Aquaculture 50:153-160.

Colt, J., G. Bouck and L. Fidler. 1986. Review of current literature and research on gas supersaturation and gas bubble trauma. American Fisheries Society, Bioengineering Section. Special Publication Number 1.

Colt, J. and K. Orwicz. 1988. Influence of water source, treatment and distribution ion the variation of dissolved gas levels in municipal water systems. Aquaculture Engineering 7:1-19.

Cornacchia, J.W. and J.E. Colt. 1984. The effects of dissolved gas supersaturation on larval striped bass (*Morone saxatilis*). Journal of Fish Diseases 7:15-27.

Coutant, C.C. and R.G. Genoway. 1968. Final report on an exploratory study of interaction of increased temperature and nitrogen supersaturation on mortality of adult salmonids. Battelle Memorial Institute, Pacific Northwest Laboratory, Richmond, Washington.

Craig, H., R.A. Wharton, C.P. McKay, Jr. 1992. Oxygen supersaturation in ice-covered Antartic lakes: biological versus physical contributions. Science 255:318-321.

Crunkilton, R.L., J.M. Czarnezki, and L. Trial. 1980. Severe gas bubble disease in the midwestern United States. Transactions of the American Fish Society 109:725-733.

D'Aoust, B.G. and M.J.R. Clark. 1980. Analysis of supersaturated air in natural waters and reservoirs. Transactions of the American Fisheries Society 109:708-724.

D'Aoust, B.G., L. Stayton and L.S. Smith. 1980. Separation of basic parameters of decompression using fingerling salmon. Undersea Biomedical Research 7:199-209.

D'Aoust, B.G. and L.S. Smith. 1974. Bends in fish. Comparative Biochemistry and Physiology, A, Comparative Physiology 49:311-321.

Davis, J.C. 1975. The exchange of oxygen at the gills of fish in response to oxygen availability. Pages 393-404 *in* Adams, W.A., editor. 1975. Chemistry and physics of aqueous gas solutions. The Electrochemical Society, Princeton, New Jersey.

Dawley, E.M. and W.J. Ebel. 1975. Effects of various concentrations of dissolved atmospheric gas on juvenile chinook salmon and steelhead trout. United States National Marine Fisheries Center, Seattle, Washington.

Dawley, E.M., M. Schiewe and B.H. Monk. 1976. Effects of long-term exposure to supersaturation of dissolved atmospheric gases on juvenile chinook salmon and steelhead trout in deep and shallow test tanks. Pages 1-10 *in* Fickeisen, D.H. and M.J. Schneider, editors. 1976. Gas bubble disease. CONF-741033, Technical Information Center, Energy Research and Development Administration, Oak Ridge, Tennessee.

DeMont, J.D. and R.W. Miller. 1972. First reported incidences of gas bubble disease in the heated effluent of a steam electric generating station. Proceedings of the Annual Conference, Southeastern Association of Game and Fish Commissioners 25:392-399.

Ebel, W.J. 1969. Supersaturation of nitrogen in the Columbia River and its effect on salmon and steelhead trout. United States National Marine Fisheries Service Fishery Bulletin 68:1-11.

Ebel, W.J., E.M. Dawley and B.H. Monk. 1971. Thermal tolerance of juvenile Pacific salmon and steelhead trout in relation to supersaturation of nitrogen gas. United States Fisheries Bulletin 69:833-843.

Ebel, W.J. and H.L. Raymond. 1976. Some experiments on the gas-disease in freshwater fishes. Bulletin of the Japanese Society of Scientific Fisheries 15: 83-87.

Edsall, D.A. 1991. Oxygen-induced gas bubble disease in rainbow trout, *Oncorhynchus mykiss* (Walbaum). Aquaculture and Fish Management 22:135-140.

Egusa, S. 1959. The gas bubble disease of fish due to excess of nitrogen. Animal Husbandry, Hiroshima University 2:157-182.

Elston, R. 1983. Histopathology of oxygen intoxication in the juvenile red abalone (*Haliotis rufescens* Swainson). Journal of Fish Diseases 6(3):101-110.

Embody, G.C. 1934. Relation of temperature to the incubation period of eggs of four species of trout. Transactions of the American Fisheries Society 64:281-292.

Epstein, P.S. and M.S. Plessat. 1950. On the stability of gas bubbles in liquid-gas solutions. Journal of Chemical Physics 18:1505-1509.

Fairbanks, R.B. abd R.P. Lawton. 1977. Occurrence of large striped mullet, *Mugil cephalus*, in Cape Cod Bay, Massachusetts. Chesapeake Science 18:309-310.

Fast, A.W. 1979. Nitrogen gas supersaturation during artificial aeration of Lake Casitas, California. The Progressive Fish-Culturist 41:153-155.

Feathers, M.G. and A.E. Knable. 1983. Effects of depressurization upon largemouth bass. North American Journal of Fish Management 3:86-90.

Fickeisen, D.H., J.C. Montegomery and M.J. Schneider. 1973. Tolerance of selected fish species to atmospheric gas supersaturation. 103rd meeting of the American Fisheries Society, September 10-12, 1973. Orlando, Florida. BNWL-SA-4794.

Fickeisen, D.H., M.J. Schneider and J.C. Montegomery. 1975. A comparative evaluation of the Weiss saturometer. Transactions of the American Fisheries Society 104:816-820.

Fickeisen, D.H. and M.J. Schneider,editors. 1976. Gas bubble disease. CONF-741033, Technical Information Center, Energy Research and Development Administration, Oak Ridge, Tennessee.

Fickeisen, D.H., J.C. Montegomery and R.W. Hanf, Jr. 1976. Effect of temperature on tolerance to dissloved gas supersaturation of black bullhead (*Ictalurus melas*). Pages 72-74 *in* Fickeisen, D.H. and M.J. Schneider, editors. 1976. Gas bubble disease. CONF-741033, Technical Information Center, Energy Research and Development Administration, Oak Ridge, Tennessee.

Fidler, L.E. 1984. A Study of biophysical phenomena associated with gas bubble trauma in fishes. Penny Applied Science, Ltd., Box 337, Valemount, BC VOC 2Z0. Contractors report to the Department of Fisheries and Oceans, Salemonid Enhancement Program, Vancouver, British Columbia, Canada.

Jones, D. and D.H. Lewis. 1976. Gas bubble disease in fry of channel catfish. Progressive Fish-Culturist 38:41.

Fox, F.E. and K.F. Herzfeld. 1954. Gas bubbles with organic skin as cavitation nuclei. Journal of Acoustical Society of America 26:984-989.

Fuss, J.T. 1983. Effective flow-through vacuum degasser for fish hatcheries. Aquaculture Engineering 2:301-307.

Gibbons, J.W. and R.R. Sharitz, editors. 1974. Thermal ecology. CONF-730505, United States Environmental Protection Agency, Washington D.C., District of Columbia.

Gray, R.H., T.L. Page and M.G. Saroglia. 1983. Behavioral response of carp, *Cyprinus carpio*, and black bullhead, *Ictalurus melas*, from Italy to gas supersaturated water. Environmental Biology of Fishes 8:163-167.

Gray, R.H., T.L. Page, M.G. Saroglia and P. Bronzi. 1982. Comparative tolerance to gas supersaturated water of carp (*Cyprinus carpio*) and black bullhead (*Ictalurus melas*) from the United States and Italy. Journal of Fish Biology 10:223-227.

Gray, R.H., T.L. Page, M.G. Saroglia and V. Festa. 1983. Tolerance of carp (*Cyprinus carpio*) and black bullhead (*Ictalurus melas*) from Italy to gas supersaturated water. Env. Biol. Fish. 8(2):163-167.

Gray, R.H., M. F. Saroglia, and G. Scarano. 1985. Comparative tolerance to gas supersaturated water of two marine fishes, *Dicentracharus labrax* and *Mugil cephalus*. Aquaculture 48:83-89.

Hartman, J. 1983. Performance and operation of Alaska Department of Fish and Game screen decks. Pages 9/1-9/7 *in* Gas supersaturation in hatcheries-causes, effects and solutions, Bio-technology Sections, American Fisheries Society, Milwaukee, Wisconsin.

Harvey, H.H. 1975. Gas disease in fishes - a review. Pages 450-485 *in* Adams, W.A., editor. 1975. Chemistry and physics of aqueous gas solutions. The Electrochemical Society, Princeton, New Jersey.

Harvey, H.H. and A.C. Cooper. 1962. Origin and treatment of supersaturated river water. Progess Report 9, International Pacific Salmon Fisheries Commission, Vancouver, Canada.

Harvey, H.H. and S.B. Smith. 1961. Supersaturation of the water supply and occurrence of gas bubble disease at Cultus Lake Trout Hatchery. Canadian Fish Culturist 30:39-46.

Harvey, E.N., D.K. Barnes, W.D. McElroy, A.H. Whiteley, D.C. Pease, and K. W. Cooper. 1944. Bubble formation in animals. Journal of Cellular and Comparative Physiology 24:1-24.

Hauck, K. 1986. Gas bubble disease due to helicopter transport of pink salmon. Transactions of the American Fisheries Society 115:630-635.

Hemmingsen, B.B. 1986. Promotion of gas bubble formation by ingested nuclei in the ciliate, *Tetrahymena pyriformis*. Cell Biophysics 8:189-200.

Hemmingsen, B.B., N.A. Steinberg, and E.A. Hemmingsen. 1985. Intracellular gas supersaturation tolerances of erythrocytes and research ghosts. Biophysics Journal 47:491-496.

Hemmingsen, E.A. 1970. Supersaturation of gases in water: absence of cavitation on decompression from high pressure. Science 167:1493-1494

Henly, E. 1952. The influence of the gas content of sea-water on fish and fish-larvae. Rapports et Proces-verbaux des Reunions, Conseil International pour l'Exploration de la Mer 131(3):24-27.

Hlastala, M.P. and L.E. Fahri. 1973. Adsorption of gas bubbles in flowing blood. Journal of Applied Physiology 35:311-316.

Hsieh, D.Y. 1965. Some analytical aspects of bubble dynamics. Journal of Basic Engineering, Transactions of the American Society of Mechanical Engineers 87:991-1005.

Jarnefelt, V.H. 1948. Der Einfluss der Stromschnellen auf den Sauerstoff und Kohlensauregehalt und das pH des Wassers im Flusse Vuoski. International Association of Theoretical and Applied Limnological Proceedings 10:210-215.

Jensen, L.D. 1974. Environmental response to thermal discharges from Marshall Steam Station, Lake Norman, North Carolina. Report to Electric Power Research Institute and Duke Power Company, Raleigh, North Carolina.

Jensen, J.O.T., A.N. Halley and J. Schnute. 1985. Literature data on salmonid response to gas supersaturation and ancillary factors. Canadian Data Report of Fisheries and Aquatic Sciences No. 151.

Jensen, J.O.T., J. Schnute and D.F. Alderice. 1986. Assessing juvenile salmonid response to gas supersaturation using a general multivariate dose-response model. Canadian Journal of Fisheries and Aquatic Sciences 43:1694-1709.

Jones, D. and D.H. Lewis. 1976. Gas bubble disease in fry of channel catfish (*Ictalurus punctatus*). Progressive Fish-Culturist 38:41.

Johnson, P.L. and D.L. King. 1979. Prediction of dissolved gas at hydraulic structures. Symposium on Reaeration Reserach, American Society of Civil Engineers, New York, New York.

Klots, C.E. 1980. Effects of hydrostatic pressure upon the solubility of gases. 1961. Limnology and Oceanography 6:365-366.

Knittel, M.D., G.A. Chapman and R.R. Garton. 1980. Effects of hydrostatic pressure on steelhead survival in air supersaturated water. Transactions of the Amercan Fisheries Society 109:755-759.

Krise, W.F. and J.W. Meade. 1988. Effects of low level gas supersaturation on lake trout (*Salvelinus namaycush*). Canadian Journal of Fisheries and Aquatic Sciences 43:1694-1709.

Krise, W.F. and R.L. Herman. 1989. Tolerance of lake trout, *Salvelinus namaycush* (Walbaum) sac fry to dissolved gas supersaturation. Journal of Fish Diseases 12:269-273.

Krise W.F. and R.A. Smith. 1991. Tolerance of juvenile lake trout exposed to gas supersaturation. Progressive Fish-Culturist 53:17-20.

Kulshrestha, A.K. and P.K. Mandal. 1982. Pathology of gas bubble disease in two air-breathing catfish (*Clarias batrachus* Linn. and *Heteropneustes fossilis* Bloch.) Aquaculture 27:13-17.

Legg, D.L. 1978. Gas supersaturation problem in the Columbia River basin. Pages 149-164 *in* U.S. Committee on the environmental effects of Large Dams. American Society of Engineers, New York, New York.

Lindroth, A. 1957. Abiogenic gas supersaturation of river water. Archiv fur Hydrobiologie 53:589-597.

Lund, M. and T.G. Heggberget. 1985. Avoidance response of two-year-old rainbow trout (*Salmo gairdneri* Richardson) to air-supersaturated water: hydrostatic compensation. Journal of Fish Biology 26:193-200.

MacDonald, J.R. and R.A. Hyatt. 1973. Supersaturation of nitrogen in water during passage through hydroelectric turbines at Mactaquac Dam. Journal of the Fisheries Research Board of Canada 30(9): 1392-1394.

MacDonald, R.W. and C.S. Wong. 1975. Factors influencing the degree of saturation of gases in seawater. Pages 214-223 *in* Adams, W.A.,editor. 1975. Chemistry and physics of aqueous gas solutions. The Electrochemical Society, Princeton, New Jersey.

Malouf, R., R. Keck, D. Maurer and C. Epifanio. 1972. Occurrence of gas-bubble-disease in three species of bivalve molluscs. Journal of the Fisheries Research Board of Canada 29:588-589.

Marcello, R.A., Jr. and R.B. Fairbanks. 1976. Gas bubble disease mortality of atlantic menhaden (Brevoortia tyrannus) at a coastal nuclear power plant. Pages 75-80 *in* Fickeisen, D.H. and M.J. Schneider, editors. 1976. Gas bubble disease. CONF-741033, Technical Information Center, Energy Research and Development Administration, Oak Ridge, Tennessee.

Marking, L.L., V.K. Dawson and J.R. Crowther. 1983. Comparison of column aerators and a vacumn degasser for treating supersaturated culture water. Progressive Fish-Culturist 45:81-83.

Marsh, M.C. 1903. A fatality among fishes in water containing an excess of dissolved air. Transactions of the American Fisheries Society 32:192-193.

Marsh, M.C. and F.P. Gorham. 1905. The gas disease in fishes. Report of the United States Bureau of Fisheries (1904):343-376.

Marshall, W. 1976. Equipment and techniques for monitoring the vertical distribution of fish in shallow water. Pages *in* Fickeisen, D.H. and M.J. Schneider, editors. 1976. Gas bubble disease. CONF-741033, Technical Information Center, Energy Research and Development Administration, Oak Ridge, Tennessee.

Mathias, J.A. and J. Barica. 1985. Gas supersaturation as a cause of early spring mortality of stocked trout. Canadian Journal of Fisheries and Aquatic Sciences 42:268-279.

May, B. 1973. Evaluation on the effects of gas bubble disease on fish populations in the Kootenai River below Libbey Dam. Proceedings of the 53rd Annual Conference, Western Association of State Fish and Game Commissioners: 525-540.

McLeod, G.C. 1978. The gas bubble disease of fish. Pages 319-339 *in* Mostofsky, D.I., editor. 1978. The behavior of fish and other aquatic animals. Academic Press. New York, NY.

McDonough, P.M. and E.A. Hemmingsen. 1985. Swimming movements initiate bubble formation in fish decompressed from elevated gas pressures. Comparative Biochemistry and Physiology 81(A):209-212.

Meekin, T.K. 1971. Levels of nitrogen supersaturation at Chief Joesph Dam under various spill conditions, phase 1. Report to United States Army Corps of Engineers, Contract NPSSU-71-796, Washington Department of Fisheries, Olympia, Washington.

Meekin, T.K. and R.L. Allen. 1974. Nitrogen gas levels in the mid-Columbia River , 1965-1971. Washington Department of Fisheries Technical Report 12:32-77.

Meekin, T.K. and B.K. Turner. 1974. Tolerance of salmonid eggs, juveniles and squawfish to supersaturated nitrogen. Washington Department of Fisheries Technical Report 12:127-153.

Meldrin, J.W., J.J. Gilt and B.R. Petrosky. 1974. The effects of temperature and chemical pollutants on the behavior of several estuarine organisms. Ichthyological Association Bulletin No. 11.

Miller, R.W. 1974. Incidence and cause of gas bubble disease. Pages 79-93 *in* J.W. Gibbons and R.R. Sharitz, editors. 1974. Thermal ecology. CONF-730505, United States Environmental Protection Agency, Washington D.C., District of Columbia.

Montegomery, J.C. and C.D. Becker. 1980. Gas bubble disease in smallmouth bass and northern squawfish from the Snake and Columbia rivers. Transactions of the American Fisheries Society 109:734-736.

National Academy of Science/National Academy of Engineering. 1972. Total Dissolved Gases (Supersaturation). Pages 135-139 *in* National Academy of Science/National Academy of Engineering, Water Quality Criteria. A Report to the Committee on Water Quality Criteria. EPA-R3-73-033.

Nebeker, A.V. 1976. Survival of *Daphnia*, crayfish and stoneflies in air supersaturated water. Journal of the Fisheries Research Board of Canada 33:1208-1212.

Nebeker, A.V., D.G. Stevens and J.R. Brett. 1976. Effects of gas supersaturated water on freshwater aquatic invertebrates. Pages 51-65 *in* Fickeisen, D.H. and M.J. Schneider, editors. 1976. Gas bubble disease. CONF-741033, Technical Information Center, Energy Research and Development Administration, Oak Ridge, Tennessee.

Nebeker, A.V., G.R. Bouck and D.G. Stevens. 1976. Carbon dioxide and oxygen-nitrogen ratios as factors affecting salmon survival in air-supersaturated water. Transactions of the American Fisheries Society 105:425-429.

Nebeker, A.V. and J.R. Brett. 1976. Effects of air supersaturated water on survival of pacific salmon and steelhead smolts. Transactions of the American Fisheries Society 105:338-342.

Nebeker, A.V., A.K. Hauck and F.D. Baker. 1979. Temperature and oxygen-nitrogen gas ratios affect fish survival in air-supersaturated water. Water Research 13:299-303.

Nebeker, A.V., A.K. Hauck, F.D. Baker and S.L. Weitz. 1980. Comparative responses of speckled dace and cutthroat trout to air-supersaturated water. Transactions of the American Fisheries Society 109:760-764.

Newcombe, T.W. 1976. Changes in blood chemistry of juvenile steelhead (*Salmo gairdneri*) following sublethal exposure to nitrogen supersaturation. Pages 96-100 *in* Fickeisen, D.H. and M.J. Schneider, editors. 1976. Gas bubble disease. CONF-741033, Technical Information Center, Energy Research and Development Administration, Oak Ridge, Tennessee.

Pauley, G.B. and R.E. Nakatani. 1967. Histopathology of "gas bubble" disease in salmon fingerlings. Journal of the Fisheries Research Board of Canada 24:867-871.

Penney, G.H. 1987. Dissolved oxygen and nitrogen concentrations in Mactaquac area waters, 1968, 1969 and 1972. Canadian Manuscript Reports of Fisheries and Aquatic Sciences 1906.

Petterson, S. 1981. Supersaturation in water from Norwegian hydro-electric power station. Pages 95-101 *in* Tiews, K., editor. Aquaculture in heated effluents and recirculation systems. Heenemann Werlagsgesellschaft mbH, Berlin.

Philp, B., M.J. Inwood, and B.A. Warren. 1972. Interactions between gas bubbles and components in the blood: implications in decompression sickness. Aerospace Medicine 43:946-953.

Post, G.W. 1983. Chapter XII, Diseases of miscellaneous origin. Pages 247-252 *in* Textbook of Fish Health. T.F.H. Publications Inc. Ltd., Neptune City, New Jersey.

Renfro, W.C. 1963. Gas-bubble mortality of fishes in Galveston Bay, Texas. Transactions of the American Fisheries Society 92:320-322.

Richardson, G.C. and R. Baca. 1976. Physics of dissolved gases and engineering problems, roundtable discussion. Pages 118-119 *in* Fickeisen, D.H. and M.J. Schneider, editors. 1976. Gas bubble disease. CONF-741033, Technical Information Center, Energy Research and Development Administration, Oak Ridge, Tennessee.

Rucker, R. 1972. Gas bubble disease of salmonids: a critical review. U.S. Bureau of Sport Fisheries and Wildlife. Technical Paper 58.

Rucker, R.R. 1976. Gas bubble disease of salmonids: variation in oxygen-nitrogen ratio with constant gas pressure. Pages 85-88 *in* Fickeisen, D.H. and M.J. Schneider, editors. 1976. Gas bubble disease. CONF-741033, Technical Information Center, Energy Research and Development Administration, Oak Ridge, Tennessee.

Rucker, R.R. 1976. Gas bubble disease of coho salmon (*Oncorhynchus kisutch*) in water with constant total gas pressure and different oxygen-nitrogen gas ratios. U.S. National Marine Fisheries Service, Fisheries Bulletin 73:915-918.

Rulifson, R.L. and R. Pine. 1976. Water quality standards. Page 120 *in* Fickeisen, D.H. and M.J. Schneider, editors. 1976. Gas bubble disease. CONF-741033, Technical Information Center, Energy Research and Development Administration, Oak Ridge, Tennessee.

Salia, S.B., editor. 1975. Fisheries and energy production: A symposium. Lexington Books, D.C. Heath and Company, Lexington, Massachussets.

Schiewe, M.H. 1974. Influence of dissolved atmospheric gas on swimming performance of juvenile chinook salmon. Transactions of the American Fisheries Society 103:717-721.

Schiewe, M.H. and D.D. Weber. 1976. Effect of gas bubble disease on lateral line function in juvenile steelhead trout. Pages *in* Fickeisen, D.H. and M.J. Schneider, editors. 1976. Gas bubble disease. CONF-741033, Technical Information Center, Energy Research and Development Administration, Oak Ridge, Tennessee.

Schneider, M.J. and B.G. D'Aoust. 1976. Analytical methods. Pages 116-117 *in* Fickeisen, D.H. and M.J. Schneider, editors. 1976. Gas bubble disease. CONF-741033, Technical Information Center, Energy Research and Development Administration, Oak Ridge, Tennessee.

Schnute, J., J.O.T. Jensen and D.F. Alderice. 1984. Assessing salmonid response to gas supersaturation with a new multivariate dose-response model. Abstracts of papers presented at 11th annual aquatic toxicity workshop, Richmond, British Columbia, Canada, November 13-15.

Scholander, P.F., L. VanDam, C.L. Claff, and W. Kanwisher. 1955. Micro-gasometric determination of dissolved oxygen and nitrogen. Biological Bulletin 109:328-334.

Shrimpton, J.M. 1990. Factors affecting swim bladder volume in rainbow trout (*Oncorhynchus mykiss*) held in gas supersaturated water. Canadian Journal of Zoology 68:962-968.

Smith, C.E. 1988. Histopathology of gas bubble disease in juvenile rainbow trout. Progressive Fish-Culturist 50:98-103.

Smith, H.A., Jr. 1974. Spillway redesign abates gas supersaturation in Columbia River. Civil Engineering 144:70-73.

Smith, P.M. 1976. Spillway modification to reduce gas supersaturation. Pages 667-671 in Symposium on inland waterways for navigation, flood control and water diversions. Volume 1. American Society of Civil Engineering. New York, New York.

Snieszko, S.F. and H.R. Axelrod. 1976. Section D: Dissolved gases (gas bubble disease) *in* Environmental Stress and Fish Diseases. T.H.F. Publications, Inc. Ltd.

Stevens, D.G., A.V. Nebeker and R.J. Baker. 1980. Avoidance responses of salmon and trout to air-supersaturated water. Transactions of the American Fisheries Society 109:751-754.

Stickney, A.P. 1968. Supersaturation of atmospheric gases in coastal water of the Gulf of Maine. United States Fish and Wildlife Service Fisheries Bulletin 67:117-123.

Stroud, R.K., G.R. Bouck and A.V. Nebeker. 1975. Pathology of acute and chronic exposure of salmonid fishes to supersaturated water. Pages 435-449 *in* Adams, W.A., editor. 1975. Chemistry and physics of aqueous gas solutions. The Electrochemical Society, Princeton, New Jersey.

Stroud, R.K. and A.V. Nebeker. 1976. A study of the pathogenics of gas bubble disease in steelhead trout (*Salmo gairdneri*). Pages 66-71 *in* Fickeisen, D.H. and M.J. Schneider, editors. 1976. Gas bubble disease. CONF-741033, Technical Information Center, Energy Research and Development Administration, Oak Ridge, Tennessee.

Supplee, V.C. and D.V. Lightner. 1976. Gas bubble disease due to oxygen supersaturation in raceway-reared california brown shrimp. Progressive Fish-Culturist 38:158-159.

Tucker, C.S. 1989. Gas supersaturation in Mississippi channel catfish hatcheries. Research Report of the Mississippi Agricultural and Forestry Experiment Station 14(21).

U.S. Committee on the environmental effects of Large Dams. Environmental effects of large dams. American Society of Engineers, New York, New York.

Van Slyke, D.D. 1934. Studies of gas and electrolyte equilibria in blood, XVIII: solubility and physical state of atmospheric nitrogen in blood cells and plasma. Journal of Biological Chemistry 105:571-580.

Weiss, R.F. 1970. The solubility of nitrogen, oxygen and argon in water and seawater. Deep Sea Research 17:721-735.

Weitkamp, D.E. 1976. Dissolved gas supersaturation: live cage bioassays at Rock Island Dam, Washington. Pages 24-36 *in* Fickeisen, D.H. and M.J. Schneider, editors. 1976. Gas bubble disease. CONF-741033, Technical Information Center, Energy Research and Development Administration, Oak Ridge, Tennessee.

Weitkamp, D.E. and M. Katz. 1977. Dissolved atmospheric gas supersaturation of water and the gas bubble disease of fish. Environmental Information Service Inc. Mercer, Island, Washington.

Weitkamp, D.E. and M. Katz. 1980. A review of dissolved gas supersaturation literature. Transactions of the American Fisheries Society 109:659-702.

Wharton, R.A. 1987. Perennial N_2 supersaturation in an Antarctic lake. Nature 325:343-344.

White, R.G., G. Phillips, G. Liknes, S. Sanford. 1986. The effects of supersaturation of dissolved gases on the fishery of the Bighorn River downstream of the Yellowtail Dam. 1985 Annual Report, Bureau of Reclamation, Missouri Basin, Montana Cooperative Fisheries Research Unit, Montana State University, Bozeman, Montana.

Wolke, R.E., and G.R. Bouck and R.K. Stroud. 1975. Gas bubble disease: a review in relation to modern energy production. Pages 239-265 *in* Salia, S.B., editor. 1975. Fisheries and energy production: A symposium. Lexington Books, D.C. Heath and Company, Lexington, Massachussets.

Woodbury, L.A. 1941. A sudden mortality of fishes accompanying a supersaturation of oxygen in Lake Waubesa, Wisconsin. Transactions of the American Fisheries Society 71:112-117.

Wright, P.B. and W.E. Mchean. 1985. The effects of aeration on the rearing of summer chinook fry (*Oncorhynchus tshawytscha*) at the Puntledge hatchery. Canadian Technical Report of Fisheries and Aquatic Science 1390.

Wyatt, E.J. and K.T. Beiningen. 1971. Nitrogen gas bubble disease related to a hatchery water supply from the forebay of a high head regulating dam. Research Reports of the Fish Commission of Oregon 3:3-12.

Yount, D.E. 1979. Application of a bubble formation model to decompression sickness in rats and humans. Aviation, Space and Environmental Medicine 50:44-50.