Evaluation of TDG Biological Effects Research:
Toward assessment of appropriate Washington State Water Quality TDG criteria for the Columbia and Snake Rivers.

A literature review

September, 2007
Washington Department of Ecology

Chris Maynard

Introduction

The purpose of this review is to provide information to assess the appropriate water quality criteria for total dissolved gas (TDG) supersaturation in freshwater in Washington. The Environmental Protection Agency under the federal Clean Water Act developed a national criterion of 110% 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 adjusted their TDG criteria upward to 115% in the forebays and 120% in the tailraces on the Columbia and Snake Rivers in order to allow spill for juvenile salmon so they can avoid harm from going through the turbines. Both states have an instantaneous limit during the fish spill season of 125% TDG.

After the literature review, a short synthesis of what is known about Gas Bubble Disease (GBD) in aquatic organisms is provided as is a short list of gaps in what is known about GBD occurrence.

For policy reviewers regarding the adequacy of the 115/120% criteria on the Columbia/Snake Rivers:

Green font = Suggested studies to review **Blue font =** Six studies to read if you don't have much time

Methods

The studies listed in this review were found through a search of 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 and USGS libraries and requests to researchers for copies. All studies obtained were reviewed.

Since the national EPA criteria of 110% TDG was recommended for states in the 1970s base on lab studies, much more research has been done on TDG biological effects; almost all of it in regards to the Columbia and Snake River salmon. This literature search focuses on the biological effects of TDG in the range of 103 to 120% TDG. This is for several reasons:

- The 115% criteria in the forebays of the dams on the Snake and Columbia is in dispute. From a water quality perspective, this dispute is about reducing protection from higher levels of TDG (120%) in order to increase protection for juvenile salmon from harm going through the turbine and providing faster passage downstream.
- Research shows that exposure to TDG levels greater than 120% harm aquatic organisms consistently enough to leave review of TDG concentrations higher than this out of consideration here.

- Potential harm to shallow dwelling organisms susceptible to 103% TDG and greater.

Also included are studies that provided information about fish depth preferences and juvenile salmonid migration timing. This is because TDG trauma is in part 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 batifish, and emerging aquatic insects may be available but were not identified or obtained.

The great majority of TDG studies investigate salmonids in the Columbia River system. Many of those studies use spring juvenile Chinook because they have been readily obtainable and easier to work with because of their large size. In selecting studies for review, I tried to obtain studies of other species of salmon, non salmonid organisms, and at all life stages. During the review, organisms of special concern became apparent because of a lack of information combined with potential surface exposure to TDG. Top amongst these were larval non-salmonid fish (Cornacchia, *The effects of dissolved gas supersaturation on larval striped bass;* and Counihan, *The effects of dissolved gas supersaturation on white sturgeon larvae*), amphibians (*Colt, Gas bubble trauma in the bullfrog*), and zooplankton (no studies found other than larval fish).

Some early studies prior to about 1974 were not requested. This is because some only measured total dissolved nitrogen. Both nitrogen and oxygen combine to contribute to gas bubble disease 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 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 is so comparisons, where possible can be made between studies. Fish depth and duration preferences are not duplicated in lab studies nor can they be entirely duplicated in live cage studies.

Literature Review

158 studies, literature searches and other documents obtained and reviewed
239 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 cy 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 5m deep drift net/container. *Result*: During the day over 70% of fish in top 3 meters. More uniform depth distribution occurred at night. Dawn and early morning found fish closer to the surface. Fish in the upper 1 meter 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 DOE, Hydropower Program, Idaho Falls, ID	Laboratory studies of the effects of pressure and dissolved gas supersaturation on turbine-passed fish	2001	
Absolom, Dawley, Sandford	NOAA Fisheries for USDE, BPA, Portland, OR Project No 96-24 Contract No	Changes in gas bubble disease signs of migrating juvenile salmonids experimentally exposed to supersaturated	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
	96BI93892	gasses 1997		
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*: Answer: Do radio transmitters affect behavior of juvenile Chinook? *Result*: 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 ✔	
Alderdice, Jensen, Schnute	Dept of Fisheries & 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	
Alderdice,	Aquaculture	An explanation for the	1986	Internal pressure salmon and trout eggs are from >15 mm mercury after fertilization,

Author	Publisher	Title	Date ✔=have copy	Summary
Jensen	49:85-88	high resistance of incubating salmon eggs to atmospheric gas supersaturation of water	✔	>25 mm Hg after 24 hours, and 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	
Anaonymous	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	
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	

Author	Publisher	Title	Date ✔ =have copy	Summary
Antcliffe, B., Fidler, Birtwell	Canadian Technical Report of Fisheries & 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
Antcliffe, B., Fidler, Birtwell	Canadian Technical Report of Fisheries & 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, 144, 116, 122 and 140% TDG at 10°C on Juvenile hatchery raised rainbow trout held 1) in shallow 0.25m water tanks and 2) exposed repeatedly to variable depths. *Results*: For fish held at 0.25m, 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 0.25m 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 3m 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 & Aquatic Sciences 2501	Effects of prior exposure to hydrostatic pressure on rainbow trout survival in air-saturated water	2003	Obtain
Aquatechnics Inc	Final report on contract No DACW68-96-	Histopathic assessment of Chinook Salmon Gill tissues exposed to	1997	

Author	Publisher	Title	Date ✔ =have copy	Summary
	D-002 Subcontract No 248800-B-B8. Battelle, Richland, WA	gas supersaturation		
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.
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	
Aspen Applied Sciences	Aspen Applied Sciences. For Battlelle NW Division, US Army Corps of Engineers,	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 evaluate 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*: Fish that died all gills occluded with bubbles, many has bubbles in the bulbous

Author	Publisher	Title	Date ✔ =have copy	Summary
	Walla Walla Dist, Fidler, L.			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 5 month old shad exposed for four hours at 10°C and 0.15 meters 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.
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 than found during sampling at 125.9% TDG when 6% of the fish sampled had symptoms. Cumulatively for four dams (Bonneville, John Day, McNary and Lower Monumental), 0.6% if smolts captured in-river 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. Time between capture and symptom monitoring, though recorded, was not included in the report.
Backman, Evans,	CRITFC, BPA project No 93-	Symptoms of gas bubble trauma induced	1997 ✔	*Purpose:* to determine external TDG signs in adult migrating sockeye, Chinook and Steelhead salmon diverted at fish ladders at Bonneville and caught by hoop-net near

Author	Publisher	Title	Date ✔ =have copy	Summary
Hawbecker	031	in salmon by total dissolved gas supersaturation of the Snake and Columbia Rivers, USA 1997 annual report		the Dalles and external signs in juvenile salmon caught in-river by purse seine and cod trawl, and beach seine. *Results*: TDG levels when juvenile salmonid symptoms were found 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%). 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.
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 and diversion at the dam and beach seine. *Results:* TDG levels when symptoms were found 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%). 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 TDG impacts to adult Chinook, sockeye & steelhead salmon at Bonneville Dam. *Results:* 1995-1999. External signs. No description of time between collection and examination except 'samples were collected whenever possible'. No difference in GBD observed between species for TDG levels <125%. Sockeye had most bubbles when >125% TDG. 0.1% observed with TDG when levels <126%..
Backman, T., Evans, Robertson	Draft Report. Columbia River Intertribal Fish Commission Project No 93-	Symptoms of gas bubble trauma induced in salmon by total dissolved gas supersaturation of the	2000	

Author	Publisher	Title	Date ✔ =have copy	Summary
	008-02	Snake and Columbia Rivers		
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 8 locations: tailrace & forebay Bonneville, John Day & 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 & 97 and two lower flow years 1998 & 1999.
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

Author	Publisher	Title	Date ✔ =have copy	Summary
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 River below Ice harbor Dam between April 22 and June 1. *Results*: Before May 17, little 'holding' was seen in the reservoir (av 6.5 hours). After May 17 many held in shallow (<2m) water for several days (av 51 hours) up to 14.5 days. Fish changed their vertical position often 0.2-0.3m/minute. They ranged from 0.0 to 12 m (limit of detection) deep, averaging 2.8 m for steelhead and 1.7m for Chinook. *Note*: Size of fish greater than actual river populations, compensation depth was best conservative estimate based on Fidler, Knittle
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 swam0.2m 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,	Western Fisheries	Gas bubble disease in resident fish below	2003 ✔	*Purpose*: Determine relative exposure of pikeminnow, bridgelip sucker, walleye, longnose sucker, largescale sucker in the river and Steelhead in net pens to TDG during

Author	Publisher	Title	Date ✔ =have copy	Summary
Morris, Gadomski, Adams, Maule, et al	Research Center, Columbia River Research Laboratory	Grand Coulee Dam		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 meters or more for each species. Species abundance changed between the three sucker species, possibly due to TDG. 7 Steelhead were also recovered from their 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.
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 meters in the Snake and 2.3 in McNary forebay. They were deeper at night than day; Chinook 1.5 meters in Snake to 3.2 meters 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	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.

Author	Publisher	Title	Date ✔=have copy	Summary
	of the American Fisheries Society 99:664-671			
Bently, Dawley, Newcolm	Pp 41-46 in DH Fiskeisen & Schneider, Gas bubble Disease. Technical info center ERDA. NTIS CONF-741033	Some effects of excess dissolved gas on squawfish	1976	
Beyer, D'Aoust, Smith	Undersea Biomed. Research 3: 321-338	Decompression-induced bubble formation in salmonids: Comparison to gas bubble disease.	1976	
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 & Bouck	1995 ✔	Identified critical assumptions of gas bubble monitoring program to check out: 1. samples taken represent entire river & 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

Author	Publisher	Title	Date ✔ =have copy	Summary
Birtwell, I., Korstrom, Fink	Dept of Oceans & 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	
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	*Purpose*: Investigate predator avoidance of juvenile salmon after exposure to 115% for 2 days, 120% for 24 hours and 130% TDG for 12 hours. *Results*: obtain report
Bjorn	Report to Corps Fish Research Scientific Review Subcommittee. Idaho Cooperative Fish and Wildlife Research Unit,	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. [reviewed incomplete report only through page 11]

Author	Publisher	Title	Date ✔ =have copy	Summary
	U of Idaho, Moscow, ID			
Blahm, McConnell, Snyder	NMFS, Prescott, OR	Effects of supersaturated Columbia River water on the survival of juvenile salmonids April to June 1972	1973	
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,	Transactions of the American Fisheries Society 109: 703-707	Etiology of gas bubble disease	1980	
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 & Aquatic Science	Effects of fasting and vitamin c on tolerance to air supersaturated	1983	

Author	Publisher	Title	Date ✔ =have copy	Summary
		water by rainbow trout		
Bouck	CR Basin Fish & Wildlife program	Conceptual Plans for Qualitatively and Quantitatively improving artificial propagation of anadromous salmonids in the Columbia River Basin	1986 ✔	
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 ratio 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

Author	Publisher	Title	Date ✔ =have copy	Summary
				signs not apparent in early mortalities, more prevalent in 6 day mortalities. Steelhead & 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".
Bouck	In Fickeisen & 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,	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

Author	Publisher	Title	Date ✔ =have copy	Summary
	USACE, and BPA. A workshop in Portland Or April 19-20, 1994			
Bowser, Toal, Robinette, Brunson	Fish culture 45:208-209	Colemic distension in channel catfish fingerlings	1983	
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	
Canadian Council of Resource and Environmental Ministers	Task Force on Water Quality Guidelines, Ottowa, ONT	Canadian Water Quality Guidelines	1987	
Carlson	Aspen Applied Sciences Inc, Kalispell, Montana Under subcontract No.	A survey of noninvasive technologies applicable to the examination of fish for signs of gas	1996 ✔	Not a study but gives background and recommends investigation into 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

Author	Publisher	Title	Date ✔ =have copy	Summary
	29245_A_1Q, Work Order No. 3	bubble disease		ultrasound and ophthalmologic techniques were recommended.
Carmichael, Tomasso	Texas Journal of Science 35:315-321	Swim Bladder stress syndrome in largemouth bass	1984	
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 20-30m 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	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 has a decrease in blood clotting time. Vascular bubbles, it was thought could cause increase clotting in fish.

Author	Publisher	Title	Date ✔=have copy	Summary
	Energy research and Development Admin, Oak Ridge, TN pp 93-95			
Chamberlain, Neill, romanowsky, Strawn	Transactions of the American Fisheries Society	Verticle responses of Atlantic Croaker to gas supersaturation and temperature change	1980	
Clay, Barker, Testaverde, Marcello, McLeod	In Fickeisen & 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 shallow a 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 & 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,	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.

Author	Publisher	Title	Date ✔ =have copy	Summary
	Portland, OR			Develop a numeric grading procedure.
Colt,	Aquaculture Eng. 5:49-85	Gas supersaturation – impact on the design and operation of aquatic systems	1986	
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.
Colt, Fidler, Elston	Aquaculture 38:127-136	Effects of gas-supersaturated water on rana catesbeiana tadpoles	1984a	
Colt, Fidler, Elston	Journal of Herpetology 18: 131-137	Gas bubble disease in the African clawed frog	1984b	
Colt, Orwicz, Brooks	Journal of World Aquaculture 18:229-236	Gas bubble trauma in the bullfrog	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
Cornacchia, Colt	Juvenile Fish Distribution. Journal of Fish	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°C. For 10-19 day old larvae 33-35%

Author	Publisher	Title	Date ✔=have copy	Summary
	Disease 7(1):15-27 7: 15-27			mortality at 106% 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 make it 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.
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. TDG trauma 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% trauma; exposed at 130% , 85% trauma.
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	
Coutant, Backman,	Report to NMFS Science	Report and recommendations Panel	1994 ✔	For the purpose of developing a GBD monitoring protocol: An assembly of scientists for a 1-1/2 day panel to answer specific questions for

Author	Publisher	Title	Date ✔ =have copy	Summary
Dawley, Fidler, Krise, Nebeker	Center, Seattle, WA	on Gas Bubble Disease		Columbia River TDG: 1. What is known about GBD? Much known about certain species in captivity mostly for mortality mostly, 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 & 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 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	
Cramer, S.	Report to the Direct Service Industries—Cramer & Associates, Inc. Gresham, OR	Seasonal changes in survival of yearling Chinook smolts emigrating through the Snake River in 1995 as estimated from	1996	Obtain report

Author	Publisher	Title	Date ✔ =have copy	Summary
		detections of PIT tags		
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, deeper water species progressively with time 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 US 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	
Dawley, Ledgerwood, Blahm, Rankis	Annual report BPA Agreement DE-A179-83BP39652	Migration characteristics and survival of Juvenile Salmonids entering the Columbia River	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
		Estuary during 1982		
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 movements rates, resident time in the estuary, effect of river flow using beach seine. *Results*: Fish 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 Chinook within 3m 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	Obtain
Dawley, E.	Report to the Corps of Engineers. Portland	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 8 hrs was 120%. TDG trauma was inconclusive; no GBD signs

Author	Publisher	Title	Date ✔ =have copy	Summary
	Contract #DACW57-85-F-0623 & Coastal Zone and Estuarine Studies Division Northwest & Alaska Fisheries Center NMFS, NOAA 2725 Montlake Blvd E, Seattle, WA			were observed. Depth preferences in the cages were observed: 2% of yearling Chinook shallower than 1.2m; 9% between 1.2 and 2.4 m. Yearling Chinook, 6% above 1.2 m. Small sample size in river showed yearlings, 48% were in the top meter. In river detections: shallower than 3m: Yearling Chinook--Spillway: 8%, Powerhouse: 22% Subyearling Chinook--Spillway: 15%, Powerhouse: 10% All were deeper at night. Detection at the dams is not likely accurate for assessing in-river migrant depths
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 8 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 meters 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

Author	Publisher	Title	Date ✔ =have copy	Summary
				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 1.8m of water in the Monumental Dam reservoir on the Snake River; this proportion increases at night for Chinook and decreases 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.
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 & 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	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 1 year 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+ river caught juvenile steelhead: 30 hours.

Author	Publisher	Title	Date ✔ =have copy	Summary
	information Center, Oak Ridge, TN			
Doulos, kindschi	Aquatic Fish Management 21:39-46	Effects of oxygen supersaturation on the culture of cutthroat trout and rainbow trout	1990	
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 0.6m deep, <105%. For freshwater and marine environments: 3/5 of scientists recommended <115% and 2/5 recommended<110% TDG.
DeHart	Fish Passage Center, BPA	2002 Annual report	2002	
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 ?% TDG. *Results*: Increase temperatures reduces 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	Effects of Supersaturation of nitrogen in the Columbia River and its effect on salmon and	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.

Author	Publisher	Title	Date ✔ =have copy	Summary
	Report Bulletin Vol 68 No 1	steelhead trout		
Ecology, WA Dept & 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‘ below Bonneville 600‘ below The Dalles 1700‘ below John Day 1000‘ 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‘ below Ice harbor 1200‘ below Lower Monumental 1500‘ below Little Goose 1500‘ below Lower Granite Flood flow levels were set above which water quality standards do not apply (7Q10)
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‘ below Priest Rapids 2000‘ below Wanupum 2000‘ below Rock Island

Author	Publisher	Title	Date ✔ =have copy	Summary
				1600‘ below Rocky Reach 2000‘ below Welles 2000‘ 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	Obtain
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	
Elston, Rensel	Aquatechnics, Carlsborg, WA & 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 and 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.

Author	Publisher	Title	Date ✔ =have copy	Summary
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 meters 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, in gills less than 5 minutes.
EPA Goldbook	EPA Goldbook	Gas, Total Dissolved	197? ✔	Review of literature and recommended 110% TDG as the nationalwater 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 being brought to surface pressures from 18 meters due to expansion of swim bladder and respiratory failure.
Feil, Rondorf	USGS, Cook, WA for USACE, Portland, OR	Evaluation of horizontal and vertical distribution of juvenile salmonid in the Snake and Columbia Rivers in relation to total dissolved gas.	1998	Obtain
Ferguson, Absolon,	Transactions of the American	Evidence of delayed mortality on juvenile	2005 ✔	*Purpose*: Investigate what effects turbine design and efficiency has on fish passage. *Results*: 46-70% of turbine mortalities were delayed mortalities—mostly from

Author	Publisher	Title	Date ✔ =have copy	Summary
Carlson, Sandford	Fisheries Society	pacific salmon passing through turbines at the Columbia River Dams		predation due to sensory impacts.
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, largescale sucker collected by beach seine in streams and ponds near the Hanford Reservation exposed to high levels of TDG at 20°C in .3 M deep water. *Results*: Whitefish least tolerant, smallmouth bass most. Bluegill and pumpkinseed had similar tolerances as were channel catfish and black bullhead, as were 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 & 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	1975	*Purpose*: Test resident species susceptibility to GBD *Results*: Mountain whitefish were the most intolerant of all species tested. Other species tested in increasing order of susceptibility were cutthroat trout, largescale

Author	Publisher	Title	Date ✔ =have copy	Summary
		River organisms		sucker, and torrent sculpin.
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 meters in 132% (± 3%) TDG. *Results*: TDG results were reported as depth compensation exposures; so though water was held at 132% saturation, 3.2 meters deep was reported as 100% TDG, 1.38 meters as 116% TDG and 120% TDG as 1 meter deep. At 1.38 meters (equivalent of 116% TDG), all mountain whitefish were dead after 96 hours and after 50 hours at 1 meter deep (120% TDG). Nine of 10 cutthroat trout were dead at 1.38 meters (116%) in 10 days and all cutthroat and suckers were dead after 34 hours at 1 meter deep (120%). 90% suckers survived at 1.38 meters (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 & 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 4 days decreased with warmer water. In : 8˚C: 127%, 12˚C: 125%, 16˚C: 124% and 20˚C 123%.
Fidler	Aspen Applied	A survey of	1996	

Author	Publisher	Title	Date ✔=have copy	Summary
	Sciences for Battelle, Richland, WA	noninvasive technologies applicable to the examination of fish for signs of gas bubble disease		
Fidler, L.E.	Penny Applied Sciences. Report to Dept of Fisheries & Oceans, BC	A study of biophysical phenomena associated with gas bubble trauma in fishes	1984	
Fidler	Doctoral dissertation, Dept of Zoology, University of British Columbia	Gas bubble trauma in fish	1988	obtain
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	
Fidler,	Contract report	British Columbia	1997	*Purpose*: Not a study but a review literature on TDG effects on salmon and trout, other

Author	Publisher	Title	Date ✔ =have copy	Summary
Miller	to BC Ministry of Environment, Environment Canada & Dept of Fisheries and Oceans by Aspen Applied Sciences	Water Quality guidelines for dissolved gas supersaturation-technical report	✔	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 & 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 first symptom beginning at 70mmhg 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 128mmhg ~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. Regardless of depth, Some species may use shallow water habitat for feeding, spawning, rearing. If fish were to swim deeper to avoid TDG [an unproved assumption for all fish] or maintain a neutral buoyancy, prime habitat is 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. [unknown in the Columbia] 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-

Author	Publisher	Title	Date ✔ =have copy	Summary
				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 shows that the other aquatic species researched showed no more sensitivity than the most sensitive species of salmonids. Good background and references to studies
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	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	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
		the lower Columbia River		
Fish Passage Center	http://www.fpc.org/documents/misc_reports/PresentationDEQ_files/frame.htm	Spill and GBD Meeting with ODEQ	2006 ✔	Gives spill & 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 monitors and criterion because of localized effects from temperature BP and biological processes.
Frizell	Bureau of Reclamation	Dissolved gas Supersaturation study for Grand Coulee Dam	1996	
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 5 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.
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	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. The sites chosen by Chum flow was slower, temperature higher (due to upwelling); the sites chosen by fall Chinook has faster flows and down-welling colder water into the gravel.

Author	Publisher	Title	Date ✔ =have copy	Summary
		Columbia River		*Note*: this study was reviewed because these shallow-water spawning, incubating, hatching species can be 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
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 externally internally radiotagged adult spring Chinook and followed April – June (higher TDG) and fall Chinook during September to mid October (100% TDG). *Results*: Spring Chinook swam deeper during the high gas (124-127%) periods than during lower gas periods and deeper than migrating adult fall Chinook.
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 0.3M of water to exposure to TDG at 8°C. *Results*: Carp mortalities began above 114.1% TDG 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 in Italy and in the Columbia at 127% at 8°C (Fickeisen 1975) in 0.35m 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	Same articles?
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	1983	Same articles?

Author	Publisher	Title	Date ✔ =have copy	Summary
		conditions		
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 0.28m 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 4 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 fish 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.
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	

Author	Publisher	Title	Date ✔ =have copy	Summary
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	
Jensen, E	Canadian Data Report, Fisheries Aquatic Sciences 501	Literature data on salmonid response to gas supersaturation and ancillary factors	1985	
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.
Johnson, Hawkes,	Annual Report NOAA NW	Monitoring of Downstream Salmon	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

Author	Publisher	Title	Date ✔=have copy	Summary
Smith, Fredricks	Div. for BPA, Portland. Project 84-14	and Steelhead at Federal Hydroelectric Facilities		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) of which there are continuous reports and information available into 2007.
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 & 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. They constantly moved up and down quickly in the water column and this varied with each reservoir: time spent in the upper 1 meter on each excursion was typically seconds and time spent >2 meters or below before ascending again was between 2,.1 and 3.4 minutes. The maximum time spent above 1 meter was 1.3 hours and above 2 meters was 19 hours. They averaged below 2 meters deep. They were above 1 meter in depth 3% at Bonneville) and 9% at Little Goose 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 in June were highest in June. 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, Burke	Idaho Cooperative Fish and Wildlife Research Unit Tech Report 2005 for the Corps of Engineers, Walla Walla & Portland Districts	Hydrostatic compensation benefits of adult Chinook salmon and steelhead migrating through the Columbia-Snake hydro-system, 2002	2005 ✔	*Purpose*: This study seems to be a compilation of the other two year 2000 tracking studies. Need to contact author. Different tags used? *Results*:
Johnson, E., Clabough, Peery, Bjornn, Stuehrenberg	Idaho Cooperative Fish and Wildlife Research Unit Tech Report 2005 for the Corps of Engineers, Walla Walla & 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 meters of the shoreline. Median migration depth varied between individual fish from 1-2 meters and 9-10 meters with the bulk of the fish averaged well below 2 meters deep. They were above 1 meter 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 meter varied from the longest time of 17 hours and above 2 meters 8.5 days to seconds

Author	Publisher	Title	Date ✔ =have copy	Summary
				with much variation between individuals and the median time spent in shallow 1 meter 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 in June. 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.
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.
Knittle, Chapman, Garton	Transactions of the American Fisheries Society 109:755-759 Missing one page	Effects of hydrostatic pressure on steelhead survival in air-supersaturated water	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*: First time surface exposure at non-lethal period, the compensation time when held at 3 meters 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 meters 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	National Fisheries &	Effects of one-year exposures to gas	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

Author	Publisher	Title	Date ✔=have copy	Summary
	Research Development Laboratory, USF&WS, Wellsboro, PA. The Progressive Fish Culturist	supersaturation on Lake Trout		°C water .15m deep. *Results*: Exposure gas levels were reduced greater than 2% to 100% TDG in the results reported for the 102% test and reduced more in the higher concentration gas treatments than reported for the incoming water because of oxygen metabolized by the fish. Few TDG measurements were either taken or reported after initial calibration. 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.
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	
Lothrop, Kiefer, Nigro, Tweit, Schaller	State, Federal & 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
Lutz, D.	Transactions of the American Fisheries	Gas supersaturation and trauma in fish downstream from a	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.

Author	Publisher	Title	Date ✔=have copy	Summary
	Society 124:423-436	Midwestern reservoir		*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.
Malouf, Maurer, Epifano			1972	Oysters, obtain
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 ✔	Obtain
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	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. and *Results*: Ch 1. Accuracy was 0.016 meter. Test group swam 0.2m 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.

Author	Publisher	Title	Date ✔ =have copy	Summary
		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		
Malouf, Keck, Maurer, Epifanio	Fisheries Resource Board, Canada	Occurrence of gas bubble disease in three species of bivalve mollusks	1972	
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 ✔	
McGrath, Dawley, Geist	PNNL-15525 Pacific Northwest National Laboratory. Prepared for the USACE,	Total dissolved gas effects on fishes of the lower Columbia River: Synthesis of the Literature 1996-2005	2006 ✔	A review of literature

Author	Publisher	Title	Date ✔ =have copy	Summary
	Portland Dist, Portland OR with USDEO contract No DE-AC05-76RL01830			
McKee, Wolf	California State Water Quality board Publication # 3-A. 550pp	Water Quality Criterion 2nd Edition	1963	
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 0.2m 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%) harm to fish needs to asses both gasses. 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].
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	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

Author	Publisher	Title	Date ✔ =have copy	Summary
		supersaturation		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 meters 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 0.27m deep water at 12˚C. *Results*: Chinook:110% no mortality in 22 days, bubbles in fins, gills and lateral line 113% average, no mortalities in 22 days. 60% had fin bubbles at 22 days 120%, 20% mortality variable from 1.7 to 5 days. >60% bubbles in fins also variable Death was 40-120 hours for Chinook and 20-35 hours in steelhead. At 130% death for Chinook was 3-6 hours, steelhead-5-7 hours Symptoms varied between species
Mesa, Warren, Mauole	National Biological Service, Columbia River Research Laboratory, Cook, WA	Progression and severity of gas bubble trauma in juvenile Chinook salmon and development of non-lethal methods for trauma assessment	Date? ~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 0.28m 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 ours 5 on.

Author	Publisher	Title	Date ✔=have copy	Summary
	Draft			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%.
Mesa, Warren, Hans, Maule Filed under Maule : Gas Bubble trauma Monitoring and research of juvenile salmonids. 1995 Annual	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 0.28m 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%.

Author report	Publisher	Title	Date ✔ =have copy	Summary
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 0.46m 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 417.5% 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.
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	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

Author	Publisher	Title	Date ✔ =have copy	Summary
		compound and dissecting microscopes		bubbles
Montgomery Watson	Project No 93-8 US 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, pressurizing them to the equivalent of 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.26m 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)
National Academy of Science/National Academy of	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

Author	Publisher	Title	Date ✔ =have copy	Summary
Engineering				
Nebeker, Stevens Brett	In DH Fickenstein & Schneider, Gas Bubble Disease. Tech Info Center, ERDA. NTIS Conf 741033	Effects of air supersaturated water on freshwater aquatic invertebrates	1976 ✔	obtain
Nebeker,	Journal of Fisheries Resource Board	Survival of Daphnia, crayfish, and stoneflies in air supersaturated water	1976	Obtain, likely the same but more detail than the study below?
Nebeker, Stevens, Brett	In DH Fickenstein & 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 meters 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.

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 meters deep and wild caught juvenile speckled dace at 10°C and 0.25 meters deep. *Results*: The longer the time of exposure, the more bubbles found in thetissue 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	
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 effects of high 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 meters) mimicking expected natural near surface preferences for these life stages. *Results*: Gas bubbles harmed these aquatic insects less at these high exposures than expected for 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

Author	Publisher	Title	Date ✔ =have copy	Summary
				four species. Many midges and mosquitoes survived 140% saturation; it was thought because of the direct air breathing mechanisms of these insects.
Nebecker, Stevens	US EPA, Corvalis, OR, Dept of Vetinary 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 0.7m 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	
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 meters 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,	USEPA,	Survival of Steelhead	1978	*Purpose*: Determine effects of TDG by exposing hatchery steelhead eggs, embryos

Author	Publisher	Title	Date ✔ =have copy	Summary
Andros, McCrady, Stevens	Corvallis, OR	trout Eggs, Embryos, and fry in air-supersaturated water	✔	and fry to various levels of TDG supersaturation in 10°C water 0.08 meters 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.
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 meters deep for 35 days. *Results*: Blood chemistry GBD signs in juvenile steelhead exposed to 105 and 110% 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	Summary Report to NOAA Fisheries	November **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.

Author	Publisher	Title	Date ✔ =have copy	Summary
Center Colt, Barney, Elston, Dawley				
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 & Snake. Identified critical uncertainties in the smolt monitoring system. Have they been resolved?—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 not exceed those established in the 1995 BiOp of 115 forebays/120% tail waters
NOAA Fsheries Colt, Barney, Elston, Dawley	A report to the NOAA Fisheries/EPA gas bubble disease technical workgroup	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.

Author	Publisher	Title	Date ✔ =have copy	Summary
	prepared by the biological monitoring inspection team			
NOAA Fisheries	Report to BPA Task 9.2	QA/QC of 1995 gas bubble trauma monitoring on the Snake and Columbia Rivers	1996 ✔	
**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, field	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	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	Risk 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
	ppE1-E26			
NOAA Fisheries	1995 BiOp FCRPS NMFS, Northwest Region	Biological opinion Section 7 Reinitiation 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 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 ✔	Obtain
NOAA Fisheries	NOAA Fisheries Service Center, Seattle, WA	Basis for flow objectives for operation of the federal Columbia River power system	1995 ✔	
NOAA Fisheries		Annual Report to the Oregon Dept 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		Annual Report to the	2000	Report includes season's GBD external monitoring on the Columbia and TDG levels in

Author	Publisher	Title	Date ✔ =have copy	Summary
Fisheries		Oregon Dept of Environmental Quality Dec. 2000		forebays and tailraces as well as flows and reasons for spilling.
Olson, Quinn	Fishery Bulletin 91:171-178	Vertical and horizontal movements of adult Chinook salmon in the Columbia River estuary	1993	Obtain
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 3m deep (from low pool el.). No other species were reported with gas bubble signs. Fish in 3m 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	
Rucker,			1974	

Author	Publisher	Title	Date ✔ =have copy	Summary
Kangas 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%.
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	
Rucker	Progressive Fish Culture 37: 101-102	Excess nitrogen gas in water not a cause of coagulated yolk disease in Chinook salmon	1975b	
Ryan, B & 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 <3m, deep in Ice Harbor Reservoir and downstream from this dam and Bonneville and determine subsamples for fish held 4m deep for 4 days at several depths from .5 to 4m. Also determine GBD in juvenile salmon caught with puse 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 developed can predict this.
Ryan, Dawley, Nelson	North American Journal of Fisheries	Modeling the effects of supersaturated dissolved gas on	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

Author	Publisher	Title	Date ✔ =have copy	Summary
	Management 20:192-204	resident aquatic biota in the main-stem Snake and Columbia rivers		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 & fish size were weakly correlated. Fish were collected from 0 and 3 meters.
Scheiwe & 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	
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 meters deep after 50% exposure mortlaity, from 117% and 120% TDG and after 35 day 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.
Schiewe & Weber	Pgs 89-92 in Gas Bubble Disease. DH Fickeisen Editor Technical Information Center, Oak	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

Author	Publisher	Title	Date ✔ =have copy	Summary
	Ridge, TN Conf-741033			
Schiewe, Miller, Dawley, Ledgerwood, Emmett	By Fisheries Research Inst. University of WA & 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.
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.
Schrank, Ryan & Dawley	Annual Report 1995 to USDOE BPA project #96-022	Effects of Dissolved Gas supersaturation on fish residing in the Snake and Columbia	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 0-3m deep water and fish held in cages at various depths.

Author	Publisher	Title	Date ✔=have copy	Summary
[also see Ryan and Dawly]	Contract No 96 AI93605	rivers. 1996		*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 & Dawley	Annual Report 1995 to USDOE BPA project #96-022 Contract No 96 AI93605	Effects of dissolved gas supersaturation on fish & 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	
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 meters 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.
Shrimpton,	Canadian	Factors affecting swim	1990b	*Purpose*: Investigate the response of swim bladders in rainbow trout to TDG.

Author	Publisher	Title	Date ✔ =have copy	Summary
Randall, Fidler	Journal of Zoology 68:962-968	bladder volume in rainbow trout	✔	*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.
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 3m deep. Of these 80% were above 2m 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	Horizontal and Vertical distribution of juvenile salmonids in upper Mayfield reservoir, Washington	1968 ✔	*Purpose*: Determine depth of downstream migration of juvenile salmon. *Results*: Eighty seven percent of juvenile salmon were above 7.3 meters. 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
	and Wildlife Service			
Stark	M.Sc Thesis, University of Idaho 104 p	Effects of water level fluctuations on benthic macroinvertebrates in the Hanford Reach, Columbia River	2001	Obtain
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 0.92m 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.
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,	Evaluation of the effects of dissolved gas supersaturation on fish	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 <1m deep and sometimes using a

Author	Publisher	Title	Date ✔=have copy	Summary
	Seattle, WA report to USACE Contract No E96930036, Portland	and invertebrates downstream of Bonneville, ice harbor, and Priest Rapids Dams, 1994		beach seine no more than 3.4m deep and electrofishing, and pump and ponar bottom samplers at depths <0.6m 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 0.5m deep but signs appeared in fish held in a 0-4m 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 3.4m deep beach seine, a stick seine sampling <1m deep, and a ponar bottom sampler at depths <2m. and caged fish held in 0.25m 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.
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	
Wedemeyer, Saunders, Clark	Marine Fishery review 42:1-14	Environmental factors affecting smoltification and early marine survival of anadromous	1980	

Author	Publisher	Title	Date ✔ =have copy	Summary
		salmonids		
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.
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 choice within the cage of water up to 4 meters 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 meters after exposure were able to recover. At 1 meter deep for

Author	Publisher	Title	Date ✔ =have copy	Summary
				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	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 Orielle from 1998-2000. *Results*: Each species remained above 2m in depth about half the time. Rainbow trout had the shallowest median depth of 1.3 meters. Variation within species between maintaining a constant depth for several days to changing depth every day by > 1 meter. 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, 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 meters 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 mention of 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

Author	Publisher	Title	Date ✔ =have copy	Summary
				channel. –see Weitcamp 2003b, *Behavior of resident fish relative to total dissolved gas supersaturation in the lower Clark Fork River*.
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 reported nitrogen saturation, higher levels than if TDG was reported instead.
Ward and J A Stanford, editors	In J.V. The Ecology of Regulated Streams, Plenum Press, New York & London, 99 365-376	Macroinvertebrate response to flow manipulation in the Strawberry River, Utah	1979	Obtain
White, Phillips, Liknes, Brammer, Connor,	Report to Montana Cooperative Fishery Unit, Montana State	Effects of supersaturation of dissolved gases on the fishery of the Bighorn River downstream of	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.

Author	Publisher	Title	Date ✔ =have copy	Summary
Fidler, Williams, Dwyer	University to USBOR, Washington DC	the Yellowtail Afterbay Dam		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 affects 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?

Synthesis of what is known about TDG effects on aquatic organisms

1. Gas bubble disease increases in fish when fish are in shallow water (depth compensation). 10% compensation roughly occurs with each meter of depth. So if 120% TDG exists, 110% would be the biological equivalent at 1 meter deep, 100% at 2 meters, etc. Gas over 100% 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.
3. Short term death from gas bubbles increase with higher concentrations
4. Short term death from gas bubbles increase with length of exposure
5. Time to short term death from gas bubbles is lengthened when pressure is increased (with increased depth)
6. Susceptibility to gas bubble harm varies between species. Salmonids are not always the most susceptible.
7. Susceptibility between salmon species varies. Spring Chinook showed less susceptibility than other salmonids species
8. Small creatures can pass gas out of the circulatory system more easily but are susceptible to air blockages in the gut.
9. Fish vary their depth according to season, time of day, species and individuals within species.
10. Depth exposure varies for benthic organisms according to their movement (if any) and river elevations/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. Saline water does not appear to affect TDG trauma.
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 varies with temperature

18. Susceptibility to gas bubble harm increases with stress and disease
19. Repeated exposure can predispose gas bubble development on existing sites
20. Field cage studies show less TDG trauma than lab studies
21. Nitrogen to oxygen levels change. Higher oxygen in the mix reduces GBD
22. Gas supersaturation measurement technology and methodology have improved. The GBD studies before about 1980 should 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.
23. 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 in what is known 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. 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 a few recent studies on radio-tagged relatively large juvenile salmonids. There is little information on free-floating and surface dwelling organisms such as larvae of fish, crustaceans, and mollusks.
- **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:** Since 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 preferences in regard to TDG. Other depth distribution/behavior studies likely exist for some species. Some studies outside this review's locale of focus would be useful to assuming certain behaviors in the Columbia/Snake and other waters of the state. However, little information exists 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 & 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**

o **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**