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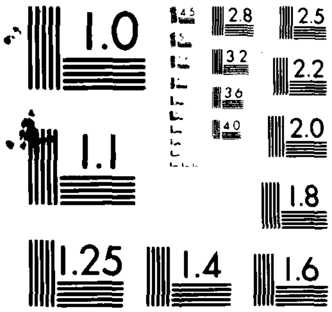

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INVESTIGATE THE POTENTIAL FOR NITROGEN SUPERSATURATION AT CLARENCE CANNON DAM AND RESERVOIR SALT RIVER, MISSOURI

A REPORT SUBMITTED TO
THE DEPARTMENT OF THE ARMY
ST. LOUIS DISTRICT, CORPS OF ENGINEERS

BY

THE INSTITUTE OF RIVER STUDIES
UNIVERSITY OF MISSOURI-ROLLA
ROLLA, MISSOURI 65401

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I. INTRODUCTION

The purpose of this investigation is to analyze the potential of the Clarence Cannon Dam and Reservoir to produce nitrogen supersaturation under any operating condition, including conditions during construction.

In order to effectively consider the potential for the dissolved nitrogen saturation problem at Cannon Dam, it is essential to establish a scientific basis for the problem. This was accomplished through comprehensive literature and computer data bank searches including a definition of the extent of knowledge.

The symptoms of what appears to have been Gas Bubble Disease (GBD) in aquatic organisms were first reported in the literature in the mid-nineteenth century (Hoppe-Seyler, 1857; Bert, 1873; Regnard, 1884). The first accurate description of GBD and its cause was given near the turn of the century in a series of papers reporting on air supersaturation problems at the Bureau of Fisheries station at Woods Hole (Gorham, 1889, 1901; Marsh, 1903, 1910; Marsh and Gorham, 1905). Details were given by these early scientists on the symptomatology, underlying causes, and physiology of this anomalous condition in fish. Indeed, Marsh and Gorham established the basic knowledge of GBD. Most subsequent investigations have only served to confirm and expand their early work.

The world wide literature dealing with GBD was recently reviewed critically by Weitkamp and Katz (1977), who have produced an excellent and authoritative compilation of information dealing with all aspects of the problem. From the historical record, the few scattered reports of GBD in the 40 to 50 years following the thorough work of Marsh and

Gorham added little of novelty or significance to our understanding of the problem. GBD received little more than minimal academic interest except for scattered reports of incidents of the condition in fish hatcheries throughout the world. The occurrence of GBD among juvenile fish in hatcheries is fairly common, and techniques have been proposed to effectively avoid or correct supersaturation problems on the small scale required for hatchery operation.

In the 1960's, interest in GBD was stimulated when the problem appeared on a much larger scale and with great consistency in the Columbia River system of the Pacific northwest, in the series of reservoirs, spillway basins and spawning channels constructed by the U.S. Army Corps of Engineers. Interest was further spurred in the 1970's as increased incidents (or perhaps increased awareness of the symptoms and diagnosis) of GBD was reported in association with supersaturation created by the heated effluents from power generating plants (Weitkamp and Katz, 1977).

In 1978 and 1979, GBD occurred at the construction site of the Harry S. Truman Dam near Warsaw, Missouri, where supersaturation in the stilling basin of an uncompleted spillway was blamed for the largest recorded fish kill in the history of the state according to the Missouri Conservation Commission. The magnitude of the problem at this particular locality, the surrounding circumstances, and the possibility that it may recur there or at other sites have prompted serious consideration of our current data base and knowledge. Concern for GBD has now spread from small hatcheries and isolated geographic areas where natural conditions are appropriate to cause the problem, to much broader geographic regions and situations of greater public interest and awareness.

II. ENVIRONMENTAL AND ENGINEERING ASPECTS OF SUPERSATURATION OF NITROGEN GAS AND GAS BUBBLE DISEASE

A. Current Understanding of Supersaturation of Nitrogen Gas (N_2) and Gas Bubble Disease (GBD)

The solubility of atmospheric gases in water is determined by the existing physical chemistry of the water, characteristics of the various gases in both the water and air, the total pressure and the temperature of the water.

Henry's Law states that the weight of any gas that dissolves in a given volume of a liquid, at constant temperature, is directly proportional to the pressure that the gas exerts above the liquid. Dalton's Law of Partial Pressures states that in a mixture of gases, each gas exerts pressure independently of the others. The partial pressure of each gas is proportional to the amount (percent by volume) of that gas in the mixture.

The solubility of gases in liquid is affected by temperature, as indicated in Figure 1. As the temperature of water increases, the volume of dissolved gas it can hold at equilibrium decreases. (International Critical Tables, also Harvey, 1975). At 1 atmosphere pressure, the nitrogen solubility data can be described by the mathematical relationship:

$$C_s = 23 - 0.55808\ T + 0.00763\ T^2$$

where C_s is the concentration of dissolved nitrogen gas in mg/l, and T is given in degrees centigrade (Richardson and Baca, 1976).

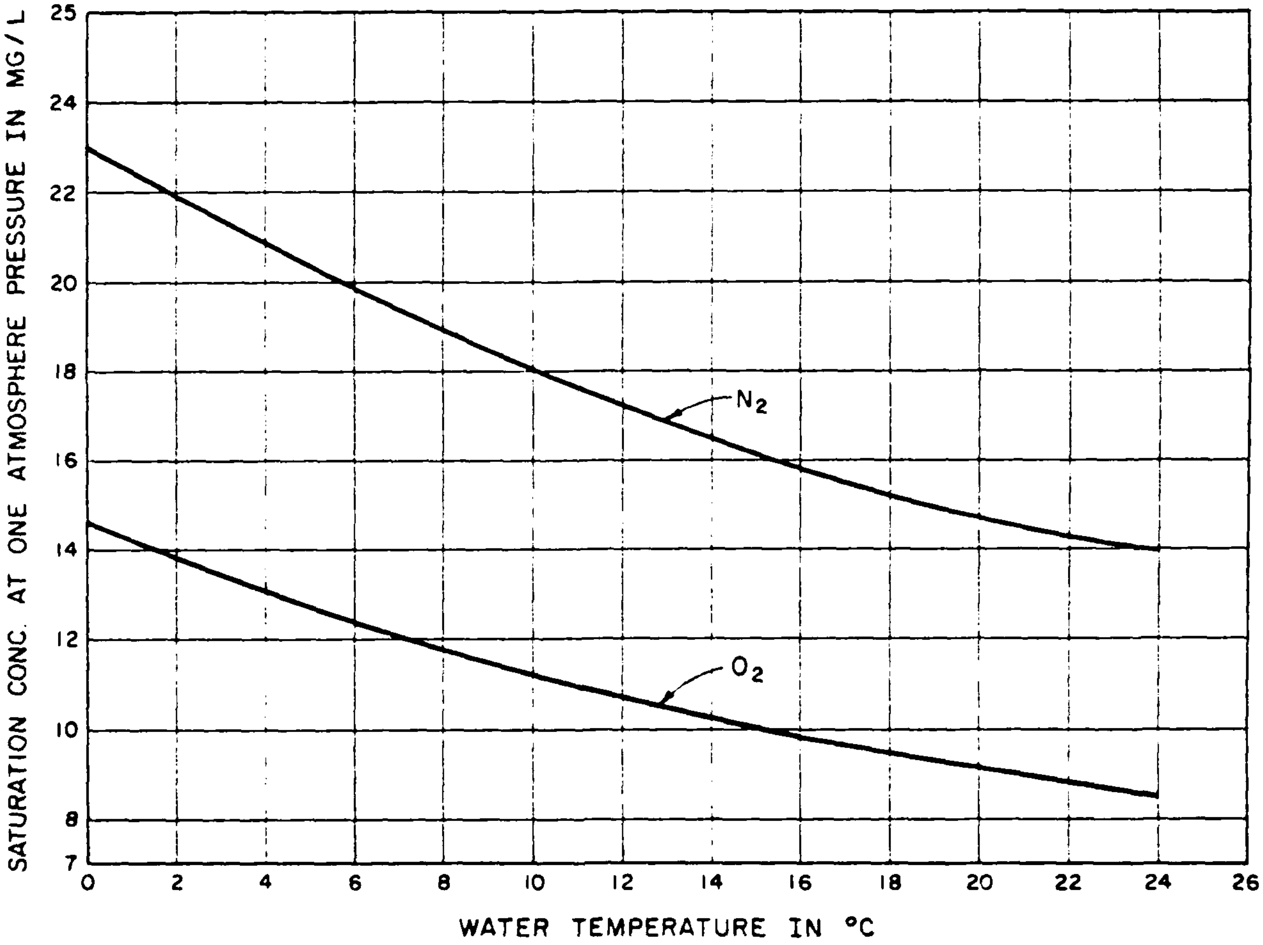

Figure 1. Dissolved gas saturation concentrations.

(from P. L. Johnson, 1975)

Oxygen is less plentiful than nitrogen in air, but is roughly twice as soluble in water. These circumstances and the fact that oxygen is commonly removed from solution by respiring organisms have great implications in the relative involvement of oxygen in the development of gas bubble disease.

In considering the solubility of a gas or mixture of gases over a solvent, it is necessary to have regard for the solvent which is in the gaseous state, since it too contributes to the total gas pressure. In the case of air over water, the total pressure of the mixture of gases is equal to the partial pressures of the individual gases plus the partial pressure of the water vapor. The vapor pressure of water increases as temperature rises. From published laboratory data (Harvey, 1975), it was determined that an error of 1 to 5% may be made in calculating theoretical concentrations of dissolved gases in water if water vapor is ignored. This, coupled with difficulties in obtaining accurate measurements is responsible for considerable debate in the literature regarding the actual solubilities of gases in water. It is generally agreed that the tabulated data given by Weiss (1970) are the best available. (See Harvey, 1975 for a good historical review.)

According to Henry's Law, the amount of gas that will dissolve in a given volume of liquid at constant temperature is directly proportional to the pressure that the gas exerts above the liquid. Pressure is increased in water by hydrostatic head. Thus, generally the amount of gas that will dissolve in water is directly proportional to depth at which a gas/liquid interface exists. The amount of gas that will enter the liquid phase from air bubbles trapped below the surface is a function of the depth and pressures existing at the time of equilibration.

The solubilities of various atmospheric gases at various depths and pressures are presented in the International Critical Tables, and in extended tables given by Macdonald and Wong, 1975, and Harvey, 1963. The calculation of theoretical solubilities at various depths becomes complicated, but the rule of thumb which states that the solubility of a gas is increased 10% for every meter of increase in water depth seems to provide a good working approximation. This is reflected in the Environmental Protection Agency's Criterion Document on Dissolved Nitrogen which states that " . . . Gas supersaturation decreases by 10% per meter of increase in water depth due to hydrostatic pressure; a gas that is at 130% saturation at the surface would be at 100% saturation at 3 meters' depth."

A condition of supersaturation is created frequently when water falling from sufficient height entrains large volumes of air in finely dispersed bubbles carried to considerable depth as the water plunges into a deep pool. Entrained atmospheric gases are driven into solution by the higher pressures existing in the pool. As the deeper layers of water approach the surface, under conditions of reduced pressure, the water becomes supersaturated.

The dissolution of atmospheric gases under pressures encountered in a deep basin (20-60 feet deep) appears to be a rapid phenomenon, the kinetics of which are poorly understood. The difficulties in determining the various physical factors involved within a region of a hydraulic jump are many and complex. It can be said that no reliable model currently exists that would permit accurate predictions of amounts and rates of atmospheric gas dissolution within a region of hydraulic jump or a large waterfall, either man-made or natural. It is readily apparent from our current understanding of physical chemistry that the amounts and rates of atmospheric gas dissolution occurring at a stilling basin will be a function of several variables, including: pressures encountered within the receiving basin as a result of hydrostatic and dynamic forces within the basin, temperature, volume of entrained air, ambient concentrations of gases in the dissolved and gaseous states, surface area available for exchange, and the time of effective contact between gases under pressure and the surrounding liquid.

Johnson (1975) has proposed the following relationship to predict the rate of gas transfer through a gas/liquid interface:

$$dC_t/dt = K(C_s-C_t)dt$$

where C_t is the existing dissolved gas concentration, C_s is the 100 percent saturated gas concentration at an effective depth, and K is the proportionality constant. A detailed discussion of this equation and Johnson's predictive model will be presented later.

Once a quantity of water becomes supersaturated with dissolved gases, there is a tendency to release the excess gas to the surrounding atmosphere. The following relationship has been suggested for natural degasification:

$$S_r = k(C-C_s)$$

where C is the concentration of dissolved gas, C_s is the equilibrium saturation level and k is a rate coefficient. The rate coefficient, k, is a function of temperature, the degree of turbulence, and the interfacial area over which the gas transfer occurs. One of the numerous correlations for k proposed in the literature is the relation:

$$k = \sqrt{\frac{D_z U}{h^3}} \qquad 1.028^{(T-20)}$$

where D_z is the film diffusion coefficient, U is the average flow velocity, h the mean water depth and T the water temperature in degrees centigrade. (Richardson and Baca, 1976)

Judging from the measured dissolved gas concentrations downstream from hydraulic structures which had demonstrated a problem with supersaturation, it is evident that the supersaturated state can persist for considerable distance downstream, and for extended periods of time. Degasification is not immediate. It is generally not as rapid as the process of gasification that occurs within a region of hydraulic jump that creates a supersaturated state. A most serious limiting factor in the process of degasification appears to be the interfacial area between the supersaturated liquid and the atmosphere. Effervescence, i.e., the formation of bubbles de novo, i.e., instantaneous from within a supersaturated liquid only occurs under conditions of extreme supersaturation, i.e., very high pressures, and is effectively inhibited at depths greater than a few inches beneath the surface with the moderate levels of supersaturation encountered in rivers and streams with hydraulic structures. As Harvey (1965) states:

> The origin of bubbles in a liquid may be de novo or the growth of gas nuclei. In both cases, the results are difficult to predict, in that bubble formation cannot be defined closely in a physical law. Henry's law states that the tension of a gas X (T) in a liquid (measured in units of pressure, such as mm Hg) is proportional to the partial pressure (P) (again in pressure units) and solubility of the gas. If the hydrostatic pressure is P,

> then the propensity for gas to leave solution may be expressed as T - P or simply ΔP. For bubble formation or growth to take place, ΔP must be positive, but how large depends on many factors. In the presence of a gas phase (any gas), a positive ΔP results in gas diffusion and growth of the gas phase. The rate of diffusion and hence growth of the gas phase is determined by the solubility of the gas. In de novo formation of bubbles, ΔP must be very large. Hemmingsen (1970) emphasized that the supersaturation at which de novo bubble formation occurs is not known; he found nitrogen left solution at ΔP of 145 atm and this may be the threshold. De novo bubble formation is influenced also by spatial configuration, with cone-shaped depressions permitting gas molecules to accumulate theoretically at ΔP = 0. Bubble formation in the sense of growth also occurs at the site of gas micronuclei. These were described by Liebermann (1957) as bubbles of less than 1μ, lodged on hydrophobic particles, which were insoluble and could exist indefinitely. These micronuclei are the sites of cavitation, boiling, etc.

If an interface exists, however, between a supersaturated liquid and the atmosphere, or an existing gas bubble, or a low pressure gas bubble created by physical disturbance of the surface as in natural riffles of shallow streams, the excess dissolved gas will equilibrate across this interface and the gas phase will grow. The natural tumbling of supersaturated water over rocks in a shallow stream, or the use of any aeration device to effectively increase the interfacial area between the water and atmospheric gases at one atmosphere of pressure is an effective method of removing excess dissolved gases. It works efficiently in natural streams, and has been used extensively in treating supersaturated waters in fish hatcheries around the world.

Harvey, et al. (1944) concluded from their studies of bubble formation in animals that gas nuclei are not free in the blood or associated with formed elements (erythrocytes, leukocytes, etc.) but reside on the vessel linings. Connective tissue, both under tension or damaged, was the site of bubble formation, presumably by giving rise to gas nuclei.

The practical significance of the kinetics of degasification of supersaturated waters is seen in the disposition of fish and other forms of aquatic life to develop gas bubbles in their tissues. Apparently, the excessive gases in solution to supersaturated waters may equilibrate across biological membranes, causing supersaturation of tissue fluids. Alternatively, tissue fluids saturated with ambient dissolved gases at one depth when brought suddenly to a shallower depth may become supersaturated. The abundance of gas nuclei within and on biological membranes permits rapid development or growth of the gas phase with the subsequent manifestation of the various symptoms of gas bubble disease.

B. Biological Aspects of Supersaturation of N_2 and GBD

1. Physiological nature of GBD: symptoms and sub-lethal effects.

Many of the details of the symptomatology of GBD were clearly stated by Marsh and Gorham in their earliest recorded observations of the problem. More recent and excellent reviews of the pathology of both acute and chronic exposure of aquatic organisms to supersaturated waters are available. (Stroud, Bouck and Nebeker 1975; Weitkamp and Katz, 1977; Harvey, 1975; Fickeisen and Schneider, 1976)

Exopthalmia or pop-eye is the one symptom most commonly associated with GBD by the novice. This particularly obvious sign is, however, frequently absent or present in only a small portion of fish suffering GBD. Exopthalmia may also be the result of causes other than GBD such as kidney disease, hypoproteinemia, mechanical injury (trauma) or parasitism.

A much more commonly reported external symptom of GBD is the occurrence of bubbles or blisters under the skin, primarily between fin rays, with frequent occurrence also on the head, the operculum, in the lining of the mouth, along the gill arches, along the lateral line, and even extending into internal organs such as liver, spleen, kidney, intestine and muscle.

Meekin and Turner (1974) and Weitkamp (1976) reported that gas bubbles in juvenile chinook suffering from induced GBD were most commonly found in the caudal fin. It appears that there is some correlation between the extent of bubble formation and the musucular activity or physical stress of surrounding tissues (Stroud and Nebeker, 1976). The possible connection between muscle activity, stress and the formation of gas micronuclei is hypothesized by these workers in what they describe as a "cascading bubble effect" in the most severely affected tissues.

In those animals that succumb to GBD, the most commonly diagnosed immediate cause of death is the formation of gas emboli within the heart and gills, causing hemostatis (blockage of blood, oxygen and nutrient flow).

Signs and lesions caused by supersaturation are dependent on the degree of supersaturation, duration of exposure and species and life stage of fish.

2. Physiological effects of supersaturation of N_2 and GBD. The physiological effects of long term or chronic exposure of aquatic organisms to various levels of supersaturation are poorly understood. It would appear that fish affected by GBD can, under many circumstances, recover completely. On the other hand, sub-lethal exposure to supersaturation may result in excessive stress, decreased lateral line sensitivity, increased buoyancy, blindness, impairment of vital tissues in gills and nares, and increased susceptibility to secondary infections of damaged tissues (Stroud, Bouck and Nebeker, 1975) The exact degree

and extent of such sub-lethal effects are variable from one situation to another, and difficult to predict. Even less is known about the effects that other environmental stresses, parasitic infestations, predation, nutrition, life cycles, etc. may have on the general susceptibility to GBD or tolerance to conditions of supersaturation. It is generally true, however, that stress applied by a single limiting factor in the environment may effectively reduce the range of tolerance of an organism to many other limiting factors. Therefore, one might expect that the tolerance to supersaturation may well be affected by a number of other physical, chemical, or biological factors acting on natural populations.

The correlation between degree of supersaturation and the onset of demonstrable characteristic lesions or other pathological symptoms of GBD is fairly well established for a number of aquatic organisms under laboratory conditions. There is little doubt, from the large number of controlled laboratory studies and cage studies recorded in the literature during the height of the problem on the Columbia River, that some species may show symptoms of GBD at saturation levels above 110%. For this reason, the early criterion established for dissolved nitrogen in regulated waters was set at 110%. Quantitative aspects of the mortality of aquatic organisms at various saturation levels were reviewed and summarized by Weitkamp and Katz (1977), and will not be repeated here. The summarizing comments made by these authors, however, include the following pertinent observations:

1. The external signs of the gas bubble disease syndrome have been presented in detail by many workers. These include exopthalmia, cutaneous bubbles and hemorrhaging. Abnormal behavior patterns are also observed.

2. The external signs in fish larvae and juvenile stages are described.

3. Gas bubble disease has been described in salmonids, cyprinids, menhaden, and warm water species.

4. Invertebrates are also susceptible to gas bubble disease. Signs have been observed in lobsters, horseshoe crabs, mollusks, hydroids, oysters, shrimp, crayfish, aquatic insects and blue crabs.

5. The internal lesions are described.

6. It is recognized that fish can recover from the disease.

7. Gas bubble disease is related to total dissolved atmospheric gas levels (nitrogen, oxygen, carbon dioxide, argon) and not to nitrogen alone.

8. A critical level of 110% saturation has been proposed for fish confined to waters of one meter or less depth. Studies have shown that at 115% total gas pressures, in shallow water, mortalities are usually first observed.
9. Fish permitted access to deeper waters, 2.5 meters or greater, can survive supersaturations of 120% for extended periods of time.

10. Field studies indicate that most juvenile salmonids are found in waters of sufficient depth for hydrostatic pressure to compensate for 120% TGP.

11. A standard of 110% TGP is not justified for most situations, because it does not take into account conditions in the natural environment nor the behavioral patterns of fish. This standard for most waters cannot be justified by the scientific knowledge and field observations that are now available.

Bently, Dawley and Newcomb (1975), Meekin and Turner (1974), Weitkamp (1976), as well as others, have shown that a variety of fish given the opportunity to sound (to dive) can survive for extended periods of time in deep water supersaturated well above 110% TGP without a significant incidence of GBD or mortalities. Fish in most waters likely to be supersaturated, assume a depth distribution adequate to compensate for supersaturation well above 110% TGP. Johnson and Dawley (1974) and Weitkamp (1976) have shown that an apparent threshold level exists near 120 to 125% TGP for young salmon that are held in water of several meters depth. Relatively small increases in this range of supersaturation produce a marked increase in the incidence of GBD and in mortalities. Below this level the incidence of GBD is low and few mortalities occur. Ebel _et al_. (1975) have described how early estimates of mortalities in the Columbia River System were considerably higher than a more recent estimate based on additional information. Both Ebel _et al_. (1973) and Bouck (1976) point out the difficulties in applying experimentally derived data to the natural situation. The differences between information derived from the laboratory and natural situations should be seriously considered in establishing or revising dissolved gas standards as well as in estimating mortalities due to GBD.

12. Intermittent exposure to high levels of supersaturation may increase the total gas pressure that fish are able to tolerate.

13. Although at least one study indicates some fish detect and avoid supersaturation the evidence of an avoidance reaction is far from conclusive.

14. The tolerance of fish to dissolved gas supersaturation is not the same at all life stages. Eggs are tolerant of levels of supersaturation that affect young and adult fish. The early life stages of hatched fish seem to be more tolerant than older juveniles.

15. A tolerance to supersaturation may be heritable.

16. In recent years studies have been conducted with many species of non-salmonid fresh water fish and marine species. In general, the tolerance of these species to supersaturation is about the same or greater than those of salmonids. (Those species showing greater tolerance of supersaturation than salmonids include: largemouth bass, carp, crappie, squawfish, bluegills and warmouth). The studies generally indicate that the tolerance of different species to supersaturation can vary considerably. Salmonids are among the least tolerant fish, but others such as Atlantic menhaden may be even less tolerant. In natural situations the tolerance of a species will be affected by behavioral patterns such as depth

distribution or attraction to heated waters. And, apparently, tolerance may be partly due to degree of muscular activity, excitement or agitation.

17. Each one meter of depth exerts additional pressure that increases the solubility of dissolved gases sufficiently to compensate for approximately 10% of saturation. In the range of depths and supersaturations normally of concern, the rule of 10% compensation per meter of water depth is a workable approximation. This means that a total gas pressure of 120% of saturation at the surface is actually only 110% at 1 m and 100% at 2 m with no change in the volume of gas dissolved or in the partial pressures. Thus the effect of depth is an important factor in determining the tolerance of fish to supersaturation in natural situations, or in the prediction of losses of fish in various situations. The results of laboratory and field bioassay experiments must be interpreted in terms of all discernible natural conditions if they are to provide accurate descriptions of what is really happening.

3. Natural occurrence of supersaturation and GBD. In his excellent review of the gas disease in fish, Harvey (1975) has considered the numerous situations in the natural environment where supersaturation occurs and the likelihood exists for GBD. He points out that well and spring waters have long been known to have variable concentrations of dissolved gases, and this has been a long-standing problem to fish hatcheries. Marsh (1910) reported that concentrations of nitrogen in one well ranged from 140 to 180% of air saturation. Rucker and Tuttle (1948) showed that the well water supplying a hatchery at Leavenworth,

Washington, showed nitrogen saturation of 144%, while springs supplying the Puyallup hatchery had oxygen saturations of 80% and nitrogen of 120%. Matsue et al. (1953) measured the nitrogen content of 15 artesian wells and two springs. Saturations ranged from 118 to 159%, with most above 140%. In view of the many ways ground waters can be increased in nitrogen saturation (geothermal heating, pressure on entrained air, organic breakdown. etc.), Harvey suggests that analyses for dissolved gases be performed on all such waters intended for fish culture purposes. And, as already stated, effective aeration procedures are well documented to reduce the level of dissolved gases in hatchery waters.

The potential for nitrogen supersaturation of natural rivers, streams, ponds and lakes and specific sites in the ocean has been amply demonstrated by the observations of several workers. (See Harvey, 1975). The literature is also replete with observations of aquatic organisms displaying the symptoms of GBD in naturally supersaturated waters. The problem is certainly not restricted to artificial impoundments and spillways.

C. Engineering Aspects of Supersaturation of N_2 and GBD

Water may become supersaturated with nitrogen through one of the following processes: (1) Nitrogen dissolved into the water under a higher pressure than atmospheric pressure and (2) Nitrogen dissolved into the water at a lower temperature.

The first mechanism (pressure) has been documented in many supersaturation problems involving engineering designs of air injection system and reservoir projects. The second mechanism (temperature) has caused supersaturation in heating of water supplies and cooling waters for power generating facilities.

Spillways of reservoir projects frequently cause air and water to be mixed and carried to substantial depths in the stilling basin. At the depths normally encountered in stilling basins the pressure may be sufficient to greatly increase the solubility of nitrogen. The nitrogen gas thus passes into solution in sufficient amounts to produce supersaturation with respect to the water surface or atmospheric pressure. Thus, hydraulic structures frequently have the capacity to supersaturate large volumes of water and cause a major problem. This has occurred at a number of hydroelectric projects in the northwestern United States. These dams have received considerable study because of their important fish resource.

A major purpose of the present study was to examine the current data base and determine, within constraints of available information, whether the possibility exists that supersaturation will occur at the Clarence Cannon Dam in northeastern Missouri. The stated goal seemed simple enough, since there are many hydraulic structures of comparable size and design in operation throughout the U.S. The problems of supersaturation have been observed over several years at a number of dams in the Pacific Northwest, and in the recent past at the construction site of the Harry S. Truman Dam in western Missouri. But, on the other hand, there are many other dam sites throughout the U.S. in general, and in the Midwest specifically, that have operated for many years without supersaturation problems.

The complex relationships among the several variables responsible for supersaturation make meaningful comparisons difficult. A difficulty lies in the inadequacy of collected data regarding all important attendant physical variables and operating conditions at the various structures. It would appear that the overlapping ranges of each factor thought to be involved in determining the level of supersaturation offer few distinctive differences between the group of structures experiencing difficulties and the group of structures without apparent problems.

The recorded occurrence of supersaturation and GBD at hydraulic structures in the midwestern U.S. seems to be limited to the episodes in 1978 and 1979 in the temporary spillway at the construction site of the Harry S. Truman Dam. Since the completion of the spillway and the subsequent inclusion of "flip-lips" added on the back side of the spillway to divert discharged waters in a more horizontal direction near the surface of the stilling pool, there have been no serious problems. Spring runoff in April and May of 1980 created some concern as gas saturation levels at Truman Dam approached 120% while discharging at the rate of 25,000 cfs. And this occurred during a period when installation of the generators was incomplete so that discharge was entirely over the spillway.

The isolated occurrence of the problem at Truman Dam is accentuated by the routine construction and operation of several similar dams in the surrounding states of Kansas, Iowa, Illinois, South Dakota, Arkansas, and Oklahoma (unpublished data provided by Corps of Engineers and Missouri Department of Conservation). There was a substantial fish kill at Gavins Point Dam in 1978, but after careful examination of many affected fish it was agreed that GBD was definitely not the cause. Gas saturation levels observed to be less than 110% below the spillway were well below the critical level and affected fish did not show the characteristic symptoms of GBD. A series of carefully documented studies was done at Gavins Point Dam to determine the levels of supersaturation that would be created at that specific structure under different operating conditions. It is very interesting that the maximum levels of supersaturation measured under conditions of combined power generation and discharge over the spillway at 15,000 cfs were of the order of 110%. Contrast these measurements with Johnson (1975) who measured 200% supersaturation with discharge rates of approximately 13,000 cfs at Grand Coulee Dam.

The relationships among the various measured physical parameters and the final degree of gas saturation are not adequately defined. In lieu of adequate data and exact relationships as discussed above, attempts to predict levels of supersaturation at Cannon Dam have little or no basis. The experience at Truman Dam indicates that it is possible supersaturation may occur given the proper conditions of operating parameters, pressure, temperature, flow rates, amounts of entrained air, etc.

Estimation of the probability of occurrence of supersaturation and attendant problems of GBD occurring at this particular site would depend upon a thorough understanding of all the physical variables and operational parameters which interact to affect gas saturation levels. The understanding of the situation is deficient in the following aspects:

1. Inaccurate information regarding actual gas saturation levels in field situations. There are various techniques for determination of dissolved gases, some of which are accurate, but confined to a laboratory environment. By far the simplest and probably most widely used method for determination of total

dissolved gas levels is the Weiss saturometer. The simplicity of the instrument, and apparent ease of operation belie the fact that in the hands of inexperienced analysts, considerable error is possible. As far as can be determined, this apparatus has not been described in any journal or other widely distributed publication. Fickeisen et al. (1975) provide a brief description and picture of the Weiss saturometer, and a similar device is produced commercially by ECO Enterprises, Seattle, Washington. Laboratory comparisons between data obtained using the Weiss saturometer and with conventional gas chromatography are very encouraging (Fickeisen et al., 1975). Very little information is available, however, in the scientific literature or in technical manuals provided by manufacturers regarding operating conditions, precautions, limitations, sources of error, accuracy in the field, etc. Comparative analyses done using early models of the commercial saturometer were found by Fickeisen et al. to be generally low and variable when operated according to the manufacturer's instructions.

D'Aoust and Smith (1974) and D'Aoust, White and Siebold (1976) describe a modification of the Weiss saturometer used to measure total dissolved gas pressure. This device, called a tensionometer, provides for sensing of the gas pressure by means of a solid state electronic pressure transducer rather than the Bourden tube gauge used in the saturometer. According to D'Aoust et al., the tensionometer has the advantages of smaller size, and a shorter response time of about eight minutes. This compares with a response time of twenty to thirty minutes for the saturometer. Agitation is required by both units to remove bubbles from the silastic tubing when the water sample is truly supersaturated. Comparison of the D'Aoust tensionometer with the Weiss saturometer commercially available has shown that the latter can under-read by as much as 40% the maximum value shown by the tensionometer. D'Aoust et al. (1976) advise that

> It is important in comparing these devices to other quantitative modes of analysis such as the Van Slyke and/or gas chromatography to keep in mind that, where supersaturation exists in the water being analyzed, tensionometers can underestimate the total dissolved gas content and quantitative methods can overestimate the dissolved gas tension because of the possible presence of microbubbles. Use of either measurement to estimate the other with solubility tables (Weiss, 1970) must be interpreted with caution. It is also emphasized that the only reliable measurements where supersaturation is present are those taken under conditions of STEADY-STATE where the readings stabilize and are reproducible. For purposes of natural water management it appears most desirable to more continuously monitor dissolved gas tension at different locations to accurately quantify and delimit the problem.

It is apparent, from comments made from field operators responsible for collecting data on saturation levels, that major problems still exist, and that many available data are inaccurate.

2. Inaccurate and insufficient information regarding various operational parameters at Cannon Dam, i.e., ranges of anticipated hydraulic head (elevation of reservoir, elevation of tail waters in the re-regulation structure), ranges of anticipated discharge rates, proportion of discharge to be released

through generator penstocks or over spillway, geometry of discharge jet into stilling basin, forces and pressures to be experienced in the stilling basin, amount of air entrained by impacting waters in the stilling basin, effective surface area for exchange of gases, temperatures involved, time of contact between pressurized air and the water needs to be studied. There exists no accurate compilation of actual field data such as these for any existing structure, much less any accurate correlation among observed variables and degree of supersaturation observed.

3. Non-existence of an accurate predictive mathematical model that considers all the variables involved at the type of structure involved. The presently available model used to predict the amount of dissolved atmospheric gases at hydraulic structures is simply inadequate. It was originally developed for the United States Department of the Interior - Bureau of Reclamation by P. L. Johnson in 1975 at the Division of General Research, Hydraulics Branch. Johnson's model "Prediction of Dissolved Gas at Hydraulic Structures" will be analyzed in order to gain a better understanding of its capabilities. The strong and the weak components will be discussed while reviewing each term of the prediction equation. General results, possible improvements and related or required research to better define the problems and parameters will be given.

The equation proposed by Johnson to predict the amount of dissolved nitrogen gas concentration in milligrams per liter of water downstream of a hydraulic structure is given as:

$$C(t) = C_s + (C_I - C_s)e^{-Kt} \tag{1}$$

C(t) is the predicted dissolved gas level below the structure. C_s is the theoretical concentration of 100% saturation within the stilling basin. Practically, this amounts to the saturating concentration calculated at two-thirds of the total depth of the basin, and assumes homogeneous mixing and saturation at all depths. C_I is the initial dissolved gas saturation level in the reservoir which can be determined empirically or assumed to be approximately 90-110% if no data are available. This parameter requires no further discussion. The parameter t is the length of time that the inflowing air-entrained jet is under pressure in the stilling basin. K is a constant of proportionality that is presumed to measure the ability of a structure to dissolve gas while operating under a particular set of conditions.

Johnson's equation (1) was derived from the process of gas transfer across an interface described by the relationship:

$$dC(t) = K[C_s - C(t)]dt \tag{2}$$

Rearranging Eq. (2)

$$dC(t) = -K[C(t) - C_s]dt \tag{3}$$

The ratio of gas transfer assuming C_s constant is

$$\frac{dC(t)}{dt} = \frac{d[C(t)-C_s]}{dt} \tag{4}$$

Rearranging Eqs. (3) and (4) before combining gives

$$-Kdt = \frac{d[C(t)-C_s]}{[C(t)-C_s]} \tag{5}$$

Integrating both sides with A_1 and A_2 as constants of integration yields

$$-Kt + A_2 = \ell n[C(t)-C_s] + A_1 \tag{6}$$

Substituting $B = A_2 - A_1$ gives

$$-Kt + B = \ell n[C(t)-C_s] \tag{7}$$

Using the law of exponents we have

$$e^{-Kt+B} = C(t) - C_s \tag{8}$$

and substituting $e^B = A$ and rearranging yields

$$C(t) = C_s + Ae^{-Kt} \tag{9}$$

Letting t = 0 and therefore $(Ct) = C_I$ we have

$$C_I = C_s + Ae^{(0)} = C_s + A \tag{10}$$

and rearranging (10)

$$A = C_I - C_s \tag{11}$$

Substituting (11) into (9) yields

$$C(t) = C_S + (C_I - C_S)e^{-Kt} \tag{12}$$

The mathematical derivation is a straightforward first order reaction and the basis on which the model was built.

Saturation concentration, C_S, is defined as the dissolved gas concentration for a given water temperature multiplied by the quantity: the barometric pressure, corrected for elevation of the structure, plus two-thirds the depth of water in the stilling basin, corrected for dimensional consistency, divided by the standard atmospheric pressure. The pressure term before being multiplied by the gas concentration is assumed to be the average absolute pressure on the dissolving bubbles in terms of standard atmospheres.

$$C_S = \left[\frac{\begin{matrix}\text{barometric pressure}\\ \text{(mm Hg)}\end{matrix} + \frac{2}{3}\,\text{(Depth ft)(304.8)/13.55}}{\text{760 mm Hg}}\right]\begin{pmatrix}\text{mg/}\ell\text{ concentration}\\ \text{at temp }^{\circ}\text{C}\end{pmatrix}$$

The assumption that the saturated concentration occurs at the point of average static pressure is certainly not substantiated. Since pressure is one of the most important variables, it should not be used for purposes of analysis when based purely on assumption. It would be most valuable if the actual pressures in the stilling basin were analyzed on the prototype. The pressure must be analyzed and quantified in terms of field data and not based on an assumption. Furthermore, it is not justifiable to calculate C_S based on the assumption of quasi static flow conditions when in actuality, the hydraulic jump is a dynamic phenomenon.

Dissolved gas concentration may or may not follow exactly the relationship of the natural logarithmic function but obviously the dissolution of gas in water can be shown to approximately follow the general characteristics of the curve. As the time increases, the amount of gas dissolved decreases. The significant range on which the function can provide measurable changes is obvious from observing the graphical relationship of the natural logarithmic equation $y = e^x$ (Figure 2). As the exponent decreases from zero, the functional relationship goes to zero and results in a predictive equation of $C(t) = C_s$. As the exponent approaches its maximum of zero, the natural logarithmic function approaches unity and results in a predictive equation of $C(t) = C_I$. Therefore, the exponent range that results in significant (measurable) change has been calculated in the graph of the natural logarithmic function in the figure. Even though it is unknown whether dissolution of gas follows this functional relationship in the stilling basin, the small significant range limits induced errors (i.e., the solution is confined between C_s and C_I) which forces a reasonable solution irrespective of utility of the approach. The corresponding relationship could actually be verified through quantitative analysis with adequate research and physical sampling correlations.

The next parameter to be evaluated is the length of time (t) over which a gas is given opportunity to be dissolved into

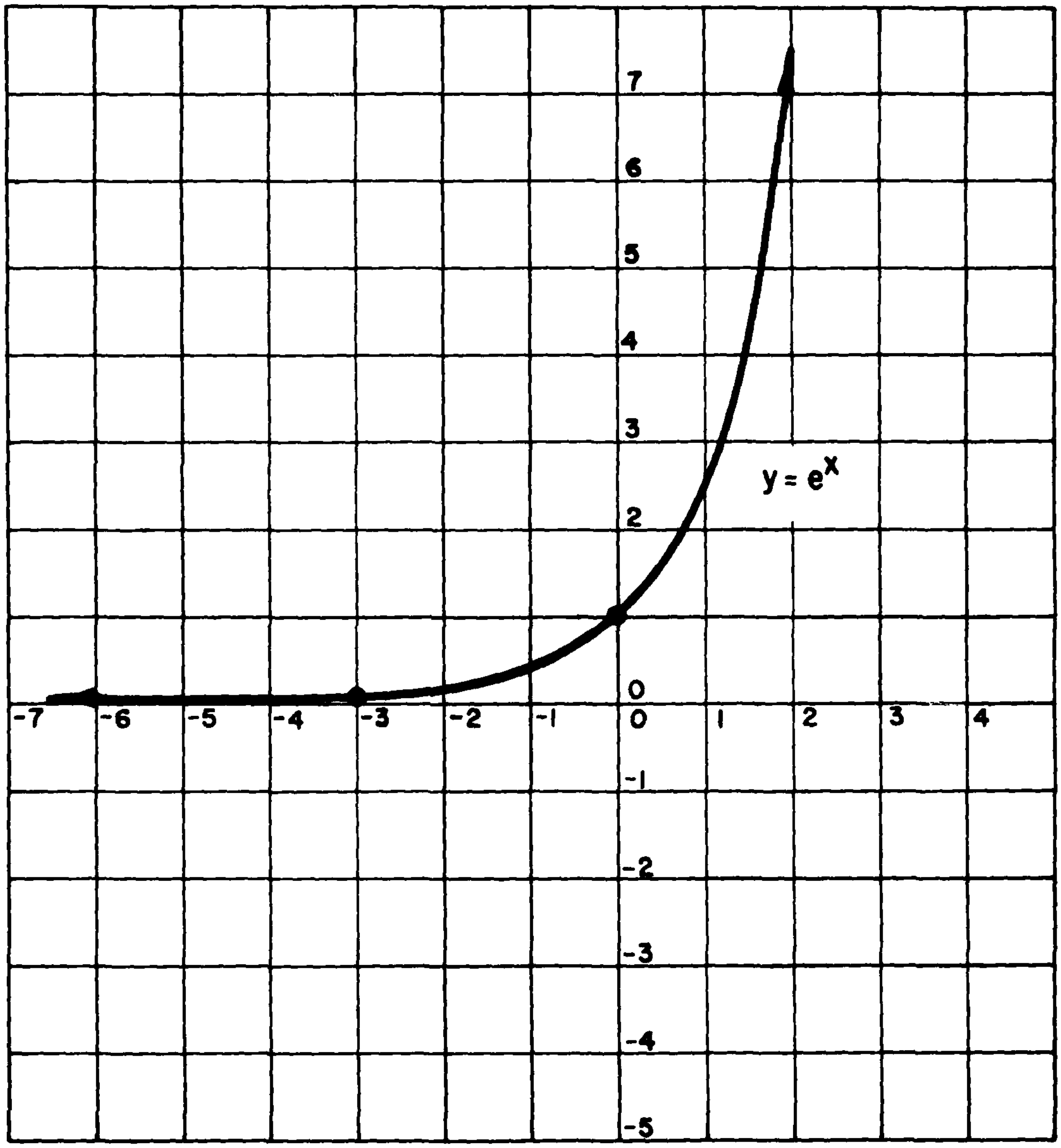

Figure 2. Graphical relationship of the natural logarithm.

the flow. The model provides for two different time computations which leads one to conclude that the element of time is really not understood. The first time increment is based on the terminal bubble velocity from which the bubble rise time is determined. This analysis was based on the time an average size bubble took to rise to the water surface under a static equilibrium flow condition. This method of predicting the amount of time the gas has to go into solution is probably incorrect and definitely oversimplified. A minute bubble in the violently turbulent, frothing emulsified action in the stilling basin is unrealistically used to determine the length of time that gas has to dissolve in the water. The alternative value of t was calculated by dividing the flow path length along the bottom of the stilling basin by the average velocity. In both cases the assumption that the head differential is equal to the velocity head of the energy equation from which the average velocity is derived is not considered to follow basic hydraulic principles. To reiterate, the time factor is not understood. The time factor must be reanalyzed and fully developed through rigorous research before this term can be appreciated for its contributions in a resulting model prediction.

The final parameter to be evaluated is the constant of proportionality K. It was developed on the basis of a geometric relationship of the hydraulic structure. K is selected from a family of curves extrapolated from prototype data. The curves are plotted as the ratio of the velocity head at the tailwater surface divided by the appropriate flow path length of water (Hv/P) vs. the ratio of the shear perimeter divided by the cross-sectional area of flow (S.P./A_{flow}). The extrapolated K-values are meaningless as far as their application to the Clarence Cannon Dam structure is concerned. No reasonable K values can be selected from the curves for use in analyzing the possibility of supersaturated nitrogen at Cannon. The validity of the actual K-curves is questionable and further research is needed before these values can be used in a predictive model.

No one really knows how the physics of a particular structure affects the amount of dissolved gas concentration because the dynamic phenomenon is not completely understood and is very difficulty to study. Some of this difficulty could be simplified by analyzing parts of the problem and quantifying the results. Presently, the model cannot predict reliable concentrations of dissolved nitrogen. The conclusions of the review of this model can be summarized in a list of required research to further develop the predictability model into a reliable tool.

a. Evaluate the K-curves as to their functional value in the predictive model (especially for the particular structure of interest).

b. Evaluate the time parameter to determine its importance in the establishing of dissolved gas concentrations, especially in comparison with the given pressure conditions.

c. Evaluate the functional relationship of gas dissolved in water and compare this to the functional relationship of the natural logarithm for compatibility.

d. Evaluate the assumption that the average saturation concentration occurs at two-thirds the depth of the tailwater. It is suggested that the concentration in the roller area be analyzed separately from that of the jet concentration.

e. Evaluate the velocities in the prototype or similar prototype in order to make a more realistic estimation.

In our judgement this model reflects the fact that Johnson realized the importance of temperature and pressure but it appears that incomplete research and analysis is the reason for the model's inadequacies. Gas is dissolved very rapidly under a given set of temperatures and pressures but escapes back to the atmosphere comparatively slowly by orders of magnitudes. Refer back to the time factor exponent of the natural logarithmic function $y = e^x$ where $x = -Kt$. At the point where the function is unity, the time is known to be zero. The final or predicted concentration then becomes equal to the initial concentration and is no longer time dependent. Suppose that the time approaches zero due to the ratio of time for dissolving gas into water T_d to the time for relieving the gas from solution T_r. In other words T_d/T_r approaches zero. Based on the above information, especially $T_d/T_r \rightarrow 0$, it might be best to let the variable of time approach zero and assume instantaneous dissolution of the gas for all practical purposes. If this is truly the case, the element of time could possibly be eliminated from the already complex situation. This needs to be rigorously verified by research. The aspect of instantaneous dissolution or so nearly instantaneous that the time is not a factor must be resolved before the model can beneficially be used as a tool.

One last note of interest in reference to the pressure in the stilling basin. A model study has been completed by WES for the Cannon project (Fletcher, 1971) and one point of interest is the pressure profiles. At the point the jet enters the tailwater pool the pressure increases to approximately twice the normal atmospheric pressure and then drops back down in a short distance to form a pressure bulb. In the area of this pressure bulb the temperature is constant and the time span is short ($\Delta T \approx 0$). This point may be the origin of the entire problem. In this region of the prototype, the parameters affecting the dissolution of gas must be analyzed. The temperature data can be accurately determined at the point of withdrawal in the reservoir but the time, velocity and most importantly the pressures must be determined in the prototype. It is necessary to study the prototype rather than a model for the dissolved gas analysis, since it is very difficult if not impossible to model the complexities involved in the interface of entrained air in water in a very turbulent flow. Is it possible to model the effective area for transfer of nitrogen, or possibly more important, the effective pressures under which the gases are being dissolved? It would be very difficult if not impossible to model these conditions. At the present time the Waterways Experiment Station (WES) is involved with only evaluating the water surface transfer rates through the use of Krypton Gas in a model study, which is more important in modelling the dissolution of gas back into atmosphere than the solution of gas into the water.

4. Other complicating factors. Dissolved gas supersaturation of water is an unstable condition that tends to return to equilibrium. It is important to recognize that water is supersaturated with atmospheric gases with respect to one atmosphere pressure at the surface of the water. Deep waters may have no tendency to lose dissolved gas, in fact, they may be undersaturated and tend, if air is present, to equilibrate toward saturation. Rapidly flowing turbulent streams may not provide total equilibration of dissolved gases with the atmosphere or homogeneous distribution of dissolved gases at all levels. Degasification of supersaturated water at the surface is a much slower process than initial gasification. Furthermore, as water is warmed downstream of a hydraulic structure, the decrease in the water's capacity to hold dissolved gas may compensate for any loss in the actual dissolved gas content and thus remain at a high level of supersaturation.

Even though one can generally say that as the discharge decreases and/or the tailwater (i.e., depth of the still basin) decreases so will the supersaturation of nitrogen at any given structure, this simple statement does not help arrive at an ability to predict either the occurrence of or under what conditions supersaturation may be a problem at Cannon Dan. For that purpose a model which basically explains the underlying phenomena involved in supersaturation at hydraulic structures is needed.

III. PHILOSOPHICAL ASPECTS OF SUPERSATURATION OF N_2 AND GBD

Although GBD occurs, often unnoticed, in a number of natural (unmodified) streams, as a rule it takes its greatest economic toll and commands greatest public attention at man-made hydraulic structures which periodically discharge water from sufficient height into a deep basin to create a supersaturated condition. The degree of supersaturation depends upon a number of environmental variables, some of which are not subject to human control.

The great public concern and complicated legal actions initiated after the recent episode of GBD at Truman Dam will, of themselves, do little or nothing to correct or eliminate the apparent paradox created by human technology. The paradox is simply one of benefits and risk. There are a number of benefits derived from the construction of dams at strategic points along a natural river. All are important to different segments of society. And yet, those segments of society who depend upon the dam and reservoir should not expect perfect human control over forces of nature so as to preclude any or all disruptions of their particular interest.

Is it humanly possible to provide 100% assurance that all possible situations that may lead to GBD have been taken into consideration and all risks removed? What would be the cost of providing such assurance? At what point do we consider that the benefits derived from any hydraulic structure outweigh the remaining risks? Society must decide its priorities.

No matter what society decides, we need a tool (model) to predict the occurrence or nonoccurrence of supersaturation of N_2 and GBD in order to prevent or evaluate the occurrence of supersaturation of N_2 and GBD.

IV. CONCLUSIONS AND RECOMMENDATIONS

As a result of consideration of the available information related to supersaturation and Gas Bubble Disease, and the application of known relationships to the situation at Clarence Cannon Dam, the following conclusions have been drawn:

1. On the basis of existing information, it cannot be stated unequivocally that supersaturation with atmospheric gases will not occur at levels sufficient to cause Gas Bubble Disease in some aquatic organisms at Cannon Dam. Given the proper conditions of runoff, flow rates, discharge rates, depth of the re-regulation pool, temperature and volumes of air entrained by impacting waters in the spillway basin, it is possible that a condition of supersaturation can be created downstream from the Clarence Cannon Dam.

2. The recent episodes of GBD at Harry S. Truman Dam in western Missouri indicate that ambient environmental conditions and operational parameters during spring runoff can combine to produce supersaturation of sufficient magnitude in Missouri to kill significant numbers of aquatic organisms. It is true that the levels of supersaturation were highest at Harry S. Truman Dam during the construction period when large amounts of water were being discharged over the temporary spillway. But levels of supersaturation observed following completion of the spillway and even after the installation of "flip-lips" in an attempt to reduce the depths and pressures exerted on entrained air within the hydraulic jump approached critical levels known to affect many species of fish.

3. The construction and operation of many other dams of similar design and subject to similar environmental and operational parameters to those experienced at Harry S. Truman Dam in the midwestern states have not resulted in recorded episodes of GBD or dangerously high levels of supersaturation. Controlled studies performed under various conditions of discharge through generator penstocks and over spillways at Gavins Point Dam in South Dakota indicated acceptable levels of supersaturation under all operating conditions studied. In fact, at rates of discharge up to 15,000 cfs, observed levels of supersaturation remained near 110% saturation, well below the critical level.

4. Fish and other aquatic organisms do not have to be caught up in the turbulent waters of the hydraulic jump to experience GBD. The supersaturated state can persist for some distance downstream from a hydraulic structure, because of the slow rates of degasification without surface disruption. Those fish affected most will be those that distribute themselves close to the surface of supersaturated waters. The natural distribution patterns and densities of native and planted fish downstream from Cannon Dam are not well understood. Seasonal alterations in depth distribution patterns are even less known. It is well established, however, that fish that assume a deeper position in the water column may not experience GBD even though surface waters are dangerously supersaturated. The level of supersaturation is effectively reduced 10% for each meter of depth within the body of supersaturated water. The degree of manifestation of the symptoms of GBD and the proportion of fish populations affected will depend on the various factors that may act to cause them to assume and maintain a shallow position in supersaturated water.

5. Fish that are affected by GBD may recover. Intermittent exposure to conditions of supersaturation, i.e. given the opportunity and ability to change depth within the body of water, generally increases the tolerance of an aquatic organism to the effects of supersaturation.

6. Stresses placed on natural populations by other limiting factors in the environment (predation, disease, parasitism, malnutrition, etc.) will tend to reduce tolerance to supersaturation. Conversely, GBD may reduce tolerance to a number of other limiting factors, and predispose aquatic organisms to the effects of those limiting factors.

7. The current model proposed by Johnson (1975) to predict levels of dissolved gas at hydraulic structures is inadequate for application to the conditions anticipated at Cannon Dam.

8. Improvements can possibly be made to Johnson's model that may allow it to be used as a predictive tool. Those improvements might include: definition of K values for hydraulic structures with physical characteristics similar to those at Cannon Dam, or simply, better definition of those environmental and operational parameters that are considered in the derivation of the proportionality constant K, more precise determination of air entrainment and pressure distribution within the stilling basin.

9. Basic investigation is needed to evaluate the quantities of air entrainment, pressures acting on the entrained air, the kinetics of dissolution of atmospheric gases in a hydraulic jump, detailed flow patterns and alterations of flow patterns as a function of discharge and/or discharge per unit width in hydraulic jumps downstream of a hydraulic structure.

Recommendations that can be made as a result of this study include the following:

1. A comprehensive investigation should be initiated to improve the applicability of current mathematical models or the possible development of a new approach for use in evaluation of supersaturation and GBD in stilling basins and rivers downstream of hydraulic structures. Without such an investigation, it is impossible to determine the potential of nitrogen supersaturation. The investigation should incorporate the following:

   a. Measurement of physical conditions at various structures, including but not limited to: temperature and dissolved nitrogen profiles in the reservoir, discharge and/or discharge per unit width, velocity and depth of jet entering the basin, amounts of air being entrained, distribution of entrained air within the stilling basin, pressures and velocities of flow within the basin, and concentrations of dissolved nitrogen at various depths and horizontal distances within the basin.

   b. Analysis of the results of these measurements.

   c. Modification of the current mathematical model or development of a new approach for the prediction of the occurrence of supersaturation.

   d. Verification of the approach against measured data.

Once these important parameters are well documented and the relationships and correlations established, it will be possible to predict the probability and establish the conditions under which supersaturation may occur at Cannon Dam. Once the conditions are known precisely, methods for reduction or elimination of the problem can be proposed and evaluated.

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