Evaluation of Total Dissolved Gas Criteria (TDG) Biological Effects Research

A literature review

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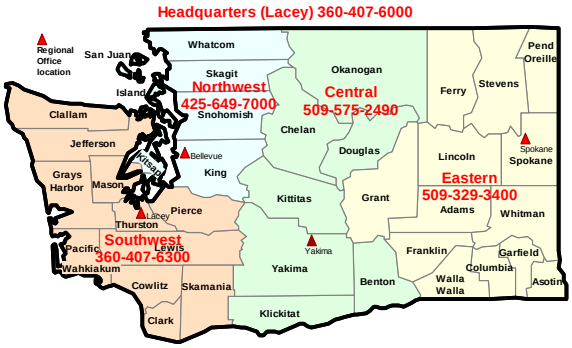

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Introduction

The purpose of this literature review is to provide information to assess the appropriate water quality criteria for total dissolved gas (TDG) supersaturation in freshwater in Washington State. The Environmental Protection Agency, under the federal Clean Water Act, developed a national criterion of 110 percent for TDG in the 1970s. This criterion was based largely on lab research, performed on juvenile salmon in the Pacific Northwest, due to concerns over high TDG levels caused by spilling water over the Columbia and Snake River dams. Since the mid 1990s, Washington and Oregon have retained their 110 percent statewide criterion but adjusted their TDG criteria upward to 115 percent in the forebays and 120 percent in the tailraces on the Columbia and Snake Rivers. This was to allow spill when juvenile salmon are migrating so they can avoid harm from going through the turbines. Both states have an instantaneous limit during the fish spill season of 125 percent TDG. Oregon has a TDG criterion of 105 percent for waters shallower than one meter and British Columbia, Canada has a guideline of 103 percent for waters shallower than one meter.

Methods

The studies listed in this review were found through a search of National Oceanic and Atmospheric Administration (NOAA) Fisheries Science Center library catalog (keywords: supersaturation, dissolved gas, gas bubble disease, gas bubble trauma); from references found in studies obtained; and from references found in other literature reviews such as Fidler's *British Columbia Water Quality Guidelines for Dissolved Gas Supersaturation-Technical Report* and Weitcamp's *A Review of Dissolved Gas Supersaturation Literature*. Studies were obtained through NOAA, state, and USGS libraries and requests to researchers for copies.

Since the national EPA criteria of 110 percent TDG was recommended for states in the 1970s based on lab studies, much more research has been done on TDG biological effects. Almost all of the studies have focused on Columbia and Snake River salmon. This literature search focuses on the biological effects of TDG in the range of 103 to 120 percent TDG. This range was chosen because:

- Research shows that exposure to TDG levels greater than 120 percent harms aquatic organisms consistently enough to omit review of higher TDG concentrations.
- Shallow-dwelling organisms are susceptible to harm from long periods of TDG exposure at 103 percent TDG and greater.
- Salmon protection groups requested removal of the 115 percent criteria in the forebays of the dams on the Snake and Columbia and regulating to 120 percent TDG levels in these rivers, in order to increase protection for juvenile salmon from harm passing through turbines and providing faster passage downstream.

Also included are studies that provided information about fish depth preferences and juvenile salmonid migration timing. This is because gas bubble trauma (GBT) is largely a function of length of exposure and depth. Further information about depth and duration preferences at

different life stages of various aquatic organisms, including zooplankton, larval fish, estuarine baitfish, and emerging aquatic insects, may be available but were neither identified nor obtained. The great majority of TDG studies investigate salmonids in the Columbia River system. Many of those studies use spring juvenile Chinook because they were readily obtainable and easier to work with because of their large size. In selecting studies for review, an attempt was made to obtain studies of other species of salmon, non salmonid organisms, and all life stages

Some early studies, prior to 1974, were not requested because some of them measured only total dissolved nitrogen. Both nitrogen and oxygen combine to contribute to gas bubble disease (GBD), so just nitrogen concentrations are misleading. Also, the uncertainty in gas supersaturation measurements with the early instruments in the field had large margins of error.

Most saltwater supersaturation studies were not selected for review. Though air saturates in saltwater at about an order of magnitude greater than in freshwater, Washington has no major known sources of human-caused gas supersaturation directly into marine waters. However, estuarine smolt behavior and depth distribution in the mouth of the Columbia is of interest here as was a review of Clay, *Observations on the effects of gas embolism in captured adult menhaden*, because of presence of herring and other baitfish in the Columbia River estuary.

Special attention was made to report depth, length of exposure, supersaturation concentrations, species, life stage, and symptoms. This was so comparisons, where possible, can be made between studies. Fish depth and duration preferences in water bodies are not duplicated in lab studies nor can they be entirely duplicated in live cage studies.

Synthesis

The following information was synthesized from what is known about TDG effects on aquatic organisms:

1. Gas bubble disease increases in fish when fish are in shallow water (depth compensation). Ten percent compensation roughly occurs with each meter of depth. So if 120 percent TDG exists, 110 percent would be the biological equivalent at 1 meter deep, 100 percent at 2 meters, etc. Gas over 100 percent can cause harm over time at surface pressure.
2. Fish cannot quickly detect TDG like they can temperature or other environmental factors. However, over time some species seem to avoid it while some species do not. Fish swim bladders began to inflate at low TDG (103.5 percent Coutant, 1994); the fish respond to this by initially swimming higher up in the water column and then spending extra energy to swim deeper to reduce swim bladder inflation.
3. Death or distress from gas bubbles increases with higher concentrations and length of exposure.
4. Time to death from gas bubbles is lengthened when pressure is increased (with increased depth).

5. Susceptibility to gas bubble harm varies between species. Salmonids are not always the most susceptible.
6. Susceptibility between salmon species varies. Spring Chinook showed less susceptibility than other salmonids species.
7. Small creatures can pass gas out of the circulatory system more easily but are susceptible to air blockages in the gut.
8. Gas bubbles occur almost exclusively outside the cell walls.
9. Fish vary their depth (and therefore TDG susceptibility) according to season, time of day, species, and individuals within species.
10. Depth exposure varies for benthic organisms according to their movement (if any), river elevations, and reservoir operations.
11. At higher TDG levels, fish can die without showing evidence of gas bubbles.
12. At low levels, fish can show internal chemical changes without evidence of gas bubbles.
13. River edges often have less TDG than the middle.
14. The toxicities of TDG in fresh water appear to be the same as for saline water. However, air saturates into marine water about an order of magnitude more than in freshwater. There are no known human sources for supersaturation in salt water in Washington.
15. Susceptibility to gas bubble harm varies with life stage. Fry stage is more susceptible, egg stage less.
16. Susceptibility to gas bubble harm increases with activity.
17. Susceptibility to gas bubble harm increases with stress and disease.
18. Repeated exposure can predispose gas bubble development on existing sites.
19. Field cage studies show less TDG trauma than lab studies.
20. Nitrogen to oxygen levels change. Higher oxygen in the mix can increase or reduce GBD.
21. Gas supersaturation measurement technology and methodology have improved. The GBD studies before about 1980 should be assigned a larger margin of error for TDG measurements. Measurements within the last 15 years have a small level of uncertainty if quality assurance plans were followed.
22. A number of depth lab or caged studies reported only maximum depth of the containers, not where fish resided in the containers, so GBD might be over reported for these situations.

Gaps

The following gaps were identified about TDG effects on aquatic organisms:

- Long-term effects of exposure. This is a difficult area to fully study, especially considering the variables in relation to migrating salmon. Some studies have been done on various aspects, but there will always be a lack of definitive information in this regard.
- Indirect effects. Again, some aspects have been studied, such as effects of certain stresses and infection.
- Gas levels in the Columbia and Snake in shallow waters areas. Pertinence should be assigned to areas where water is moving substantially slower next to the shore, heavy growth of aquatic plants occur (such as above Rocky reach dam), and shallow water areas such as flats and the estuary.
- Depth distribution of aquatic organisms and shallow water exposure. Depth determines how the organism will experience TDG. Organisms residing deeper will experience less of the effects of TDG than organisms residing in shallow waters. There are some good recent studies on radio-tagged large juvenile salmonids and adults in the Columbia River. There is little information on free-floating and surface dwelling organisms such as larvae of fish, crustaceans, and mollusks. There is likely substantial information on depths of resident fish and benthic organisms separate from TDG literature.
- Duration of exposure and behavior. TDG is more toxic the longer the organism is exposed. Aquatic creatures move and river levels fluctuate with dam operations.
- Species specific tolerances.
- Life stage tolerances.
- Species-specific distribution and tolerances:
    - Salmon: Because spring Chinook and steelhead juveniles are larger than other juvenile salmon, most studies used these fish, especially recently, for radio tagging to assess depth preferences. That leaves less known about sockeye, coho, chum, and fall Chinook juveniles during their emergence and fry stages, but especially when holding and rearing as juveniles and smolt stages.
    - Resident and other anadromous fish. This review only looked at depth preference studies in regard to TDG. Other depth distribution/behavior studies likely exist for some species. Some studies outside this review's focus would be useful to assuming certain behaviors in the Columbia/Snake and other waters of the state. However, little information appears to exist on depth preferences and usage in the Columbia and Snake mainstem for the following species at critical life stages (juvenile, fry, rearing juveniles, adults, adult spawning):
        - Sturgeon. There may be depth distribution information for adult sturgeon. There is one study on trauma to sturgeon fry.
        - Whitefish.

        - Shad.
        - Lamprey (3 species). No published trauma information, long holding times in very shallow water at the dams for Pacific Lamprey, shallow spawning, different blood chemistry.
        - Suckers.
        - Others – warm water introduced spiny rays (large and smallmouth bass, crappie, bluegill, pumpkinseed walleye, yellow perch), minnows (carp, chiselmouth, shiners, peamouth, tench, N. pikeminnow) sculpin, stickleback, bullhead and catfish, estuarine fish—herring, anchovy.
    - Other aquatic organisms: Susceptibility to TDG has not been reviewed because of a lack of studies. Depth preference and duration information at different life stages is sparse. For dam-controlled waters, depth preference is not the correct term for many benthic organisms since reservoir and to a lesser extent tailwater elevations are controlled by dam operations and often fluctuate daily.
        - Clams, mussels and snails, larvae and adults.
        - Aquatic insect larvae rearing, emergence.
        - Crayfish, freshwater shrimp, crabs--larvae and other stages.
        - Salamanders, frogs.
        - Zooplankton (free and surface floating organisms) larvae of fish, mollusks, arthropods.
        - Phytoplankton (free-floating and surface-floating organisms) copepods, algae, diatoms, formanifera, dinoflagelates.
        - Other organisms: worms, amphipods, isopods.

Recommendations

The following recommendations are made for evaluating appropriate Washington water quality criteria for TDG:

- Enough is known about gas bubble disease (GBD) in salmonids at all life stages.
- Depth and duration of aquatic organisms in various habitats of Washington's rivers are important factors. Understand that depth varies with life stage and within a population of the same species—enough that for salmon, mean species preference depths and durations are not protective. Depth also varies with river operations on a dam-controlled river—while this affects fish, it also affects benthic organisms.
- Organisms that appear to be the most threatened with harm from TDG are surface dwelling at least at some stage of their life cycle: amphibians and plankton including fish larvae and food chain organisms. Until more is known about these organisms' exposures, a margin of safety is advised.

Literature Review

162 studies, and other documents obtained and reviewed
272 studies and other documents listed

Author	Publisher	Title	Date ✔=have copy	Summary
Abernathy, Dauble, Johnson	Pacific Northwest National Laboratory, Richland, WA for BPA, Portland. Draft progress report Ecology 1996	Feasibility study for evaluating cumulative exposure of downstream migrant juvenile salmonids to total dissolved gas	1997 ✔	***Purpose*:** Understand juvenile Chinook and rainbow trout depth preferences when migrating downstream above Ice harbor Dam to McNary Dam using 5 meters (m) deep drift net/container. ***Result*:** During the day over 70% of fish in top 3 m. More uniform depth distribution occurred at night. Dawn and early morning found fish closer to the surface. Fish in the upper 1 m were observed during the day. The drifts were floats at river current velocity attempting to stay near the thalweg. Hatchery juvenile rainbow trout and fall Chinook salmon were used. Remote visual monitoring was used as fish sounded when researches were near the net pen.
Abernathy, Amidan, cada.	Report of the Pacific Northwest national Laboratories to the Dept. of Energy, Hydropower Program, Idaho Falls, ID	Laboratory studies of the effects of pressure and dissolved gas supersaturation on turbine-passed fish	2001	Report unavailable
Absolom, Dawley, Sandford	NOAA Fisheries for USDE, BPA, Portland, OR Project No 96-24 Contract No 96BI93892	Changes in gas bubble disease signs of migrating juvenile salmonids experimentally exposed to supersaturated gasses 1997	1999 ✔	***Purpose*:** Understand if gas bubble trauma (GBD) signs change as a result of changes in pressure experienced by juvenile salmon going through turbines. ***Results*:** Inconclusive for juvenile coho.

Author	Publisher	Title	Date ✔ =have copy	Summary
Adams, Rondorf, Evans, Kelly	Transactions of the American Fisheries Society	Effects of surgically and gastrically implanted radio transmitters on growth and feeding behavior of juvenile Chinook salmon	1998a ✔	***Purpose*:** Do radio transmitters affect behavior of juvenile Chinook? ***Result*:** No, the study did not show depth preferences as either affected or not affected by radio implants.
Adams, Rondorf, Evans, Kelly	Canadian Journal of Fisheries and Aquatic Sciences 55:781-787	Effects of surgically and gastrically implanted radio transmitters on swimming performance and predator avoidance of juvenile Chinook salmon	1998b ✔	Report unavailable
Alderdice, Jensen, Schnute	Dept of Fisheries and Oceans, Pacific Biological Station, Canada Canadian Technical Report Fisheries and Aquatic Sciences 1386: 48 pages	An assessment of the influence of ancillary factors on the response of salmonids in the Nechako River to total dissolved gas pressure	1985	Report unavailable
Alderdice, Jensen	Aquaculture 49:85-88	An explanation for the high resistance of incubating salmon eggs to atmospheric gas supersaturation of water	1986 ✔	Internal pressure in salmon and trout eggs are from >15 mm mercury after fertilization, >25 mm Hg after 24 hours, to 50-90 mm Hg near hatching depending on species. This is enough to compensate for levels of TDG at 111.8% TDG for eggs near the surface with a pressure of 90 mm Hg, for 106% TDG for eggs with an internal pressure of 50 mm Hg, and 102% TDG for eggs just fertilized with an internal pressure of 15 mm Hg.
Alikunhi, Ramachandran, Chaudhari	Proc Natural Institute Science, India	Mortality of carp fry under supersaturation of dissolved oxygen in water	1951	Report unavailable

Author	Publisher	Title	Date ✔ =have copy	Summary
Anonymous	In Proceeding of the 28th Annual Meeting of American Association of Veterinary Laboratory Diagnosticians, Turlock CA	Method for rapid fixation for preservation of tissue emphysema: Diagnosis of gas bubble disease in hatchery-reared rainbow trout.	1985	Report unavailable
Append Applied Sciences LTD	Unpublished report to BC Hydro, Catlegar, British Columbia 8p	TGP performance measures for the Mica water use plan derivation summary	2003	Report unavailable
Antcliffe, Kiesler, Thompson, Lockhart, Metner, Roome	Canadian Technical Rep Fish Aquatic Science 0(2142):I-XII, 1-101	Monitoring of Mountain Whitefish from the Columbia River system near Castlegar, British Columbia	1997	Report unavailable
Antcliffe, B., Fidler, Birtwell	Canadian Technical Report of Fisheries and Aquatic Sciences 2500	Lethal and sublethal responses of rainbow trout and coho fry to elevated dissolved gas supersaturation and temperature	2003 ✔	**Purpose:** Study effects of 114, 118 and 125% TDG at 10°C - 18°C on hatchery rainbow trout and coho salmon fry in shallow tanks (0.1 to 0.25m) and their ability to escape to cover. ***Results***: 118% TDG at 15°C, 3% rainbow trout had bubbles on operculum; no significant effect on their ability to escape to cover. No differences were seen between control groups for tests at 114% TDG at 10°C

Author	Publisher	Title	Date ✔ =have copy	Summary
Antcliffe, B., Fidler, Birtwell	Canadian Technical Report of Fisheries and Aquatic Sciences 2370: 1-70 Copy is draft	Effects of dissolved gas supersaturation on the survival and condition of juvenile rainbow trout under static and dynamic exposure scenarios	2002 ✔	**Purpose**: Test the effect of 110, 114, 116, 122 and 140% TDG at 10°C on juvenile hatchery-raised rainbow trout held 1) in shallow 0.25 m water tanks and 2) exposed repeatedly to variable depths. **Results**: For fish held at 0.25 m at 122% TDG, 50% died after 2.3 days. At 116%, 42% died after nine days. At 114% all fish survived for six days. High variability for time until death for those exposed to 122% TDG. For fish held repeatedly at variable depths from 0.25 m to below compensation depth, onset of mortality and cumulative mortality was significantly reduced. 0.25 m shallow test: no external gas bubble symptoms were present in 48% of the fish that died after exposure to 122% TDG; however 100% of these fish had bubbles in the gill filaments. For the test where fish that died had access to 3 m of water, 38% had no external signs but 100% had bubbles in the gill filaments. Bubbles in the caudal fin were found in 53% of the fish with access to deeper water compared to 52% in the shallow tanks.
Antcliffe, B., Fidler, Birtwell	Canadian Technical Report of Fisheries and Aquatic Sciences 2501	Effects of prior exposure to hydrostatic pressure on rainbow trout survival in air-saturated water	2003	Report unavailable
Aquatechnics Inc	Final report on contract No DACW68-96-D-002 Subcontract No 248800-B-B8. Battelle, Richland, WA	Histopathic assessment of Chinook salmon gill tissues exposed to gas supersaturation	1997	Report unavailable
Arntzen, Panther, Geist, Dawley	Pacific Northwest National Lab, Prepared for USACE, Portland, OR Contract No. DE-AC05-76RL01830	Total dissolved gas monitoring in chum salmon spawning gravels below Bonneville Dam	2007 ✔	***Purpose***: Determine TDG levels in chum spawning gravel below Bonneville Dam during 2006 and measure depth of redds below the water surface. ***Result***: Pressure in the gravel where sac-fry chum are found, and therefore susceptibility to TDG is heavily influenced by river level. Assumed >103% TDG would harm sac-fry. 2006 was a high water year, depth-compensated pressure at the gravel level never reached levels >103% TDG. In lower water years, such as 2005, sac-fry could experience harmful levels of TDG exposure because depth compensation would be less.

Author	Publisher	Title	Date ✔ =have copy	Summary
Aspen Applied Science Fidler	Report to Montgomery Watson, Bellevue, WA	A review of historic levels of dissolved gas supersaturation in the Columbia and Snake rivers and its effect on the survival of juvenile and adult anadromous salmonids.	1996	Report unavailable
Aspen Applied Sciences	Aspen Applied Sciences. For Battlelle NW Division, US Army Corps of Engineers, Walla Walla Dist, Fidler, L.	Laboratory physiology studies for configuring and calibrating the dynamic gas bubble trauma mortality model	1998 ✔	***Purpose***: Determine the relationships of bubble formation in the gill arches to bubble formation in the heart to bubble formation in the circulatory system of Chinook juvenile salmon. This included evaluating existing studies and conducting several studies. Also included the development of a model to predict cumulative GBD in migrating juvenile salmon in the Columbia River. ***Result***: In fish that died, all gills were occluded with bubbles, many had bubbles in the bulbous arteriosus. As bubbles form in the heart they are dislodged and distributed to smaller arteries eventually blocking circulation and resulting in death. Activity of the fish can increase time to mortality. A model (DGBDM) was developed to track bubble formation in the vascular system including the relationship of bubble development in the gill filaments to bubbles in the heart.
Backman, Ross, Krise	North American Journal of Fisheries Management 11:67-71	Tolerance of subyearling American Shad to short-term exposure to gas supersaturation	1991 ✔	***Purpose***: Observe the survival and behavioral effects of 101-128% TDG on juvenile, hatchery-raised five-month-old shad exposed for four hours at 10°C and 0.15 m deep. This is the downstream migration life stage for these fish. ***Results***: External bubbles were present only at 128% TDG in three hours, fifty-two minutes for fish exposed for four hours, and no survival loss was found on these fish after another 23 days at [presumably] 100% TDG. No significant difference in thirteen forms of behavior was observed at any TDG concentration. No depth compensation behavior was possible in the shallow tanks.

Author	Publisher	Title	Date ✔ =have copy	Summary
Backman, Evans, Hawbecker	CRITFC, BPA project No 93-031	Symptoms of gas bubble trauma induced in salmon by total dissolved gas supersaturation of the Snake and Columbia Rivers, USA 1996 annual report	1997 ✔	***Purpose:*** Determine external TDG signs in adult migrating sockeye, Chinook and steelhead salmon at Columbia River dams, and external signs in juvenile salmon caught in-river by purse seine and cod trawl. ***Results:*** TDG levels for juvenile salmonids symptoms varied from 109.5% when 4% of the fish had more severe gas trauma to 125.9% TDG when 6% of the fish sampled had symptoms. Cumulatively for four dams (Bonneville, John Day, McNary and Lower Monumental), of smolts captured in-river, 0.6% had TDG trauma symptoms, while at the same time 3.3% of the smolts captured in the fish bypass at upstream dam facilities at the dams had TDG trauma symptoms. However, each dam site varied in measured trauma between 0.3% and 7% for in-river caught fish and 0.7% and 10.5% for bypass caught fish. 0.2% of sampled fish showed external TDG trauma at Bonneville dam. ***Note:*** Time between capture and symptom monitoring, though recorded, was not included in the report.
Backman, Evans, Hawbecker	CRITFC, BPA project No 93-031	Symptoms of gas bubble trauma induced in salmon by total dissolved gas supersaturation of the Snake and Columbia Rivers, USA 1997 annual report	1997 ✔	***Purpose:*** Determine external TDG signs in adult migrating sockeye, Chinook and steelhead salmon diverted at fish ladders at Bonneville and caught by hoop-net near the Dalles, and external signs in juvenile salmon caught in-river by purse seine, cod trawl, and beach seine. ***Results***: When juvenile salmonid symptoms were found, TDG levels varied from around 110% to 128%. More juvenile bypass-caught salmon had GBD symptoms than fish caught in-river with nets. Adult sockeye had more TDG bubble trauma as a percent of their population (15.5%) than steelhead (7.1%) or Chinook (0.5%). ***Note:*** For adults, TDG levels were taken as mean from fixed monitoring sites but not written into the report for daily TDG levels to compare with GBD. Time between capture and symptom monitoring, though recorded, was not included in the report.

Author	Publisher	Title	Date ✔ =have copy	Summary
Backman, Evans, Hawbecker	CRITFC, BPA project No 93-008-02	Symptoms of gas bubble trauma induced in salmon by total dissolved gas supersaturation of the Snake and Columbia Rivers, USA 1998 annual report	1999 ✔	***Purpose:*** Determine gas bubble disease representing in-river conditions for juvenile salmon on the lower Columbia River and for adult migrating salmon. Fish were sampled by purse seine, hoop-net, diversion at the dam, and beach seine. ***Results:*** When symptoms were found, TDG levels were between 116% and 126% at Bonneville dam. More fish at the fish passage facilities had symptoms than during the in-river sampling (2% compared to 0.9%). ***Note:*** Time between capture and symptom monitoring, though recorded, was not included in the report.
Backman, T., Evans	North American Journal of Fisheries Management 22:579-584	Gas bubble trauma incidence in adult salmonids in the Columbia River basin	2002 ✔	***Purpose***: Assess Columbia river external gas bubble signs for adult Chinook, sockeye and steelhead salmon at Bonneville Dam. ***Results:*** 1995-1999. External signs. No difference in GBD observed between species for TDG levels <125%. Sockeye had the most bubbles when >125% TDG. 0.1% observed with TDG when levels <126%. *Note:* No description of time between collection and examination except samples were collected whenever possible.
Backman, T., Evans, Robertson	Draft Report. Columbia River Intertribal Fish Commission Project No 93-008-02	Symptoms of gas bubble trauma induced in salmon by total dissolved gas supersaturation of the Snake and Columbia rivers	2000	Report unavailable
Backman, T., Evans, Robertson, Hawbecker	North American Journal of Fisheries Management 22: 965-972	Gas bubble trauma incidence in juvenile salmonids in the lower Columbia and Snake rivers	2002 ✔	***Purpose***: Assess extent of GBD in smolts during migration throughout the Columbia River hydropower system at eight locations: tailrace and forebay Bonneville, John Day and McNary, forebay of Dalles and Lower Monumental. Seine sampling in morning and evening for four years. Steelhead, sockeye, Chinook, coho, yellow perch, walleye, suckers, and pikeminnow examined for external signs on fins, lateral lines, and eyes. ***Results***: <2% total fish exhibited signs; steelhead the most at 2.3%. 1.9% of resident fish showed signs. Lab predictions overestimate the GBD incidence. More fish with GBD in bypass samples than in river samples…may result from bypass conditions. Two high flow years 1996 and 1997 and two lower flow years 1998 and 1999.

Author	Publisher	Title	Date ✔ =have copy	Summary
Becker, Abernathy, Dauble	Pacific Northwest National Laboratory, Hydro Review	Identifying the effects on fish of changes in water pressure during turbine passage	2003 ✔	***Purpose***: Determine how sharp increases and decreases in pressure (simulating passage through turbines) and TDG levels affect juvenile fall Chinook, rainbow trout, and bluegill survival. Fish were acclimatized to surface and 30' depth pressures of 135, 120, and 100% TDG. ***Results***: At turbine operation (50pKa): Chinook: 3% exposed to 120% and acclimated to surface pressures were injured. Bluegill: death rate for surface acclimated fish 7% at 120% TDG; injuries 43-100%. Depth acclimated fish injuries were 50-63%. Turbine operation between 2 and 10 pKa is equal to within 1% of peak efficiency increases changes in pressure and thus harm to Chinook salmon and bluegill. Differences in susceptibility between bluegill and salmon are likely attributable to differences in swim bladder structure and function.
BC Hydro, Crawford, Tenant, Bright, MacLean	B.C. Hydro Strategic Fisheries Report No SFP99-Gen-06. Canada	A selected bibliography of literature on total gas pressure and related fisheries impacts	1999 ✔	A literature review. Also includes marine waters.
Beeman, J., Haner, Maule	In Gas Bubble Disease Monitoring and research of juvenile salmonids. USDOE, BPA, Project #96-021 Contract No 96A193279, Portland OR	Vertical and horizontal distribution of individual juvenile salmonids based on radio telemetry	1998 ✔ (every other page only)	***Purpose***: Identify depth use of juvenile hatchery Chinook and steelhead in the Columbia and Snake rivers below Ice harbor Dam between April 22 and June 1. ***Results***: Before May 17, little 'holding' was seen in the reservoir (avg. 6.5 hours). After May 17 many held in shallow (<2 m) water for several days (avg. 51 hours) up to 14.5 days. Fish changed their vertical position often 0.2-0.3 m/minute. They ranged from 0.0 to 12 m (limit of detection) deep, averaging 2.8 m for steelhead and 1.7 m for Chinook. ***Note***: Size of fish greater than actual river populations. Compensation depth was best conservative estimate based on Fidler, Knittle.

Author	Publisher	Title	Date ✔ =have copy	Summary
Beeman, Haner, Maule Filed under Maule : Gas Bubble trauma Monitoring and research of juvenile salmonids. 1995 Annual report	USGS, Columbia River Research Laboratory, Cook, WA	Gas bubble trauma monitoring and research of juvenile salmonids. 1995 Annual report Ch 1. Vertical and horizontal distribution of individual juvenile salmonids based on radio-telemetry.	1997 ✔	***Purpose***: Learn about vertical and horizontal distribution in the Columbia and accuracy and effect on fish of implanted radio tags in juvenile steelhead at 13°C. ***Results***: Accuracy was 0.016 meter. Test group swam 0.2 m shallower. Depth indications were somewhat affected by temperature. Buoyancy of fish was not affected. Detection distances decreased with depth. Tracking a small sample of fish in the McNary pool showed depths of 1.08m to 4.27 m at 119.5-125.8% TDG. No clear pattern was found between the three individuals tracked.
Beeman, J., Venditti, Morris, Gadomski, Adams, Maule, et al	Western Fisheries Research Center, Columbia River Research Laboratory	Gas bubble disease in resident fish below Grand Coulee Dam	2003 ✔	***Purpose***: Determine relative exposure of pikeminnow, bridgelip sucker, walleye, longnose sucker, largescale sucker in the in Lake Rufous Woods and steelhead in net pens to TDG during a three year study in Lake Rufous Woods using tags to record depth of fish and temperature. ***Results***: 17 wild fish tags recovered from fish implanted with temperature archive tags. Fish often changed depth sharply between day and night. Most species were deeper at night. Median depth varied between species. Depth for individual fish also varied within the species. Depth also varied for each species with the season. The largest variation was found in large-scale sucker from about 0.3 m to 16 m. All species were found at one time or another within 1 meter of the surface although the median was 2 m or more for each species. Species abundance changed between the three sucker species, possibly due to TDG. Seven steelhead were also recovered from the net pens. The depth of these fish was much shallower than for the wild fish, with most of the time spent at less than 1 meter, although the nets were 7.3 m deep. The author suggested that the net pens influenced depth chosen by the steelhead.

Author	Publisher	Title	Date ✔ =have copy	Summary
Beeman, Maule	USGS Western Fisheries Research Center. American Fisheries Society	Migration Depths of juvenile Chinook salmon and steelhead relative to total dissolved gas supersaturation in a Columbia River reservoir	2006 ✔	***Purpose***: Determine migration depths of juvenile Chinook and steelhead in the McNary Pool. ***Results***: Mean depth of steelhead was 2 m in the Snake and 2.3 in McNary forebay. They were deeper at night than day; Chinook 1.5 m in Snake to 3.2 m near forebay; deeper in day than night. Duration: migration rates McNary Pool: Chinook - 107 km/day in 1998 and 63 km/day in 1997 and 1999. Steelhead – 50 km/day 1997 and 36 m/day in 1999.
Beiningen, Ebel	Bureau of Commercial Fisheries, Seattle, WA 7 Transactions of the American Fisheries Society 99:664-671	Effects of John Day Dam on dissolved nitrogen concentrations and salmon in the Columbia River, 1968	1970 ✔	***Purpose***: Measure TDG to determine the effect of John Day Dam on TDG. ***Result***: John Day spill produced high gas >125% and caused fish mortalities.
Bently, Dawley, Newcolm	Canadian Technical Report of Fisheries and Aquatic Sciences 2343:1-128	Effects of supersaturated dissolved atmospheric gases on northern squawfish, Ptychocheiilus oregonensis	1981 ✔	***Purpose:*** Assess TDG effects on wild captured pike minnows held in 10°C water at 0.25 meter deep at 99.8, 107, 110, 117.2, 120.4 and 126.1 % TDG saturation. Learn about pike minnow food intake, movement, and depth distribution relative to TDG levels in the Snake River, Washington. ***Results:*** Lab: 32% mortality in 12 days at 117.2% TDG; 89% had GBD at 110% TDG; 14% had GBD at 107%TDG. No signs of GBD at 100% TDG. Food intake decreased and food preference changed as TDG increased. Field: 23,000 pike minnow were tagged; the recaptures gave information on migration behavior in relation to existing TDG concentrations at the time, which were between 99.6 and ~130% TDG. Upstream movement almost stopped during periods of TDG above 'normal'. Downstream recoveries were when TDG was 'high'. Gill net recoveries found 2% of the pike minnow were above 3m depth when TDG was between 116-130% TDG. 46% of these captures showed signs of GBD. During periods of high gas at the tailrace of Little Goose Dam 3% of the pike minnow were feeding; when TDG levels were low, 100% of the fish were feeding as shown by stomach contents of captured fish.

Author	Publisher	Title	Date ✔ =have copy	Summary
Beyer, D'Aoust, Smith	Undersea Biomed. Research 3: 321-338	Decompression-induced bubble formation in salmonids: Comparison to gas bubble disease.	1976	Report unavailable
Biological Monitoring Inspection Team Dawley, Colt, Elston	A report to the NMFS and EPA Technical Work Group	Research priorities related to gas bubble monitoring needs in the Columbia River Basin Also see NW Fisheries Science Center Panel Report and Bouck	1995 ✔	Identified critical assumptions of gas bubble monitoring program to check out: 1. Samples taken represent entire river and include high risk areas. 2. Signs in fish represent fish in the river near this site over the whole day. 3. No significant mortality between sample sites. 4. Clinical signs don't change during collection. 5. Sample size adequate. 6. All signs and their significance are known. 7. Relationship between exterior bubbles and mortality are known. The group listed research tasks to study these assumptions. This was not a study but important background to evaluate subsequent studies.
Birtwell, I., Korstrom, Fink	Dept of Oceans and Fisheries, Marine Environment and Habitat Science Div, Science Branch, Pacific Region, Vancouver, BC	The susceptibility of juvenile chum salmon to predation following sublethal exposure to elevated temperature and dissolved gas supersaturation in sea water	1998	Report unavailable
Birtwell, I., Korstrom, Fink	Canadian Technical Report of Fisheries and Aquatic Sciences 2343:1-128	The susceptibility of juvenile chum salmon to predation following sublethal exposure to elevated temperature and dissolved gas supersaturation in seawater	2001	Report unavailable

Author	Publisher	Title	Date ✔ =have copy	Summary
Bjorn	Report to Corps Fish Research Scientific Review Subcommittee. Idaho Cooperative Fish and Wildlife Research Unit, U of Idaho, Moscow, ID	Dissolved gas concentrations, spill, and adult salmon with head burns in the lower Snake River-1993	1993 ✔	***Purpose***: Track radiotagged adult spring Chinook from John Day Dam upriver in relation to TDG exposure. ***Results***: Concentrations ranged from 105-140% TDG. Head burns were observed. Table showed headburns in ~14% of tagged adults from May through July. ***Note:*** Reviewed incomplete report only through page 11.
Blahm, McConnell, Snyder	NMFS, Prescott, OR	Effects of supersaturated Columbia River water on the survival of juvenile salmonids April to June 1972	1973	Report unavailable
Blahm, McConnell, Snyder	NOAA Technical report NMFS SSRF-688, Seattle, WA	Effect of gas supersaturated Columbia River water on the survival of juvenile Chinook and coho salmon	1975 ✔	***Purpose***: Investigate TDG effects on juvenile Chinook and coho salmon in deepwater rather than shallow water tanks. ***Results***: Chinook may have detected TDG. Steelhead did not. Lab conditions, (especially shallow water tank studies) differ from river conditions.
Bouck	Report prepared for Direct Service Industries by Cramer and Associates, Gresham, OR	A survey of dissolved gas levels in fish passage facilities at the Columbia and Snake River dams.	1996	Report unavailable
Bouck,	Transactions of the American Fisheries Society 109: 703-707	Etiology of gas bubble disease	1980	Report unavailable

Author	Publisher	Title	Date ✔ =have copy	Summary
Bouck, King	Fish Biology 23:293-300	Tolerance to gas supersaturation in fresh water and sea water by steelhead trout	1983 ✔	***Purpose***: Better understand the effects of TDG exposure on steelhead smolts' acclimatization to salt water. The freshwater and seawater was held at 125% TDG and between 12 and 13°C. ***Results***: Time to mortality was similar between fresh and salt water. Gas absorption from air into the water was observed in salt water at about 10 times greater than in fresh water.
Bouck, King	Fish and Aquatic Science	Effects of fasting and vitamin C on tolerance to air supersaturated water by rainbow trout	1983	Report unavailable
Bouck	CR Basin Fish and Wildlife program	Conceptual plans for qualitatively and quantitatively improving artificial propagation of anadromous salmonids in the Columbia River Basin	1986	Report unavailable

Author	Publisher	Title	Date ✔ =have copy	Summary
Bouck, Nebeker, Stevens	Western Toxicology Station, Corvallis, Oregon, EPA 600/3-76-054	Mortality, saltwater adaptation, and reproduction of fish exposed to gas supersaturated water	1976 ✔	***Purpose***: Assess TDG trauma to salmon and largemouth bass at various life stages: mortality, saltwater adaptation, and maturation and fertilization. Lab study using continuous exposure 1 meter deep tanks mostly at 10°C. Tests were done at 130, 125, 120, 115 and 110% TDG. ***Result***: A ratio of tolerance to TDG at 120%/10°C was made for the fish studied. This may be useful in reviewing other TDG studies of specific species since many of the studies have used the most easily available and largest juveniles, spring Chinook. Species/Tolerance ratios: Spring Chinook adult ♀/1.34, ♂/1.37, smolt/1.27; Rainbow trout parr/1.42, yearling/1.06, parr/1.42; steelhead adult, ♀gravid/2.34, ♂gravid/2.04, smolt/1.32, parr/2.10; sockeye adult/2.11, smolt/1.48, parr/2.10; coho adult ♀gravid/1.22, ♂gravid/1.90, post smolts/1.00, jack mature/1.44, parr/4.66; largemouth bass adult/>6.00. Emphysema in bass fins but fed on juvenile salmonids after 10 days at 125%. No mortality at 120% after 12 days. Temperature tests were performed at 10° and 18°C in which fish showed definite differences in hours to mortality yet due to variables, the conclusion was that more studies were needed. Entering seawater did not cause any increase in gas bubble trauma symptoms in coho smolts. Behavior of fish influenced time to mortality. Behavioral differences in individual fish within a species and between species were observed. 125% lethal to all salmon in 6 days—external signs not apparent in early mortalities, more prevalent in 6 day mortalities. Steelhead and rainbow trout developed more external signs than other salmonids. At 120% TDG, gravid females less tolerant among coho. Adult salmon: 50% mortality 3-4 days for adults. First mortality 16 hours for steelhead parr. At 115%, sensitivities were as followed for ET50 in days: sockeye parr 4.2, coho 7.5, steelhead parr 11.2, spring Chinook adult 21.9. Sex related differences for adult gravid Chinook was more pronounced than at 120% TDG. Exothalmia, emphysema, fungal infections were more pronounced due to longer exposure. Internal bubbles in muscle tissue in 14 days and increased during the following 7 days to resemble “Swiss cheese”.

Author	Publisher	Title	Date ✔=have copy	Summary
Bouck	In Fickeisen and Shneider, gas Bubble Disease. Tech info center. ERDA NTIS Conf 741033	Supersaturation and fishery observations in selected alpine Oregon streams	1976 ✔	***Purpose***: Preliminary investigation into thermally occurring TDG fish kills to understand the impact to the population and apply this knowledge to the larger Columbia River. ***Results***: Hatchery salmonid fish kills occurred at 105%. Wild populations were apparently unaffected. Invertebrates (aquatic insects) had a good representative population.
Bouck	Transactions of the American Fisheries Society 109: 703-303, 1980	Etiology of gas bubble disease	1980 ✔	Gas bubble disease 101
Bouck, editor	Sponsored by Portland Chapter of the American Fisheries Society, USEPA, USACE, and BPA. A workshop in Portland Or April 19-20, 1994	Notes from a workshop on gas supersaturation and its research needs in the Columbia River	1994	Not a study. Provides an indication of data gaps such as gas levels in backwater areas, resident fish and other aquatic species behavior, depth, and habitat use at all life stages in the Columbia
Bowser, Toal, Robinette, Brunson	Fish culture 45:208-209	Colemic distension in channel catfish fingerlings	1983	Report unavailable
Boyd, Watten, Goubier, Ruiquan	Aquaculture Engineering 13 (1):31-39	Gas supersaturation in surface waters of aquaculture ponds	1994	Report unavailable
Boyer, P.	Report to Army Corps of Engineers, Portland, OR Contract #DACW57-74-C-0146	Lower Columbia and Snake Rivers: nitrogen (gas) supersaturation and related data, analysis and interpretation.	1974	Report unavailable

Author	Publisher	Title	Date ✔ =have copy	Summary
Brammer	Thesis, Montana State University, Bozeman, MT	The effects of supersaturation of dissolved gases on aquatic invertebrates of the Bighorn River downstream of Yellowtail Afterbay Dam	1991	Report unavailable
Brisson	Aquaculture 47: 97-99	Gas bubble disease observed in pink shrimp Penaeus brasiliensis and Penaeus paulensis	1985 ✔	***Purpose***: Assess the cause of death and review GBD symptoms of juvenile and adult shrimp, bivalves, gastropods, echinoderm, crabs, and barnacles held in a tank between 19-22.8°C in 35% saline water after air-supersaturated water was inadvertently introduced. ***Result***: Behavior symptoms in shrimp: first signs were convulsions, disorientation, rapid swimming, jumping, swimming vertically both up and down then spinning around. Then after 1-4 minutes, the shrimp floated, then died. Gas bubbles were visible under the carapaces, the hemocoel, ventral surface, the gills, and appendages. Oxygen levels during this time were 7.48 ml/l, 30% higher than background levels. No nitrogen levels were measured.
Canadian Council of Resource and Environmental Ministers	Task Force on Water Quality Guidelines, Ottowa, ONT	Canadian Water Quality Guidelines	1987	Report unavailable
Carlson	Aspen Applied Sciences Inc, Kalispell, Montana Under subcontract No. 29245_A_1Q, Work Order No. 3	A survey of noninvasive technologies applicable to the examination of fish for signs of gas bubble disease	1996 ✔	Not a study but gives background and recommends investigating improvements to current external biological monitoring in the Columbia for gas bubble trauma. ***Purpose***: Improve gas bubble trauma monitoring to include non-invasive internal bubble detection. ***Results***: No studies link external bubble signs to mortality. Investigations into ultrasound and ophthalmologic techniques were recommended.
Carmichael, Tomasso	Texas Journal of Science 35:315-321	Swim bladder stress syndrome in largemouth bass	1984	Report unavailable

Author	Publisher	Title	Date ✔ =have copy	Summary
Carroll	USACE, Contract No DACW68-03-D-0003	TDG forebay fixed monitoring station review and evaluation for lower Snake River projects and McNary Dam	2004 ✔	***Purpose***: to assess representativeness of the forebay monitors and recommend improvements ***Results***: Elevated TDG resulting from thermal spikes from surface water drawn by the TDG sensors on its way into turbines was characterized for McNary and the lower four Snake River dams. McNary had the largest thermally induced spikes of 5-6% saturation. Spikes only rarely occurred at Lower Monumental and Little Goose. Relocation of the forebay instruments on the face of these five dams was recommended to deeper 20-30 m water and upstream at the tip of the navigation lock from the face of the dams.
Casillas, Smith, D'Aoust	In Gas Bubble Disease: Proceedings of a Workshop held in Richland, WA, Oct 8-9, 1974. Edited by Fiskeisen and Schneider. CONF-741033. Tech Info Centre, US Energy research and Development Admin, Oak Ridge, TN pp 93-95	Effects of stress on salmonid blood clotting mechanisms	1976 ✔	***Purpose***: Investigate the contribution of blood clotting to mortality of year old hatchery rainbow trout and rainbow trout from Chester Lake. These trout were of an unknown age but similar size and exposed to stress from physical exertion. ***Results***: Stressed fish have a decrease in blood clotting time. Vascular bubbles, it was thought, could cause increase clotting in fish.
Chamberlain, Neill, Romanowsky, Strawn	Transactions of the American Fisheries Society	Vertical responses of Atlantic Croaker to gas supersaturation and temperature change	1980 ✔	***Purpose:*** Understand the depth preference behavior of an estuarine fish when exposed to TDG (and separately also to elevated oxygen and nitrogen). ***Results:*** When exposed to TDG an initial movement upward was observed followed by a movement downward where fish swam erratically and often with their heads down. The authors hypothesized that the upward movements were due to initial buoyant effect of TDG air in the swim bladder and the downward movement was to compensate.

Author	Publisher	Title	Date ✔ =have copy	Summary
Clay, Barker, Testaverde, Marcello, McLeod	In Fickeisen and Shneider, gas Bubble Disease. Tech infor center. ERDA NTIS Conf 741033	Observations on the effects of gas embolism in captured adult menhaden	1976 ✔	***Purpose***: Ascertain the effects of TDG at various levels on adult Menhaden at 22°C. ***Results***: At 110% TDG mucous, erratic swimming and death within 24 hours. Bubbles in eyes, intestines, roof of mouth, arteries, fins, operculum, gills. Depth was not mentioned but a shallow 145 gallon tank is assumed. Note: This was of interest because of lack of information on TDG effects on estuarine herring and anchovies.
Cochnauer	Idaho Dept of Fish and Game, Lewiston	Summarization of gas bubble trauma monitoring in the Clearwater River, Idaho, 1995-1999	1999 ✔	***Purpose***: Monitor gas bubble trauma in resident fish species in the Clearwater River below Dworshak Dam to the Memorial Bridge from April 15 to August 15 1995 through 1999. ***Results***: Most of the GBD was found during high flow years with TDG >120%. The closer to the source of the TDG (Dworshak Dam) the greater the incidence of trauma.
Colt, Fidler, Elston, Watson	Montgomery Watson. Report to BPA Project No 93-008. Report No 66208-1, Portland, OR	Review of monitoring plans for gas bubble disease signs and gas supersaturation levels on the Columbia and Snake Rivers	1994 ✔	***Purpose***: Review existing knowledge and recommend protocol for detecting GBD in salmon. ***Recommendations***: 1. Not in current protocol--Examine gill lamellae. Examine fish from forebay and tailrace and compare with those examined in collection facilities. 2. Incorporated into current protocol: do not examine for swim bladder over-inflation, kidney and intestine bubbles. Examine fin rays using a compound microscope. Develop a numeric grading procedure.
Colt	Aquaculture Eng. 5:49-85	Gas supersaturation – impact on the design and operation of aquatic systems	1986	Report unavailable
Colt, Orwicz, Brooks	Aquaculture 50:153-160	Impacts of gas supersaturation on the growth of juvenile channel catfish	1985 ✔	***Purpose***: Assess the effects of TDG on the growth of juvenile channel catfish at 24°C ***Results***: 1% mortality at 110% TDG in 35 days, 56% mortality at 115% in 35 days.

Author	Publisher	Title	Date ✔ =have copy	Summary
Colt, Fidler, Elston	Aquaculture 38:127-136	Effects of gas-supersaturated water on rana catesbeiana tadpoles	1984a ✔	***Purpose***: Learn about the effect of TDG exposure on bullfrog tadpoles exposed between 21-24 °C. ***Results***: Tadpoles began to float to the surface when exposed to as little as 114% TDG. At over 120% TDG, all tadpoles floated within 24 hours. Inflation of the intestines and gallbladder was the cause and no signs of subcutaneous bubbles were observed. Upon lowering TDG to 100%, tadpoles recovered within 3 days. The number of bacteria, Aeromonas hydrophila (redleg disease) increased tenfold after 6 and 7 days of exposure to >120% TDG and decreased after TDG levels were reduced to normal.
Colt, Fidler, Elston	Journal of Herpetology 18: 131-137	Gas bubble disease in the African clawed frog	1984b ✔	***Purpose***: To assess gas bubble disease in the African Clawed Frog (Xenopus laevis). ***Results***: Exposures were from 151-185 mm Hg. For 151 mm Hg (~120%TDG), signs began with inability to locate and eat food; within one-two days bubbles formed—initially in webbing and at the same time a reduced mucous coating of the skin. Gas bubbles became progressively larger and extensive over time; this progressed to hemorrhages and loss of ability to stay submerged by 48 to 7 2 hours. For higher gas levels, symptoms were more severe including massive bubbles under the skin, little blood in enlarged heart, bubbles clearly visible in arteries, veins, stomach and other internal organs.
Colt, Orwicz, Brooks	Journal of World Aquaculture Society 18 (4):229-236	Gas bubble trauma in the bullfrog Rana catesbeiana	1987 ✔	***Purpose***: To assess gas bubble trauma in adult bullfrogs ***Results***: Above 116.5% TDG all frogs had blistering of the skin and bubbles in the cardiovascular system. Secondary bacterial infections and bubbles in the vascular system caused mortalities.
Colt, Bouck, Fidler	Special publication No 1 Report NO DOE/BP 808, Portland, OR	Review of current literature and research on gas supersaturation and gas bubble trauma	1987 ✔	Literature Review.
Colt, Orwicz, Brooks	California Fish and Game 77(1):41-50	Gas supersaturation in the American River California USA	1991 ✔	***Purpose***: Measure air supersaturation in a dammed river in California. ***Results***: High TDG, greater that 110%, was measured during flood period.

Author	Publisher	Title	Date ✔ =have copy	Summary
Cornacchia, Colt	Juvenile Fish Distribution. Journal of Fish Disease 7(1):15-27 7: 15-27	The effects of dissolved gas supersaturation on larval striped bass	1984 ✔	***Purpose***: Understand response of larval striped bass 10 cm deep to known levels of TDG up to 106% in saline and freshwater at 17.6-19.7°C. ***Results***: Increase in swim bladder volume at 103% TDG. For 10-19 day old larvae 33-35% mortality at 106% TDG for fish exposed for 3-3.25 days compared to 10% mortality for control; feeding behavior appeared to be reduced. For 31 day old larvae, symptoms of GBD were not present but growth was reduced. Larval striped bass and other pelagic fish are surface oriented. The biggest effect of gas bubbles in larval bass is blocking passage of food and destruction of intestinal villi. The small size of larvae makes them susceptible to rapid changes in buoyancy from gas bubbles. ***Note***: What aquatic species have ichthioplanktonic larvae found at the surface in the Columbia/Snake during periods of spill? If there are any, the 110% criterion is insufficient to protect them, according to this study.
Counihan, T., Miller, Mesa, Parsley	Transaction of the American Fisheries Society 127:316-322	The effects of dissolved gas supersaturation on white sturgeon larvae	1998 ✔	***Purpose***: Assess the effects of dissolved gas on newly hatched white sturgeon larvae and older stages of development at 118% and 131% TDG at 0.25m deep at ~15.4°C. ***Results***: Behavior was affected but not quantified. Larvae exposed to 118% TDG were surface oriented, and the control group not exposed to supersaturation remained at the bottom of the tank. GBD was higher as the larvae aged from newly hatched through different stages of development. Though no mortalities occurred at 118% TDG, symptoms were apparent within 15 minutes. Exposed at 118%, 50% GBD; exposed at 130%, 85% GBD.
Coutant, Genoway	Report to US Bureau of Commercial Fisheries, Battelle Memorial Inst. Pacific NW Laboratory, Richland, WA	An exploratory study of interaction of increased temperature and nitrogen supersaturation on mortality of adult salmon	1976	Report unavailable

Author	Publisher	Title	Date ✔ =have copy	Summary
Coutant, Backman, Dawley, Fidler, Krise, Nebeker	Report to NMFS Science Center, Seattle, WA	Report and recommendations Panel on Gas Bubble Disease	1994 ✔	For the purpose of developing a GBD monitoring protocol: An assembly of scientists gathered for a 1-1/2 day panel to answer specific questions for Columbia River TDG: 1. What is known about GBD? Much known about certain species in captivity mostly for mortality, don't know much in river systems. Little known about sub-lethal and behavioral. Bubble formation variability between species under different conditions not understood. 2. GB signs in salmon in labs: lethal 115%-118% in cardiovascular system; subdermal emphysema and bubbles in lat. line at 110%; inflation of swim bladder 103% in fry and juveniles; Rupture of swim bladder in small fish 110%; eye lesions 102%; bubbles in intestinal tract 102-110%; loss of swimming ability 106%; reduced growth 102-105%; immune suppression 108%; reduced ability to adapt to saltwater. . Recommended physical TDG monitoring over GBD monitoring as more reliable. . 1994 literature shows no clear relationship between GBD signs and damage for firm TDG thresholds. . Effects above 110% in direction of damage; below 110% adequate although indications of harm exist below this level. ***Note:*** Useful background to understand the limits of the current GBD monitoring in the Columbia.
Craig, Wharton, McKay	Science 255:318-321	Oxygen supersaturation in ice covered Antarctic lakes: biological vs. physical contributions	1992	Report unavailable
Cramer, S.	Report to the Direct Service Industries—Cramer and Associates, Inc. Gresham, OR	Seasonal changes in survival of yearling Chinook smolts emigrating through the Snake River in 1995 as estimated from detections of PIT tags	1996	Report unavailable

Author	Publisher	Title	Date ✔ =have copy	Summary
Crawford, Tenant, Bright	For BC Hydro Strategic Fisheries Report No SFP99-GEN-06	A selected bibliography of literature on total gas pressure and related fisheries impacts	1999 ✔	A literature bibliography
Crunkilton, Czarnezki, trial	Transactions of the American fisheries Society 109:725-733	Severe gas bubble disease in a warm-water fishery in the midwestern United States	1980 ✔	***Purpose***: Describe effects of TDG on fish in a shallow water part of a reservoir below Harry S. Truman Dam on the Osage River. ***Results***: Surface dwelling and near shore warm-water fish species were killed first, followed by deeper water species progressively with increased duration of exposure. Temperature appeared to have an effect as no mortalities were observed when water was 2°C at 135% TDG but mortalities were encountered at the same saturation but water temperature at 13°C. This may be related to increase in swimming activity near the surface.
Dauble, Mueller	For U.S. Dept of Energy BPA Project No 93-026	Factors affecting the survival of upstream migrant adult salmonids in the Columbia River basin	1993 ✔	A short literature search to evaluate in part, TDG levels on adult salmon.
D'Aoust, Clark	Transactions of the American fisheries Society 109: 708-724	Analysis of supersaturated air in natural water and reservoirs	1980 ✔	***Purpose***: Improve TDG monitoring/detection methods. ***Results***: Lab analysis can slightly overestimate TDG levels because of bubble formation. In-situ detection was recommended/preferred.
Dawley, Ledgerwood, Blahm, Rankis	Annual report BPA Agreement DE-A179-83BP39652	Migration characteristics and survival of Juvenile Salmonids entering the Columbia River estuary during 1982	1984 ✔	***Purpose***: In part to assess migrational timing and movement rates of juvenile salmon in the Columbia River estuary using beach and purse seines from March – December excluding October. ***Results***: Migration times were slowest for groups that wintered in the system and for small subyearling Chinook released after mid-June.

Author	Publisher	Title	Date ✔ =have copy	Summary
Dawley, Ledgerwood, Blahm, Rankis	Annual report BPA Agreement DE-A179-83BP39652	Migration characteristics and survival of Juvenile Salmonids entering the Columbia River estuary during 1983	1984 ✔	***Purpose***: Multifold, including documenting juvenile fall Chinook movement rates, diel movement rates, resident time in the estuary, and effect of river flow using beach seine to capture fish. ***Results***: Fish were found in shallow near shore habitats throughout the estuary rather than in deeper water. Yearling Chinook, coho, and steelhead were more abundant in deeper waters. 95% of fall juvenile Chinook were within 3 m of surface. Juvenile fall Chinook found in the estuary May through September. Aquatic insect were the most important food items for juvenile salmon; abundance of food at this stage likely affects adult survival. ***Note***: Protection of the food sources from effects of TDG should be investigated.
Dawley, Ledgerwood, Blahm, Sims, Durkin, Kirn, Rankis, Monan, Ossiander	Report of Research to BPA, Portland, OR. Contract No DE-AI79-84BP39652, Project No. 81-102 and Coastal Zone and Estuarine Studies Div. NW and Alaska Fisheries Center NMFS, Seattle, WA	Migration characteristics, biological observations, and relative survival of juvenile salmonids entering the Columbia River estuary, 1966-1983	1986	Report unavailable

Author	Publisher	Title	Date ✔ =have copy	Summary
Dawley, E.	Report to the Corps of Engineers. Portland Contract #DACW57-85-F-0623 and Coastal Zone and Estuarine Studies Division Northwest and Alaska Fisheries Center NMFS, NOAA 2725 Montlake Blvd E, Seattle, WA	Effects of 1985-86 levels of dissolved gas on salmonids in the Columbia River	1986 ✔	***Purpose***: Assess effects of TDG on spring and summer (yearling and subyearling) hatchery and river-captured Chinook held in cages at Cages at 0-1, 1-2, 3-4 and 1-6 m. ***Results***: Since TDG levels in the Columbia were low in June, supersaturation came only in bursts; highest eight hours was 120%. TDG trauma was inconclusive; no GBD signs were observed. Depth preferences in the cages were observed: 2% of yearling Chinook shallower than 1.2 m; 9% between 1.2 and 2.4 m. Yearling Chinook, 6% above 1.2 m. Small sample size in river showed that for yearlings, 48% were in the top meter. In river detections: shallower than 3 m: Yearling Chinook--Spillway: 8%, Powerhouse: 22%; Subyearling Chinook--Spillway: 15%, Powerhouse: 10%. All were deeper at night. Detection at the dams is likely not accurate for assessing in-river migrant depths.

Author	Publisher	Title	Date ✔ =have copy	Summary
Dawley, Blahm, Snyder, Ebel	NOAA under contract with BPA	Studies on effects of supersaturation of dissolved gasses on fish	1975 ✔	***Purpose***: Multiple aspects of TDG were investigated including detection or avoidance of TDG, effects of intermittent exposure of eight species of fish, predator response, bioassays to determine effect of depth on survival, and physiological effects of TDG and of oxygen/nitrogen ratio. ***Results***: Juvenile fall Chinook avoided TDG at 130% and thus may have detected TDG in some way but they did not avoid mortality. Steelhead showed no detection or avoidance behavior at 130% TDG. There was a wide variety of individual behavior. Juvenile steelhead preferred shallower water when there was turbidity present. Time to 50% mortality at 120% TDG shallow water tank at 10-13°C: rainbow trout 6 days, coho 2.5 days, whitefish 3-4 days, steelhead 3 days. Whitefish mortalities did not improve with exposure to unsupersaturated water. Deepwater cages were used to expose seven species of fish 2.5 m deep to ambient river TDG levels: Cutthroat trout took 49 days for 27% to die at average of 124% TDG; juvenile Chinook took 55 days for 11% mortality at gas levels between 112-129%, average was 120%; smelt took 12 days for 40% to die exposed between 119-122% TDG; no crappie nor pikeminnow deaths were recorded with gas levels between 117-123%; suckers experienced 2% mortality held for 46 days between 115-124% - average 120% TDG. Survival was better in the deeper tanks than in 1 m deep tanks. Pikeminnows reduced fish consumption as TDG levels increased in a 0.25m tank in 10-13°C water; from 100% TDG 14.3 grams of food a day (gfd), 107%TDG 11.2 gfd, 110%TDG 10.9 gfd, 117%TDG 6.2 gfd, and 120%TDG 2.3 gfd. 46% of net captured juvenile Chinook and 29% of steelhead trout were found migrating in the upper 1.8 m of water in the Monumental Dam reservoir on the Snake River. This proportion increased at night for Chinook and decreased for steelhead; no depth preferences were discovered for effects of changes in turbidity, temperature and solar illumination at the time. Juvenile Chinook reduced swimming distance when exposed to TDG concentrations >106%, although steelhead swam the same distance. Changes in blood plasma chemistry at 110% TDG were found in steelhead smolts.

Author	Publisher	Title	Date ✔ =have copy	Summary
Dawley, E., Ebel	Fisheries Bulletin 73(4): 787-796	Effects of various concentrations of dissolved atmospheric gas on juvenile Chinook salmon and steelhead trout	1975 ✔	***Purpose***: Assess TDG effects on juvenile yearling hatchery spring Chinook and juvenile hatchery steelhead in 0.25m deep water at 15°C. ***Results***: 10% mortality of steelhead at 111% TDG after 11 days; 10% mortality at 116% TDG after 1 day. At 106% TDG after 35 days, growth and swimming performance affected. Steelhead less tolerant than the juvenile spring Chinook.
Dawley, E., Schwiewe, Monk	Pg 1-10 in Gas bubble disease, D.H. Fickeisen and JJ Schneider (editors) Conf 741033. Technical information Center, Oak Ridge, TN	Effects on long-term exposure to supersaturation of dissolved atmospheric gases on juvenile Chinook salmon and steelhead trout in deep and shallow test tanks	1976 ✔	***Purpose***: Assess the different responses to TDG of hatchery fall Chinook and year-old steelhead held in shallow and deep water. ***Results***: Juvenile fall Chinook more tolerant than 1-year-old steelhead. 10 inches deep: 120% TDG -- 50% mortality in Chinook fry: 22 days. 50% mortality in 1 year-old+ river caught juvenile steelhead: 30 hours.
Doulos, Kindschi	Aquatic Fish Management 21:39-46	Effects of oxygen supersaturation on the culture of cutthroat trout and rainbow trout	1990	Report unavailable
Dunnigan	Montana Fish, Wildlife and Parks, Helena, MT 30p	Kootenai River fisheries monitoring results from the spill events at Libby Dam, June-July 2002	2002	Report unavailable
Ebel, Bennington, Bouck, Penrose Weitkamp. Edited by Thurston, Russo et al	American Fisheries Society pp 113-118	Gases, total dissolved. A review of the EPA Redbook: quality criteria for water.	1979 ✔	***Purpose***: Assess the adequacy of EPA's 110% TDG criterion. ***Results***: Two separate criteria are needed: one for open natural waters and one for receiving waters for hatcheries. A duration of exposure is also needed. Criteria proposed: where fish are restricted to less than 0.6 m deep, <105%. For freshwater and marine environments: 3/5 of scientists recommended <115% and 2/5 recommended<110% TDG.

Author	Publisher	Title	Date ✔ =have copy	Summary
Ebel, Dawley, Monk	Fisheries Bulletin 69:833-843	Thermal tolerance of juvenile Pacific salmon and steelhead trout in relation to supersaturation of nitrogen gas	1971 ✔	***Purpose***: Understand the TDG affect on temperature tolerance of juvenile hatchery and wild Chinook salmon, hatchery juvenile coho, and hatchery steelhead at increased TDG. ***Results***: Increased temperatures reduce tolerance of hatchery steelhead, coho, spring Chinook to TDG. Coho most resistant, followed by Chinook, then steelhead.
Ebel, Raymond, Monan, Farr, Tanonaka	NOAA Fisheries, Seattle, WA, Northwest Fisheries Center Report Bulletin Vol 68 No 1	Effects of supersaturation of nitrogen in the Columbia River and its effect on salmon and steelhead trout	1975 ✔	***Purpose***: Evaluate effects of TDG on juvenile and adult salmon and steelhead trout through review of lab and field studies. ***Results***: Recommended remedial actions.
Ecology, WA Dept and OR DEQ	Publication No 02-03-004	Total maximum daily load for the lower Columbia River total dissolved gas	2002 ✔	***Purpose***: Set TDG load allocations for the four dams on the lower Columbia River in order to meet numeric TDG water quality standards criteria. ***Results***: Short-term compliance points were set at the fixed monitors in the tailraces below each dam. Long-term compliance points were set at: 1700 feet below Bonneville. 60 feet' below The Dalles. 1700 feet below John Day. 1000 feet below McNary. Flood flow levels were set above which water quality standards do not apply (7Q10).
Ecology, WA Dept	Publication No 03-03-020	Total maximum daily load for the Snake River total dissolved gas	2003 ✔	***Purpose***: Set TDG load allocations for the four dams on the lower Snake River in order to meet numeric TDG water quality standards criteria. ***Results***: Short-term compliance points were set at the fixed monitors in the tailraces below each dam and in the forebays. Long-term compliance points were set at: 1300 feet below Ice harbor. 120 feet' below Lower Monumental. 1500 feet below Little Goose. 150 feet' below Lower Granite. Flood flow levels were set above which water quality standards do not apply (7Q10).

Author	Publisher	Title	Date ✔ =have copy	Summary
Ecology, WA Dept	Publication No 04-03-002	Total maximum daily load for the Mid-Columbia River total dissolved gas	2004 ✔	***Purpose***: Set TDG load allocations for the seven dams on the mid-Columbia River in order to meet numeric TDG water quality standards criteria. ***Results***: Short-term compliance points were set at the fixed monitors in the tailraces below each dam and in the forebays of the lower five dams. Long-term compliance points were set at: 1500 feet below Priest Rapids. 2000 feet below Wanupum. 200 feet‘ below Rock Island. 1600 feet below Rocky Reach. 2000 feet below Welles. 200 feet‘ below Chief Joseph. End of spillway below Grand Coulee. Flood flow levels were set above which water quality standards do not apply (7Q10).
Edsall, Smith	Aquaculture 90:251-259	Performance of rainbow trout and Snake River cutthroat trout reared in oxygen-saturated water	1990	Report unavailable
Elston	Final report to Confederated Tribes of the Colville Reservation and Columbia River Fish Farms	Fish kills in resident fish caused by spill at Grand Coulee Dam in 1997	1998	Report unavailable
Elston	Journal of Fish Diseases 6:101-110	Histopathology of oxygen intoxication in the juvenile red abalone, Haliotis rufescens Swainson	1983 ✔	***Purpose***: Learn about the effects of supersaturated oxygen between 152 and 203% on red abalone held in shallow saltwater containers at 22-23°C and removed at intervals for 48 hours. ***Results***: After 3 hours, loss of red pigmentation, swelling and behavioral changes after 12 hours, variation observed. Enlargement of cellular vacuales, separation of nerve sheaths, oxygen bubbles in vascular spaces.

Author	Publisher	Title	Date ✔ =have copy	Summary
Elston, Rensel	Aquatechnics, Carlsborg, WA and Rensel Associates, Arlington, WA Unpublished?	Fish mortality and losses from gas supersaturated Columbia River water at Columbia River Fish Farms	1996 ✔	***Purpose***: Document salmonid mortality in net pens from TDG coming from Grand Coulee Dam and above. ***Results***: External bubbles were found in 95% of the rainbow trout mortalities when two fish kills occurred. During this time levels of TDG at the net pens in mid to late April were measures at 120% and greater.
Elston, Colt, Frelier, Mayberry, Maslen	Journal of Aquatic Animal Health 9:258-264	Differential diagnosis of gas emboli in the gills of steelhead and other salmonid fishes	1997 ✔	***Purpose***: Evaluate the disappearance of gas emboli in out-migrating hatchery juvenile steelhead and spring Chinook gills when the fish were killed and removed from water after being exposed to 123% TDG. ***Results***: Gill air bubbles dissipate quickly. Observations miscounted lipid structures as air bubbles in 47% of the observations.
Elston, Colt, Abernathy, Maslen	Journal of Aquatic Animal Health Vol 9 317-321. BNo 4	Gas bubble reabsorbtion in Chinook salmon: pressurization effects	1997 ✔	***Purpose***: Expose juvenile hatchery spring Chinook to 123% TDG for 16-20 hours then increase pressure to equivalent of 90 m of depth for 5, 30, 60 and 120 minutes to see if gas bubble reabsorption occurred. ***Results***: 50% bubble reabsorption in fins occurred between 5 and 30 minutes; for lateral line in less than 5 minutes; and in gills less than 5 minutes.
EPA Goldbook	EPA Goldbook	Gas, total dissolved	197? ✔	Review of literature and recommended 110% TDG as the national water quality criteria. Most of the studies reviewed were on the on northwest Snake and Columbia River salmonids.
Feathers, Knable	California Polytechnic State University, San Louis Opispo, CA. North American Journal of Fisheries Management 3:86-90	Effects of depressurization upon largemouth bass	1983 ✔	***Purpose***: Observe effect of depressurization on adult largemouth bass. ***Results***: Largemouth bass experienced mortalities upon being brought to surface pressures from 18 m due to expansion of swim bladder and respiratory failure.

Author	Publisher	Title	Date ✔ =have copy	Summary
Feil, Rondorf	USGS, Cook, WA for USACE, Portland, OR Project Code DGAS-97(2)-1, Contract Nos E96960051 and E96970052 Online: http://www.nwp.usace.army.mil/PM/E/reports/afep/misc/FinalGasReport.pdf	Evaluation of horizontal and vertical distribution of juvenile salmonid in the Snake and Columbia Rivers in relation to total dissolved gas.	2000	***Purpose***: Detect depth distribution in the upper four m of the water column on four reaches of McNary Reservoir, Columbia River by remotely observing juvenile salmonid preferred depths from June 19 – July 26, 1996 (TDG levels between 113-124%) and May 1997 (TDG levels between 112 and 129%). Chapter 1. Test and improve accuracy of hydroacoustic surveys for accuracy in detecting juvenile salmon. Chapters 2 and 3. Determine the distribution of subyearling Chinook salmon. ***Results:*** Chapter 1. Detection rates fell as wind speed increased. At low wind speeds (0-5 mph) detection rates were between 96-99% but dropped to less than 55% when wind speed became greater than 15 mph. Chapters 2 and 3. In 1996 (Ch. 2), day and night fish density was more than 3 times greater upstream of the Walla Walla River than in the reaches downstream and concentrated in the center of the river. More fish were less than 2 m deep during the day than during the night in the lower reaches of the reservoir, but in the upper reservoir (above Walla Walla River) vertical distribution was evenly divided between day and night fewer fish were detected in water less than 2 m deep. In 1997, seasonal trends occurred during mid-May when there was a shift to shallower depths in 2 of the 3 sampling sites of between 7 and 8 m for two weeks in May. TDG varied between the day and nighttime spill—as much as 12%. Highest density of smolts was near the shorelines both day and night. Fish were more abundant above the compensation depth in the daytime than the night. Fish were detected higher in the water column in the middle of the river than the shoreline. The hypothesis was that smolting fish (as measured by levels of ATPase) swam in the middle of the river and higher in the water column.
Ferguson, Absolon, Carlson, Sandford	Transactions of the American Fisheries Society	Evidence of delayed mortality on juvenile pacific salmon passing through turbines at the Columbia River Dams	2005 ✔	***Purpose***: Investigate what effects turbine design and efficiency have on fish passage. ***Results***: 46-70% of turbine mortalities were delayed mortalities—mostly from predation due to sensory impacts of passing through turbines.

Author	Publisher	Title	Date ✔ =have copy	Summary
Fickestein, Montgomery, Schneider	American Fisheries Society 103rd annual meeting. Orlando, FL. Unpublished MS	Tolerance of selected fish species to atmospheric gas supersaturation	1973 ✔	***Purpose***: Examine bluegill, pumpkinseed, carp, channel catfish, black bullhead, rainbow trout, yolk sac fry rainbow trout (from hatchery), smallmouth bass, mountain whitefish, and largescale sucker collected by beach seine in streams and ponds near the Hanford Reservation exposed to TDG supersaturation at 20° C in .3 m deep water. ***Results***: Whitefish least tolerant, smallmouth bass most. Bluegill and pumpkinseed had similar tolerances as did channel catfish and black bullhead, as did 4-month and 22-month rainbow trout. Yolk sac fry rainbow trout developed lethal bubbles in the yolk sac at 113.7%.
Fickeisen, Schneider, editors	Batelle, Pacific Northwest Laboratories, US Atomic Energy Commission, conf-741033. US Energy research and Dev Admin, Tech Info Center, Oak Ridge, TN	Gas bubble disease: proceedings from a workshop in Richland, WA	1974 ✔	Numerous articles reviewed under individual authors in this document
Fickeisen, Montgomery	Battelle, PNW Laboratories, Richland, WA	Dissolved gas supersaturation: bioassays of Kootenay River organisms	1975	***Purpose***: Test resident species' susceptibility to GBD. ***Results***: Mountain whitefish were the most intolerant of all species tested. Other species tested in decreasing order of susceptibility were cutthroat trout, largescale sucker, and torrent sculpin.

Author	Publisher	Title	Date ✔ =have copy	Summary
Fickeisen, Montgomery	Transactions of the American Fisheries Society, 107(2): 376-381	Tolerances of fishes to dissolved gas supersaturation in deep tank bioassays	1978 ✔	***Purpose***: Test tolerance of mountain whitefish, cutthroat trout, largescale sucker, and torrent sculpin to exposure for 10 days to 10° C water at various depths to 3.2 m in 132% (± 3%) TDG. ***Results***: TDG results were reported as depth compensation exposures, so though water was held at 132% saturation, 3.2 m deep was reported as 100% TDG, 1.38 m as 116% TDG, and 120% TDG as 1 m deep. At 1.38 m (equivalent of 116% TDG), all mountain whitefish were dead after 96 hours and after 50 hours at 1 m deep (120% TDG). Nine of 10 cutthroat trout were dead at 1.38 m (116%) in 10 days and all cutthroat and suckers were dead after 34 hours at 1 m deep (120%). 90% suckers survived at 1.38 m (116%). Torrent sculpin did not die after exposure to 116 and 120% TDG equivalents but lost equilibrium at 120% TDG equivalent after 233 hours that caused them to float into the water column and struggle against this when bubbles as large as ¼ their body size formed.
Fickeisen, Montgomery, Hanf	Battelle, Pacific Northwest Laboratories, US Atomic Energy Commission, conf-741033. US Energy research and Dev Admin, Tech Info Center, Oak Ridge, TN pp72-74	Effect of temperature on tolerance to dissolved gas supersaturation of black bullhead.	1976 ✔	***Purpose***: Test black bullhead response when exposed to TDG and temperature in shallow water 0.35m deep. ***Results***: Death was manifested as massive bubble blockages in the heart. Time to 50% mortality in four days decreased with warmer water. In 8°C: 127%; 12°C: 125%; 16°C: 124%; and 20°C 123%.
Fidler	Aspen Applied Sciences for Battelle, Richland, WA	A survey of noninvasive technologies applicable to the examination of fish for signs of gas bubble disease	1996	Report unavailable

Author	Publisher	Title	Date ✔ =have copy	Summary
Fidler, L.E.	Penny Applied Sciences. Report to Dept of Fisheries and Oceans, BC	A study of biophysical phenomena associated with gas bubble trauma in fishes	1984	Report unavailable
Fidler	Doctoral dissertation, Dept of Zoology, University of British Columbia	Gas bubble trauma in fish	1988	Report unavailable
Fidler, L.	Prepared for Montgomery Watson. Report to BPA project No 93-08. Portland, OR Contract No DE-AC79-93BP66208 Portland OR	Allowable gas saturation for fish passing hydroelectric dams.	1996	Report unavailable

Author	Publisher	Title	Date ✔ =have copy	Summary
Fidler, Miller	Contract report to BC Ministry of Environment, Environment Canada and Dept of Fisheries and Oceans by Aspen Applied Sciences	British Columbia Water Quality guidelines for dissolved gas supersaturation-technical report	1997 ✔	***Purpose***: Not a study but a review of literature on TDG effects on salmon and trout, other fish species, invertebrates, amphibians, and plants and algae to develop water quality TDG guidelines for BC, Canada. ***Results***: Arrived at province-wide guidelines: 110% and 103% for waters shallower than 1 meter and stream edges. Salmon and cutthroat trout: review included many Columbia River studies. Evaluated Jensen's model (1986) for which the 110% (75mmhg) USA guideline was partially based. Sockeye >50 mm 116% first deaths. Cutthroat trout 115% first deaths. Swim bladder over-inflation is the first symptom, beginning at 70 mmhg in rainbow trout less than 20 cm. Larger fish did not have this symptom (Shrimpton). Small fish swim deeper to regain neutral buoyancy up to 90 mmhg (~113% TDG), above this, they do not. Invertebrates: 111% lethal threshold insects (Nebeker et al) and crayfish 120-127%. Came to the conclusion that fresh water invertebrates can be as sensitive to TDG as fresh water fish. Amphibians: Three studies but no data about time to mortality. At 128 mmhg ~117%TDG, adult bullfrogs had extensive blistering on skin and in vascular system. Plants: 110% theorized as appropriate for aquatic plants, especially plankton because bubble formation occurs at this level and can float the plants to the surface. No studies exist on this though. Habitat and habitat use important when applying TDG guidelines because of potential for depth compensation. Some species may use shallow water habitat for feeding, spawning, rearing. If fish were to swim deeper to avoid TDG or maintain a neutral buoyancy, prime habitat would be lost to them and they may be placed at risk for predation and have less forage. Percent oxygen to nitrogen affects fish reactions to TDG. Recognized a need for more information for other fish species like sturgeon and for research on fish behavior in relation to TDG exposure. Recognized a need for site-specific evaluation of habitat use for each water body in question. Recognized a lack of information on species other than trout and salmon; however, felt comfortable that present data show that the other aquatic species researched showed no more sensitivity than the most sensitive species of salmonids. Good background and references to studies.

Author	Publisher	Title	Date ✔ =have copy	Summary
Fidler, L., Miller	Aspen Applied Sciences, draft	Biological effects of total gas pressure on fish and aquatic biota and outstanding research needs	1999 draft ✔	Short review of literature of biological effects of TDG on anadromous and resident fish species and identify research needs. Came to the conclusion that biological monitoring needs to show a better correlation between internal and external trauma signs. Non-steady state (non-lab) information is needed to show spatial and temporal movements; cumulative and chronic effects need more study; quantify acute, chronic, and indirect effects on resident species; better understand effects of TDG on overall ecology of aquatic communities including plants and invertebrates.
Fish Passage Center	Unpublished report	2007 Gas bubble trauma monitoring and data reporting for 2007	2007 ✔	Update on 2007 spill season and gas. Sampling two days/week for spring and fall Chinook and steelhead on the Columbia and one day/wk on the Snake Rivers. Gas bubble signs were ranked from zero (no bubbles present) to four (>50% of unpaired fins with presence of bubbles). For the first time in the over ten-year monitoring program late migrating steelhead displayed bubbles in the Snake River when TDG levels were below 110%.
Fish Passage Center	Web Query Site: http://www.fpc.org/smolt/gbtqueries/GBTwebsum_query.html	Gas bubble monitoring data for 1996 to 2006	2007	Data from the biological salmon smolt monitoring stations on the Columbia River system. Can query database for year, species, and location.
Fish Passage Center	http://www.fpc.org/documents/misc_reports/1999_ODEQ_annualreport.pdf	1999 Annual report to the Department of Environmental Quality: physical and biological monitoring of TDG in the lower Columbia River	1999 ✔	Update on 1999 spill season and gas. GBD monitoring, physical monitoring, comparison with fish spill and spill due to lack of load and flows higher than capacity. Shows more spill occurs due to lack of load and hydraulic capacity.
Fish Passage Center	http://www.fpc.org/documents/misc_reports/2000_ODEQ_annualreport.pdf	2000 annual report to the Department of Environmental Quality: physical and biological monitoring of TDG in the lower Columbia River	2000 ✔	Update on 2000 spill season and gas. GBD monitoring, physical monitoring, comparison with fish spill and spill due to lack of load and flows higher than capacity. Shows more spill occurs due to lack of load and hydraulic capacity.

Author	Publisher	Title	Date ✔ =have copy	Summary
Fish Passage Center	Fish Passage Center, BPA	2002 annual report to the Department of Environmental Quality: physical and biological monitoring of TDG in the lower Columbia River	2002	Report unavailable
Fish Passage Center	http://www.fpc.org/documents/misc_reports/PresentationDEQ_files/frame.htm	Spill and GBD meeting with ODEQ	2006 ✔	Gives spill and TDG data from 2001 to 2006 to promote a river-wide criterion of 120% TDG in the mixed river. Advocates removal of the 115% forebay criterion and monitors because of localized effects from temperature, barometric pressure, and biological processes.
Frizell	Bureau of Reclamation	Dissolved gas supersaturation study for Grand Coulee Dam	1996	Report unavailable
Gale, W., Maule, Postera, Peters	River Research and Applications 20:565-576	Acute exposure to gas-supersaturated water does not affect reproductive success of female adult Chinook salmon late in maturation.	2004 ✔	***Purpose***: Temporarily expose mature adult female hatchery Chinook held at 0.5m deep to TDG levels at 115, 120, 125 and 130% to see subsequent affects on reproductive success beginning five days later. ***Results***: No effect on average egg weight, diameter, egg mortality, or gonodosomatic index. Chinook Salmon exposed to 114 to 125.5% TDG for 10-68 hours. Within 10-68 hours were removed, ending their exposure when they showed signs of moribundity. The symptoms included death 118.8% in 10 hours, rapid erratic swimming, jumping and inability to remain upright. At 114.1%, the first mortalities did not occur until 46 hours. No elevated disease as a result of exposure was found in spawning females.

Author	Publisher	Title	Date ✔ =have copy	Summary
Geist, Hanrahan, Arntzen	N Am Journal of Fisheries Management 22:1077-1085	Physiochemical characteristics of the hyporheic zone affect redd site selection by Chum salmon and fall Chinook salmon in the Columbia River	2002 ✔	***Purpose***: Understand the depth preferences and redd site selection for spawning chum and Fall Chinook below Bonneville Dam. ***Results***: Flow and water temperature were significantly different between the two sites. At the sites chosen by chum, flow was slower and temperature higher (due to upwelling); the sites chosen by fall Chinook had faster flows and down-welling colder water into the gravel. ***Note*:** This study was reviewed because these shallow-water spawning, incubating, hatching species can be sensitive and susceptible to levels of TDG above 103%.
Gorham, Marsh	Report of the US Bureau of Fisheries 1904	The gas disease in fishes	1905	First large-scale investigation into GBD for a variety of aquatic life.
Grassell, Hampton, McDonald	Fish and Wildlife Operations, Power Operations Dept, Public Utility District 1 of Chelan County, Wenatchee, WA	Gas bubble trauma monitoring at Rocky Reach and Rock Island Dams 2000	2000 ✔	***Purpose:*** Determine if juvenile spring and fall Chinook and steelhead show signs of GBD and determine if Rocky Reach Dam operations cause GBD. ***Results***: 1.74% higher incidence of GBD was found at Rock Island, the lower dam, a 50% increase in GBD. Bubbles in unpaired fins and lateral lines were seen for all species (3.47% of total fish examined) and no eye occlusion were seen. 6.4% of spring Chinook had GBD, 2.1% of fall Chinook, and 1.5% of steelhead. *Note*: TDG levels were not reported although this information exists elsewhere.
Gray, Haynes	Transactions of the American Fisheries Society 106(vol. 6):617-620	Depth distribution of adult Chinook salmon in relation to season and gas supersaturated water	1977 ✔	***Purpose***: Find out the depth preference of radio-tagged adult spring Chinook tracked from April – June (higher TDG) and fall Chinook tracked during September to mid October (100% TDG). ***Results***: Spring Chinook swam deeper during the high gas (124-127%) and high flow periods than during lower gas/lower flow periods and deeper than migrating adult fall Chinook.

Author	Publisher	Title	Date ✔ =have copy	Summary
Gray, Page, Saroglia, Bronzi	The Fisheries Society of the British Isles. 20:223-227	Comparative tolerance to gas supersaturated water of carp and blackhead bullhead from the USA and Italy	1982 ✔	***Purpose***: Evaluate the tolerance of juvenile carp and juvenile black bullhead held in 0.3 m of water to exposure to TDG at 8°C. ***Results***: Carp mortalities began above 114.1% TDG at 96 hours. Black bullhead mortalities began above 107% TDG after 96 hours of exposure. There was ±4-8% uncertainty in the TDG measurements. In Italy for black bullhead, mortalities began at 107.2% TDG at 8°C and in the Columbia at 127% at 8°C (Fickeisen 1975) in water 0.35 m deep. For carp, no mortalities were observed after 96 hours exposure to 135% TDG—the depth was the same as the Italian study but the temperature was 20°C (Fickeisen 1973).
Gray, Page, Saroglia	Environmental Biology Fish. 8:163-167	Behavioral response of carp and black bullhead to gas supersaturated water	1983	Report unavailable
Gray, Page, Saroglia, Fest	Environmental Pollution Series A. 30:125-133	Tolerance of carp and black bullhead to gas supersaturated water under lotic and lentic conditions	1983	Report unavailable
Hagen, J. Weitcamp, D.E. Weitcamp	Unpublished report Parametrix to Grant County PUD 18p + appendices	Biological monitoring for incidence of gas bubble disease at Priest Rapids Dam 1997	1998 ✔	***Purpose***: Learn about external signs of GBD occurrence in juvenile Chinook, sockeye, and steelhead exposed to TDG in the Columbia River and sampled at the gatewells across the powerhouse at Priest Rapids Dam. First of three years of study reports. ***Results***: During May and June, 11% gas bubble signs were found when TDG was higher than 120%. In July and August 2.3% signs were found when TDG averaged 116%. Incidence varied by species. Chinook examined exhibited more bubbles (8.7%), then steelhead (9.4%), and then 21.5% sockeye.

<table>
<tr><th>Author</th><th>Publisher</th><th>Title</th><th>Date
✔ =have copy</th><th>Summary</th></tr>
<tr><td>Hagen, J. Weitcamp, D.E. Weitcamp</td><td>Unpublished report Parametrix to Grant County PUD 18p + appendices</td><td>Biological monitoring for incidence of gas bubble disease at Priest Rapids Dam 1998</td><td>1999
✔</td><td>Purpose: Learn about external signs of GBD occurrence in juvenile Chinook, sockeye, and steelhead exposed to TDG in the Columbia River and sampled at the gatewells across the powerhouse at Priest Rapids Dam. Second of three years of study reports.
Results: 3.8% of the spring juvenile migrants (exposed at an average of 116% TDG between Wanupum forebay and Priest Rapid forebay) and 4.7% of the summer juvenile migrants (exposed between 107-117% TDG between Wanupum forebay and Priest Rapid forebay) exhibited external GBD signs; these were almost all summer juvenile Chinook.. A small sampling of juvenile coho in the spring indicated that they showed more signs (9.1%), then Chinook (4.9%), then steelhead (3.2%) and finally sockeye (1.5%).</td></tr>
<tr><td>Hagen, J. Weitcamp, D.E. Weitcamp</td><td>Unpublished report Parametrix to Grant County PUD 18p + appendices</td><td>Biological monitoring for incidence of gas bubble disease at Priest Rapids Dam 1999</td><td>2000
✔</td><td>Purpose: Learn about external signs of GBD occurrence in juvenile Chinook, sockeye, and steelhead exposed to TDG in the Columbia River and sampled at the gatewells across the powerhouse at Priest Rapids Dam. Third of three years of study reports.
Results: 3.6% of juvenile salmon in the spring and 2.7% during the summer showed external bubble signs. Spring TDG averaged 114% (range 106-122%) and summer 113%. Spring bubble signs - Chinook 4%, sockeye 2.5%, steelhead 3.1%, and coho 4.6%. Summer bubble signs – Chinook 1.6%, coho 50%.

GBD at Priest Rapids Dam and seasonal TDG averages 1996-1999
<table>
<tr><th>Season</th><th>Year</th><th>%GBD</th><th>%TDG</th></tr>
<tr><td>Spring</td><td>1999</td><td>3.6</td><td>114</td></tr>
<tr><td></td><td>1998</td><td>3.8</td><td>116</td></tr>
<tr><td></td><td>1997</td><td>11.1</td><td>130</td></tr>
<tr><td></td><td>1996</td><td>8.5</td><td>124</td></tr>
<tr><td>Summer</td><td>1999</td><td>1.7</td><td>113</td></tr>
<tr><td></td><td>1998</td><td>4.7</td><td>113</td></tr>
<tr><td></td><td>1997</td><td>2.3</td><td>116</td></tr>
<tr><td></td><td>1996</td><td>1.8</td><td>117</td></tr>
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Author	Publisher	Title	Date ✔ =have copy	Summary
Hans, K., Mesa, Maule	Journal of Aquatic Animal Health 11:383-390	Rate of disappearance of gas bubble trauma signs in juvenile salmonids	1999 ✔	***Purpose***: Evaluate rate of disappearance of gas bubbles in gill filaments, lateral line, fins, eyes, and opercula of yearling hatchery spring Chinook and juvenile steelhead after being held in 0.28 m of water at 12°C and 120 and 130% TDG long enough to kill 20%-50% of the fish (and removing them) and then having TDG reduced to 104% within one hour in the same tank. ***Results***: After being returned to 104% saturated water, gas bubbles disappeared in gills within an hour. Gas bubbles disappeared externally more slowly, steelhead still had 50% prevalence of bubbles after four days. Lethargic behavior ended within 30 minutes.
Hans, Maule Filed under Maule : Gas Bubble trauma Monitoring and research of juvenile salmonids. 1995 Annual report	USGS, Columbia River Research Laboratory, Cook, WA	Gas Bubble trauma Monitoring and research of juvenile salmonids. 1995 annual report Gas bubble trauma signs in juvenile salmonids at dams on the Snake and Columbia Rivers	1997 ✔	***Purpose***: Determine the proportions of juvenile salmon that had external lateral and fin bubbles at Lower Granite, Little Goose and Lower Monumental, McNary, John Day and Bonneville dams in 1994 within 15 minutes to one hour after capture. ***Results***: Snake River fish never had more than 10% with bubble signs, usually less than 5%, the average 0.3-0.7%. The Columbia River fish had more bubbles than Snake River fish, exceeded 10% several times, mostly for steelhead. No correlation between fin and lateral line bubble formation but more prevalent in fins. 3.7% of the fish examined in the lower Columbia had signs of bubbles. Fish spill was occurring at the time of the study and gas levels ranged from below to above 120% TDG.
Harvey, Barnes, McElroy, Whitely, Pease, Cooper	Journal of Cellular and Comparative Physiology 24:1-22	Bubble formation in animals I. physical factors	1944	Report unavailable
Hauck	Transactions of the American Fisheries Society 115:630-635	Gas bubble disease due to helicopter transport of young pink salmon	1986 ✔	***Purpose:*** Analyze the effects of rapidly reduced barometric pressure on juvenile pink salmon. ***Results***: Reduced pressure increased TDG saturation to from 99.9% to 109.4% (ΔP 5mm Hg). Swelling behind the head and bubbles were observed in 95% of fish recaptured after 21 hours. Tissue changes were found in fish preserved immediately on decompression (after the flight).

Author	Publisher	Title	Date ✔ =have copy	Summary
Hemmingsen	Cell Biophysics 8:189-199	Promotion of gas bubble formation by ingested nuclei in the ciliate, Tetrahymena pyriformis	1986 ✔	***Purpose:*** Understand what causes the formation of bubbles in the food vacuoles of Tetrahymena pyriformis, the only cellular structure known, at the time, to form bubbles within the cell, even at high nitrogen levels. ***Results:*** Cells are extremely resistant to formation of nitrogen gas bubbles. The presence of graphite and carmine particles formed bubbles at 10 atm but when ingested, these compounds did not form bubbles within the cells. Ingested air bubbles in the food vacuoles though, did serve to form bubbles within the cells at high pressures. Bubbles in cells disappeared after recompression. Cell rupture occurred above 25 atm. Without air bubble introduction into the cell vacuaoles, no formation of bubbles occurred below 150 atm.
Hemmingsen, B.B., Steinberg, E.A. Hemmingsen	Biophysics Journal 47:491-496	Intracellular gas supersaturation tolerances of erythocytes and research ghosts	1985 ✔	***Purpose***: Understand the formation of bubbles in human, chicken, and toad whole and skeletal red blood cells when exposed to high nitrogen gas supersaturated in water. ***Results***: Though chicken and toad cells were less resistant to gas bubble formation within the cells, all cells tested had extremely high resistance to internal gas bubble formation, much more than ambient water conditions—up to 300 atmospheres of nitrogen. ***Note***: This finding is consistent with gas bubble disease symptoms in aquatic organisms: gas bubble signs appear outside the cellular structures.
Hildebrand	Contract report by R.L. and L. Environmental Services Ltd to BC Hydro, Environmental Resources, Vancouver BC	Lower Columbia River fisheries inventory-1990 studies. Vol 1 Main Report	1991	Report unavailable
Hnath, Westers, Ketola	No source sited	The effects of nitrogen gas supersaturation on the development of eye lesions in coho salmon, and possible mediating effects of a test diet	1986	Report unavailable

Author	Publisher	Title	Date ✔ =have copy	Summary
Jensen, E	Aquaculture 68(2): 131-139	Combined effects of gas supersaturation and dissolved oxygen levels on steelhead (Salmo gardineri) eggs, larvae and fry	1988 ✔	***Purpose***: Find out the effects of exposure of rainbow trout eggs, larvae, and fry held in 10°C water 0.25 m deep up to 72 days from 100 to 110% TDG with oxygen (O) levels varying between 48 and 97% and nitrogen (N) levels varying between 103 and 127%. ***Results***: Hatching rates were unaffected by TDG or TDG mixtures. Egg weight (embryo/yolk ratio) was reduced about 6% at 97% O and up to 8% at 49% O but seemed unaffected by N saturation concentrations. 1.4% opercular deformities 3 days after hatching at 110% TDG.
Jensen, E., Schnute, Alderdice	Canadian Journal of Fisheries and Aquatic Science 43(9):1694-1709	Assessing juvenile salmonids response to gas supersaturation using a general multivariate doe-response model	1986 ✔	***Purpose***: Compile existing literature to build a model to assess effects of TDG on juvenile Chinook, coho, sockeye and steelhead using 50% lethal exposure time. ***Results***: The author was reluctant to commit to a recommended level but stated that safe levels of TDG range from 103% to 114.8% depending on water depth and fish size. The model included temperature, oxygen to nitrogen ratio, fish length, depth, and time to 50% death.
Jensen, E	Proceeds from the Fish Culturists Conference, Courtenay, BC Canada pp 15-22	Effect of TGP and total water hardness in steelhead eggs and alevins	1980	Report unavailable
Jensen, E	Canadian Data Report, Fisheries Aquatic Sciences 501	Literature data on salmonid response to gas supersaturation and ancillary factors	1985	Report unavailable
Johnson, P.T.	J Invertebrate Pathology 27, 247-253	Gas bubble disease in the blue crab	1976 ✔	***Purpose***: Through dissection, study gas bubble trauma in intermolt juvenile blue crabs by taking advantage of an unplanned TDG supersaturation event in a crab holding tank that killed 1/3 of the crabs and returning survivors to normal saturation levels with slowly varying temperatures from 6-18°C. ***Results*:** Bubbles were still present in the gills 35 days after being retuned to ambient saturation water. Gills, heart and antennal glands were the most affected. Gas levels were never measured.

Author	Publisher	Title	Date ✔ =have copy	Summary
Johnson, Hawkes, Smith, Fredricks	Annual Report NOAA NW Div. for BPA, Portland. Project 84-14	Monitoring of downstream salmon and steelhead at federal hydroelectric facilities	1988 ✔	***Purpose***: As part of the continuing smolt monitoring on the Columbia and Snake, assess gatewell collection system captured salmon smolts at Lower Granite, McNary John Day and Bonneville Dams during outmigration seasons. ***Results***: Found no relevance to TDG except to show numbers of juvenile anadromous salmon (and a few other fish like smelt and shad) for which there are continuous reports and information available into 2007.
Johnson, E,L.; Clabough, Peery, Bennett, Bjorn, Caudill, Richmond	River Research and Applications, 23:963-978, Wiley InterScience	Estimating adult Chinook salmon exposure to dissolved gas supersaturation downstream of hydroelectric dams using telemetry and hydrodynamic models	2007 ✔	***Purpose:*** Understand vertical depth and lateral migration path preferences of upstream migrating tagged adult spring and summer Chinook salmon in relation to predicted TDG five miles below Bonneville Dam and 9.5 miles below Ice Harbor Dam. ***Results:*** Salmon usually migrated close to shore where the predicted TDG levels were less than in the middle of the river. They occasionally crossed from one side to the other but mostly stayed along one shoreline. However, this behavior was not found to be caused by detection and avoidance of TDG. Based on the MASS2 model TDG predictions, below Bonneville, salmon were in shallow enough water to be potentially affected by TDG (mostly below 115% in the river during the study) 4% of the time. Below Ice Harbor Dam, the fish were exposed 12% of the time, likely due to the shallower nature of this part of the river. It would be useful to have exposure times and differences in depth between individuals to be reported in more detail; however, information about this can be found in other studies.

Author	Publisher	Title	Date ✔ =have copy	Summary
Johnson, E., Clabough, Bennett, Bjornn, Peery, Caudill	Transactions of the American Fisheries Society 134:1213-1227 and Idaho Cooperative Fish and Wildlife Research Unit Tech Report 2005 for the Corps of Engineers, Walla Walla and Portland Districts	Migration depths of adult spring and summer Chinook salmon in the lower Columbia and Snake Rivers in relation to dissolved gas supersaturation	2005 ✔	***Purpose***: Learn more about the preferred migration depths and potential TDG exposure of 131 (recovered) out of 238 radiotagged spring and summer adult Chinook 9 km below Bonneville Dam on the Columbia River up to Lower Granite Dam on the Snake Rivers in the spring and summer of 2000. ***Results***: Time to travel from below Bonneville to Lower Granite was up to 40 days. Average recorded depth varied with different reservoirs and different dams, deeper at Bonneville and the Dalles, greater in the Lower Columbia tailraces than the Snake River dam tailraces, shallowest at Ice Harbor. Individual depth preferences varied some consistently using shallower water. The salmon constantly and quickly moved up and down in the water column and this varied with each reservoir. Time spent in the upper 1 m on each excursion was typically seconds and time spent >2 m or below before ascending again was between 2.1 and 3.4 minutes. The maximum time spent above 1 m was 1.3 hours and above 2 m was 19 hours. They averaged below 2 m deep. They were above 1 m in depth 3% at Bonneville and 9% at Little Goose most of the time. They migrated close to shore and were deeper in tailraces. There was no indication that the salmon avoided higher TDG levels by maintaining depth compensation. Shallow fishladder areas at the dams were assumed to be 100% saturation due to degassing resulting from the turbulent nature of these fishways. ***Note***: Spill occurred June July and August of this year at most dams on the Columbia system with the exception of Snake River dams in July and August. Gas levels were highest in June. Rough TDG levels were found in this report but more detailed information can be found in historic hourly and daily TDG levels from monitoring performed by the USGS and the Corps.
Johnson, E., Clabough, Peery, Burke	Idaho Cooperative Fish and Wildlife Research Unit Tech Report 2005 for the Corps of Engineers, Walla Walla and Portland Districts	Hydrostatic compensation benefits of adult Chinook salmon and steelhead migrating through the Columbia-Snake hydro-system, 2002	2005	Report unavailable

Author	Publisher	Title	Date ✔ =have copy	Summary
Johnson, E., Clabough, Peery, Bjornn, Stuehrenberg	Idaho Cooperative Fish and Wildlife Research Unit Tech Report 2005 for the Corps of Engineers, Walla Walla and Portland Districts	Migration depths of adult steelhead in the lower Columbia and Snake Rivers in relation to dissolved gas supersaturation	2005 ✔	***Purpose***: Learn more about the preferred migration depths and potential TDG exposure of 115 (recovered and usable) out of 201 tagged adult steelhead 9 km below Bonneville Dam on the Columbia River up to Lower Granite Dam on the Snake Rivers using radio tags in the spring and summer of 2000. Also, detect daytime migration pathways for 28 individual fish in the tailraces below Bonneville and Ice Harbor Dams to estimate TDG exposure. ***Results***: There was no indication that steelhead detected or avoided areas of higher gas. Most steelhead migrated within 50 m of the shoreline. Median migration depth varied between individual fish from 1-2 m and 9-10 m with the bulk of the fish averaged well below 2 m deep. They were above 1 m in depth 9.6% of the time at Lower Monumental reservoir, 23.4% in the Bonneville tailrace, 1.3% in the McNary tailrace, and 2.3% of the time in the Dalles reservoir. They were deeper in the tailraces than in the reservoirs except for Bonneville. The duration spent above 1 m varied from the longest time of 17 hours and above 2 m 8.5 days to seconds, with much variation between individuals. The median time spent in shallow 1 m water was 6 minutes at Lower Monumental reservoir to 68 minutes in the Bonneville reservoir. ***Notes***: Recommended additional research on TDG effects on these fish subject to short but frequent exposure. Spill occurred June July and August of this year at most dams on the Columbia system with the exception of Snake River dams in July and August. Gas levels in June were highest. Course TDG levels were found in this report but more detailed information can be found in historic hourly and daily TDG levels from monitoring performed by the USGS and the Corps.

Author	Publisher	Title	Date ✔ =have copy	Summary
Johnson, E., Clabough, Peery, Bjornn,	Idaho Cooperative Fish and Wildlife Research Unit Tech Report 2008-2 for the Corps of Engineers, Walla Walla and Portland Districts Report for Project ADS-00-5	Migration depths of adult Chinook salmon and steelhead in the lower Columbia and Snake Rivers in relation to dissolved gas exposure, 2002	2008 ✔	***Purpose***: Learn more about the preferred migration depths and potential TDG exposure by radio-tagging 184 Chinook and 231 steelhead at Bonneville Dam. Track migration, preferred depths and temperatures through the lower Columbia River to the Snake River for Chinook, up the Snake also for steelhead. Compare depths to gas levels. ***Results***: **Chinook**: 124 tags were evaluated. Individual fish varied in depth but each individual was consistent in depth preference between the reservoirs. The fish tended to migrate closer to the surface above the Dalles (27.7% <2 m deep), deeper in the Bonneville pool (9.8% <2 m deep). They generally migrated deeper in the tailrace than the pool. The fish varied their depth, spending seconds to minutes above 2 m before descending for typically 60 minutes before resurfacing. The longest time spent in water <2 m was 18 hours, the longest in water <1 m was 4.1 hours. **Steelhead**: 170 tags were used to evaluate depth of migration. The time spent at depths in reservoirs shallower than 2 m ranged from 34.8% at Little Goose to 11.4% at Bonneville. Time spent at depths shallower than 1 m were 13.5% in Lower Monumental to 2.9% in the Dalles reservoir. The time spent shallower than 2 m in tailraces ranged from 37% at Bonneville to 6.2% at Ice Harbor. The time spent shallower than 1 m in tailraces ranged from 21.1% of the time at Bonneville to 0.5% in the tailrace of Ice Harbor dam. The adults often changed their depth in the water column like Chinook, although they spent less time generally below 2 m (30 minutes) before reascending. Some fish spent several days at depths shallower than 1 and 2 m. Steelhead tracked outside the spill season showed a similar preference for changing depth, indicating that this behavior is not likely induced by TDG. A weak to weakly significant correlation of depth preference to gas levels was found for some locations but not others for both Chinook and steelhead.
Jones, Lewis	Progressive Fish Culture Vol 38, No 1 January	Gas bubble disease in fry channel catfish	1976 ✔	***Purpose***: Document catfish fry mortalities due to TDG held in shallow water at 22-25°C. ***Results***: No TDG levels cited. Bubbles found in peritoneal cavity causing 85% mortality in one week and causing interference with equilibrium causing the fish to swim on their back.

Author	Publisher	Title	Date ✔ =have copy	Summary
Knittle, Chapman, Garton	Transactions of the American Fisheries Society 109:755-759	Effects of hydrostatic pressure on steelhead survival in air-supersaturated water Missing one page	1980 ✔	***Purpose***: Test for the effects of exposure to TDG from 120 to 140% on juvenile hatchery steelhead at various depths and repeated exposures and recovery times. ***Results***: For the first time surface exposure at non-lethal durations, the compensation time when held at 3 m was 1-2 hours at 120% TDG, longer for higher concentrations. The longer the fish remained at depth, the longer the time to death when re-exposed at the surface.
Krise, Herman	Journal of Aquatic Animal Health 3:248-253	Resistance of underyearling and yearling Atlantic salmon and lake trout to supersaturation with air	1991 ✔	**Purpose:** Determine LL50 and GBD signs on hatchery juvenile lake trout and two ages of juvenile Atlantic salmon held for 96 hours in 8.6 to 10°C water 0.15 m deep at 101 to 129% TDG. **Results:** Deaths occurred from 102.4% TDG and up for Atlantic salmon and 119.3% for lake trout. Larger lake trout and Atlantic salmon experienced greater TDG effects at lower concentrations.
Krise, Herman	Canadian Journal of Fisheries Aquatic Science 45:666-674	Effects of low level gas supersaturation on lake trout (Salvelinus namaycush)	1988 ✔	***Purpose:*** Learn the effects of TDG levels up to 111% Lake Trout held at 9.3°C for 98 days at .15 m depth as they developed from eggs, embryos, to alevin. ***Results:*** No significant statistical affect on hatching, weight gain, mortality, feeding. May have been GBD but the authors were unsure.
Krise, Herman	Journal of Fish Diseases 12:269-273	Tolerance of lake trout Salvelinus namaycush sac fry to dissolved gas supersaturation	1989 ✔	***Purpose***: Learn about the physical effects of TDG levels of 101-120% on lake trout sac fry exposed at 10°C in 25 gallon aquariums for 15 and 36 days, from hatching to 'swim-up'. ***Results***: Subcutaneous, hemorrhage was noticed at all levels of TDG. 99% survival of those exposed at 120% TDG and 96% survival of those exposed to 101% TDG though bubbles in fish were noticed in all samples. Pattern emerged of fish suffering more debilitating gas bubble damage the higher the gas pressure.
Krise, Mead, Smith	Progressive Fish Culturist 52:45-50	Effects of feeding rate and gas supersaturation on survival and growth of lake trout	1990	Report unavailable
Krise, Smith	Progressive Fish Culturist 55:177-179	Eye abnormalities of lake trout exposed to gas supersaturation	1993	Report unavailable

Author	Publisher	Title	Date ✔ =have copy	Summary
Krise	National Fisheries and Research Development Laboratory, USF and WS, Wellsboro, PA. The Progressive Fish Culturist	Effects of one-year exposures to gas supersaturation on Lake Trout	1993 ✔	***Purpose***: Determine the effect of long-term, one-year constant exposure of juvenile lake trout to incoming levels of 100.5, 102, 105, 106, 108 and 110% TDG on growth in 9.4 °C water 0.15 m deep. ***Results***: Those exposed with incoming water measured at 110%, 29% died in 100 days and few additional mortalities were experienced for rest of the year from this group. Behavior changed and weight gain was reduced. ***Note:*** Actual exposure gas levels were 2% lower than reported for the 102% test and even lower than reported for the higher concentration gas treatments. This is because TDG was measured for incoming water but oxygen was metabolized by the fish thus reducing the actual supersaturation in the tanks. Few TDG measurements were either taken or reported after initial calibration.
Kulshrestha, Mandal	Aquaculture 27::13-17	Pathology of gas bubble disease in two air-breathing catfish Clarias batrachus, Linn. and Heteropneustes fossilis, Bloch	1982 ✔	***Purpose***: Understand the physiological effects of TDG on two species of air breathing catfish held up to 96 hours in 25°C water in shallow aquaria. ***Results***: Before 24 hours, swimming became disoriented. After 48 hours, bubbles appeared externally, after 72 hours, blood in the bubbles, some ruptured and necrosis began. After 96 hours (assuming same TDG concentration) fish seemed to recover, bleeding stopped and began swimming normally. Internal lesions in the liver, intestines, mucous cells by 48 hours. Hemoglobin was reduced by half and by 72 hours, an elimination of erythrocytes. ***Note***: TDG levels were not reported.
Lichatowich	Technical Report 6 of 11. Prepared for the US Dept of Energy, BPA. Project No. 93-013. Contract No. DE-AM79-93BP99654	Ocean carrying capacity. Recovery issues for threatened and endangered Snake River salmon	1993	Report unavailable
Lothrop, Kiefer, Nigro, Tweit, Schaller	State, Federal and Tribal Fishery Joint Technical Staff Memo Letter to Oregon Dept of Environmental Quality	Technical comments on the US Army Corps of Engineers application for a waiver to Oregon's total dissolved gas standard	2007 ✔	Provides arguments for relieving the TDG criterion of 115% in the forebays of the dams on the lower Columbia and Snake Rivers.

Author	Publisher	Title	Date ✔ =have copy	Summary
Lund, Heggberget	Journal of Fisheries Biology 26:193-200	Avoidance response of two year old rainbow trout, Salmo gardineri Richardson, to air-supersaturated water	1985	***Purpose***: See if two year-old rainbow trout held in 8°C water saturated between 115-125% TDG compensate by swimming deeper. ***Results***: No detection or avoidance response to TDG was found.
Lutz, D.	Transactions of the American Fisheries Society 124:423-436	Gas supersaturation and trauma in fish downstream from a Midwestern reservoir	1995 ✔	***Purpose***: Collect data and analyze TDG and external gas bubble gas bubble signs in fish below Red Rock Dam on the Des Moines River to determine cause of 15 fish kills over 10 years. ***Results***: Over 10 years, fish kills occurred when TDG was between 109 and 126% TDG. Fish killed were gizzard shad, largemouth bass, walleye, buffalo, carp, channel catfish, white bass, and drum. Several internal examinations revealed gas emboli in the circulatory system.
Machado, Bell, Trapp, Garling, Kevern	Canadian Journal of Fisheries and Aquatic Sciences 46:74-80	Effect of carbon monoxide exposure on gas bubble disease in rainbow trout (Salmo gardineri)	1989 ✔	***Purpose:*** Discover if the change to hemoglobin in rainbow trout fry from exposure to carbon monoxide resulted in changes in the effects of subsequent exposure to TDG at 116%, 124% and greater at 12°C in a 10L tank. ***Results***: Exposure to carbon dioxide increased the time to mortality but did not convey significant reductions in overall mortality.

Author	Publisher	Title	Date ✔ =have copy	Summary
Machado. Garling, Kevern, Trapp, Bell	Canadian Journal of Fisheries and Aquatic Sciences 44:1985-1994	Hispothology and the pathogenesis of embolism (gas bubble disease) in rainbow trout (Salmo gardineri)	1987 ✔	***Purpose***: Correlate early stage of GBD with signs in hatchery rainbow trout fry held in 12°C water at 0.12 m deep and with varying levels of oxygen (O) to nitrogen (N) saturation but TDG between 94 and 116% for up to 60 days. ***Results***: Few GBD signs were observed in fish behavior until a few minutes before death. Then signs included convulsing, loss of equilibrium, buoyancy, and aimless swimming, mouth agape, and gills flared. Fish appeared to die during periods of increased muscular activity such as feeding or disturbances. Every dead fish had displacement of the blood by air bubbles in the gill filaments. Also found were eye popping and external bubbles. Nitrogen as high as 117% was not lethal if oxygen was >100%. Oxygen to nitrogen ratios influenced mortalities: • 2.5% mortality for fish exposed for 3 days at 111.% TDG, 113.% N and 105.% O. • 28% mortality in 10 days at 113% TDG, 115% N and 108% O. • 0.5% mortality in 17 days at 105% TDG, 109-111 % N and 85-93% O.
Marotz, Sylvester, Dunnigan, Ostrowski, DeShazer, Wachsmuth, Benner, Hensler, Benson	Report by Montana Fish, Wildlife and Parks to BPA Administration, Portland, OR 48p	Incremental analysis of Libby Dam operation during 2006 and gas bubble trauma in Kootenai River fish resulting from spillway discharge	2007	Report unavailable
Maule, Hans, Swihart	Draft NW Biological Science Center, Columbia River Research Laboratory, Cook, WA	Gas bubble trauma in juvenile salmonids at dams on the Snake and Columbia rivers. Annual report 1995	1996 ✔	Report unavailable

Author	Publisher	Title	Date ✔=have copy	Summary
Marking	Fish and Wildlife Leflet 9, USFandWS, Washington DC 10p	Gas supersaturation in fisheries: causes, concerns and cures	1987b	Report unavailable
Marotz, Sylvester, Dunnigen, Ostrowski, DeShazer, Wachsmuth, Benner, Hensler, Benson	Report by Montana Fish and Wildlife and Parks to BPA Administration, Portland, OR 48p	Incremental analysis of Libby Dam operation during 2006 and gas bubble trauma in Kootenai River fish resulting from spillway discharge	2007	Report unavailable
Mathias, Barica	Canadian Journal of Fisheries and Aquatic Sciences 42:268-279	Gas supersaturation as a cause of early spring mortality of stocked trout	1985 ✔	***Purpose:*** Learn if ice-covered shallow lakes cause nitrogen supersaturation causing mortality of fingerling hatchery raised rainbow trout in April held in cages at various depths beneath the ice in the center and near the shore of four lakes that had previously experienced anoxic conditions in the winter. ***Results:*** The four lakes studied had three different oxygen profiles: oxygen poor, supersaturated, and layered where supersaturated water overlaid an oxygen depleted layer. Fish showed symptoms of GBD when concentrations of dissolved oxygen were greater than 18 mg/L. Nitrogen was not measured but estimated using a model the authors developed. Partial pressure of nitrogen under ice in the spring was not that of the air (80% roughly) or that of water that is mechanically mixed as in spill from dams. Nitrogen formed a greater percentage of the mix. GBD from TDG (calculated levels) correlated with other caged studies. Results suggest that in shallow lakes with ice thickness of 15% of the depth or greater, supersaturation can occur.
Maule	Report by USGS for BPA Contract 96-AI-93279 Portland OR	Annual summary report of publications and reports produced by the monitoring program	2005	Report unavailable

Author	Publisher	Title	Date ✔ =have copy	Summary
Maule, Mesa, Hans, Warren, Swihart	USGS, Columbia River Research Laboratory, Cook, WA	Gas Bubble trauma Monitoring and research of juvenile salmonids. 1995 Annual report Consists of study reports by Beeman (Ch 1) entitled Vertical and horizontal distribution of individual juvenile salmonids based on radio-telemetry; Hans (Ch 2) entitled Gas bubble trauma signs in juvenile salmonids at dams on the Snake and Columbia rivers; and Mesa (Ch 3) entitled Progression and severity of gas bubble trauma in juvenile Chinook salmon and development of non-lethal methods for trauma assessment	1997 ✔	***Purpose***: Ch 1. Learn about vertical and horizontal distribution in the Columbia and accuracy and effect on fish of implanted radio tags in juvenile steelhead at 13°C. Ch. 2. Detect gas bubble trauma in downstream migrating salmon. Ch. 3. Assess validity of external examinations of bubbles for juvenile salmon. ***Results***: Ch. 1. Accuracy was 0.016 m. Test group swam 0.2 m shallower. Depth indications were somewhat affected by temperature. Buoyancy of fish was not affected. Detection distances decreased with depth. Tracking a small sample of fish in the McNary pool showed depths of 1.08 m to 4.27 m at 119.5-125.8% TDG. No clear pattern was found between the three individuals tracked.
Malouf, Keck, Maurer, Epifanio	Fisheries Resource Board, Canada	Occurrence of gas bubble disease in three species of bivalve mollusks	1972	Report unavailable

Author	Publisher	Title	Date ✔ =have copy	Summary
Maule, Mesa, Hans, Warren, Swihart	USGS, Columbia River Research Laboratory, Cook, WA	Gas bubble trauma monitoring and research of juvenile salmonids. 1996 Annual report	1997	Report unavailable
McDonough, Hemmingsten	Comparative Biochemistry and Physiology 81 A:209-212	Swimming movement initiates gas bubble formation in fish decompressed from elevated gas pressures	1985	Report unavailable
McInerny	Water, Air, and Soil Pollution 49(1-2):7-15	Gas bubble disease in three fish inhabiting the heated discharge of a steam electric station using hypolimnetic cooling water	1990 ✔	***Purpose***: Investigate the impacts of 100-~120% TDG on largemouth bass, bluegill, and white bass in a heated water discharge canal 5-11 m deep between November and June for two years. ***Results*** : Report graphed less than 5% GBD for largemouth bass and bluegill at TDG levels <~115%. When TDG levels rose to between ~115 and ~120%, GBD signs peaked at ~28% of largemouth bass, ~25% of bluegill, and ~18% of white bass. TDG levels were >110% from ~December to mid May and above 115% from about February to May. Intake temperatures (from a stratified lake) influenced gas concentrations. ***Note***: Severity of GBD, depth of fish captured, and exact TDG levels were not reported. Duration of TDG in the canal was not reported and would depend on the hours of operation of the coal-fired plant. Report indicated fairly consistent continuous operation. Discharge temperatures were not reported. Residence time of fish in discharge water canal was not investigated but full residence during the study was probably assumed.

Author	Publisher	Title	Date ✔ =have copy	Summary
McGrath, Dawley, Geist	PNNL-15525 Pacific Northwest National Laboratory. Prepared for the USACE, Portland Dist, Portland OR with USDEO contract No DE-AC05-76RL01830	Total dissolved gas effects on fishes of the lower Columbia River: synthesis of the literature 1996-2005	2006 ✔	A review of literature.
McKee, Wolf	California State Water Quality Board Publication # 3-A. 550pp	Water quality criterion 2nd edition	1963	Report unavailable
Meekin, Turner	Washington Dept. of Fisheries Tech Report 12:78-126	Tolerance of salmonid eggs, juveniles, and squawfish to supersaturated nitrogen	1974 ✔	***Purpose***: Assess vulnerability of eyed fall Chinook eggs, summer Chinook eggs and juveniles, coho juveniles, steelhead eggs and juveniles, and pike minnow adults in various TDG exposures at 8.6-9.4°C 0.2 m deep. ***Results***: Green and eyed Chinook eggs hatched in 122% N while steelhead eggs suffered mortality at 122%. All salmon juveniles survived 112% N for 27-32 days. Pikeminnow became lethargic when exposed for 17 days at 120% N. Realized that since these tests used nitrogen to supersaturate the water, keeping oxygen lower than saturation (88%) both gasses need to be used to asses harm to fish, not just nitrogen. Elevated nitrogen without elevated oxygen does not mimic conditions usually found in the Columbia/Snake [except possibly in the upper Pend Orielle or portions of the mid-Columbia where aquatic plants are abundant].

Author	Publisher	Title	Date ✔ =have copy	Summary
Meekin, Allen	Washington Dept of Fisheries Technical Report 12	Summer Chinook and sockeye salmon mortality in the upper Columbia River and its relationship to nitrogen supersaturation	1974 ✔	***Purpose***: Assess the impact of TDG on pre-spawning adult summer Chinook and sockeye with boat and aerial searches correlated with measurement of TDG. ***Results***: Estimated mortalities of Chinook were between 5.5% (1970 escapement) and 59% (1967) of Wells Dam summer Chinook. Sockeye mortalities could not be estimated. The carcasses found floating in the river coincided with the times of spilling and TDG in excess of ~116% TDG. In 1970, few floating carcasses were found when fish were not subjected to levels higher than ~114% TDG. The majority of the carcasses were found below Chief Joseph Dam. Other species of dead floating fish were also found: steelhead trout, suckers, carp, peamouth chub, and chiselmouth chub.
Mesa, M., Warren	Canadian Journal of Fisheries and Aquatic Sciences vol 54 no 4 pp 757-764	Predator avoidance ability of juvenile Chinook salmon subjected to sublethal exposures of gas supersaturated water.	1997 ✔	***Purpose:*** Assess the ability of juvenile Chinook with different severity of GBD in 16-17°C water 1.2 m deep and exposed in 112% TDG for 13 days, 120% for 8 hours and 130% for 3.5 hours to avoid predation by pikeminnows. ***Results:*** Increased predation only in those Chinook exposed to 130% TDG. 73% of those exposed to 112% TDG had lateral line bubbles. Chinook exposed to 112% TDG had more severe fin bubbles (91% of all fish) as compared fish exposed to higher levels of 120% (13%). Bubbles in gill filaments were in 34% of the fish at 112% TDG and 10% at 120% TDG.
Mesa, M., Maule, Weiland	Transactions of the American Fisheries Society. 129:174-185	Progression and severity of gas bubble trauma in juvenile salmonids	2000 ✔	***Purpose***: Look at juvenile hatchery spring Chinook and hatchery steelhead for progression and sublethal effects at 110, 120 and 130% TDG in 0.27 m deep water at 12°C. ***Results***: Chinook:110% TDG no mortality in 22 days, bubbles in fins, gills and lateral line; 113% TDG average, no mortalities in 22 days. 60% had fin bubbles at 22 days at 120% TDG. A 20% mortality rate varied from 1.7 to 5 days. Death was 40-120 hours for Chinook and 20-35 hours in steelhead. At 130% TDG death for Chinook was 3-6 hours, steelhead-5-7 hours. Symptoms varied between species.

Author	Publisher	Title	Date ✔ =have copy	Summary
Mesa, Warren, Mauole	National Biological Service, Columbia River Research Laboratory, Cook, WA Draft	Progression and severity of gas bubble trauma in juvenile Chinook salmon and development of non-lethal methods for trauma assessment	~1995 ✔	***Purpose***: Assess progression of external and gill arch bubbles in juvenile hatchery spring Chinook and a few two year old fall Chinook held at 12°C in 0.28 m deep tanks exposed to 112% TDG for 22 days, 120% TDG for 80 hours and 130% for 9 hours TDG in separate experiments. ***Results***: At 130% TDG, 50% mortality was in about 6 hours. Variability in lateral line bubbles increased with time. Bubble formation in fins held at a steady peak after 6-8 hours. Severity rating of 1 most common. Rating of 2-3 showed only during hours 5 on. 85-100% of fish had bubbles after 4 hours. Gill bubbles varied between individuals, species and trials but growth moderate and steady for the first 5 hours. Fish that died had gills covered with bubbled in combination with other bubble signs. At 120% TDG, 50% mortality and 50% occlusion in lateral line after 60 hours. All fish had bubbles in lateral line. Fin bubble severity showed caudal, anal and dorsal fins had highest severity. Fish with no fin bubbles only in the first 24 hours. Rating of fin bubble severity category 2-3 appeared after 30 hours and made up 40-80% of samples during hours 54-80. Gill bubbles apparent but variable and associated with other signs. At 112% TDG there were no mortalities after 22 days. Lateral line bubbles were <5% of fish but sometimes exceeded 50% occlusion toward the end of the study. Severity on fins increased gradually throughout the trial. Caudal fins showed trend in increasing average severity. Few fish with severity of 2-3 in the first 12 days but became more common after day 12. After the first 13 days, 80% has fin bubbles. Gill bubble occurrence infrequent. Eye protrusion occurred in 14%.

Author	Publisher	Title	Date ✔ =have copy	Summary
Mesa, Warren, Hans, Maule Filed under Maule : Gas Bubble trauma Monitoring and research of juvenile salmonids. 1995 Annual report	USGS, Columbia River Research Laboratory, Cook, WA	Gas bubble trauma monitoring and research of juvenile salmonids. 1995 Annual report Ch 3. Progression and severity of gas bubble trauma in juvenile Chinook salmon and development of non-lethal methods for trauma assessment	1996 ✔	***Purpose***: Assess progression of GBD at 110, 120 and 130% TDG at 12°C 0.28 m deep. Assess the validity of external examinations of bubbles for hatchery juvenile Chinook. Determine the best way to assess GBD in juvenile salmon that does not harm them, is quick and accurate. ***Result***: At 120% TDG mortality reached 43% in about 75 hours. Bubbles were present in 75% of the samples on the lateral line with fairly consistent amount of occlusions between fish. Prevalence of bubbles in fin erratic but averaged 50%. Gill arch bubbles never above 50% but erratic between fish sampled. At 110% TDG during 13-day trial bubbles increased gradually in dorsal fin bubbles and remained at 60% of the fish after 5 days. Gill bubbles affected less than 15% of the fish sampled, Eye popping occurred in 24%.
Monk, Dawley, Beiningen	NOAA Data report 102	Concentrations of dissolved gasses in the Willamette, Cowlitz, and Boise Rivers 1970-72	1975 ✔	***Purpose***: Understand the relationship between flows, dam discharges and TDG on the Cowlitz, Willamette and Boise Rivers. ***Results***: Analytical method likely had large uncertainty. For Mayfield Dam on the Cowlitz River, gas levels were above forebay levels with one measurement over water quality standards at 110.9%.
Monk, B., Dawley, Absolon	Annual Report 1996 Project No 96-24. US DOE, BPA, Portland, OR Contract No 96-AI-93-892	Changes in gas bubble disease signs and survival of migrating juvenile salmonids experimentally exposed to supersaturated gasses	1997 ✔	***Purpose***: Find out if GBD signs in hatchery juvenile steelhead exposed to 113 - 117% TDG for 54 hours at 12°C 0.46 m deep change with differences in pressure when fish go through the sampling station/bypass at Columbia/Snake River dams and if GBD cause indirect and direct decreased survival. ***Results***: 38% of released fish were recaptured and examined after 4.2-10 hours in the river. TDG in river after release was between 114 and 128%. Controls with 0% bubbles on release had an average of 3.3% bubbles on capture, exposed fish 37.5% bubbles on release and 47.5% upon capture. No difference in survival of unexposed control fish and exposed fish was detected at the lower dams. Other comparisons with net pen held fish and released fish for reabsorption of bubbles showed faster reabsorption for released fish. Large steelhead were likely not as susceptible to predators so another test using smaller fish was recommended.

Author	Publisher	Title	Date ✔ =have copy	Summary
Montgomery, Becker	Transactions of the American Fisheries Society, 109: 734-736, 1980	Gas bubble disease in smallmouth bass and northern squawfish from the Snake and Columbia rivers	1980 ✔	***Purpose***: Investigate presence of external gas bubbles in hook and line caught pikeminnow and smallmouth bass during presence of 110% TDG or greater in the Snake and Columbia Rivers. ***Results***: 72% of smallmouth bass and 84% of pikeminnow has bubbles in fins, operculum, and body.
Montgomery Watson	Project No 93-8 Task 9.3bUS DOE, BPA	Comparison of clinical signs of gas bubble disease in the gills of smolts using both compound and dissecting microscopes	1995 ✔	***Purpose***: Compare two methods of looking for gas bubble disease in Chinook and steelhead at McNary Dam and Ice Harbor Dam. ***Results***: Stereo microscope examination may be more effective at detecting bubbles in gill filaments than with a compound microscope. Each method depends on the size of bubbles.
Montgomery Watson	Project No 93-8 U.S. DOE, BPA Portland, OR. Contract No DE-AC79—93BP66208	Allowable gas supersaturation for fish passing hydroelectric dams. Task 8. Bubble reabsorption in a simulated smolt bypass system – concert assessment	1995 ✔	***Purpose***: Examine if clinical signs of external bubbles are disappearing, being reabsorbed during spring juvenile Chinook passage through the fish bypass system at Columbia and Snake River dams by subjecting juvenile spring Chinook to pressures equivalent to 100 feet of water, depressurizing and looking for bubble signs and reabsorption.. ***Results***: The smolt monitoring program may be underestimating prevalence of bubbles in fins. Suggested further research: 1. Better understand kinetics of reabsorption and regrowth. 2. Develop and validate protocols for examining gas bubble trauma. 3. Identify and assess the use of lesions or biochemical indicators. 4. Develop accurate pressure exposure time histories for smolts. 5. Compare bubbles from smolts in the forebay and tailrace and bypass system.
Morris, R., Beeman, VanderKooi, Maule	Comparative Biochemistry and Physiology A135:309-320	Lateral line pore bubble diameters correlate with development of gas bubble trauma signs in several Columbia fishes	2003 ✔	***Purpose***: Evaluate the relationship of lateral line pore diameters in longnose sucker, largescale sucker, pikeminnow, juvenile hatchery fall Chinook salmon and redside shiner to lateral line occlusion and TDG exposure time to 115, 125 and 130% TDG in.26 m deep water at 12°C. ***Results***: There was a relationship between lateral line pore sizes and presence of gas bubbles on the lateral line. Previous studies that compared different species GBD susceptibility based on lateral line occlusion should be suspect. Bubbles exit from the fish with larger pours. Species in order of increasing pour size were red side shiner (smallest pores), Chinook, pike minnow, largescale sucker, and longnose sucker (largest pores).

Author	Publisher	Title	Date ✔ =have copy	Summary
National Academy of Science/National Academy of Engineering	USEPA report: EPA-R-73-033 Washington DC Pp 131-139	Water quality criteria 1972	1973	Recommended limit 110% TDG. Several factors increase GBD including high fat, activity, temperature, shallow depth, increased osmoregularity, decreased blood pressure.
Nebeker,	Journal of Fisheries Resource Board	Survival of daphnia, crayfish, and stoneflies in air supersaturated water	1976	Report unavailable
Nebeker, Stevens, Brett	In DH Fickenstein and Schneider, Gas Bubble Disease. Tech Info Center, ERDA. NTIS Conf 741033	Effects of gas supersaturation on freshwater aquatic invertebrates	1976 ✔	***Purpose***: Determine effects of TDG at various concentrations on Daphnia, crayfish, 3 species of stoneflies, and compare toxicities to juvenile steelhead. ***Results***: Daphnia held at 12°C ~0.25 m deep. At 110% TDG 10% died in 170 hours, at 120% 50% died in 93 hours. Bubbles were found in the gut blocking digestion. Assumed death occurred from starvation. Bubbles were also found in the brood pouch. Susceptibility similar to steelhead though mode of death differs. Adult crayfish experienced no deaths at 120% TDG during a 30 day test at 12°C. Susceptibility less than steelhead. Larval Stoneflies held at 12°C on rock substrate for 96 hours, no deaths but a few bubbles were observed on the surface of the stoneflies. At higher levels, bubbles formed on the surface and the gills and floated the larvae off the bottom to the surface. At the surface, sometimes the bubbles popped and the larvae sank to the bottom again. Stoneflies held at 115% had no observable effect. Susceptibility less than steelhead though indirect mode of death in the wild due to predation from floating into the water column could be significant.
Nebeker, Hauck, Baker	Water Resources 13: 299-303	Temperature and oxygen-nitrogen ratios affect fish survival in air-supersaturated water	1979	Report unavailable

Author	Publisher	Title	Date ✔ =have copy	Summary
Nebeker, Hauck, Baker, Weitz	USEPA, Corvalis, OR. Transactions of the American Fisheries Society 109:760-764	Comparative response of speckled dace and cutthroat trout to air-supersaturated water	1980 ✔	***Purpose***: Determine and compare lethal time to 50% mortality at various levels of TDG concentrations for hatchery raised juvenile cutthroat trout and adults at 12°C and 0.6 m deep and wild caught juvenile speckled dace at 10°C and 0.25 m deep. ***Results***: The longer the time of exposure, the more bubbles found in the tissue and bloodstream, fish held at high concentrations often died prior to external signs of bubbles. Cutthroat trout: • At 113% TDG 20% mortality was 185 hours (juveniles). • At 120% TDG 20% mortality was 20 hours (juveniles). • At 118% TDG 20% mortality was 142 hours (adults). • At 121% TDG 20% mortality was 34 hours (adults). Speckled Dace: • At 119% TDG, 20% mortality was 550 hours.
Nebeker, Hauck, Baker	Water Resources 13: 299-303	Temperature and oxygen-nitrogen ratios affect fish survival in air-supersaturated water	1979	Report unavailable
Nebeker, Baker, Weitz	Journal of Freshwater Ecology 1(3):243-250	Survival and adult emergence of aquatic insects in air-supersaturated water	1981 ✔	***Purpose***: Understand time to mortality from exposure to TDG supersaturation (125-150%) on adult emergence, pupae and last larval molt of mayfly, caddisfly, midge and mosquito in 15°C shallow water (maximum depth 0.15 m) mimicking expected natural near surface preferences for these life stages. ***Results***: Gas bubbles killed these aquatic insects less at these higher exposures than TDG levels that would kill juvenile salmonids. Decreasing time to mortality with decreasing concentrations, for instance, time to 50% mortality for mayflies was 1.8 days at 135% TDG and 5.2 days at 125% TDG. Varying susceptibility was observed between these four species. Many midges and mosquitoes survived 140% saturation; it was thought because of the direct air breathing mechanisms of these insects.

Author	Publisher	Title	Date ✔ =have copy	Summary
Nebecker, Stevens	U.S. EPA, Corvalis, OR, Dept of Veterinary Medicine, OSU Fisheries resource Board, Canada 33:2629-2633	Effects of Air supersaturated water on adult sockeye salmon	1976 ✔	***Purpose***: Understand the effects of high levels of TDG on adult Columbia River sockeye salmon held for 35 days at 0.7 m deep at 12°C. ***Results***: 110% TDG, no signs. Lethal threshold determined to be 114% TDG. 115% - 21 days until first death. 120% - 3 days until first death. Bubble evidence in fins and internally as well as lesions and infections.
Nebecker, Brett	Transactions of the American Fisheries Society 105: 338-342	Effects of air supersaturated water on survival of Pacific salmon and steelhead smolts	1976	Report unavailable
Nebecker, Bouck, Stevens	Transactions of the American Fisheries Society, 176, No. 3	Carbon dioxide and oxygen-nitrogen ratios as factors affecting salmon survival in air-supersaturated water	1976 ✔	***Purpose***: Determine the time to 50% death for juvenile hatchery sockeye salmon held at 15-16°C at 0.6 m deep using varying supersaturation ratios of dissolved oxygen to nitrogen in at constant saturations of 120, 125 and 130% TDG. ***Results***: At 120% TDG with 117.2% oxygen and 121.3% nitrogen time to 50% death was 71 hours. At 120% TDG but 170.5% oxygen and 107% nitrogen only 7% of the fish died in 167 hours. However, more extensive and severe external signs of bubble disease developed in fish exposed to abnormally high oxygen/nitrogen ratios. Cause of death at 120% was bubble blockages of blood flow in the capillaries. Total dissolved gas pressure is more important than the mix. Though oxygen to nitrogen ratios have an effect, the results seem to conflict with greater time to mortality for lower oxygen ratios but more bubble signs with higher oxygen ratios.
Nebecker, Andros, McCrady, Stevens	U.S. EPA, Corvallis, OR	Survival of steelhead trout eggs, embryos, and fry in air-supersaturated water	1978 ✔	***Purpose***: Determine effects of TDG by exposing hatchery steelhead eggs, embryos, and fry to various levels of TDG supersaturation in 10°C water 0.08 m deep. ***Results***: Eggs and embryos showed no signs of trauma exposed to 126.7% TDG for 20 days. As the fish developed after 20 days into the swim-up stage mortality rapidly occurred until 45% mortality occurred at 115.3% TDG, 67% at 118.4% TDG after 52 days. Fish that survived grew as well as the control group, showing a wide range of tolerance. No acclimation occurred for swim-up fry when exposed to high TDG during eggs and embryo stages. Newly hatched fry and eggs are more tolerant of TDG than later life stages.

Author	Publisher	Title	Date ✔ =have copy	Summary
Newcolm, T.	Journal of Fisheries Research Board of Canada 31:1953-1957	Changes in blood chemistry of juvenile steelhead trout following exposure to nitrogen supersaturation	1974 ✔	***Purpose***: Determine changes in blood chemistry of hatchery juvenile steelhead exposed to 99, 102, 105, and 110% (±2% TDG) TDG at 15°C in water 0.23 m deep for 35 days. ***Results***: TDG: at 105% there was increase serum potassium and phosphate; decline in serum albumin, calcium, cholesterol, total protein and alkaline phosphatase. External bubble signs were in 46% of the fish exposed to 110% TDG.
NOAA Fisheries NW Fisheries Science Center	Summary Report to NOAA Fisheries	June, 1995 first working group meeting of panel on gas bubble disease	1995 ✔	This and the following two workshops are important to understanding the strengths and limitations of the current GBD monitoring program and hence the data from the past 10 years of smolt monitoring.
NOAA Fisheries NW Fisheries Science Center Colt, Barney, Elston, Dawley	Summary Report to NOAA Fisheries	November 1995, second working group Meeting of panel on gas bubble disease	1995 ✔	Evaluation of the smolt GBD monitoring program and recommended improvements to quality of sampling: document statistical basis for program; determine accuracy of precision of monitoring protocols; create and use a quality assurance program; provide audits to see if protocols are followed; provide additional facilities and a management structure for consistency.
NOAA Fisheries NW Fisheries Science Center	Summary Report to NOAA Fisheries	April 1996, third working group meeting of panel on gas bubble disease Feb 1-3	1996	Recommended monitoring for 1996 for Columbia and Snake. Identified critical uncertainties in the smolt monitoring system. Loss or gain of bubbles as the fish traverse the reservoirs. Mortality in the reservoirs. GBD bubbles and mortality not clearly related. Ranked and wanted to test these assumptions: 1. Relation between bubbles in fins, gill lateral line and mortality are known. 2. Bubble signs don't change during collection and examination. 3. Signs in sampled fish are representative of the river and the day. 4. Samples represent high risk locations. 5. Sample size is statistically adequate. 6. Key signs of gbd and their significance are known. Recommended gas concentrations did not exceed those established in the 1995 BiOp of 115 forebays/120% tail waters.

Author	Publisher	Title	Date ✔ =have copy	Summary
NOAA Fisheries Colt, Barney, Elston, Dawley	A report to the NOAA Fisheries/EPA gas bubble disease technical workgroup prepared by the biological monitoring inspection team	Research priorities related to gas bubble monitoring needs in the Columbia River Basin	1995 ✔	Listed critical assumptions made by the smolt monitoring program and recommended systematically investigating them.
NOAA Fisheries	Report to BPA Task 9.2	QA/QC of 1995 gas bubble trauma monitoring on the Snake and Columbia rivers	1996	Report unavailable
**NOAA Fisheries	1995 BiOp (Sockeye FCRPS)	Biological opinion for Idaho sockeye	1995 ✔	Summarizes literature.
NOAA Fisheries	1998 Supplemental to the 1995 BiOp (Steelhead listing)	Supplemental biological opinion for three steelhead species	1998 ✔	Recognizes the need for spill to be balanced with negative affects of spill (TDG). Continued focus on spill to 115/120% only at night at most dams.
NOAA Fisheries	NOAA Fisheries Annual Report to Oregon Dept of Env Quality 1998	Juvenile, Columbia and Snake rivers juvenile salmon GBD monitoring	1997-2000	GBD monitoring report. 25% or less bubbles on a single fin considered minor. More than 1% of the juvenile salmon have this much sign at 115% TDG. A lot of other flow and GBD monitoring information in this report—also under FPC-Fish Passage Center references.
NOAA Fisheries	1995 Risk Assessment	Spill and 1995 risk management risk	1995 ✔	Summarizes literature up to 1995 to support a fish spill program on the Columbia and Snake that will raise TDG levels >110%.
NOAA Fisheries	2000 BiOp (FCRPS) Appendix E ppE1-E26	Assessment for spill program described in 2000 draft BiOp	2000 ✔	Summarizes literature after 1995 to support a fish spill program on the Columbia and Snake that will raise TDG levels >110%. Describes and supports the NOAA Fisheries risk assessment done in 1995.

Author	Publisher	Title	Date ✔ =have copy	Summary
NOAA Fisheries	1995 BiOp FCRPS NMFS, Northwest Region	Biological opinion Section 7 re-initiation of consultation on 1994-1998 operation of the federal Columbia River power system and juvenile transportation program in 1995 and future years	1995 ✔	Recognizes the need for spill to be balanced with negative affects of spill (TDG). In river juvenile salmon benefit from spill to 120 to 125% TDG. Forebay monitoring sites planned for use until tailrace monitoring stations are better correlated to fish experience. Recommended limiting spill to 115% as a 12 hour average in the forebays. Intent is for long-term exposure not to exceed 115% for juvenile salmon and adults to avoid potential sublethal effects. Recognized that fish would be depth compensated to an unknown degree so 110% TDG could be exceeded and recognized that TDG fluctuates with spill patterns—like an emphasis on nighttime spill. Long term exposure should not be more than 110% TDG because of concerns about sublethal effects. Ideally recommended specific TDG levels for each dam [the TMDL sort of did this through compliance points].
NOAA Fisheries	2000 BiOp for the Columbia Snake River,	Water quality revised prudent alternatives (RPAs) pages 9.120-9.129	2000 ✔	Recognized 115/120% TDG allowed for spill as an interim strategy, the long term goal (by 2010-2015) is 110%.
NOAA Fisheries	2004 BiOp (FCRPS)		2004	Report unavailable
NOAA Fisheries	NOAA Fisheries Service Center, Seattle, WA	Basis for flow objectives for operation of the federal Columbia River power system	1995	Report unavailable
NOAA Fisheries		Annual report to the Oregon Department of Environmental Quality Feb. 2000	1999	Report includes season's GBD external monitoring on the Columbia and TDG levels in forebays and tailraces as well as flows and reasons for spilling.
NOAA Fisheries		Annual Report to the Oregon Department of Environmental Quality Dec. 2000	2000	Report includes season's GBD external monitoring on the Columbia and TDG levels in forebays and tailraces as well as flows and reasons for spilling.

Author	Publisher	Title	Date ✔ =have copy	Summary
Olson, Quinn	Fishery Bulletin 91:171-178	Vertical and horizontal movements of adult Chinook salmon in the Columbia River estuary	1993	Report unavailable
Parametrix Inc	Unpublished report to Avista Corporation, Spokane, WA 40p + appendices	Physical and biological evaluations of total dissolved gas conditions at Cabinet Gorge and Noxon Rapids hydroelectrical projects – spring 1997	1997 ✔	***Purpose:*** Evaluate resident fish (largescale sucker, peamouth, pikeminnow, redside shiner, brown trout) caught by electrofishing, downstream migrating kokanee fry caught with a fyke net, and juvenile rainbow and cutthroat trout held in 2 m deep cages at an undisclosed depth all downstream from Cabinet Gorge dam on the Pend Orielle River during a high flow year when flows would exceed a 7Q10 high flow if established by Washington State and TDG was > than 122% from May through June. ***Results:*** Of all the 108 resident fish examined, 5 largescale suckers and one brown trout exhibited gas bubble signs of >5% on their unpaired fins for a total of 5.5% occurrence at this level of bubble detection. 71% of the largescale suckers had gas bubbles (5 out of 7). Two of the 114 kokanee fry showed exophthalmia. Mortality occurred in most of the fish in the live cages within a few days.
Parametrix Inc	Unpublished report to Avista Corporation, Spokane, WA	Fish behavior evaluation lower Clark Fork River, 1998	1999 ✔	***Purpose***: Learn about vertical (depth) and horizontal preferences of cutthroat, rainbow and bull trout, pikeminnow, mountain whitefish and largescale sucker through tracking with radiotags in the Clark Fork River during the spring spill (higher TDG) period. ***Results***: For 26 days, brown trout were found within 3 feet of the surface 14% of the time. The time the narrowest depth preference was observed was during highest flows when fish inhabited the bottom, though some in shallower water toward the shoreline where velocities were less. The 2 rainbows trout from surface to 2 m. The cutthroat depth preferences were different for the two radiotagged fish; the bull trout mean depth was 3 m; northern pikeminnow had a greater depth range than the trouts; frequently near the surface to 15 m. The largescale sucker had the shallowest depth distribution of the tagged species. Trout had the same depth preference day and night while suckers were shallower in the afternoon and night and the pikeminnow shallower at night.

Author	Publisher	Title	Date ✔ =have copy	Summary
Parametrix Inc	Unpublished report to Avista Corporation, Spokane, WA	Fish behavior evaluation lower Clark Fork River, 1999	1999 ✔	***Purpose***: A second year to learn about vertical (depth) and horizontal preferences of cutthroat, rainbow and bull trout, pikeminnow, mountain whitefish and largescale sucker through tracking with radiotags in the Clark Fork River during the spring spill (higher TDG) period. ***Results***: Much of the deeper water habitat that would provide depth compensation for TDG during high flows is in the middle of the river but is unavailable during high flows due to high velocities. 20% of the time, brown trout were within 1 m of the surface. No pattern of behavior associated with TDG levels was observed. Though they moved laterally in the river, their depth preferences remained the same. 53% of the Rainbow trout were within 1 m of the surface. They appeared slightly deeper during the day. 40% of the detections for cutthroat trout were within 1 m of the surface. Bull trout median depth was about 5-6 feet. 1% of the detections for pikeminnow were above 1 m deep. Deepest in the early morning. (?)% of the largescale sucker depths were shallower than 1 m deep.
Parametrix Inc	Unpublished report to Avista Corporation, Spokane, WA	Fish behavior evaluation lower Clark Fork River, 2000	2000 ✔	***Purpose***: A third year to learn about vertical (depth) and horizontal preferences of cutthroat, rainbow and bull trout, pikeminnow, mountain whitefish and largescale sucker through tracking with radiotags in the Clark Fork River during the spring spill (higher TDG) period. ***Results***: Brown trout median depth varied between 1.7 and 5.5 m. Bull trout were found between 0.9 m to 3.8 m deep. Cutthroat trout averaged 1.6 m deep. Rainbow trout were found between 0.3 and 5.9 m deep. Brown trout were slightly deeper during the day, the cutthroat and rainbow showed no preference. Median hourly depth for individual cutthroat was 0.3 m to 2.5 m. Hydroaccoustic survey in Lake Pend Orielle showed that less than 65 fish per acre occupy the top 20 feet of the water column during the daylight hours. ***Note***: The above three years of studies for the tagged fish give information of depth preferences during the times the radio tags were detected. Was a shallow detection for a fish that surfaced for a few moments? Or was it spending the day there?
Parametrix Inc	Unpublished report to Avista Corporation, Spokane, WA 35p + appendices	Gas bubble disease in the lower Clark Fork River, 1999	1999b	Report unavailable

Author	Publisher	Title	Date ✔ =have copy	Summary
Parametrix	Appendix A Rocky reach Hydroelectric Project No 2145 draft Chelan PUD prepared by Parametrix	Total dissolved gas biological effects 2001	2002 ✔	***Purpose***: Assess potential of TDG to harm aquatic organisms by determining their location and effect of TDG on macro invertebrates (at 05 m and 3 m deep) during late April, May, and June, and resident fish collected by beach seine from six sites below Rocky Reach Dam in 2001 (a low-flow/no spill/no TDG year). ***Results***: TDG levels were from 105 – 109% with occasional spikes to 115% for a few hours. 94 taxonomic groups were collected. Midges were most abundant, then bristle worms, snails, bivalves, sow bugs, scuds, caddis flies, and roundworms. Each site has a relatively unique composition of benthic macro invertebrates due to variability of habitat. Macro invertebrate abundance increased as the season progressed. One midge larvae and one sow bug collected at 0.5 m showed signs of GBD. No resident fish showed signs.
Parametrix	Appendix A Rocky reach Hydroelectric Project No 2145 draft Chelan PUD prepared by Parametrix	Total dissolved gas biological effects 2002	2003 ✔	***Purpose***: Assess potential of TDG to harm aquatic organisms by determining their location and effect of TDG on macroinvertebrates and resident fish below Rocky Reach Dam in 2002. ***Results***: 95% of the organisms were midges, bristleworms, hydras, snails, bivalves, sow bugs, scuds, caddis flies, and roundworms; the species composition changed from May to mid-August. 1,303 invertebrates were sampled for GBD: 9.1% of mayflies at ~118% TDG and 0.05% of bristle worms at ~113% TDG had bubble signs at 3 m deep (from low pool el.). No other species were reported with gas bubble signs. Fish in 3 m or less water caught by beach seine. 3000 were examined for GBD. Four species accounted for 98.6% of samples: three-spined stickleback, redside shiner, pikeminnow, and chiselmouth. Hemorrhages in the eyes fins and lateral lines and swellings were observed in 1-18% of stickleback during the summer but only one fish was found with existing bubbles. 46-98% of redside shiners and pikeminnows had hemorrhaging. All sand rollers on July 17 had GBD signs when TDG was ~120%. ***Note*:** One instructive aspect of this study is to show depth of fish and aquatic invertebrates in the mid-Columbia River and associated potential exposure to TDG. Actual gas levels that the organisms were exposed to that had GBD signs is difficult to know.
Pauley, Nakatani			1967	Report unavailable
Rucker, Kangas			1974	Report unavailable

Author	Publisher	Title	Date ✔ =have copy	Summary
Richter, Naymik, Chandler	Idaho Power Report to FERC on project No 1971	HCC gas bubble trauma monitoring study	2006 ✔	***Purpose***: Monitor for external bubble signs in mostly resident electro-shocked fish above Hell's Canyon Dam on the Snake River. ***Results***: Depth of collected fish was not reported. No gas bubbles were found when prior conditions were >120% for 20 species. Bubbles were found when conditions were >125%.
Richter, Naymik, Chandler	Idaho Power Co, Boise, ID 38p	HCC [Hells Canyon Complex] gas bubble trauma monitoring study	2007	Report unavailable
Rucker	National Marine Fisheries Service Bulletin 73(4) 915-918	Gas bubble disease mortalities of coho salmon, Onchorhynchus kisutch, in water with constant total gas pressure and different oxygen-nitrogen ratios	1975a	Report unavailable
Rucker	Progressive Fish Culture 37: 101-102	Excess nitrogen gas in water not a cause of coagulated yolk disease in Chinook salmon	1975b	Report unavailable
Ryan, B and Dawley, E.	Northwest Fisheries Science Center, NOAA BPA contract #96-BI-93605	Effects of dissolved gas supersaturation on fish residing in the Snake and Columbia Rivers. 1997	1998 ✔	***Purpose***: Determine GBD in 27 species of resident fish caught in water <3 m deep in Ice Harbor Reservoir and downstream from this dam and Bonneville and determine subsamples for fish held 4 m deep for 4 days at several depths from .5 to 4 m. Also determine GBD in juvenile salmon caught with purse seine below Ice Harbor Dam. ***Results***: TDG levels dropped below 120% after mid-June. TDG signs decreased significantly in resident fish below 120% TDG in the reaches studied. The model described in 2000 (below) can predict this.

Author	Publisher	Title	Date ✔ =have copy	Summary
Ryan, Dawley, Nelson	North American Journal of Fisheries Management 20:192-204	Modeling the effects of supersaturated dissolved gas on resident aquatic biota in the main-stem Snake and Columbia Rivers	2000 ✔	***Purpose***: Correlate TDG levels and exposure to bubble signs in non resident aquatic organisms. ***Results***: Developed a model using 1994-97 observed data correlating gas exposure and duration with the appearance of external bubbles in 27 species of aquatic organisms. Successfully predicted certain GBD signs at levels greater than 120%. GBD greater for captured fish than free. Temperature and fish size were weakly correlated. Fish were collected from 0 and 3 m.
Saeed, alThobaiti	The Veterinary Record 140:682-684	Gas bubble disease in farmed fish in Saudi Arabia	1997	Report unavailable
Scheiwe and Richmond	Battelle Ecological Modeling 147:233-252	Fish individual numeric simulator (FINS): a particle-based model of juvenile salmonids movement and dissolved gas exposure history in the Columbia River basin.	2002	Report unavailable
Schiewe, M	Transactions of the American Fisheries Society: No. 4, 103:717-721	Influence of dissolved atmospheric gas on swimming performance of juvenile Chinook salmon	1974 ✔	***Purpose***: Learn about effect of different levels of TDG exposure at 15° C in tanks 0.25 m deep after 50% exposure mortality, from 117% and 120% TDG and after 35 days of exposure at 104, 106 and 112% TDG on swimming performance against a fixed flow and recovery ability of juvenile hatchery spring Chinook salmon exposed at 120% TDG. ***Results***: For swimming performance with no recovery period, fish were less active at 106, 112, 117 and 120% TDG (± 2%). Recovery occurred in 2 hours of exposure to 100% TDG.

Author	Publisher	Title	Date ✔ =have copy	Summary
Schiewe and Weber	Pgs 89-92 in Gas Bubble Disease. DH Fickeisen Editor Technical Information Center, Oak Ridge, TN Conf-741033	Effects of gas bubble disease on lateral line function in juvenile steelhead trout	1976 ✔	***Purpose***: Assess the effect of 118% (±4%) TDG on nerve responses of juvenile hatchery steelhead held at 13-15°C in shallow water. ***Results***: TDG lateral line occlusion affected reactions of juvenile steelhead.
Schiewe, Miller, Dawley, Ledgerwood, Emmett	By Fisheries Research Inst. University of WA and Dept of Oceanography, OSU for BPA Contract No DE-AI79-88BP92866 Project No 88-159	Quality and behavior of juvenile salmonids in the Columbia River estuary near-shore ocean	1989 ✔	***Purpose***: Understand how nearshore estuary conditions affect spring Chinook smolt quality and identify relationships among smolt quality, migration behavior, environmental conditions, and survival. ***Results***: Water quality samples taken did not include TDG.
Schisler, Bergersen, Walker	North American Journal of Aquaculture 61:175-183	Evaluation of chronic gas supersaturation on growth, morbidity, and mortality of fingerling rainbow trout infected with Myxobolus cerebralis	1999 ✔	***Purpose***: Find out if TDG levels of 110, 107.5, 105, and 100-102.5 % influenced the affect of whirling disease on fingerling rainbow trout held in shallow water at 12.5°C for 22 weeks. ***Results***: The TDG levels tested did affect the symptoms of whirling disease. GBD in the form of bubbles was found in fish exposed to 105% TDG and higher.
Schneider	NOAA Fisheries	Spill and 1995 risk management	1995 ✔	Literature review and risk assessment from risk of juvenile salmon downstream migrants harm from turbine injury and indirect effects of turbines against the harm from gas bubble disease.
Schneider	NOAA Fisheries Appendix E	Spill and 2000 risk management	2000	Obtain/review.
Scholz	Fisheries Research Center, Eastern Washington University	Gas bubble trauma in Lake Roosevelt fishes	2000 ✔	***Purpose***: Investigate gas bubble disease in 29 resident fish species greater than 100 mm long in Lake Roosevelt during a high flow year. ***Results***: 65.3% of fish sampled had GBD when TDG ranged from 115 to 132%. Percent of fish with GBD varied between species.

Author	Publisher	Title	Date ✔ =have copy	Summary
Schrank, Ryan and Dawley [also see Ryan and Dawly]	Annual Report 1995 to USDOE BPA project #96-022 Contract No 96 AI93605	Effects of dissolved gas supersaturation on fish residing in the Snake and Columbia rivers. 1996	1998 ✔	***Purpose:*** Analyze body surface and gill signs of TDG in resident fish in the Priest Rapids Reservoir and downstream from Priest Rapids Dam, Bonneville, and Ice Harbor Dams during a high flow year using fish caught in 0-3 m deep water and fish held in cages at various depths. ***Results:*** Developed a correlation between TDG concentrations and predicted gas bubble signs. Tried to develop a mortality model but there were no clear signs between mortality and bubble signs in captive fish. Shallow side areas measured for TDG were about 7% TDG less than in the main river. Some fish developed GBD when TDG was below 120%, symptoms increased with increased TDG saturation. For instance, 2.5% of sucker fry displayed bubbles in the body cavity when TDG levels were 115-119%. At 120-125%, 40.2% of the sucker fry showed severe bubble trauma.
Schrank, Ryan and Dawley	Annual Report 1995 to USDOE BPA project #96-022 Contract No 96 AI93605	Effects of dissolved gas supersaturation on fish and invertebrates in the Priest Rapids reservoir and downstream from Bonneville and Ice Harbor Dams, 1995	1997	Obtain or see if this is a duplicate study.
Shirahata	Bulletin of the Freshwater Fisheries Laboratory, Tokyo	Experiments on nitrogen gas bubble disease with rainbow trout fry	1966	Report unavailable
Shrimpton Randall, Fidler	Canadian Journal of Zoology 68:969-973	Assessing the effects of positive buoyancy on rainbow trout held in gas supersaturated water	1989 or 1990a ✔	***Purpose***: Assess the physical and behavioral effect of swim bladder over-inflation on rainbow trout held at 100 and 120% TDG in a column of water 2 m deep. ***Results***: Swim bladder over-inflation caused a buoyancy in small (>10 gram) fish that was compensated up to a point by fish holding deeper and spending more energy swimming to hold deeper and tend to swim in a head down position. Larger fish had less swim bladder-to-body ratio and showed less compensation behavior. Smaller fish cannot vent excess swim bladder air as well as larger fish at higher pressures.

Author	Publisher	Title	Date ✔=have copy	Summary
Shrimpton, Randall, Fidler	Canadian Journal of Zoology 68:962-968	Factors affecting swim bladder volume in rainbow trout	1990b ✔	***Purpose***: Investigate the response of swim bladders in rainbow trout to TDG. ***Results***: Gas begins to accumulate through diffusion in the swim bladder at 103.5% TDG. Accumulation in the swim bladder is partially a function of the ability to vent the accumulated gas. Smaller fish are more affected for two reasons, less ability to vent gas at a given pressure than larger fish and air volume to weight is greater.
Schneider	NOAA Fisheries. Unpublished report for the Washington and Oregon adaptive management team	Washington and Oregon State-Adaptive management team Draft resident fish literature review	2008 ✔	Reviews 37 studies, reports and letters dealing with effects of TDG on non-salmonid organisms (and some salmon). Provides a table of effects for comparison.
Schrock, Beeman, Haner, Hans, Hotchkiss, Sauter, Vanderkooi, Gale, Petrusso, Maule	USGS Columbia River Research Laboratory, Cook, WA for USDE, BPA Portland, OR Project No 87-401 Contract No DE-AI179-87BP35245	Assessment of smolt condition for travel time analysis. Project review 1987-1997	1997 ✔	***Purpose***: Find out how long it takes for juvenile salmon to migrate down the Columbia and Snake River and the effect of migration timing on smoltification and fish health. ***Results***: In-river migration timing is an important part of the smoltification process and plays a large part in smolt condition. River flow was the only significant predictor of travel time for steelhead, while additional factors affected time of travel for spring Chinook.
Smith	MFR Paper 1081 From Marine Fisheries Review Vol 36, No 8, August 1974	Distribution of seaward migrating Chinook salmon and steelhead trout in the Snake River above Lower Monumental Dam.	1974 ✔	***Purpose:*** Determine migration depth of juvenile Chinook and steelhead above Lower Monumental Dam to assess exposure to TDG. ***Results:*** 58% Chinook and 36% steelhead above 3 m deep. Of these 80% were above 2 m deep. Steelhead were distributed uniformly across the reservoir, Chinook toward the middle.
Smith, Pugh, Monan	Special Scientific Report—Fisheries No 566. US Dept of Interior Fish and Wildlife Service	Horizontal and vertical distribution of juvenile salmonids in upper Mayfield reservoir, Washington	1968 ✔	***Purpose***: Determine depth of downstream migration of juvenile salmon. ***Results***: 87% of juvenile salmon were above 7.3 m. Fish species captured were not mentioned but acknowledged that sampling varied with abundance and size of fish and fluctuations in flow.

Author	Publisher	Title	Date ✔ =have copy	Summary
Smith	The Progressive Fish Culturist 50:98-103	Communications: Histopathy of gas bubble disease in juvenile rainbow trout	1988	Report unavailable
Speare	Journal of Comparative Pathology 103:421-432	Histopathology and ultrastructure of ocular lesions associated with gas bubble disease in salmonids	1991	Report unavailable
Speare	Journal of Comparative Pathology 104:327-335	Endothelial lesions associated with gas bubble disease in fish	1991	Report unavailable
Stark	M.Sc Thesis, University of Idaho 104 p	Effects of water level fluctuations on benthic macroinvertebrates in the Hanford Reach, Columbia River	2001	Report unavailable
Stevens, Nebeker, Baker	Transactions of the American Fisheries Society 109: 751-754	Avoidance response of salmon and trout to air-supersaturated water	1980 ✔	***Purpose***: Determine if juvenile hatchery sockeye, coho, Chinook, rainbow trout, and steelhead horizontally avoided air supersaturated water at 115, 125 and 145% TDG in water 0.92 m deep. ***Results***: Steelhead did not show avoidance behavior. Sockeye, coho, Chinook and rainbow trout consistently avoided 125 and 145% TDG but not always 115% TDG.

Author	Publisher	Title	Date ✔ =have copy	Summary
Stroud, Bouck, Nebeker	The Electrochemical Society, Princeton, NJ. PP 435-489 in W.A. Adams [editor], Chemistry and physics of aqueous gas solutions and Tech. paper No 3957	Pathology of acute and chronic exposure of salmonid fishes to gas supersaturated water	1975 ✔	A write-up synthesizing 26 scientific studies of effects of TDG on: eggs, fry, juveniles and adult salmon.
Toner, Ryan, Dawley	NMFS NW Fisheries Science Center, Seattle, WA report to USACE Contract No E96930036, Portland	Evaluation of the effects of dissolved gas supersaturation on fish and invertebrates downstream of Bonneville, Ice Harbor, and Priest Rapids Dams, 1994	1995 ✔	***Purpose***: Evaluate external bubbles of in-river TDG on 22 species of fish and 23 species of invertebrates below Bonneville at RkM 229-218 and Ice Harbor Dam at RkM 13.7-1.6 primarily using a stick seine sampling <1 m deep and sometimes using a beach seine no more than 3.4m deep and electrofishing, and pump and ponar bottom samplers at depths <0.6 m and a surface plankton net. Evaluate aquatic organisms held in cages for TDG harm. ***Results***: Only bubbles seen downstream from Bonneville were from juvenile spring Chinook in May when TDG levels were between 110 and 119%. Higher levels of TDG at Ice Harbor to 132% caused higher levels of GBD in fish and invertebrates at this location. In order of descending symptoms, smallmouth bass had the most, then yellow perch, largemouth bass, pumpkinseed, and largescale suckers. In caged fish held between 114-117% TDG, most signs were from fish within 0.5 m deep but signs appeared in fish held in a 0-4 m pen. Hatchery fish seemed more susceptible to TDG.
Toner, Dawley	NMFS NW Fisheries Science Center, Seattle, WA report to USACE Contract No E96940029 Portland	Evaluation of the effects of dissolved gas supersaturation on fish and invertebrates downstream of Bonneville, Ice Harbor, and Priest Rapids Dams, 1993	1995 ✔	***Purpose***: Evaluate effect of in-river TDG on 17 species of fish and 3 species of invertebrates below Bonneville at RkM 62-228 using a 3.4 m deep beach seine, a stick seine sampling <1 m deep, and a ponar bottom sampler at depths <2 m. and caged fish held in 0.25 m deep water. ***Results***: Some external signs of GBD were observed but it was difficult to draw any conclusions about what levels affected the organisms because of small and varying sample size (5 insect larvae for instance), or varying capture methods, or inconsistency of TDG concentrations such as dilution from the Willamette and levels between areas of the river and in duration.

Author	Publisher	Title	Date ✔ =have copy	Summary
Venditti, Robinson, Beeman, Adams, Maule	USGS, Cook, WA for USBOR, Boise	Gas bubble disease in resident fish below Grand Coulee Dam: 1999 annual report of research	2001	Report unavailable
Ward and J A Stanford, editors	In J.V. The Ecology of Regulated Streams, Plenum Press, New York and London, 99 365-376	Macroinvertebrate response to flow manipulation in the Strawberry River, Utah	1979	Report unavailable
Wedemeyer, Saunders, Clark	Marine Fishery review 42:1-14	Environmental factors affecting smoltification and early marine survival of anadromous salmonids	1980	Report unavailable
Weber, Schiewe	NMFS NW Fisheries Center, Seattle, WA, Fisheries Biologist 1976	Morphology and function of the lateral line of juvenile steelhead trout in relation to gas bubble disease	1976 ✔	***Purpose***: Compare normal lateral line electric responses to those of juvenile steelhead held at different temperature with bubbles present in the lateral line. ***Results*:** Bubbles in the lateral line block the sensory nerves from responding to stimuli, preventing fish from detecting objects or predators. This can be reversed when bubbles disappear. There was a strong correlation to temperature.
Weiland, Mesa, Maule	Journal of Aquatic Animal Health 11:123-129	Influence of infection with Renibacterium salmoninarum on susceptibility of juvenile spring Chinook salmon to gas bubble trauma.	1999 ✔	***Purpose***: Investigate the influence of infection with Renibacterium salmoninarium (Rs) on juvenile hatchery spring Chinook on susceptibility to 120% GBD at 12°C for 96 hours. ***Results***: GBD deaths occurred sooner and more often in infected juvenile Chinook.

Author	Publisher	Title	Date ✔ =have copy	Summary
Weitcamp,	Parametrix for Idaho Power Company	Dissolved gas supersaturation in the Columbia River system: salmon bioassay, and depth distribution studies 1973 and 1974	1974 ✔	***Purpose***: Understand effects of gas supersaturation on depth distribution at Rock Island Dam. ***Results***: See Weitcamp 1977 doctoral dissertation.
Weitcamp	University of Washington. College of Fisheries Doctoral thesis	Gas bubble disease of resident fish and juvenile salmonids in the Columbia River system	1977 ✔	***Purpose***: Evaluate the adequacy of lab studies on biological impacts of TDG to represent impacts of TDG on caged pre-smolting juvenile hatchery Chinook salmon in the Rock Island Dam forebay on the Columbia River. ***Results***: When provided with a choice within the cage of water up to 4 m in depth, no mortalities occurred within 20 days at 120-128% TDG; no actual depth recording of the fish was able to be made. Intermittent exposure to surface pressures reduced GBD. Most fish held at 3-4 m after exposure were able to recover. At 1 meter deep for 10 days at 119-123% TDG mortalities occurred; below this depth mortalities occurred between 123-26% TDG.
Weitcamp	Parametrix, Seattle, WA	Dissolved gas supersaturation: Live cage bioassays at Rock Island Dam, Washington	1975 ✔	***Purpose***: Understand effects of gas supersaturation on depth distribution at Rock Island Dam. ***Results*:** See Weitcamp 1977 doctoral dissertation.
Weitcamp, Sullivan, Swant, SosSantos	Transactions of the American Fisheries Society 132:865-876	Gas bubble disease in resident fish in the lower Clark Fork river	2003a ✔	***Purpose***: Learn about the occurrence of external signs of bubbles in 17 species of resident fish collected within 2 m of the surface mostly in side channels of the lower Clark Fork River from 1997-2000. Also learn about effects of high TDG on cutthroat and rainbow trout held in live cages. ***Results***: Low incidence of gas bubble trauma found. During high flow years when TDG was >120% more fish had bubbles. When TDG was less than 120%, 1 brown trout was found with bubbles. TDG levels were reported from monitors located at the dams. No side channel TDG levels was mentioned though these areas were reported as monitored for TDG. ***Note*:** Since TDG levels are known to be substantially less in side channels of other rivers, TDG measurement/maps are needed for comparison or a study about behavior of resident fish in the Clark Fork regarding time spent between side channels and main channel. –see Weitcamp 2003b, *Behavior of resident fish relative to total dissolved gas supersaturation in the lower Clark Fork River*.

Author	Publisher	Title	Date ✔ =have copy	Summary
Weitcamp, Sullivan, Swant, SosSantos	Transactions of the American Fisheries Society and unpublished report to Avista Corp by Parametrix	Behavior of resident fish relative to total dissolved gas supersaturation in the lower Clark Fork river.	2003b ✔	***Purpose***: Determine depth preference behavior over time for 27 radio-tagged rainbow trout, 14 cutthroat trout, 16 brown trout, 6 bull trout, 4, whitefish, 5 pikeminnow and 7 largescale suckers in the Clark Fork River and Lake Pend Oreille from 1998-2000. ***Results***: Each species remained above 2 m in depth about half the time. Rainbow trout had the shallowest median depth of 1.3 m. Variation within species between maintaining a constant depth for several days to changing depth every day by > 1 m. Tagged fish mostly detected near the edges of the river. Recorded TDG levels where fish were detected were within 1-2% of the station monitors in the mainstem and TDG levels were within 1-2% across the river.
Weitcamp	Parametrix, unpublished review	Draft total dissolved gas literature 1980-2007. An annotated bibiliography	2008 ✔	A compilation of available literature dealing with TDG. Includes a key-word index.
Weitkamp	Parametrix, American Fisheries Society	A review of dissolved gas supersaturation literature	1980 ✔	Literature review.
Wesley, Ebel	Fishery Bulletin Vol 68 No 1 Bureau of Commercial Fisheries Biological Laboratory, Seattle, WA	Supersaturation of nitrogen in the Columbia River and its effect on salmon and steelhead trout	1969 ✔	***Purpose***: Learn about the nitrogen supersaturation in the Columbia River at 26 stations mid-reservoir in the forebays and on the spill side at ~10 meter depths from Grand Coulee Dam to Astoria in 1966 and from Priest rapids Dam on down in 1967. ***Results***: Nitrogen was near 100% saturation when spill was not occurring and high in the spring and summer during spills. ***Note***: Early research often reported nitrogen saturation which showed higher levels than if TDG was reported instead.

Author	Publisher	Title	Date ✔ =have copy	Summary
White, Phillips, Liknes, Brammer, Connor, Fidler, Williams, Dwyer	Report to Montana Cooperative Fishery Unit, Montana State University to USBOR, Washington DC	Effects of supersaturation of dissolved gases on the fishery of the Bighorn River downstream of the Yellowtail Afterbay Dam	1991 ✔	***Purpose***: Understand the effects of TDG on brown and rainbow trout in a low gradient (~3feet/mile) relatively shallow river. ***Results***: Brown trout showed earlier symptoms at less saturation than rainbow trout. GBD (observable signs) increased more rapidly in large fish. Swim bladder inflation occurs ~103% and causes undo buoyancy especially in trout fry and juveniles. Vascular system bubbles formed at 112% TDG. ***Note***: In this river, the percent of oxygen to nitrogen increased downstream. Higher oxygen in the mix means less effects on aquatic organisms. Is there any study in the Columbia that looked at this, especially in areas of high plant populations like the Rocky Reach pool?