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Total Dissolved Gas Effects on Fishes of the Lower Columbia River



K. E. McGrath
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D. R. Geist

Final Report

March 2006

Prepared for the U.S. Army Corps of Engineers
Portland District, Portland, Oregon
Under a Related Services Agreement
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**Pacific Northwest
National Laboratory**
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Cover photo: Bonneville Dam Spillway
Image courtesy of the U.S. Army Corps of Engineers, Portland District, Portland, Oregon

Summary

Gas supersaturation problems generated by spill from dams on the Columbia River were first identified in the 1960s. Since that time, considerable research has been conducted on effects of gas supersaturation on aquatic life, primarily juvenile salmonids. Also since that time, modifications to dam structures and operations have reduced supersaturated gas levels produced by the dams. The limit for total dissolved gas saturation (TDGS) as mandated by current U.S. Environmental Protection Agency water quality criteria is 110%. To facilitate the downstream migration of juvenile salmonids, state regulatory agencies issue waivers up to 115% TDGS in downstream reaches where spill and powerhouse flows mix and up to 120% TDGS in dam tailraces. Recently, gas supersaturation as a water quality issue resurfaced as concerns have grown regarding chronic effects of spill-related total dissolved gas on salmonids, including incubating embryos and larvae, resident fish species, and other aquatic organisms.

Because of current concerns, and because the last comprehensive review of research on supersaturation effects on fishes was conducted in 1997, the U.S. Army Corps of Engineers (Portland District) requested a review of the recent supersaturation literature. Pacific Northwest National Laboratory conducted the review to determine whether recent literature 1) contributed new perspectives or information on current water management issues in the lower Columbia River or 2) suggested new or previously identified issues that may not be adequately addressed by the current 110% TDGS limit and the 115/120% TDGS water quality waiver.

Our review of recent work determined that newer research supports previous research indicating that short-term exposure to up to 120% TDGS does not produce significant effects on migratory juvenile or adult salmonids when compensating water depths are available. Monitoring programs at Snake and Columbia river dams, reservoirs, and tailwaters from 1993 to the early 2000s documented low incidence of significant gas bubble disease in Columbia River salmonids, resident fishes, or other taxa. However, from the new literature we reviewed, we identified five areas of concern in which total dissolved gas levels lower than the water quality waiver limit may affect fishes of the Columbia River. These areas of concern are 1) sensitive and vulnerable species or life stages, 2) long-term chronic or multiple exposure, 3) vulnerable habitats and reaches, 4) incubating fish in hyporheic habitats, and 5) community and ecosystem impacts. These issues were prevalent in the studies we reviewed and, in some cases, have been clearly identified in previous work.

We discuss these issues and provide additional sources of information for each issue from new and, in some cases, previous research publications. We identify conditions and species/life stages with the greatest likelihood of being affected by gas bubble disease and discuss uncertainties due to lack of scientific data for assessment. Finally, with respect to the Columbia River downstream of Bonneville Dam, we suggest that existing data are not sufficient to fully evaluate the sublethal and community-level effects of TDGS on salmonid and non-salmonid fishes incubating and rearing in shallow areas that may be exposed to TDGS for long periods of time. We identify two areas in which specific research is needed to fully evaluate the effects to fish from less than 120% TDGS. The first is the effect of TDG on salmon embryos (primarily sac fry) incubating in hyporheic habitats below Bonneville Dam. The second is the effects of TDG on larval resident (non-salmonid) fishes that rear and reside in the shallow water habitats below Bonneville Dam.

Abbreviations and Acronyms

BiOp	Biological Opinion
BKD	bacterial kidney disease (see also Rs)
EI	Exposure Index
EPA	U.S. Environmental Protection Agency
ESA	Endangered Species Act of 1973
FCRPS	Federal Columbia River Power System
FINS	Fish Individual-Based Numerical Simulator
FTP	File Transfer Protocol
GBD	gas bubble disease, also referred to as gas bubble trauma or GBT in some literature
hyporheic	the saturated zone under a river or stream, composed of stream bed substrate filled with water that originates from both the stream and the groundwater system
hypoxia	deficiency in the amount of oxygen reaching body tissues
littoral	the region near the shoreline of a body of fresh or salt water
LT _x	exposure time to X% mortality; e.g., LT ₅₀ = time to 50% mortality
NMFS	National Marine Fisheries Service; also known as NOAA Fisheries
pO ₂	partial pressure of oxygen
rm	river mile
Rs	<i>Renibacterium salmoninarum</i> infection (see also BKD)
SMP	smolt monitoring program
TDG	total dissolved gas, used as a general/conceptual term for all combined dissolved gases in water
TDGS	total dissolved gas saturation; TDG refers specifically to saturation percentage

Scientific Names of Fishes

Common Name	Scientific Name
Bridgelip sucker	<i>Catostomus columbianus</i>
Brown trout	<i>Salmo trutta</i>
Bull trout	<i>Salvelinus confluentus</i>
Chinook salmon	<i>Oncorhynchus tshawytscha</i>
Chum salmon	<i>Oncorhynchus keta</i>
Cutthroat trout	<i>Oncorhynchus clarki</i>
Coho salmon	<i>Oncorhynchus kisutch</i>
Kokanee	<i>Oncorhynchus nerka</i>
Lake trout	<i>Salvelinus namaycush</i>
Largemouth bass	<i>Micropterus salmoides</i>
Largescale sucker	<i>Catostomus macrocheilus</i>
Longnose sucker	<i>Catostomus catostomus</i>
Mountain whitefish	<i>Prosopium williamsoni</i>
Northern pikeminnow	<i>Ptychocheilus oregonensis</i>
Peamouth	<i>Mylocheilus caurinus</i>
Pumpkinseed	<i>Lepomis gibbosus</i>
Rainbow trout	<i>Oncorhynchus mykiss</i>
Redside shiner	<i>Richardsonius balteatus</i>
Sculpin	<i>Cottus spp.</i>
Smallmouth bass	<i>Micropterus dolomieu</i>
Striped bass	<i>Morone saxatilis</i>
Sockeye salmon	<i>Oncorhynchus nerka</i>
Steelhead	<i>Oncorhynchus mykiss</i>
Threespine stickleback	<i>Gasterosteus aculeatus</i>
Walleye	<i>Stizostedion vitreum</i>
White sturgeon	<i>Acipenser transmontanus</i>
Yellow perch	<i>Perca flavescens</i>

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Background

Gas supersaturation generated by spill from dams on the Columbia River was first acknowledged as an environmental concern in 1965 (Ebel and Raymond 1976). Following extensive assessment, the U.S. Environmental Protection Agency (EPA) adopted a nationwide water quality criterion of 110% total dissolved gas saturation (TDGS) for the protection of aquatic life (NAS/NAE 1973). The 110% TDGS criterion remains in effect (EPA 1987). During the 1970s when the water quality criterion for total dissolved gas (TDG) was put in effect, the limit often could not be met by hydropower facility operators on the Columbia River during involuntary spill when river discharge exceeded the hydroelectric capacity of the dams.

During the 1970s and 1980s, considerable research was conducted on effects of gas supersaturation on aquatic life, primarily juvenile salmonids. Relatively little attention was given to other species or salmonid adults, sac fry, or eggs. Also during that time, the addition of large water storage reservoirs and modifications to existing dams (including spillway deflectors and increased hydroelectric capacity) reduced total dissolved gas levels during both voluntary and involuntary spill. Ebel and Raymond (1976) and Weitkamp and Katz (1980) summarized research conducted during that period.

Beginning in the early 1990s, water quality agencies issued limited water quality waivers to facilitate spill for downstream juvenile salmonid migration. Monitoring studies over a ten-year period and TDG modeling efforts, extensively reviewed in the 1995 and 2000 Biological Opinions, indicated that TDGS levels between 110% and 120% had minimal impacts on aquatic biota in river environments (NOAA 1995, 2000). Therefore, waivers to the water quality criterion were granted that permitted up to 115% TDGS in downstream reaches where spill and powerhouse flows were mixed and up to 120% TDGS in dam tailraces where flows from spillways were separated from those of powerhouse discharge (NOAA 1995).

Recently, gas supersaturation as a water quality issue resurfaced (USACE et al. 2004) as concerns have grown regarding acute and chronic effects of total dissolved gas on salmonids, resident fish species, and other aquatic organisms. Of particular concern are total dissolved gas levels in the salmon egg incubation environment during spill. Elevated total dissolved gas levels within salmon redds may diminish survival of chum and fall Chinook salmon progeny downstream from Bonneville Dam. Literature reviews by Weitkamp and Katz (1980), Colt et al. (1986), White et al. (1991), and Fidler and Miller (1997) were the last efforts to summarize research conducted prior to 1996. More recent information may be available that would contribute to evaluations of the effects of total dissolved gas on migrating salmonids and other aquatic organisms of the lower Columbia River.

Objectives and Approach

Our objectives were to identify new or ongoing issues that may not be adequately addressed by the existing water quality criterion (110% TDGS) and waiver limits (115%/120% TDGS) and to provide recommendations regarding the adequacy of the existing limits for TDG. We reviewed literature on TDG and gas bubble disease (GBD) from throughout the Columbia River Basin, including research conducted outside the basin when appropriate. We limited our assessment of potential impacts to the lower Columbia River between Bonneville Dam and river mile (rm) 46. This reach was selected because it has been emphasized as an area of concern for juvenile fall Chinook salmon in the 2004 Federal Columbia River Power System (FCRPS) Biological Opinion (BiOp; NOAA 2004) and Updated Proposed Action (USACE et al. 2004). In addition, mean daily TDGS levels downstream from rm 46 are generally less than 115% when there is no involuntary spill at Bonneville Dam (Boyer 1974; USGS 1996; NMFS^(a); Schneider 2005). We focused on research findings in both gray and peer-reviewed literature published since 1996. However, because some of the issues raised in these works referenced or were based upon earlier work, we reviewed or cited older work when necessary to fully describe specific issues. We focused our assessment on fall Chinook salmon and chum salmon sac fry and juveniles because they are listed under the Endangered Species Act of 1973 (ESA) and because juvenile Chinook salmon are present in the lower Columbia River during the spring and summer spill periods and may therefore have the highest likelihood of being adversely affected by gas supersaturation. Although we focused on these two species, we reviewed recent research and identified issues that pertained to broader aquatic resources of the Columbia River.

Our approach was to review and summarize primary literature. In the appendix to this report, we provide an annotated bibliography of relevant new literature on gas supersaturation effects on aquatic organisms of the lower Columbia River as well as selected older reports that contain important background information or implications for current gas supersaturation issues. We combined the information from the reviews with empirical data from the river reach downstream of Bonneville Dam (and/or our collective knowledge of the specific habitat types or species life histories from the lower river) into an assessment of potential impacts. In some cases, our findings of specific impacts are reiterations of previous findings that have not been completely resolved. In other cases, our findings are new interpretations of older information. In still other cases, we found new information that warrants additional consideration. We did not address management actions (e.g., TDG monitoring locations) in this review.

^(a) National Marine Fisheries Service unpublished reports documenting biweekly measures of temperature and dissolved gas levels during spring and summer from 1967 through 1976 at various sites in the Columbia and Snake rivers, including the estuary.

Summary of Findings

Results of recent TDG research and monitoring are relevant to TDG management and monitoring in the Columbia River Basin, including the focal area downstream of Bonneville Dam. We provide the following summary of findings regarding four topic areas identified from the review of new work: 1) effects of TDG on migrating salmonids, 2) efficacy of monitoring programs, 3) ongoing effects of TDG within the Columbia River Basin, and 4) TDG downstream of Bonneville Dam. The first three topic areas relate to the Columbia River Basin as a whole and may or may not be relevant to the focal area downstream of Bonneville Dam. The fourth topic area is oriented specifically toward the focal area and is intended to provide fisheries and water managers with assessments of TDG impacts and information availability specific to this area.

Effects of Total Dissolved Gas on Migrating Salmonids

Recent literature supports the existing general view that effects on migratory juvenile and adult salmonids are minimal from short-term TDGS levels lower than 120% when compensatory depths are available. During periods of voluntary spill when TDGS averaged 120% or less, monitoring and assessment programs in the Snake and Columbia rivers from 1995 to the early 2000s consistently documented low incidence of significant GBD in migrating juvenile adult or juvenile salmonids as well as resident fishes or other taxa (Toner and Dawley 1995; Ryan and Dawley 1998; NMFS 1999; NOAA 2000; Ryan et al. 2000; Backman and Evans 2002; Backman et al. 2002; Weitkamp et al. 2003a). Monitoring found low incidence of GBD, even in high flow years (1997-1998; e.g., Backman et al. 2000; Backman and Evans 2002; Backman et al. 2002). Johnson et al. (2005) found that adult salmonids spent most of their time deeper than 2 m, and Gale et al. (2004) found that acute exposure up to 125.5% TDGS affected several reproductive characteristics of adult female Chinook salmon. Antcliffe et al. (2003) concluded that exposure to 118% TDGS may have no effect on migrating smolts because predator avoidance, a sensitive sublethal indicator of toxic response, was not impaired at this TDG level.

Efficacy of Monitoring Programs

Several new research reports provide information that may provide additional guidance to TDG monitoring programs. First, new information is available regarding the effects of sample collection location in ongoing monitoring efforts. Montgomery Watson (1995; see also Elston et al. 1997a) found that pressurization of TDGS-exposed juvenile Chinook salmon, potentially similar to pressures experienced by juveniles sampled in the smolt monitoring program (SMP), significantly reduced GBD disease incidence. This finding suggests that the SMP may underestimate GBD incidence in the Columbia River system. Conversely, Backman et al. (2000; see also Backman and Evans 2002, Backman et al. 2002) sampled juvenile salmonids throughout the Columbia River, and concluded that GBD incidence reported by the SMP overestimated GBD compared to their in-river sampling. They concluded that the biological monitoring program should be redesigned based on their model results to include both SMP and in-river data. Monk et al. (1997) examined effects of powerhouse and juvenile bypass facility

passage on GBD incidence and severity and found that dam passage had complex effects on GBD incidence and severity, with increased GBD severity in some individuals and decreased severity in others.

New research also contributes to sample collection and GBD evaluation protocols. Elston et al. (1997b) suggested that monitoring programs may be misclassifying lipid-filled structures that had the appearance of gas bubbles, and that SMP may overestimate GBD incidence if lipid structures are mistaken for GBD symptoms. Mesa et al. (2000) evaluated the progression of GBD in Chinook salmon and steelhead and identified four limitations to using GBD to assess gas supersaturation effects on Columbia River fishes: 1) considerable inter-individual variability, 2) limited knowledge of GBD relationship to exposure history of fish in the wild, 3) variability in GBD persistence, and 4) an inconsistent relationship between GBD and mortality. Backman et al. (2000) concluded that adult salmonids have been underrepresented in GBD monitoring and research and that biological criteria (GBD incidence and severity) should take precedence over physical criteria (TDGS level). Finally, Weiland et al. (1999) concluded that the SMP may underestimate effects of GBD on outmigrant survival because it does not consider synergistic effects with other sources of mortality, such as disease.

Ongoing Effects of Total Dissolved Gas in the Columbia River Basin

Assessments done as part of GBD monitoring programs were limited to superficial external examination of small subsamples of the relevant fish populations, with little or no magnification. Monitoring programs do not quantify mortality due to indirect effects of TDGS exposure, evaluate sublethal effects, or examine effects on interspecific interactions. Our review suggests that TDGS at levels lower than 120% may detrimentally affect sensitive species and life stages of fishes or other organisms of the Columbia River system under certain circumstances. In some cases, temporary waiver of the water quality limit allowing 115%/120% TDGS during spill for downstream migrating salmonids may have detrimental impacts on other organisms, depending on water depth, temperature, and the physiological health of the organism. In some circumstances, even the EPA water quality criterion of 110% TDGS may not adequately protect aquatic life. Long-term exposure to supersaturated TDG or repeated exposures, particularly in shallow-water habitats, may exceed tolerance and cause deleterious sublethal effects or synergistic effects with disease, environmental stressors, or toxins. Impacts of supersaturated TDG on incubating salmonids and larval resident fishes downstream from Bonneville Dam are poorly understood and worthy of concern. Through our review of recent literature, we identified issues of concern if 1) strong empirical evidence suggested TDG impacts on aquatic life or 2) if there was evidence of impact but insufficient or equivocal information to dismiss the issue. The issues we identified are described in greater detail in the following sections. For convenience, we have organized our discussion into five areas:

- sensitive and vulnerable species or life stages
- long-term chronic or multiple exposures
- vulnerable habitats and reaches
- incubating fish in hyporheic habitats
- community and ecosystem impacts.

Sensitive and Vulnerable Species or Life Stages

Some species and life stages are more sensitive or vulnerable to elevated TDG levels of GBD than others due to differences in physiology, morphology, or habitat use (Beeman et al. 2003; Weitkamp et al. 2003a,b). Many fish species vary their use of depth daily (or more frequently), and several species in the Columbia River spend much of their time at depths less than 2 m (Beeman et al. 2003; Johnson et al. 2005). Northern pikeminnow, suckers, and larval fishes of many species appear to be particularly vulnerable to elevated TDG levels because they prefer shallower, littoral habitats (NAS/NAE 1973; Fidler and Miller 1997; Beeman et al. 2003). For example, Schrank et al. (1998 and unpublished data) observed catostomid fry with signs of GBD downstream from Bonneville Dam. At 115 to 120% TDGS, 3% of the fry sampled exhibited large bubbles in the body cavity that disrupted normal swimming behavior, while at 120 to 125% TDGS, 40% displayed large bubbles. Fidler and Miller (1997) concluded that smaller juvenile salmonids were most sensitive to elevated TDG levels. They showed that swim bladder overinflation could occur at 103% TDGS without depth compensation. Gas bubbles in the gut or mouth of larval fishes may cause fish to rise or swim abnormally or erratically (Weitkamp and Katz 1980 and references therein). Comparative studies of adult salmonids suggest variation in sensitivity to GBD, with sockeye salmon, brown trout, bull trout, and steelhead more sensitive and Chinook salmon less sensitive to GBD (Weitkamp and Katz 1980; White et al. 1991; Backman and Evans 2002; Weitkamp et al. 2003b). Beeman et al. (2003) and Morris et al. (2003) found susceptibility to GBD was associated with lateral line pore morphology, among other factors. White et al. (1991) found rainbow trout to be most vulnerable to GBD in the Bighorn River, Montana, during spring as spawners moved into shallow side channels to spawn. Finally, Counihan et al. (1998) suggested that developmental stages of larval fish differ in their susceptibility to GBD. They found that white sturgeon larvae were most sensitive to GBD immediately after conversion from respiration via diffusion through the skin into the yolk sac to gill respiration because arterial dissolved oxygen levels are higher than the mixed arterial and venous blood of the yolk sac. Also, developmentally older white sturgeon with GBD spent more time at the water surface and positioned upside down or head up compared to control fish. The authors concluded that positive buoyancy produced by sublethal GBD may affect dispersal and predation risk of larval white sturgeon.

Long-Term Chronic or Multiple Exposures

Supersaturated gas conditions can exist throughout most of the lower Snake and Columbia rivers for extended periods (Ebel and Raymond 1976; NMFS 1999). Long-term chronic exposure to levels as low as 110 to 115% TDGS may produce serious sublethal effects and signs of GBD (Lutz 1995; Mesa et al. 2000; Beeman et al. 2003). Effects of multiple exposures on GBD incidence and severity are poorly understood. Detrimental effects of supersaturated TDG exposure may be reduced by return to low TDG levels or time spent at compensating depths. In some cases, exposure to dissolved gas supersaturation followed by depth compensation has resulted in lengthened LT_{50} values upon re-exposure (e.g., Knittel et al. 1980; Fidler 1988; Antcliffe et al. 2002), whereas in other cases re-exposure decreased resistance times (Ebel et al. 1971; White et al. 1991 and references therein). For example, analyses by Cramer (1996) showed that the survival rate of outmigrating smolts was high and smolts were able to withstand TDGS up to 130% in a small reach of the Snake River near Ice Harbor Dam but only if TDGS levels encountered at upstream dams were maintained below the 115%/120% TDGS waiver limits. Exposure to

TDGS levels higher than waiver limits combined with 130% TDGS near Ice Harbor Dam significantly reduced downstream migration survival rate. White et al. (1991) found that juvenile brown trout repeatedly exposed to 118% TDGS and given 30 days to recover between exposures developed more severe GBD with each successive exposure. Bubbles from earlier exposures apparently led to more rapid development of GBD signs upon re-exposure, and tissue damage from earlier exposures weakened test fish.

Mortality may be from factors other than GBD itself, such as disease, increased vulnerability to predation, or reduced swimming performance. Huchzermeyer (2003) suggested that the effect of chronic GBD on susceptibility to infection may be underestimated. Weiland et al. (1999) showed that low-level chronic TDGS exposure (less than 120%) combined with *Renibacterium salmoninarum* infection (Rs or bacterial kidney disease, BKD) shortened the time to mortality of exposed fish compared to uninfected individuals. They concluded that BKD may turn sublethal GBD exposure into lethal exposure. Synergistic effects of disease and GBD on incubating embryos and sac fry are possible because Rs transmits both vertically (from parent to offspring) and horizontally (from individual to individual) (Weiland et al. 1999). White et al. (1991) exposed juvenile brown trout to elevated TDG levels combined with bacteria exposure challenge treatments and found increased numbers of bacteria in kidney samples of fish exposed to elevated TDG compared to unexposed fish. Toner and Dawley (1995) suggested that caudal fins may be particularly susceptible to GBD and that sublethal exposure to TDGS may lead to secondary fungal infection of GBD-damaged tissues in the caudal peduncle. Lutz (1995) linked fin rot and infection to chronic GBD and suggested that the EPA water quality criterion of 110% TDGS may not be adequate for chronically supersaturated waters.

In a laboratory study, Dawley and Ebel (1975) found reduced growth (in addition to substantial mortality) of age-1 spring Chinook salmon and steelhead at 106% TDGS in shallow water. White et al. (1991) found TDGS levels of 112-114% were sublethal but produced excess buoyancy in up to 50% of test organisms, which affected swimming performance. Fidler and Miller (1997) concluded that chronic GBD without visible signs can produce mortality at sublethal TDG levels potentially due to uncompensated swim-bladder overinflation affecting swimming performance and increasing stress. Schiewe (1974) found that 106% TDGS in shallow tanks reduced swimming performance of juvenile Chinook salmon. Schiewe and Weber (1976) measured diminished sensory perception, potentially affecting predator avoidance, as a consequence of gas bubbles developing in the lateral line at 118% TDGS. Newcomb (1974) found alterations in blood chemistry that could be related to hypoxia and tissue necrosis in laboratory studies of steelhead yearlings at 110% TDGS.

Several studies have found increased vulnerability of juvenile salmonids to predation after elevated TDG exposure but not at levels lower than 120%. Birtwell et al. (2001) demonstrated that 120% and 130% TDGS exposure combined with an increased temperature treatment increased predation vulnerability of juvenile chum salmon in both shallow and depth-compensating tanks, but 115% TDGS did not increase vulnerability of test fish to predation. Mesa and Warren (1997) found that exposure of juvenile Chinook to 130% TDGS for 3.5 hours in shallow tanks showed increased vulnerability to predation, whereas exposure to 112% TDGS for 13 days or 120% TDGS for 8 hours did not increase

predation vulnerability. Increased vulnerability to predation appears to result from exposure to higher TDG levels such that GBD signs occur in the lateral line (affecting predator detection) and gills (affecting swimming performance; Mesa and Warren 1997).

Vulnerable Habitats and Reaches

Certain habitats and river reaches may produce TDG conditions that have serious effects on aquatic organisms. Areas with elevated rates of photosynthesis and/or elevated water temperatures in side channels or backwaters naturally produce conditions of elevated TDG (NAS/NAE 1973). Combined with elevated TDG from hydropower operations, these areas may reach TDG levels producing lethal or sublethal effects on fish and other organisms. In addition, shallow areas do not provide hydrostatic compensation for elevated TDG. Johnson et al. (2005) found that although adult Chinook salmon generally used depths 2 m or deeper in the lower Snake River, they spent significantly more time near the surface below Ice Harbor Dam, likely because of the limited depth available along the shallow southern shore in that area. Considerable literature suggests that relatively low TDG levels may produce sublethal or lethal effects when uncompensated (e.g., see **Incubating Fish in Hyporheic Habitats** below). For example, TDGS levels below 110% may produce GBD in larval fish (Fidler and Miller 1997) in shallow areas; juvenile fishes may be regularly exposed to TDG levels up to 110% in shallow waters (e.g., Beeman et al. 1997).

Incubating Fish in Hyporheic Habitats

A thorough search of the literature located no empirical documentation of hyporheic TDG levels. Incubating fishes are vulnerable to GBD, and hyporheic areas may present a special case of supersaturated TDG exposure. Although embryos are able to tolerate higher TDG than are older stages, GBD in salmonid sac fry has been documented at TDGS levels as low as 101%. For example, Krise and Herman (1989) found intracranial hemorrhaging and subcutaneous bubbles in lake trout sac fry after 15 days exposure to 101% TDGS and visible bubbles (intra-orbital, head, and abdomen) after 40 days exposure to 105% TDGS. Wood (1979) observed air bubbles and death in advanced salmon sac and newly buttoned-up fry at 103 to 104% TDGS. In response to 112-128% TDGS, Rucker and Kangas (1974) found 12 to 83% mortality in Chinook salmon fry from hatching to 50 days old. Sockeye salmon sac fry experienced GBD and mortality at 108-110% TDGS (Harvey and Cooper 1962). Counihan et al. (1998) identified effects on incubating white sturgeon at 115% TDGS. They found that developmentally older white sturgeon with GBD spent more time at the water surface and positioned upside down or head up compared to control fish and concluded that positive buoyancy produced by sublethal GBD may affect dispersal and predation risk of larval white sturgeon. Nebeker et al. (1978) reported mortality of steelhead sac fry exposed to 115% TDGS beginning after 52 days of exposure and reaching 45% after 92 days of exposure. Montgomery and Becker (1980) found gas bubbles and some mortality of rainbow trout sac fry at 113% TDGS. Cornacchia and Colt (1984) described swim bladder overinflation in striped bass sac fry at 103% TDGS. Shrimpton et al. (1990a, b) found swim bladder overinflation and changes in behavior and depth distribution of juvenile rainbow trout.

Community and Ecosystem Impacts

Because fish differ in vulnerability and sensitivity to GBD, and invertebrates and other food organisms also are sensitive to GBD (White et al. 1991), extended exposure to elevated TDG in the lower Columbia River may alter aquatic community composition and dynamics. Monitoring of GBD in resident fish, salmonids, and invertebrates downstream from Bonneville Dam during 1993-1997 (Toner and Dawley 1995; Toner et al. 1995; Schrank et al. 1997; Ryan and Dawley 1998; Schrank et al. 1998; Ryan et al. 2000) suggested that up to 120% TDGS had minor impacts on all aquatic biota examined. However, in 2 of 5 years (1996 and 1997), involuntary spill produced substantially higher TDG levels, resulting in significant GBD prevalence and some mortality to resident fish (based on in situ holding studies; Ryan and Dawley 1998; Schrank et al. 1998); no impacts to invertebrates were observed. Certain species, such as smallmouth bass, sculpin, and northern pikeminnow, consistently showed greater GBD prevalence than other species (Toner et al. 1995; Schrank et al. 1997; Ryan and Dawley 1998; Schrank et al. 1998). During years of high TDG levels, susceptible species likely suffered higher mortality rates that may have altered fish community composition (Ryan and Dawley 1998).

A change in dominance from largescale sucker to longnose sucker in Rufus Woods Lake downstream of Grand Coulee Dam from the 1970s to the 1990s may have been due in part to the greater sensitivity of largescale sucker to GBD (Venditti et al. 2001; Beeman et al. 2003). Areas with chronic elevated TDG may become dominated by the species most resistant to GBD, decreasing species diversity (Lutz 1995). White et al. (1991) found changes in the benthic invertebrate community of the Bighorn River, Montana, following elevated TDG exposure. They found that the invertebrate species with reduced frequency of occurrence, or that were missing after exposure, also were more sensitive to supersaturated TDG in laboratory bioassays. However, Nebeker et al. (1981) observed that invertebrates were more tolerant of TDGS than were fish.

Total Dissolved Gas Downstream of Bonneville Dam

Research Needs

Through review of recent TDG literature, we identified two specific research needs in the focal area downstream of Bonneville Dam. First, existing information is insufficient to evaluate impacts of TDG on chum and fall Chinook salmon incubating below Bonneville Dam. These species spawn in shallow areas below the dam and may be especially vulnerable to GBD. Chum salmon spawn in relatively shallow water, and although fall Chinook salmon spawn in deeper areas, these areas are characterized by downwelling where water quality within the incubation environment is similar to that of surface water (Geist et al. 2002). The limited depths available over some spawning areas and incubation areas may not provide sufficient compensation for the 115% TDGS commonly documented during spill and the higher TDG levels seen occasionally. There are currently no data available, new or otherwise, on TDGS levels in incubation habitats or on TDGS effects on incubating chum salmon. The U.S. Army Corps of Engineers has funded a study to collect TDG levels in chum salmon spawning areas downstream of Bonneville Dam. As shown in **Incubating Fish in Hyporheic Habitats** (above), levels as low as 103% have been documented to cause mortality in sac fry. Continued investigation into the TDGS levels in the

incubating environment below Bonneville Dam is warranted. Depending on findings from field efforts, laboratory studies exposing chum salmon embryos to elevated TDG also may be warranted.

Second, in extremely shallow areas, TDGS levels below the 110% EPA water quality criterion may have detrimental impacts on non-salmonid larval fishes rearing and residing downstream of Bonneville Dam (NAS/NAE 1973). Available data suggest that rearing salmonids are not affected by TDGS below 120% downstream of the dam (Backman et al. 2000, 2002). However, evidence is equivocal regarding exposure of larval non-salmonid resident fishes to TDGS below 120% in shallow water areas downstream of Bonneville Dam. Toner et al. (1995) found that shallow backwater areas sampled below Bonneville Dam had lower TDG levels than adjacent deeper, higher-velocity areas due either to a lack of exchange with elevated TDG water in the main channel or to greater gas dissipation associated with the higher ratio of surface area to volume in shallow water areas. In contrast, Schrank et al. (1998 and unpublished data) documented 40.2% incidence of severe GBD in catostomid larvae captured in shallow water downstream from Bonneville Dam at 120 to 125% TDGS, with 2.5% GBD incidence at 115 to 120% TDGS. It is not known whether organisms in habitats with naturally elevated TDG levels, such as backwater areas, are particularly vulnerable to additional TDGS contributions or if they have adapted to elevated TDG and therefore may be resilient to additional contributions. We conclude with regard to the Columbia River downstream of Bonneville Dam that 1) the availability of depth to aquatic organisms of concern is limited due to the abundance of littoral habitats in the nonimpounded river, and 2) the nature of special areas that may create vulnerability from elevated TDG levels is poorly documented and poorly understood. Additional data are needed before the significance of this issue can be fully evaluated.

Other Potential Total Dissolved Gas Issues Downstream of Bonneville Dam

While we are not recommending additional research, our review suggests that two additional unresolved TDG issues downstream of Bonneville Dam may warrant additional agency consideration and/or a more thorough review of available data. First, literature from elsewhere on the Columbia River Basin suggests long-term and multiple TDGS exposure below 115% TDGS during continuous voluntary spill for up to several months may produce sublethal effects on ESA-listed juvenile salmonids and non-salmonids below Bonneville Dam. Factors that influence the likelihood of sublethal toxicity include relative timing, level and duration of TDG exposure, and TDG level and duration during recovery periods. Chronic and sublethal exposure may have synergistic effects with other stressors such as elevated water temperatures, disease, and impaired function that may increase vulnerability to predation. Long-term and sublethal effects as described in **Long-Term Chronic or Multiple Exposures** (above) may be as likely to occur downstream of Bonneville Dam as elsewhere in the Columbia River system. We were unable to find specific studies conducted in the focal area that examined this issue.

Second, changes in fish community composition downstream of Bonneville Dam resulting from differential TDG sensitivity have not been well documented. Monitoring of resident fish downstream from Bonneville Dam indicated that GBD had minor impacts at TDGS levels below 120% (Toner and Dawley 1995; Schrank et al. 1997), with the potential exception of catostomids as discussed earlier (Schrank et al. 1998; Ryan et al. 2000). The limited evidence available from other studies in the Columbia Basin suggests that long-term impacts of GBD could alter aquatic community composition.

The magnitude of ecosystem changes is likely related directly to levels of dissolved gas saturation exposure. TDG levels in the Columbia River system, including downstream of Bonneville Dam, have been significantly reduced since the problem was first identified in the 1960s. It is possible that the fish community below the dam, if altered by extreme high TDG levels, may be returning to pre-impact conditions. However, this is conjecture, as no substantive data have documented long-term recovery of the aquatic community downstream of Bonneville Dam.

Conclusions

Our review of the recent literature on gas supersaturation supports five key conclusions:

- New studies conducted since the last major review support earlier findings that short-term TDGS below 120% does not have significant effects on migrating salmonids (adult and juvenile) when compensating depths are available.
- New information exists that may provide additional guidance to TDG monitoring programs.
- Five issues of concern are identified because either empirical evidence suggests impacts on aquatic organisms of the Columbia River or evidence is insufficient to evaluate the issue: 1) sensitive and vulnerable species or life stages, 2) long-term chronic or multiple exposures, 3) vulnerable habitats and reaches, 4) incubating fish in hyporheic habitats, and 5) community and ecosystem impacts.
- In the focal area downstream of Bonneville Dam, research is needed on TDG effects on 1) incubating salmonids and 2) non-salmonids rearing in shallow littoral areas.
- Two additional issues are unresolved downstream of Bonneville Dam: 1) long-term chronic exposure and 2) effects on fish communities. These issues may warrant additional agency review.

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Appendix

Annotated Bibliography of Gas Supersaturation Literature

Appendix

Annotated Bibliography of Gas Supersaturation Literature

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

In laboratory experiments, age 0 rainbow trout (37–52 mm) and coho salmon (~ 35 mm) were exposed to total dissolved gas saturation (TDGS) of 114, 118, or 125% in combination with elevated temperature (15 or 18°C) for exposure durations of 36 hr to 7 d. The 114 and 118% TDGS exposures at 0.1 m depth of rainbow trout for 7-8 d did not produce mortality, swim bladder overinflation or rupture, or altered escape to cover behavior. The most severe treatment (125% TDGS exposure at 0.1 m depth and 18°C for 36 hr (rainbow trout) and 100 hr (coho salmon)) produced elevated mortality of 27% and 30%, respectively, compared to 0% in the controls. TDGS exposed fish of both species were more stuporous. Escape time of exposed fish of both species was longer but was significantly different only in rainbow trout since response variability was high among replicates. Swim bladder overinflation or rupture and external gas bubble disease (GBD) signs were not frequently observed in exposed fish and therefore may not be sensitive indicators of TDGS toxicity. Ability to escape predators may be reduced at 125% but not at 118% TDGS.

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

This document reports a series of short-term static (single, shallow depth) and dynamic (volitional depth, varying depth) laboratory tests with juvenile rainbow trout (110 mm) at 10°C. TDGS levels tested were 110-140%. In static tests at 0.25 m depth, time to mortality was inversely related to TDG %, with the LT₅₀ ranging from longer than the test duration of 6 d at TDG below 122% to 5.1 hr at 140%. All test fish survived 114% for 6 d and 110% for 9 d. Static results were consistent with threshold equations of Fidler and Miller (1997), which suggest that 115 to 117% TDGS is required to initiate bubble formation at sea level. TDG-exposed fish behaved abnormally (e.g., lethargy, sporadic and erratic swimming before death). Dynamic laboratory tests simulated wild fish use of depth. Fish were held at the surface at 122% for the LT₁₀, below compensation depth for 3 h and then returned to the surface. This cycle of depth change was repeated four times per sample, with 10% mortality per cycle. LT₁₀, LT₂₀, LT₃₀, and LT₄₀ were compared between static and dynamic tests to examine effects of depth on survival. Mortality of fish exposed to 122% TDG in the 1-m and 2.5-m depth volitional tests was 22% and 0%, respectively, compared to 89% in the static (shallow) test. Dynamic tests allowing use of depth significantly delayed onset of mortality and reduced cumulative mortality. In some cases, previous use of depth reduced mortality rate at the surface once mortality was re-initiated. Volitional depth tests supported general findings that depths to 2 m compensate for up to 120% TDGS. Sample fish were highly variable in their

use of depth in volitional tests. The authors concluded that for short exposures and for species that are less susceptible to GBD, 110% is conservative when compensatory depths are available.

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

In a laboratory experiment, juvenile rainbow trout (96 mm) were exposed to hydrostatic pressure treatment (= 2.5 m depth) for 4 hr and then to 122% TDGS for 48 hr. Fish that did not receive the hydrostatic pressure prior to TDG exposure had slightly higher cumulative mortality than TDG-exposed fish that received the hydrostatic pressure treatment, but differences were not significant after 24 hr exposure to TDG. The authors concluded that fish use of depth before encountering lethal TDG levels did not lengthen time to first mortality or decrease cumulative mortality under their test conditions. They suggested that effects of previous exposure to hydrostatic pressure (use of depth) may be more pronounced after short exposures to higher TDG levels and after exposure to greater hydrostatic pressures than were used in this study. They also suggest that in shallow habitats, previous use of depth will not significantly increase survival from TDGS exposure.

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

Adult Chinook and sockeye salmon and steelhead were collected at Bonneville Dam from 1995 to 1999 to relate GBD to TDGS greater than 110%. Polynomial regression models were able to link GBD with TDG level for sockeye salmon and steelhead but not for Chinook salmon. Severe fin occlusion was seen in the former two species when TDGS was greater than 126%, whereas this GBD symptom was rarely seen in Chinook salmon even at levels greater than 130%. GBD was uncommon below 125% in any species, whereas above 125%, species differences became apparent. Sockeye salmon were the most sensitive, followed by steelhead. Although GBD incidence increased with increasing TDG, severity was generally minor, below 126%. Involuntary spill produced most of the GBD observed. Speed and depth of migration upriver may explain species differences observed. The authors conclude that controlled spill is unlikely to produce GBD symptoms and that the 110% U.S. Environmental Protection Agency (EPA) water quality criterion for TDGS is too restrictive.

Backman, T.W.H., A.F. Evans, and M.S. Robertson. 2000. *Symptoms of gas bubble trauma induced in salmon (*Oncorhynchus spp.*) by total dissolved gas supersaturation of the Snake and Columbia Rivers, USA. Draft report. Columbia River Inter-Tribal Fish Commission, Project No. 93-008-02, Contract No. 95BI39861 to the U.S. Department of Energy, Bonneville Power Administration, Portland, OR.*

Report summarizes work conducted during 1996-1999: 1) monitoring GBD in adult salmonids in the fish ladder below Bonneville Dam, 2) sampling juvenile salmonids at numerous locations in the lower Columbia and Snake rivers, and 3) development of a predictive model to describe the TDGS-GBD relationship in migrating juvenile salmonids. Few symptoms of GBD were found in any species when TDGS was below 125%. Sockeye was the most susceptible, followed by steelhead. During juvenile sampling, flow and TDGS varied considerably. Few juvenile salmonids exhibited GBD, even during high

flow (= high TDGS) years. Average incidence was 1.2%, with a maximum of 2.2% during the highest flow year, 1997. Symptom severity was also low. GBD incidence was higher above 125% TDGS, up to 9.1%. Steelhead were the most susceptible, followed by sockeye salmon. The accuracy of the smolt monitoring program (SMP) was evaluated. The authors found GBD incidence reported by the SMP was significantly higher than in-river sampling summarized in this report. Cubic regression models with a high measure of fit (R^2 0.78–0.81) were developed that differed in mean number of fish required. The authors concluded that these models represent a substantial improvement over models using 24-hr mean TDGS at the location of capture. The authors also concluded that adult salmonids have been under-represented in GBD monitoring and research, the TDGS 110% national standard is too general and restrictive for the Columbia and Snake rivers and should be reevaluated, biological criteria (GBD incidence and severity) should take precedence over physical criteria (TDGS level), and the biological monitoring program should be redesigned based on model results to include both SMP and in-river data collection. The report contains the data published in Backman et al. (2002) and Backman and Evans (2002).

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

Incidence of juvenile salmonid (steelhead, sockeye, Chinook, coho) GBD associated with voluntary and involuntary spill at eight sites in the FCRPS was documented during 1996-1999. Flows were high and elevated TDG was highest during 1996 and 1997 whereas 1998 and 1999 were low-flow years. GBD symptoms on the body, unpaired fin, eye, opercula, and lateral line were examined and severity (% covered with bubbles) was assessed. Fewer than 2% of collected fish had symptoms, and symptoms were generally of low severity. Steelhead had the greatest prevalence, with 2.3%. GBD was associated with TDG level, with similar GBD:TDG relationships defined for fish collected above, in, and below dam bypass facilities. Incidence was lower than expected from results of laboratory studies, probably due to depth compensation. In-river collections usually had lower GBD prevalence than collections from bypass facilities, counter to expectation. The authors conclude that this was probably due to the relatively high proportion of steelhead, which are more susceptible to GBD than salmon species, in bypass systems. Deep entry into bypass systems may produce GBD. TDGS greater than 130% was required to exceed NMFS biological criteria of 15% GBD prevalence in juvenile salmonids.

Beeman, J.W., P.V. Haner, and A.G. Maule. 1997. Vertical and horizontal distribution of individual juvenile salmonids based on telemetry. In Maule, A.G., J. Beeman, K.M. Hans, M.G. Mesa, P. Haner, and J.J. Warren (Editors). *Gas bubble disease monitoring and research of juvenile salmonids*. U.S. Department of Energy, Bonneville Power Administration, Project Number 96-021, Contract Number 96A193279, Portland, OR.

Pressure-sensitive radio tags were implanted in juvenile steelhead, and the fish were released below Ice Harbor Dam. Fish used depths of 0.23 to 9.54 m (median depth 1.08-4.27 m). Incident TDGS was 119.8 to 125.8%, but test fish would have experienced 82.4 to 107.4% due to depth compensation. Various aspects of tag performance were tested, including precision, accuracy, and effects of depth and distance on tag detection. Deeper tags and tags at the water surface were harder to find, with the potential to produce biased data. Implantation of a 2.2-g tag did not affect ability to maintain neutral buoyancy in 85-g steelhead. There was no apparent relationship between TDG and depth, suggesting that juvenile

steelhead did not avoid TDGS greater than 100%. Depth use reduced TDG exposure by approximately 24%, which may explain the low incidence of GBD documented by monitoring programs.

Beeman, J.W., D.A. Venditti, R.G. Morris, D.M. Gadomski, B.J. Adams, S.P. VanderKooi, T.C. Robinson, and A.G. Maule. 2003. Gas bubble disease in resident fish below Grand Coulee Dam. Final report of research. Western Fisheries Research Center, Columbia River Research Laboratory, USGS, Cook, WA.

This work is a comprehensive study of GBD incidence and effects on fishes of Rufus Woods Lake (Chief Joseph Reservoir) below Grand Coulee Dam. Chapters include 1) depth and hydrostatic compensation of wild and farmed fish, 2) progression and lethality of GBD, 3) fish community composition, 4) effects of TDG exposure on growth, and 5) correlation of lateral line pore diameter with GBD (see also Morris et al. 2003). Median depths used were steelhead (1.6 m), northern pikeminnow (2.0 m), bridgelip sucker (2.8 m), walleye (3.7 m), longnose sucker (5.2 m), largescale sucker (6.8 m). Northern pikeminnow and steelhead spent 49.1% and 56.4% of their time, respectively, in the upper 1-m interval (depth -0.32 to 1.99 m) of the water column. Other species spent 12.2% to 32.3% of their time in this depth zone. All individuals of all species monitored migrated vertically on a diel cycle at least part of the time. Most fish were shallower during the day than at night, but longnose sucker and some walleye tended to be shallower during the night. Based on depth preference relative to tailwater elevation and elevated TDG, steelhead, northern pikeminnow, and bridgelip sucker would be expected to have the greatest exposure to elevated TDG levels. The relative abundances of the three sucker species changed since the 1970s, potentially associated with TDG exposure and greater sensitivity of largescale and bridgelip suckers to GBD as well as other changes in environmental conditions between sampling periods. Reduced growth was not associated with higher TDG levels. Laboratory work included examination of GBD development and mortality associated with TDG exposure in primarily juveniles of several resident species. GBD signs at TDGS exposures of 115, 125, or 130% in shallow water were unpredictable except in long-term exposure to 115%. Fish exposed to 125 or 130% died before extensive GBD formed, whereas long-term exposure to 115% produced the most extensive GBD. LT_{50} was highly variable among species, with a ten-fold difference among species exposed to 125% TDGS. The authors suggest that species differences in rate of cutaneous respiration may influence GBD development differences among species. They also suggest that extensive GBD in resident fishes may be indicative of low-level chronic TDG exposure, whereas low-level GBD in external tissues plus bubbles in gills and the arterial system may indicate short-term acute exposure.

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

Juvenile chum salmon (~95 mm) were exposed to a rise in temperature from 11.0 to 20.7°C and TDGS of 115% for 48 hr, 120% for 24 hr, or 130% for 12 hr, and then returned to ambient temperature and TDG levels. Control and exposed fish were then examined for GBD or challenged in predation survival trials of either 60 min in shallow raceways or ≤ 90 min in deeper (2.4 m) raceways. Preliminary resistance bioassays at TDGS 120, 125, 130, and 140% at 20.3°C were first conducted to identify LT_{10} and LT_{50} for each exposure and to identify appropriate exposures for predation challenge trials. Some mortality was

observed at each exposure, with mortality increasing with TDG treatment. Significant but low GBD incidence (lateral line and caudal fin but not gills) was found in all treatments. Exophthalmia was evidenced in the 120% and 130% treatments. In the shallow water predation challenge, predation rate was higher on exposed fish in 8 or more tests (of 15), but the difference was significant only in the 120% and 130% TDGS exposures. In the deeper predation challenges, predation rate was significantly higher on only 120% TDGS exposed fish. Treated fish were more susceptible to predation in all three treatments, with higher predation efficiency in mixes containing exposed fish. Increased vulnerability to predation was evidenced in the 120% TDGS treatment even though GBD incidence was low.

Boyer, P.B. 1974. Lower Columbia and lower Snake rivers: nitrogen (gas) supersaturation and related data, analysis and interpretation. Report to the U.S. Army Corps of Engineers, Contracts DACW57-74-C-0146, DACW57-75-C-0055, Portland, OR.

Summarizes available Corps of Engineers dissolved nitrogen data for the Snake and Columbia rivers. As long as spill continues, these rivers are unable to purge themselves of excess gases due to loss of flow, turbulence, and velocity resulting from river regulation. Water through locks, turbines, and skeleton bays (reserved for future turbines) does not contribute to TDG levels, so flow through these structures reduces tailwater TDG levels when mixed. As of 1974, TDGS in excess of 110% was frequently seen for approximately 90 days through the entire river system, from the Canadian border to the ocean. Elevated TDG was especially serious because this period coincided with upstream and downstream migration of salmonids. Gas supersaturation was one justification for barging and trucking of hatchery fish past sections of the river with the highest TDG levels. Report includes methods for predicting dissolved nitrogen in spill water, the influence of turbine water on TDGS, and corrections for elevation, depth, and salinity. It also includes predicted TDG levels and duration curves considering upstream storage, spillway flow deflectors, and two power generation discharges. Toxicity test literature and NMFS studies on juvenile salmonids are summarized. An analysis of the effects of supersaturation on adult run size is attempted, but supersaturation is not able to be singled out from other potential sources of population decline.

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

In a laboratory study with white sturgeon larvae beginning 24 hr after hatch in shallow water (maximum depth 25 cm), 50% and 85% GBD incidence were observed at 118% and 131% TDGS, respectively. GBD was observed in the buccal cavity and nares within 15 min after exposure during various stages of development beginning 2 to 3 days after hatch. No GBD was seen in developmental stages earlier than Stage 33 (stages defined for and particular to ascipenserid larvae) or in controls. GBD developed as quickly but was more prevalent at older stages. Blood flow through gill filaments and to the caudal region was stagnant (hemostasis) even when the heart was beating. No mortality was recorded in the 118% treatment after 10 days; 50% mortality was observed after 13 days at 131%, with most mortality occurring within 4 days of exposure. Older developmental stages with GBD swam to the water surface, upside down or head up, whereas controls visited the surface but always returned to the tank bottom and became more benthic with development. Bubbles produced positive buoyancy that may affect dispersal and predation risk. Developmental stages first showing GBD at mouth, then opercula and gills. These sites may have been bubble nucleation sites. Once a bubble forms, diffusion into the bubble can happen

at any TDGS greater than 100%, and bubble size can increase quickly. At early developmental stages, larvae are not effective at expelling bubbles. Mechanical sampling may dislodge bubbles in buccal cavity and underestimate GBD incidence in field settings. Ascipenserid larvae may be less sensitive to restricted water flow through the buccal cavity because gill filaments extend beyond the operculum during early developmental stages to facilitate respiration. Sensitivity to GBD appears to occur at the developmental stages during which respiration switches from diffusion through the skin into the yolk sac, to blood circulation through the gills. The probability of bubble formation increases with gill respiration because diffusion into the yolk sac mixes arterial and venous blood whereas gill respiration separates the two systems. Bubbles are most likely to form in arterial blood because of pO₂ (partial pressure of oxygen) in the blood is highest. The depth of dispersing larvae is unknown; this study may be worst case. Larvae usually incubate in the first 8 km below dams during April to July, when TDG can be highest. Behavior changes suggest deleterious effects at sublethal exposures, including impaired swimming performance.

Cramer, S.P. 1996. Seasonal changes in survival of yearling Chinook smolts emigrating through the Snake River in 1995 as estimated from detections of PIT tags. Report to Direct Services Industries by S.P. Cramer & Associates, Inc., Gresham, OR.

PIT-tagged Chinook salmon smolts were released at Lower Granite Dam and interrogated at Little Goose, Lower Monumental, McNary, and John Day dams during 1995. The author concluded that "survival for Chinook smolts was high during most of the smolt outmigration. However, excessive dissolved gas caused by spill at Snake River dams sharply reduced survival during mid May. Survival did not increase as spill increased." The author observed that "smolts withstood supersaturation levels up to 130% below Ice Harbor Dam only when supersaturation was less than 115% in the tailrace of Lower Monumental Dam, 113% in the tailrace of Little Goose Dam and less than 110% in the tailrace of Lower Granite Dam."

Dawley, E.M. 1986. Effects of 1985-86 levels of dissolved gas on salmonids in the Columbia River. Report to the Corps of Engineers, Contract DACW57-85-F-0623, Portland, OR.

In a 1985 field study near The Dalles Dam, with daily exposures of 111-118% TDGS for about 8 hr and <110% TDGS for 16 hr, no signs of GBD were observed in either naturally migrating fish or fish held in pens at the surface or at greater depth. Vertical distributions of fish in the reservoir and in pens suggested that most fish would be provided substantial pressure compensation for high levels of TDG. In 1986, when TDGS ranged from 123 to 130% through the McNary to Bonneville Dam reach, GBD signs were observed in about 15% of steelhead, 1% of coho salmon, and 0% of Chinook and sockeye salmon.

Dawley, E.M. and W.J. Ebel. 1975. Effects of various concentrations of dissolved atmospheric gas on juvenile Chinook salmon and steelhead trout. *Fisheries Bulletin* 73(4):787-796.

Bioassays on age-1 spring Chinook salmon (115-126 mm) and steelhead (124-135 mm) in shallow water displayed substantial mortality at 111% TDGS. At 106% TDGS, growth and swimming performance were impaired. At 111% TDGS, blood chemistry was affected. Steelhead used in bioassays were larger and less tolerant of elevated TDG than the smaller Chinook salmon.

Dawley, E.M., M. Schiewe, and B. Monk. 1976. Effects of long-term exposure to supersaturation of dissolved atmospheric gases on juvenile Chinook salmon and steelhead trout in deep and shallow test tanks. Pages 1-10 in: Gas bubble disease. D.H. Fickeisen and J.J. Schneider (Editors). CONF-741033. Technical Information Center, Oak Ridge, TN.

Juvenile fall Chinook salmon (39-41 mm) were substantially more tolerant of dissolved gas than steelhead (164-196 mm). At 120% TDGS, Chinook salmon and steelhead LT_{50} s were 22 d and 30 hr, respectively. Water depth in 2.5-m tanks appeared to compensate for about 10% and 10 to 15% of effective TDG for Chinook salmon and steelhead, respectively. Average depth of fish in the deep tanks was directly correlated with TDG level with fish held at 124 and 127% averaging 0.5 to 1 m greater depth than fish tested at 100 and 105% TDGS. Increased tank depth allowed compensation, but mortalities still occurred.

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

Elevated TDG exposure diminished thermal tolerance of hatchery steelhead (179 mm), hatchery coho salmon (117-134 mm), and hatchery (134 mm) and wild (129 mm) spring Chinook salmon. Pre-test exposure to elevated TDG lowered resistance to mortality from combined high temperatures and supersaturation. Resistance was greatest for coho salmon followed by Chinook salmon and then steelhead.

Elston, R., J. Colt, S. Abernethy, and W. Maslen. 1997a. Gas bubble reabsorption in Chinook salmon: pressurization effects. *Journal of Aquatic Animal Health* 9(4):317-321.

Juvenile Chinook salmon (130 mm) were exposed to the ΔP equivalent of 123% TDG in shallow water for 16-20 hr. Half of exposed fish were then pressurized to 30.5 m head (310 kPa) for 5, 30, 60, or 120 min. Treatment and control (TDGS exposed but unpressurized) fish were examined for GBD. Pressurization for 5 min resulted in substantial reduction in GBD symptoms in fins, lateral lines, and gills. The time for 50% bubble coverage loss was 5-30 min, < 5 min, and < 5 min for fins, lateral line, and gills, respectively. Combined prevalence (all body locations) of GBD signs was not significantly different between controls and the 5 min pressurization treatment but was significantly reduced at all other pressurization times. The authors suggest that the smolt monitoring program may underestimate the impact of GBD in the Snake and Columbia rivers because gas bubble reabsorption may be occurring in fish examined in smolt bypass facilities. See also Montgomery Watson (1995).

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

Steelhead and Chinook salmon smolts were exposed to 123% TDGS for 16-20 hr until moderate to extensive GBD was observed. Timing of dissipation and appearance of air bubbles was differentiated from similar structures that did not dissipate. GBD bubbles dissipated from excised gills in less than 2 min (smallest bubbles) to 15 min (large bubbles). Lipid-containing structures were identified that were similar to air bubbles in location, shape, and ability to occlude gill filament arteries. Unlike air bubbles, they did not diffuse within 2 hr, tended to be less reflective, were usually located in the distal aspect of

primary lamellae, and were sometimes amoeba-like in shape. Lipid structures were seen in 40.7% of steelhead smolts examined. Monitoring programs may be misclassifying lipid bodies as GBD and overestimating the incidence of GBD. Fish caught to determine GBD incidence must be examined immediately because gill air bubbles dissipate quickly.

Fidler, L.E. 1996. Allowable gas supersaturation for fish passing hydroelectric dams. Task 7.0. A review of historic levels of dissolved gas supersaturation in the Columbia and Snake Rivers and its effects on the survival of juvenile and adult anadromous salmonids. Prepared for Montgomery Watson, Bellevue, WA. Report to Bonneville Power Administration. Project No. 93-08. Contract No. DE-AC79-93BP66208, Portland, OR.

A literature review to establish relationships among TDG, flow, spill and survival of juvenile and adult salmonids. Included development of a Microsoft Access database archived in Pacific States Marine Fisheries Commission's FTP site containing historic information on hatchery releases, juvenile travel time, dam and weir counts, juvenile transportation, GBD signs, GBD bioassay data, fisheries harvest, adult salmon dam counts, survival estimates, and hatchery returns. Survival data were insufficient to establish relationships among TDG and the identified variables for both juvenile and adult salmon because of unknown effects from other parameters affecting survival such as predation, dam passage mortality, water temperatures, disease, ocean survival, and fallback at dams.

Fidler, L.E. and S.B. Miller. 1997. British Columbia water quality guidelines for the protection of aquatic biota from dissolved gas supersaturation - technical report. Aspen Applied Sciences Limited report to the BC Ministry of Environment, Lands and Parks, Environment Canada, Department of Fisheries and Oceans, Vancouver, BC.

Data and literature are reviewed for developing water quality standards for British Columbia. Therefore, focus is on evaluation of existing information, particularly work linking elevated TDG to mortality and GBD symptom development, factors affecting toxicity, and identification of thresholds. Literature review is comprehensive but focused on research not included in earlier reviews. Factors influencing toxicity of excess dissolved gases to aquatic organisms include water depth, fish species, body size, habitat availability and use, exposure history, pO₂, and temperature. GBD symptoms that are major sources of mortality are reviewed. Three conceptual thresholds for the protection of aquatic life are identified: TDG levels required for overinflation of the swim bladder, GBD symptoms in gills and external surfaces, and bubbles in the cardiovascular system. Development of GBD is associated with bubble nucleation sites and factors influencing the phase change from liquid to gas. Surface tension and other surface phenomena resist bubble formation and nucleation site stability, creating thresholds. Equations defining thresholds, from Fidler (1984), are discussed. Nucleation sites may be larger in river environments with high levels of suspended solids than in laboratory settings with "clean" water sources. Although temperature does not affect threshold TDG levels, once a threshold has been exceeded, the rate of bubble growth and, therefore, GBD progression toward lethality, is strongly temperature-dependent. The role of depth in influencing TDG experienced by fish is not simple. After exposure to threshold TDG levels such that bubble formation is initiated, any TDGS level greater than 100% will contribute to bubble growth and additional development of GBD. Affected fish must go to a depth compensating for the TDG at which bubble formation began for symptom development to reverse. Chronic GBD without visible bubbles can produce mortality at TDG levels below apparent thresholds, potentially due to uncompensated swim bladder overinflation affecting swimming performance and placing additional stress

on organisms. Fish do not appear to be able to control swim bladder overinflation under dissolved gas stress, particularly small fish. Sources of elevated TDG are reviewed and include groundwater (bacterial action elevating CO₂, natural high N₂ levels) and elevated atmospheric pressure associated with storms. Storms are not usually sufficient to produce elevated TDG but may exacerbate pre-existing high TDG conditions. Reporting and measurement of dissolved gas levels are summarized, largely from Colt (1983, 1984, 1986). Terms associated with supersaturation are defined, including delta P (ΔP), TDG, and TDGS. Use of ΔP is recommended because it incorporates the influence of atmospheric pressure and is therefore a direct measure of the potential for development of GBD in aquatic organisms. If TDGS is used, barometric pressure or altitude must also be reported.

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

Adult Chinook salmon exposure to 114.1 to 125.5% TDGS for 10 to 68 hr produced no effect on relative fecundity, gonadosomatic index, or average egg weight or diameter. No relationship was observed between TDG treatment and cumulative mortality at eyed egg or button-up stages. In some fish, time between exposure and spawning was limited to only 5 days. Chinook salmon may be the most resistant to GBD of all the Pacific salmon species; other species such as steelhead or sockeye salmon may show reproductive effects at these TDG levels. Exposure details may mimic TDG levels, exposure duration, and water depth experienced by migrating adult salmonids as they pass one Columbia River dam.

Hans, K.M., M.G. Mesa, and A.G. Maule. 1999. Rate of disappearance of gas bubble trauma signs in juvenile salmonids. *Journal of Aquatic Animal Health* 11:383-390.

Yearling spring Chinook salmon (138 mm) and steelhead (248 mm) were exposed to 120 or 130% TDGS until the LT₂₀ and LT₅₀ were produced. GBD symptom dissipation was observed after return to ~100% TDGS with no depth compensation. Gill filament bubbles were much reduced after 1 hr and were gone after 2 hr under nonsaturated conditions. Symptoms were greatly reduced in the lateral line after 5 hr, although 50% had some symptoms after 6 hr. External surface bubbles were more persistent, returning to low levels of bubbles after 48 hr with some remaining after 4 days. Fish were lethargic as mortality approached 50%, but exposed fish became more active within 30 min after return to nonsaturated water. Recovery from the 120% TDGS treatment was relatively quick (1-2 hr), whereas recovery was slower after exposure to 130% (up to 4 hr for significant recovery and beyond the length of the test for some GBD). Remaining bubbles may facilitate formation of new bubbles after re-exposure. Lateral line bubbles are difficult to interpret because they may be due to recent low-level exposure or previous higher-level exposure. External bubbles are easier to observe but are poor predictors of GBD severity or exposure history.

Jensen, J.O.T., J. Schnute, and D.F. Alderdice. 1986. Assessing juvenile salmonids response to gas supersaturation using a general multivariate dose - response model. *Canadian Journal of Fisheries and Aquatic Science* 43(9):1694-1709.

All available bioassay data were evaluated, and levels of TDG causing mortality of salmonids in shallow water were examined, delineated by species, size, water temperature and percent oxygen. Generally, supersaturation levels 105% and lower were safe for all fish. GBD tolerance was inversely correlated

with water temperatures below 9°C but unaffected above 9°C. Fish smaller than 65 mm exhibited the greatest tolerance, but at larger size, tolerance was unrelated to size. Tolerance increased with increased ratio of oxygen to nitrogen.

Johnson, E.L., T.S. Clabough, D.H. Bennett, T.C. Bjornn, C.A. Peery, and C.C. Caudill. 2005. Migration depths of adult spring and summer Chinook salmon in the lower Columbia and Snake rivers in relation to dissolved gas supersaturation. *Transactions of the American Fisheries Society* 134:1213-1227.

Adult spring and summer Chinook salmon were tagged with depth/temperature recorders at Bonneville Dam and monitored to Lower Granite Dam for up to 40 days during 2000, a low to average flow year. TDGS never exceeded 120%. Relationships between depth use in tailraces (dam passage) and reservoirs and TDG were analyzed. Fish were deeper than 2 m most of the time, with periods lasting minutes spent at shallower depths. Fish were at least 1 m deep 90.7 to 97.0% of the time, and at least 2 m deep 66.0 to 85.1% of the time. Median depth across all detections per location was greater than 2 to 3 m at all locations, with greater depth used in Bonneville and The Dalles reservoirs. There was no evidence that fish avoided higher TDG levels. Individual fish were consistent from reservoir to reservoir with respect to depth use (some preferring deeper water and some preferring shallower water). Fish spent the most time near the surface below Ice Harbor Dam, likely related to the relatively shallow water (2-3 m) along the south shore. No GBD problems were identified under average river conditions even though tissues were likely supersaturated. Effects of multiple short exposures to TDGS greater than 100% near the water surface are not well understood.

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

Fish kills below Red Rock Dam, Iowa, during 1983-1994 were associated with TDGS levels in excess of 110%. Fish kills occurred during periods of low discharge when tailwater depth was reduced and availability of compensating depth was limited. Thus, severe fish kills were more associated with post-spill water depth, when TDG at the river bottom was not compensated, than extreme high TDG levels. Secondary indications of chronic GBD, such as fin rot and infection, were observed. The author suggests that the EPA water quality criterion of 110% may not be adequate for chronically supersaturated waters.

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

In a laboratory study of juvenile Chinook salmon (104-107 mm), fish were exposed to 112% TDGS for 13 days, 120% for 8 hr, or 130% for 3.5 hr in shallow tanks (precluding depth compensation). Only fish in the 130% TDGS exposure group showed increased vulnerability to predation by northern pikeminnow. GBD with extensive occlusion of lateral line and gill filaments was most severe in the 130% exposure, whereas GBD in the fins was most severe in the 112% exposure. All exposures produced some GBD. The 130% exposure killed a small number of test fish. Acute exposure increased predation vulnerability, whereas chronic exposure did not. Lateral line and gill occlusion may have impaired predator detection and swimming performance (including burst swim speed), respectively.

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

GBD prevalence and severity were documented in juvenile Chinook salmon (133-150 mm) and steelhead (204-220 mm) exposed to 110, 120, or 130% TDGS in shallow water (28 cm). In steelhead, after 22 days exposure to 110%, no mortality and few signs of GBD were observed in the lateral line or gills, but bubbles were common in fins and worsened over time. At 120%, LT_{20} was 40-120 hr in Chinook salmon and 20-35 min in steelhead. Steelhead demonstrated greater individual variability in symptom severity and prevalence and time to mortality. Lateral line bubble severity in Chinook salmon was strongly linked to mortality; in this species, only bubbles in the lateral line worsened over time. At 130%, LT_{20} in Chinook salmon was 3-6 hr and in steelhead was 5-7 hr. Severity of symptoms was strongly linked to mortality in both species. GBD links to mortality were variable across tissues and species. Tissue GBD varied considerably in persistence, link to supersaturated TDG, progression, time to first response, and variability among individuals. Four limitations to using external GBD to assess TDGS effects were identified: 1) considerable inter-individual variability, 2) limited knowledge of GBD relationship to exposure history of fish in the wild, 3) variability in GBD persistence, 4) an inconsistent relationship between GBD and mortality.

Monk, B.H., R.F. Absolon, and E.M. Dawley. 1997. Changes in gas bubble disease signs and survival of migrating juvenile salmonids experimentally exposed to supersaturated gasses. Annual Report 1996. Contract Number 96-AI-93-892, Project Number 96-24. U.S. Department of Energy, Bonneville Power Administration. Portland, OR.

Juvenile steelhead exposure to 113-117% TDGS for 54 hr in shallow water produced 5-10% mortality and GBD prevalence of 23 to 51% after 30-58 hr. Exposed and non-exposed fish were released upstream of Little Goose Dam or held in net pens at 5 m depth in the Little Goose forebay. Effects of powerhouse and juvenile bypass facility passage on GBD incidence and severity and survival to downstream dams were examined. Effect of dam passage on GBD prevalence was not simple. Fish navigated the bypass facility in 3.3 to 10.1 hr (mean ~ 6 hr). Of fish with initial GBD symptoms, 47% no longer had signs after reservoir, turbine intake and bypass passage compared to 22% of exposed fish held in net pens. GBD severity in passing fish decreased in 29.6% and stayed the same in 66.0%, compared to 36.7% and 38.8%, respectively, of net pen fish. A similar percentage (~8%) of fish developed GBD passing the dam versus those held in net pens. In fish passing Little Goose Dam, it was unclear whether loss of GBD occurred due to use of compensating depth in the forebay prior to passage or hydrostatic pressure encountered during dam passage. No difference in survival of supersaturated TDG exposed and non-exposed fish during migration to downstream dams was detected. GBD bubbles in the lateral line and gills could not be documented because scales were too thick and pigmentation was too dark, and, would have required sacrifice, respectively. Fin and operculum GBD were documented. Lack of effect on survival may be due to the use of relatively large steelhead, which move quickly downstream relative to the Chinook salmon used by Mesa et al. (1997).

Montgomery Watson. 1995. Allowable gas supersaturation for fish passing hydroelectric dams. Task 8. Bubble reabsorption in a simulated smolt bypass system - concept assessment. Project Number 93-008, Contract Number DE-AC79-93BP66208. U.S. Department of Energy, Bonneville Power Administration, Portland, OR.

Juvenile spring Chinook salmon (~130 mm) were exposed to approximately 123% TDGS for 16-20 hr and then exposed to 5, 30, 60, or 120 min pressurization to simulate passage through a juvenile dam bypass facility. GBD was examined before and after pressurization. Exposure to 100 ft head for 5 min resulted in significant reduction in GBD in fins, lateral line, and gills. Gills lost GBD fastest, followed by the lateral line. Fins were slower to lose GBD symptoms. 50% loss of bubbles in fins was observed in the 5- and 30-min pressure treatments. After 120 min, almost all GBD symptoms were gone. GBD reduction may occur during bypass because only 5 min resulted in significant loss of GBD. Bubbles dissipate as quickly as 2 min from excised gills and less than 10 min in intact fish out of supersaturated water. Small bubbles dissipate in less than 2 min, larger bubbles in 3 to 8 min. Heating during observation would accelerate GBD loss. Gill bubbles were counted in live fish; sacrifice was not required. Residual lesions consisting of hemostasis (blood in connective tissue) were observed where bubbles had been. Lesions could be used as indicators of GBD in the monitoring program. It is not known how long it takes for a juvenile salmonid to navigate the bypass system. See also Elston et al. (1997a).

Morris, R.G., J.W. Beeman, S.P. VanderKooi, and A.G. Maule. 2003. Lateral line pore bubble diameters correlate with the development of gas bubble trauma signs in several Columbia River fishes. *Comparative Biochemistry and Physiology* A135:309-320.

Adult longnose sucker, largescale sucker, northern pikeminnow, redbreast shiner, and 1+ Chinook salmon were examined for differences in lateral line pore size mean and variation. These species were exposed to 115, 125, or 130% TDGS in a laboratory study at shallow depth. Lateral line occlusion was inversely related to pore size but was not directly related to TDGS or duration of exposure. Lateral line occlusion was highest in northern pikeminnow, followed by Chinook salmon. Bubble retention in the lateral line was related to pore size, with larger pores more able to release bubbles as well as facilitate exchange of fluids and gases. Reduced sensitivity to lateral line GBD in juvenile fish was suggested because scales may not yet fully enclose lateral line pores. Pore diameter must be considered when using lateral line occlusion to compare GBD among species. The shift in dominance from largescale sucker to longnose sucker in Chief Joseph Reservoir may be due to differences in sensitivity to TDGS; largescale suckers have smaller pores and are more sensitive to TDGS than are longnose suckers (see Beeman et al. 2003).

NAS/NAE (National Academy of Science/National Academy of Engineering). 1973. Water quality criteria 1972. U.S. Environmental Protection Agency Report EPA-R-73-033. Washington, DC.

Total dissolved gases (supersaturation) is included in the dissolved gases section (pp. 131-139). Topics include etiologic factors, GBD syndrome and effects, analytical considerations, total dissolved gas pressure criteria, and recommendations. The nature of gas nuclei and factors influencing bubble development, including hydrostatic pressure and surface tension, are discussed. At high TDGS, physical activity, metabolic heat, increased osmolarity, and decreased blood pressure encourage GBD formation because these factors reduce gas solubility. Body fat content may also influence GBD susceptibility,

suggesting that Pacific salmon may be more susceptible earlier in their spawning migration. Variation in GBD susceptibility among species may also be related to differences in body fat content. Bubbles likely form first on external body surfaces where total hydrostatic pressure is least and an interface exists. Bubbles may form last in blood because blood pressure and plasma viscosity oppose bubble formation. Species reproducing in or preferring shallow water habitats may be more vulnerable to elevated TDG levels. TDG pressure criteria must protect aquatic organisms of the shallow littoral zone, particularly where existing supersaturation may be worsened by heating, photosynthetic O₂ production, or other factors. The recommended TDGS limit is 110% of existing atmospheric pressure.

Newcomb, T.W. 1974. Changes in blood chemistry of juvenile steelhead trout, *Salmo gairdneri* following exposure to nitrogen supersaturation. *Journal of the Fisheries Research Board of Canada* 31:1953-1957.

Steelhead at 21 g were held in shallow test tanks at TDGS levels ranging from 100 to 110%. At 110% TDGS, blood chemistry was affected, with increased serum potassium and phosphate and decreased serum albumin, calcium, cholesterol, total protein and alkaline phosphatase in exposed fish. The changes may reflect hypoxia and tissue necrosis.

NMFS (National Marine Fisheries Service). 1999. 1998 Annual Report. Oregon Department of Environmental Quality. Portland, OR.

During 1995-1998, systematic assessment of GBD signs among juvenile salmon passing dams on the Columbia and Snake Rivers produced many thousands of data points, allowing correlation with TDG in the reservoirs and upstream locations. Minor signs of GBD (defined as < 25% coverage of a single fin) increased above 1% of fish when TDGS increased above 115%. When TDGS ranged from 120 to 125%, GBD stayed below the threshold (15% of migrants with minor signs or 5% with severe signs (> 25% coverage of one fin)), above which efforts are made to decrease spill at upstream dams.

NMFS (National Marine Fisheries Service). 1997, 1998, 2000 annual reports. Oregon Department of Environmental Quality. Portland, OR.

NMFS TDG monitoring and assessment were conducted from 1995-2000, and additional annual reports are available. Because NMFS (1999) provides considerable data for a variety of TDG levels throughout the Columbia River basin, we did not review reports from other years.

NOAA (National Oceanographic and Atmospheric Administration). 2000. Appendix E. Risk assessment for spill program described in 2000 draft biological opinion. Pages E1-E26 in: Federal Columbia River Power System (FCRPS) biological opinion.

Presents justification for the continued exception to state water quality standard for TDGS (110%) during spill for the facilitation of juvenile salmonid outmigration. Summarizes differences in tissue response to elevated TDG. Lateral line, fin, and gills differ in bubble formation, variability among individuals, disease progression over time (with continued exposure), response time to exposure, acute versus chronic response, longevity and stability of GBD symptoms, ease of ranking and observation of symptoms, and association with mortality. Reviews history of research and regulation of TDG in the FCRPS. TDG toxicity literature suggests minimal effects on adult and juvenile salmonids from TDGS 120-125% if

compensating depths are available. A summary of system flow volumes, TDG associated with voluntary and involuntary spill, and resulting GBD during 1996-1999 is presented, including definition of action levels for elevated TDG resulting from voluntary spill based on GBD prevalence and severity. Action levels were not reached from voluntary spill during this period but were exceeded during periods of involuntary (forced) spill due to system volume exceeding capacity and turbine passage limits. Sockeye salmon were most affected during involuntary spill (with up to 15.6% GBD). A risk assessment reported in the 1995 Biological Opinion (BiOp) identified 120-125% as a breakpoint between gains from additional spill for juvenile passage and losses to mortality from GBD. Turbine and spill mortality of juvenile salmonids are 6.6-13.5, and 0-2%, respectively. The 1995 risk assessment compared no spill for juvenile salmonids (baseline), spill consistent with the 1992 BiOp (limited to 110% TDGS), and 80% fish passage efficiency (115-120% TDGS spill cap). Additional modeling using the SIMPAS model in the 2000 BiOp used updated risk assessment metrics and incorporated additional exposure time modeling, barging and reservoir passage. The 2000 SIMPAS model supports the 1995 conclusions, suggesting a system-wide 4 to 6% increase in survival of juvenile salmonids associated with spill producing 120-125% TDGS. The model assessment was made for spring, summer, and fall Chinook salmon, sockeye salmon, and steelhead.

Ryan, B.A. and E.M. Dawley. 1998. Effects of dissolved gas supersaturation on fish residing in the Snake and Columbia rivers, 1997. BPA Contract Number 96-BI-93605, Contract 96-022-00. U.S. Department of Energy, Bonneville Power Administration, and Fish Ecology Division, Northwest Fisheries Science Center, National Oceanic and Atmospheric Administration, Portland, OR.

Field study examining incident GBD associated with elevated TDG during 1997 as well as reporting net pen studies used to model GBD associations with supersaturated TDG and mortality of resident fish and juvenile salmonids. GBD symptoms examined included bubbles on fins, head, eyes, body surface. 1997 was a high spill year, producing elevated TDGS of ~125% for up to 45 days and up to 130%, and 9-30% GBD prevalence in resident fish, and 13.7-49% GBD prevalence in juvenile salmonids throughout the FCRPS. GBD prevalence increased downstream; Ice Harbor levels were not representative of levels further downstream. Below Bonneville Dam, TDGS levels up to 143% were observed with levels ~130% for most of May and June. GBD prevalence was 7% for resident fish, of which 33% were severe. The report also includes discharge, TDG, and GBD prevalence data for 1994, 1995 and 1996, for Ice Harbor tailrace, Priest Rapids tailrace and reservoir, and Bonneville tailrace. The report documents development of the Exposure Index (EI) linking GBD and 7-day supersaturated TDG exposure presented in Ryan et al. (2000). Net pen studies of smallmouth bass, yellow perch, and peamouth were successful in linking 7-day supersaturated TDG exposure with GBD prevalence. The authors conclude that monitoring of resident species for GBD is no longer necessary because at TDGS less than 120% GBD is minimal and greater than 120% (up to 144%), the EI model can successfully predict GBD prevalence. They also conclude that monitoring in dam tailraces does not represent the TDG experienced by migrants, especially in shallow reaches and areas below dams where TDG is high.

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

During 1994-1997, GBD incidence in juvenile and adult non-salmonid fishes collected from the Columbia and Snake rivers was documented associated with TDG monitoring data. Exposures included 125-135% TDGS for up to 5 to 9 consecutive weeks. Collected fish were placed in net pens with different depth conditions (0-0.5, 2-3, 0-4 m). An EI for non-salmonids was developed linking 7-day TDG exposure to GBD incidence. At TDGS less than 120%, GBD was rare. At TDGS greater than 120%, the EI model effectively predicted GBD incidence. GBD was greater for captive fish than river-collected fish. Temperature and fish size weakly correlated with GBD incidence. A relationship between mortality and GBD could not be developed.

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

The FINS model is combined with the MASS2 hydrodynamics and transport model to characterize individual fish movement relative to TDG conditions. Telemetry data for juvenile steelhead and spring Chinook salmon movement downstream from McNary Dam during 1997 and 1998 (data from Beeman et al. 1998) are used to parameterize the FINS model. Results suggest that juvenile salmonid movement is primarily passive with local water velocity (via advection). Variation in juvenile movement from the advective model was higher in 1998 (a moderate flow year) than in 1997 (a very high flow year), suggesting that fish respond to flow-mediated differences in habitat, such as availability of lateral holding habitats. TDG dynamics and relationships to fish movement or depth use are not presented.

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

Chinook salmon juveniles (~16 g) in shallow test tanks were stressed at various TDG levels for up to 35 d or until the LT₁₀ or LT₅₀ was reached. Survivors were tested in a swimming performance challenge at a water velocity of 1.28 m/sec and maximum swimming distance recorded. At 106% TDGS and above, swimming performance was significantly reduced whereas exposure to 104% did not affect swimming performance. After a recovery period of 2 hr or less, supersaturated TDG-exposed fish performed as well as controls. Reduced swimming performance may be significant in a river environment when encountering dams or predators.

Schiewe, M.H. and D.D. Weber. 1976. Effects of gas bubble disease on lateral line function in juvenile steelhead trout. Pages 89-92 in: Gas bubble disease. D.H. Fickeisen, and J.J. Schneider (Editors). CONF-741033. Technical Information Center, Oak Ridge, TN.

Steelhead (202 mm) were immobilized and held at 118% TDGS while electrophysiological response of afferent lateral line nerve fibers was monitored. When physical stimuli were applied to detect reaction differences, response was diminished or eliminated when bubbles occluded lateral line pockets. Normal

function was regained after a few hours in equilibrated water. The lateral line is thought to be an important organ for sensing environmental obstacles and predators; debilitated function could diminish survival.

Schrank, B.P., B.A. Ryan, and E.M. Dawley. 1997. Effects of dissolved gas supersaturation on fish and invertebrates in Priest Rapids Reservoir, and downstream from Bonneville and Ice Harbor dams, 1995. Annual Report 1995. Contract Number 96-AI-93605, Project Number 96-022. U.S. Department of Energy, Bonneville Power Administration, Portland, OR.

GBD incidence was reported for resident non-salmonids (adult and juvenile) and juvenile salmonids in Priest Rapids Reservoir, below Priest Rapids Dam, and below Ice Harbor and Bonneville Dams. Methods and results are largely captured in Ryan and Dawley (1998). Below Ice Harbor Dam, TDGS averaged approximately 130% from mid-May through mid-June due to turbine outages. GBD prevalence among resident fish sampled averaged approximately 15%. During the period of high TDG, resident fish and hatchery fall Chinook salmon held 4 days in net pens (to 4 m depth) exhibited substantial mortality up to 16% and 84%, respectively. Downstream from Bonneville Dam, TDGS rarely exceeded 120%, and prevalence of GBD was 0.1% for resident fish and 0.0% for salmonids. Lateral line GBD was observed in 8.6% of resident fish and 0.0% of salmonids. GBD signs averaged 37 and 52%, respectively, for resident and salmonid fish held 4 days in net pens. Of 1,303 individuals of 12 taxa of invertebrates examined at Bonneville and Ice Harbor dams, only 3 individuals showed GBD signs. Includes some data linking GBD to TDG at each study location.

Schrank, B.P., B.A. Ryan, and E.M. Dawley. 1998. Effects of dissolved gas supersaturation on fish residing in the Snake and Columbia rivers, 1996. Annual Report 1996. Contract Number 96-AI-93605, Project Number 96-022. U.S. Department of Energy, Bonneville Power Administration, Portland, OR.

GBD incidence was reported for resident non-salmonids (adult, juvenile, fry) and juvenile salmonids below Ice Harbor Dam, in Priest Rapids Reservoir, below Priest Rapids Dam, and below Bonneville Dam. Methods and results are largely captured in Ryan and Dawley (1998). At 115.0 to 119.9% TDGS, 2.5% of Catostomidae (sucker) fry displayed bubbles in the body cavity. At 120 to 125% TDGS, 40.2% displayed severe GBD signs. The report includes data linking specific dam discharges to elevated TDG. For example, at Bonneville Dam, spills greater than 200 kcfs (with total release greater than 400 kcfs) produced daily average TDGS levels higher than 125% and GBD prevalence up to 15.8%.

Toner, M.A. and E.M. Dawley. 1995. Evaluation of the effects of dissolved gas supersaturation on fish and invertebrates downstream from Bonneville Dam, 1993. National Marine Fisheries Service report to the U.S. Army Corps of Engineers, Contract Number E96930036, Portland, OR.

Juvenile salmonids, resident fish, and invertebrates were collected at 18 locations below Bonneville Dam (river km 228-62) and examined for GBD associated with concurrently measured TDG. Incidence of GBD was low in all species examined. During the collection period, TDGS was recorded at Warrendale of up to 128% for 4 days, with greater than 120% for 9 days. At collection locations, TDGS ranged from 103 to 122% (mean 112%). Resident fish collected during the study were placed in live cages to induce GBD when restricted to shallow water. External signs of GBD were infrequent and documented in only 6

of 20 fish species collected. Coho salmon and steelhead were most sensitive, with 3% and 2% GBD prevalence, respectively. Other species with GBD less than 1% included sticklebacks, peamouth, and other salmonids. GBD included bubbles in the anal and caudal fins. Sublethal GBD may be associated with dysfunction of the caudal fin and development of fungal infections leading to delayed mortality. TDGS at Warrendale was 1 to 12% higher than below Bonneville Dam. TDG below the Willamette River is lower than above due to dilution by the Willamette River.

Toner, M.A., B. Ryan, and E.M. Dawley. 1995. Evaluation of the effects of dissolved gas supersaturation on fish and invertebrates downstream from Bonneville, Ice Harbor, and Priest Rapids dams, 1994. Report to U.S. Army Corps of Engineers, Contract E96940029, Portland, OR.

Resident fish and invertebrates and associated TDGS data were collected during 1994 from below Bonneville and Ice Harbor dams and above and below Priest Rapids Dam. Four-day net pen studies of resident fish and juvenile hatchery fall Chinook salmon under three depth conditions (0-0.5 m, 1.5-2.5 m, 0-4 m) were also conducted. GBD incidence in resident fish below Ice Harbor Dam was 5 to 10% during the highest TDG period but not at the other three sites. Eleven of 22 species sampled had some incidence of GBD below Ice Harbor Dam. Species with the greatest GBD prevalence were smallmouth bass, yellow perch, largemouth bass, pumpkinseed, and largescale sucker. The most common GBD symptoms were subcutaneous bubbles on the dorsal and caudal fin, with the majority of the fin occluded. TDGS at this site reached 136% on several days, with TDGS greater than 130% for 7 to 11 hours/day. No GBD was observed at any site when mean TDGS was 110% with a maximum of 115%. Net pen studies suggested that hatchery age 0 fall Chinook salmon are more sensitive to elevated TDG than resident fish because prevalence was higher and resident fish were exposed longer than hatchery fish. Some GBD was observed in net pen studies at TDGS of 114-117%, particularly in the shallow pens but also in the 0- to 4-m pens. The most common sign in net pen studies was bubbles in the lateral line; fin ray bubbles were less frequently observed, but occurrence was more consistently related to TDG levels than were lateral line bubbles. Net pen studies suggest juvenile fall Chinook salmon do not use depth to avoid elevated TDG levels. Shallow areas with little current had lower TDG levels than areas with swift current, due either to a lack of exchange with high TDG water or to greater gas dissipation associated with the greater surface area to volume ratio of shallow water.

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

From Introduction: many outmigrant juveniles in the Columbia River are infected with *Renibacterium salmoninarum* (Rs), producing bacterial kidney disease (BKD). Highly infected individuals will probably die of BKD, although mortality is highly variable. This paper: juvenile spring Chinook salmon (153 mm) infected with Rs were exposed to 120% TDGS for 96 hr in shallow water (28 cm) to examine effects of infection on susceptibility to GBD. GBD in gills and fins and LT_{20} were recorded. LT_{20} was 37 hr in infected fish, 16% earlier than in non-infected fish. Fish dying earlier had higher infection levels than surviving fish and more gill filament occlusion. Some mortality began at 24 hr; most occurred after 31 to 36 hr. Almost 25% of fish that died had low to moderate infection levels, whereas approximately 33% of surviving fish had high infection levels. Overall, fish with moderate to high levels of infection were more vulnerable to the effects of supersaturated TDG and died sooner. Much individual variation

was observed. Most of the mortality observed was attributed to GBD because severe gill filament occlusion was observed. The GBD monitoring program may underestimate effects of GBD on outmigrant survival because it does not consider synergistic effects with other sources of mortality. BKD may turn sublethal GBD exposure into lethal exposure.

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

A comprehensive review of the gas supersaturation literature published prior to 1980. Topics include a history of gas bubble disease (early observations, Columbia River system, other recent observations), the gas bubble syndrome (external signs in eggs, fry and larvae, adults, non-salmonids, invertebrates, internal lesions, cause of death, recovery from GBD, physiological and behavioral effects, nitrogen-oxygen total gas pressure, critical level of supersaturation), tolerance to supersaturation (salmonids at near surface pressure, hydrostatic compensation, intermittent exposure, detection and avoidance, life stage, heritability, temperature, saltwater adaptation, non-salmonids), causes of supersaturation (air injection, hydroelectric projects, thermal increases, natural causes), solutions to supersaturation, dissolved gas analysis, and regulation of supersaturation. Factors affecting solubility of gases in water include dissolved solids content, characteristics of the gases, total pressure, and temperature. Dissolved solids content is not relevant to freshwater systems. Nitrogen, oxygen, and argon are the gases of importance, at partial pressures of 78, 21, and 1%, respectively. Although oxygen has one-quarter the partial pressure of nitrogen, it is twice as soluble in water. Therefore, it is half as plentiful as nitrogen. The problem of supersaturation was first recognized in the late 1800s, with symptoms described in the early 1900s. Early problems were mostly associated with hatcheries, from accidental production of supersaturated conditions and from use of groundwater having naturally elevated TDG. Supersaturation problems in the Columbia and Snake rivers were first recognized during the 1960s. Through the 1960s and 1970s, the problem received considerable attention. Supersaturated water enters the Columbia River in the United States from the Snake River and Canada and is never able to equilibrate. Thus, the problem continues downstream throughout the lower Columbia River. Most studies through this period focused on dissolved nitrogen based on the assumption that dissolved oxygen could be regulated by biological processes because it is biologically active whereas nitrogen is biologically inert. Solutions considered included barge and truck transport of juveniles around problem reaches as well as to reduce turbine mortality, construction of spillway flow deflectors, and use of perforated bulkheads to reduce hydraulic head in operational turbines and skeleton turbine bays. By the late 1970s, the supersaturation problem on the Snake and Columbia rivers was considered solved.

Weitkamp, D.E., R.D. Sullivan, T. Swant, and J. DosSantos. 2003a. Behavior of resident fish relative to total dissolved gas supersaturation in the lower Clark Fork River. *Transactions of the American Fisheries Society* 132:856-864.

Field study of adult resident fish, including salmonids (rainbow trout, brown trout, cutthroat trout, bull trout) exposed during 1998-2000 to TDGS levels usually less than 120% but higher than 125% for ~1.5 months during 1999. Most fish spent sufficient time at depths greater than 2 m to avoid or recover from short exposures to supersaturated TDG. Authors conclude that laboratory study exposures in shallow water overestimate effects of TDG because the study design does not permit depth compensation. In this paper, fish appeared to use depth to avoid exposure and/or allow recovery. GBD incidence reported in companion paper below.

Weitkamp, D.E., R.D. Sullivan, T. Swant, and J. DosSantos. 2003b. Gas bubble disease in resident fish of the lower Clark Fork River. *Transactions of the American Fisheries Society* 132:865-876.

Field study of adult resident fish, primarily largescale sucker, northern pikeminnow, peamouth, mountain whitefish but including salmonids (rainbow trout, brown trout, cutthroat trout, bull trout), and caged juvenile rainbow trout and kokanee exposed to incident supersaturated TDG during 1997-2000. Fish were collected by electrofishing and seining from water depths of 2 m or less above and below Cabinet Gorge Dam, Idaho. Cages were 2 m (rainbow trout) and 9 m (kokanee) deep. TDGS was very high in 1997 (up to 150%, and 130% or higher continuously for ~ 2 months), high in 1999 (120-130% for ~1.5 months), and lower in 1998 (short-term TDGS to 120%) and 2000 (short-term TDGS to 130%). Overall GBD incidence was: 1997, 5.6%, 1998, 0.1%, 1999, 5.9%, 2000, 0.1%. GBD was species-specific, with largescale suckers and brown trout more vulnerable than other species. In 1999, after TDGS exposure of 130% or more, GBD symptoms did not appear for several weeks following exposure. Exposed fish either resided at sufficient depths to avoid or recover from exposures or left the study area. Caged juvenile rainbow trout exposed to 140-150% for 4 d or 123-138% for 15 d experienced 100% and less than 20% mortality, respectively, at 2 m maximum depth. Caged juvenile kokanee exposed to 125% TDGS had no mortality and no GBD symptoms after 15 d at 9 m maximum depth. Authors conclude that 1) this study overestimated GBD because all fish were collected at 2 m or less, 2) GBD incidence was lower than expected, even in high TDG years, and 3) 120-130% TDGS had no effect on adult resident fish because they avoided and/or recovered from exposure by using depth sufficient to compensate for elevated TDG.

White, R.G., G. Phillips, G. Liknes, J. Brammer, W. Connor, L. Fidler, T. Williams and W.P. Dwyer. 1991. Effects of supersaturation of dissolved gases on the fishery of the Bighorn River downstream of the Yellowtail Afterbay Dam, Completion report of Montana Cooperative Fishery Unit, Montana State University, to U.S. Bureau of Reclamation, Washington, DC.

Comprehensive study of exposure and effects of gas supersaturation on invertebrates and fishes. The eight project objectives were to examine or determine 1) physical and physiological factors influencing GBD incidence, 2) the relationship between TDG levels and GBD symptoms in adult and juvenile trout, 3) the relationship between behavior and habitat selection and TDGS susceptibility, 4) the relationship between TDG and invertebrate and forage fish communities, 5) effects of GBD on trout catchability, 6) mechanisms of higher GBD incidence in brown trout than in rainbow trout, 7) safe TDG levels for various stages of brown and rainbow trout, and 8) effects of dam operation on TDG levels. 112% TDGS did not affect growth, cause significant mortality, or impair feeding behavior of juvenile brown or rainbow trout. TDGS exposure in juvenile brown trout combined with bacteria challenge treatments resulted in increased numbers of bacteria in kidney samples of TDGS-exposed fish compared to unexposed fish. Ability of juvenile trout to recover from GBD decreased after multiple TDG exposures. Tissue damage from earlier exposures weakened fish, and bubbles from earlier exposure led to more rapid GBD symptom development upon re-exposure. Rainbow trout GBD incidence was highest during spring spawning as spawners moved into shallow side channels to spawn. Theoretical models were developed based on data obtained from the literature and empirical studies that identified TDG thresholds for bubble development in trout in the vascular system, environmental water (re: bubble development in the buccal cavity and between gill lamella), subdermal bubbles on external surfaces, and overinflation of the swim

bladder. Mortality thresholds were determined at 110-112% (associated with bubbles in the buccal cavity) and 115-119% (associated with extracorporeal bubbles). TDGS levels of 112-114% were sublethal but produced excess buoyancy in up to 50% of test organisms, which affected swimming performance. Fish did not appear to avoid elevated TDG levels. Invertebrate communities were significantly different before and after TDG exposure. Invertebrate species with reduced frequency of occurrence or that were missing after exposure were also more sensitive to TDG in laboratory bioassays.