TOTAL DISSOLVED GAS LITERATURE 1980-2007, AN ANNOTATED BIBLIOGRAPHY

Prepared by

Don E. Weitkamp Ph D
PARAMETRIX
411 108th Ave. NE, Suite 1800
Bellevue, Washington 98004-5571

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ACRONYMS

atms	atmospheres of pressure (14.7 lb/in^2, 760 mm Hg)
cfs	cubic feet per second
ΔP	delta pressure, pressure differential
ESA	Endangered Species Act
FERC	Federal Energy Regulatory Commission
ft	feet
g	gram
GBD	gas bubble disease
h	hour
kcfs	1,000 cubic feet per second
LC_{50}	lethal concentration causing 50% mortality
LT_{50}	lethal time, to 50% mortality of test fish
m	meter
mm Hg	millimeters mercury, pressure
m/s	meters per second
N_2	nitrogen, gas
O_2	oxygen, gas
%	percent
RKm	river kilometer
RM	river mile
TDG	total dissolved gas
TDGP	total dissolved gas pressure
TGP	total gas pressure

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INTRODUCTION

The bibliography is a compilation of available literature dealing with total dissolved gas (TDG) supersaturation that has been produced since we produced a similar compilation in 1980 (Weitkamp and Katz 1980). This annotated bibliography was developed to provide easy access to summaries of the substantial volume of information on TDG supersaturation that has been produced over the last 27 years. The newer literature reviewed herein includes both published papers and unpublished monitoring reports from a variety of studies covering many different aspects of TDG supersaturation and its biological effects. A few earlier papers are also included that were not included or adequately covered by (Weitkamp and Katz 1980).

These reports are arranged alphabetically. A key word index is provided to facilitate searches for specific types of information. Each entry begins with a reference for the report. Each reference is followed by a summary of the reference, or in many cases a slightly modified version of the author's abstract. The abstracts use the descriptive words used by each report's author(s) as much as practical. However, any errors in interpretation are the responsibility of the annotated bibliographies author.

Although this is an attempt to be thorough in gathering pertinent literature, there are annual monitoring reports and likely some obscure reports have not been acquired for this review. Where annual reports are superseded by completion or summary reports, only the latter are included. This bibliography does not included the numerous design and analysis reports dealing with TDG supersaturation control measures and TDG monitoring data at hydroelectric projects.

This review summarizes a substantial number of field investigations that have produced a much greater understanding of TDG effects in natural conditions (rivers, lakes, etc.) as opposed to laboratory conditions and net pen conditions. With TDG supersaturation, where hydrostatic pressure has a great effect on the TDG level actually encountered by the organism, natural conditions are considerably different than laboratory and net pen conditions that limit the depth available to fish, thus the biological effects are considerably different. Unlike other water quality parameters, the mitigating effects of hydrostatic pressure must be considered in any evaluation of the biological effects of TDG supersaturation.

There are several terminology issues that may be aided by a short discussion to introduce this bibliography.

Gas Bubble Disease v Gas Bubble Trauma

According to the conventions for biological nomenclature there are several tenants that are applicable to determining the appropriate word for this malady, "disease" or "trauma". Biological terminology generally follows two applicable tenants:

- The more technically appropriate word or term applies where there is a clear distinction among the alternatives.

- Historic precedence applies in the absence of a clear technical preference (use the word or term historically first applied).

Thus, the term "disease" is more appropriate than "trauma" for the following reasons.

1. Definitions of the words "disease" and "trauma" in medical dictionaries are ambiguous and overlapping. The following are several examples

Blacks Medical Dictionary

Disease: Any abnormality of bodily structure or function, other than those arising directly from physical injury.

Trauma: The term used to indicate disorders due to wounds or injuries.

Dorlin's Illustrated Medical Dictionary

Disease: Any deviation from or interruption of the normal structure or function of any part, organ, or system (or combination thereof) of the body that is manifested by a characteristic set of symptoms and signs and whose etiology, pathology, and prognosis may be known or unknown.

Trauma: A wound or injury, whether physical or psychic.

Stedman's Medical Dictionary

Disease: 1. An interruption, cessation, or disorder of body functions, systems, or organs. SYN illness, morbus, sickness. 2. A morbid entity characterized usually by at least two of these criteria: recognized etiologic agent(s), identifiable group of signs and symptoms, or consistent anatomical alterations. 3. Literally, dis-ease, the opposite of ease, when something is wrong with a bodily function.

Trauma: 1. Physical injury to an infant during its delivery: 2. The supposed emotional injury, inflicted by events incident to birth, upon an infant which allegedly appears in symdelic form in patients with mental illness.

2. The word "disease" has clear historical precedence. The malady produced in fish by total dissolved gas (TDG) supersaturation was identified for many years by the term "gas bubble disease". Early in the 1900s Gorham (1901)[1] first identified the malady as gas-bubble disease in the title of his publication. The word trauma does not appear to have been used until the mid-1980s when it was used in a peer reviewed publication by Alderdice and Jensen (1985), who expressed preference for trauma because pathogens are not primarily involved. Jensen et al. (1986) attributed use of trauma to an earlier report by Fidler (1984). As indicated by the definitions of "disease", the term does not necessarily imply that pathogens are involved.

GBD "signs" v "symptoms"

Use of the word "signs" is more appropriate than the word "symptoms" in addressing the various visible manifestations of GBD. It is appropriate to use "symptoms" for human disorders where the suffering individual is capable of communicating their feelings to others. The word "signs" is appropriate for all other animals and plants where the observer determines the characteristics of the malady.

[1] Gorham, F. P. 1901. The gas bubble disease of fish and its causes. Bulletin of the United States Fish Commission (1899) 19:33-37.

Pressure: mm Hg, Thor, percent saturation

Each of these terms is correctly used to refer to the amount of gas dissolved within a liquid such as water. Most scientists and many others commonly understand the term percent saturation as referring to the amount of an element or compound, such as a gas, that is present in the liquid relative to the amount the liquid can hold at the appropriate or reported temperature and pressure conditions. Use of the technical terms "mm Hg" and "Thor" as indicators of vapor pressure is not widely understood outside that portion of the scientific community commonly dealing with dissolved solutions and related matters. Although the use of these technical terms conveys more precise and often more accurate information, the terms also result in intelligible communication to only a relatively small audience. The term used by the authors in their reports is used in this annotated bibliography, which is commonly percent of saturation.

Hydrostatic Pressure

An understanding of TDG supersaturation and GBD requires an understanding of hydrostatic pressure and how it affects both total dissolved gas (TDG) levels or pressures and GBD. TDG is the only regulated water quality parameter that is greatly influenced by hydrostatic pressure, leading many to fail to understand the significance of hydrostatic pressure. The following figure demonstrates the approximate degree of effect hydrostatic pressure has on dissolved atmospheric gases with depth and thus the potential biological effects.

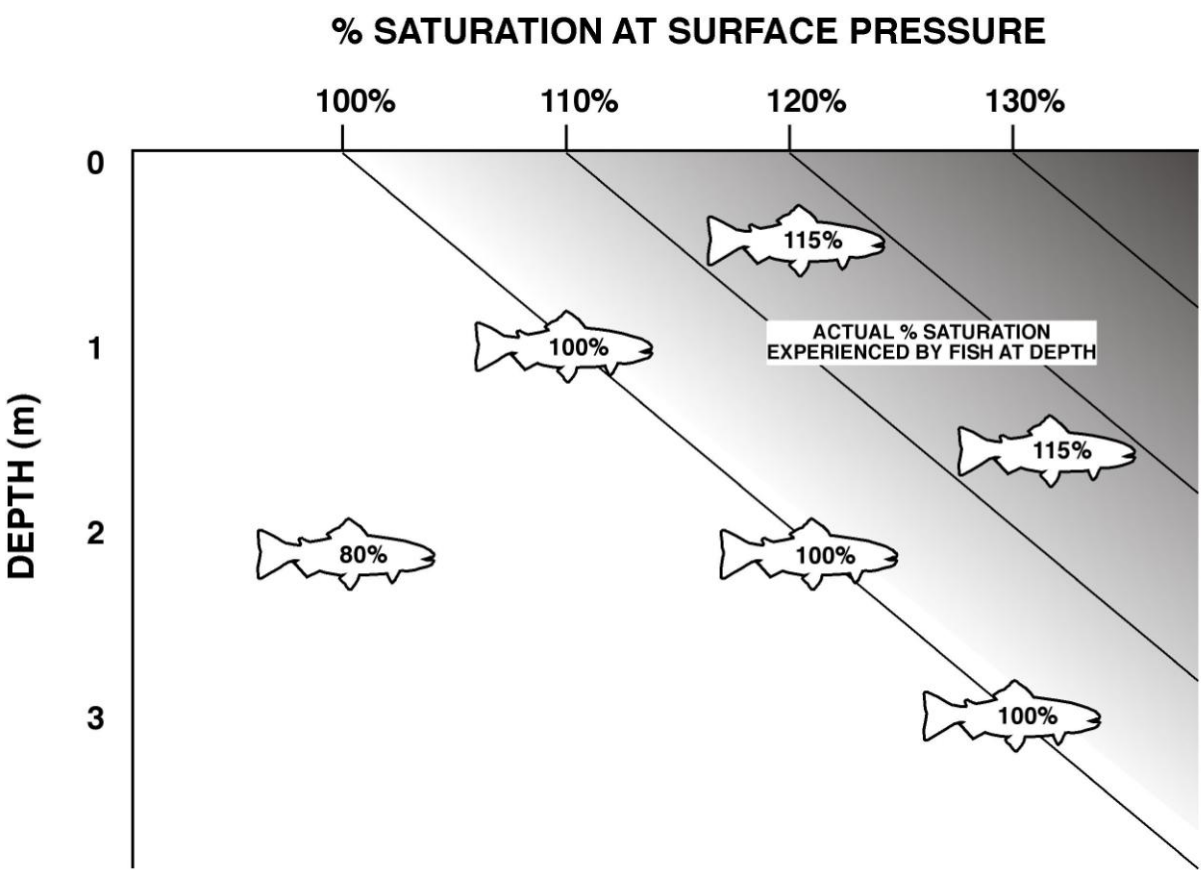

Figure 1. Relationship of measured and actual TDG levels experienced by fish at various depths.

The weight of water is substantial (1 m^3 = 1,000 kg, 1 ft^3 = 62.4 lb) resulting in rapidly increasing pressure with increasing depth. With increased pressure the amount or quantity of gas that will dissolve in the water also rapidly increases. The net result is that at a depth of about 10 m (33.9 ft) the pressure on a water molecule or a biological organism is double that of the pressure at the water surface (atmospheric) pressure. It is the effect of pressure on solubility of gases that results in supersaturation (relative to surface pressure). As long as the pressure remains constant or increases, the dissolved gases have no propensity to come out of solution to form bubbles. Only when the pressure is substantially reduced (generally about 10%) do the gases have a substantial tendency to come out of solution and form bubbles.

Definitions of Common Terms:

GBD: Gas bubble disease involves the formation of bubbles within the tissues of an organism that results in visible signs (bubbles or emphysema), or internal bubbles that result in tissue damage.

TGP : Total gas pressure is the total of all partial gas pressures within the water plus the vapor pressure, commonly expressed as percent saturation (at the local barometric pressure-atmospheric + hydraulic).

ΔP : Pressure differential, the difference between total gas pressure and local barometric pressure.

ANNOTATED BIBLIOGRAPHIES

A

Abernethy, C. S., B. G. Amidan, G. F. Čada. 2001. Laboratory studies of the effects of pressure and dissolved gas supersaturation on turbine-passed fish. Final Report FY 2000. Pacific Northwest National Laboratory, Richland, Washington. 61 p. http://www.pnl.gov/main/publications/external/technical_reports/PNNL-13470.pdf

The gas supersaturation level that causes acute gas bubble disease (GBD) varies among species. Resistance to acute GBD, from greatest to least, is bluegill > fall Chinook salmon > rainbow trout. Bluegills also had a lower incidence of chronic GBD signs than did fall Chinook salmon and rainbow trout. The frequency, type, and severity of injuries related to pressure changes during turbine passage vary among species. Bluegills, and presumably most physoclistous fish, are extremely susceptible to swim bladder rupture when exposed to the sudden pressure change during turbine passage. The total dissolved gas level had only a small additive effect on the injury/death rate due to the pressure spike.

Fall Chinook salmon suffered ruptured swim bladders, but at a much lower rate than bluegills. When acclimated to elevated gas levels at 191 kPa, the turbine passage sequence also caused instantaneous bubble formation in a small number of fish, resulting in immediate death. Swim bladder rupture was not observed in rainbow trout, regardless of total dissolved gas (TDG) level or acclimation pressure. If dissolved gas supersaturation is not a problem, their experiments suggest that the brief low pressure spike to about 0.1 atmosphere downstream from the turbine runner will cause little direct mortality among surface-acclimated salmonids. If fish are entrained from greater depths, such that their swim bladders contain more gas and will expand more during the low pressure spike, the injury and mortality rates will be higher. Injury/mortality rates would likely be reduced or eliminated if the nadir of the turbine pressure spike was higher, as is expected to be the case with new fish-friendly turbine designs. A follow-up series of tests is needed under a modified pressure regime that more closely reflects conditions expected in new turbine designs, or with a nadir of ~50 kPa. The low pressure spike is especially a problem if the water is highly supersaturated with gases (well beyond water quality standards), and the fish respond to the supersaturation by depth compensation.

Abernethy, C. S., D. D. Dauble, and R. L. Johnson. 1997. Feasibility study for evaluating cumulative exposure of downstream migrant juvenile salmonids to total dissolved gas. Report DOE/ID-10853, U.S. Department of Energy, Idaho Operations Office. 66 p. http://pisces.bpa.gov/release/documents/documentviewer.aspx?doc=62611-12

They demonstrated that it was feasible to assemble and deploy a large net pen, using off-the shelf equipment, for mobile monitoring of TDG exposure in the lower Snake and mid-Columbia river area. They were able to accurately monitor vertical and lateral distribution of smolts in the net pen and to document diel differences in their behavior. They observed that fish sounded in response to researcher activity on the net pen perimeter platform. Thus, in-transit monitoring for GBD or mortality would affect fish depth distribution and exposure to TDG. Their principal recommendations for future studies are directed at improving maneuverability of the net pen in adverse weather conditions, providing more vertical space for fish to distribute if they so choose, and applying new acoustics technology to simultaneously collect fish distribution data from within and outside of the net pen.

Absolon, R. F., E. M. Dawley, B. P. Sandford. 1999. Changes in gas bubble disease signs of migrating juvenile salmonids experimentally exposed to supersaturated gasses, 1997. Annual Report 1997 to Bonneville Power Administration, Portland, Oregon. 22 p. http://pisces.bpa.gov/release/documents/documentviewer.aspx?doc=93892-2

Juvenile coho salmon were collected from the smolt monitoring facility at John Day Dam and by gatewell dip netting. Test fish were first PIT tagged and held in circular tanks (1,114-L capacity) where they were exposed to supersaturated gas conditions (average 114.6%). After 48 h exposure time, test fish were examined and the severity of external emphysema recorded. Prevalence of GBD signs ranged from 21 to 86%, averaging 64%. Test fish were released upstream from Turbine Gatewell 8B at the top of the turbine intake ceiling (elevation 61 m Mean Sea Level). Dip netting was conducted in Gatewell 8B to recapture test fish, which were separated from the dip-net catch based on the presence of recent PIT-tag scars. Elapsed time from release to recapture ranged from 20 to 70 minutes for the first recapture effort and from 110 minutes to 3 h for the second recapture effort. Recaptured fish were re-examined using the same technique as the pre-release exam. They recapture a total of 372 (49%) released fish. Recaptured fish did not exhibit a statistically significant change in GBD-sign severity (2.9 to 2.8 index units). Prevalence of GBD signs also did not change. At release, 64% of test fish had signs compared to 65% at recapture. Forebay dissolved gas levels averaged 122.5% of saturation during the test Period.

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.

Embryonic salmon are more resistant to total dissolved gas supersaturation than post-hatch stages. This resistance is explained by hydrostatic pressure within the egg capsule that is higher than atmospheric pressure. Internal pressures are at least 15 mm Hg in eggs, increasing to 50 mm Hg in fertilized embryos, and to as much as 90 mm Hg near hatching. The internal pressures of 50-90 mm Hg are equivalent to about 107-112% saturation at atmospheric pressure.

The authors suggest mortality responses of TDG supersaturation fall into two categories, chronic and acute resulting extra-vascular and intravascular bubble growth respectively. Etiologies and rate processes may be different for each category or phase.

Antcliffe, B. L., I. K. Birtwell, and L. E. Fidler. 2003. Lethal and sublethal responses of rainbow trout (*Oncorhynchus mykiss*) and coho (*Oncorhynchus kisutch*) fry to elevated dissolved gas supersaturation and temperature. Canadian Technical Report Fisheries and Aquatic Sciences 2500. 18 p.

Lethal and sublethal responses of rainbow trout and coho salmon fry to elevated total dissolved gas (TDG) supersaturation and temperature were compared in laboratory experiments. Sublethal behavioral responses were also examined. Survivors were challenged in escape to cover tests to assess behavioral responses not apparent to observers. All treatments (114% TDG, 10°C, 0.25 m, 118% TDG, 15°C, 0.25 m; 125% TDG, 18°C, 0.1 m) failed to produce swim bladder over inflation or rupture, or behavioral effects as compared to control fish treated equally except with air-equilibrated water. The ability of test fish to escape to cover was compromised significantly only at the most severe treatment, which was the only treatment resulting in mortality. These results indicate that swim bladder over inflation was accommodated by these free-swimming fish and that lethal exposures were required to elicit a significant adverse behavioral response of survivors.

Antcliffe, B. L., L. E. Fidler, and I. K. Birtwell. 2002. Effect of dissolved gas supersaturation on the survival and condition of juvenile rainbow trout (*Oncorhynchus mykiss*) under static and dynamic exposure scenarios. Canadian Technical Reports Fisheries and Aquatic Sciences 2370: 70 p.

They exposed juvenile rainbow trout to 110%, 114%, 116%, 122% and 144 % of saturation in water depths of 0.25 m at 10°C. The LT_{50} (time to 50% mortality) was 5.1 h at 140% TDG and 55 h at 122% TDG. At 116% TDG mortality was 42% after a 9 day exposure. All fish survived exposure to 114% TDG for six days, and 110% TDG for nine days. These results are consistent with the threshold equations of Fidler and Miller (1997) that predict water surface differential pressure (ΔP) required to initiate bubble growth in the cardiovascular system or gill filaments of rainbow trout (which equates to approximately 115% to 117% TDG at sea level).

Volitional exposures at 122% TDG (10°C) provided access to depths from 0-1 m, and 0-2.5 m. In dynamic exposures they held fish in cages cycled in a deep tank between the surface (0-0.25 m) for a duration that killed 10% of the sample, then held below the compensation depth for 3 h, and the cycle repeated four times. The cumulative mortality was from 0 to 10% during the first surface interval, and from approximately 10% to 20%, 20% to 30%, and 30% to 40% during the second, third, and fourth surface intervals. 0

Fish use of water depths greater 0.25 m in the 0-1m volitional cage significantly delayed the onset of mortality and reduced cumulative mortality. The time to initiation of mortality was about 36 h compared to 14 h for the static exposure, with cumulative mortality of 22% in the 1 m volition cage and 89% in the static cage for a 96 h exposure. Dynamic exposure delayed re-initiation of mortality when fish were cycled from below the compensation depth, and in some cases reduced the mortality rate at the surface. The absence of mortality at 122% TDG with water depths from 0 to 2.5 m provided evidence that fish occupied depths that compensated for the TDG. Approximately half the fish that died from exposure to TDG greater than 120% had no external GBD signs. Many survivors also had no external GBD signs.

Antcliffe, B. L., L. E. Fidler, and I. K. Birtwell. 2003. Effect of prior exposure to hydrostatic pressure on rainbow trout (*Oncorhynchus mykiss*) survival in air-supersaturated water. Canadian Technical Report Fisheries and Aquatic Sciences 2501. 11 p.

They assessed the effects of TDG supersaturation on juvenile rainbow trout at exposures of 110%, 114%, 116%, 122% and 144 % of saturation in water depths of 0.25 m at 10°C. The LT_{50} was 5.1 h at 140% TDG pressure and 55 h at 122% of saturation. At 116% saturation the cumulative mortality was 42% at 9 days of exposure. All fish survived exposure to 114% saturation for 6 days, and 110% saturation for 9 days. These results are consistent with Fidler (1988) who concluded bubble growth in the vascular system requires a ΔP of about 115% to 117% of saturation at sea level. Increasing the depth of the tank to 1m increased the initiation of mortality from 14 h (0.25 m depth) to 36 h at 122% of saturation. Cumulative mortality during a 96 h test with a depth of 1 m was only 22%, compared to 89% mortality with the 0.25 m depth.

Other tests exposed juveniles to 122% of saturation in cages 0.25 m deep held at the surface for a duration necessary to kill 10% of the fish, then at a depth of 2.5-2.75 m (compensatory depth) for 3 h or 6 h before returning to the surface. The cycle was repeated four times with a surface duration necessary to produce an additional 10% mortality with each cycle. Fish held at depth for 6 h had substantially longer times to initiation of mortality in the 2-4 cycles.

Aspen Applied Sciences Ltd. 2003. TGP performance measures for the Mica water use plan a derivation summary. Unpublished report to BC Hydro, Castlegar, British Columbia, Canada. 8 p.

This project developed predictions for Columbia River total dissolved gas pressures (TDGP) and the corresponding GBD relative risk factors calculated. The spreadsheets were designed using daily average discharge conditions from previous analyses. The risk factor columns were summed over the yearly operations to give a single yearly relative risk factor. This cumulative relative risk factor could then be used for comparing different yearly operational scenarios (e.g., different yearly hydrographs).

B

Backman, T. W. H., and A. F. Evans. 2002. Gas bubble trauma incidence in adult salmonids in the Columbia River Basin. North American Journal of Fisheries Management 22:579–584.

Very few studies have focused on the health threat to adult salmonids from gas bubble disease (GBD) caused by water spill at hydroelectric dams in the Columbia River basin. From 1995 to 1999, 4,667 adult Chinook salmon *Oncorhynchus tshawytscha*, 1,878 sockeye salmon *O. nerka*, and 1,431 steelhead *O. mykiss* at Bonneville Dam were examined to determine the incidence of GBD relative to total dissolved gas supersaturation (TDGS) levels. Polynomial regression models were constructed to determine whether an association existed between increasing levels of TDGS and the incidence of GBD. For sockeye salmon and steelhead, they found a significant positive association between TDGS and the incidence of GBD. However, no statistically significant relationship between TDGS and GBD was found for Chinook salmon. Most GBD signs were minor (<5% fin occlusion), with severe bubbles (>26% fin occlusion) being observed in sockeye salmon (15 fish) and steelhead (2 fish) only when TDGS exceeded 126%. Chinook salmon were rarely observed with GBD, despite the sampling of large numbers when TDGS exceeded 130%.

Backman, T. W. H., A. F. Evans, M. S. Robertson, M. A. Hawbecker. 2002. Gas bubble trauma incidence in juvenile salmonids in the lower Columbia and Snake Rivers. North American Journal of Fisheries Management 22:965–972.

Gas bubble disease (GBD) remains a controversial issue in the lower Columbia and Snake rivers. Despite improvements in the design of spillways at each hydroelectric project, spill continues to produce total dissolved gas (TDG) supersaturation greater than the 110% standard in these rivers. Waivers of the gas standard, 115% TDG in the forebay and 120% TDG in the tailrace, are granted from mid-April through August to allow for increased spill to aid juvenile salmonid migration. Because few studies are based on field-collected data, they chose to monitor uncertainty regarding the actual incidence of GBD signs on juvenile salmonids under various TDG concentrations within the Columbia and Snake Rivers. From 1996 through 1999, they collected smolts from upstream and downstream from dams and compared their incidence of GBD signs with that of smolts collected by the Smolt Monitoring Program in dam bypasses. They found that fewer than 2% of salmonids displayed external GBD signs, and most of those had less than 5% fin occlusion. Gas bubble disease is more common at higher TDG values in fish bypassed at dams than in fish collected upstream or downstream from dams. However, the data for each group follow the same trend of increasing GBD with increasing TDG and produce similar regression curves. The incidence and severity of in-river and bypass GBD signs are less than expected from laboratory studies.

Backman, W. W. H., R. M. Ross, and W. F. Krise. 1991. Tolerance of subyearling American shad to short-term exposure to gas supersaturation. North American Journal of Fisheries Management 11:67-71.

Subyearling American shad *Alosa sapidissima* normally migrate from rivers in the fall and may encounter changes in gas supersaturation levels while traversing hydroelectric dams. To determine whether changes in behavior or survival occur during these events, they exposed subyearling American shad to five levels of gas supersaturation that included pressure increases above equilibrium (ΔP) from 10 to 205 mm Hg (101–128% saturation) for 4 h. Multifactor analysis of variance showed no significant differences in behavior or survival of fish before or after treatment. Gas bubbles were observed on external tissues of fish only at the highest treatment level (ΔP = 205 mm Hg). Factor analysis elucidated three categories of behavioral organization under experimental conditions: boundary, social, and nonsocial behavior. Under gas supersaturation conditions thought to occur in dammed rivers of the eastern USA, the behavior of subyearling American shad does not appear to be affected in a way that might reduce survival during migration.

Becker, S. M., C. S. Abernethy, and D. D. Dauble. 2003. Identifying the effects on fish of changes in water pressure during turbine passage. Hydro Review September p. 1-5.

The information presented in this publication is provided in greater detail in Abernethy et al. 2001. They found fall Chinook salmon, rainbow trout, and bluegill experienced a range of survival and types of injuries resulting from specific pressure drops as well as from pressure decreases with total dissolved gas levels as an additive factor. With a pressure nadir (low point) of 2 to 10 kPa, that simulates the low pressures encountered during turbine passage, 5% of Chinook acclimated at 120% and 135% TDG died from the pressure drop within one hour. Necropsies revealed massive gas bubbles in the heart (TDG 135%) and gas bubble blockage in the afferent lamellar arteries of the gills (TDG 120%), both blocking blood flow to the gills. No rainbow died from the nadir of the 2 to 10 kPa pressure drop, however some rainbow developed a black spot on their heads after 24 h, with the incidence increasing at higher TDG levels. Reduction of pressures to 50 kPa, 68 kPa and 95 kPa produced few or no injuries or mortalities. Bluegills were much more susceptible to injury with a 43% mortality (135% TDG) and a high injury rate. They concluded that species differences are related to differences in swim bladder structure.

Beeman, J. W., P. V. Haner, and A. G. Maule. 1997. Vertical and horizontal distribution of individual juvenile salmonids based on radiotelemetry. Pages 1-37 in Maule, A. G., J. Beeman, K. M. Hans, M. G. Mesa, P. Haner, and J. J. Warren. 1997. Gas bubble disease monitoring and research of juvenile salmonids. Annual Report 1996 (Project 96-021), Bonneville Power Administration, Portland, Oregon.

They found a miniature pressure-sensitive radio transmitter is sufficiently accurate and precise, after compensation for water temperature, to be used to determine the depth of tagged-fish to within 0.32 m of the true depth. Preliminary data from a small number of fish indicates that depth protects migrating juvenile steelhead from total dissolved gas supersaturation.

Beeman, J. W., P. V. Haner, T. C. Robinson, and A. G. Maule. 1998. Vertical and horizontal distribution of individual juvenile salmonids based on radio telemetry. Unpublished report by U. S. Geological Survey, Columbia River Research Laboratory, Cook, Washington.

Copy not available.

Beeman, J. W., and A. G. Maule. 2006. Migration depths of juvenile Chinook salmon and steelhead relative to total dissolved gas supersaturation in a Columbia River reservoir. Transactions of the American Fisheries Society 135:584-594.

The in situ depths of juvenile salmonids were studied to determine whether hydrostatic compensation was sufficient to protect them from gas bubble disease (GBD) during exposure to total dissolved gas (TDG) supersaturation from a regional spill program at dams meant to improve salmonid passage survival. Yearling Chinook salmon *Oncorhynchus tshawytscha* and juvenile steelhead *O. mykiss* implanted with pressure-sensing radio transmitters were monitored from boats while they were migrating between the tailrace of Ice Harbor Dam on the Snake River and the forebay of McNary Dam on the Columbia River during 1997-1999. The TDG generally decreased with distance from the tailrace of the dam and was within levels known to cause GBD signs and mortality in laboratory bioassays. Results of repeated-measures analysis of variance indicated that the mean depths of juvenile steelhead were similar throughout the study area, ranging from 2.0 m in the Snake River to 2.3 m near the McNary Dam forebay. The mean depths of yearling Chinook salmon generally increased with distance from Ice Harbor Dam, ranging from 1.5 m in the Snake River to 3.2 m near the forebay. Juvenile steelhead were deeper at night than during the day, and yearling Chinook salmon were deeper during the day than at night. The TDG level was a significant covariate in models of the migration depth and rates of each species, but no effect of fish size was detected. Hydrostatic compensation, along with short exposure times in the area of greatest TDG, reduced the effects of TDG exposure below those generally shown to elicit GBD signs or mortality. Based on these factors, their results indicate that the TDG limits of the regional spill program were safe for these juvenile salmonids.

Beeman, J. W., T. C. Robinson, S. P. VanderKooi, and P. V. Haner. 1999. Gas bubble trauma monitoring and research of juvenile salmonids, 1998 Annual Report. Prepared by U.S. Geological Survey for Bonneville Power Administration, Portland, Oregon, contract 96-AI-93279.

This report summarizes data collected to determine the *in-situ* depths and TDG exposure of juvenile salmonids in an effort to determine if hydrostatic compensation could explain differences between expected and observed signs of GBD found through the GBD monitoring program. This research used a new pressure-sensitive radio tag to determine *in-situ* depths of juvenile salmonids. The transmitters were placed in yearling Chinook and steelhead in field studies during 1997 and 1998. This report describes *in-situ* data collected in 1998. They found that the median migration depths of juvenile salmonids in McNary reservoir were sufficient to compensate for ambient TDG levels from 117% to 124%, based on a 9.6% hydrostatic compensation per meter of depth. This corresponds to a compensation of 132 to 184 mm Hg of ambient total gas pressure, enough to result in fewer signs of GBD than expected from shallow-tank bioassays. Although TDG levels in McNary reservoir were lower in 1998 than 1997 fish depths were similar in both years. The median migration depths of juvenile Chinook salmon and steelhead in 1998 were 2.4 m, ranging from the water surface to about 12 m. Both species moved up and down in the water column. Their depths in the near-dam forebay were similar to those in the nearby area of the reservoir. The migrations through the study area in 1998 were direct, without the holding behavior noted after mid-May in 1997. Differences in river discharge and elevation are the likely explanations for this change in behavior.

Beeman, J. W., S. P. VanderKooi, P. V. Haner, and A. G. Maule. 2003a. Gas bubble monitoring and research of juvenile salmonids. Annual Report of 1999 Research by U. S. Geological Survey, Columbia River Research Laboratory, to Bonneville Power Administration, Portland, Oregon. 34 p.

This report summarizes data collected to determine the *in-situ* depth distribution and TDG exposure of juvenile salmonids to determine if hydrostatic compensation offered some protection. Juvenile salmon were tagged with pressure-sensitive radio tags and released in McNary Reservoir. The median migration depths of Chinook and steelhead were sufficient to compensate for ambient TDG level of 117% to 126%, based on a 9.6% hydrostatic compensation per meter. This corresponds to a compensation of 132-198 mm Hg. The results support finder fewer GBD signs than expected in the monitoring program. Depths of juvenile salmon were similar in 1997, 1998, and 1999. The median migration depth of juvenile Chinook was 2.4 m in 1999, ranging from the surface to about 10 m deep. Steelhead had a slightly deeper median depth of 2.7 m, and were as deep as 12m

Beeman, J. W., D. A. Venditti, R. G. Morris, B. J. Adams, and A. G. Maule. 2003b. Chapter I: Depths and hydrostatic compensation of farmed fish and wild fish in Rufus Woods Lake. Pages 2-47 in, Beeman, J. W., D. A. Venditti, R. G. Morris, D. M. Gadomski, B. J. Adams, S. P. VanderKooi, T.C. Robinson, and A. G. Maule. 2003. Gas bubble disease in resident fish below Grand Coulee Dam final report of research. U.S. Geological Survey, Western Fisheries Research Laboratory, Cook, Washington. http://wfrc.usgs.gov/pubs/reportpdf/usgsfrgbdgrandcouleedam.pdf#page=8

Archive depth sensing tags were implanted in adult fish of several species to record the depths and temperatures experienced during 16-156 days following release in Lake Rufus Woods downstream from Grand Coulee Dam. Species tagged included triploid steelhead (*Oncorhynchus mykiss*) reared in commercial net pens, wild bridgelip sucker (*Catostomus columbianus*), largescale sucker (*C. macrocheilus*), longnose sucker (*C. catostomus*), northern pikeminnow (*Ptychocheilus oregonensis*), and walleye (*Stizostedion vitreum*). Tags recorded depth (pressure) and temperature every 15 minutes. Tags were recovered from 7 net pen fish, and 17 wild fish. The data showed abrupt depth changes by all fish near sunrise and sunset, with most fish deeper at night than during the day. Longnose suckers and some walleye were shallower during the day and deeper at night. Median depths were steelhead-1.6 m, northern pikeminnow-2.0 m, bridgelip sucker-2.8 m, walleye-3.7 m, longnose sucker 5.2 m, and largescale sucker 6.8 m. The depths of the wild fish were greater than the fish from the net pens. TDG levels during the study were too low to cause gas bubble disease.

Beeman, J. W., D. A. Venditti, R. G. Morris, D. M. Gadomski, B. J. Adams, S. P. VanderKooi, T. C. Robinson, and A. G. Maule. 2003c. Gas bubble disease in resident fish below Grand Coulee Dam final report of research. U.S. Geological Survey, Western Fisheries Research Laboratory, Cook, Washington. 157 p. http://wfrc.usgs.gov/pubs/reportpdf/usgsfrgbdgrandcouleedam.pdf#page=54

This is the final report for research conducted in and related to total dissolved gas supersaturation in

Lake Rufus Woods, the Columbia River reservoir immediately downstream from Grand Coulee Dam in eastern Washington. The final report contains five independent papers dealing with various aspects of the biological effects of TDG supersaturation. They examined over 8000 resident fish for signs of gas bubble disease, examined annual growth increments of several species relative to ambient TDG, and recorded the in-situ depths and temperatures of several species using miniature recorders surgically implanted in both resident fish and triploid steelhead reared in commercial net pens.

Laboratory evaluations of gas bubble disease sign progression and lethality were conducted on longnose sucker, largescale sucker, northern pikeminnow, redside shiner, and walleye. Fish exposed to 125% and 130% TDG died prior to extensive GBD sign formation. The times to 50% mortality (LT_{50}) for all test species were twice as long at 125% as at 130% of saturation. Species sensitivities for 125% of saturation were northern pikeminnow ≥ largescale sucker > longnose sucker > redside shiver > walleye and at 130% were largescale sucker > northern pikeminnow > longnose sucker ≥ reside shiner > walleye.

They examined the growth of resident fishes in Rufus Woods Lake downstream from Grand Coulee Dam to determine if years of high TDG corresponded to years of poor growth. Only walleye had differences in growth based on the environment with growth greater in 1996 than in 1998. As TDG supersaturation was much higher in 1996 than in 1998 they expected the opposite trend would occur in if TDG supersaturation restricted growth.

They evaluated the progression of GBD signs in laboratory exposures, observing differences in the diameters of trunk lateral line pores. Pore diameters differed significantly ($P < 0.0001$) among species (longnose sucker >largescale sucker > northern pikeminnow ≥ Chinook salmon ≥ redside shiner). At all supersaturation levels evaluated, percent of lateral line occlusion was inversely related to pore size but was not generally related to total dissolved gas level or time of exposure.

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

Northern pikeminnow (formerly northern squawfish) were confined in shallow tanks (water depth 0.25 m) for 12 days to study their tolerance to various concentrations of total dissolved gas (TDG). The exposure levels ranged from 100 to 126% of saturation, levels that occur in the Columbia and Snake Rivers during high flow periods. Mortality did not occur in tests at or below 110% of saturation, but 32% of the fish exposed to 117% died within 12 days, and 100% died within 20 hrs at 126%. Average daily food consumption of squawfish decreased in proportion to increased TDG levels. At 100% the pikeminnows consumed 14,2 g/d, at 117% consumption decreased to 6.2 g/d, and 2.3 g/d at 126%. Field investigations indicated that pikeminnows may not be seriously affected by TDG supersaturation from 117 to 141% of saturation. Gill net sampling showed that most pikeminnow were below a depth of 3 m and were therefore not exposed to true supersaturation. High TDG levels did not appear to hinder movement of pikeminnow within 92 km of the study area. Pikeminnow captured by purse seine adjacent to dams were actively feeding on juvenile salmon.

Birtwell, I. K., J. S. Korstrom, M. Komatsu, B. J. Fink, L. I. Richmond, and R. P. Fink. 2001. The susceptibility of juvenile chum salmon (*Oncorhynchus keta*) to predation following sublethal exposure to elevated temperature and dissolved gas supersaturation in seawater. Canadian Technical Report Fisheries and Aquatic Sciences 2343. 147 p.

This is one of a series of reports describing studies on the effects of heated seawater on juvenile chum salmon (*Oncorhynchus keta*). The studies were initiated in response to concerns regarding the potential effects on salmon due to the thermal discharge from British Columbia Hydro and Power Authority's (BC Hydro Burrard Generating Station, into the marine waters of Port Moody Arm, Burrard Inlet, BC, Canada. This study assesses the vulnerability of chum salmon to predation following exposure to various conditions. Chum acclimated to 11 °C seawater were exposed in 43 cm deep tanks to a progressive rise to 21 °C and TDG levels 115%, 120% and 130% for 48-h, 24-h, and 12-h periods respectively. Copper and quillback rockfish (*Sebastes caurinus, Sebastes maliger*), kelp greenling (*Hexagrammus decagrammus*), and Pacific staghorn sculpin (*Leptocottus armatus*) were the predators. Test fish died only in the 130% treatment, in which all fish showed GBD signs. At both 120% and 130% TDG exposures they did not observe a significant difference of treated and control fish eater in individual tests, but did detect significantly greater predation on treated fish in the pooled data.

Bouck, G. R. 1980. Etiology of gas bubble disease. Transactions of the American Fisheries Society 119:703-707.

Gas bubble disease is defined as a noninfectious, physically induced process caused by uncompensated hyperbaric pressure of total dissolved gases. Emboli that form in the blood can cause homeostasis. Three stages of the disease are identified; 1) a latent period of gas equilibration, nonlethal cavitation, and increasing morbidity; 2) rapid and heavy mortality: and 3) protracted survival despite lesions and dysfunction resulting in total mortality. These stages appear to be based on laboratory observations where fish are subjected to lethal supersaturation conditions.

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

The "gasometer" is a device that measures differential dissolved-gas pressures (ΔP) in water relative to barometric pressure (as does the "Weiss saturometer"), but operates continuously without human attention. The gasometer can be plumbed into a water-supply system and requires 8 liters/minute of water or more at 60 kilopascals. The gasometer's surfaces are nontoxic, and flow-through water can be used for fish culture. The gasometer may be connected to a small submersible pump and operated as a portable unit. The gasometer can activate an alarm system and thus protect fish from hyperbaric (supersaturation) or hypobaric gas pressures (usually due to low dissolved oxygen). Instructions are included for calculating and reporting data including the pressure and saturation of individual gases. Construction and performance standards are given for the gasometer. Occasional cleaning is required to remove biofouling from the gas-permeable tubing.

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

Four spring-fed streams in Oregon were monitored at easily accessible locations downstream from the springs at varying periods over a year. These streams showed strongly seasonal variation in gas supersaturation. The hyperbaric pressure of dissolved gas (ΔP mmHg) ranged from a maximum ΔP of 40-70 mmHg in May-September to lows of 5-30 mmHg in winter. Dissolved gas levels followed the same trends at each stream, but hyperbaric pressures were substantially different among the streams. Seasonal temperature differences (6-11 ºC) in several of the streams contributed to the seasonal changes in TDG pressure.

Bouck, G. R. 1996. A survey of dissolved gas levels in fish passage facilities at Columbia and Snake River dams. Report prepared for Direct Service Industries, by S. P. Cramer & Associates, Inc., Gresham, Oregon.

Copy not available

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.

There still is need for research on gas supersaturation as it relates to gas bubble disease. Better methods are required for both measurement and treatment of gas-supersaturated water. We must understand more about physiological and ecosystem responses to high gas pressures if existing tolerance data for individual species are to be applied accurately to field or fish-cultural situations. A better training program is needed for scientists, engineers, and facility operators involved in the monitoring and mitigation of gas-supersaturated waters.

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

Groups of steelhead smolts were reared in seawater (29‰) for two weeks after which about half were returned to seawater. Subsequently they exposed to supersaturation of about 125% of saturation (ΔP of 190 mm Hg) in the water (0.3 m deep) in which they were reared. Sea water was easier to supersaturate with air and required only about 10% of the entrained air which was required in fresh water at the same temperature and pressure. Mean time to first mortality was sooner in sea water. There was not a significant difference in the mean times to death of fish in the two treatments, although fish in freshwater appeared to survive longer.

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

They tested removal of total dissolved gas supersaturation (degassing) using plunges, screens and columns packed with Glitch Ballast rings (1.58, 2.54 and 3.81 cm outside diameter), Tri-pac spheres (4-6 cm outside diameter), or Olin 12-gauge shotcups. Plunges and screens did not provide biologically adequate degassing when hyperbaric pressure (ΔP) exceeded about 50 mm Hg (about 106% barometric pressure). Ballast rings of 2.54 cm size proved more effective than the other sizes or the Tri-pac spheres or shotcups. The effluent gas levels were a function of incoming level of supersaturation, column height, packing type and size, water flow rate and flow rate/cm^2 column. They concluded that packed columns can generally produce biologically acceptable levels of dissolved gases ($\Delta P \leq 15$ mm Hg) when they are adequately designed, properly operated and regularly monitored. However, a single-pass column may not be adequate to protect ultra-sensitive species or life stages of fish and other organisms in shallow water.

Boyd, C. E., B. J. Watten, V. Goubier, and W. Ruiquan. 1994. Gas supersaturation in surface waters of aquaculture ponds. Aquacultural Engineering 13(1):31-39.

During the 1988 and 1989 growing seasons, dissolved gas pressures were measured in 0.04 ha to 0.06 ha earthen ponds (n = 17) used to produce channel catfish or bluegill sunfish, both with and without supplemental aeration. Surface waters in early morning hours (0630 to 0830 h) were typically saturated with nitrogen (N_2) and argon (Ar), less than saturated with dissolved oxygen (DO), and supersaturated with carbon dioxide. Total gas pressures (ΔP) were low, averaging -40 mmHg (range -127 to 62 mmHg). During afternoon hours (1300 to 1500 h) ΔP increased to a mean of 111 mm Hg (range -46 to 334 mm Hg); 34% of afternoon ΔP values were above that known to cause mortality in channel catfish during continuous exposure bioassays (115 mm Hg), yet no excessive mortality was observed. High afternoon ΔP values resulted from DO supersaturation caused by phytoplankton photosynthesis and, to a lesser extent, N_2 and Ar supersaturation. The N_2 and Ar supersaturation apparently resulted from cooling and saturation of surface waters with air during evening hours, and the subsequent increase in water temperature during daylight hours (daily increase = 3-4 ºC; range 1-1 to 7-9 ºC) without sufficient gas release.

Brammer, J. A. 1991. The effects of supersaturation of dissolved gases on aquatic invertebrates of the Bighorn River downstream of Yellowtail Afterbay Dam. Thesis, Montana State University, Bozeman, Montana. 132 p.

The objective of this study was to determine if dissolved gas supersaturation levels in the Bighorn River adversely affect aquatic invertebrates. Benthic and drift samples were collected in August 1986, and April and -September 1987. Sampling sites were 2.4 and 14.5 river kilometers (RKm) downstream from the Yellowtail Afterbay Dam, with the upstream site representing an area where higher incidence of GBD occurred in fish. Supersaturation ranged up to 123%. Community composition was similar between sites and taxa were representative of those commonly found below deep release impoundments. Community structure was similar between sites during April 1987, but differed strongly during late summer and fall sampling periods. Summer temperature differences between sites coincided with the period of highest gas saturation levels confounding interpretation. Eight invertebrate taxa which differed in abundance, between sites and were considered the best candidates for being affected by dissolved gas supersaturation were tested in controlled bioassays. Susceptibility differed between taxa, but all those tested were negatively affected by mean ΔP levels of 181 mm Hg or greater. *Baetis tricaudatis* was the most susceptible with adverse, effects apparent at. ΔP levels of 113 mm Hg. *Ephemerella inermis* and *Tricorythodes minutus* appeared to have susceptibility, thresholds near a ΔP of 120 mm Hg. These levels commonly occur in the Bighorn River. Invertebrate, sensitivity to high gas saturation levels was expressed through increased buoyancy, which could, cause involuntary drift. Total invertebrate densities were greater at RKm 14.5, however densities at RKm 2.4 were not low, ranging from 32,658 to 41,761 organisms/m^2. If dissolved gas supersaturation is causing downstream displacement of invertebrates, upstream migration before oviposition appears to be somewhat compensatory.

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

Gas bubble disease was observed in pink shrimp (*Penaeus brasiliensis, P. paulensis*) held in indoor tanks of unidentified depth. Shrimp began exhibiting convulsions, disorientation and rapid swimming followed by death of most within a few hours. Total dissolved gas pressures were not measured. Dissolved oxygen concentrations were found to be as high as 9.5 mg/l at 21-22 °C (~130% saturation) shortly following the incident. The shrimp developed air-bubbles within their body cavities and fluids that produced convulsions. Other species experiencing mortalities were gastropods (*Bulla striata, Fissurella* sp.), bivalves (*Loevicardium* sp.), an echinoderm (*Lytechinus variegatus*), small barnacles, small crabs, and other shrimps. Supersaturation was caused by air leaks allowing and air water mixture to occur under pressure in a pumped water supply.

C

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.

Vertical responses of juvenile Atlantic croakers (*Micropogon undulatus*) to acute supersaturation of ~145% TDG and to changing temperature were observed in a 2.5-m-tall test cylinder supplied with flowing estuarine water. Supersaturation caused an initial upward movement of fish, although a compensatory downward response seemed to occur after 2-4 hours of exposure. Supersaturation of oxygen resulted in an almost immediate downward movement of fish. Abrupt upward displacement of fish followed water-temperature changes, especially increases. Similarities between the behavior of croakers in these experiments and the behavior of other physoclists after swimbladder volume manipulation suggested that gas supersaturation caused the swim bladders of test fish to inflate, resulting first in upward drift and then in downward swimming to restore neutral buoyancy. A nonlinear response model incorporating this hypothesis accounted for 62% of the variation (over all experiments) in mean vertical displacement of the croakers. Supersaturation-induced inflation of the swim bladder may provide physoclistous fishes a direct mechanism for avoiding gas bubble disease by stimulating the fish to descend to a depth at which no gas has a relative saturation value greater than 100%.

Cochnauer, T. 2000. Summarization of gas bubble trauma monitoring in the Clearwater River, Idaho, 1995-1999. Project Report by Idaho Department of Fish and Game to Bonneville Power Administration, Portland, Oregon. http://pisces.bpa.gov/release/documents/documentviewer.aspx?doc=31259-3

They addressed the extent of gas bubble disease (GBD) in resident fish species, along with anadromous fish species ((steelhead trout *Oncorhynchus mykiss*, Chinook salmon *Oncorhynchus tshawytscha*, coho salmon *Oncorhynchus kisutch* and Pacific lamprey *Lampetra tridentata*) also present in the Clearwater River during a time of flow augmentation (mid-April to mid-August). Monitoring was conducted in the North Fork Clearwater River from Dworshak Dam downstream to its confluence with the Clearwater River and in 41 miles of the Clearwater River downstream to the Snake River at Lewiston. During 5 years over 30,000 fish were examined. The TDG levels exceeded 110% for more than a month during each year and in 1995-1997 exceeded 120% for 10, 17 and 20 days respectively. The incidence of GBD signs was less than 1%. Rainbow trout showed the highest incidence of GBD (4.5% and 9.4%) in 1996 and 1997 when TDG exceeded 120% for the greatest number of days. Most fish showing GBD signs had the lowest rank (mild signs). Small numbers of mountain whitefish and largescale sucker were also observed to exhibit signs of GBD. The incidence of GBD decreased with increasing distance from Dworshak Dam as TDG levels dissipated.

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

This paper discusses the physics of dissolved gases and its terminology. He proposes a provisional standard for computation and reporting dissolved gas levels in freshwater and sea water. Total gas pressure should be reported in terms of excess pressure (ΔP), while component gases such as nitrogen, argon, oxygen, and water vapor should be reported in terms of partial or excess pressure. Barometric pressure, dissolved oxygen, water temperature, and salinity must also be reported. (although some papers have followed this recommendation, most dealing with the biological effects of TDG supersaturation still report TDG levels as percent saturation.).

Colt, J. 1984a. Computation of dissolved gas concentrations in water as functions of temperature, salinity, and pressure. American Fisheries Society, Special Publication 14, Bethesda, Maryland. 155 p.

This handbook provides a thorough review of the various factors involved in total dissolved gas (TDG) supersaturation and the terminology used by those dealing with the physical aspects of TDG. Calculation used to compute TDG and partial pressures of gas components along with various tables used in the calculations are provided.

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

Total dissolved gas levels were monitored at 19 locations in the Sacramento River system during 1981-1982. Dissolved gas levels in the Sacramento River were influence by supersaturated water from the Feather and American rivers. The highest TDG levels in the Sacramento River were measured immediately downstream from the Feather River. Dissolved gas levels are reported as ΔP, mm Hg. During the spring to early summer of each year the ΔP reached the range of 40-50 mm Hg in the lower Sacramento River. Levels of dissolved gas measured in the river are related to levels previously found to be lethal (ΔP of 42 mm Hg) to striped bass larvae held under laboratory conditions (Cornacchia and Colt 1984). Differences in hydrostatic pressure between larvae at depth in the river as compared to lethal laboratory conditions are not discussed. Striped bass larvae do need to reach the surface to fill their swim bladder, however their general depth distribution in the river is likely somewhat deeper. In the laboratory the larvae were positively phototactic and commonly found near the surface.

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

Based on published mass transfer models for the packed column, detailed information is presented on the operational characteristics for degassing as a function of environmental and operating conditions. A mass transfer model for vacuum packed is provided and operational limitations are presented. Column heights in the range of 1-3 m are commonly needed to meet the criteria of ΔP = 20 mmHg and DO of ≥ 90%.

Colt, J., G. Bouck, and L. Fidler. 1986. Review of current literature and research on gas supersaturation and gas bubble trauma. Report DOE/BP-808 Bonneville Power Administration, Portland, Oregon. 54 p. http://pisces.bpa.gov/release/documents/documentviewer.aspx?doc=808

This report is to present recently published information and on-going research dealing with the various areas of gas supersaturation. Much information in this field is published as agency reports with limited circulation and as ‘a result may not be readily accessible to many people. To increase communication between interested parties in the field of gas supersaturation research and control, addresses and telephone numbers of all people responding to the questionnaire are included. Extensive examination of affected animals has failed to consistently identify pathogenic organisms. Water quality sampling has shown that chronic levels of gas supersaturation are commonly present during a significant period of the year. Water quality criteria for gas supersaturation were formulated to protect migrating salmon and trout that experience high levels of gas supersaturation for relatively short periods of time. Small marine fish larvae are significantly more sensitive to gas superstition than salmonids. They concluded the present water quality criteria for gas supersaturation are not adequate for the protection of either salmonids under chronic exposure or marine fish larvae, especially in aquaria or hatcheries.

Colt, J. L. Fidler, and R. Elston. 1994. Review of monitoring plans for gas bubble disease signs and gas supersaturation levels on the Columbia and Snake Rivers. Project Report No. 93-008, Bonneville Power Administration, Portland, Oregon. 198 p.

The authors reviewed GBD monitoring procedures at eight sites on the Columbia and Snake Rivers in 1994. They determined that the smolt and adult monitoring programs should be reviewed in terms of the data requirements and procedures which are needed to make the program statistically valid. The skin peel procedure used for observation of bubbles in the lateral line does not appear to be valid. They concluded that some of the observations for GBD were subjective and should be omitted from future programs. Experimental validation of the GBD protocols and scoring criteria are needed. Problems occurred with the distribution of both biological and dissolved gas data during parts of the spill period. Formal policies on data reduction, quality assurance, and data distribution were needed for both the biological and physical monitoring programs.

They concluded that the level of accuracy and reliability of the GBD monitoring, and the dissolved gas monitoring program may not have been adequate for real-time management of the spill program at that time. This was related to the lack of Standard Operating Procedures (SOPS) for the operation of dissolved gas monitoring equipment, the lack of SOPS for the overall monitoring program, and the lack of a Quality Assurance Program. Thirty-one specific recommendations are presented in the report and are summarized in Section 14 (pages 50 to 53).

Colt, J., K. Orwicz, and D. Brooks. 1984. Effects of gas-supersaturated water on *Rana catesbeiana* tadpoles. Aquaculture 38(2):127-136.

Tadpoles (*Rana catesbeiana*) were exposed to TDG supersaturated water at depths less than 0.25 m produced gas inflation of the gastrointestinal tract. Affected tadpoles floated either with their left sides elevated or on their backs on the surface. These signs were reversed by reducing the dissolved gas levels. A 4-day exposure to a ΔP of 160 to 170 mm Hg had no effect on survival during 30 days post-exposure observation. A 10-day exposure increased mortality and the levels of systemic *Aeromonas hydrophila* bacteria, redleg disease. Bacterial levels returned to control levels after 6 days of recovery.

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

Juvenile catfish were exposed to total gas pressures of –3 to 117 mm Hg in 40-L aquaria of unspecified water depth, but apparently not more than 25 cm based on aquaria dimensions (28 x 25 x 49 cm). Fish exposed for 35 days had a 1% mortality at 76 mm Hg (110% of saturation), and a 54% mortality at 117 mm Hg (115% of saturation). At 115% of saturation most of the mortality (40%) occurred within the first eight days, with the additional 14% occurring over the following 27 days of the experiment. Approximately 50% of the fish held in 110% of saturation had white colored and eroded dorsal fins.

These signs were not evident in fish held at 115% of saturation. No detectable pathological signs were observed in the histological examination of organs and tissues of surviving fish. The growth of surviving fish was not influence by TDG supersaturation.

Colt, J., K. Orwicz, and D. L. Brooks. 1987. Gas bubble trauma in the bullfrog *Rana catesbeiana*. Journal of the World Aquaculture Society 18(4):229–236.

Adult bullfrogs, *Rana catesbeiana*, were exposed to water supersaturated with atmospheric air. Exposure to a differential pressure (ΔP) of 250 mm Hg (TDG = 132.9% of atmospheric pressure) resulted in a 40% mortality within one day owing to the accumulation of gas in the vascular system. Exposure to a ΔP of 128 mm Hg (TDG = 117%) for four days had no effect on bullfrog mortality, but produced subcutaneous gas bubbles in the webbing and on body surfaces, followed by hyperemia (tissue engorged with blood through blood vessel dilation), and petechial (small subcutaneous hemorrhage spots) and large subcutaneous hemorrhage spots. Owing to accumulation of gas under the skin, these frogs typically floated and were unable to remain submerged. These clinical signs are similar to those commonly reported for "redleg" disease syndrome in bullfrogs. When held at a ΔP of 67 mm Hg (TDG = 109%) for 27 days, no clinical GBD signs were observed.

Colt, J. E., K. Orwicz, and D. Brooks. 1991. Gas supersaturation in the American River California USA. California Fish and Game 77(1):41-50.

Dissolved-gas supersaturation was monitored in the American River during 1982-1983 and 1985-1986. Dissolved gas levels during spring and summer were considerably higher than had been reported necessary to produce increased mortality due to chronic GBD in hatchery salmonids. The source of this gas supersaturation was from natural mechanisms: air entrainment, solar heating, and photosynthesis. During central California's major flood of February 1986, acutely lethal levels of gas supersaturation (200-240 mm Hg) were present in the American River and resulted in significant mortality of salmonid fishes at the American River and Nimbus hatcheries. The most probable source of this gas supersaturation was air entrainment at Folsom Dam. The impact of the high dissolved gas levels in hatchery water supplies was reduced with the installation of degassing structures in the raceway headworks.

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

The use of submerged aerators in hatcheries can produce lethal levels of dissolved gases. Because the mass-transfer relationships for oxygen, nitrogen, and argon are similar, the aerators with the highest oxygen transfer efficiencies also produce the highest levels of TDG. The dissolved-gas levels produced by aeration depend on ΔS_{∞}, the percent gas supersaturation in the aeration basin after a long period of aeration divided by the depth of the aeration basin; N_0, the standard transfer efficiency; the depth of the aeration basin; and the number of aerators used in series. The effect of these parameters on dissolved-gas concentrations are presented for conditions typical of trout and salmon hatcheries. The prevention of lethal and sublethal gas levels will result in a significant decrease in the efficiency of submerged aeration systems for oxygen transfer in aquaculture.

Counihan, T. D., A. I. Miller, M. G. Mesa, and M. J. Parsley. 1998. The effects of dissolved gas supersaturation on white sturgeon larvae. Transactions of the American Fisheries Society 127:316-322.

White sturgeon (*Acipenser transmontanus*) spawned in the Columbia River can be exposed to total dissolved gas supersaturation. The timing and location of white sturgeon spawning and the dispersal of white sturgeon larvae from incubation areas makes the larval stage potentially vulnerable to the effects of TDG. To assess the effects of TDG supersaturation larvae were exposed to 118% and 131% of TDG saturation in the laboratory with maximum available depths of 25 cm. Exposure times of 15 minutes were sufficient to produce a bubble in the buccal cavity and/or nares, and it first occurred at developmental stages characterized by the formation of the mouth and gills. No mortality occurred in larvae held at 118% of saturation for 10 days. A 13 day exposure to 131% saturated water caused a 50% mortality of the larvae. GBD in the larvae resulted in positive buoyancy and altered behavior. The depth distribution of white sturgeon larvae in the Columbia River is unknown. These results appear to represent a worst-case condition for the larvae that may experience hydrostatic compensation provided by greater water depth in the river conditions.

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

They found gas bubble disease (GBD) in larval striped bass *Morone saxatilis* (Walbaum) was characterized by over inflation of the swim bladder and the formation of intestinal bubbles. This accumulation of gas hindered the fish's normal swimming. In extreme cases nearly the entire digestive tract was reduced to a squamous inner epithelium surrounded by a thin serosa. A significant increase in swim bladder volume was observed at total gas pressures as low as 102.9% saturation and mortality increased at 105.6-106.0% saturation in exposure at depths of 10 cm or less. Sensitivity of the larvae decreased with age. Thirty-day old larvae were less sensitive to gas supersaturation than 10-19 day-old larvae.

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

Gas bubble disease downstream from Harry S. Truman Dam, sited on the upper Osage River and spilling into Lake of the Ozarks, caused the largest fish kill on record in Missouri. This is the first recorded evidence of serious supersaturation in the Midwest. Total gas saturation levels up to 139% killed nearly a half million fish in the upper 85 km of the Osage Arm, Lake of the Ozarks, during April-June, 1978 and 1979. Gas supersaturation occurred throughout the 150 km of this main-stem reservoir. Nitrogen was the primary gas responsible for gas bubble disease mortalities. Pelagic and near-shore species suffered the earliest and heaviest mortalities, but fish characteristic of deeper waters were increasingly killed as supersaturation persisted. Instream cage bioassays defined the zone of lethal supersaturation. Some mortality occurred in bottom-dwelling fish of several species, due to long-term intermittent exposure. Susceptibility to gas bubble disease was related to fish size.

D

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.

Supersaturation of air or other gases in water can be caused by a temperature increase, air or gas injection by pressurized pumping, or turbulent injection by falling water which traps air when spills are allowed by hydroelectric projects. Evaluation of TDG supersaturation requires both an understanding of the physics of the situation and practical knowledge of a number of alternative techniques for analysis. These range from complex, exacting procedures commonly used in the biomedical analytical laboratory to simple, portable methods well suited to use in the field or continuous monitoring. The authors reviewed and refined several of these methods, developed others, have compare a number of relevant techniques in the field and laboratory. This paper is useful for understanding how TDG measurements were made prior to the nearly uniform use of modern equipment that employs semipermeable membranes.

Dauble, D. D., and R. P. Muller. 1993. Factors affecting the survival of upstream migrant adult salmonids in the Columbia River Basin. Recovery issues for threatened and endangered Snake River salmon technical report 9 of 11. Report, Battelle, Pacific Northwest Laboratories, Richland, Washington. 72 p.

The Bonneville Power Administration was developing conservation planning documentation to support the National Marine Fisheries Service's recovery plan for Columbia Basin salmonid stocks that are currently listed under the Endangered Species Act (ESA). Information from the conservation planning documentation will be used as a partial scientific basis for identifying alternative conservation strategies and to make recommendations toward conserving, rebuilding, and ultimately removing these salmon stocks from the list of endangered species. This report describes the adult upstream survival study, a synthesis of biological analyses related to conditions affecting the survival of adult upstream migrant salmonids in the Columbia River system. The objective of the adult upstream survival study was to analyze existing data related to increasing the survival of adult migrant salmonids returning to the Snake River system. The fate and accountability of each stock during its upstream migration period and the uncertainties associated with measurements of escapement and survival were evaluated. Operational measures that affected the survival of adult salmon were evaluated including existing conditions, augmented flows from upstream storage release, and drawdown of mainstem reservoirs.

They concluded that dissolved gases then imposed a moderate risk on spring and summer Chinook salmon because they migrate during the spring spill period. This risk would be reduced under the natural river option because there would be little or no spill over the Snake River dams. However, relative risk at the lower Columbia River dams could be higher if increased flows and higher spill were encountered there. Because of their migration timing, there is little or no risk to fall Chinook salmon from high concentrations of dissolved gases.

Dawley, E. M. 1986. Effect of 1985-86 levels of dissolved gas on salmonids in the Columbia River. Report DACW57-85-F-0623 by National Marine Fisheries Service, Seattle, Washington. 31 p.

Gas bubble disease (GBD) in the Columbia and Snake Rivers became evident in the 1960s and was attributed to supersaturation caused by high volumes of water flowing over spillways at dams. During 1985 and 1986, the impacts of supersaturation in the lower Columbia River (McNary Dam to the estuary) were minimal to juvenile and adult salmonids. In 1985 TDG levels seldom exceeded 120%. During the week of the highest TDG levels (first week in May) monitoring of migrants at The Dalles and Bonneville Dams did not detect any fish with GBD signs. GBD signs were not observed in yearling Chinook held for 5 days (TDG 111-118%) in live cages with depths of 0-1, 2-3, 3-4, and 0-6 m. The small numbers of mortalities were not attributed to GBD. Hydroacoustic observations of the vertical distribution of migrant salmonids in The Dalles Dam forebay indicated that 50% of yearling Chinook were within 4.6 m of the surface. Subyearling Chinook were deeper with 50% within 9 m of the surface. Less than 20% tended to be within the top 3 m, and both groups tended to be deeper at night than during the day.

In 1986 rapid snowmelt produced TDG levels of ≥120% throughout much of the river in late May and early June. In early June GBD signs (predominately cutaneous bubbles) were observed in one or two fins of 0-7% of fish observed. At Bonneville Dam juvenile steelhead had a 13-16% incidence of GBD signs during a three day period, with 2% showing severe signs (massive areas of bubbles in fins, on opercula's, on in buccal cavities). GBD signs were not observed in 28 adult Chinook and steelhead examined at McNary Dam (RKm 470, RM 292).

Dawson, V. 1986. Computer program calculation of gas supersaturation in water. Progressive Fish Culturist 48:142-146.

This paper provides a short computer program, written in BASIC for the Apple IIe or IBM PC computer, efficiently performs all the calculations required to determine gas pressure and percent saturation values for water. Input for the program is limited to empirical determinations of barometric pressure, water temperature, differential dissolved gas pressures, dissolved oxygen, and salinity. An optional routine is included for obtaining a printed report of input data and results. The program can be easily modified to run on most other microcomputers that use BASIC programming language.

Dunnigan, J. L. 2002. Kootenai River fisheries monitoring results from the spill events at Libby Dam, June-July 2002. Montana Fish, Wildlife and Parks, Helena, Montana. 30 p.

Spill at Libby Dam on the Kootenai River during June and July produced TDG supersaturation (120->125%) during spill events that lasted from less than one hour to 58 h in duration. TDG supersaturation resulted in GBD signs in fish observed within 1.7 miles downstream from the dam. Captive fish were held in cages, fish were collected from the river by electrofishing, and radio telemetry was used to track fish movement or displacement during spill. All captive fish had GBD signs during spill, while less than 1% of the fish collected by electrofishing showed GBD signs. Hydrostatic compensation apparently explains the observed different responses to TDG supersaturated water for captive fish and fish captured via electrofishing, although available river depths were not great (ft). Due to the narrow range of depths available within the hoop traps (2-ft diameter) used to collect fish and relatively shallow positioning of the hoop traps (3-6 ft), captive fish had little opportunity for hydrostatic compensation. The majority of the bull trout, rainbow trout and mountain whitefish captured via electrofishing downstream from Libby Dam on July 24, one week after the final spill event at Libby Dam, exhibited fin damage. This damage was presumably caused by necrosis of the fin tissue between the fin rays that was initially caused by gas emboli within the fins. Although the supersaturated water tends to remain along the left bank downstream from Libby Dam, they did not detect avoidance of this area by radio tagged fish.

Duvall, D., M. Clement, and T. Dresser. 2002. Biological monitoring of gas bubble trauma occurrence at Priest Rapids Dam, 1996-2002. Final Report, Public Utility District No. 2 of Grant County, Ephrata, Washington. 66 p.

The PUD monitored total dissolved gas (TDG) levels and its effects on juvenile salmonids since 1996. The report contains data collected during the 2001 and 2002 spring and summer spill seasons and summarizes data from 1996-1999. Chinook (*Oncorhynchus tshawytscha*), sockeye (*O. nerka*), coho *(O. kisutch*) and steelhead (*O. mykiss*) were captured and observed for external signs of gas bubble disease (GBD) at Priest Rapids Dam gatewells. Monitoring followed the protocol utilized by the Fish Passage Center's (FPC) Smolt Monitoring Program which is used at many locations throughout the Columbia and Snake Rivers. The objective was to continue GBD fish examinations and record the presence of bubbles observed on salmonids as they migrate through the project.

A total of 1,818 juvenile salmonids were examined for GBD signs during the 2001 spring spill season, with 3.9% found to exhibit some signs. During the summer spill conditions in 2001, 1352 fish (predominantly Chinook) were examined with GBD signs observed in 2.7%. The average level of TDG was 109.8%. The lowest incidence of GBD was found in 1999 with only 1.7% of fish examined showing external signs with average TDG rate of 113%. The two highest GBD rates of 5.8% and 4.7% were during periods when TDG levels averaged 113% (2000 and 1998 respectively).

A total of 3170 fish were captured, examined for the incidence of GBD, and released downstream from Priest Rapids Dam during the 2001 season. The total GBD rate was 3.3%. The relatively low rate could possibly be attributed to an overall low water year due to low snow pack levels the previous winter. During the spring spill 2002 season, a total of 1243 fish were examined for GBD signs. Fifty four fish were found to have GBD signs with a total rate of 4.3% with an average TDG% saturation in Priest Rapids forebay of 116.3% on examination days. An additional 1,035 fish were also examined for GBD during summer spill with 5.9% of all fish displaying GBD signs. Only Chinook exhibited signs of GBD. The maximum observed GBD rate occurred during the 1997 spring with 11.1% of fish showing GBD signs during a period with average TDG of 130%. The lowest observed rate of GBD was 3.6% during spring spill in 1999 with TDG levels of 114%. During summer spill conditions, 2002 had the highest GBD rate of 5.9% and with an average TDG level of 120.1%. The lowest GBD rate was 1.7% in 1999 with an average TDG level of 113%. In reviewing the previous 7 seasons of data, it can be generally surmised that higher levels of TDG will lead to a higher incidence of GBD but many other factors will also ultimately decide the exposure of migrating salmonids to GBD. For data reported in 2000-2002, more than 90% of the fish showing GBD signs had minor rank 1 signs (5% or less of area affected), and none had sever rank 4 signs (> 50% of area affected).

E

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

Juvenile abalone were exposed to supersaturated oxygen conditions (about 150–200% of saturation) in order to reproduce similar conditions encountered in intensive husbandry systems and to then study the resultant lesions. Depigmentation, lethargy and swelling of tissues were observed clinically. Histopathology showed that the cytoplasmic vacuoles of large haemocytes were enlarged. Oxygen emboli were observed throughout the muscular tissue and connective tissue but separation of fibrous neural sheath from nerve cell bodies and surrounding tissue was the predominant lesion. Chromatin of the nuclei of nerve cells became marginated. Gaseous emboli were observed at various other locations in the vascular system. At termination of the experiment all animals sampled bacteriologically showed systemic infection with *Vibrio alginolyticus*. The clinical signs appeared to result from mechanical interference caused by the accumulation of oxygen and from dysfunction of neural structures. The predominant histopathological changes occurred after only 3 h or less exposure time.

Elston, R., J. Colt, S. Abernethy, and W. Maslen. 1997a. Gas bubble reabsorption in Chinook salmon: pressurization effects. Journal of Aquatic Animal Health 9:317-321.

Gas bubble disease (GBD) was experimentally produced in young Chinook (*Oncorhynchus tshawytscha*) in 39-L laboratory aquaria for about 20 hr. Test fish were then exposed to pressure equivalent to a head of 30.5 m. Fish were then examined for GBD signs following exposure to the increased pressure of 5, 30, 60, and 120 minutes. Bubbles were quickly lost from gills and the lateral line, but substantially slower from the fins. Bubbles in gills were found to dissipate in less than 10 minutes in preliminary experiments. Bubbles in the lateral line were nearly absent at 30 minutes following application of the increased pressure. Bubbles in fins were reduced by 50% by 30 minutes at the increased pressure head and were nearly absent at 120 minutes.

Elston, R., J. Colt, P. Frelier, M. Mayberry, and W. Maslen. 1997b. Differential diagnoses of gas emboli in the gills of steelhead and other salmonid fishes. Journal of Aquatic Animal Health 9:258-264.

Monitoring of salmonid smolts in the Columbia River system during the 1994-96 outmigration periods revealed that it could be difficult to identify and distinguish true gas emboli (resulting from GBD) from other microscopic tissue structures observed during examination of wet mounts of gill tissues. Laboratory exposure of steelhead *Oncorhynchus mykiss* and Chinook salmon *O. tshawytscha* to supersaturated water and field examinations of 477 out migrant steelhead were conducted to characterize the appearance of true gas emboli in gills and to differentiate these from other similarly appearing structures. Gas emboli completely dissipated from excised gills within approximately 2-15 minutes under typical observation conditions and within about 30 minutes in intact gills of fish removed from the water. Gas emboli were glistening, elongated, rapidly diffusing intravascular bodies when examined in wet mounts of gill tissue. Other glistening amoeboid globules found at the distal aspect of primary lamellae were non-diffusing. Histochemical analysis demonstrated that these structures were osmiophilic, indicating their lipid character. The source and function of these extra vascular osmiophilic structures is unknown. Diffusibility, shape, location in the gill filament, and reflectance are the key characteristics to distinguishing lipid bodies from true gas emboli.

F

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

The effects of induced, rapid depressurization upon largemouth bass (*Micropterus salmoides*), simulating conditions common to deep-water angling, were examined. Depths of 0.0, 9.1, 18.3, and 27.4 m were simulated in a large hyperbaric chamber. Statistical analyses indicated that significant mortality occurred when fish were depressurized from simulated depths of 18.3 and 27.4 m. Individuals depressurized from all depths experienced bloating and some external hemorrhaging, while those depressurized from simulated depths of 18.3 and 27.4 m experienced severe internal hemorrhaging and formation of gas bubbles in their blood. If largemouth bass are caught at depths greater than 18.3 m, at least 40% mortality will result from depressurization alone. Therefore, anglers may have to refrain from fishing at these depths if they intend to release their catch.

Feil, D. H., and D. W. Rondorf. 2000. Horizontal and vertical distribution of juvenile salmonids in the Columbia River in relation to total dissolved gas. Unpublished report to U.S. Army Corps of Engineers, Portland District, Portland, Oregon. 100p. http://www.nwp.usace.army.mil/PM/E/reports/afep/misc/FinalGasReport.pdf.

In general, larger percentages of migrants were observed above the depth of compensation during daytime sampling. During early-May daytime sampling in McNary reservoir, they found that 23% near the WA shore, 33% near the center (CTR), and 18% of the total fish density near the Oregon shore were at or above the TDG compensation depth (2 m). However, during nighttime sampling, they found that only 14% of those near the Washington shore, 20% at the CTR, and 9% of the total fish density near the Oregon shore were at or above the TDG compensation depth (2 m). During mid-May stationary point sampling, they found that 18% at Washington shore, 39% at CTR, and 30% of the total fish density at the OR shore site were at or above the TDG compensation depth (2 m WA; 2.5 m OR/CTR) during the daytime. During nighttime sampling, 18% of the total fish density at the Washington shore, 23% at the CTR, and 25% at the Oregon shore site were at or above the TDG compensation depth. During the late-May sampling period, when mostly subyearling Chinook salmon were present in the reservoir, they found that 3% near the Washington shore, 40% at the CTR, and 24% of the total fish density near the OR shore were at or above the TDG compensation depth (2 m). During nighttime sampling, they found that 19% near the Washington shore, 23% at the CTR, and 28% of the total fish density near the Oregon shore were at or above the TDG compensation depth (2 m).

Fickeisen, D. H., and J. C. Montgomery. 1978. Tolerances of fishes to dissolved gas supersaturation in deep tank bioassays. Transactions of the American Fisheries Society 107:376–381.

Four species of fish were tested for tolerance to dissolved atmospheric gas supersaturation in 10-day bioassays conducted in a 3.2 m deep tank. Fish were held in 20 cm deep cages within the tank at depths representing true TDG supersaturation of 100% to 128%. All mountain whitefish (*Prosopium williamsoni*) and cutthroat trout (*Salmo clarki*) exposed to 128% TDG died within one day and all at 124% TDG died within 2 days. At 120% TDG most all whitefish and cutthroat were dead by the fourth day. Largescale sucker (*Catostomus machrocheilus*) were more resistant to TDG supersaturation with complete mortality at 124% TDG taking six days and 20% of the fish remaining alive through 10 days at 120% TDG. Torrent sculpins (*Cottus rhotheus*) were highly resistant with 50% surviving 120% through 10 days at 128% TDG and only 30% mortality at 120% TDG. The increasing hydrostatic pressure due to water depth reduced the levels of saturation of dissolved gases and increased survival of each species. Torrent sculpins typically developed large bubbles of gas which caused them to float and would contribute indirectly to death.

Fidler, L. 2003. TGP performance measures for the Columbia River WUP, a brief summary. Unpublished report to B.C. Hydro, Castlegar, British Columbia. 8 p.

He concluded that TDG supersaturation was not an important factor in comparing the different operational alternatives considered in the Water Use Planning (WUP), however, it has been important from the perspective of the dramatic reductions that have taken place in Columbia River TDG levels since the early 1990s. Hildebrand (1991) found low levels of GBD signs in free-swimming fish despite high TDG levels. Reexamination of the 1990 river TDG levels (Aspen Applied Sciences Ltd. 2002) established that rather than the reported TDG levels of 119-121% measured by Hildebrand were actually in the 137-140% range. The high levels resulted in rapid deaths of the caged fish (Hildebrand 1991). The extremely high TDG levels were the result of all river flow passing through the dam spillways for more than 200 days continuously during 1990. He concluded that running the 1990 operations through the cumulative risk assessment analyses would show that the difference between the 1990 operations and those specified by the current local operating order might produce at least an order of magnitude difference in cumulative risk factors. Overall, between 1990 and the current local operating order, there could potentially be up to 4 orders of magnitude improvement in GBD risk in the Columbia River.

Fidler, L. E. 1988. Gas bubble trauma in fish. Dissertation, University of British Columbia, Vancouver, British Columbia.

Fish exposed to gas supersaturated water often experience gas bubble disease (GBD). GBD is an acute condition involving various forms of bubble growth both internal and external. Theoretical models are developed that establish thresholds for bubble growth and apply to:

1. Bubble growth in the fish's vascular system.
2. Bubble growth in water that can occur in the buccal cavity and between gill lamella.
3. Over inflation of the swimbladder.
4. Subdermal bubbles under external skin (i.e. opercula surface, between fin rays, lining of mouth).

He established the effective size of nucleation sites based on literature data and a two phase experimental program exposing fish in shallow water (10 cm). Various filters based on length, species, TDG, oxygen partial pressure (pO_2), and other criteria were applied to a database of over 1,000 records. This analysis suggested that a lower threshold occurs at TDG level of 1.1 atms and a higher threshold at 1.15 to 1.18 atms. However, he did not establish that the apparent mortality thresholds correspond to thresholds for bubble growth predicted by the theoretical models.

A preliminary experimental study showed that arterial pO_2, hematocrits, and blood pressure yield unique responses to bubble growth over specific ranges of TDG. The experiments also indicated that the lower mortality threshold is associated with a combination of subdermal bubble growth in the mouth and extracorporeal bubbles growing between gill lamella. A second set of experiments confirm the lower mortality threshold of 1.1 atms, and that the upper TDG threshold of 1.15 to 1.18 atms corresponds to the threshold for intravascular bubble growth. The results also confirm that intravascular bubble growth thresholds are dependent on water pO_2. The effective size of nucleation sites responsible for bubble formation and growth were then back calculated from the theoretical threshold equations.

Fidler, L. E., and S. B. Miller. 1993. British Columbia water quality guidelines for dissolved gas supersaturation. Unpublished Report, British Columbia Ministry of Environment, Canada Department of Fisheries and Oceans, Victoria, British Columbia. http://www.env.gov.bc.ca/wat/wq/BCguidelines/tgp/index.html

This document provides a review of available literature on causes and effects of TDG supersaturation and a summary of TDG supersaturation information available for British Columbia.

Fryer, J. K. 1995. Investigations of adult salmonids at Bonneville Dam for gas bubble disease. Columbia River Inter-Tribal Fish Commission report to National Marine Fisheries Service, Portland Oregon. 10 p.

Sockeye *(Oncorhynchus nerka*) and Chinook salmon (*O. tshawytscha*) and steelhead (*O. mykiss*) were trapped and examined at the Bonneville Dam Fisheries Engineering and Research Laboratory, located at river km 225 on the mainstem Columbia River. Sampling was conducted three days-per-week during the period between May 14 and June 24, 1995 for 6 to 8 h/day. He estimated that 3.1% to 4.2% of the adult salmonids passing Bonneville Dam were sampled. No visible GBD signs were observed at Bonneville Dam between May 14 and June 24. In a separate co-operative research study conducted with the Yakama Indian Nation, the Confederated Tribes of the Umatilla Indian Reservation, and the Washington Department of Fish and Wildlife at the Hanford Reach, Washington, no visible GBD signs were noted in the approximately 185,000 juvenile fall Chinook salmon sampled for this study.

G

Gale, W. L., A. G. Maule, A. Postera, and M. H. Peters. 2004. Acute exposure to gas-supersaturated water does not affect reproductive success of female adult Chinook salmon late in maturation. River Research and Applications 20(5):565-576.

The goal of this project was to determine if acute exposure to total dissolved gas (TDG) supersaturation affects the reproductive performance of female Chinook salmon late in their maturation. During this study, adult female spring Chinook salmon were exposed to mean TDGS levels of 114.1% to 125.5% in water depths of 0.5 m. They ended exposures at first mortality, or at the appearance of impending death (due to TDG exposure). These signs were typified by rapid and erratic swimming and jumping, followed by an apparent inability to remain upright in the water. Based on this criterion, exposures lasted from 10 to 68 h and were inversely related to TDG levels. There was no effect of TDG supersaturation on pre-spawning mortality or fecundity when comparing treatment fish to experimental controls or the general hatchery population four to six weeks after exposures. Egg quality, based on egg weight and egg diameter, did not differ between treatment and control fish. Fertilization rate and survival to eyed-stage was high (> 94%) for all groups. With the exception of *Renibacterium salmoninarum* (the causative agent of bacterial kidney disease; BKD), no viral or bacterial fish pathogens were isolated from experimental fish. The prevalence (about 45%) and severity of *R. salmoninarum* did not differ among the groups or the general hatchery population. They conclude that these acute exposures to moderate levels of gas-supersaturated water - perhaps similar to that experienced by immigrating adult salmon as they approach and pass a hydropower dam on the Columbia River - did not affect reproductive success of female Chinook salmon late in their maturation. These results are most applicable to summer and fall Chinook salmon, which migrate in the summer/fall and spawn shortly after reaching their natal streams.

Gledert, D. A., J. S. Gulliver, and S. C. Wilhelnms. 1998. Modeling dissolved gas supersaturation below spillway plunge pools. Journal of Hydraulic Engineering 124:513-521.

Supersaturation of dissolved gases, primarily nitrogen and oxygen, can cause gas bubble disease, and eventual mortality, in fish. This potential threat is currently a concern in efforts to aid anadromous fish survival in the northwestern United States. In an effort to better understand dissolved gas supersaturation

and assist in its mitigation, physically based relationships have been expanded and developed to predict dissolved gas supersaturation downstream from spillways. This paper discusses the predictive technique as applied to the dissolved gas supersaturation that occurs because of conditions within the stilling basin and the river reaches immediately downstream of the structure. Gas transfer across both the water surface and the bubble interface are considered. Extensive field data from three spillways on the Columbia and Snake Rivers is used to fit coefficients that the predictive relationships require. The inclusion of more physically based parameters will allow for the evaluation of the operation and design of the structures and may provide insight for efforts to mitigate high dissolved gas concentrations downstream of such structures.

Grassell, A. C., and W. M. Hampton. 2001. Gas bubble trauma monitoring at Rocky Reach and Rock Island dams, 2001. Final Report, Chelan County Public Utility District, Wenatchee, Washington. 33 p. + appendices. http://www.chelanpud.org/rr_relicense/existing/hcp/Studies/2001%20Report.pdf

Chelan PUD monitored total dissolved gas (TDG) at Rock Island and Rocky Reach hydroelectric projects from April 1 - August 31 2001. This is normally the period of spring and summer spill programs to aid the juvenile salmonid out migrations. However, spill regimens were reduced due to the drought conditions in 2001. No water was spilled at Rocky Reach Dam in 2001. Summer spill did not occur at Rock Island Dam. Spill for juvenile fish passage occurred at Rock Island Dam from April 20 - June 17. During the spring the TDG levels at Rocky Reach forebay averaged 108% (104-113%), and in the tailrace averaged 108% (105-113%). Downstream in the Rocky Reach forebay TDG levels averaged 105% (100-110%), and in the tailrace averaged 113% (102-121%). Summer TDG averages were similar.

Grassell, A. C., W. Hampton, and R. D. McDonald. 2000a. Gas bubble trauma monitoring at Rocky Reach and Rock Island dams, 2000. Chelan County Public Utility District, Wenatchee, Washington. 23 p. + appendix. http://www.chelanpud.org/rr_relicense/existing/hcp/Studies/3852_1.pdf

Monitoring of juvenile salmon was conducted again in 2000 at Rocky Reach and Rock Island Dams following the Fish Passage Center protocols. They examined 7,697 juvenile Chinook salmon and steelhead, 4,100 at Rocky Reach Dam and 3,597 at Rock Island Dam. The incidence of GBD was 2.73% at Rocky Reach Dam and 3.47% at Rock Island Dam. The occurrence of GBD in juvenile salmon at Rocky Reach Dam indicates the fish are experiencing GBD prior to reaching the Chelan County PUD projects. The incidence of GBD was significantly higher at Rock Island Dam than at the upstream Rocky Reach Dam.

Grassell, A. C., W. Hampton, and R. D. McDonald. 2000b. Total dissolved gas monitoring at Rocky Reach and Rock Island Dams, 2000. Chelan County Public Utility District, Wenatchee, Washington. 56 p. + appendix. http://www.chelanpud.org/rr_relicense/existing/hcp/Studies/3851_1.pdf

During the spring the TDG levels at Rocky Reach forebay averaged 108% (100-121%), and in the tailrace averaged 111% (103-132%). Downstream in the Rocky Reach forebay TDG levels averaged 107% (102-123%), and in the tailrace averaged 111% (103-122%). Summer TDG averages were similar with lower peaks in the range of levels.

Gray, R. H., T. L. Page, M. G. Saroglia, and P. Bronzi. 1982. Comparative tolerance to gas supersaturation of carp, *Cyprinus carpio*, and black bullhead, *Ictalurus melas*, from the U.S.A. and Italy. Journal of Fisheries Biology 20:223-227.

A nine chambered circular apparatus (rosette) was used to test the ability of carp (*Cyprinus carpio*) and black bullhead (*Ictalurus melas*) from Italy, to detect and avoid lethal concentrations of gas supersaturated water. Carp and black bullhead from Europe were evaluated to determine tolerance to TDG supersaturation and compared to similar tests of the same species previously performed on individuals from the Columbia River. Fish were exposed to supersaturated water (110% to >150% of saturation) in tanks with water 30-cm deep. Neither species immediately avoided gas supersaturated water. Although the fish eventually avoided extremes of 146% saturation (total gas pressure) after GBD signs developed, this response did not necessarily preclude mortality. They observed no avoidance to supersaturation levels near the 96 h LC_{50}. Thus, avoidance will not protect these species from gas bubble disease mortalities and gas levels in culture facilities should be maintained below hazardous thresholds. Black bullhead from Italy were slightly more susceptible to supersaturation than Columbia River fish. The authors suggest the difference in apparent susceptibility to supersaturation may be due to adaptation of Columbia River fish whose population has experience supersaturation for many years.

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

The behavioral response of carp and black bullheads to supersaturated water was tested in circular tanks having peripheral chambers open to the center. The flow from the periphery provided an opportunity for the fish to choose between supersaturated and saturated water chambers. Fish were provided the opportunity to choose chambers with 98-100%, 114% and 146% of saturation, as well as a central area with 120% of saturation. Initially most fish of each species were in the mixed central area (120%), with many in the 146% chambers. Black bullhead remained in the 146% water at 6 hr, but departed after 24 hr. Black bullhead were not in the central area after 48 hr, with 60% of them in the 114% chambers. Carp showed less ability to detect and avoid supersaturated water. Carp tended to be in each of the chambers in similar numbers from 24 h to the end of the test.

Gray, R. H., T. L. Page, M. G. Saroglia and V. Festa. 1983b. Tolerance of carp *Cyprinus carpio* and black bullhead *Ictalurus melas* to gas-supersaturated water under lotic and lentic conditions. Environmental Pollution (Series A) 30:125-133.

Carp and black bullhead from Italy were exposed to supersaturated water in flowing water conditions where they were forced to swim (lotic) and in previously tested quiescent conditions (lentic). Both species tended to be more susceptible to the effects of supersaturation when forced to swim. The data indicated the opposite was true for carp above levels of 133% of saturation. The results of this test may have been influenced by the test conditions. Those fish forced to swim were exposed in water only 10-cm depth, while those not forced to swim were held in water 30-cm deep potentially decreasing the actual levels of TDG supersaturation they were exposed to.

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

Post larvae and fingerling sea bass (*Dicentrarchus labrax*) and striped mullet (*Bugil cephalus*) were exposed to supersaturated seawater in laboratory tanks. Post larvae were placed in 60-l tanks with water depths of 30 cm. Fingerlings were placed in 200-l tanks of unidentified water depth.

The 90 h LC_{50} values were 127% total gas pressure for sea bass post larvae and 129 % for striped mullet post larvae at a temperature of 20° C. For fingerlings the respective 90 h LC_{50} values were 116% and 125%. At 26° C the 90 h LC_{50} values were lower (116%) for sea bass post larvae. The mortality threshold was determined to be 115% TDG.

Two patterns of bubble formation were observed. Post-larval sea bass commonly developed one large bubble inside the body cavity near apparently decreasing the size of the swim bladder. Fingerling sea bass infrequently developed the large bubble, but commonly developed several small bubbles in gills, fins and internal blood vessels.

H

Hagen, E., J. Weitkamp, and D. E. Weitkamp. 1998. Biological monitoring for incidence of gas bubble disease at Priest Rapids Dam, 1997. Unpublished report by Parametrix, Inc. to Public Utility District No. 2 of Grant County. 18p + appendices.

Chinook, steelhead and sockeye were collected from turbine intake gatewells by dip-net sampling. All sampled gatewells had fish removed as completely as practical the preceding day. Fish within the gatewells tend to be the portion of the population closest to the surface since they volitionally enter the gatewell from the roof of the turbine intake.

The incidence of GBD during the spring in yearling Chinook was 8.7%, steelhead 9.4%, and sockeye 21.5%. TDG levels during the spring monitoring were in the range of 120% to greater than 135% of saturation. During the summer TDG levels were lower in the range of 110-125%. Subyearling Chinook collected during the summer also had a lower incidence of GBD (2.3%). Most of the fish showed mild GBD signs (rank 1-2). More severe GBD signs (rank 3-4) were observed in 1.3% of Chinook, 1.9% of steelhead, and 3.6% of sockeye during the spring.

Hagen, E., and D. E. Weitkamp. 1999a. Biological monitoring for incidence of gas bubble disease at Priest Rapids Dam, 1998. Unpublished report by Parametrix, Inc. to Public Utility District No. 2 of Grant County. 19p + appendices.

Chinook, steelhead and sockeye were collected from Priest Rapids dam turbine intake gatewells by dip net using the same procedures as Hagen et al (1998). Spring migrants had an incidence of GBD in Chinook of 4.5%, steelhead 3.2%, and sockeye 1.2%. Severity of these GBD signs was generally minor with most fish showing only one or two bubbles in one fin. Only a single fish was observed with rank 3 signs. During the spring TDG levels ranged from 110% to briefly over 125%, but were generally around 112-118% upstream from Priest Rapids Dam.

During the summer migration period TDG levels were generally in the range of 110-115% of saturation. Subyearling Chinook collected during the summer period had 4.7% with signs of GBD. All but 3 fish were assigned a rank 1 severity.

Hagen, E., and D. E. Weitkamp. 2000. Biological monitoring for incidence of gas bubble disease at Priest Rapids Dam, 1999. Draft unpublished report by Parametrix, Inc. to Public Utility District No. 2 of Grant County. 18p + appendices.

Chinook, steelhead and sockeye were collected from turbine intake gatewells by dip net gatewells by dip net using the same procedures as Hagen et al (1998). Yearling Chinook collected in the spring showed 4.0% with rank 1 signs of GBD. No fish were observed with more severe signs. Steelhead had a 3.1% incidence of signs, sockeye a 2.5% incidence, and coho a 4.6% incidence. Upstream TDG levels were in the range of 106-122% of saturation during the spring monitoring period.

Subyearling Chinook migrating during the summer had a 1.7% incidence of signs of GBD. All the subyearlings with GBD signs were classified as rank 1. During the summer TDG levels were 107-119% of saturation upstream during the monitoring period.

Hampton, M. W. 2002. Total dissolved gas monitoring at Rocky Reach and Rock Island Dams, 2002. Unpublished report by Chelan County Public Utility District No. 1 of Chelan County, Wenatchee, Washington. 29 p. + appendix. http://www.midcolumbiahcp.org/Studies/2002%20Report.pdf

The Chelan County PUD monitored total dissolved gas (TDG) at Rocky Reach and Rock Island Dams from April 1 through August 31, 2002. This monitoring coincided with the spring and summer spill programs for fish passage. The first objective of this study was to collect real time data to monitor the District's compliance with the modified Washington State Department of Ecology (WDOE) water quality standards for TDG throughout the duration of the 2002 spill for fish passage programs. Additionally, the District obtained TDG data from Grant County PUD to track the compliance of the modified state water quality standards in the Wanapum Dam forebay. Throughout the monitoring season, the District was out of compliance a total of 39 days in the Rocky Reach forebay, 25 days in the Rocky Reach tailrace, 46 days in the Rock Island forebay, 53 days in the Rock Island tailrace, and 70 days in the Wanapum forebay.

In the spring average TDG levels in the Rocky Reach forebay were 111% (104-128%) and in the tailrace were 113% (105-128%). Downstream at Rock Island spring forebay TDG levels averaged 113% (106-125%) and tailrace levels 118% (106-127). During the summer Rocky Reach forebay levels averaged 115% (108-136%) and tailrace levels 116% (109-132%), and Rock Island forebay levels were similar at 115% (107-130) and tailrace levels 119% (110-130%).

They evaluated the relationship between the change in TDG from the forebay to the tailrace at both projects compared to various volumes of spill and differing percentages of total river flow spilled. During the spring TDG monitoring season at Rocky Reach Dam, there was weak correlation between the change in TDG and total volume spilled (r^2=0.2467) and a moderate correlation between change in TDG and percent river flow spilled (r^2=0.3531). Spring TDG monitoring at Rock Island Dam showed a weak relationship between the change in TDG and total volume spilled (r^2=0.0934) and a moderate correlation between the change in TDG and percent river flow spilled (r^2=0.4484). Summer TDG monitoring at Rocky Reach Dam showed a very weak correlation between the change in TDG and total volume spilled (r^2=0.0128) and between the change in TDG and percent river flow spilled (r^2=0.0017). Summer TDG monitoring at Rock Island Dam showed a weak negative correlation between the change in TDG and the total volume spilled (r^2=0.1602) and a moderate correlation between the change in TDG to percent river flow spilled (r_2=0.3379).

They evaluated the representativeness of the fixed monitoring sites (FMS) located in the tailrace of both Rocky Reach and Rock Island Dams. Transect monitoring showed a slight difference in TDG levels between the east, middle, and west channels of Rocky Reach and Rock Island Dams at the fixed monitoring sites. The PUD concluded that TDG conditions in the river at the fixed monitoring sites are as representative of TDG conditions outside of the aerated zone as any other location that could be chosen.

Hampton, M. W. 2003. Total dissolved gas monitoring at Rocky Reach and Rock Island Dams, 2003. Unpublished report by Chelan County Public Utility District No. 1 of Chelan County, Wenatchee, Washington. 13 p. + appendix. http://www.chelanpud.org/rr_relicense/existing/hcp/Studies/2003%20Report.pdf

At the Rocky Reach forebay spring TDG levels were 107% (104-113%) and in the tailrace were 109% (104-114%). At Rock Island Dam the spring forebay TDG levels averaged 109% (103-114%) and tailrace levels 115% (102-119). During the summer Rocky Reach forebay levels averaged 111% (105-119%) and tailrace levels 112% (110-116%), and Rock Island forebay levels were similar at 111% (104-116) and tailrace levels 115% (104-119%).

Throughout the monitoring season, the District was out of compliance a total of 5 days in the Rocky Reach forebay, 0 days in the Rocky Reach tailrace, 2 days in the Rock Island forebay, 12 days in the Rock Island tailrace, and 8 days in the Wanapum forebay. During the spring TDG monitoring season at Rocky Reach Dam, there was strong correlation between the change in TDG and total volume spilled (r_2=0.8004) and a moderate correlation between change in TDG and percent river flow spilled (r_2=0.5649). Spring TDG monitoring at Rock Island Dam showed a strong relationship between the change in TDG and total volume spilled (r_2=0.8025) and a strong correlation between the change in TDG and percent river flow spilled (r_2=0.6546). Summer TDG monitoring at Rocky Reach Dam showed a weak correlation between the change in TDG and total volume spilled (r_2=0.1315) and a very weak correlation between the change in TDG and percent river flow spilled (r_2=0.0093). Summer TDG monitoring at Rock Island Dam showed a moderate correlation between the change in TDG and the total volume spilled (r_2=0.5468) and a weak negative correlation between the change in TDG to percent river flow spilled (r_2=0.2257).

Hampton, M. W., and R. D. McDonald. 1998. Gas bubble trauma monitoring at Rocky Reach and Rock Island Dams, 1998. Final Report by Chelan County Public Utility District No. 1 of Chelan County, Wenatchee, Washington. 29p + appendix. http://www.chelanpud.org/rr_relicense/existing/hcp/Studies/1752_1.pdf

Monitoring followed the same procedures as Murdoch and McDonald (1997). At Rocky Reach the incidence of GBD signs in yearling Chinook was 4.2%, subyearling Chinook 1.1% and steelhead 4.5% during the monitoring period. TDG levels ranged between 110% and 121% of saturation when GBD signs were observed in most of the fish. None of the fish examined at Rocky Reach exhibited rank 3-4 signs. Three of the 3.545 fish examined had bubbles in an eye.

The incidence of GBD in fish at Rock Is. was similar with 4.4% in yearling Chinook, 1,2% in subyearling Chinook, and 2.7% in steelhead. TDG levels at Rock Is. were commonly in the range of

107% to 117% when GBD signs were observed. Four of 5,895 fish examined had bubbles in an eye. All fish at both dams were confined in shallow (0.8 m RR, <0.3 m RIs) flowing river water for 0.5 to 24 h prior to examination.

Hampton, M. W., and R. D. McDonald. 2000. Gas bubble trauma monitoring at Rocky Reach and Rock Island Dams, 1999. Final Report, Chelan County Public Utility District No. 1 of Chelan County, Wenatchee, Washington. 24 p. + appendices. http://www.chelanpud.org/rr_relicense/existing/hcp/Studies/99report.pdf

Monitoring followed the same procedures as Murdoch and McDonald (1997). At Rocky Reach the incidence of GBD signs in yearling Chinook was 1.1%, subyearling Chinook 1.0% and steelhead 1.1% during the monitoring period. No fish exhibited rank 3-4 signs of GBD. TDG levels ranged between 108% and 118% of saturation when GBD signs were observed in most of the fish.

The incidence of GBD in fish at Rock Is. was higher with 2.4% in yearling Chinook, 2.1% in subyearling Chinook, and 0.2% in steelhead. TDG levels at Rock Is. were commonly in the range of 108% to 113% when GBD signs were observed. None of the fish examined had bubbles in an eye. All fish at both dams were confined in shallow (0.8 m RR, <0.3 m RIs) flowing river water (supersaturated) for 0.5 to 24 h prior to examination.

Hans, K. M., and A. G. Maule. 1997. Gas bubble trauma signs in juvenile salmonids at dams on the Snake and Columbia Rivers. 1997. Pages 38-54 in Maule, A. G., J. Beeman, K. M. Hans, M. G. Mesa, P. Haner, and J. J. Warren. Gas bubble disease monitoring and research of juvenile salmonids. Annual Report 1996 (Project 96-021), Bonneville Power Administration, Portland, Oregon.

The TDG levels in the Ice Harbor and John Day tailraces exceeded 120% for 8 of the first 10 weeks in the monitoring season in 1996. The overall the incidence of GBD was low, 10% or less, except for spring Chinook at Rock Island Dam. In the Snake River GBD signs were observed in only 3.7% of spring Chinook and 5.9% of steelhead. At the lower Columbia River dams, 2.3% of spring Chinook and 7.3% of steelhead had GBD signs. At Bonneville Dam the incidence of GBD signs was 0.8% for spring Chinook and 9.9% for steelhead. Steelhead showed a higher incidence of GBD signs at all dams. At Rock Island Dam in the mid-Columbia the incidence of GBD signs was 49.4% compared to 2.3% for the lower Columbia River dams. In the Snake River and lower Columbia GBD signs increased in fish sampled downriver, but the severity of signs did not show a similar increase downriver.

Hans, K. M., M. G. Mesa and A. G. Maule. 1999. Rate of disappearance of gas bubble trauma signs in juvenile salmonids. Journal of Aquatic Animal Health 11:383-389.

Juvenile Chinook salmon (*Oncorhynchus tshawytscha*) and steelhead (*O. mykiss*) were exposed to high levels of TDG (120-130%) in shallow water (28 cm) within 228 L circular treatment tanks at a temperature of 12 °C. The young Chinook were in the size range of 138 ± mm (28 ± 7 g), and the steelhead 249 ± 17 mm (127 ± 24 g). Fish were exposed for periods of 4-96 hr, and examined at periods of ½ to 24 hrs. At the end of treatment water supply to the treatment tank was changed to 104% TDG, which reduced water within the tank to 104% TDG within one hour. Examination of treated and control fish (104% TDG) looked for bubbles in gills by examination under 40-100 X magnification. Bubbles in the later line and external surfaces were identified under 8-40 X magnification.

The incidence of fish with bubbles in gill filaments reduced rapidly from 70% at the end of treatment to 10% within one hour. Following 5.5 h exposure 100% of the fish had bubbles in the lateral line. Prevalence of lateral line bubbles did not decreased until 4.5 h following reduction of TDG and remained in more than 50% of the fish at 5.5 hr. However, percent occlusion of the lateral line was nearly 50% at the end of treatment and gradually declined to less than 10% at 3 hr. Prevalence of bubbles on external surfaces decreased slowly from about 95% at the end of exposure to about 40% at the end of four days.

Fish became lethargic during exposure to TDG supersaturation, but returned to normal behavior rapidly following reduced TDG supersaturation. Within 30 min following changing the water source to the 104% TDG water supply the fish activity increased notably.

Hargreaves, J. A., and C. S. Tucker. 1999. Design and construction of degassing units for catfish hatcheries. Southern Regional Aquacultural Center Publication No. 191, Mississippi State University. 8 p.

They used packed column aerators as a simple and effective way to manage gas supersaturation problems packed-column aerators. Packed columns serve two roles, depending upon the quality of incoming water. If the water is supersaturated with dissolved gases, then a properly designed and constructed packed column will relieve the supersaturated condition. If the dissolved oxygen concentration of the water is low, a properly designed and constructed packed column will also saturate the water with dissolved oxygen. A packed column consists of a vertical vessel filled with packing medium. The medium should have a large (about 90 percent) void or empty space per unit volume and should pack in a way that allows the water flow to break up randomly into a thin film that trickles down through the column, following a very circuitous pathway.

Harvey, E. N., D. K. Barnes, W. D. McElroy, A. H. Whiteley, C. C. Pease, and K. W. Cooper. 1944. Bubble formation in animals I. Physical factors. Journal of Cellular and Comparative Physiology 24:1-22.

Experimentally bubbles do not form within living single cells even after decompression from very high gas pressure, but they may appear inside dead or injured cells. Bubbles form abundantly in both arteries and veins and can be seen in many tissues after compression-decompression (6-8 atmospheres) experiments with resting animals. They occasionally occur in eye humors, cerebrospinal fluid and amniotic fluid but have never been observed in bladder urine. In a liquid, bubbles may be formed de novo if ΔP, the difference between the gas tension, t, and hydrostatic pressure (P) is sufficiently high, or they may appear from a nucleus, i.e., a minute gas phase already present or formed de novo under certain special conditions. If the nucleus is spherical, it will be stable only at a critical size, which depends on the surface tension- and ΔP. If the nucleus adheres to a surface, the geometry of the surface, the shape of the gas-liquid-solid junction, advancing and receding contact angles between gas and surface, as well as surface tension and AP determine stability. Change in size of gas nuclei depends on (1) diffusion of gas into the nucleus, (2) creeping of the gas-liquid-solid boundary, determined by advancing and receding contact angles, and (3) adjustment of the gas-liquid surface for minimum area consistent with the gas content of the nucleus and the hydrostatic pressure, a process hindered by the inertia and viscosity of the liquid, and only important when the absolute hydrostatic pressure is negative, i.e., the liquid is under tension.

Diffusion varies as actual gas pressure in the nucleus minus gas tension in solution, gas solubility, gas diffusion constant and area of gas-liquid surface. Spherical nuclei grow indefinitely above a critical size; attached nuclei grow indefinitely above a critical pressure difference. The high solubility of $C0_2$ favors rapid diffusion.

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

When 0.2-g pink salmon *Oncorhynchus gorbuscha* were carried by helicopter in Alaska, total gas pressure in the transport water reached 71.3 mm Hg (109.4% of barometric pressure). Gross and microscopic lesions in swim bladders of fish progressed during transport to tympanitic dilatation, then to separation of laminae and rupture. Other associated signs and lesions were exophthalmia, cranial swelling, edematous gill lamellae, hemoperitoneum, emphysema of the yolk sac, and distension and rupture of the yolk sac membrane. Rapid reduction of barometric pressure during the flight and the subsequent increase in dissolved-gas supersaturation caused gas bubble disease and tissue alterations that affected health and survival of the fish.

Heggberget, T. G. 1984. Effect of supersaturated water on fish in River Nidelva, southern Norway. Journal of Fish Biology 24:65-74.

Fish mortalities in the River Nidelva, South Norway in 1978, were suspected to be caused by gas bubble disease. In June 1980, the hydrological situation occurring in the Nidelva in 1978 was reconstructed, and the effects were analyzed by keeping fish in cages. Brown trout (*Salmo trutta*), perch (*Perca fluviatilis*), and eel (*Anguilla anguilla*) were exposed to supersaturated water (120-180% of saturation) in cages in the River Nidelva, southern Norway. Fish held at a depth of 3 m suffered limited mortality, while fish held near the surface all died within hours to two days. Examination of the dead fish showed that most were killed by gas bubble disease. The results also showed that brown trout, *Salmo trutta*, was the least tolerant, and eel was the most tolerant to dissolved gas supersaturation. Only fish kept near the surface were killed while fish kept at 3 m depth were mildly affected due to hydrostatic pressure compensation. In contrast to the situation in 1978, few of the wild fish were killed during the experiment in 1980. Diving observations and gillnet catches indicated the river population was not affected by the high levels of supersaturation due to the depth distribution of the resident fish. A previous mortality of many fish in 1978 may have been due to a more prolonged period of supersaturation.

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

Cells of the ciliate *Tetrahymena pyriformis* were, suspended with carmine or graphite particles or with Halobacterium gas vesicles, all of which promote bubble formation in aqueous suspensions when tested with 10 atm and above (0.1-0.5 x 10^7 Pa) (carmine and graphite) or 25 atm and above (gas vesicles) of nitrogen supersaturation. All three particles were ingested, but only the gas vesicles promoted intracellular gas bubble formation if the cells containing them were nitrogen or methane saturated in a slow stepwise fashion prior to rapid decompression. Cell rupture did not occur until gas saturation pressures greater than 25 atm were used; this suggests that the ciliate pellicle and cytoplasm cannot resist the mechanical forces of an expanding gas phase induced by decompression from between 25 and 50 atm and thus provides an estimate of the physical strength of these cellular components. The inability of the ingested carmine, graphite, and collapsed gas vesicles to induce intracellular. gas bubble formation suggests that the phagocytic process somehow altered them.

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.

Intact mammalian, avian, and amphibian erythrocytes were saturated with up to 300 atm nitrogen or argon gas and rapidly decompressed. Despite the profuse nucleation of gas bubbles in the suspending fluid, no evidence of intracellular gas bubble nucleation was found; all or most of the cells remained intact and little or no hemoglobin escaped. Internal bubbles were similarly absent from resealed ghosts of human erythrocytes as shown by lack of disintegration and by retention of an entrapped fluorescent compound. The absence of bubbles may indicate that much of the internal water does not have the same nucleation properties as external water.

Hibbs, D. E., and J. S. Gulliver. 1997. Prediction of effective saturation concentration at spillway plunge pools. Journal of Hydraulic Engineering 123:940-949.

Bubbles entrained in spillway plunge pools are subject to the hydrostatic force of the water column, increasing the pressure within the entrained bubbles. This phenomenon is important for the exchange of atmospheric gases such as nitrogen and oxygen, often causing dissolved gas supersaturation downstream of the plunge pool. A weighted average or effective bubble depth is introduced to predict more accurately gas transfer at spillways. A theory is developed for estimating the effective bubble depth given the spillway angle of inclination, velocity, and depth of flow at jet impact and tailwater depth. The relationship is fitted to dissolved oxygen and methane data previously reported by the authors and is successfully applied to four Bureau of Reclamation spillways for which both oxygen and nitrogen measurements were available.

Hildebrand, L. 1991. Lower Columbia River Fisheries Inventory - 1990 Studies. Vol. 1, Main Report. Contract report by R.L. & L. Environmental Services Ltd. to B.C. Hydro, Environmental Resources, Vancouver, B.C. (not seen, from Fidler 2003)

Monitoring studies of the impacts of TDG supersaturation to fish in the Columbia River, downstream from the Hugh L. Keenleyside Dam, showed low incidence of GBD signs in live fish. TDG levels measured in the river immediately downstream from HLK dam have been commonly up to 133% during spring spill in the 1970s into the 1990s, sometimes exceeding 104% of saturation. Fish held in cages in shallow water died from GBD much sooner than would be indicated by the measured TDG. However, a later review of the data (Fidler 2003) showed that the actual TDG levels (137%-140%) were much higher that had been reported (119%-121%).

Hnath, J. G., H. Westers, and H. G. Ketola. 1986. The effects of nitrogen gas supersaturation on the development of eye lesions in coho salmon, and possible mediating effects of a test diet. (not seen, from Colt et al. 1986)

Coho salmon eggs were incubated, hatched, and reared at total gas levels of 100, 102, and 106% in a laboratory experiment. Each of four diets was fed at each gas level from fry to smoltification. The four diets were the Atlantic salmon, diet ASD2-30, ASD2-30 with 10% dried liver, Biodiet starter followed by OMP, and Bfodfet alone. Neither diet nor level of gas had a significant influence of the overall incidence of cataracts or eye lesions growth and mortality. Both diet and gas level had a significant effect on In hatchery tests. An experimental diet (T-2) reduced the incidence of corneal lesions and cataracts when compared to the OMP diet,

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Jensen, J. O. T. 1980. Effects of total gas pressure, temperature and total water hardness on steelhead eggs, and alevins. A progress report. Pages 15-22 in Proceedings 31st Northwest Fish Culture Conference, Courtenay, British Columbia.

Steelhead alevins and embryos were exposed to supersaturated water (102%, 106%, and 110 % of saturation) in Heath trays (water depth probably no more than 3-4 cm). Egg mortality was not affected at any of the TDG levels tested. Alevins were only marginally affected with a slight increase in mortality at the 110% TDG level. A marginal incidence (1.4%) of opercular deformities occurred a few days after hatching, caused by gas bubble growth in the buccal cavity of larvae at 110% TDG. A few fry (2.6%) exposed to 111% TDG and 48% 0_2 exhibited GBD signs involving burst swim bladders. Multiple linear regression analysis of dry embryo/yolk ratios indicated that embryo and early larval growth was reduced both by excess TDG and low O_2 levels at 32 and 50 days post fertilization (R_2 = 0.900 and 0.812, respectively). However, fry size was not significantly (R_2 = 0.390) correlated with either TDG or O_2 level after 21 days (72 days post fertilization) of feeding ad libitum.

Jensen, J. O. T. 1988. Combined effects of gas supersaturation and dissolved oxygen levels on steelhead (*Salmo gairdneri*) eggs, larvae, and fry. Aquaculture 68(2): 131-139.

Steelhead eggs, larvae, and fry were exposed to combinations of atmospheric gas supersaturation (102-111% TDG) and dissolved oxygen (DO 48-98%) at 10°C. Egg-to-fry mortality was low (range 0.4-10.8%) and was not significantly affected by excess TDG or low DO levels (P> 0.10). A marginal incidence (1.4%) of opercular deformities, caused by gas bubble growth in the buccal cavity of larvae a few days after hatching, was observed at TDG levels of about 110%. A small percentage of fry (2.6%) exposed to 111% TdG and 48% DO exhibited GBD signs involving burst swim bladders. Multiple linear regression analysis of dry embryo/yolk ratios indicated that embryo and early larval growth was reduced both by excess TDG and low 0_2 levels at 32 and 50 days (R_2 = 0.900 and 0.812, respectively) post fertilization. However, after 21 days (72 days post fertilization) of feeding ad libitum, fry size was not significantly (R_2 = 0.390) correlated with either TDG or O_2 level.

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 Fisheries and Aquatic Sciences No. 501.

A literature search for quantitative data pertaining to salmonid response (effective time to 50% mortality, ET_{50}) to TDG levels yielded 621 records from 23 publications. Two subsets of these data were compiled. Data subset 1, comprising 171 records, provided information on ET_{50} among juvenile salmonids exposed to excess TDG and ancillary variables including water depth, temperature, fish length, and barometric pressure. Data subset 2 included 81 records with information on dissolved oxygen and nitrogen levels (or oxygen/nitrogen ratios) as a further ancillary variable. These data were used by Schnute, Jensen, and Alderdice (1986) to model implicit multivariable relations between ET_{50} and TDG levels as influenced by the ancillary variables.

Jensen, J. O. T., J. Schnute, and D. F. Alderdice. 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.

The initial discussion provides a good review of the factors involved in TDG measurement and calculation. They point out that hydrostatic pressure is a major factor in determining the level of supersaturation to which an organism is exposed. One meter of water is equivalent to the pressure of 74 mm Hg, or compensates for approximately 10% TDG at a barometric pressure of 760 mm Hg. The boundary between chronic and acute GBD appears to lie in the range of 108-110% TDG for organisms held in shallow water.

This assessment of the effects of TDG supersaturation uses data derived from literature for Chinook, coho, sockeye and steelhead. Most of the data are for fish exposed in mean test depths of 0.5 m, maximum of 1 m. Their analysis relates exposure time to 50% mortality (ET_{50}) to percent TDG. Eighteen different models are examined that explore different factors influencing the effects of TDG supersaturation. The 96% confidence intervals for the calculated ET_{50} at a range of TDG levels are broad, in the range of 20-25% of saturation for TDG levels up to 120% of saturation. For these shallow water conditions they concluded apparent safe levels for 50 day exposures to TDG supersaturation are 104-115% TDG. The authors concluded the lack of comprehensive data prevented them from making statements with adequate precision.

Johnson, E. L., T. S. Clabough, D. H. Bennett, T. C. Bjornn, C. A. Peery, and C. C. Caudill. 2005. Migration depths of adult spring and summer Chinook Salmon in the lower Columbia and Snake Rivers in relation to dissolved gas supersaturation. Transactions of the American Fisheries Society 134:1213-1227. http://www.cnr.uidaho.edu/uiferl/pdf%20reports/TDG%20AFS%20Aug05.pdf

Water spilling over Columbia and Snake River dams during the spring and summer produces plumes with high TDG that extend downstream of dam spillways and throughout reservoirs and produces gas-supersaturated conditions throughout the water column. During the spring and summer of 2000, 228 adult Chinook salmon *Oncorhynchus tshawytscha* were tagged at Bonneville Dam with archival radio data storage transmitters (RDSTs) that recorded depth and water temperature as the fish migrated through dams and reservoirs of the lower Columbia and Snake rivers. Swimming depths from 131 of the 228 adult spring and summer Chinook salmon tagged with RDSTs were used to estimate the potential for gas bubble formation given in-river dissolved gas concentrations and hydrostatic compensation. They found that adult spring and summer Chinook salmon spent a majority of the time at depths that would have provided adequate hydrostatic compensation for in-river dissolved gas conditions during this study, which were at or slightly below long-term averages. Adult spring and summer Chinook salmon spent a majority of their time at depths deeper than 2 m, interspersed with periods lasting minutes at depths shallower than 2 m. Statistical associations were weak between the percent and duration of time fish occupied depths near the surface and dissolved gas concentrations, suggesting a lack of behavioral avoidance. Collectively, these data suggest little potential for negative effects of gas supersaturation on adult spring and summer Chinook salmon under average river conditions, despite the fact that fish tissues were probably supersaturated with dissolved gases.

Johnson, E. L., T. S. Clabough, C. A. Peery, D. H. Bennett, T. C. Bjornn, C. C. Caudill, C. A. Peery, and M. C. Richmond. 2007. Estimating adult Chinook salmon exposure to dissolved gas supersaturation downstream of hydroelectric dams using telemetry and hydrodynamic models. River Research and Applications 23:963-978.

This report appears to contain much of the information previously presented in Johnson, Claybough, et al. 2005. Spill at Columbia and Snake River dams produces a downstream plume of water with high TDG supersaturation that may be positioned along either shore or mid-channel, depending on dam operations. They obtained spatial data on fish migration paths and migration depths for adult spring and summer Chinook salmon, *Oncorhynchus tshawytscha*, during 2000. Migration paths were compared to output from a two-dimensional (2-dimensional) hydrodynamic and dissolved gas model to estimate the potential for GBD expression and to test for behavioral avoidance of the high TDGS plume. They observed that salmon swam sufficiently deep in the water column to receive complete hydrostatic compensation 95.9% of the time spent in the Bonneville Dam tailrace and 88.1% of the time in the Ice Harbor Dam tailrace. The majority of depth uncompensated exposure occurred at TDGS levels >115%. Adult Chinook salmon tended to migrate near the shoreline and they tended to remain in relatively deep water. Adults moved into the high dissolved-gas plume as often as they moved out of it downstream of Bonneville Dam, providing no evidence that adults moved laterally to avoid areas with elevated dissolved gas levels. When water depths decreased due to reduced river discharge, adults tended to migrate in the deeper navigation channel downstream from Ice Harbor Dam. The strong influence of dam operations on the position of the high-TDGS plume and shoreline-orientation behaviors of adults suggest that exposure of adult salmonids to high-TDGS conditions may be minimized using operational conditions that direct the spilled water mid-channel.

Johnson, E., T. Reischel, C. Peery, D. Bennett, T. Bjornn, and L. Stuehrenberg. 2005. Migration depths of adult spring–summer Chinook salmon in the lower Columbia and Snake Rivers in relation to dissolved gas supersaturation. Technical Report 2004-8, University of Idaho, for project ADS-00-5, U.S. Army Corps of Engineers, Walla Walla, Washington. 56 p.

Dissolved gas supersaturation in the Columbia and Snake rivers routinely occurs during the spring and summer freshet as a result of water spilling over dams and can be lethal to fish. Measurable plumes of high dissolved gas extend downstream of dam spillways and produces TDG supersaturated conditions that do not equilibrate in reservoirs. Based on modeling results, the extent of the dissolved gas plume downstream from Bonneville Dam before dissipating is at least 10 km and the lateral position of the plume is highly dependent on dam powerhouse operation and spill volume. During the spring and summer of 2000, 228-adult Chinook salmon *Oncorhynchus tshawytscha* were tagged at Bonneville Dam with archival radio data storage transmitters (RDSTs) that recorded depth of migration every 5 seconds and water temperature every minute. Migration depth is instrumental in determining levels of exposure due to the effects of hydrostatic pressure that provides compensation that limits the effects of supersaturation (hydrostatic compensation). They evaluated the swimming depths of 131 fish with RDSTs to determine in situ swimming depths in relation to water with elevated dissolved gas concentrations as they migrated from the Bonneville Dam tailrace upstream to Lower Granite Dam. Migration paths of 54 individual fish were monitored in the tailraces of Bonneville and Ice Harbor dams and collaborated with output from a two-dimensional dissolved gas model to estimate exposure levels. This report appears to contain the information presented in Johnson, Claybough, et al. 2005.

They found that adult spring–summer Chinook salmon spent a majority of their time at depths deeper than 2 m (providing hydrostatic compensation for at least 20% TDG). The adults generally spent only several minutes at one time at depths shallower than 2 m. The longest periods individual fish spent at depths shallower than 1 m and 2 m deep was 1.3 h and 19.5 h, respectively. Based on analysis of locations of 54 fish and dissolved gas model results downstream of Bonneville and Ice Harbor dams, uncompensated exposure based on modeled dissolved gas levels (typically less than 130% TDG) was estimated to be 4.1% of the time fish spent in the Bonneville tailrace and 11.9 % of the time spent in the Ice Harbor tailrace. Less than 1% of this exposure was at or higher than 115% which is considered a conservative level of exposure known to cause GBD and mortality. Adult spring–summer Chinook salmon tended to migrate near the shoreline with approximately equal proportions of fish entering or leaving areas of the river with elevated dissolved gas levels. No significant association existed between crossing the river and the position of the dissolved gas plume downstream of Bonneville Dam. Statistical associations were also weak between dissolved gas concentrations and the percent and duration of time fish occupied near-surface waters.

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

They held young steelhead (*Oncorhynchus mykiss*) suspended in 0.2 m deep cages at depths with the tops of the cages at 0.1, 0.5 and 1.0 m in water supersaturated with air at levels from 120% to 140% TDG. Survival times of fish held at 10, 50, and 100 cm depth increased with increasing depth at a given level of supersaturation. When the hydrostatic pressure (7.4 mm Hg per 10 cm of water depth) was subtracted from the excess gas pressure (relative to surface barometric pressure), mortality curves (times to 50% mortality versus excess gas pressure) for fish at all three depths essentially coincided. The significant measure of supersaturation appears to be the pressure of dissolved gases in excess of the sum of barometric and hydrostatic pressures. Steelhead held near the surface in supersaturated water for a near-lethal period and then lowered to a depth providing total hydrostatic compensation appeared to recover completely in about 2 hr. The longer fish remained at depth, the longer their survival time when they subsequently were re-exposed to surface conditions.

Koehler, V. A., and R. D. McDonald. 1997. Total dissolved gas monitoring at Rocky Reach and Rock Island Hydroelectric Projects in 1997. Final Repot, Chelan County PUD No. 1, Wenatchee, Washington. 57 p. http://www.midcolumbiahcp.org/Studies/E4(11)-212.pdf

The TDG monitoring effort was conducted to determine if the PUD was in compliance with the temporary waiver to water quality standards and to examine the effect of dam operations (volume spilled, percent river flow spilled, location of spill) on fluctuations of TOG in the river downstream from the projects. To maintain federally mandated spill levels implemented to speed the migration rate of downstream migrating salmonids, the Washington State Department of Ecology granted the District a temporary waiver to the TDG water quality criterion for March 15 through August 15, 1997. TDG levels as measured in the forebays of Rock Island and Wanapum dams were not to exceed 115%, and Rocky Reach and Rock Island tailwater was not to exceed 120%. These standards are based on the average of the 12 highest hourly TOG readings. The waiver also provided that the maximum hourly TDG level should not exceed 125%.

They also examined the rate of dissipation and the distribution of TOG between the forebays of Rocky Reach and Rock Island dams in the spring and summer of 1997 by conducting weekly TDG transects downstream from the projects. The results of this study indicated that TOG levels increased as water passed from the forebay to the tailrace of both Rocky Reach and Rock Island Dams. This change in percent TDG was consistently greater at Rock Island than Rocky Reach Dam, even with very little or no spill. Transect data collected in the tailraces of Rocky Reach Dam showed that during the periods of high spill, there was a clear gradient as TDG levels decreased from the east channel towards the west channel. During periods of low spill, however, the gradient became reversed and increased from the east channel to the west channel, with slightly higher TDG levels downstream from the powerhouse. There was no clear gradient in TDG levels downstream from Rock Island Dam.

Koehler, V. A., and R. D. McDonald. 1999. Total dissolved gas monitoring at Rocky Reach and Rock Island Hydroelectric Projects in 1998. Final Repot, Chelan County PUD No. 1, Wenatchee, Washington. 60 p. http://www.chelanpud.org/rr_relicense/existing/hcp/Studies/1751_1.pdf

In 1998 TDG levels in the forebay of Rocky Reach Dam averaged 109% (range 100% - 121%). Tailrace TDG level averaged 111% (range 106% - 128%). At Rock Island Dam forebay the average TDG level was 109% (range 103% - 125%). In the Rock Island tailrace the average TDG level was 115% (range 103% - 128%), an increase of 6% from the forebay. At both dams a small average increase in TDG levels was measured from the forebays to the tailrace when no spill was occurring.

Krise, W. F. 1993. Effects of one-year exposures to gas supersaturation on lake trout. Progressive-Fish Culturist 55:169-176.

Lake trout (*Salvelinus namaycush*) were reared for 1 year in water 15 cm deep with one of six levels of incoming differential gas pressure (ΔP mm Hg): 4, 17, 33, 43, 58, or 75 mm Hg. Growth and survival of fish were evaluated as measures of response to the potential long-term stress of elevated dissolved gases in rearing water. Mortality rates were not different among fish held in supersaturated water up to △P 58 (108% of total gas saturation), but mortality at ΔP 75 (110% saturation) was significantly higher after day 28. From days 21 to 35, the number of non-feeding, moribund fish increased with increasing gas level. By day 56, the length and weight of fish were significantly greater at ΔP 4 than at higher gas levels. Growth rate reductions were evident for lake trout in ΔP 17 and above for more than 252 d. Feed conversion efficiency was significantly better in fish held at ΔPs 4 and 17 than at higher pressures. Lake trout grew fastest and most efficiently at ΔP 4 for 252 d, but ΔP 58 was also a safe rearing level in terms of mortality. There were no signs of gas bubble formation in fish held at or below ΔP 58 and only 3% of the fish at ΔP 75 exhibited emphysemas after 269 d of exposure. For optimum growth of juvenile lake trout, total dissolved gas levels should be less than ΔP 17, probably near ΔP 0.

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.

The tolerance of sac fry of lake trout to the acute effects of gas supersaturation in water 15 cm deep, from hatching to swim-up, was tested using six gas levels, ranging from ΔP 8 to 148 (101-120% TDG). Although many fish were moribund by the time the yolk was nearly absorbed, mortality during the 40-day study was negligible; survival to swim-up was 96–99%, including 99% survival at ΔP 148 (120% TDG). Of fish examined at ΔP 42 (106% TDG), 40% showed bubble formation around the rim of the eye. Signs of GBD were greatest at ΔP 119 (116% TDG) and 148 (120% TDG), and included intestinal bubbles, a distended abdomen, and bubbles around the eye, in the mouth and in jaw tissues.

Krise, W. F., and R. L. Herman. 1991. Resistance of under-yearling and yearling Atlantic salmon and lake trout to supersaturation with air. Journal of Aquatic Animal Health 3:248–253.

Juvenile Atlantic salmon *Salmo salar* and lake trout *Salvelinus namaycush* of different sizes were exposed for 96 h to water supersaturated with air. Under yearlings (Atlantic salmon shorter than 66 ± 8 mm [mean total length ± SD] and lake trout shorter than 96 mm) were resistant to high TDG pressures. The level of supersaturation causing 50% mortality was lower for yearling Atlantic salmon (148 ± 17 mm long) than for under yearling Atlantic salmon, and sensitivity to supersaturation was greater in lake trout 96 ± 1 to 153 ± 17 mm long than in those 23 ± 1 to 46 ± 4 mm long. Incidence of cutaneous emphysema and other signs of gas bubble disease increased as supersaturation increased. The number of bubbles and number of sites with bubbles were higher in the older fish. Among fish 150 ± 17 mm long, Atlantic salmon seemed to be less resistant to gas supersaturation than did lake trout.

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 Science 45:666-674.

Embryos, eleuthero embryos, and alevins of lake trout (*Salvelinus namaycush*) were reared in 1 of 10 TDG levels ranging from ΔP 13 to 81 mm Hg (102-111% TDG) above ambient barometric pressure in water 15 cm deep. Rearing water was soft, temperature was 9.3 ºC, and the exogenous feeding portion of the test lasted 98 d. The supersaturation levels tested had no effect on the total survival of eggs, eleuthero embryos, or alevins, and condition factor and mean weight of fish in each treatment were statistically unchanged at the end of the study. Most of the fish that died during the feeding trial were small, had a below-average condition factor, and showed petechial hemorrhaging in the abdominal region. Length frequency distributions differed significantly among treatment groups after 56 d of feeding and remained different through 98 d. There was no difference in weight gain, condition factor, food conversion, and mortality, indicating that these measures are not useful for predicting or monitoring effects within the range of gas levels tested. The estimated incipient lowest level of effect of gas supersaturation remains unclear.

Krise, W. F., J. W. Meade, and R. A. Smith. 1990. Effect of feeding rate and gas supersaturation on survival and growth of lake trout. Progressive Fish Culturist 52:45–50.

Fingerling lake trout (*Salvelinus namaycush*) were reared for 35 d in water with total dissolved gas pressures of 46, 78, 108, or 159 mmHg above ambient conditions (ΔP). Within each gas pressure treatment, daily feeding rations were (1) 1.7% of the total weight of fish in the heaviest of three replicates, (2) 1.7% of the weight of fish in each individual tank, or (3) 0.9% of the weight in each tank (underfeeding). Signs of GBD were first observed as hemorrhagic spots on the eyes of some fish reared at ΔP = 46, and external evidence of GBD increased as ΔP increased. All fish sampled at ΔP = 159 showed signs of gas bubble disease; the most common were eye hemorrhage and bubble formation inside the mouth. Mortality was 11% or less among fish reared at gas levels up to ΔP = 108. Mortality was as high as 55% at ΔP = 159, but did not differ among feeding treatments. Net weight gain by fish was low at ΔP = 159 because of both high mortality and slow growth. Growth was slowest for underfed fish at all gas levels, and underfed fish consistently showed increasing injury as gas pressures increased. Calculation of feeding rate on the basis of fish weight in individual tanks allowed the most cost-efficient food distribution. Culture of lake trout at ΔP < 46 is recommended.

Krise, W. F., and R. A. Smith. 1993. Eye abnormalities of lake trout exposed to gas supersaturation. Progressive Fish-Culturist 55:177-179.

Lake trout (*Salvelinus namaycush*) reared for one year at six levels of differential (excess) gas pressure (ΔP 4, 17, 33, 43, 58, and 75 mm Hg above equilibrium) were examined for incidences of eye abnormalities including nuclear cataracts, hemorrhages, corneal swelling, cloudiness, rupture, and loss of eyes. Frequencies of nuclear cataracts, eye hemorrhages, cloudy corneas, and bilateral anomalies were not directly related to increasing dissolved gas pressures. However, incidences of corneal swelling and of all abnormalities combined increased with gas supersaturation above ΔP 4.

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.

Histopathology of gas bubble disease produced by TDG supersaturation in two catfishes was studied. The catfish were held in 40-l aquaria. The levels and cause of supersaturation are not reported, nor are the water depths. Histopathology in *Heteropneustes fossilis* was not described due to heavy mortality of this species within the first 24 hr. These fish were held in a smaller aquarium (40 L) and possibly shallower water than *Clarias Batrachus*(100 L). Degenerative changes observed include focal necrosis, pyknotic nuclei and cordal disarray in the liver within 48-72 hr. Degeneration of intestinal epithelium extending into the submucosa occurred within 72 hr. All these changes became more pronounced by 96 hr. Kidneys showed degeneration of real epithelium by 48 hr, with shrinkage of tubules and glomeruli by 72 h leading to loss of most cellular architecture by 96 hr. Erythrocytes were swollen and immature abnormally prevalent by 48 hr. Erythrocyte count and haemoglobin content decreased through 72 hr, but increased at 96 hr.

L

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 Fisheries Biology 26:193-200.

Two-year old rainbow trout were exposed to supersaturated water (117-125% of saturation) in tanks 1.6-m deep. A consistent avoidance response was not observed in these fish. Fish held in equilibrated water and those held in supersaturated water did not have significantly different depth distributions. However, fish restricted to the upper 30 cm of the tanks with supersaturated water suffered higher (100%) rates of mortality than fish allowed to seek the depth of choice (43% mortality), and those restricted to 0.3-1.6 m (28% mortality) within the tanks during 200 h exposures. The distribution of fish in the volitional tank did not indicate that they sensed or actively avoided the TDG supersaturation.

Lutz, D. S. 1995. Gas supersaturation and gas bubble trauma in fish downstream from a Midwestern reservoir. Transactions of the American Fisheries Society 124:423-436.

Dissolved gas data were collected downstream from Red Rock Dam, Iowa; a moderately sized Midwestern reservoir over a period of 10 years. Among 281 observations from August 1983 through April 1994, the gas pressure differential (ΔP) averaged 119 mm Hg (116.0% of saturation) and discharge averaged 245.0 m^3/s. A maximum ΔP of 251 mm Hg (133.6% TDG) was associated with record release rates during the flood of 1993. Three-fourths of the 281 observations exceeded the U.S. Environmental

Protection Agency's criterion of 76 mm Hg as ΔP (110% of saturation). The estimated maximum depth during monitoring was 0.6-5.2 m. Periodic examinations of live fish and of fish collected from fish kills demonstrated sublethal and lethal gas bubble disease in fish downstream from the dam. Fifteen fish kills were recorded with TDG levels averaging 121% during the kills, however the highest TDG levels (134%) did not result in fish mortality. The occurrence of periodic gas supersaturation-induced fish kills was linked to continued high dissolved gas pressures during periods when the discharge from the reservoir was substantially decreased. Lower discharge rates decreased river depth and lowered compensating hydrostatic pressure.

M

Machado, J. P., T. G. Bell, A. L. Trapp, D. L. Garling Jr., and N. R. Kevern. 1989. Effect of carbon monoxide exposure on gas bubble disease in rainbow trout (*Salmo gairdneri*). Canadian Journal of Fisheries and Aquatic Sciences 46:74-80.

Cumulative mortalities of 100, 50, 20, and 0% due to GBD occurred with exposure of rainbow trout *(Salmo gairdneri)* to supersaturated water at 136, 130, 124, and 116% total dissolved gas saturation (TDG), respectively for 180 min. At 130% TDG, a prior exposure to carbon monoxide (CO), which converted 80% of the hemoglobin to carboxyhemoglobin (COHb), significantly prolonged survival time, but cumulative mortality was insignificantly reduced in the same group. Histologically, all supersaturation mortalities had branchial lesions for GBD (characterized by gas displacement of blood from the afferent arterioles of the gill filaments), while 70% had gas emboli in the retinal choroid gland. At a TDG of 100%, these histological lesions were hot observed and the CO 80% COHb conversion did not induce mortality within 120 min. Breathing movements of both control and CO-exposed fish slowed greatly when a TDG of 130% was imposed; however, the COHb conversion initiated tachypnea and the CO-treated fish maintained a relatively higher respiratory rate when exposed to supersaturation conditions for a period which was proportional to their prolonged survival time. They concluded that the initial formation of gas emboli preceding fatal GBD was delayed as a result of a CO-inhibited function of hemoglobin.

Machado, J. P., D. L. Garling Jr., N. R. Kevern, A. L. Trapp, and T. G. Bell. 1987. Histopathology and the pathogenesis of embolism (gas bubble disease) in rainbow trout (*Salmo gairdneri*). Canadian Journal of Fisheries and Aquatic Sciences 44:1985-1994.

Rainbow trout *{Salmo gairdneri)* affected with gas bubble disease (GBD) were examined histologically to determine the pathogenesis of the early stages of gas emboli formation. Rainbow trout were exposed to TDG supersaturation in 12 cm deep rearing trays. Lesions preserved by a rapid fixation method were located in tissues associated with acid-secreting glands or with high metabolic requirements. Following the development of small gas emboli formed in the retinal-chorio capillaries, a progressive development of unilateral exophthalmia was detected. A lesion found in every treated moribund fish but never in controls was gas displacement of the blood from the afferent arteriole within the gill filaments. The exposure of fish to well water containing graded levels of atmospheric gases from 114% to 118% nitrogen and. 103% to 110% oxygen saturation resulted in high mortality. However, fish held in nitrogen varying between 103% and 117% and oxygen from 50% to 94% saturation experienced insignificant mortality. They suggest that hatchery oxygen levels should be maintained below 100% if nitrogen supersaturation is present to reduce mortality from GBD.

Maitland, T., L. Praye, A. Reeves, and B. Brown. 2003. Rock Island Dam smolt and gas bubble trauma monitoring, 2003. Public Utility District #1 of Chelan County, Wenatchee, Washington. 20 p. + appendices. http://www.midcolumbiahcp.org/Studies/2003finalbypassrpt.pdf

Emigrating juvenile Chinook *Oncorhynchus tshawytscha*, sockeye *O. nerka*, coho *O. kisutch* salmon, and steelhead *O. mykiss* were examined and counted at the Rock Island Dam bypass trap from 1 April - 31 August 2003. Total river flow and Powerhouse No. 2 flow during bypass trap operations averaged 118.9 kcfs and 86.7 kcfs, respectively. Spill for fish passage began on 17 April and continued through 17 August. In 2003, the Rock Island Dam trapping facility collected 79,103 target salmonids. Included were 2,982 (3.8%) mortalities that occurred during trapping, sampling, or tagging. Of the 71,230 fish examined, 3.3% showed signs of descaling. A total of 2,608 salmonids were examined for gas bubble disease, with 2.1% showing external signs. Juvenile migrants collected at Rock Island might develop additional GBD signs while in the bypass channel or holding flume because of the shallow water depth (15-38 cm) in the holding tank below the dewatering screen that prevent fish from maintaining hydrostatic compensation.

Marotz, B., R. Sylvester, J. Dunnigan, T. Ostrowski, J. DeShazer, J. Wachsmuth, M. Benner, M. Hensler, and N. Benson. 2007. Incremental analysis of Libby Dam operation during 2006 and gas bubble trauma in Kootenai River fish resulting from spillway discharge. Report by Montana Fish, Wildlife and Parks to Bonneville Power Administration, Portland, Oregon. 48 p.

Water spilled at Libby Dam in northwestern Montana June 8-27, 2006 caused TDG supersaturation in the Kootenai River downstream. Spill caused TDG supersaturation in the Kootenai River exceeding Montana's gas saturation standard of 110 % for 20 consecutive days. TDG levels peaked at 131%. The location of the spillway near the left bank produced a TDG gradient across the river channel, with higher TDG at the left bank. Dissolved gas was mixed across the channel approximately 8 km downstream from the dam.

Fish examined for GBD signs were captured by electrofishing along the right and left banks. GBD was observed in rainbow trout (*Oncorhynchus mykiss*), westslope cutthroat trout (*O. clarki lewisii*), kokanee (*O. nerka*), bull trout (*Salvelinus confluentus*) and mountain whitefish (*Prosopium williamsoni*). Signs in trout were observed on the fourth day of spill and increased in frequency as spill continued. GBD was greater in fish collected along the left bank where TDG was highest. After 11 days of spill, all bull trout and westslope cutthroat trout captured had GBD signs, including multiple hemorrhages on the ventral surface of the body, bubbles in fins, eyes, dermis on the operculum and split fins. Hemorrhaging on the ventral body surface increased when gas saturation approached 131%, and then apparently reduced when TDG levels reduced toward 124%. The frequency of GBD reached 92% in mountain whitefish and 93 % in rainbow.

Population estimates before and after the 2006 spill event did not detect impacts to trout populations in the Kootenai River. Comparisons of length frequencies and recaptures of tagged fish indicated that few if any fish were displaced downstream during the high discharge event.

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.

They reported TDG supersaturation produced by reduced liquid volume in a lake resulting from ice formation that confined the total volume of dissolved gas. Rainbow trout (*Oncorhynchus mykiss*) fingerlings, stocked through the ice of shallow prairie lakes, experienced high mortality even though algal photosynthesis had returned whole-lake oxygen concentrations to normal levels prior to ice melting. Fish caged beneath the ice showed signs of asphyxiation or gas bubble disease, depending on depth. Asphyxiation occurred at oxygen concentrations below 4 mg/L. Total dissolved gas tension is identified as the primary cause of bubble disease and resulting mortality, and the relative contributions of oxygen and nitrogen to total gas tension are demonstrated. Significant mortalities were associated with oxygen relative partial pressures (gas partial pressure relative to total hydrostatic pressure) exceeding 0.2, but only when accompanied by nitrogen relative partial pressures above 1.1. Total relative gas tension under these circumstances exceeded 1.3. An increase in nitrogen partial pressures over the winter was attributed to the physical freeze-out of nitrogen from the ice in shallow lakes where reduction of lake volume due to ice formation is substantial. As water freezes, the dissolved gases are forced into the remaining water. During the spring, lethal levels of gas supersaturation may be present in shallow prairie lakes.

Marking, L. L. 1987a. Evaluation of gas supersaturation treatment equipment at fish hatcheries in Michigan and Wisconsin. Progressive Fish-Culturist 49:208–21.

Fish hatcheries operated in Michigan and Wisconsin by the U.S. Fish and Wildlife Service and in Michigan by the Michigan Department of Natural Resources have reported severe mortalities of lake trout (*Salvelinus namaycush*) in recent years, largely from gas bubble disease caused by gas supersaturation. Until 1985, the systems most commonly used to alleviate this condition were packed column aeration units and vacuum degassers. Sensitive species require water that is both free of gas supersaturation and has high dissolved oxygen. Packed column aeration decreases supersaturation to about 104% and simultaneously increases dissolved oxygen in the treated water. Vacuum degassers can decrease supersaturation to less than 100%, but the negative pressure applied in this process also reduces the dissolved oxygen. Oxygen injection systems effectively decrease nitrogen and total gas pressure to less than 100% and increase oxygen to saturation or even higher desired concentrations. Oxygen generators are cost-effective because operating expenses are largely or completely offset by the improved production and vigor of the fish produced. Although all the details of oxygen generation systems have not been published, the technology is at hand and commercial units are available. Oxygen injection systems should be seriously considered for use in hatcheries being renovated or in new construction, if gas supersaturation is a problem or if increased production is a goal.

Marking, L. L. 1987b. Gas supersaturation in fisheries: causes, concerns, and cures. Fish and Wildlife Leaflet 9, U.S. Fish and Wildlife Service, Washington D.C. 10 p.

The leaflet reviews the general characteristics of GBD and TDG supersaturation based on basic literature sources. Both cultured and wild fish have been lost to GBD which is caused by supersaturation of air in water. Gas bubbles form in the bloodstream and visibly on external surfaces of fish an in lesions in mouth cavities and eye sockets. Extreme exposure leads to "popeye," disequilibrium, and death. Treatment of gas-supersaturated water by packed-column aeration, vacuum degassing, or oxygen injection alleviates the problem. Oxygen injection into hatchery water efficiently removes nitrogen gas and increases dissolved oxygen to level that may increase fish production.

Maule, A. G. 2005. Gas bubble disease monitoring and research of juvenile salmonids, 2004 Annual Report. Report by U.S. Geological Survey for the Bonneville Power Administration. Contract 96-AI-93279. Portland, Oregon.

This is a brief summary identifying the reports and publications produced by the monitoring program.

Maule, A. G., B. J. Adams, R. G. Morris, J. W. Beeman, and D. A. Venditti. 2003. Chapter IV: Growth of resident fishes does not correlate with years of high gas supersaturated water. Pages 109-133 in, Beeman, J. W., D. A. Venditti, R. G. Morris, D. M. Gadomski, B. J. Adams, S. P. VanderKooi, T. C. Robinson, and A. G. Maule. Gas bubble disease in resident fish below Grand Coulee Dam final report of research. U.S. Geological Survey, Western Fisheries Research Laboratory, Cook, Washington. http://wfrc.usgs.gov/pubs/reportpdf/usgsfrgbdgrandcouleedam.pdf#page=54

They examined the growth of resident fish in Rufus Woods Lake by counting annual growth rings (annuli) and back calculating length-at-age. Scale samples were collected from over 7,000 fish. Species examined were rainbow trout (*Oncorhynchus mykiss*), longnose suckers (*Catostomus catostomus*), northern pikeminnow (*Ptychocheilus oregonensis*), and walleye (*Stizostedion vitreum*). Each species had differences in incremental scale growth, generally decreasing with age. None of the species showed growth differences related to TDG levels recorded in the reservoir during their life period of 1996 to 1998. TDG levels were high in 1996 at greater than 120% during April and May. During the extremely high runoff year of 1997 were recorded as high as 151% and remained between 125 and 130% for at least 4 days. A second high TDG period in 1997 had TDG levels over 130% for three weeks in late May and June. In 1998 and 1999 TDG levels remained low, generally at or below 110%. Walleye did show a growth differential however, it was the opposite of what would be predicted base on the much higher TDG levels in 1996 that in 1998. They concluded differences in age-at-length, especially for rainbow trout and northern pikeminnow, were not sufficiently large to suggest annual environmental influences (TDG supersaturation) on fish growth.

Maule, A. G., J. Beeman, K. M. Hans, M. G. Mesa, P. Haner, and J. J. Warren. 1997a. Gas bubble disease monitoring and research of juvenile salmonids. Annual Report 1996 (Project 96-021), Bonneville Power Administration, Portland, Oregon. 112 p. http://pisces.bpa.gov/release/documents/documentviewer.aspx?doc=93279-1

This document describes the GBD monitoring activities for 1996-1997. The report has three chapters referenced as separate reports (Beeman and Maule 1997, Hans and Maule 1997, Mesa et al. 1997) that contain data and analyses of the three main elements of the project: field research to determine the vertical distribution of migrating juvenile salmonids, monitoring of juvenile migrants at dams on the Snake and Columbia rivers, and laboratory experiments to describe the progression of gas bubble disease signs leading to mortality.

The major findings are: a miniature pressure-sensitive radio transmitter was found to be accurate and precise to determine the depth of tagged-fish to within 0.32 m of the true depth, and preliminary data suggest that depth protects migrating juvenile steelhead from total dissolved gas supersaturation (Beeman and Maule). As in 1995, few fish had any GBD signs and the prevalence and severity increased as fish migrated downstream and in response to changing gas supersaturation (Hans and Maule). It also appeared GBD was not a threat to migrating juvenile salmonids when TDG supersaturation was < 120%

(Hans and Maule). Laboratory studies suggest that external examinations are appropriate for determining the severity of gas bubble disease in juvenile salmonids (Mesa et al.). The authors developed a new method for examining gill arches for intravascular bubbles by clamping the ventral aorta to reduce bleeding when arches were removed (Mesa et al.).

Maule, A. G., M. G. Mesa, K. M. Hans, J. J. Warren, and M. P. Swihart. 1997b. Gas bubble trauma monitoring and research of juvenile salmonids. Annual Report 1995 (Project 87-401), Bonneville Power Administration, Portland, Oregon. http://www.efw.bpa.gov/publications/D35245-6.pdf

Initial findings from the 1995 laboratory studies showed no single sign of GBD that was clearly correlated with mortality; but many signs become progressively worse over time. Understanding both prevalence and severity of GBD signs in several tissues is necessary to account for exposure history, individual variation, and possible mortality. Bubbles in the lateral line were the earliest sign of GBD, showed a progressive worsening over time and had low inter-individual variation; however, bubbles in the lateral line may develop poorly during chronic exposures to high TDG. Bubbles in the fins had high prevalence, showed a progressive worsening over time, and may be a relatively persistent sign of GBD; however, there is no truly quantitative method for evaluating severity of fin bubbles, and signs may not develop during acute exposures to high TDG. Bubbles in the gills appear to be the proximate cause of death in fish, and therefore, are extremely relevant; however, these bubbles may only be relevant at high TDG levels, show little progressive change over time, had a high degree of inter-individual variation, may collapse easily, and are difficult to examine and count.

Monitoring juvenile salmonids (Chinook salmon and steelhead), at three dams on the Snake River and three dams on the lower Columbia River, for GBD signs showed few fish had any signs of GBD, but it appeared that prevalence and severity increased as fish migrated downstream. There was no apparent correlation between GBD signs in the fins, lateral line or gills. Prevalence and severity of GBD in migrating fish was suggestive of long term, nonlethal exposure to relatively low level gas supersaturated water (112%), as seen in the laboratory studies. It appeared that GBD was not a threat to migrating juvenile salmonids in 1995.

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

Newly hatched rainbow trout and channel catfish, along with tidepool sculpins and larval Jefferson's salamanders were equilibrated with elevated gas pressures then rapidly decompressed to ambient pressure. The animals were exposed to dissolved gas supersaturation in shallow glass dishes containing 4 ml of water. The animals were equilibrated for 30 minutes in a pressure chamber to high dissolved gas levels. The newly hatched forms tolerated extremely high gas supersaturation. Equilibration pressures of 80-120 atm argon were required for *in vivo* bubble formation. During subsequent larval development, the equilibration pressures required decreased to just 5-10 atm and bubbles originated in the fins. Bubbles tended to form in the caudal fins of fish. Anesthetizing older fish before decompression prevented bubble formation in the fins. This suggests that swimming movements mechanically initiate bubbles, possibly by a tribonucleation mechanism (nucleation at points of rubbing contact between solid structures).

McGrath, K. E., E. Dawley, and D. R. Geist. 2006. Total dissolved gas effects on fishes of the Columbia River. Unpublished report to Army Corps of Engineers, Portland District, Portland Oregon, 40 p.

To facilitate the downstream migration of juvenile salmonids, state regulatory agencies have issued waivers up to 120% TDGS in dam tailraces. Recently, gas supersaturation as a water quality issue has resurfaced as concerns have grown regarding chronic effects of spill-related total dissolved gas on salmonids, including incubating embryos and larvae, resident fish species, and other aquatic organisms. They reviewed recent supersaturation literature to determine whether recent literature 1) contributed new perspectives or information on current water management issues in the lower Columbia River or 2) suggested new or previously-identified issues that may not be adequately addressed by the current 110% TDG limit and the 115/120% TDG water quality waiver.

Their review of recent work determined that newer research supports previous research indicating that short-term exposure up to 120% TDG does not produce significant effects on migratory juvenile or adult salmonids when compensating water depths are available. Monitoring programs at Snake and Columbia River dams, reservoirs, and tail waters from 1993 to the early 2000s documented low incidence of significant gas bubble disease in Columbia River salmonids, resident fishes, or other taxa. However, from the new literature they reviewed, they identified five areas of concern in which total dissolved gas levels lower than the water quality waiver limit may impact fishes of the Columbia River. These areas of concern are 1) sensitive and vulnerable species or life stages, 2) long-term chronic or multiple exposure, 3) vulnerable habitats and reaches, 4) incubating fish in hyporheic habitats, and 5) community and ecosystem impacts. These issues were prevalent in the studies they reviewed and in some cases have been clearly identified in past work. They identify conditions and species/life stages with the greatest likelihood of being impacted by GBD and discuss uncertainties due to lack of scientific data for assessment. They suggest that existing data for the Columbia River downstream from Bonneville Dam are not sufficient to fully evaluate the sublethal and community level effects of TDG supersaturation on salmonid and non-salmonid fishes incubating and rearing in shallow areas that may be exposed to TDG supersaturation for long periods of time. They identify the need for additional research to fully evaluate the effects from <120% TDGS on salmon embryos (primarily sac fry) incubating in hyporheic habitats downstream from Bonneville Dam. Also, the effects of TDG on larval resident (non-salmonid) fishes that rear and reside in the shallow water habitats downstream from Bonneville Dam.

McInerny, M. C. 1990. Gas-bubble disease in three fish species inhabiting the heated discharge of a steam-electric station using hypolimnetic cooling water. Water, Air, & Soil Pollution 49(1-2):7-15.

White bass (*Morone chrysops*), bluegill (*Lepomis macrochirus*), and largemouth bass (*Micropterus salmoides*) inhabiting the heated discharge canal (depth 5-10 m) of Duke Power Company's Marshall Steam Station, Lake Norman, North Carolina, were examined for GBD signs of during the winters of 1982–1983 and 1983–1984. GBD signs in the fish included bubbles and exophthalmia. Peak percentages of these fish species with GBD occurred between late February and early May each year, corresponding with peaks in TDG levels (118-121%) in the discharge water and decreasing dissolved oxygen. Cooling and warming water temperatures, and thermal stratification of Lake Norman influenced saturation of dissolved gases in the hypolimnetic intake water of Marshall Steam Station, and directly affected the variability in total gas saturation in the discharge canal. Temperature change in the condenser cooling water and electricity output were unrelated to the within-year variability in total gas saturation and GBD. The use of hypolimnetic water for cooling at this station restricts the time to a few months that levels of total gas saturation are sufficient to induce GBD, but probably led to higher peaks in GBD than if epilimnetic water was used. Among years, levels of GBD in white bass, bluegill, and largemouth bass were higher when mean temperature changes of the condenser cooling water at Marshall Steam Station were higher, and when intake water temperatures were coldest. No mortalities were reported.

Mesa, M. G., and J. J. Warren. 1997. Predator avoidance ability of juvenile Chinook salmon (*Oncorhynchus tshawytscha*) subjected to sublethal exposure of gas-supersaturated water. Canadian Journal of Fisheries and Aquatic Sciences 54:757-764.

They assessed the effects of GBD on the predator avoidance ability of juvenile Chinook salmon (*Oncorhynchus tshawytscha*), by testing groups of fish that differed in prevalence and severity of gas emboli in their lateral lines, fins, and gills by exposing them to 112% TDG for 13 days, 120% TDG for 8 h, or 130% TDG for 3.5 h in water 30 cm deep. They subjected exposed and unexposed control fish simultaneously to predation by northern squawfish (*Ptychocheilus oregonensis*) in water of normal gas saturation in 6, 18, and 10 tests using prey exposed to 112, 120, and 130% TDG, respectively. Only fish exposed to 130% TDG showed a significant increase in vulnerability to predation. The GBD signs exhibited by fish sampled just prior to predator exposure were generally more severe in fish exposed to 130% TDG, which had the most extensive occlusion of the lateral line and gill filaments with gas emboli. Fish exposed to 112% TDG had the most severe GBD signs in the fins. These results suggest that fish showing GBD signs similar to those of the fish exposed to 130% TDG, regardless of their precise exposure history, may be more vulnerable to predation.

Mesa, M. G., J. J. Warren, K. M. Hans and A. G. Maule. 1997. Progression and severity of gas bubble trauma in juvenile Chinook salmon and development of non-lethal methods for trauma assessment. Pages 55-90 in Maule, A. G., J. Beeman, K. M. Hans, M. G. Mesa, P. Haner, and J. J. Warren. 1997. Gas bubble disease monitoring and research of juvenile salmonids. Annual Report 1996 (Project 96-021), Bonneville Power Administration, Portland, Oregon.

They concluded that laboratory studies suggest external examinations are appropriate for determining the severity of gas bubble disease in juvenile salmonids. At 130% TDG in water 28 cm deep, they found no juvenile Chinook died during the first 5 h of each trial, but then mortalities increased steadily to about 50% by 9 h. Occlusion of the lateral line increased linearly before reaching average peaks of about 20-30% at the end of a trial in 75-100% of test fish. The average severity of bubbles in the fins was low for the first 3-4 h, but then increased gradually. The mean number of gill filaments with bubbles was low during the first 6 h before increasing slightly near the end. With 120% TDG exposure mortalities followed a sigmoid curve reaching about 43% at 58 h. The average lateral line occlusion increased only slightly, never exceeding 20%. The average severity of bubbles in fins was 0.35 for the first 42 h, then increased to 1% during the next 12 h. The average number of gill filaments with bubbles was zero during the first 24 h, then increased to erratic maximum levels between 30-50 h. Other GBD signs included: 11% of fish with bubbles in the pelvic fins, 7% pectoral fins, 9% opercula's, 2% inside the mouth, and 18% exophthalmia. They also developed a new method for examining gill arches for intravascular bubbles by clamping the ventral aorta to reduce bleeding when arches were removed.

Mesa M. G., L. K. Weiland, and A.G. Maule. 2000. Progression and severity of gas bubble trauma in juvenile salmonids. Transactions of the American Fisheries Society 129:174-185.

They conducted laboratory experiments to assess the progression and to quantify the severity of GBD signs in juvenile Chinook salmon *Oncorhynchus tshawytscha* and steelhead *Oncorhynchus mykiss* exposed to different levels of total dissolved gas (TDG), and related these signs to the likelihood of mortality. When fish were exposed to 110% TDG for up to 22 d in water 28 cm deep, no fish died, and there were few GBD signs in the lateral line or gills. Bubbles in the fins, however, were relatively common, and they progressively worsened over the experimental period. When fish were exposed to 120% TDG for up to 140 h, Chinook salmon had an LT_{20} (time to mortality of 20% of test fish) ranging from 40 to 120 h, whereas the steelhead LT_{20} ranging from 20 to 35 h. In steelhead, bubbles in the lateral line, fins, and gills displayed poor trends of worsening over time, showed substantial inter-individual variability, and were poorly related to mortality. In Chinook salmon, only bubbles in the lateral line showed a distinct worsening over time, and the severity of bubbles in the lateral line was highly correlated with mortality. When fish were exposed to 130% TDG for up to 11 h, the LT_{20} for Chinook salmon ranged from 3 to 6 h, whereas that for steelhead ranged from 5 to 7 h. In Chinook salmon, bubbles in the lateral line and fins, but not those in the gills, showed distinct trends of worsening over time. In steelhead, bubbles in the lateral line displayed the most significant trend of progressive severity. In both species at 130% TDG, the severity of all GBD signs was highly correlated with mortality. The progressive nature of GBD and the methods we developed to examine fish for GBD may be useful for monitoring programs that aim to assess the severity of dissolved gas supersaturation exposures experienced by fish in the wild. However, the efficacy of such programs seems substantially hindered by problems associated with (1) the variable persistence of GBD signs; (2) the inconsistent relation of GBD signs to mortality; (3) the insufficient knowledge of the relation between exposure history and GBD sign development for fish in the wild; and (4) an extreme amount of inter-individual variation in terms of susceptibility to GBD.

Miller, T. D., and R. D. Heaton. 1994. Lower Snake River total dissolved gas management and monitoring. Lake and Reservoir Management 9(2): 99 p.

Passing water over spillways at run-of-the-river dams on the Lower Snake River causes TDG supersaturation that often exceeds the State and Federal water quality standards of 110%. Increased spill designed to improve threatened and endangered juvenile anadromous salmonid downstream passage conditions can result, paradoxically, in TDG concentrations that are known to be harmful to these same species. In May of 1994 the National Marine Fisheries Service and U.S. Fish and Wildlife Service requested emergency voluntary spill operations be implemented to improve smolt survival past the Corps dams on the Lower Snake and Lower Columbia rivers. Oregon and Washington state water quality agencies granted temporary water quality rule waivers allowing increased TDG, where measured, not to exceed 120%. They also required intensive monitoring in the tail-waters to assure compliance with the temporary standard. Simple and multiple linear regression models show that most of the variation in TDG pressures can be explained by spill discharge alone. Spill was managed to TDG levels on a real-time basis, and spill caps were set to protect the ecosystem in the face of questionable benefit of spill for anadromous smolt passage. Results of the monitoring to date, from a system-wide perspective, and physical characteristics of the projects are discussed.

Monk, B. K., R. F. Absolon, and E. M. Dawley. 1997. Changes in gas bubble disease signs and survival of migrating juvenile salmonids experimentally exposed to supersaturated gasses annual report 1996. Unpublished report to Bonneville Power Administration, Portland, Oregon. 33 p.

Hatchery steelhead were captured at Little Goose and Lower Granite Dams, marked with passive integrated transponder (PIT) tags, and then experimentally exposed to TDG supersaturated water averaging 113-117% of saturation for about 54 h in a depth of 46 cm. Exposure was terminated when mortality reached 5 to 10%. Resulting prevalence of GBD signs among treatment fish varied from 23 to 51%, averaging 7.6%. Following exposure, test fish were individually evaluated for signs of GBD. Seven replicates of 300 test and control fish (treated identically to test fish except not exposed to dissolved gas supersaturation) were then released about 400 m upstream from Little Goose Dam. Two additional groups of test fish were released directly in front of the turbine intake. About 38% of the treatment and control fish were automatically collected by a PIT-tag selector gate as they passed through the juvenile fish bypass system at Little Goose Dam (average time from release to recapture ranged from 3.3 to 10.1 h). Each recovered fish was anesthetized and reexamined for signs of GBD. Changes in signs attributable to time spent in the forebay, prior to dam passage, were assessed using additional groups of experimentally exposed fish that were held in a net-pen in the forebay at Little Goose Dam. Estimates of relative survival differences between test and control fish groups were obtained from PIT-tag interrogations at Little Goose, Lower Monumental, and McNary Dams during migration.

Of test fish that displayed external GBD signs (subdermal emphysema on fins and opercula) when released, about 47% no longer had signs at recovery following migration to the dam, and passage through the turbine intake and the juvenile bypass system. The percentages of fish that lost GBD signs varied directly with, but were only mildly correlated to forebay TDG levels. Of test fish displaying no GBD signs at release, 5.9% showed GBD signs at recovery. The control fish that displayed no GBD signs when released had a 3.8% prevalence of GBD signs at recovery.

In test fish recovered displaying GBD signs, average severity of signs decreased somewhat, from 1.5 to 1.2 index units (183 fish decreased, 407 no change, and 27 increased). Following experimental exposure to supersaturation, test fish often had GBD signs that were more severe than those commonly seen on juvenile salmonids examined from the river. Thus, they segregated data to examine changes occurring throughout the range of severity. Generally, fish displaying minor GBD signs at release (~20% emphysema coverage and less than l-mm-diameter bubbles of one fin or operculum), showed a slight increase in severity of GBD signs at recovery. Fish with greater severity of GBD signs showed progressively decreased severity at reexamination.

Among fish held in the net-pens, only about 22% had lost GBD signs at reexamination (range of times similar to recovery times of forebay released fish), or about half of the loss observed among fish passing into and through the bypass system. Of the treatment fish displaying no GBD signs at entry to the net-pen, 8.1% showed GBD signs after holding (similar to fish passing into and through the bypass system), although generally the severity of those signs was minor. Control fish were not held in the net-pen. Average severity of GBD signs decreased 0.2 index units (69 fish decreased, 73 no change, and 46 increased). As with free-swimming test fish, those displaying minor GBD signs showed a slight increase of sign severity. Fish with greater severity of signs showed progressively decreased severity at re-examination. Changes in severity were directly, but only mildly correlated with dissolved gas levels in the forebay. No statistical difference in survival was observed for GBD-challenged steelhead compared with unchallenged counterparts, either at passage through Little Goose Dam or at passage through the other dams downstream.

Monk, B. H., C. W. Long, and E. M. Dawley. 1980. Feasibility of siphons for degassing water. Transactions of the American Fisheries Society 109:765-768.

Siphons of 5.1, 10.2, and 15.2 cm inside diameter were tested at several vacuum heads and flow rates as a means to reduce dissolved gas levels. They found this means could lower the nitrogen content of supersaturated water by up to 20% of saturation (to 103% or less). Turbulence within the siphons was the primary factor lowering the dissolved gas level of water.

Montgomery, 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.

In 1975 and 1976, 179 smallmouth bass (*Micropterus dolomieui*) and 85 northern squawfish (*Ptychocheilus oregonensis*) were collected by angling from the lower Snake and mid-Columbia Rivers, southeastern Washington during periods of TDG supersaturation (>115% of TDG saturation). All fish were examined externally for GBD signs. Fish were obtained from fishermen with holding conditions/durations for the fish prior to examination not described. Since all fish were examined alive it is likely fish were held in shallow water for some period prior to examination. Emboli were found beneath membranes of the opercula, body, and fins of 72% of the smallmouth bass and 84% of the northern pikeminnow. Hemorrhage was also noted on the caudal, anal, and pectoral fins of several smallmouth bass. Presence of GBD signs corresponded to the spring runoff when total dissolved gas supersaturation in river water exceeded 115%.

Montgomery Watson. 1995. Allowable gas supersaturation for fish passing hydroelectric dams. Task 8. Bubble reabsorption in a simulated smolt by pass system-concept assessment. Unpublished report to Bonneville Power Administration, Portland, Oregon.

The purpose of this experimental work was to assess quickly the likelihood of gas bubble reabsorption in smolts during simulated bypass passage. The examination of smolts at the Columbia and Snake River dams for GBD signs is used to manage the spill program and ensure that the smolts are not adversely impacted by the elevated levels of dissolved gas supersaturation produced by the spill. Only smolts that pass through the smolt bypass system are examined. Smolts that pass through the turbines or over the spillways are not sampled. There is limited sampling of smolts for examination for clinical GBD signs from the reservoir, forebay, or tailrace. A pressurization of 5 min. (shortest time tested) to 100 ft of head resulted in a significant reduction in GBD signs in the fins, lateral line, and gills. They conclude that if the reabsorption potential of pressure-time history for smolts is similar to the 5 min. pressurization treatment, the current smolt monitoring program may be underestimating the prevalence of GBD in the Columbia River.

At a total dissolved gas pressure of 125%, the hydrostatic compensation depth is approximately 8.2 ft. If the smolts remain below this depth, gas will be transferred from any existing bubbles into the water and the GBD signs will disappear. Therefore, it is not necessary for smolts to remain at 100 ft for 5 minutes for significant reabsorption to occur. The exposure of 5 min. at 100 ft of head has a reabsorption potential of -0.50 ft/day. The required times for other depths are presented. In terms of the reabsorption potential, 62 minutes at 20 ft or 23 min. at 40 ft are equivalent to the 5 min. at 100 ft used in this experimental work. This computation is based on the assumption of a river total gas pressure = 125% and ignores the contribution of the pressurization and depressurization phases in the computation of equivalent times.

Morris R. G., J. W. Beeman, S. P. VanderKooi, and A. G. Maule. 2003a. Lateral line pore diameters correlate with the development of gas bubble trauma signs in several Columbia River fishes. Comparative Biochemistry and Physiology A 135(2):309-20.

A common indicator of GBD is the percent of the lateral line occluded with gas bubbles; however, this effect has never been examined in relation to lateral line morphology. The effects of 115, 125 and 130% total dissolved gas levels were evaluated on five fish species common to the upper Columbia River. Trunk lateral line pore diameters differed significantly ($P<0.0001$) among species (longnose sucker>largescale sucker>northern pikeminnow ≥ Chinook salmon ≥ redside shiner). At all TDG supersaturation levels evaluated, the percent of lateral line occlusion exhibited an inverse correlation to pore size but was not generally related to the TDG level or duration of exposure. This study suggests that the differences in lateral line pore diameters between species should be considered when using lateral line occlusion as a GBD indicator.

Morris, R. G., J. W. Beeman, S. P. VanderKooi, and A. G. Maule. 2003b. Chapter V: Lateral line pore diameters correlate with development of gas bubble trauma signs in several Columbia River fishes. Pages 134-157 in, Beeman, J. W., D. A. Venditti, R. G. Morris, D. M. Gadomski, B. J. Adams, S. P. VanderKooi, T.C. Robinson, and A. G. Maule. Gas bubble disease in resident fish below Grand Coulee Dam final report of research. U.S. Geological Survey, Western Fisheries Research Laboratory, Cook, Washington.

Bubbles in the later line of fishes are a commonly observed indicator of gas bubble disease (GBD) also referred to as gas bubble trauma. Juvenile Chinook salmon (*Oncorhynchus tshawytscha*), largescale sucker (*C. macrocheilus*), longnose sucker (*C. catostomus*), and redside shiner (*Richardsonius balteatus*) were exposed to 115, 125 and 130% TDG in 155 L tanks with water depths of 0.26 m. Lateral line pore diameters among the species were significantly different with longnose sucker > largescale sucker > northern pikeminnow > Chinook salmon > redside shiner. At each TDG level the percent of lateral line occlusion by bubbles was inversely correlated to pore size, but was generally not related to TDG level or exposure duration.

Murdoch, K. G., and R. D. McDonald. 1997. Gas bubble trauma monitoring at Rocky Reach and Rock Island Dams, 1997. Unpublished report by Chelan County Public Utility District No. 1 of Chelan County, Wenatchee, Washington. 22p + appendix.

Juvenile Chinook salmon and steelhead migrating past Rocky Reach and Rock Island dams on the mid-Columbia River were sampled and monitored for GBD signs. At Rocky Reach Dam (RKm 761) fish were collected from turbine intake gatewells (Unit 1) and a surface collector for a bypass system. At Rock Island Dam (RKm 730) juveniles were collected from turbine intake gatewells through submerged orifices into an inclined screen trap. Collected fish were held in shallow water (0.8 m at Rocky Reach, <0.3 m at Rock Is.) for up to 24 h prior to examination.

Signs of GBD were seen in 6.3% of Chinook and 11.7 % of steelhead at Rocky Reach Dam. At Rock Is. Dam GBD signs were observed in 14.9% of yearling Chinook, 2.5% of subyearling (summer) Chinook and 12.7% of steelhead. The percentage of fish with GBD signs increased substantially when TDG levels exceeded 120% of saturation. Signs of GBD were generally very minor (rank 1-2). Rank 3-4 GBD signs were seen in about 1.4% of steelhead and 1.2% of yearling Chinook at Rock Island. Subyearling Chinook had a low incidence (0.1%) of the more severe signs at Rock Is. At Rocky Reach the more sever signs were detected in 1.1% of yearling Chinook and steelhead. At both dams a small percentage (0.3-1.4%) had bubbles in one or both eyes. Signs of GBD may develop in some of the fish during the period they are confined in shallow water between collection and examination (0.5-24 hr). Fish were provided a pumped river water supply during holding. Total dissolved gas levels were commonly in the range of 125-135% of saturation during late May and early June when the highest incidence of GBD was identified.

MWH. 2003. Gas abatement techniques at Rocky Reach Hydroelectric Project. Unpublished report to Public Utility District No. 1 of Chelan County. Wenatchee, Washington. 58 p**.** **http://www.chelanpud.org/rr_relicense/study/reports/6167_1.pdf#search=%22%22Fickeisen%22%20%22Dissolved%20Gas%20Supersaturation%22%22**

This study involved investigating the literature and interviewing professionals with gas abatement experience with the objective of identifying possible solutions to decrease the TDG downstream from Rocky Reach Dam. Two operational alternatives were identified and both of these should be explored further.

Alternative O1, Maximize Powerhouse Flows, requires that the fish spill requirements be decreased and the reduced flows be passed through the powerhouse. This would require that the new juvenile bypass system achieve enough survival success that the fish spill can be decreased. Alternative O2, optimizing spill from gates 2 through 12, shows promise based on TDG measurements taken in two operational trials in spring of 2002. These data indicated that by altering the standard spill pattern, a decrease in saturation of up to 7% might be achieved during maximum fish spill of 62,500 cfs. Alternative O2 could be implemented immediately, if permission to alter the standard spill pattern can be obtained. Since there is only a small amount of data for this alternative, further data should be gathered.

There were several alternatives (S2, S12, S13, and S16) that prevented gas from entering the water as it passed from upstream to downstream of the dam. These all involved some kind of pressurized flow so that the water was not exposed to the atmosphere. All these were very expensive and exposed downstream migrating fish to possible injury. The only alternative that might be possible in this class of alternatives was S16, Additional Powerhouse. A suitable juvenile bypass system could be built for the new powerhouse, and the powerhouse might be able to recover some of the cost of the alternative. However this was not recommended since other alternatives for TDG reduction showed more promise. Another class of structural alternatives (S4, S6, and S15) showed promise of passing river flow without increasing the TDG were baffled or stepped spillways. These dissipate energy over the length of the spillway so that the flow enters the tailrace with minimal energy. The affect of these alternatives is to evenly degas supersaturated water from the upstream pool. However, due to inefficiencies some supersaturation would be carried into the tailrace. These alternatives also could be injurious to downstream migrants and are very expensive. Another class of structural alternatives (S1, S8, S9, S10, S11, and S18) shows promise of reducing TDG downstream of Rocky Reach. The common approach taken by these alternatives is to keep the turbulence of the spilling water on the surface, not allowing it to be transported deep in the water column where entrained air is driven into solution. These types of alternatives are recommended by the Portland and Walla Walla Districts of the Corps of engineers in their Dissolved Gas Abatement Study for their dams on the lower Snake and Columbia Rivers. Although the cost of these alternatives is less than most of the others their cost can be substantial. Other alternatives considered involved a combination of the above structural alternatives. Some other alternatives added spillways to decrease the unit discharge, such as S5, S7, and S14. The benefit relative to the cost of these is small compared to other alternatives. In general these produced little TDG benefit for a high cost. Alternative S17, Divider Wall between powerhouse and spillway, did not show enough TDG reduction benefit to justify its cost.

Myers, R., and S. E. Parkinson. 2002. Hells Canyon Complex total dissolved gas study. Technical Report Appendix E.2.2-4 by Idaho Power Company, Boise, Idaho. 68 p.

As is the case with most hydroelectric projects, spilling water at projects in the Hells Canyon Complex causes total dissolved gas (TDG) levels to exceed the 110% saturation limit for protecting aquatic biota. Levels in the tailwater of Hells Canyon Dam have been measured as high as 135% saturation, with resulting in-river levels in excess of 110% saturation for up to 60 miles downstream. Measured levels in the tailwater of Brownlee Dam approach 125%, with little dissipation downstream through Oxbow and Hells Canyon reservoirs. A predictive numerical modeling tool was developed as a part of this study to provide TDG boundary condition information to water quality and habitat models for resource impact evaluation. Based on the results of spill tests, spilling water from the upper spill gates at Brownlee Dam helps minimize TDG levels in the tailwater. Also, physical modeling of Hells Canyon Dam shows that flow deflectors installed on the dam's spillway may reduce TDG levels at total spill flows of less than 30 kcfs. Although flow deflectors show promise for reducing elevated TDG levels at a qualitative modeling level, it is difficult to predict what levels of TDG will occur downstream from the project under all spill conditions with the deflectors in place.

N

Nebeker, A. V., F. D. Baker, and S. L. Weitz. 1981. Survival and adult emergence of aquatic insects in air-supersaturated water. Journal of Freshwater Ecology 1:243-246.

They exposed mayflies *Timpanoga hecuba*, caddisflies *Dicosmoecus gilvipes*, mosquitoes *Culex peus*, and midges *Cricotopus* sp. to TDG supersaturation in laboratory tests to determine the effects on survival and adult emergence. The 96 h LC_{50} for the mayfly was 129% TDG. At 125% TDG the LT_{50} for the mayfly was 2.7 d, while at 135% TDG the LT_{50} for the caddis fly was 45 d. Adult midges and mosquitoes emerged at TDG levels > 140%. Adult mayflies and caddis flies did not emerge at TDG levels of about 134% and higher. They found all insects were more tolerant of TDG supersaturation than fish.

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(3):299-303.

Juvenile Chinook, coho, and sockeye salmon, and steelhead trout were tested at 8, 9, 10, 12, 15, and 20 °C at TDG levels of 115, 116, 117, 118, and 120% in shallow water (0.6 m). The effect of different temperatures and constant TDG level on survival of the fish varied with species. Increased temperatures caused a very significant increase in steelhead mortality, a significant increase in Chinook deaths, but no significant effect on coho or sockeye mortality. Using regression models, highly significant ($P<0.001$) and significant ($P<0.005$) temperature effects were shown on steelhead and Chinook, respectively. For sockeye and coho, such regressions did not show a significant effect of temperature for either the LT_{50} or LT_{20}. Mixed gas tests with steelhead showed that there was a significant difference ($P<0.05$) in time to death at different O_2/N_2 ratios when fish were tested at the same total dissolved gas pressure.

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.

Speckled dace (*Rhinichthys osculus*) are more tolerant of air-supersaturated water than adult or juvenile cutthroat trout (*Oncorhynchus clarki*) in laboratory tests (depth 25 cm). Speckled dace tested at TDG levels from 110 to 142% saturation and had a 96-h median lethal concentration (LC_{50}) of 140%, a 7-d LC_{50} of 137%, and 2-week LC_{50}'s of 129 and 131% saturation. The estimated mean threshold concentration, based on time to 50% death (TM_{50}), was 123% saturation. The speckled dace also exhibited consistent external signs of gas bubble disease. Cutthroat trout were tested from 111 to 130% saturation and had 96-hour LC_{50}'s of 119-120% (adults) and 119% (juveniles) saturation. The cutthroat 2-week LC_{50} wash 118% (adults) and 115% (juveniles). Estimated mean threshold concentrations (from TM_{50} values) were 117% (adults) and 114% (juveniles) saturation. The GBD signs exhibited by the cutthroat trout were similar to those seen with other salmonids examined in earlier studies.

Nichol, D. G., and E. A. Chilton. 2006. Recuperation and behaviour of Pacific cod after barotrauma. ICES Journal of Marine Science 63:83-94p

They captured tagged with data-storage tags 624 Pacific cod and released in the Gulf of Alaska and eastern Bering Sea from 2001 to 2003. Cod were captured with pot or jig gear at depths ranging from 32 to 127 m. As of January 2004, 272 tags (44%) were recovered, with fish at liberty from 2 days to 1.5 years. The tags, which collected time, depth, and temperature information, revealed behavior patterns common to nearly all recaptured fish. Analysis of swimbladder function suggests that these patterns resulted from swimbladder ruptures and deflation. In most cases, fish immediately dived to the bottom and then, within hours, returned to shallower depths. Fish that subsequently descended back to the depth at which they were captured, did so at rates ranging from 4.9 to 23.2 m/day. Observations of bubbles being released from cod as they neared the surface during capture, indicated that cod swimbladders can rupture. A series of X-rays taken of live cod immediately after capture and subsequently at 24 h, revealed that ruptured swimbladders were sealed within 24 h. The loss of gas from the swimbladder, and the subsequent loss in buoyancy, inhibited most cod from remaining near the bottom. Their quick return to shallow water after an initial escape response indicates either a need or preference to reside at a depth at which they are more neutrally buoyant. Although rates of descent were highly variable among individuals, smaller individuals tended to descend faster than larger ones. Rates of descent were most likely limited by the secretion rate of gas into the swimbladder. Future tagging work for species such as Pacific cod need to recognize the recuperation period that is necessary before natural vertical or horizontal migrations can be evaluated.

O

Orlins, J. J., and J. S. Gulliver. 2000. Dissolved gas supersaturation downstream of a spillway. II: Computational model. Journal of Hydraulic Research 38(2):151-159.

The increase in dissolved gas concentration downstream of hydraulic structures such as dam spillways can be harmful to most fish species. The increased TDG increases observed at numerous hydroelectric dams on the Columbia and Snake Rivers in Washington State have produced concern that the TDG supersaturation may increase mortality in juvenile and adult salmonids. Modifications to the spillway and/or its tailrace at some of these dams have or will be installed to help lower the TDG levels produced downstream from the dams. At Wanapum Dam on the mid-Columbia River, spillway modifications were designed and evaluated using a combination of physical and numerical models. The physical model provided information about the hydraulics associated with different spillway modifications. The numerical model calculated the concentration of total dissolved gas based upon hydrodynamic data from the physical model and mass transport relations developed for air-water flows. This article describes the numerical model development and application.

P

Parametrix, Inc. 1997. Physical and biological evaluations of total dissolved gas conditions at Cabinet Gorge and Noxon Rapids Hydroelectric Projects - spring 1997. Unpublished report to Washington Water Power Co. (Avista Corporation), Spokane, Washington. 40 p + Appendices.

Four fixed monitoring stations were established in the forebay and tailrace areas of Noxon Rapids and Cabinet Gorge Dams to monitor TDG levels between April 23 and July 14, 1997. River water in the Noxon Rapids forebay ranged from 107-126% TDG during the spill period, typically exceeding the 110% of saturation criteria. The daily average spill during the sampling period reached 63% of total river flow at Noxon Rapids Dam (76 kcfs) and 77% of total flow at Cabinet Gorge Dam (107 kcfs). The resulting TDG levels ranged from 104% to 126% of saturation downstream of Noxon Rapids Dam, and from 119% to 158% of saturation downstream of Cabinet Gorge Dam during the monitoring period. Under the conditions present in 1997 (112-116% TDG in Noxon Rapids forebay), spilling greater than 17% of the total river flow at Noxon Rapids Dam typically resulted in TDG levels in excess of 115% of saturation. TDG levels downstream of Cabinet Gorge Dam exceeded 115% of saturation throughout the monitoring period, with spill levels typically greater than 20% of total river flow.

The TDG plume in Lake Pend Oreille indicated relatively high TDG levels throughout the northern arm of the lake. Although a 10% decrease in TDG levels occurred between the river delta and Sandpoint, TDG levels still exceeded 125% of saturation at Sandpoint mid-way through the spill period (May 30). The study results indicate an extensive lateral distribution of the supersaturated plume in the north arm of the lake. The depth of the plume also exceeded 15 m throughout most of this area.

Biological implications of the high TDG levels in resident fish were investigated by collecting fish at several locations downstream from Cabinet Gorge Dam by electrofishing. These fish were examined for external GBD signs. resident fish species collected from shallow-water habitats exhibited only minor GBD signs and a low incidence of GBD signs. These data indicate that wild resident fish spend sufficient time at compensation depths to avoid severe GBD and mortality, resulting from exposure to the high TDG levels that occurred in 1997. Hatchery rainbow and cutthroat trout were also held in live cages in the river, and periodically examined for GBD signs and/or mortalities. Fish held in live cages were confined to shallow water (<2 m deep) and unable to reach pressure compensation depths to minimize the effects of high TDG levels, suffered rapid and high mortality rates. Kokanee fry released from the Cabinet Gorge Hatchery on July 2 and collected by a floating fyke net just prior to entering Lake Pend Oreille within 14 h of their release also showed no external GBD symptoms.

Parametrix, Inc. 1999a. Gas bubble disease lower Clark Fork River, 1998. Unpublished report to Avista Corporation, Spokane, Washington. 32 p + Appendices.

Resident fish were collected by electrofishing, fyke netting, and Oneida trapping is the lower Clark Fork River downstream from Cabinet Gorge Dam. Captured fish were evaluated for GBD signs according to the Columbia River Research Laboratory protocols. Gas bubble disease was absent from resident fish collected in the lower Clark Fork River during the spill season. About 2,500 captured fish were examined between May 4 and July 16, 1988 with only a single fish showing signs of GBD. This fish was collected prior to initiation of spill at either Cabinet Gorge or Noxon Rapids dams and had a low severity of GBD signs. The extremely low incidence of GBD indicates that fish using the lower Clark Fork River are able to avoid the moderately high levels of gas supersaturation (115-120% of saturation) experienced in 1998. By residing at depths of 1.5 to 2 m (4.9 to 6.6 ft) fish can avoid the effects of supersaturation through the compensatory hydrostatic pressure afforded by these depths. Parametrix (1998b) found that radio-tagged resident fish monitored in the lower Clark Fork River were spending substantial periods of time at these depths.

Approximately 5,000 hatchery cutthroat trout were released into the lower Clark Fork River during spill conditions to provide fish with a known exposure history for recapture. Only eleven of these fish were recaptured, apparently due to rapid migration to Pend Oreille Lake. No GBD signs were observed in the captured cutthroat during exposure to TDG levels of up to 120%. In addition, radio tags were inserted into ten hatchery cutthroat trout to monitor behavior in the lower river during spill conditions. The recapture information and the radio telemetry data indicate that these hatchery fish remained in the river for at least 3 days.

Parametrix, Inc. 1999b. Gas bubble disease lower Clark Fork River, 1999. Unpublished report to Avista Corporation, Spokane, Washington. 35 p + Appendices.

Fish were captured in the lower Clark Fork River downstream from Cabinet Gorge Dam by electrofishing, beach seining, and Oneida trapping. A total of 6,474 resident fish were collected and examined between May 3 and July 14, 1999. GBD signs were observed primarily in suckers (11%) and yellow bullhead (14%) when TDG levels peaked during the first week in June to between 125% and 130% of saturation.. The majority of these fish (>60%) had relatively minor signs of GBD (rate 1-2). Only three salmonids, one brown trout and two kokanee, were observed with mild signs of GBD (rate 1-2). Only two species on non-salmonids had more than a minor incidence of GBD during a month when TDG levels were % (peak 137%). Those portions of the sucker and yellow bullhead populations present in shallow water had incidences of GBD of 11% and 14% respectively. The severity of the disease was generally minor with most fish showing one to several bubbles in a fin. No GBD signs were observed in any fish collected prior to the beginning of spill or during the post-spill monitoring period.

Monitoring included a release of approximately 8,000 hatchery cutthroat trout into the side channel of the lower Clark Fork River during spill. None of these fish were recaptured, indicating they either immediately migrated downstream out of the sampling area or remained too deep to be captured by electrofishing.

Kokanee fry in held in a 9-m deep live-cage to determine if these fish are likely to incur biological effects due to supersaturation. None of the young kokanee showed GBD signs. Hydroacoustic monitoring of their depth distribution indicated the kokanee remained sufficiently deep most of each day to avoid the biological effects of TDG supersaturation within the range that occurred in Lake Pend Oreille.

Parametrix, Inc. 2000b. Analysis of total dissolved gas data, Rocky Reach Dam, 1997 – 2000, final report Rocky Reach Hydroelectric Project No. 2145. Prepared by Parametrix, Inc., Kirkland, Washington, for Chelan PUD. http://www.chelanpud.org/rr_relicense/study/reports/2420_1.PDF

This report provides an analysis of total dissolved gas (TDG) data for Rocky Reach Dam. Data are available for spill periods from 1997 through 2000 for appropriate forebay and downstream monitoring locations. The analysis was undertaken to identify factors influencing changes in TDG levels at Rocky Reach during the spill periods. Spilling water at Rocky Reach Dam produces supersaturation just as spilling does at other dams. However, at Rocky Reach the major factor determining downstream TDG levels is the level of dissolved gas in the water arriving at the forebay. The TDG levels in incoming water plays a greater role in determining downstream TDG levels than any other factor. Generally TDG levels in the forebay water increase at the same time that spill occurs or increases at Rocky Reach Dam, because increasing river flows result in increasing spill at upstream dams. Spill at Rocky Reach Dam only produces minor increases TDG levels. During the years of 1998-2000 TDG levels increased only slightly during the spill period (1-3% of saturation on average, range –5% to +15%). Average TDG levels during these years remained below 110% of saturation, although point measurements ranged from 100% to 120% of saturation. These conditions occurred with total river flows ranging from less than 100 kcfs to about 275 kcfs. Increases in TDG levels were only slightly greater at higher river flows.

During the extremely high flow year of 1997, total river flows reached nearly 400 kcfs and maximum spill volumes approached 300 kcfs. However, TDG levels did not increase substantially from the forebay to the downstream monitoring location at Rocky Reach. During the 1997 spill period TDG levels were commonly high (110-135% of saturation), but average levels did not increase from the forebay to the tailrace at Rocky Reach Dam. Although the distance from the Rocky Reach tailrace monitoring location to Rock Island forebay is only about 15 miles, there is a slight decrease in TDG levels over this distance. Correlations of patterns of TDG levels at the two locations indicate the travel time of water bearing dissolved gas from spill discharge was in the range of seven to 13 hours during the spill periods evaluated. Evaluations of different spill gate configurations used at Rocky Reach Dam suggest that configurations using a greater number of gates tend to minimize the increases in TDG from the forebay to the tailrace. There is also some indication that the increases in TDG between the forebay and the tailrace might not follow a linear relationship with spill volume at the project. However, this non-linear relationship was only apparent during the 1997 high flow year.

Parametrix, Inc. 2002. Total dissolved gas biological effects report, Rocky Reach Hydroelectric Project No. 2145. Unpublished report by Parametrix, Inc. and R.L. & L. Services Ltd. to Chelan County PUD, Wenatchee, Washington. 162 p.

The report describes the results of the second year of investigation of effects of TDG supersaturation on fish and aquatic invertebrates downstream from Rocky Reach Dam. The exceptionally dry winter and subsequent low runoff in the Columbia River basin during 2000-01 precluded spill events that normally aid juvenile salmonid out-migration during the first year of this investigation . Mean TDG levels were only in the range of 105% to 109% of saturation in 2001 with occasional TDG spikes of 112% to 115% for a few hours duration. No GBD signs were observed in the 3,777 resident fish examined, and only 2 of 7,405 invertebrates examined had GBD signs.

In 2002 spill Rocky Reach Dam spilled over about 92% of the monitoring period (April 3 to August 21). Downstream TDG levels remained below 120% during 92% of the monitoring period, and below 125%

of saturation about 97% of the time. Peak TDG levels exceeded 130% of saturation (134% maximum), these levels less than 1% of the time (28 of 3,361 hours). Benthic macroinvertebrates were collected from six sites in the immediate tailrace area and up to 5.6 km downstream from Rocky Reach Dam. One bristle worm and one mayfly (*Hexagenia* sp.) exhibited GBD signs, comprising 0.02% of the total of 9,885 invertebrates examined. During the spring 2,134 resident fish were examined with none showing GBD signs (TDG 103% to 127%). An additional 866 resident fish were examined for GBD signs from early July to late August, with 160 (18%) showing some GBD signs when TDG reach a high of 134%. Species with GBD signs included three-spined stickleback (50.5%), northern pikeminnow (22.0%), redside shiner (15.5%), peamouth (7.6%), and chiselmouth (3.7%). Most of the signs consisted of slight hemorrhaging between the fin rays, at the base of the fins and in the lateral line. However, some fish exhibited more severe signs such as subcutaneous hemorrhaging and swelling of the caudal peduncle and opercular area, as well as hemorrhaging in multiple fins. Despite the relatively high incidence of hemorrhaging, actual bubbles were observed in only one fish (in the branchiostegal region of a stickleback).

Parametrix, Inc. 2005. Determine if project operation results in supersaturation of atmospheric gases in Lower Niagara River. Report to New York Power Authority, New York. 59 p + appendix. http://niagara.nypa.gov/ALP%20working%20documents/finalreports/IS27.pdf

They surveyed TDG levels in the lower Niagara River from Niagara Falls to downstream from the U.S. and Canadian hydroelectric projects. The TDG levels downstream from the Falls and upstream from the projects were consistently greater than 121% of saturation during the tourist season monitoring period (averaging 126.3%), while TDG levels about a mile or more downstream were consistently below 118% of saturation (averaging 113.6%). At the same time, TDG levels recorded in the turbine discharge plume from the U.S. project were consistently below 109% of saturation (averaging 102.9%) despite a 300 ft head. Similar differences were observed in November (non-tourist season), although the TDG levels at all locations were typically at least 3% of saturation lower than in August. Discharge from the U.S. power station reduced naturally produced TDG levels through the dilution of the higher TDG water resulting produced at Niagara Falls. The average reduction during the tourist season was 12.7% of saturation (8 – 16% range), and 15% of saturation during the non-tourist season (range 9 – 18%).

Parametrix. 2006. Cabinet Gorge and Noxon Rapids Hydroelectric Projects – 2006 total dissolved gas monitoring. Unpublished report to Avista Corporation, Spokane, Washington. 36 p + Appendices.

In 2006 TDG levels downstream from Cabinet Gorge Dam exceeded 125% of saturation for 320 hours in the spring of 2006. Despite these high TDG levels, only 29 (2.1%) of the 1,354 resident fish examined showed GBD signs. Fish were observed with GBD signs about one week after the peak TDG levels of the season (137%). However, only one fish was observed with GBD signs after June 9, despite nearly continuous TDG levels of 118-126% through June 23. Unlike prior years of high TDG, suckers did not show GBD signs in 2006. Bullheads had the highest incidence (38%) of GBD although only a small number were captured (32). None of the 328 trout had GBD signs except 5 of the brown trout (3.8%) despite the substantial period of TDG exceeding 120%. One of 164 whitefish showed GBD signs. As in previous years with high TDG levels, those fish exhibiting signs of GBD generally had bubbles only in the dorsal or caudal fins.

Parker, N. C., K. Strawn, and T. Kaehler. 1976. Hydrological parameters and gas bubble disease in a mariculture pond and flow through aquaria receiving heated effluent. Proceedings of the Annual Conference of the Southeastern Association of Fish and Wildlife Agencies 30:179-191. (from csa.com)

Total dissolved gas, dissolved oxygen, dissolved nitrogen, pH, conductivity, temperature, and turbidity were monitored to determine diel and annual changes in a mariculture pond and in aquaria supplied with water discharged from a power plant. The diel and annual ranges of all hydrological parameters were greater in the pond than in aquaria. Diel patterns were similar in both cases but the amplitude was attenuated in the laboratory aquaria. Gas bubble disease (GBD) developed in 17 marine and estuarine fishes and in grass shrimps in the laboratory. GBD was more prevalent in aquaria at higher temperatures than in aquaria at lower temperatures. The disease occurred only in the winter months and was simultaneously found in fish in aquaria and in fish cultured in cages in the discharge canal. GBD was attributed to nitrogen supersaturation produced as water passed through the power plant and also to pump cavitation and to changing fish from water of high saturation to water of low saturation during cleaning of tanks

Praye, L., and J. B. Walter. 2002. Rock Island Dam smolt and gas bubble trauma monitoring, 2002. Public Utility District #1 of Chelan County, Wenatchee, Washington. http://www.midcolumbiahcp.org/Studies/RISmolttrap02.pdf

Emigrating juvenile Chinook *Oncorhynchus tshawytscha*, sockeye *O. nerka*, coho *O. kisutch* salmon, and steelhead *O. mykiss* were examined and counted at the Rock Island Dam bypass trap from April 1, - August 31, 2002. This was the 18th consecutive year that the juvenile spring and summer salmonid emigration was monitored at Rock Island Dam. Total river flow and Powerhouse No. 2 flow during bypass trap operations averaged 153.5 kcfs and 101.4 kcfs, respectively. Spill for fish passage began on April 14 and continued through August 27. In 2002, the Rock Island Dam trapping facility collected 128,939 target salmonids. This included 3,410 (2.6%) mortalities that occurred during trapping, sampling, or tagging. Of the 121,338 fish examined, 4.7% showed signs of descaleing. Gas bubble disease was also examined for 3,691 salmonids with 2.3% showing external signs. The middle 80% of the total juvenile salmonid emigration passed Rock Island Dam during a 61-day period from 3 May - 3 July. The duration of the middle 80% passage was 51 days for yearling Chinook, 77 days for subyearling Chinook, 27 days for steelhead, 58 days for sockeye, and 49 days for coho. A total of 14,984 salmonids were tagged with passive integrated transponder (PIT) tags between April 17 and August 19. An additional 2,526 previously PIT tagged salmonids from other projects were detected. The bypass trap incidental catch totaled 88,973 fish. Of which, 98.8% were three-spine stickleback *Gasterosteus aculeatus* and 0.3% were non-target salmonids (i.e. steelhead kelts, rainbow trout, adult sockeye, kokanee, bull trout *Salvelinus confluentus*, cutthroat trout *O. clarki*, brown trout *Salmo trutta*, and mountain whitefish *Prosopium williamsoni*).

Politano, M., P. Carrica, C. Turan, and L. Weber. 2004. Prediction of the total dissolved gas downstream of spillways using a two-phase flow model. Page 310 in Sehlke, G., D. F. Hayes, and D. K. Stevens (editors). Critical Transitions in Water and Environmental Resources Management, Salt Lake City, Utah.

Some numerical studies have been conducted in the past to predict TDG downstream from spillways, most of them based on experimental correlations for the gas volume fraction. A better approach to predict the TDG is possible using a two-phase flow model. This method is based on the two-fluid model to calculate the gas volume fraction and velocity of the bubbles. A transport equation for the TDG is solved considering the mass exchange with the bubbles. They assume one variable bubble size, which may change due to local mass transfer and pressure. The simultaneous solution of a bubble number density equation allows the prediction of the bubble size. The two-phase equations were implemented CFDShip-Iowa, and a parallel, multiblock RANS solver developed at IIHR. Results of TDG, gas volume fraction, bubble number density are discussed. The numerical results of TDG are compared with available field data in the stilling basin of Wanapum Dam on Columbia River.

R

R. L. & L. Environmental Services Ltd. 2000. Kootenay River total gas pressure monitoring, 1999 investigations. Report No. 739D to Columbia River Integrated Environmental Monitoring Program, Nelson, British Columbia, Canada. 25 p.

During medium and high discharge periods, when total discharge from Kootenay Lake exceeded maximum Kootenay Canal discharge (581 m^3/s), spillways at Corra Linn Dam were used to release excess discharge. Use of spillways at this dam and at all downstream facilities increased TDG, but the major contributions were from the Lower Bonnington Dam and Brilliant Dam spillways. The test at Lower Bonnington between flows over the dam spillways and the natural cascade showed that discharge over the natural falls reduced TDG levels. This spillway operational change reduced TDG levels, but at the expense of reduced energy generation at the City of Nelson and Upper Bonnington plants because of increased tailwater elevation. Dilution of Lower Bonnington spill by low TDG discharge from Kootenay Canal and the Slocan River reduced the amount of TDG measured downstream and reduced the possibility of detrimental effects on fish (i.e., gas bubble trauma). The amount of TDG generated by Kootenay Canal was relatively low when compared to Lower Bonnington; however, based on data from the medium flow monitoring session, all TDG produced by generation at Kootenay Canal appeared to be associated with only one of the four turbines. On July 5 the suspect turbine was temporarily disengaged, reducing total discharge of about 800 to 600 m^3/s. This resulted in a reduction of Kootenay Canal tailrace TDG by approximately 50 mm Hg to a level identical to the Corra Linn forebay. Subsequent reactivation of the turbine, Kootenay Canal tailrace TDG increased to the pre-deactivation level as reservoir head and power production approached maximum capacity on 6 July. The reason for increased production of TDG by this unit is unknown. Spills at Brilliant Dam under the operational characteristics that existed during this study apparently do not result in TDG increases in the tailrace above a threshold level of about 128% of saturation, even though the volume of spilled water increased.

Richmond, M. C., W. A. Perkins, T. D. Scheibe. 1999. Two-dimensional hydrodynamics, water quality, and fish exposure modeling of the Columbia and Snake rivers. Part 1: Summary and Model Formulation. Final Report by Battelle Pacific Northwest to U.S. Army Corps of Engineers, Walla Walla District, Walla Walla, Washington..

Richter, T. J., J. Naymik, and J. A. Chandler. 2007. HCC gas bubble trauma monitoring study. Idaho Power Company, Boise, Idaho. 38 p.

The Idaho Power Company monitored salmonid and nonsalmonid species for GBD signs caused by periods of spill discharge within the Hells Canyon Complex (HCC) during 2006. Total dissolved gas

(TDG) levels associated with the spill ranged from 90% to 143% of saturation. The TDG levels downstream from Brownlee Dam were near or exceeded 130% from early April through mid-May. Fish were collected by jet boat-base electrofishing (near surface) from the reservoirs downstream from Brownlee and Oxbow Dams and the Snake River downstream from Hells Canyon Dam where the TDG supersaturation occurred. Fish were examined and ranked following the USGS (1997) protocols. Twenty fish species were collected during the investigation. No GBD signs were observed during periods when TDG levels remained below 120%. However, GBD signs were present in fish exposed to TDG levels above 120% within the 12 h period prior to sampling, mid-April to mid-May. White crappie (*Pomoxis annularis*) (22%), smallmouth bass (*Micropterus dolomieui*) (14%), and rainbow trout (*Oncorhynchus mykiss*) (17%) had the highest rates of GBD. Chinook salmon (*O. tshawytscha*), kokanee (*O. nerka*), mottled sculpin (*Cottus bairdi*), pumpkinseed (*Lepomis gibbosus*), and steelhead (*O. mykiss*) did not show any GBD signs. The Brownlee Dam tailrace area had the highest incidence of GBD (17.5%). Following 30 consecutive days of TDG levels exceeding 120%, 63% of all fish collected downstream from Brownlee Dam showed some GBD signs. They consistently observed GBD signs exceeding rank 2 when TDG levels exceeded 125%.

Ryan, B. A., and E. M. Dawley. 1998. Effects of dissolved gas supersaturation on fish residing in the Snake and Columbia Rivers, 1997. Unpublished report by National Oceanic and Atmospheric Administration to Bonneville Power Administration, Portland Oregon. 60 p.

Monitoring of fish from Ice Harbor reservoir and downstream, and downstream from Bonneville Dam was conducted in 1997 during the period of exceptionally high spill that produced exceptionally high TDG levels (125 to >140% of saturation). Fish were collected by electrofishing and shoreline beach seine. GBD signs were observed in 20 of 27 species collected. In Ice Harbor reservoir 7.9% of resident fish showed GBD signs and 3.4% of the fish from downstream from Ice Harbor during the high TDG levels. The incidence of GBD signs was highest in suckers, northern pikeminnow, bluegill, pumpkinseed, smallmouth bass, and largemouth bass. During this period TDG levels downstream from Ice Harbor Dam the near or greater than 139% for about two months. Downstream from Bonneville Dam only 6 of 1,003 salmonids (>1%) were observed with GBD signs, and 7% of resident fish had GBD signs, although TDG levels remained near 130% during most of May and June, reaching a peak of 144%. Most of the samples downstream from Bonneville Dam were collected early in the year when TDG levels did not exceed 117%. Monitoring of resident fish downstream from Priest Rapids Dam when TDG levels did not exceed 120% failed to detect GBD signs. When TDG levels reached a high of 123% and exceeded 120% for over three weeks, the incidence of GBD signs rose to 0.9%. However, during the two occasions when TDG levels exceeded 130% the incidence of GBD signs in resident fish was up to 23.1%.

Smallmouth bass, yellow perch, and peamouth were also held in net pens (0-0.5, 2-3, 0-4m) during the period of high TDG, generally greater than 120%. In 5 of 17 holding periods the incidence of fish with GBD signs (mostly bubbles in lateral line) increased (0.9-18%) in fish held in pens upstream from Ice Harbor Dam. The highest incidences of GBD were in fish held in the 0-0.5 m cage. Downstream GBD signs increased (0.2-59%) during 19 of 24 holding periods, with mortality of 0.9-57%. They were not able to identify a clear correlation between external GBD signs and mortality in captive fish.

Ryan, B. A., E. M. Dawley, and R. A. Nelson. 2000. Modeling the effects of supersaturated dissolved gas on resident aquatic biota in the main-stem Snake and Columbia Rivers. North American Journal of Fisheries Management 20:192-204.

During the spring freshets of 1994-1997 they surveyed non-salmonid fishes and invertebrates for signs of gas bubble disease (GBD) in the Columbia and Snake Rivers. Total dissolved gas levels often exceed 110% of saturation (EPA criterion) in the Columbia and Snake Rivers in the spring of these years. Spring high flows and turbine outages were conditions over which there was little control that produced high volumes of water discharged over spillways producing high levels of TDG supersaturation. They also conducted 7-d live-cage experiments in three river reaches where TDG commonly exceeded 120% of saturation. The authors developed an index based on fish sampled at specific times and places together with mean daily TDG supersaturation ranked and summed over a 7-day period. Using observation of 39,924 nonsalmonid fishes the authors produced a mathematical equivalence model for TDG supersaturation duration and level of exposure strongly correlated with the prevalence of GBD ($R^2 = 0.79$). Signs of GBD were rare when TDG remained below 120% of saturation. When TDG was in the range of 120-130% of saturation the incidence of GBD was commonly in the range of 15-25% of the fish sampled. Since all fish were collected from shallow water by either electrofishing or shallow beach seine these numbers likely exceed the incidence of GBD in the entire population. GBD signs in fish were rare when TDG levels were below 120%. When TDGS levels exceeded 120% the model reliably predicted the extent to which fish displayed external GBD signs. They concluded this simple model is a reliable predictor of external GBD signs resulting from prolonged exposure to TDG supersaturation. They attempted to evaluate GBD-related mortality over the 4 years of net-pen holding experiments. The high variability they observed in these evaluations and the paucity of dead fish recovered from these rivers, caused them to conclude that an accurate model relating TDG supersaturation to mortality could not be developed using these methods. Their attempt to evaluate GBD-related mortality over the four years of net-pen holding experiments was not successful due to the paucity of dead fish recovered.

S

Saeed, M. O., and S. A. al-Thobaiti. 1997. Gas bubble disease in farmed fish in Saudi Arabia. The Veterinary Record 140:682-684.

Four outbreaks of gas bubble disease were encountered among farmed fish in Saudi Arabia. Two of them occurred among subadult (52.5 g) saltwater tilapia (*Oreochromis spilurus*), the first affecting about 50% of the stock and resulting in about 30% mortality, and the second affecting about 25% of the population with about 5% mortality. Another outbreak occurred among adult (270 g) brackish water (5‰ salinity) tilapia (*Oreochromis niloticus*), affecting about 40% of the population with about 25% mortality. The fourth outbreak occurred among three month old (15 g) grouper (*Epinephelus fuscogutiatus*) and resulted in 10% mortality. In all cases the TDG level ranged between 111 and 113% saturation with nitrogen supersaturated while oxygen was below saturation. The outbreaks were alleviated by reducing the gas pressure by splashing the source water or by switching to a source of water with lower gas pressure. However, in *O niloticus* the conditions of gas supersaturation resulted in a heavy infection by monogenetic trematodes.

Scheibe, T. D., and M. C. Richmond. 2002. Fish individual-based numerical simulator (FINS)A: a particle-based model of juvenile salmonid movement and dissolved gas exposure history in the Columbia River basin. Ecological Modeling 147:233-252.

This paper describes a numerical model of juvenile salmonid movements in the Columbia and Snake

Rivers. The model, called the Fish Individual-based Numerical Simulator or FINS, employs a discrete, particle-based approach to simulate the movements and history of exposure to dissolved gases of individual fish. FINS is linked to a two-dimensional (vertically-averaged) hydrodynamic simulator that quantifies local water velocity, temperature, and dissolved gas levels as a function of river flow rates and dam operations. Simulated gas exposure histories can be input to biological mortality models to predict the effects of various river configurations on fish injury and mortality due to TDG supersaturation. Therefore, FINS serves as a critical linkage between hydrodynamic models of the river system and models of biological effects. The FINS model parameters were based on observations of individual fish movements collected using radiotelemetry methods during 1997 and 1998. A quasi-inverse approach was used to decouple fish swimming movements from advection with the local water velocity, allowing inference of time series of non-advective displacements of individual fish from the radiotelemetry data. Statistical analyzes of these displacements confirm that strong temporal correlation of fish swimming behavior persists in some cases over several hours. A correlated random-walk model was employed to simulate the observed behavior, and parameters of the model were estimated that lead to close correspondence between predictions and observations.

Scheibe, T, M. Richmond, and L. Fidler. 2002. Impacts of individual fish movement patterns on estimates of mortality due to dissolved gas supersaturation in the Columbia River Basin. Hydrovision 2002, HCI Publications, Kansas City, MO. 12 p. http://www.tceworld.co.in/E-Library/Matulyaenter/CD%20ROM%20References/Soft%20Copy%20of%20Seminars,%20Conferences/HydroVision%202002%20Conference%20Papers/Papers/155

Spatial and temporal distributions of dissolved gases in the Columbia and Snake Rivers vary due to many factors including river channel and dam geometries, operational decisions, and natural variations in flow rates. As a result, the dissolved gas exposure histories experienced by migrating juvenile salmonids can vary significantly among individual fish. A discrete, particle-based model of individual fish movements and dissolved gas exposure history has been developed and applied to examine the effects of such variability on estimates of fish mortality. The model, called the Fish Individual based Numerical Simulator or FINS, is linked to a two-dimensional (vertically-averaged) hydrodynamic simulator that quantifies local water velocity, temperature, and dissolved gas levels as a function of river flow rates and dam operations. Simulated gas exposure histories are then input to biological mortality models to predict the effects of various river configurations on fish injury and mortality due to dissolved gas supersaturation. This model framework provides a critical linkage between hydrodynamic models of the river system and models of biological effects

FINS model parameters were estimated and validated based on observations of individual fish movements collected using radiotelemetry methods during 1997 and 1998. The model was then used to simulate exposure histories under selected operational scenarios. They compare mortality rates estimated using the FINS model approach (incorporating individual behavior and spatial and temporal variability) to those estimated using average exposure times and levels as is done in traditional lumped parameter model approaches.

Schisler, G. J., and E. P. Bergersen. 1999. Identification of gas supersaturation sources in the Upper Colorado River, USA. Regulated Rivers: Research & Management 15(4):301-310.

Atmospheric gas saturation levels were monitored throughout a 40-km reach of the upper Colorado River during the summer and fall of 1995 to identify possible sources of gas supersaturation in the river. Gas saturation data from seven fixed sampling points and 40 random sampling points were analyzed using analysis of variance (ANOVA) and multiple regression methods. The lowest TDG levels (ΔP=27) were found with the bottom release of Williams Fork Reservoir. The highest TDG levels (ΔP=77) occurred with spillway releases at Windy Gap Reservoir and the confluence of Willow Creek and the Colorado River. Spatial and temporal effects were determined to be significant contributors to TDG levels. TDG supersaturation in the study area originated from both man-made and natural sources. Water discharged from the spillway of Windy Gap Reservoir was found to be the main source of man-made supersaturation, while photosynthetic activity of aquatic plants was determined to be the natural source of TDG supersaturation in the study area.

Schisler, G. J., E. P. Bergersen, and P. G. Walker. 1999. Evaluation of chronic gas supersaturation on growth, morbidity, and mortality of fingerling rainbow trout infected with *Myxobolus cerebralis.* North American Journal of Aquaculture 61:175–183.

The effect of environmental stressors on trout infected with *Myxobolus cerebralis*, the causative agent of whirling disease, is of great interest because the parasite has spread to most areas of the United States that support wild trout populations. TDG supersaturation is an environmental stressor found in at least two rivers in Colorado where *M. cerebralis* exists, and year-class losses of rainbow trout *Oncorhynchus mykiss* have occurred. Both of these stress factors may also occur in fish culture operations. A controlled laboratory experiment was conducted to test the hypothesis that chronic low levels of gas supersaturation affect growth, morbidity, and mortality of fingerling rainbow trout infected with *M. cerebralis*. Fingerling rainbow trout, exposed and unexposed to *M. cerebralis,* were held in gas saturations of 110, 107.5, 105, and 100–102.5% for 22 weeks. Significant effects on growth, morbidity, and survival were found due to *M. cerebralis* infection. TDG saturation levels tested did not significantly affect growth, morbidity, or survival of fish in this experiment. TDG levels in forebay water are retained during turbine passage.

Schneider, M. L. 2000. Risk assessment for spill program described in 2000 draft biological opinion. Appendix E, 2000 FCRPS Biological Opinion, National Marine Fisheries Service, Portland, Oregon. 30 p.

This assessment addresses the 120% TDG ceiling in light of the findings of the "Spill and 1995 Risk Management" report (1995 report) prepared by the region's fishery agencies and tribes (WDFW et al. 1995), the findings of research before and during implementation of the 1995 FCRPS Biological Opinion, and the results of the physical and biological monitoring program conducted from 1995 to the present. Two spill program scenarios are evaluated using the SIMPAS model, which compares the potential juvenile salmonid survival improvement due to increased spill against the risks of increasing total dissolved gas above the 110% water quality standard. The National Marine Fisheries Service (NMFS) concludes in this updated assessment that the risk associated with a managed spill program to the 120% TDG level is warranted by the projected 4% to 6% increase in system survival of juvenile salmonids. Recent research and biological monitoring results support the findings of the 1995 report, which predicted that TDG in the 120%-to-125% range, coupled with vertical distribution fish passage information indicating that most fish migrate at depths providing some gas compensation, would not cause juvenile or adult salmon mortalities exceeding the expected benefits of spillway passage. NMFS finds little evidence that this expected survival improvement would be reduced by mortality related to GBD. The NMFS also concludes that physical and biological monitoring of GBD signs can continue to be used to indicate dissolved gas exposure in adult and juvenile salmon migrants.

Schneider, M. L., and K. Barko. 2006. Total dissolved gas characterization of the Lower Columbia River below Bonneville Dam. Unpublished report to US Army Engineer District, Portland, Oregon. 104 p.

They reviewed available TDG monitoring records the Lower Columbia River downstream from Bonneville Dam. Spill at Bonneville Dam was continuous during the fish passage season with the exception of low flow conditions during 2001. Bonneville Dam spill was infrequent outside of the fish passage season. During 1995-1999 Bonneville Dam spilled on average 40 or more days outside of the fish passage season and spilled over 300 kcfs during February of 1996. TDG exchange in spillway water with the 18 flow deflectors for the standard spill pattern was directly related to the specific spillway discharge and weakly related to the tailwater stage. A uniform spill pattern across all spill bays during low tailwater stages minimizes the TDG generated. The average cross sectional TDG level generated for spills of 50, 100, 150, 200, and 250 kcfs were 115%, 120%, 125%, 130%, and 135% of saturation as observed in 2002. Mass exchange at the air/water surface results in a gradual loss of TDG in the Lower Columbia River as water moves downstream. Breaking wind waves can greatly increase the rate of degassing in this reach. TDG pressure changes can also result from temperature fluctuations, 1.5 ºC can produce about a 3.5% change at temperatures near 15 ºC. Daily variation in DO of about 0.5 mg/L can result in a 1% change in TDG pressure.

The TDG saturation during high flow years can exceed 120% of saturation for several months throughout the entire lower Columbia River reach from Bonneville Dam to RM 42. A peak TDG pressure greater than 140% was observed in the tailwater of Bonneville Dam during the 1996 and 1997 flood events.

Schnute, J., and J. O. T. Jensen. 1986. A general multivariate dose-response model. Canadian Journal of Fisheries and Aquatic Sciences 43:1684-1693.

They investigated the effects of TDG supersaturation on juvenile salmonids (Chinook, coho, sockeye, and steelhead) using data compiled from the literature. They relate exposure time to 50% mortality (ET_{50}) to TDG levels, component levels of dissolved oxygen (O_2%) and nitrogen (N_2%), water depth, temperature, barometric pressure (BP), and fish size. They used a tabular histogram is employed for exploratory data analysis. Statistical hypotheses they formulated and tested using the described in Jensen et al. (1985). When modeled in response to TDG level, the ET_{50} follows a typical exponential dose-response relationship. Based on the full data set water depth and fish length significantly improve the model's ability to explain variations in ET_{50}. Based on a smaller subset of the data, either of the factors O_2% or N_2% also improves the model fit significantly. For 50-d exposures, apparently ' safe ' levels of TDG range from 103.8 to 114.8%, depending on associated factor levels of water depth and fish size.

Schubert, A. L. S., C. D. Nielsen, and D. B. Noltie. 1993. Habitat use and gas bubble disease in southern cavefish (*Typhlichthys subterraneus*). International Journal of Speleology 22:131-143.

This paper presents *in situ* observation of habitat use by southern cave fish (*Typhlichthys subterraneus*) in a Missouri boxed spring. In addition, they document the first recorded case of gas bubble disease in specimens of this species held in laboratory conditions (shallow water). The cavefish were collected from a site where they tended to remain near or within the substrate at a depth of about 2.5 m. Three cavefish transferred to laboratory conditions (30.5 cm deep). After 16 days in the laboratory, aeration was added to the aquaria resulting in one of two fish having a bloated swim bladder within 12 h. No other signs are reported to indicate that fish suffered from gas bubble disease. The fish recovered within

8 h following removal of the aeration. No measurements of dissolved gas conditions in the spring or laboratory water are included in the paper although the laboratory water passed through a 12 m aeration tower, likely producing gas equilibrated water.

Schrank, B. P., E. M. Dawley and B. Ryan. 1997. Evaluation of the effects of dissolved gas supersaturation on fish and invertebrates in Priest Rapids Reservoir, and downstream from Bonneville and Ice Harbor Dams, 1995. Unpublished report, National Marine Fisheries Service, Northwest Fisheries Science Center, Seattle, Washington. 45 p.

In 1995 they monitored the prevalence and severity of GBD by sampling fish and invertebrates downstream from Ice Harbor and Bonneville Dams, and upstream from Priest Rapids Dam by electrofishing and beach seines. Visual examination (2.5-5 magnification) of organisms for primary assessment of external GBD signs (subcutaneous emphysema on fins, head, eyes, and body surface). Groups of invertebrates and resident nonsalmonid fish species were held in net-pens for 4 d and then reexamined for prevalence and severity of GBD. Additionally, hatchery-reared subyearling fall Chinook salmon obtained from Bonneville Hatchery were held in net-pens downstream from Bonneville Dam and downstream from Ice Harbor Dam. They used: surface cages (0-0.5 m), submerged cages (2-3 m), and large net-pens with an inclined bottom (0-4 m).

Downstream from Ice Harbor Dam they examined 2 salmonids, 2,823 nonsalmonids, and 499 invertebrates (April 20 to August 14). A relatively high incidence of GBD was observed in smallmouth bass (16.5%), crappie *(Pomozis spp.,* 13.6%), and brown bullhead (11.8%). Only cladocera (3.5%) showed GBD signs among invertebrates collected. TDG levels were extremely high downstream from Ice Harbor Dam between May 8 and June 20 as a result of turbine outages at Ice Harbor Dam that caused high spill rates. TDG levels remained near or above 130%, reaching a peak of 138% during this period. GBD signs were observed in 20% of sampled resident fish when TDG levels were near the peak. Downstream from Ice Harbor GBD signs in fish were not observed in most species, but were relatively high in peamouth (9.4%), northern pikeminnow (23.5%), and largescale sucker (16%). The TDG levels were generally 115-125% during this period.

Downstream from Bonneville Dam GBD was also only observed in cladocerans of the invertebrates examined. They reported GBD signs in 0.5% of cladocerans when TDG levels were frequently in the range of 115-120% for several months.

Upstream from Priest Rapids Dam GBD signs (~5% resident fish) were observed in only one of five sampling periods with TDG levels of 118 - 125%. GBD signs were highest in sandroller (5.6%), sculpin (4.8%), and smallmouth bass (1.6%), but rare or not observed in other species.

They examined 127 salmonids, 1,936 nonsalmonids, and 804 invertebrates downstream from Bonneville Dam for GBD signs (April 13 to August 15). The TDG levels were in the range of 114-120% from early May to mid-August. Only one stickleback and one sculpin were observed with GBD signs, however, bubbles were observed in the lateral lines of 3.8% of fish examined closely with magnification.

Fish held downstream from Ice Harbor Dam in shallow net pens for 4-day periods exhibited GBD signs when TDG levels ranged from 115 to 130% of saturation. Most GBD signs were observed among fish held near the surface (0-0.5 m). The prevalence of GBD signs averaged 97% for nonsalmonids and 80% for hatchery Chinook held in surface cages. GBD signs were 37% in nonsalmonids and 52% in hatchery

Chinook in the 0-4 m net pen, and 40% and 6% respectively in the 2-3 m cage. Resident fish often had GBD signs when they were placed in the net pens. At the end of the 4-day tests the incidence of GBD signs among the resident fish often persisted and sometimes increased. Mortality of nonsalmonids and Chinook was highest for fish held in the shallow cage, second highest for fish held in the 0-4 m net pen and lowest for those in the deep cage. Chinook held in the shallow cages experienced mortality 58% to 100% mortality. Mortality was 0 to 16% for nonsalmonids and 1 to 84% for salmonids in the 0-4 m net pens. When TDG decreased to about 118% the mortality of captive fish was negligible.

Downstream from Ice Harbor Dam, GBD prevalence in captive resident fish held 4 days in 0-4 m net pens was higher than in resident fish sampled in the river 1 to 7 days later. They concluded mortality rates of juvenile salmonids held in 0-4 m net pens were also not representative of river migrants because of duration of exposure and depth restrictions.

Schrank, B. P., B. Ryan and E. M. Dawley. 1998. Effects of dissolved gas supersaturation on fish residing in the Snake and Columbia Rivers, 1996. Report by National Marine Fisheries Service, to U.S. Army Corps of Engineers, North Pacific Division, Portland, Oregon. 68 p. http://www.efw.bpa.gov/publications/D93605-1.pdf.

During the period of high spill in 1996, they monitored the prevalence and severity of GBD by sampling resident fish (electrofishing, beach seine) in Priest Rapids Reservoir and downstream from Priest Rapids, Ice Harbor, and Bonneville Dams. Non-salmonid species were also held in pens for 4 days (0-0.5 m, 2-3 m, and 0-4 m with inward sloping side).

They examined 1,172 salmonid fishes, 1,227 non-salmonid fry, and 9,905 non-salmonid fishes for signs of GBD. Signs of GBD in fish were prevalent downstream from Ice Harbor Dam and in Priest Rapids Reservoir. In other reaches, downstream from Bonneville and Priest Rapids Dams, GBD signs were less prevalent. From 1 to 15 km downstream from Bonneville Dam, TDG levels reached 140%, but daily averages remained above 125% from May 30 to June 20. On June 13, prevalence of GBD signs among individual daily fish samples reached 15.8%. Signs of GBD were observed in 14.3% of all fry sampled downstream from Bonneville Dam.

From 15 to 47 km downstream from Priest Rapids Dam (Hanford Reach), TDGS reached 130%, and daily averages remained above 120% from 24 May to 2 1 July. GBD signs were observed in 2.8% of salmonids and 6.5% of resident fish. In Priest Rapids Reservoir TDG reached 136% and daily averages remained above 125% from May 27 to June 24 as a result of freshet flow past Wanapum Dam. In Priest Rapids reservoir they observed a relatively high incidence of GBD with suckers 26.6%, chiselmouth 6.9%, stickleback 5.9%, pumpkinseed, 5.1%, bluegill 16.7%, and sculpin 15.6%. Prevalence of GBD signs downstream from Priest Rapids Dam among resident species averaged 6.5% with sucker 13.2%, northern pikeminnow 2.1%, chiselmouth 4.5%, and smallmouth bass 7.7%.

Downstream from Ice Harbor Dam, TDG reached 142%, and daily averages almost always exceeded 130% from April 1 to 30 and from May 15 to June 24 as a result of freshet flows and turbine outages at Ice Harbor Dam. Prevalence of GBD signs was high with 6 species having 11-22% incidences of GBD. Downstream from Bonneville Dam TDG levels were generally 120-140% during late May and June. However, resident fish generally had a low incidence of GBD, except suckers (3.3%), northern pikeminnow (3.4%), redside shiner (2.5%), and sculpin (3.4%). Salmonids show high incidences of GBD with Chinook 4%, coho 13.3% and steelhead 12.5%

Resident non-salmonid fish used for the net-pen studies were taken from the river and often had GBD signs prior to introduction to the pens. After 4 days of holding GBD signs among the captive fish usually persisted and generally showed an increase in prevalence. Downstream from Bonneville Dam, fish held in the 0- to 4-m pen showed GBD signs in 7 of the 13 holding periods, with GBD prevalence ranging from 0 to 58.4%. Prevalence of GBD signs increased during every 4-day holding period between May 17 and June 24. When prevalence of GBD signs increased, mortality ranged from 0 to 4%. Upstream from Priest Rapids Dam, fish held in the 0-4 m pen showed increases of external GBD signs in 15 of the 16 holding periods; prevalence of GBD signs ranged from 0 to 70%. When prevalence of GBD signs increased, mortality ranged from 0 to 33%. Downstream from Ice Harbor Dam, fish held in the 0-4 m pen showed increases of GBD signs in 9 of the 13 holding periods; prevalence of signs ranging from 0 to 86 0%. When prevalence of external GBD signs increased, mortality ranged from 4 to 33%.

They found no clear correlation between GBD signs and mortality in captive fish when data from all species were combined.

Shaw, P. 1998. Gas generation equations for CRiSP 1.6. University of Washington, Seattle, Washington. http://www.cbr.washington.edu/d_gas/tdg_manual.pdf

New equations have provided for gas production from spill in the CRiSP.1.6 model. The Waterways Experiment Station (WES) has developed, as a part of the US Army Corps' Gas Abatement study, these new equations as an improvement over GASPILL which had been the predominantly used model for gas production. The new equations are an empirical fit of spill data and monitoring data collected by the Corps. TDG percent of saturation in water exiting the tailrace of a dam is predicted as a function of the amount of discharge in kcfs. This level of TDG is not necessarily the highest level of gas reached, but rather the level of gas in the spill water after some of the more turbulent processes have stabilized. The calibration for each dam was generally fit to the nearest downstream monitor, which is typically about a mile downstream of the dam.

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

They examined the response of rainbow trout (*Oncorhynchus mykiss*) swim bladders to TDG supersaturation. Fish with cannulas surgically inserted into their swim bladders were exposed to water with 104% TDG in 8 cm deep flow through a darkened restraining box. Fish held in supersaturated water without access to the surface showed an increase in swim bladder pressure, with the response showing a strong dependence on the TDG pressure and the oxygen partial pressure of the water. The minimum level of TDG supersaturation observed to cause a response corresponded to a c*P* of 27 mmHg (P_{O2} = 160 mmHg, 1 mmHg = 133 3 Pa). The threshold ΔP for swim bladder inflation increased as the partial pressure of the water increased. Passive movement of supersaturated gases from the arterial system into the swim bladder causes a rise in swim bladder pressure until the diffusion gradient is nil or the gas is expelled through the pneumatic duct. The threshold for release of gas through the pneumatic duct is dependent on fish size with small fish having a higher duct release pressure and thus a high degree of pressure buildup in the bladder than larger fish.

Shrimpton, J. M., D. J. Randall, and L. E. Fidler. 1990b. Assessing the effects of positive buoyancy on rainbow trout (*Oncorhynchus mykiss*) held in gas supersaturated water. Canadian Journal of Zoology 68:969- 973.

They examined the effects of swim bladder over inflation associated with TDG supersaturation in rainbow trout (*Oncorhynchus mykiss*). Changes in swim bladder volume with increased swim bladder pressure were measured in fish subjected to decreased ambient pressure. Swim bladder volume expands in relation to excess pressure resulting in a decrease in density and positive buoyancy of the fish. Small fish were adversely affected by exposure to TDG supersaturated water because of the high bladder pressure required to expel gas through the pneumatic duct. Changes in behavior and depth distribution of fish exposed to TDG supersaturated water were observed in 2 m deep by 0.5 cm square observation column. Large changes in density caused small fish to increase their depth to compensate for the swim bladder expansion. Although swim bladder inflation occurs for all fish sizes, the impact is greatest for small fish

Schriever, E., T. Cochnauer, and T. Feldner. 1999. Gas bubble trauma monitoring in the Clearwater River Drainage, Idaho. 1999 Annual Report, DOE/BP-31259-2, Bonneville Power Administration, Portland, Oregon. 21 p.

They electrofished the 39 miles of the free-flowing lower Clearwater River and 1.5 miles of the North Fork Clearwater River downstream from Dworshak Dam during the spring and summer months of 1999. Resident fish were for GBD signs during the periods of spill and non-spill from Dworshak Dam. They collected 6,083 fish representing 20 species. Only seven fish (0.12%) were found to have GBD signs. Sampling periods when GBD signs were most prevalent were coincident with peak discharge and subsequent elevated levels of total dissolved gas from Dworshak Dam. Four of the 7 fish had GBD rank 1. The 3 fish with GBD rank 2 were species likely entrained through Dworshak Dam.

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

Histologic examinations were made of tissues from rainbow trout (*Salmo gairdneri*) grossly demonstrating gas bubble disease. Gas emboli were observed in vessels of gill filaments, in postorbital hemorrhages, and the atrium, ventricle, and bulbus arteriosus of the heart. Emphysemas were apparent in the dermis, between the dermis and epidermis, and in areolar connective tissue of fins, gill arches, and in the roofs of mouths. Necrosis, inflammation, and plasma leakage were sometimes associated with emphysemas.

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.

Chinook (*Oncorhynchus tshawytscha*), coho (*O. kisutch*), sockeye (*O. nerka*), steelhead (anadromous *O. mykiss*), and rainbow (resident *O. mykiss*) were exposed to supersaturated water in a shallow round tank having peripheral compartments with water having different levels of supersaturation (115%, 125%, and 145%). Steelhead did not consistently avoid the highly supersaturated water and died from GBD. Generally the young salmon and rainbow avoided the 125% and 145% of saturation compartments. Steelhead lack of avoidance was attributed to their aggressive or territorial behavior.

Speare, D. J. 1990. Histopathology and ultrastructure of ocular lesions associated with gas bubble disease in salmonids. Journal of Comparative Pathology 103:421-432,

Ocular lesions associated with natural and experimental outbreaks of GBD in commercial salmonids were assessed histologically and by scanning electron microscopy. Small gas emboli were first detected in the choroid gland of the posterior uvea. In subacute and chronic cases, bubble size increased markedly and localization in retrobulbar and periocular sites was favored. During the acute phase of GBD, ocular lesions were limited to anatomical displacement of tissue and local degeneration of compressed tissues around the perimeter of bubbles. Subacute sequelae included the formation of anterior synechia, lens cataract, and suppurative panophthalmitis. During chronic stages, when large retrobulbar bubbles had caused severe exophthalmia, there was stretching of the optic nerve and of retinal blood vessels and severe distortion of the posterior aspects of the globe. The sequential development, pathogenesis and persistence of ocular lesions associated with GBD in fish are discussed.

Speare, D. J. 1991. Endothelial lesions associated with gas bubble disease in fish. Journal of Comparative Pathology 104:327-335,

Two groups of healthy Chinook salmon (*Oncorhynchus tshawytscha*) were experimentally exposed to gas supersaturated groundwater (110-124% TDG) in shallow laboratory conditions. Gross lesions consistent with GBD developed. Vascular lesions associated with intravascular gas bubbles were examined with light and scanning electron microscopy. Dermal blood vessels containing gas bubbles were severely dilated. Additionally, the gas bubbles were spatially associated with endothelial lesions ranging from cellular degeneration to exfoliation. The resulting regions of exposed subendothelial connective tissue were sparsely covered by small unidentified adherent cells and strands of fibrin. In the light of these findings, the similarities in vascular pathology between GBD in fish and decompression disease in man are discussed, particularly with respect to the initiation of haemostatic disorders in both conditions.

Sullivan, R. D., D. E. Weitkamp, T. Swant, and J. DosSantos. 2004. Changing spill patterns to control dissolved gas supersaturation. Hydro Review August :106-112.

Studies indicate that changing the normal spill gate configurations used at the lower Clark Fork River hydroelectric projects substantially reduced downstream total dissolved gas (TDG) supersaturation. Investigation of operational procedures at Noxon Rapids and Cabinet Gorge dams between 1996 and 2001 demonstrated how various spill gate combinations, and other factors at the two dams influence TDG levels. Controlled spill tests at Noxon Rapids Dam indicated It appears the combination of greater air entrainment with the flip bucket design together with entrainment of air bubbles in the powerhouse discharge resulted in the higher TDG levels when a gate close to the powerhouse was used. At Cabinet Gorge Dam controlled spill tests demonstrated TDG levels could be reduced by as much as 13% of saturation using certain gate combinations. It appears that gates near the powerhouse and over the deeper portion of the stilling basin allow greater and deeper entrainment of bubbles into the powerhouse discharge resulting in higher TDG levels. These observations demonstrate the unique properties of each dam that lead to higher or lower TDG levels downstream.

T

Tanner, D. Q., M. W. Johnston, and H. M. Bragg. 2002. Total dissolved gas and water temperature in the Lower Columbia River, Oregon and Washington, 2002: Quality-assurance data and comparison to water-quality standards. Water-Resources Investigations Report 02-4283, U.S. Geological Survey, to Army Corps of Engineers, Portland, Oregon. 18 p.

For the eight monitoring sites in water year 2002, an average of 99.6% of the total-dissolved-gas data were received in real time by the USGS satellite downlink and were within 1% saturation of the expected value, based on calibration data and ambient river conditions at adjacent sites. Most field checks of TDG sensors with a secondary standard were within 1% of saturation. Field checks of barometric pressure and water temperature were usually within 1 mm Hg and 0.05 ºC respectively. The TDG standard of 110% saturation was exceeded at seven of the eight monitoring sites. The sites at Camas and Bonneville are considered forebay sites and had the most days exceeding the variance of 115% saturation. The forebay exceedances may have been the result of the cumulative effects of significant spill throughout the lower Columbia River. Apparently, the TDG levels did not dissipate rapidly enough downstream from the dams before reaching the next monitoring site. Water temperatures were usually above 20 ºC from mid-July to mid-September at each of the seven lower Columbia River sites.

Toner, M. A. 1993. Evaluation of effects of dissolved gas supersaturation on fish and invertebrates downstream of Bonneville Dam, 1993. Report by National Marine Fisheries Service to U.S. Army Corps of Engineers, North Pacific Division, Portland, Oregon.

Copy not available.

Toner, M. A. and E. M. Dawley. 1995. Evaluation of the effects of dissolved gas supersaturation on fish and invertebrates downstream from Bonneville Dam, 1993. Unpublished report by Coastal Zone and Estuarine Studies Division, Northwest Fisheries Science Center. 34p. + Appendix.

They monitored the occurrence of GBD in juvenile salmonids and other aquatic biota during the 1993 high spring flow in the Columbia River downstream from Bonneville Dam. Fish and invertebrates were collected with a 50-m beach seine, a 7.5-m seine and a Ponar bottom sampler at 18 locations between RKm 228 and 62. Dissolved gas saturation levels at the upstream end reached 128% on 4 days, with daily mean values above 120% on 9 days. However, TDG measured at the sampling locations from April 27 through June 14 averaged only 112% (range 103 to 122%). During May 11-21 concentrations above 120% occurred upstream from RKm 179.

External GBD signs were infrequent, with a low prevalence of GBD in 6 of the 20 species examined. Mild GBD signs (small blisters between fin rays) were observed in less than 1% of the juvenile Chinook (n = 1,648) and peamouth (n = 238), in 3% of the juvenile coho salmon (n = 711), and in 2% of the juvenile steelhead (n = 50). Moderate to severe GBD signs (large blisters on the body and exophthalmia) were observed in less than 1% of the sticklebacks (n = 906) and prickly sculpins (n = 174) examined. No evidence of GBD was observed in invertebrates (dragonfly larvae *Gomphus* sp., crayfish, and Asian clams *Corbicula* sp.).

Toner, M. A., B. Ryan and E. M. Dawley. 1995. Evaluation of the effects of dissolved gas supersaturation on fish and invertebrates downstream from Bonneville, Ice Harbor, and Priest Rapids Dams, 1994. Unpublished report by Coastal Zone and Estuarine Studies Division, Northwest Fisheries Science Center. 38p.

They monitored the prevalence of GBD in juvenile salmonids, resident fishes (electrofishing) and invertebrates in four river reaches: downstream from Bonneville and Ice Harbor Dams, and upstream and downstream from Priest Rapids Dam in 1994 during the high spill period. They examined 2,082 juvenile salmonids, 11,976 nonsalmonids, and 4,133 invertebrates for GBD signs. GBD signs were prevalent downstream from Ice Harbor Dam, but were rare in the other river reaches sampled. TDG levels reached 136% of saturation downstream from Ice Harbor Dam on May 9, 10 and 11, and were higher than 130% for 7 to 11 hours each day. GBD signs were observed in 5 to 10% of resident fish captured during May. One or more individuals of half of the 22 species captured had some GBD signs. When TDG levels at the sampling sites dropped to a daily average of 110% of saturation with peaks no higher than 115%, GBD signs among sampled fish disappeared. Signs of GBD were observed in only one species of fish captured downstream from Bonneville and Priest Rapids Dams, and in no fish captured upstream from Priest Rapids Dam. However, TDG levels never exceeded 120% of saturation at the sampling sites in those reaches, and only occasionally did levels in mid-river exceed 120%. GBD varied among species, but the most prevalent were subcutaneous emphysema in the dorsal and/or caudal fins, with a majority of the fm surface often covered. Of the invertebrates sampled, only cladocerans showed GBD signs and only at a minimal prevalence at Ice Harbor, but not in any collected at Bonneville Dam.

V

VanderKooi, S. P., R. G. Morris, J. W., Beeman, and A. G. Maule. 2003. Chapter II: The progression and lethality of gas bubble disease in resident fish in Rufus Woods Lake. Pages 48-86 in, Beeman, J. W., D. A. Venditti, R. G. Morris, D. M. Gadomski, B. J. Adams, S. P. VanderKooi, T. C. Robinson, and A. G. Maule. Gas bubble disease in resident fish below Grand Coulee Dam final report of research. U.S. Geological Survey, Western Fisheries Research Laboratory, Cook, Washington. http://wfrc.usgs.gov/pubs/reportpdf/usgsfrgbdgrandcouleedam.pdf#page=54

The progression of GBD signs and time to death were observed in several species of resident fish held in 155 L tanks with a water depth of 0.26 m. Test fish were obtained by electrofishing in Rufus Woods Lake or from the Columbia River Hanford Reach. Largescale sucker (*C. macrocheilus*), longnose sucker (*C. catostomus*), northern pikeminnow (*Ptycocheilus oregonensis*), redside shiner (*Richardsonius balteatus*), and walleye (*Stizostedion vitreum*) were exposed to TDG levels of 115, 125 and 130% of saturation. At 115% TDG little mortality was observed, even at the exposure depth of 0.26 m, during up to 4 weeks exposure. However, the most dramatic GBD signs were observed in fish of each species exposed to 115% TDG. Progression of GBD signs was unpredictable, except that prolonged exposure to 115% TDG resulted in the most exaggerated signs. Percent lateral line occlusion and percent of gill filaments with bubbles were significantly higher at 125% TDG than at 125%, however fin and eye bubble severity ratings did not differ significantly between the two levels. Exophthalmia was only observed at 115% TDG following 216 hrs exposure. Exposure to 125% and 130% TDG caused mortalities without extensive signs of GBD. Time to mortality (LC_{50}) at 125% TDG were northern pikeminnow-15.2 hr, largescale sucker-17 hr, longnose sucker 56 hr, redside shiner 116 hr, and walleye

169 hr. At 130% TDG LC_{50} times were approximately half or less than at 125% TDG.

W

Weber, L., H Huang, and Y. Lai. 1982. Numerical Modeling of Dissolved Gas Supersaturation Downstream of Spillway. Unpublished report, Iowa Institute of Hydraulic Research, University of Iowa, Iowa City, Iowa.

In the USA there was an urgent need to investigating ways to reduce gas supersaturation at that time. This numerical model was developed to meet the need and cutting experimental cost. Based on the recent advances in the fields of air bubble entrainment, numerical gas saturation, supersaturation and flow simulations, the method for building 2D and 3D models are discussed in the paper. Preliminary simulation results shows the proposed comprehensive numerical model can well simulate the gas supersaturation downstream of dam spillway, as well as suggest possible methods of solving problem by parameter studies

Weiland, L. K., M. G. Mesa, and A. G. Maule. 1999. Influence of infection with *Renibacterium salmoninarum* on of juvenile spring Chinook salmon to gas bubble trauma. Journal of Aquatic Animal Health 11:123-129.

They exposed juvenile spring Chinook *Oncorhynchus tshawytscha* to bacterial kidney disease *Renibacterium salmoninarum* (Rs) during studies to evaluate the progression and severity of gas bubble disease in the laboratory. Fish with established Rs infection were exposed to flow trough TDG levels of 120% in circular tanks containing 113 L with a depth of 28 cm. Signs of GBD in fins and gills were monitored during the 96 h exposure, along with Rs infection levels in kidneys by enzyme-linked immunosorbent assay and mortality (ELISA). Mortality occurred rapidly with exposure to 120% TDG resulting in an LC_{20} of about 37 h, which was earlier than fish without Rs signs exposed under similar conditions. Fish dying early had significantly higher Rs infection levels (mean ± SE ELISA absorbance = 1.532 ± 0.108) than fish that survived for 96 h (mean ± SE ELISA absorbance = 0.828 ± 0.137). Early mortalities also had a significantly greater number of gill filaments occluded with bubbles than those that survived for 96 hr. However, fish surviving for 96 h had a significantly higher median fin severity ranking than those that died early. These results indicate the fish with moderate to high levels of Rs infection area more vulnerable to the effects of TDG supersaturation and die sooner than fish with lower levels of Rs infection.

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

A detailed review of most gas bubble disease and dissolved gas supersaturation research through 1979. The review discusses all aspects of total dissolved gas (TDG) covered by literature from the 1800s through 1979. Included are the various causes of TDG, characteristics and causes of gas bubble disease (GBD), recorded incidents of GBD under natural conditions, and species of GBD reported to have incurred GBD.

Weitkamp, D. E., and R. P. Sullivan. 2000. Analysis of total dissolved gas data Rocky Reach Dam 1997-2000. Unpublished report to Chelan County PUD No. 1, Wenatchee, Washington. 26 p. http://www.chelanpud.org/rr_relicense/existing/hcp/Studies/E4(22)-382.pdf

Downstream from Rocky Reach Dam TDG levels varied highly during the four years, with high levels in 1997 related to high total river flow. TDG levels were highly correlated the amount of spill and the percentage of total flow spilled. Changes in TDG levels from the forebay to the tailrace ranged from -5% to +15% of saturation.

Weitkamp, D. E., R. P. Sullivan, T. Swant, and J. DosSantos. 2003. Behavior of resident fish relative to TDG supersaturation in the Lower Clark Fork River. Transactions of the American Fisheries 132:856-864.

Behavior of resident fish exposed to total dissolved gas (TDG) supersaturation in Pacific Northwest rivers greatly influences the degree of supersaturation these fish actually experience. Because TDG supersaturation is a physical condition that is moderated by hydrostatic pressure, the depths occupied by fish during supersaturation conditions determine the biological effects experienced by members of the exposed population. Equipping fish with depth sensing radio tags documented that many of the fish spend sufficient time at depths of several meters or greater where they are not exposed to TDG supersaturation. These depths also provide an opportunity to recover from short-term exposure to supersaturation experienced by the fish during the periods they occupy shallower depths. Most species tagged had median and average depth distributions of about two meters or greater providing compensation for TDG supersaturation in the range of 120% of saturation or greater. Tagged rainbow trout generally remained in the river for only brief periods before returning to Lake Pend Oreille or tributaries to the lower Clark Fork River, where they were no longer exposed to TDG supersaturation.

Weitkamp, D. E., R. P. Sullivan, T. Swant, and J. DosSantos. 2003. Gas Bubble Disease in Resident Fish of the Lower Clark Fork River. Transactions of the American Fisheries Society 132:865-876.

Gas bubble disease (GBD) occurs in resident fish of the lower Clark Fork River exposed to total dissolved gas (TDG) supersaturation produced by spill at upstream hydroelectric projects. This report describes the incidence and severity of GBD observed in fish routinely collected by electrofishing and other techniques during periods of high supersaturation from 1997 to 2000. These data include GBD observations for 1997, a year of extremely high runoff resulting in TDG levels approaching 150% of saturation, and 1999, a year of moderately high TDG levels (typically 120-130% of saturation). Although electrofishing only samples that portion of the fish populations present near the river surface (upper 2m) in a deep stream (3-25m) like the lower Clark Fork, the observed incidence and severity of GBD was substantially lower than anticipated for the levels of TDG measured. They observed relatively high incidences of GBD in largescale and longnose suckers, and yellow bullhead during one or more of the four years. It appears that the majority of fish are spending sufficient time at depths that avoid or mediate both the incidence and severity of GBD when TDG supersaturation is in the range of 120-130% of saturation. Fish also have access to a number of tributaries that have little or no supersaturation, and to Lake Pend Oreille where fish commonly occupy depths providing hydrostatic compensation that eliminates exposure to supersaturation.

White, R. G., G. Phillips, G. Liknes, J. Brammer, W. Connor, L. Fiddler, T. Williams, and W. P. Dwyer. 1991. Effects of supersaturation of dissolved gases on the fishery of the Bighorn River downstream of the Yellowtail Afterbay Dam. Completion Report to Bureau of Reclamation, Missouri Basin, by Montana Cooperative Fisheries Research Unit, Montana State University, Bozeman, Montana. 710 p.

The Yellowtail Afterbay Dam (re-regulation dam) produced total dissolved gas supersaturation for many years leading to a high incidence of gas bubble disease (GBD) in rainbow and brown trout, particularly among brown trout larger than 356 mm. The incidence of GBD in brown trout was highest (28 - 65%) immediately downstream from the dam. Signs of GBD were only observed in fish within the first 8 km downstream, about the distance at which dissolved gas supersaturation dissipated. The incidence of GBD in rainbow trout was always lower, except during spawning when rainbow exceeded brown trout during the period when they moved into a shallow side channel. Different levels of TDG did not appear to influence the distribution of rainbow trout. Mean DG supersaturation near the dam was 116% of saturation and ranged from about 105-123%, with a downstream range of 102-128%. Trout were concentrated along river banks during the winter and spring, and used bank and mid-channel areas during the summer and fall. The incidence of GBD decreased during periods of mid-channel use.

They developed models describing bubble growth based on available literature and laboratory bioassays. They determined juvenile trout became more susceptible to 125% saturation in bioassays as they grew. Larger fish were more likely to die faster than small fish held within the same shallow depths. Repeated exposures of juvenile brown trout to 118% saturation following 30 d recovery periods, produced more severe signs with each exposure. Juveniles did not appear to acclimate to supersaturation, but some individuals did appear to be more tolerant.

Benthic and drift samples of macroinvertebrates were collected near the dam and at RKm 14.5. No differences were noted in the spring, but community structure was strongly different during the late summer and fall following the high TDG period. However, temperature also differed between the two sites during the summer confounding interpretation of the observed differences. Bioassays of macroinvertebrates showed most were negatively affected by 127% TDG or greater. *Baetis tiicaudatus* was the most susceptible with adverse effects observed at 115% TDG. *Ephemerella inermis* and *Tricorthyodes minutus* had a susceptibility threshold near 118% TDG.

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