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ASSESSMENT OF THE INFLUENCE OF GAS SUPERSATURATION ON SALMONIDS IN THE NECHAKO RIVER IN RELATION TO KEMANO COMPLETION

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by

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SUMMARY AND RECOMMENDATIONS

Recommendations are presented for salmonids in the Nechako as follows:

(1) An examination of the available literature and current investigations of TGP indicate that there are two forms of GBT, which we call chronic and acute. Chronic GBT is seen to occur over a range of about 105-109.7% TGP. Acute GBT is seen to occur at TGP levels of 110% or greater. Chronic GBT produces low rates of mortality (1.4-5.0%) over long exposures (43-122 days). Acute GBT shows a typical toxicological relation between exposure period and TGP (%) level and produces substantial rates of mortality over much shorter exposure intervals.

(2) The TGP (%) boundary between chronic and acute levels of GBT is neither singular nor fixed. It varies with TGP level in relation to the combination of levels of ancillary variables simultaneously applied. The ancillary variables have a "sparing effect" on response to TGP at alevin and early fry size and apparently at subadult and adult fish size, higher dissolved O_2/lower dissolved N_2 ratios, and greater water depth. Lower barometric pressure appears to raise the TGP (%) threshold, but current data are insufficient to prove the relationship. The boundary region between chronic and acute GBT is estimated to vary accordingly between approximately 108 and 116% TGP, depending on the levels of ancillary variables simultaneously applied.

(3) In a current study, juvenile salmonids are found to distribute themselves in the water column in relation to TGP level. In this specific example, the mode of fish distribution, relative to the compensation depth, occurs at progressively deeper levels as TGP increases, reaching a maximum at the compensation depth at 110-112% saturation. At TGP levels above 110-112% saturation the mode of distribution rises rapidly above the compensation depth. Therefore, the proportion of individuals in a group that would be found above the modal depth would also vary with TGP level. At TGP levels above 110-112% most to all test individuals show observable symptoms of GBT. We suspect that small to negligible proportions respectively are at risk in relation to the lower levels of mortality found in the chronic range of TGP levels from below 110 to 105%.

(4) We conclude from the literature reviewed and new data available to us that the following TGP levels on the Nechako River may be considered satisfactory:

(i) juvenile chinook - for levels of the ancillary variables appropriate to the upper Nechako River, the boundary for acute GBT conditions is estimated to be 110% TGP. Therefore we recommend that TGP (%) levels be maintained below 110% saturation at all times. Although acute GBT would not be anticipated at TGP levels below 110%, some chronic mortality - (e.g. 1.5%-5%) could occur. To guard against chronic mortality, TGP (%) levels should not exceed 104-105%.

(ii) adult sockeye - the few data available suggest that TGP levels in the Nechako to which migrating sockeye are exposed should not exceed 110% at any time.

(5) For reasonable growth of chinook juveniles on the upper Nechako River (above the Nautley confluence) we recommend that temperature control be instituted in the period of maximum summer heating. This control would provide a "temperature window", with respect to growth on available food resources, of 12.5 to 17.5°C. That is, temperature control on the upper Nechako should provide water starting at 12.5°C at Cheslatta Flats with sufficient discharge so that downstream temperature does not exceed 17.5°C just above the Nautley River confluence. Two alternatives suggested for achieving temperature control are:

(i) A two-port structure at Kenney Dam to deliver a) hypolimnion water (e.g. 6.0-7.2°C) and b) surface water, through equilibration devices to bring the discharged water to saturation in dissolved gases. Control of temperature and discharge would then provide equilibrated water at or near 12.5°C at Cheslatta Flats below Grand Canyon.

(ii) Two separate discharges, a cool water (6.0 - 7.2°C) discharge through an equilibration device at Kenney Dam and a warm water discharge via Cheslatta Falls (e.g. 18.0°C), the two flows to converge at Cheslatta Flats. This alternative would require storage facilities above Cheslatta Falls so that water discharge could be controlled. This second alternative is considered inferior to the first in that the warm water discharged over Cheslatta Falls initially is supersaturated and remains supersaturated as a result of its fall into the Cheslatta Falls plunge pool (e.g. 108-110% TGP). Mixing of the Kenney and Cheslatta flows could be regulated with respect to temperature and discharge, but calculations show that the mixed flow at Cheslatta Flats would begin at approximately 105-106% TGP. In view of the increase in temperature that would occur downstream, and the associated rise in TGP level accompanying that increase, the second alternative probably would not meet recommended TGP criteria (TGP levels to remain below 110% to a point just above the Nautley junction). Modelling is recommended to determine the appropriateness of the two alternatives.

(6) For protection of adult sockeye migrating through the lower Nechako we recommend that water temperatures from the Nautley confluence downstream be maintained at or below an average temperature of 17.5°C, and not exceed 20°C at any time, during the period of maximum summer heating. Historically, water temperatures in the lower Nechako have exceeded 17.5°C. Nevertheless, the requirements of the species are set by the species itself, and in our judgement risks may be held to a reasonable

level if temperatures are maintained at or below 17.5°C. Because of the history of higher temperatures in the Nechako, we recommend, as a secondary target, that temperatures not exceed 20°C, with a final target of 17.5°C whenever possible.

(7) Rates of temperature change and change in TGP levels downstream from Cheslatta Flats could be modified by associated changes in volume of water discharged (under temperature control) into the upper river. Rates of increase in temperature and TGP most likely would be dampened and modified by increases in discharge volume as indicated (point 5). We recommend that TGP level and temperature be controlled in the upper Nechako as outlined, and that the benefits of that control be extended downstream through increase in discharge volume. We recommend that simulation studies be undertaken to estimate the simultaneous relations between temperature, TGP and discharge and their optimization with respect to the TGP and temperature criteria outlined both for juvenile chinook upstream and for adult migrating sockeye downstream in the Nechako River.

(8) We suggest further that the recommendations made herein be reviewed in broader context in relation to the general ecological requirements of salmonids, particularly with respect to conditions associated with discharge (depth, velocity, fluctuations in depth and velocity, bed load transport, deposition of fine particulate matter, fluctuation in wetted perimeter) that will influence gravel quality and food production in the Nechako River.

ABSTRACT

Alderdice, D. F. and J. O. T. Jensen. 1985. Assessment of the influence of gas supersaturation on salmonids in the Nechako River in relation to Kemano Completion. Can. Tech. Rep. Fish. Aquat. Sci. 1386: 48 p.

Following a historical review of developments on the Nechako River, information is reviewed on total gas pressure (TGP), temperature and discharge conditions for pre-Kemano I and Kemano I periods. Although emphasis is placed on a search for TGP criteria, the high association between TGP, temperature and discharge requires an examination of all three variables. A summary is presented of the physical principles affecting solution of atmospheric gases, the biological effects of supersaturation in producing gas bubble trauma (GBT) in salmonids, the influence of hydrostatic pressure on depth compensation in GBT, and ancillary factors (temperature, fish size, dissolved O_2/N_2 gas ratios, water depth, barometric pressure) that modify the biological response to TGP. TGP criteria are reviewed as currently published. Recent developments in the understanding of TGP effects on salmonids are presented in relation to the action of ancillary variables on biological response, chronic GBT problems in shallow water culture, the biophysics of bubble growth in fish blood, and vertical distribution of salmonids in supersaturated water. TGP criteria are suggested in relation to GBT. As well, these ongoing studies provide a new view on the biological effects of TGP, and on that basis new temperature criteria are re-examined for growth of juvenile chinook salmon in the upper Nechako River and for the well-being of adult sockeye migrating through the lower Nechako. The need for consideration of rates of discharge of water into the upper Nechako is suggested insofar as discharge influences TGP levels and temperatures in the Nechako River.

RÉSUMÉ

Alderdice, D. F. and J. O. T. Jensen. 1985. Assessment of the influence of gas supersaturation on salmonids in the Nechako River in relation to Kemano Completion. Can. Tech. Rep. Fish. Aquat. Sci. 1386: 48 p.

Après avoir fait l'historique des aménagements sur la rivière Nechako, on passe en revue l'information sur les conditions de pression totale des gaz (PTG), de température et de débit avant et après le projet hydro-électrique de Kemano I. Bien que l'accent soit mis sur la recherche de critères de PTG, le fait qu'il y ait une relation étroite entre la PTG, la température et le débit exige qu'on examine ces trois variables. On présente un résumé des principes physiques qui influent sur la dissolution des gaz atmosphériques, des effets biologiques de la sursaturation qui provoque le traumatisme des bulles de gaz (TBG) chez les salmonidés, de l'influence de la pression hydrostatique sur le mécanisme de compensation à la profondeur dans le TBG et des facteurs auxiliaires (température, taille des poissons, rapports entre l'oxygène et l'azote dissous, profondeur de l'eau, pression barométrique) qui modifient la réponse biologique à la PTG. On examine les critères de PTG tels que publiés actuellement. On présente les progrès récents réalisés dans la compréhension des effets de la PTG sur les salmonidés en fonction de l'action des variables auxiliaires sur la réponse biologique, des problèmes chroniques de TBG dans l'élevage en eaux peu profondes, de la biophysique de la formation de bulles dans le sang des poissons et de la distribution verticale des salmonidés dans l'eau sursaturé. On propose des critères de PTG par rapport au TBG. Aussi, ces études ouvrent une nouvelle perspective sur les effets biologiques de la PTG, et, sur cette base, de nouveaux critères de température sont réexaminés pour favoriser la croissance de jeunes saumons quinnats dans le cours supérieur de la rivière Nechako et pour assurer le bien-être des saumons rouges adultes qui migrent en passant dans le cours inférieur de la rivière. On estime qu'il faut tenir compte des débits d'eau dans le cours supérieur de la rivière Nechako dans la mesure où le débit influe sur les niveaux de PTG et sur les températures dans cette rivière.

INTRODUCTION

HISTORICAL

A water licence was issued to the Aluminum Company of Canada in December, 1950 to develop storage capacity in the Nechako River watershed upstream of Cheslatta River and in the Nanika River watershed upstream of Glacier Creek (F & MS and IPSFC 1979). Development of the Nechako system, labelled Kemano I, resulted in a 300-ft. (91.5-m) rock-filled dam (Kenney Dam) at Grand Canyon on the upper Nechako River (Fig. 1) (IPSFC 1979). There is no discharge of water at Kenney Dam, and the former riverbed between Kenney Dam and Cheslatta Falls (Fig. 2)--the Grand Canyon--is now dry. Release of surface waters from the 350 sq. mile Nechako Reservoir behind the dam occurs at Skins Lake spillway. There water is discharged into a chain of lakes (Skins, Cheslatta, Murray Lakes) formerly a tributary system to the Nechako River. Water discharged into this system enters the former riverbed of the Nechako at Cheslatta Falls (which we call Cheslatta Flats), hence the Nechako River currently originates at Cheslatta Falls. The waters impounded by Kenney Dam are diverted at the western end of the reservoir, via a 10-mile power tunnel, to hydro-electric generating facilities at Kemano on the Kemano River about 10 miles upstream from Gardner Canal on the British Columbia coast. Power generated at Kemano is conducted overland to Alcan's aluminum smelter at Kitimat. Studies were conducted from 1951 to 1953 by the federal Fisheries and Marine Service, and by the International Pacific Salmon Fisheries Commission (F & MS and IPSFC 1979, F & MS 1979, IPSFC 1979). Recommendations made relate to a) adequate water flows for migration of chinook and sockeye salmon to spawning grounds on the upper Nechako and tributary river watersheds, respectively; b) higher expected water temperatures in the Nechako River and their threat to salmon stocks using the system; and c) reduction in chinook salmon spawning area in the upper Nechako as a consequence of reduced discharge in the Nechako. In particular, it was recommended that adequate quantities of cooling water be discharged from the Nechako reservoir to maintain near-normal temperature regimes in the main flow of the Nechako River.

In 1970 the B. C. Provincial Government began discussing development of residual unused Kemano capacity. This proposed development, identified as Kemano II, would involve utilization of the balance of unused Nechako River capacity as well as water from the Nanika-Morice watershed (Fig. 1). The Dean River at that time also was included as part of the scheme for increased storage (Fig. 1). A further extension, the pumping of Morice Lake water into the Nechako reservoir was also considered (Fig. 1). Discussions continued in 1971 and 1974, at which time the Dean River was excluded from further consideration. At that time it was agreed that the fish and wildlife agencies concerned (Fisheries and Marine Service, International Pacific Salmon Fisheries Commission, B. C. Fish and Wildlife Branch) would attempt to define their environmental concerns and propose studies needed to assess potential problems. These recommendations were duly made (F & MS and IPSFC 1979, F & MS 1979, IPSFC 1979).

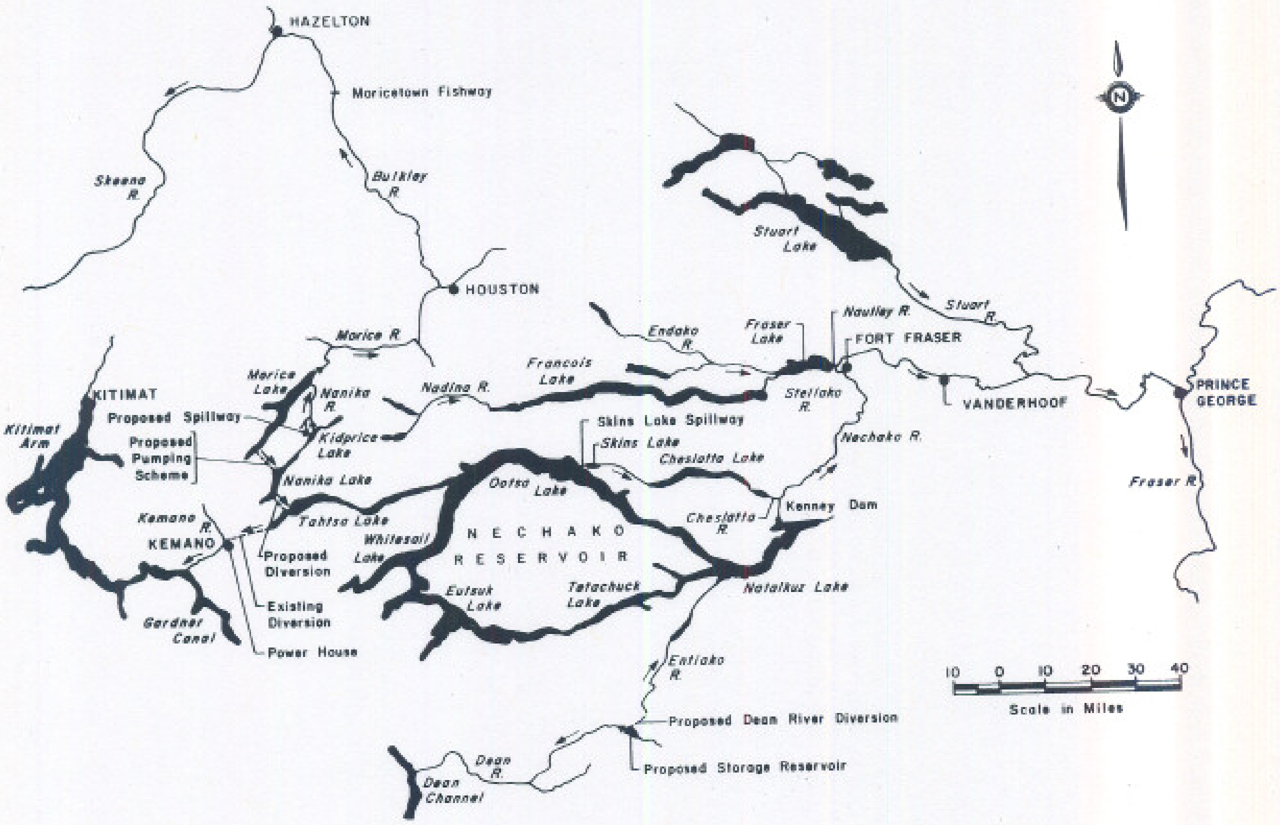

Fig. 1. The Nechako reservoir, after the building of Kenney Dam, and the lower Nechako River and its main tributaries, the Nautley and Stuart rivers. Reservoir waters flow westward for power generation at Kemano, or eastward, via Skins Lake Spillway and the Cheslatta Lake chain, to enter the former bed of the Nechako River. Also shown is the Nanika-Morice-Bulkley system, which reports to the Skeena River, and the proposed Dean River diversion, now abandoned (from F & MS and IPSFC 1979).

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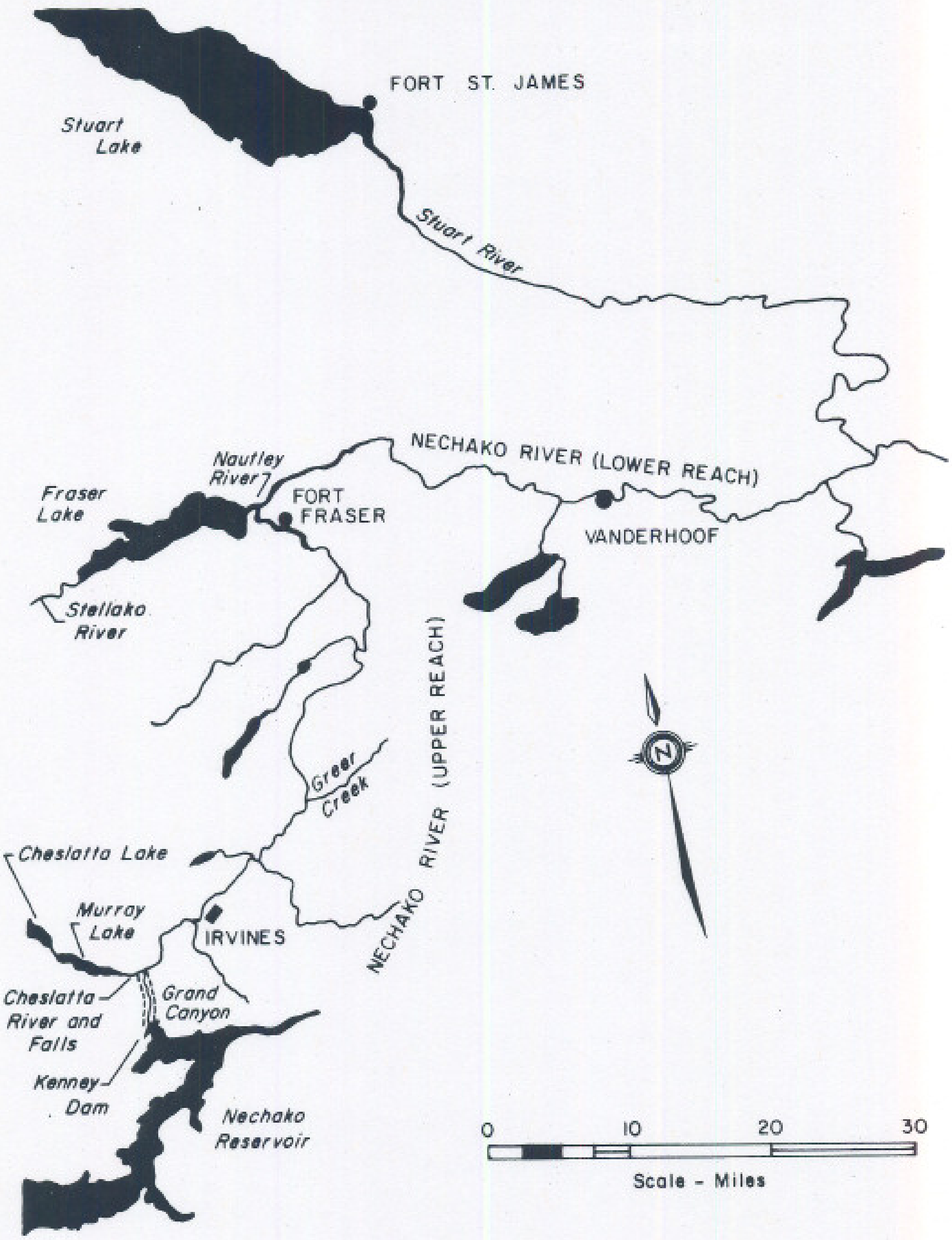

Fig. 2. Upper Nechako River from Kenney Dam and Cheslatta Falls to the Stuart River confluence (from IPSFC 1979).

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Alcan then proceeded to plan for development of the remaining storage potential granted in its original water licence. Initially, complete diversion of the Nechako River above Kenney Dam was proposed. Subsequently this was modified because of the environmental concerns raised. A schedule of flows was proposed for various periods of the year to maintain chinook habitat in the upper Nechako and to control river temperature for protection of migrating adult sockeye in the lower Nechako upstream to the Nautley River confluence. A discharge of 1100 cfs (31.1m^3/s) could be provided during the sockeye migration period by blending surface waters (Skins Lake spillway via Cheslatta Falls) with cold water from a deep intake behind Kenney Dam. Flows proposed by Alcan would be (IPSFC 1983):

December - March	500 cfs (14.2m^3/s)
April - August	1100 cfs (31.1m^3/s)
September - October	1000 cfs (28.3m^3/s)
November	900 cfs (25.5m^3/s)

These flows would provide an average of 16% (range, 9-31%) of pre-Kemano I flows, measured at Fort Fraser, for the upper Nechako River. This proposal, labelled Kemano Completion, replaced the original (Kemano II) proposal for further development of Nechako storage capacity.

Kenney Dam was constructed (Kemano I) during the early 1950s. Reservoir filling began in 1952. No water was discharged to the Nechako River from October 1952 to June 1953; thereafter intermittent releases were made between June 1955 and January 1957. Pre-Kemano I flows in the upper Nechako during the chinook spawning period ranged between 4000 and 7000 cfs (113.3 - 198.2m^3/s). Since then, spills of reservoir water have been by way of Skins Lake and Cheslatta Falls, with discharges at times up to 17000 cfs (481.4m^3/s). In November 1979, Alcan reduced the flow to 450 cfs (12.7m^3/s) and proposed to maintain that level through the 1980 sockeye adult migration period. This was altered by B. C. Supreme Court injunction to provide enough flow for fish protection; compliance has occurred since that time. Mean monthly discharges into the upper Nechako, measured at Fort Fraser (IPSFC 1983) compared with proposed Kemano completion flows, range as follows:

Period	Range, cfs (m^3/s)	Annual average, cfs (m^3/s)	% of Pre-Kemano I
Pre-Kemano I	Feb., 2130 (60.3) - June, 26800 (758.9)	7130 (201.9)	100
Kemano I	Feb., 401 (11.4) - Sept., 17445 (494.0)	4743 (134.3)	66.5
Kemano Completion (proposed)	Feb., 528 (15.0) - May, 2068 (58.4)	1107 (31.3)	15.5

Upper Nechako flows during Kemano I therefore average (1957 - 82) 66.5% of pre-Kemano flows. Alcan's proposed flow release under Kemano completion would remove the equivalent of 84.5% of the pre-Kemano annual average flow.

Chinook salmon have spawned in the Nechako River mostly above its confluence with the Nautley River. Estimated chinook spawning populations in the Nechako River (1935 - 1977) are shown in Table 1 (F & MS 1979). Sockeye adults migrating through the lower Nechako River en route to tributary spawning grounds for the same period are shown in Table 2 (IPSFC 1979).

PROBLEM AND OBJECTIVES

The problem in general remains one of defining the environmental requirements of the chinook and sockeye populations utilizing the Nechako River and recommending the establishment of criteria or conditions that will preserve the natural stocks and the natural salmon producing potential of all rivers (including the Nechako) that would be affected by the proposed development (Dept. Fish. & Oceans 1984). The specific objective of this review is to define the biological effects of dissolved gas supersaturation on salmonids in the Nechako River system, and to provide guidelines for biological effects of gas supersaturation that might be encountered in other waters affected by Alcan's proposed development. It will be shown that there are elevated levels of gas supersaturation in the Nechako River involving, among other factors, supersaturation occurring as a result of water from Cheslatta Falls falling into a plunge pool. It also will be shown that dissolved gas levels in the Nechako River are inseparably linked to weather conditions, water temperatures, levels of discharge into the upper Nechako and the manner in which water may be discharged either through the Skins Lake spillway (via Cheslatta Falls) or from Kenney Dam. Hence all three factors (supersaturation, water temperature, discharge) must be considered in examining the problem.

DISSOLVED GAS SUPERSATURATION

Description. The amount of constituent gases in atmospheric air that will dissolve in water depends on the proportion of each gas in the air and the solubility of each constituent gas. A given volume of atmospheric air contains 78.084% nitrogen (N_2), 20.946% oxygen (O_2) and 0.934% argon (Ar); the remaining 0.036% comprises noble gases, hydrocarbons and trace gases (Colt 1983). Solubility of gases in fresh water depends on temperature and pressure. As the three gases indicated make up over 99.9% of atmospheric air, further discussion is confined to those gases. For technical and biological reasons N_2 and Ar are considered together; both are inert gases, which do not take part in biological reactions.

To summarize Colt (1983), for atmospheric gas in equilibrium with water, the pressure of each (i^{th}) constituent gas in the liquid phase (l) is the same as that in the gas phase (g):

(1) $P_i^{\ell} = P_i^{g}$

Table 1. Estimated escapement of Chinook salmon in the Nechako River from 1935 to 1977.

Year	No.	Year	No.
1935	1000-2000	1956	100-300
1936	500-1000	1957	Present[2]
1937	2000-5000	1958	None[2]
1938	500-1000	1959	None[2]
1939	1000-2000	1960	50-100
1940	2000-5000	1961	300-400
1941	1000-2000	1962	300-500
1942	300-500	1963	300-500
1943	100-300	1964	600-800
1944	100-300	1965	300-500
1945	500-1000	1966	400-500
1946	500-1000	1967	500-1000
1947	-	1968	300-500
1948	Medium	1969	300-500
1949	2000-5000	1970	500-1000
1950	1000-2000	1971	300-500
1951	2000-5000	1972	300-500
1952	2000-5000[1]	1973	500-1000
1953	300-500	1974	500-1500
1954	1000-2000	1975	1000-2000
1955	300-500	1976	1000-2000[3]

[1]Egg mortality estimated at 95%.

[2]1957-1959: Heavy silting of river resulting from high discharge from Skins Lake Spillway.

[3]Special chinook salmon fishery closure and mesh restrictions in effect

(from F & MS 1979).

Table 2. Sockeye salmon spawning populations in Nechako River Tributaries.

Year	Nadina River Early	Nadina River Late	Stellako River	Stuart System Early	Stuart System Late	Total all runs
1938	272	-	6943	7671	62	14,948
1939	23	p	2585	979	-	3587
1940	70	-	3276	335	279	3960
1941	525	45	8566	6535	10,231	25,902
1942	686	-	91,840	8474	p	101,000
1943	83	-	14,897	2738	-	17,718
1944	29	-	5768	717	46	6560
1945	1405	205	20,826	31,913	67,964	122,313
1946	1401	-	245,172	9243	2116	257,932
1947	589	-	59,904	13,849	52	74,394
1948	291	-	16,213	20,960	1049	38,513
1949	25,168	-	104,835	582,228	107,752	819,983
1950	4325	774	145,108	59,443	5843	215,493
1951	1005	175	96,208	61,041	4402	162,831
1952	2829	38	40,466	33,582	1975	78,890
1953	27,114	14,438	43,688	154,312	369,023	608,575
1954	2032	770	141,882	35,058	5470	185,212
1955	798	108	51,746	2170	7618	62,440
1956	1613	83	38,459	25,157	1454	66,766
1957	31,744	29,146	38,921	235,033	531,130	865,974
1958	854	718	112,273	38,812	23,638	176,295
1959	2106	1013	79,355	2670	8225	93,369
1960	1,755	157	38,884	14,572	2961	58,329
1961	18,578	17,544	47,241	199,136	411,105	693,604
1962	758	1683	124,495	26,716	18,689	172,341
1963	4363	7304	138,805	4628	3237	158,337
1964	1597	232	31,047	2421	1900	37,197
1965	3,920	11,293	39,418	23,045	214,958	292,634
1966	93	1784	101,684	10,859	9032	123,452
1967	4232	7790	91,525	21,069	1642	126,258
1968	1021	1496	30,420	1587	470	34,994
1969	8681	27,898	49,341	109,818	207,057	402,795
1970	78	3939	45,876	32,747	15,055	97,695
1971	3302	14,525	39,726	95,942	1535	155,030
1972	966	2702	36,771	5086	8704	54,229
1973	2759	16,737	30,755	300,653	214,343	565,247
1974	34	3,825	41,473	51,536	14,627	111,495
1975	1817	15,319	176,079	85,499	14,229	292,943

Uncha, Nithi, Ormonde, Endako (small tributaries of the Fraser-Francois System) included with early Nadina.

Tagetochlain (tributary of Nadina River) included with late Nadina.

p = Some spawners were present but not counted.

\- = No observations were made

(from IPSFC 1979).

In moist air, saturated with water vapour,

(2) $P_i^g = X_i(BP - P_{H_2O})$

where X_i = mole fraction (volume percent) of the i^{th} gas

BP = barometric pressure (mm Hg)

P_{H_2O} = vapour pressure of water (mm Hg)

The concentration of the i^{th} gas in the liquid phase, in equilibrium with the gas phase, is

(3) $C_i^* = 1000K_i \beta_i X_i (BP - P_{H_2O})/760$

where C_i^* = the equilibrium concentration (saturation) of the i^{th} gas dissolved in a unit volume of water at standard temperature and pressure (STP)(0°C, 760 mm Hg)

K_i = ratio of one gram molecular weight of the i^{th} gas to the volume of 1 mole of the gas at STP.

β_i = Bunsen coefficient (Colt 1980), the volume of gas dissolved per unit volume of water at a given temperature when the partial pressure of the i^{th} gas is one atmosphere.

Under natural conditions the measured concentration of a gas (C_i) rarely is in equilibrium with the partial pressure in the gas phase. The partial pressure in the liquid phase that would be in equilibrium with the measured concentration, the dissolved gas pressure, is for the ith gas

(4) $P_i^\ell = \frac{C_i}{\beta_i}\left(\frac{760}{1000K}\right)$

Then the total dissolved gas pressure in the liquid phase is

5) $TGP = \left(\sum_{i=1}^{n} P_i^\ell\right) + P_{H_2O}$,

while that in the gas phase is

6) $BP = \left(\sum_{i=1}^{n} P_i^g\right) + P_{H_2O}$

Generally, then

7) $TGP=P^{\ell}_{N_2}+P^{\ell}_{O_2}+P^{\ell}_{Ar}+P^{\ell}_{H_2O}$, and

8) $BP=P^{g}_{N_2}+P^{g}_{O_2}+P^{g}_{Ar}+P^{g}_{H_2O}$

Under natural conditions three things can occur in water:

TGP>BP (water is supersaturated)
TGP=BP (in equilibrium)
TGP<BP (water is undersaturated)

Hence, percentage saturation may be reported in terms of the constituent gases, or in terms of the total of the dissolved gases:

9) TGP (% saturation)=(100·TGP)/BP

Where the percentage saturation of the measured gases is restricted specifically to N_2, Ar and O_2, then

10) $S=0.79018S_{N_2+Ar}+0.20946S_{O_2}$

where S=combined saturation level of N_2+Ar and O_2 (%)

S_{N_2+Ar}=saturation level of N_2+Ar (%)

S_{O_2}= saturation level of O_2 (%)

In the 1970's the direct measure of total gas pressure (TGP) became possible with the development of the membrane diffusion method of measurement. Resulting instruments (saturometer, tensionometer) measure ΔP, the differential pressure between BP and TGP:

11) ΔP=TGP-BP (mm Hg)

Hence, a measure of TGP may be obtained from

12) $BP+\Delta P=(P_{N_2+Ar}+P_{O_2}+P_{H_2O})$ = TGP

Early work on gas bubble trauma (GBT) in fishes assumed that biological problems were the result of N_2 supersaturation. In the early to mid-1970s it became clear that the problem was one involving all dissolved gases, or total gas pressure. ΔP now is recognized as the driving force for bubble growth in fish blood and tissue and that TGP>BP (supersaturation) is the cause of GBT. Although TGP=BP+ΔP is recognized as the most meaningful expression of gas supersaturation, there is a strong tendency to continue the convention of reporting dissolved gas levels in terms of percentage saturation. Percentage TGP, relative to BP at the water surface, may be reported as

$$13)\quad TGP(\%)=\frac{(BP+\Delta P)}{BP}.100$$

Equation 13 has been shown to be superior to other alternatives (Colt 1983); this method of reporting dissolved gas levels and TGP will be followed here.

Supersaturation of natural waters can occur through entrainment of air in the plunging water of spillways and waterfalls (e.g. Cheslatta Falls), introduction of air into pressurized water systems, through photosynthesis in natural waters, and through natural or artificial heating of water (Weitkamp and Katz 1980).

Biological Effects of Supersaturation. In supersaturated water (TGP>BP), fishes can develop bubbles of gas in the tissues or circulatory system, similar to the problem of "bends" in the human diver. Bubble growth can occur when the difference in TGP in blood and tissue and that in the external environment (water) is great enough to exceed downloading that would occur naturally through diffusion and gill ventilation. The biophysics of bubble growth in fish blood is being examined (Fidler 1984) but is still in the developmental phase.

Of the various life stages of salmonids, the egg tends to be most resistant to the effects of excess (ΔP>0) TGP. Yolksac larvae appear to remain relatively resistant. Advanced fry, some weeks after yolk absorption and swim-up (emergence) appear to be the most susceptible (Harvey and Cooper 1962; Nebeker et al. 1978). It seems that susceptibility in older stages is a function of body size (Weitkamp and Katz 1980), susceptibility decreasing with increasing body mass. The latter may reflect the increased size of the vessels in the circulatory system, and the fact that smaller vessels in smaller fish would be occluded more readily by gas bubbles in the vessels.

It appears that internal (hydrostatic) pressure in salmon eggs (50-90 mm Hg) (Alderdice et al. 1984) is responsible for the increased resistance to TGP found in salmonid eggs. Hydrostatic pressure compensates for excess TGP at the rate of about 1% excess TGP (or about 7.3 mm Hg)/10 cm of water depth. Internal egg pressures of 50-90 mm Hg are equivalent to water pressures at depths of 0.69 to 1.23 m. Therefore eggs having an internal pressure of 50-90 mm Hg, held at zero depth, would be at the equivalent of 100% saturation when the TGP in the surrounding water is 107 to 112% saturation, respectively. In addition, yolksac larvae may be less susceptible to excess TGP because of their large yolk sac, and the fact that N_2 gas is much more soluble in its lipid medium than in water (Fidler 1984).

In the juvenile stage, symptoms of GBT include bubble formation in the midgut (Cornacchia and Colt 1984) (striped bass) and in the buccal cavity (Jensen 1980). There also may be hyperinflation or rupture of the swim bladder (Jensen MS). Midgut involvement is seen to damage digestive epithelium (Cornacchia and Colt 1984), a problem that could lead to reduced digestive function in later stages. Bubbles in the buccal cavity were associated with abnormal opercular development and low grade mortality (Jensen 1980). Swim bladder hyperinflation would affect buoyancy, tending to bring the alevin, a poor swimmer, into surface waters where the TGP problem would be magnified.

In juvenile salmonids subcutaneous bubble formation can occur. Other GBT-induced problems include exophthalmia (popeye), and gas bubble formation behind the cornea and in connective tissue of the eye. Blisters may form in the fin rays, lining of the mouth, buccal cavity, on the head, opercula or jaws. Bubbles may form in the scale pockets of the lateral line. Haemorrhaging may accompany bubble formation in the integument at the base of the paired fins and caudal fin. Other symptoms include loss of equilibrium, inability to swim against a current, inability to avoid obstacles, swimming near the surface, and in acute cases uncontrolled muscular activity. Reduced growth and lethargic feeding responses also have been noted (Weitkamp and Katz 1980).

Symptoms of GBT in adult salmonids are similar to those seen in juveniles. Internal symptoms include auricular and ventricular emphysema, occluded branchial arterioles, gill filament degeneration, enlarged spleen, necrotic changes in the kidney, liver and intestine, emphysema of the peritoneum lining the kidney and ribs and under the pericardium, haemorrhage in muscle, brain, nares and gonads, mesentery edema, muscular emphysema, emboli in the choroid plexus causing retinal detachment and haemorrhaging into the eye (Weitkamp and Katz 1980).

Hydrostatic Pressure and Depth Compensation. As indicated earlier increased depth provides proportional protection against excess TGP. Gas bubbles can form at a given depth only if the TGP is greater than the total pressure (BP + hydrostatic pressure) at that depth. The total pressure at depth Z (Colt 1980) is

14) $P = BP + \rho g Z$

where ρ=density of water (kg/m^3)
g=acceleration due to gravity (m/s^2)
Z=depth (m)

Colt (1983) shows that the risks from supersaturation at depth depend on the difference between the total dissolved gas pressure at the surface (BP+ΔP) and the hydrostatic pressure (BP+ρgZ) at depth Z. This difference,

the uncompensated ΔP is

15) $\Delta P_{uncomp} = \Delta P - \rho g Z$

In a uniformly mixed water column, ΔP_{uncomp} would decrease 73.53 mm Hg/m of depth (at 10°C). Thus, when TGP is 110% at the water surface (BP = 760 mm Hg, ΔP = 76 mm Hg), at a depth of 1 m the ΔP_{uncomp} = 76-(73.53x1) = 2.47 mm Hg. Therefore at a depth of 1 m, compensation is virtually complete.

That is,

$$16)\quad TGP_{uncomp} = \left(\frac{BP + \Delta P}{P}\right) \times 100 = \left(\frac{760 + 76}{760+(73.53 \times 1)}\right) \times 100 = 100.3\%, \text{ or}$$

approximately saturation.

The question remains as to whether fish make use of compensation depths, if available, to avoid the effects of excess TGP. The existing evidence on the question is equivocal (Weitkamp and Katz 1980). It is not known whether salmonids can "sense" excess TGP. Fish do sound, however, as a behavioural response to alarm or danger. By analogy, a first symptom of decompression sickness in a human diver is pain; it is possible that fish also respond to the symptoms of excess TGP by diving to deeper water. While such activity could reduce the risks associated with GBT, it also could prevent the fish from feeding and growing normally. As a result, the longer time spent at smaller body size would decrease the potential for survival to the adult stage through increased risks from predation.

Factors Modifying Response to TGP. A survey of the existing literature indicates that there are a number of ancillary variables that modify the response of fishes to excess TGP. Among these, two have been mentioned: fish size and water depth. In general, the literature suggests that a "sparing effect" on response to excess TGP occurs at greater depth, very small and subadult and larger fish size, lower temperature, higher O_2/lower N_2 ratios and possibly lower BP. In relation to BP, if the driving force for bubble growth (ΔP) were 60 mm Hg at sea level, then by (13)

$$TGP\ (\%) = \left(\frac{760+60}{760}\right).100 = 107.9\%$$

For arguments sake, if this level of TGP (%) at ΔP=60 mm Hg were taken as the threshold for GBT, than at 2800 ft altitude (688 mm Hg) the same ΔP would be equivalent to 108.7% TGP. For a given ΔP this could be construed as a rise in the threshold (% TGP) resulting from a lower BP. The result would appear to be a small sparing effect associated with lower BP, although at this time there is insufficient data to examine the relation further. However, little is known about the rate of change of pressure associated with disequilibrium between tissue and environmental pressures. A rapid rate of change of BP may affect the rate of downloading of gas from tissue in the same manner as would occur with a sudden change in ΔP or depth. Hence, the passage of weather systems over waters with elevated ΔP may influence the viability of fishes inhabiting those waters. The problem would seem to be analogous to that of rate of adaptation to temperature change (acclimation). A slow change in total pressure could allow the animal to adapt at all pressures below the threshold. Rapid changes in total pressure could cause problems at TGP (%) levels below the threshold through lack of time for adaptation to occur. This aspect of biological response to excess TGP is virtually unknown and unexplored.

TGP Criteria. The USEPA (1976) concludes that total dissolved gas concentrations should not exceed 110% of saturation at existing atmospheric and hydrostatic pressures; it is concluded that this level should afford protection for both freshwater and marine life. Thurston et al. (1979) in reviewing the USEPA (1976) criterion of 110% saturation, conclude there is insufficient data and understanding to support the one level. Based on existing data, they conclude the criterion could be established at 110, 115 or 120% saturation. There remains the question in their arguments as to whether water vapour pressure should be included in a consideration of biological effects of TGP. Colt (1983) since then has shown conclusively that water vapour pressure is part of the driving force (ΔP) for bubble formation. Removal of vapour pressure from the numerator in (13) produces a figure for TGP which is about 1.2% too low. Thurston et al. (1979) also make a distinction between criteria for hatcheries, where waters tend to be shallow, and natural waters. They argue that fish will tend to occupy deeper levels in natural waters, thereby making use of hydrostatic compensation to offset the effects of supersaturation. These arguments tend to support criteria varying from <105% saturation for shallow waters (eg<60 cm) to 110% or more for other situations. One of their recommendations (Part V; point, page 116) is somewhat ambiguous. It states "110 percent saturation is too high to enforce stringently in situations where anadromous salmonids are provided depth compensation of one or more meters, particularly when exposure times would be limited to less than 30 days". This could be interpreted from their preceding discussion (p.114) as meaning that levels greater than 110% could be exceeded if adequate justification could be provided. In this there appears to be confusion between jurisdictional and biological criteria. These authors also note that the modifying effects of ancillary variables on response to TGP are recognized but not quantified in the criteria, although higher temperature (Coutant and Genoway 1968; Ebel et al. 1971) and lack of compensation depth (Knittel et al. 1980) are known to accelerate adverse effects of excess TGP.

SUMMARY OF NECHAKO RIVER FIELD DATA

The preceding remarks to this point have been made to provide orientation. Attention is now directed to the Nechako River and its alleged TGP problem. A summary of available information follows (Tables 3, 4, 5) relating to measured TGP levels in the Nechako River system. Examination of Tables 3, 4, 5 suggests the following. In the July-August period, the period of concern when solar heating is maximal,

(1) The degree of supersaturation of water above Cheslatta Falls is variable, and

(i) where the level of supersaturation is low, it may be increased by the plunge over the falls;

(ii) where the level of supersaturation is higher, it may be decreased by the plunge over the falls. Presumably this variability is related to volume discharge at Skins Lake spillway and the plunge depth at Cheslatta Falls, weather conditions, water temperature and changes in barometric pressure.

(2) TGP in water leaving the Cheslatta Falls plunge pool (as the Nechako River) varies between approximately 108-110% saturation (measured).

Table 3. Data on TGP measurements for the Nechako River from Envirocon 1984, Vol. 2, Sectn. C, Appendix Tables C1.1 - C1.4; reproduced with permission of the Aluminum Company of Canada. TGP estimates calculated by Eq. 10; O_2/N_2 ratios added (Flow (cfs)=m^3/s x 35.315).

Location	Date	Time (h)	Flow (m^3/s)	Water temp. (°C)	BP (mm Hg)	Dissolved O_2 (mg/L)	Dissolved O_2 (%)	Dissolved N_2 (mg/L)	Dissolved N_2 (%)	Total Gas Satn. (%)	O_2/N_2
Above	5/27/82	1635	-	6.7	708.8	11.5	100.6	19.1	105.8	104.7	0.95
Cheslatta	6/10/82	1300	-	11.4	699.4	10.5	104.5	17.9	110.7	109.4	0.94
Falls	6/19/82	1220	-	14.5	706.3	10.3	107.5	17.4	113.3	112.1	0.95
	7/6/82	1330	-	18.0	701.3	9.27	105.8	16.1	104.8	105.1	1.01
Below	5/27/82	1410	-	7.0	708.8	12.1	106.1	20.1	110.9	109.9	0.96
Cheslatta	6/10/82	1500	-	12.4	706.2	10.3	103.4	17.8	110.5	109.0	0.94
Falls	6/19/82	1415	-	15.0	705.8	9.81	104.6	16.8	110.7	109.4	0.96
	7/6/82	1550	-	18.5	702.8	9.54	109.0	16.5	108.0	108.4	1.01
At	5/27/82	1917	61.1	8.2	707.3	11.8	106.7	18.9	107.2	107.1	1.00
Irvine's						11.5	103.7	19.0	108.0	107.1	0.96
Lodge	6/10/82	1845	56.7	14.1	706.6	10.2	106.5	16.8	108.4	108.0	0.98
	6/19/82	1700	61.6	18.0	704.9	9.69	110.2	15.5	109.0	109.2	1.01
	7/16/82	1900	65.9	18.5	703.6	9.56	109.3	16.0	104.5	105.7	1.05
At Greer	5/28/82	1115	-	8.0	714.1	12.2	109.1	18.4	103.4	104.6	1.06
Creek	6/10/82	2000	-	16.3	703.6	9.46	104.7	16.2	107.6	107.0	0.97
	6/19/82	1815	-	19.0	704.6	9.28	106.7	15.3	108.9	108.4	0.98
	7/6/82	2030	-	18.5	704.3	9.29	106.2	15.7	102.4	103.4	1.04
Archie	5/28/82	1305	103.7	10.9	719.3	11.6	110.8	17.8	104.6	105.9	1.06
Adam's	6/10/82	2130	-	17.6	709.6	9.07	101.4	15.4	105.7	104.8	0.96
Farm	6/19/82	2000	-	22.5	705.0	8.54	105.4	13.6	104.5	104.7	1.01
	7/7/82	1400	-	19.0	706.9	9.60	109.8	15.6	102.8	104.5	1.06

Table 4. Data on TGP measurements for the Nechako River (Gordon and Martens, 1981) (O_2/N_2 estimates added). (Flow (cfs)=m^3/sX35.315) (Total gas saturation based on "moist air" values as tabled in original).

Location	Date	Time (h)	Flow (m^3/s)	Water temp. (°C)	Dissolved O_2 (mg/L)	Dissolved O_2 (%)	Dissolved N_2 (mg/L)	Dissolved N_2 (%)	Total gas Satn. (%)	O_2/N_2
Above Cheslatta Falls	8/7/80	1315	36.8+	16.0	9.0	99.3	15.55	101.5	101.0	0.98
Below Cheslatta Falls	8/7/80	1420	36.8+	16.5	9.4	104.3	16.57	109.0	107.8	0.96
At Irvine's Lodge	8/6/80	1800	36.8	17.0	9.73	108.8	15.92	105.1	105.7	1.04
	8/7/80	0830		15.3	9.3	100.0	16.33	104.3	103.3	0.96
		0935		15.5	9.5	102.8	16.26	104.2	103.8	0.99
		1035		15.0	9.7	103.8	16.70	106.2	105.5	0.98
At Greer Creek	8/7/80	1945	36.8	19.0	9.4	109.9	15.58	106.5	107.0	1.03
		2040		18.8	9.35	108.9	15.62	106.4	106.7	1.02
		2145		18.5	9.2	106.4	15.71	106.3	106.1	1.00
Fort Fraser	8/9/80	0615	36.8	17.1	8.1	90.8	15.30	101.0	98.9	0.90
		0700		17.1	8.05	90.4	15.31	101.0	98.9	0.90
		0800		17.0	8.1	90.4	15.31	100.9	98.7	0.90
		1700	36.8	19.2	9.2	108.1	15.28	104.9	105.4	1.03
		1800		19.7	9.2	109.3	15.23	105.4	106.0	1.04
		1900		19.8	9.05	107.8	15.18	105.2	105.6	1.02

Table 4 (cont'd)

Location	Date	Time (h)	Flow (m^3/s)	Water temp. (°C)	Dissolved O_2 (mg/L)	Dissolved O_2 (%)	Dissolved N_2 (mg/L)	Dissolved N_2 (%)	Total gas Satn. (%)	O_2/N_2
Nautley	8/8/80	1950	(17.8)	20.5	9.6	116.0	14.95	104.7	106.9	1.11
River inflow		2040		20.1	9.15	109.6	15.04	104.7	105.6	1.05
into Nechako										
Vanderhoof	8/9/80	1750	54.7	21.6	8.95	110.0	14.54	103.1	104.4	1.07
		1850		21.2	9.05	110.4	14.58	102.8	104.3	1.07
		1950		21.2	9.00	109.7	14.53	102.5	103.8	1.07
Upstream of	8/11/80	1450	54.7	21.0	8.95	108.0	14.80	103.6	104.4	1.04
confluence		1550		21.0	9.00	108.6	14.92	104.4	105.1	1.04
with Stuart		1650		21.0	9.00	108.7	14.93	104.5	105.2	1.04
R. (Finmore)										
(Stuart R.	8/11/80	1900	171.9	19.5	8.4	98.6	14.90	101.9	101.1	0.96
inflow into		1940		19.8	8.4	99.3	14.80	101.7	101.1	0.98
Nechako)										
Prince	8/12/80	1420	226.5	20.2	8.75	103.4	15.22	104.1	103.8	0.99
George		1520		20.8	8.8	105.1	15.11	104.3	104.4	1.01
		1620		21.1	8.8	106.0	15.13	105.6	104.2	1.00
		1800		21.1	8.8	106.0	14.81	103.4	103.8	1.03

Table 5. Data on TGP measurements for the Nechako River (IPSFC 1979) (O_2/N_2 estimates added) (Total gas saturation computed as in Table 4).

Location	Date	Water temp. (°C)	Dissolved O_2 (mg/L)	Dissolved O_2 (%)	Dissolved N_2 (mg/L)	Dissolved N_2 (%)	Total gas Satn. (%)	O_2/N_2
Nechako Reservoir near Kenney Dam (depth, m)								
15.2	7/27/74	14.0	8.99	99.22	16.33	107.12	105.4	
30.5		7.8	9.10	86.71	18.95	110.06	105.1	
45.7		5.6	7.54	68.08	19.59	108.86	100.3	
61.0		5.0	6.75	59.96	19.61	107.58	97.6	
15.2	8/22/74	16.1	7.65	88.95	15.83	108.44	104.3	
30.5		6.4	7.95	73.50	19.20	108.76	101.3	
45.7		5.1	7.07	62.94	19.57	107.58	98.2	
61.0		5.5	6.41	57.65	19.60	108.59	97.9	
15.2	8/11/75	15.2	8.60	98.90	14.99	100.60	100.2	
30.5		7.2	8.80	83.70	18.49	107.55	102.5	
45.7		5.6	8.35	76.30	19.61	110.20	103.1	
61.0		5.5	8.60	78.30	20.04	112.35	105.2	
Below Cheslatta Falls	8/22/74	16.4	8.89	102.1	16.58	112.3	110.1	0.91
At Greer Creek	8/22/74	16.0	8.55	96.8	16.08	107.7	105.4	0.90
Fort Fraser	8/22/74	14.5	8.56	91.7	15.74	99.9	98.1	0.92
(Nautley R. inflow)	8/12/75	19.2	10.88	128.2	15.05	102.80	108.1	1.25
(Stuart R. near mouth)	8/14/75	19.0	9.25	103.4	16.46	108.07	107.1	0.96

(3) There may be considerable variation in TGP at a given location downstream from Cheslatta Falls over a 24-hour period. This variation would reflect diurnal increases in TGP, due to solar heating of the water, counteracted by reaeration of the water tending to bring dissolved gases to equilibrium.

(4) There is an apparent general decrease in TGP downstream from a maximum at Cheslatta Falls (108-110%) to a maximum of 105-107% at Prince George. However, temporary maxima in TGP may occur above Fort Fraser and below the Nautley River confluence.

(5) TGP levels in the Nechako reservoir behind Kenney Dam vary with depth. At depth, dissolved oxygen tends to be undersaturated; dissolved nitrogen tend to be supersaturated. However, in terms of TGP (%) the water column in the reservoir is not far from saturation (98-105% TGP).

(6) The Nautley and Stuart Rivers, tributaries to the Nechako, may be somewhat higher in TGP level (106-107% saturation), possibly from solar heating or from photosynthetic activity of phytoplankton.

Although the tabled data are few, they do provide an indication of absolute values and trends in the Nechako system in the period of maximum solar heating.

Attempts also have been made to model dynamic changes in TGP in the Nechako River (Tables 6, 7, 8), during the movement of a body of water downstream, while it is subject to temperature change, reaeration, mixing with tributary inflows and other environmental factors affecting dissolved gas solubilities as well as concentrations. Involved in these models are estimates of reaeration coefficients (K_2) for various sections of the river. Table 6 presents modelled TGP levels, compared with measured values, provided by Envirocon (1984). Similar modelled data are reproduced from Servizi and Saxvik (1981) and Servizi and Williams (1981) for the Nechako River (Tables 7, 8).

The estimated TGP levels in the Nechako River below Cheslatta Falls (Tables 6, 7, 8) are based on specific assumed flows from Kenney Dam, from Cheslatta Falls and from the Nautley River, all at specific starting temperatures, and in the period of maximum summer heating. The authors modelled conditions as shown to examine changes that would occur in the Nechako in relation to nursery conditions for chinook juveniles above the Nautley confluence (Table 6) and in relation to migration of sockeye adults in the main river as the fish proceed upstream to the Stuart and Nautley Rivers (Tables 7, 8). The results, of course, relate to specific sets of conditions, which will vary depending on actual weather conditions, barometric pressures, air and water temperatures, water depth, flow rates, and reaeration coefficients. The estimates do provide an indication of expected TGP levels in the Nechako. Under the conditions modelled:

Table 6. Modelled gas saturation levels in the upper Nechako River above the Nautley confluence based on assumed flows from the Kenney reservoir hypolimnion (58% of total flow, at 7.2°C) and from the Murray - Cheslatta Skins Lake system (42% of total flow, at 18.3°C), combining to provide a total flow at 10°C. Source: Envirocon 1984, Vol. 2, Sectn. C, Table 3.4.1; reproduced with permission of the Aluminum Company of Canada.

Location	Date	Time (h)	Measured Temp. (°C)	Measured N_2 (mg/L)	Measured TGP (%)	Modelled[a] Temp. (°C)	Modelled[a] N_2 (mg/L)	Modelled[a] TGP (%)	Modelled[b] N_2 (mg/L)	Modelled[b] TGP (%)
Cheslatta Falls	7/22/82	1100	15.6	17.50	114.4	15.7	17.47	117.0	16.84	111.3
Cutoff Creek		1600	16.4	16.63	104.4	15.9	16.39	110.1	16.29	108.4
Greer Creek		2200	16.0	16.27	106.3	15.6	15.97	106.5	15.98	105.9
Archie Adam's	7/23/82	1200	16.7	15.70	103.8	15.7	15.41	104.1	15.43	103.7
Cheslatta	8/5/82	1200	16.8	16.76	110.9	17.1	16.75	114.5	16.83	114.4
Cutoff Creek		1800	16.8	16.56	110.1	17.2	16.44	112.7	16.19	110.6
Greer Creek		2200	16.7	16.29	107.1	17.0	15.96	109.1	15.82	107.6
Archie Adam's	8/6/82	1200	16.7	15.67	103.0	17.4	15.23	104.6	15.17	104.1

[a] Using measured K_2 values and measured gas concentrations, Cheslatta Falls, and BP.
[b] Using estimated K_2 values and average gas concentrations, Cheslatta Falls, and average BP.

Table 7. Modelled TGP levels in the Nechako River for flows of 113.3 m^3/s* at Cheslatta and flows of 18.7* and 72.2 m^3/s* from the Nautley River at 21.9°C (based on Servizi and Saxvik 1981). Dissolved oxygen and nitrogen levels at Cheslatta Flats assumed to be (A) 100% and (B) 110% for each gas. The 113.3 m^3/s water is a cooling flow (7.2°C) presumed to be discharged at Kenney Dam. Bracketed values are those for the Nautley River inflow. Discharge, cfs = m^3/s x 35.315* (Equivalent TGP (%) calculated as in Table 4).

Location 3 (72.2 m^3/s)*	Water temp. (°C)	(A) Dissolved gas		(% Sat)	(B) Dissolved gas		(% Sat)
		(N_2)	(O_2)	(TGP)	(N_2)	(O_2)	(TGP)
Cheslatta Falls	7.2	100	100	100	110	110	110
Irvine's Lodge	7.9	101	101	101	108	109	108
Greer Creek	9.8	105	105	105	111	112	111
Above Nautley R.	13.4	109	110	109	113	114	113
(Nautley R)	(21.9)	(105	110	106)	(105	110	106)
1st hr below Nautley	16.8	108	110	109	111	113	111
Vanderhoof	18.6	107	109	108	109	110	107
Above Stuart River	19.7	105	106	105	106	106	106
(18.7 m^3/s)*							
Cheslatta Falls	7.2	100	100	100	110	110	110
Irvine's Lodge	7.9	101	101	101	108	109	108
Greer Creek	9.8	105	105	105	111	112	111
Above Nautley River	13.4	109	110	109	113	114	113
(Nautley R)	(21.9)	(105	110	106)	(105	110	106)
1st hr below Nautley	16.8	109	110	109	112	114	113
Vanderhoof	18.6	109	110	109	111	112	111
Above Stuart River	19.7	106	107	106	107	107	107

Table 8. Peak total gas saturation levels (%) expected to occur in the Nechako River downstream from the Nautley River confluence, modelled for two levels of O_2 and N_2 saturation in the upper Nechako at the base of Cheslatta Falls. The period considered is that associated with maximum summer heating of the Nechako, and assumes a discharge of hypolimnion water at 7.2°C from the reservoir at Kenney Dam. Flows: upper Nechako above Nautley - 123 m^3/s*; Nautley - 18.7 m^3/s* at 21.9°C; objective - to maintain Nechako River flows at or below 20°C above the Stuart River confluence (from Servizi and Saxvik 1981; Servizi and Williams 1981) (Equivalent TGP (%) calculated as in Table 4).

Nechako River at Cheslatta Falls							
N_2 (% sat)	O_2 (% sat)	Starting hour, Nautley River[1]	Temp. Nautley (°C)	Peak hrs downstream from Nautley (h)	N_2 Peak (% sat)	O_2 Peak (% sat)	Equiv. TGP (%)
110	110	1200	15.6	5	115.8	118.8	116.4
110	110	0600	12.8	11	113.7	116.0	114.2
110	110	2200	15.6	18	114.1	116.3	114.6
110	87	1200	15.6	5	115.8	111.9	115.0
110	87	0600	12.8	11	113.7	110.5	113.0
110	87	2200	15.6	18	114.1	112.0	113.7

[1]Assuming saturation levels in the Nautley River of 105% (N_2) and 125% (O_2).
*123 m^3/s = 4340 cfs; 18.7 m^3/s = 660 cfs.

(1) With potential cooling flows of 7.2°C from Kenney Dam, temperatures in the upper Nechako could reach maxima of 15-17°C near Fort Fraser, and 17-20°C between the Nautley confluence and the Nechako above its confluence with the Stuart.

(2) TGP levels downstream of Cheslatta Falls would likely reach peak levels of 110-116% TGP in the upper Nechako above the Nautley confluence and levels of 105-107% TGP above the Stuart River confluence.

RECENT DEVELOPMENTS IN TGP CRITERIA FOR SALMONIDS

TOTAL GAS PRESSURE

An extensive review and quantitative analysis of the existing literature on total gas pressure as it affects salmonids recently has been completed (Jensen et al. 1985, Jensen et al. MS). Some 621 records of response to TGP were assembled and modelled as:

ET50 = f (TGP, temperature, fish size, O_2/N_2 ratio, water depth, BP)

where ET50 = effective time to 50% mortality in experimental groups of juvenile salmonids exposed to various levels of TGP at combinations of levels of the remaining ancillary variables.

The relation between ET50 and TGP resembles a rectangular hyperbola, as found by Knittel et al. (1980) for steelhead trout. Subsets of the total data set provided the opportunity to assess the influence of the ancilary variables on the ET50 - TGP relationship, using a technique developed by Schnute and McKinnell (1984). The technique provides a quantitative evaluation and statistical affirmation of the "sparing effect" on survival time in juvenile salmonids exposed to excess TGP at

(i) greater water depth,
(ii) higher O_2/lower N_2 ratios of dissolved gases, and provisionally
(iii) fish size

The influence of fish size appears to be marginal ($p=0.098$), and a significant reduction in the unexplained variance did not occur when temperature ($p=0.51$) and BP ($p=0.80$) where included in the analysis.

The relation between predicted ET50 and fish size is in agreement with some reported results (Weitkamp and Katz 1980). Based on the literature and the current analyses (Jensen et al. 1985, Jensen et al. (MS)) we assume that alevins and early fry are most tolerant of excess TGP, that tolerance is reduced in larger juveniles, and increases again toward the adult stage. The range of sizes available in the current data analysis (45-209 mm) does not include larger subadults and adults. The second-order relation between tolerance and fish size (with a minimum in the larger juvenile) would tend to explain some of the diverse results in the literature, which could yield differing interpretations depending on the section of the total size range examined. We conclude at this time that fish size should be included on a provisional basis as an operative ancillary factor. Further studies are needed for clarification.

We conclude that the lack of association with temperature is real, as the range of temperatures examined (8-20°C) is fairly broad. However, the fact that BP did not show a significant relation to tolerance may be due to the limited range of barometric pressures examined (736-760 mm Hg). As indicated earlier, the effect of a decrease in BP suggests a rise in the acute TGP threshold may occur with increased altitude, even though ΔP were to remain constant. We conclude at this time that BP should be excluded, provisionally, as an operative ancillary variable. Obviously, further work also is required to examine this question.

The above analysis (Jensen et al. MS) shows very clearly, as might be anticipated, that there is no single curve describing TGP stimulus and ET50 response. Rather, there is a family of hyperbolae generated by the action of the ancillary variables and modifying the ET50 - TGP relationship. It follows that there is a family of threshold TGP values associated with the family of possible ET50 - TGP curves, threshold levels of TGP being those levels below which salmonids should be free of acute GBT symptoms. Table 9 shows a representative series of TGP levels (effective concentrations, % saturation) that would produce 50% mortality in groups of juvenile salmonids over an exposure interval of 50 days (50-d EC50). These are taken as close estimates of TGP levels that would just fail to produce mortality in similar groups over the same exposure interval (50-d EC0). The tabled estimates range from about 108 to 116% excess TGP. There are no ET50 estimates for TGP levels below 110% in the original data; as will be explained later this may signify that intra-vascular bubble formation associated with acute GBT may have a threshold at excess TGP levels near 110% saturation. However, the successful modelling of the complex relation between response and TGP level, as modified by the ancillary variables, is considered a major step in defining the basic problem, particularly in showing the relative magnitude and direction of change in response associated with the ancillary variables, the need for further data at TGP levels below 110%, and the fact that safe exposure to TGP must be based on a range of threshold values.

CHRONIC TGP PROBLEMS IN A HATCHERY ENVIRONMENT

Wright and McLean (MS) reported the results of a controlled study of the influence of low levels of excess TGP on chinook salmon fry in a hatchery

Table 9. Estimates of 50-day effective concentrations (50-d EC50) of TGP (% saturation) that would produce 50% mortality among test groups of juvenile salmonids. Computations based on methods of Jensen et al. (MS) for data compiled in Jensen et al. 1985. Levels of ancillary variables shown in brackets are means of the data sets from which the EC50 estimates were obtained with reference to the remaining variables modelled.

A. O_2/N_2 ratio: (0.94)

Depth (m)	Temp. (°C)	Fish length (mm)	50-d EC50 (% satn.) at BP (mm HG)[1] 760	688
(0.54)	(13.1)	(119.8)	110.9	112.0
0.1	(13.1)	(119.8)	109.8	110.8
1.0	(13.1)	(119.8)	114.8	116.3
(0.54)	20	(119.8)	110.6	111.7
(0.54)	8	(119.8)	112.5	113.8
(0.54)	(13.1)	200	110.6	111.7
(0.54)	(13.1)	65	111.0	112.2
(0.54)	(13.1)	45	116.0	117.7

B. Depth: (0.47 m) Temp: (12.8°C) Fish length: (112.5 mm)

O_2/N_2	O_2 (% satn)	N_2 (% satn)	760	688
0.5	60.5	121.0	108.2	109.1
0.8	91.3	114.1	107.7	108.5
1.0	110.4	110.4	109.2	110.2
1.2	128.0	106.7	110.2	111.3

C. O_2/N_2 ratio: (0.94)

Depth (m)	Temp. (°C)	Fish length (mm)	760	688
0.1	8	200	108.1	108.9
0.1	20	200	108.1	108.9
0.1	8	65	109.8	110.8
0.1	20	65	109.8	110.8
0.1	8	45	114.8	116.3
0.1	20	45	114.8	116.3

[1]Shown at two levels of BP, although BP cannot be shown, with the data available, to account for a significant portion of the residual variance.

environment. Between February and June 1983 four groups of fry were held in four channels each 6.1 m long x 0.813 m wide and 0.406 m deep. Initial density was 50,000 fry per channel and density was reduced to 15,000 fry per channel after eight weeks of culture. Two of these, as test groups, were supplied with water from the Puntledge River. The remaining two, as control groups, were supplied with water passed through aeration devices to reduce TGP levels to near saturation. A number of parameters were monitored through a 122-day culture period (Table 10). Correcting the 122-day mortality in the test groups for mortality in the controls, a mortality rate of 2.5% can be attributed to the level of TGP in the test groups. Hence over the 122-day exposure period juvenile chinook growing from 38 to 92 mm in length and 0.5 to about 8.75 g in weight incurred 2.5% mortality from exposure to TGP levels averaging 105.1% with a maximum of 106.0%.

BIOPHYSICS OF BUBBLE GROWTH IN FISH TISSUE

Fidler (1984) conducted a study of the role of biophysical phenomena in GBT in fishes. He concludes that a better understanding of the problem will require new studies on such parameters as blood surface tension, number and size of nucleation sites for bubble growth, compliance characteristics of the vascular system, gas diffusion rates through fish integument, and the functional properties of the swim bladder. Fidler distinguishes two types of GBT that would differ in their rate of bubble growth. "Type I" would occur with progressive development of symptoms in the circulatory path in fish exposed to excess TGP in shallow water. "Type II" trauma would result from the simultaneous development of symptoms in all tissues in fish exposed to the same level of excess TGP, but under circumstances characterized, for example, by rapid movement of a fish from below to above the compensation depth. The two types of exposure may be related to differences in migratory behaviour. Sockeye adults moving through the lower Nechako to the Stuart and Nautley Rivers could be subject to the first type, which would be initiated by extra-vascular bubble growth in affected tissues. This type of trauma could inhibit spawning of chinook adults in the upper Nechako in sections of the river subject to diurnal pulses in supersaturation resulting from solar heating of water originating at Cheslatta Falls (see Table 7). Type II trauma could occur in swim-up fry moving from the gravel to near-surface waters and in juveniles frequenting the upper layers in their feeding excursions. Fidler's work points to the possibility that the two potential modes of action are the basis for two observably different mortality patterns generally identified with excess TGP level. The first type (Type I), usually seen in shallow water culture, could result in low, chronic levels of mortality (e.g. Wright and McLean 1984; Table 10). Under such conditions swim bladder hyperinflation may occur in young fry and juveniles (Jensen MS). Jensen (1980) noted mortality occurring in steelhead alevins associated with bubble lodgement in the buccal cavity. Cornacchia and Colt (1984) found bubble formation and damage to gut epithelium in striped bass larvae; in their study significant increase in swim bladder volume occurred at 102.9% TGP with increased mortality beginning at 105.6-106.0% TGP. The range of TGP levels associated with these extra-vascular events theoretically would begin just above 100% TGP (Fidler 1984) and extend upward to a level somewhere between

Table 10. Summary of test and control parameters and results of exposure of chinook salmon fry to low levels of TGP in a hatchery environment (from Wright and McLean MS). (A slight variation in the method of calculating TGP(%) would make the TGP values of Wright and McLean too high by ≯ 0.08% compared with derivation of TGP levels by equation (13).

Parameter	Test groups 1	Test groups 2	Control groups 1	Control groups 2
Fish				
Mean length (mm) @ week 1	38.38	38.50	39.07	38.91
Mean weight (g) @ week 1	0.42	0.44	0.55	0.45
Mean length (mm) @ week 17	91.15	91.17	92.28	91.32
Mean weight (g) @ week 17	8.40	8.71	9.12	8.72
Water				
Mean (and range) TGP (%) over 122 days (inlet)	105.1 (104-106)		101.1 (99-102)	
Max. TGP (%) (at wk 8) at inlet	106.0		101.5	
Mean O_2/N_2 ratio	0.91		0.97	
Peak O_2/N_2 ratio	0.79		0.96	
Mortality				
over 122 days (%)	4.4	3.7	1.6	1.5
average (%)	4.1		1.6	

105 and 110%. Our own estimates from modelling of literature data would indicate the upper boundary varies in relation to levels of ancillary variables applied simultaneously. We suspect that the upper boundary of this chronic range of TGP-induced trauma would occur at TGP levels near 108-110%. The second type of GBT (Fidler's Type II), associated with intra-vascular events then is equated with acute GBT, which we suggest occurs above approximately 108-110%, but again varying in relation to combinations of levels of ancillary variables simultaneously applied.

VERTICAL DISTRIBUTION OF SALMONIDS IN SUPERSATURATED WATER

A further study (J. M. Shrimpton, Univ. Victoria, Victoria, B.C. pers. comm.) currently has examined the relations between excess TGP, compensation depth and distribution of juvenile coho salmonids in a 3-m deep water column at controlled levels of excess TGP. Shrimpton finds that the modal depth of fish distribution varies in relation to the level of TGP established in the column. The modal depth moves downward as TGP levels are increased above 100% saturation, and the modal depth initially is below the compensation depth. The rate of change in the modal depth declines with increasing TGP so that the modal depth occurs at the compensation depth in the vicinity of 110-112% TGP. At still higher levels of TGP, the modal depth rises above the compensation depth and the fish show visible signs of GBT. These signs include bubble formation on the fins and integument of the body, a lowering of the dorsal fin against the dorsal body surface, and a peculiar arching of the vertebral column and body antero-posteriorly. It is significant that a substantial number of the test fish are found above the compensation depth at TGP levels above approximately 110-112% saturation. An interpretation of these data at this time would support the assumption that there are physiological as well as behavioural components in the response of juvenile salmonids to excess TGP. With the modal distributions observed there would be portions of each sample population above the compensation depth, the proportion above the compensation depth increasing at higher TGP levels. Hence, some part of the total population in an experiment could be at risk at all levels of TGP at and above a minimum threshold for chronic GBT near 105% TGP.

SYNTHESIS BASED ON NEW TGP DATA

It is significant to note that the results of the recent and ongoing studies mentioned tend to reinforce each other, even though some of the boundary conditions are not as yet clearly defined. The work of Fidler (1984) suggests there are two types of gas bubble trauma, which we call chronic and acute. Chronic GBT appears to be associated with extra-vascular bubble formation (Jensen 1980; Cornacchia and Colt 1984; Jensen MS), and appears to occur at TGP levels between 105% (Wright and McLean 1984), or slightly lower based on most recent results (P. Wright, Lanzville, B.C., pers. comm.), and a maximum near 110% (Fidler 1984). Acute GBT appears to be associated with intra-vascular bubble formation, and occurs at TGP levels of about 110% or greater. However, there is no sharp boundary between the chronic and acute GBT ranges. The modelled literature data of Jensen et al. (MS) indicate that thresholds for the hyperbolic relation between effective time of exposure to 50% mortality (ET50, response) and acute levels of TGP (concentration) for juvenile salmonids lie in the range of about 108-116%, depending on the combination of levels of ancillary variables simultaneously applied. We also suspect that the TGP level at which the modal and compensation depths coincide, 110-112%, for a sample of juvenile salmonids distributed in a water column (J. M. Shrimpton, Univ. Victoria, pers. comm.), is equivalent to the TGP level transitional between the chronic and acute GBT ranges. At TGP levels in the chronic range, mortality rates tend to be low (Wright and McLean 1984; Jensen et al. 1985) compared with the higher, more rapid mortalities that occur in the acute range of TGP. We suspect from Shrimpton's (Univ. Victoria pers. comm.) data that low-grade mortality in the chronic range of TGP may occur as a proportion of the fish, free to move in the water column, is found above the compensation depth. This may be a behavioural phenomenon related to dominance in a group where the more dominant individuals would displace less dominant individuals in the competition for available territorial space. Among free-swimming stages, chronic GBT may be more lethal in younger fish, compared with adults, because of the possibility of relatively greater tissue damage occurring from bubble formation in a smaller tissue mass, the lower potential for mobility of the smaller fish, and the potential for increased predation. Acute GBT may also be more lethal in younger fish as intra-vascular bubble formation may more readily occlude the lumina of the vessels in the smaller vascular system of the smaller fish. Figure 3 is a graphic attempt to show these presumed interrelations.

OTHER EFFECTS OF TEMPERATURE

In the Nechako River, temperature will influence viability of salmonids for several important reasons, including:

(1) natural food production and growth of juvenile chinook in the upper Nechako,
(2) influence on susceptibility of salmonids to fish diseases endemic to the region, and
(3) influence of higher temperatures on adult sockeye migrating through the lower Nechako to reach spawning areas above the tributary Nautley and Stuart rivers.

These three relationships are discussed as follows.

Growth rate of juvenile salmonids is a function of ration level and temperature. On maximum daily rations, Brett et al. (1982) show that the optimum temperature for growth of juvenile Nechako chinook is about 19°C. On maximum daily rations, juvenile chinook grow more slowly at temperatures both above and below 19°C. In the natural environment, however, growth usually is limited by lower food availability; usually there is not sufficient food to allow growth to occur at the maximum potential rate. Brett et al. (1982) conclude that the growth rate of Nechako River juveniles is equivalent to that provided by a daily food intake providing 60% of maximum potential growth.

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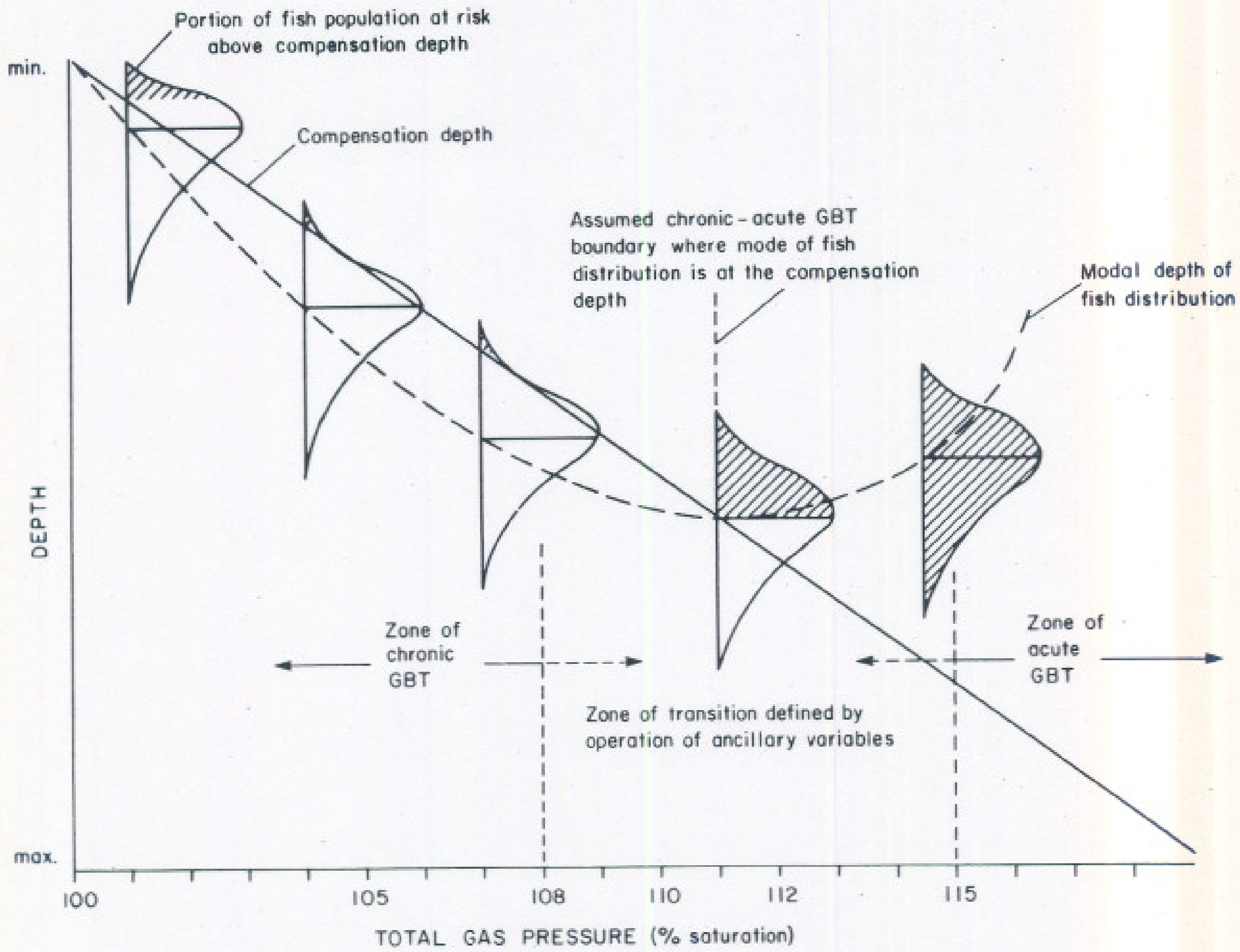
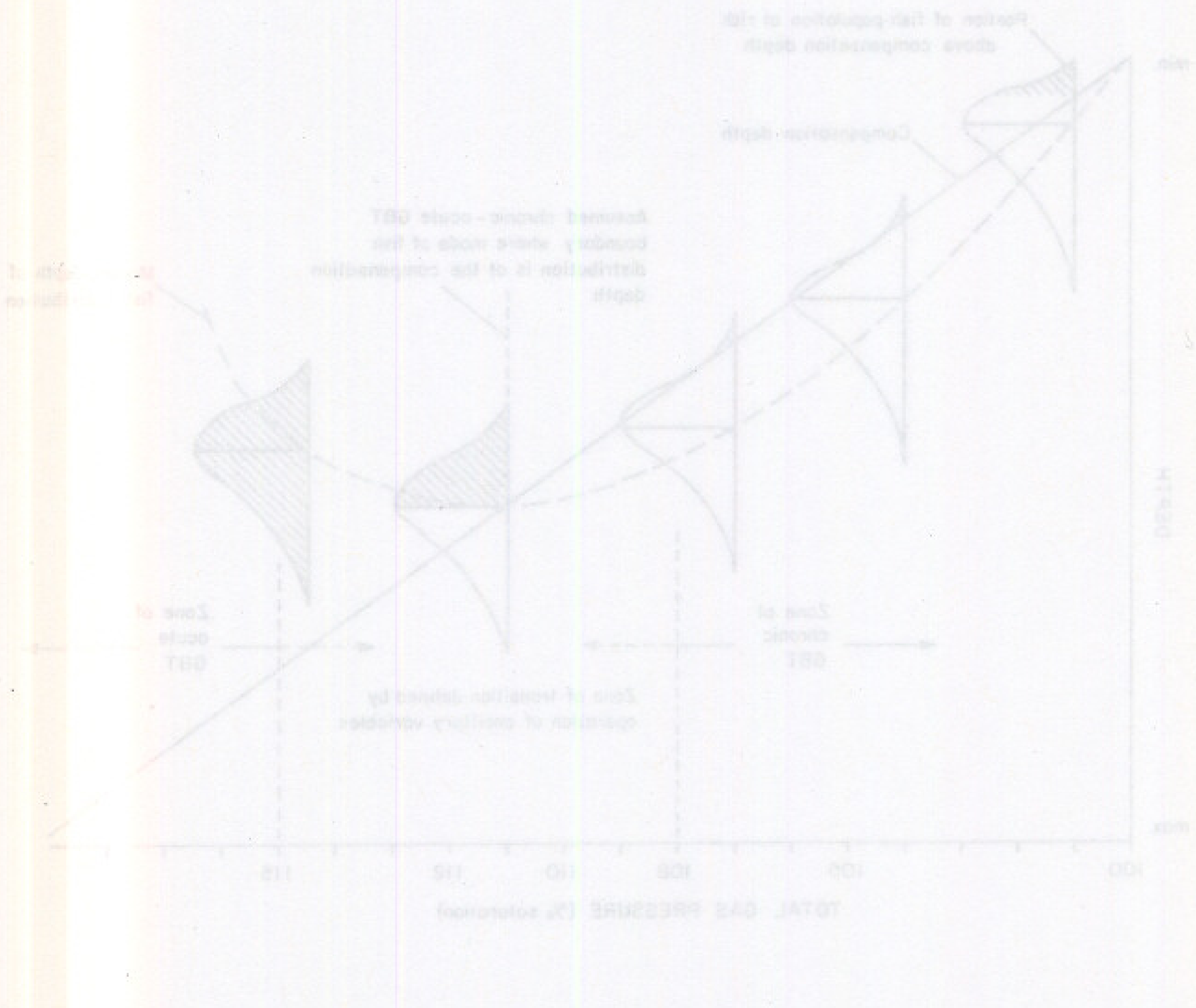


Fig. 3. Representation of the associations involving excess TGP indicated in the data of Jensen et al. (MS), Fidler (1984), Wright and McLean (1984) and Shrimpton (Univ. Victoria, pers. comm.). Zones of chronic and acute GBT are separated by a boundary region (about 108-116% TGP) whose specific position is fixed by the combination of levels of ancillary variables (temperature, fish size, O_2/N_2 ratio, water depth) simultaneously applied. The estimated chronic-acute GBT boundary for salmonids on the upper Nechako is 110% TGP. The modal depth of fish distribution (dashed line) crosses the compensation depth line at 110-112% TGP at a depth of 1.2-1.25 m (J. M. Shrimpton, Univ. Victoria, pers. comm.). Portions of the distribution of fish presumed to be above the compensation depth, at increasing levels of TGP, are suggested by the hatched portion of each distribution. TGP, compensated by hydrostatic pressure, would be 100% (saturation) on the compensation depth line.



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Through the interdependence of ration level and temperature, the optimum temperature for growth declines from 19°C (maximum rations) in relation to the level of food availability. For example at 60% of maximum ration, the estimated level of food availability in the Nechako, optimum growth shifts downward to a temperature near 14.8°C. Further, it is likely that 60% of ration availability is not constant; if one therefore assumes a minimum daily available ration of 0.9 of 60%, then the range of temperatures around 14.8°C that would accommodate growth on a (0.9 x 60) 54% ration would be about 12-17°C (est. from Fig. 8, Brett et al. 1982). This study was extended in 1983 by C. Clarke (Pac. Biol. Stn., Nanaimo, B.C. pers. comm.). In a second series of tests, growth of Nechako River chinook fry was found to be equivalent to that provided by a daily ration 50% of the saturation level of food availability. At that level of availability, food utilization is optimized at 13.6°C, and is greater than 0.9 of the available level within a temperature range of 12.7-16.5°C. Clarke also recommends that temperatures not exceed 17.5°C nor drop below 12.5°C to ensure at least 80% of optimum food conversion efficiency. These data on ration and growth are summarized in the following.

	Brett et al. 1982	Clarke (pers. comm.)
Temp. of max. growth on max. ration (100% availability) (°C)	19.0	-
Est. level of food availability on the Nechako River (% of maximum)	60	50
Temp. of max. growth at available ration level, Nechako River (°C)	14.8	13.6
Temp. range giving 0.9 of available growth maximum (°C)	12-17	12.7-16.5
Temp. range giving 0.8 of max food conversion efficiency (°C)	-	12.5-17.5

On the basis of these results, the "temperature window" for reasonable growth of juvenile chinook salmon in the upper Nechako River is taken as 12.5-17.5°C. This range provides an indication of the temperatures that could be accomodated in the upper Nechako River in relation to the potential discharge of cooling water from Kenney Dam for alleviation of the effects of higher temperatures downstream during the adult sockeye migration. From helicopter counts of spawning redds in the Nechako River in 1974 (F and MS 1979), about two-thirds were found between Cheslatta Falls and the Nautley River confluence; the remaining one-third were found between the Nautley River confluence and Vanderhoof, downstream. Therefore, the river reaches where the temperature window would apply for growth of juvenile chinook are taken as:

(i) primarily from Cheslatta Falls to the Nautley confluence
(ii) secondarily from the Nautley confluence to Vanderhoof.

The second concern associated with temperature level is that related to infectious disease. Disease essentially is an ecological problem resulting from the disturbance of a dynamic equilibrium involving a host (the fish), a pathogen (the disease-causing agent), and the environment (G. R. Bell, Pac. Biol. Stn., Nanaimo pers. comm.). Water temperature is a major environmental factor influencing this equilibrium. Elevated temperatures can potentiate, predispose, or stress a fish so that other factors in the system, such as disease organisms, may prevail--usually to the detriment of the host. Other stressors, such as excess TGP, may further stress the host, causing a further detrimental effect (Wedemeyer et al. 1976). In general, temperatures of 1-12°C are not inimical to salmonids; temperatures in the higher part of that range may even improve the effectiveness of a fish's defense mechanisms against disease agents. Between 12 and 18°C there is a probable increase in susceptibility to infectious disease, as well as an acceleration of the progress of a disease. Above 18°C this trend would continue to the ultimate temperature for heat death for juvenile chinook, 25.1 ± 0.1°C (Brett 1952). Outbreak of columnaris disease has been associated with water temperatures in excess of 15.6°C. <u>Saprolegnia</u> infections proceed more rapidly at temperatures above 15.6°C. Although such data are limited, they suggest that an acceptable upper temperature limit equivalent to that for 0.8 of available growth potential of juvenile chinooks (17.5°C) also should be a reasonable boundary for risk from infectious disease promoted by higher temperatures in the Nechako River above Vanderhoof. Hence, the boundary condition for potential juvenile growth is used as a boundary for risk from disease in both juvenile chinook and adult migrating sockeye. Generally speaking, juvenile salmonids tend to be more susceptible to disease than adults. Therefore the 17.5°C proposed boundary, based on juvenile growth should also be adequate for adults. In this we prefer to try to provide a reasonable answer to the question "what do the fish need", rather than to argue for a negotiated solution on any other basis.

The third concern associated with higher temperatures, as indicated, is the annual migration of adult sockeye through the lower Nechako en route to tributary spawning grounds. An indication of temperatures found in the Nechako and its two main tributaries (Nautley, Stuart rivers) during the migration period is given in Table 11. Although the temperature records are fragmentary, they give an indication of the levels of temperature in the rivers in question prior to and following diversion of the upper Nechako watershed. The records in general indicate that average temperatures in the system were near or above the 17.5°C boundary, suggested in the previous section, before diversion occurred. They also indicate that average temperatures in general are somewhat higher in the Nechako, as well as the Nautley and Stuart rivers, following diversion (Kemano I). We conclude that pre-diversion maximum temperatures frequently may have been greater than 17.5°C in the Nechako River below the Nautley confluence and that Kemano I modifications to the upper Nechako resulted in increased maxima. We suspect that minor differences in average and maximum temperatures on the Nechako can be critical because of the high temperature level at which these variations can occur.

Notably it appears that average and maximum temperatures of the Nechako, below its confluence with the Nautley, may be lethal on occasion to adult sockeye during their migratory period. Under laboratory conditions the upper ultimate incipient lethal temperature for juvenile sockeye is 24.8°C

(Brett 1956). However, in the field, adult sockeye may succumb at temperatures several degrees Celcius lower, where high temperature acts in concert with the presence of disease organisms. Servizi and Jensen (1977), noting that adult travel time between the mouth of the Nechako and the Nautley was about four days, performed a number of 96-hr temperature tolerance tests. They found that tolerance approached an asymptote near 24°C after 1-2 days exposure. However a second stanza of mortality then occurred with its asymptote between 21-22°C. The first part of the mortality distribution undoubtedly was a response to high temperature. The second stanza was associated with lesions of Flexibacter columnaris, a ubiquitous organism in the Fraser system. Since the test fish were first treated with antibiotic and chemotherapeutics against bactererial and fungal infection, untreated fish could have died at lower temperatures, down to 15.6°C, as previously indicated.

Other data support a further reduction in a field application of lethal temperatures. Swimming performance of sockeye is reduced at higher temperatures; IPSFC (1983) suggests 19.4°C as a preferable upper temperature limit. Losses to adult sockeye have been associated with temperatures of 20-21.7°C in the Nechako and 20.6-21.7°C in the Stuart River (IPSFC 1983). High temperatures during adult migration also have been found to diminish spawning success. For the early Stuart run, each 0.56°C (1°F) increase in temperature between 15.6 and 21.1°C (Nechako and Stuart rivers) was noted to reduce spawning success by 1.2%. Similarly, for the early Nadina run (via the Nautley River) each 0.56°C increase in temperature between 17.2 and 19.4°C (Nechako above Stuart river) resulted in a 12.4% decrease in spawning success (IPSFC 1983). These and other influences of temperature clearly show that there is a reduced probability of survival of adults and a decrease in spawning success starting at temperatures about 1.9°C below the 17.5°C boundary developed earlier. Hence, the 17.5°C boundary can hardly be considered conservative; there is argument for its reduction to 15.6°C but no credibility in suggesting an increase above 17.5°C. Until further evidence is available, we conclude that 17.5°C is an acceptable boundary for the minimizing of deleterious high temperature effects. These estimates revise earlier suggestions that 20°C should be considered the highest mean daily water temperature deemed safe for adult sockeye migrants (IPSFC 1979).

The following argument is now made. Maximum scope for activity occurs in sockeye at 15°C (Brett 1976). This physiological optimum is taken as a zero boundary for stress and other deleterious effects of high temperature, direct or indirect. Temperature-related losses have been shown to occur above 20°C; thus, temperature-induced stress must increase between 15 and 20°C. An acceptable level of temperature-induced stress between these limits becomes a matter of judgement, and we suggest an acceptable level to be 17.5°C. Therefore, adult sockeye migrants in the Nechako already are at risk from high temperature (Table 11). Hence, the level of risk should not be increased by subsequent developments related to existing diversion characteristics, if Nechako River sockeye adult migrants are to be protected and maintained. Based on the data presented we recommend that efforts be made to

(1) reduce the average temperature of the Nechako (from the Nautley confluence to Prince George) during the adult sockeye migration period to 17.5°C, and

Table 11. Estimates of average and maximum temperatures in the Nechako River and its two main tributaries, the Nautley and Stuart rivers, in the period of adult sockeye migration for two intervals--pre-Kemano I and Kemano I (assembled from IPSFC 1983).

Period	Nautley R.	Nechako R. above Stuart R.	Stuart R.	Nechako R. below Stuart R.	Nechako R. above Prince George
Pre-Kemano I					
aver. (°C)	18.2 (52)[1]	<17[2]	16.5 (50-51)	-	-
max	21.7 (52)	21.1[3]	-	-	22.5 (42)
Kemano I					
aver. (°C)	19.3 (71)	17.4 (58-82)	17.2 (57-58)	22.8 (71)	21.7-22.5 (59-60)
max	22.8 (71)	25.2 (71)	-	22.3	23.5 (71)

[1] Year temperature was recorded (in brackets).
[2] Estimated from air and water temperature records.
[3] Estimated from pre-diversion flows.

(2) ensure that daily maximum temperatures do not exceed 20°C.

INFLUENCE OF DISCHARGE

The volume of water discharged into the upper Nechako River is the third of three important interrelated variables that will influence water quality in the Nechako River. Rate of temperature change in the period of maximum temperature will be influenced largely by transfer of solar energy to the water. Rate of change of water temperature also will influence changes in total gas pressure. Both of these variables will be influenced by rate of re-aeration of the water, which itself is influenced by volume discharged. In general, on the upper Nechako these processes will lead to an increase in temperature to a maximum as a unit of water moves downstream. TGP levels will increase to a maximum and diminish thereafter downstream as TGP levels tend to move toward equilibrium. The magnitude of these changes should be dampened at higher rates of discharge into the upper Nechako. Hence, higher flows in the upper Nechako should result in lower temperatures and TGP levels downstream.

Practical problems occur, however, where Alcan attempts to minimize discharge into the upper Nechako in order to conserve water for generation of hydroelectric power. Lower rates of discharge result in higher downstream temperatures. Injunction flows, which provide some improvement, have depended on discharge of warm surface waters over Cheslatta Falls. At prevailing temperatures in periods of maximum solar heating, large quantities of water then must be discharged to provide any moderation of downstream temperatures (e.g. current injunction flows). In addition, discharges via Cheslatta Falls tend to raise the TGP level of the water initially at the head of the upper Nechako. A cold water source at the head of the upper Nechako would provide a means of lowering temperatures downstream, and likely at lower discharge levels; however, rate of heating of the colder water could result in a greater rise in TGP level. Obviously, modelling of the interrelations between volume flow, temperature and TGP level is essential at this stage in a search for alternatives. A cold water discharge of hypolimnion water by submerged intake was requested at the time Kenney Dam was constructed, but no action was taken. Hence, the problem persists of trying to optimize relations between temperature, TGP and discharge to provide biological requirements downstream, and is seen as one associated with Kemano I construction.

Some previous simulations of expected temperatures in the Nechako above the Stuart confluence have been made assuming the presence of cold water releases from the Kenney reservoir hypolimnion (IPSFC 1979). These simulations have assumed the release of 45°F (7.2°C) cooling water at Kenney Dam. A typical example (IPSFC 1979) shows that about 3950 cfs (111.9 m^3/s) of cooling water from Kenney Dam (7.2°C) would warm to about 20°C (including the Nautley inflow at 20-21.6°C) in the Nechako above the Stuart River confluence. This regime would not provide temperatures of 17.5°C in the lower Nechako. In addition the 7.2°C temperature would be too low to provide temperatures in the required temperature window for juvenile chinook growth (12.5-17.5°C) for an undetermined portion of the upper Nechako. Alternatively, a discharge of 4000 cfs (113.3 m^3/s) of cooling water at Kenney Dam at 12.8°C, near the required starting temperature of 12.5°C, would result in temperatures of 20.8-21.9°C above the Stuart confluence, too high for migrating sockeye adults. A further alternative is to discharge cooling water (e.g. at 6.0°C) from Kenney Dam and mix it with the warmer waters (about 18°C) discharged via Cheslatta Falls. The higher temperature of the latter could produce an appropriate temperature of the mixed flow (12.5°C) at Cheslatta Flats, the head of the Nechako River. Again, the lower initial temperature (12.5°C) could result in more rapid heating of the water and elevation of associated TGP levels. In addition, TGP levels could be increased initially by the action of the Cheslatta Falls plunge pool. Furthermore, a control structure would be needed at the downstream end of Murray Lake to provide flow control and therefore temperature control of the mixed (Murray Lake surface water, Kenney Dam hypolimnion water) flow forming the upper Nechako. Otherwise the 3-day transit time for water from Skins Lake spillway to arrive at Cheslatta Falls would prevent adjustment for flow rate or temperature at intervals of anything less than about 3 days duration.

We reiterate the need for further modelling studies to determine the possible relations between volume discharge, temperature and TGP. It would seem at this time that a most reasonable scenerio to satisfy chinook juvenile and adult sockeye temperature requirements would be provision of a cooling flow of 12.5°C starting at Cheslatta Flats below the falls. We suggest that the total cooling flow should originate at Kenney Dam with mixing of hypolimnion and surface waters to provide the appropriate starting temperature. A twin port structure at Kenney Dam would provide high control over both temperature and flow rate. An equilibration valve on the outlet would bring dissolved gas levels to near-equilibrium (saturation); conversely if Cheslatta Falls were the source of warmer water for mixing, that water undoutedly would initially be above saturation in TGP (Tables 3, 4, 5). Hence, while this latter alternative could provide for temperature control, TGP levels could be a problem as the warm water component would be supersaturated initially. This problem would not occur if the total cooling flow were gas-equilibrated at Kenney Dam. In addition, as a cooling flow of 4000 cfs (113.3 m^3/s) at 12.8°C would not provide appropriate temperatures for adult sockeye in the lower Nechako, it is more than likely that a total cooling flow from Kenney Dam would require discharges of more than 4000 cfs.

So far we have arrived at an argument for temperature control in the upper Nechado to provide a window of 12.5-17.5°C for juvenile chinook growth, and an average maximum (17.5°C) and ultimate maximum (20°C) for adult sockeye migration in the lower river. Concern could be expressed that the higher flows required to meet these objectives might be too liberal with respect to Alcan's needs for water storage. An examination of temperature records (1958-1982) for the Nechako River above the Stuart River confluence (IPSFC 1983, their Fig. 6) provides a perspective. In the period of maximum heating (42 days: 10 July-20 August) water temperatures equalled or exceeded 17.5°C an average of 18-19 days per year; temperatures equalled or exceeded 20°C an average of 3-4 days per year.

In summary, a twin port structure at Kenney Dam would appear to provide the best solution to biological problems both in the upper and lower Nechako River. Discharge of gas-equilibrated water at a temperature near 12.5°C would provide appropriate temperature in the upper Nechako. This gas-equilibrated option would provide water at Cheslatta Flats near 100% saturation, the best of all perceived practical solutions. Rates of heating and associated rates of increase of TGP downstream then are seen to be a function of rate of discharge at a given temperature, with increases in temperature and TGP being dampened by increase in volume discharged. We repeat, the options imbedded may only be explored through further modelling of temperature, TGP and discharge as simultaneous variables.

DISCUSSION

It is now fully recognized that gas bubble trauma (GBT) in fishes occurs as a result of supersaturation of dissolved atmospheric gases in water, the gases normally involved being O_2, N_2 and Ar. The total dissolved gas pressure

$$TGP = BP + \Delta P$$

$$\text{where } \Delta P = (P_{N_2+Ar}+P_{O_2}+P_{H_2O}) - BP$$

A positive value of ΔP is the driving force producing GBT; that is $\Delta P > 0$ when

$$(P_{N_2+Ar}+P_{O_2}+P_{H_2O}) > BP$$

TOTAL GAS PRESSURE AND GBT

<u>Chronic vs acute GBT</u>. New data and analyses strongly suggest that GBT can be divided into two forms, chronic and acute, depending on the level of TGP to which the fish is exposed, the stage of development at exposure, and the combination of levels of ancillary variables applied concomitantly at the time of exposure. There are very few records relating salmonid mortality to TGP levels below 110% saturation. Four such records available to us (Wright and McLean 1984; Jensen et al. 1985, their Table 2) show mortalities of 1.4 to 5.0% for TGP levels of 105.0-109.7% saturation over exposure periods of 43 to 122 days. That of Wright and McLean (1984) is a well-conducted large-scale test corrected for mortality in the controls; this study provides an estimate of 2.5% TGP-induced mortality among juvenile chinook held at an average level of 105.1% TGP over a period of 122 days (Table 10). We presume this chronic range extends from at least 105.1 to 109.7% TGP. The new evidence and new analyses indicate that acute GBT begins around 110% TGP. In the acute zone, GBT produces mortality with a typical hyperbolic relation between response (e.g. mortality) and TGP level; the higher the TGP level the more rapidly GBT mortality (ET50) occurs. The biophysics of blood gas transfer and bubble growth in blood (Fidler 1984), and the work of Shrimpton (U. Victoria, Victoria pers. comm.) on location of fish in a supersaturated column of water, suggest that a general boundary between chronic and acute circumstances may occur around 110-112% TGP.

Ancillary variables and the chronic-acute boundary. The boundary between chronic and acute conditions of GBT, however, does not occur at a single, fixed level of excess TGP. The actual boundary occurs within a range of TGP levels, and the range is a function of other modifying variables applied simultaneously. That is,

ET50 = f(TGP, fish size, O_2/N_2 ratio, water depth)

Modelling of the available literature data (Jensen et al. MS, Jensen et al. 1985) shows (Table 9) that the transition zone between chronic and acute GBT (Fig. 3) may vary between about 108 to 116% TGP in relation to sets of levels of the ancillary variables. We conclude a "sparing" effect occurs, associated with the variables, at

- very small (early fry) and large (subadult to adult) fish size
- high O_2/lower N_2 ratios (e.g. >1.0)
- greater water depth

From Tables 3, 4, 5, O_2/N_2 ratios in the Nechako River rise from about 0.96 below Cheslatta Falls to about 1.00 upstream from the Nautley. Dissolved gases in the Nautley ($O_2/N_2 \simeq 1.14$) raise the ratio in the Nechako from the confluence to about 1.06-1.07 at Vanderhoof and above the Stuart confluence. The ratio for Stuart River water (~0.97) and continuing re-aeration tend to decrease the ratio in the lower Nechako; at Prince George it is about 1.01. Hence, O_2/N_2 ratios in the Nechako River are about 1.0, the lowest being 0.96 immediately below Cheslatta Falls (Tables 3, 4, 5). From Table 9 a 50-day EC50 estimate of 110% TGP for juvenile chinook was obtained by applying the ancillary conditions of 0.1 m water depth, 8-20°C, O_2/N_2 ratio $\simeq$ 1.0, and fish size $\geqslant$ 65 mm, followed by an adjustment of the TGP (%) value for a BP of about 700 mm Hg. The 110% TGP estimate is taken as the best available estimate of the boundary between chronic and acute GBT conditions applied to the upper Nechako River.

In summary, ancillary variables move the boundary between chronic and acute GBT conditions between about 108 and 116% TGP. The TGP boundary for a specific water will depend on levels of fish size, O_2/N_2 ratio, and water depth simultaneously applied. We recommend that TGP levels on the Nechako be considered of acute concern at levels of 110% or greater and that primary efforts be directed to limiting TGP levels to those below 110%. Of secondary concern are TGP levels in the chronic range (about 105 to <110%) that are likely to be associated with chronic, low-grade mortality. To guard against the possibility of chronic GBT occurring would require that TGP levels on the Nechako River not exceed a level of about 105%.

Water depth and pressure compensation. Do salmonids respond to excess TGP by diving to or frequenting greater water depths where hydrostatic pressure tends to compensate for excess TGP? Theoretically fish remaining below the compensation depth should be able to avoid symptoms of GBT. If fish are free to move below the compensation depth, will they do so? The only data available to us that throw some light on the subject are those of J. M. Shrimpton (U. Victoria, Victoria pers. comm.) (Fig. 3). Distribution modes occur below compensation depths up to levels of about 110-112% saturation. At that point the mode occurs at the compensation depth. Above 110-112% TGP the mode occurs above the compensation depth and individuals show symptoms of GBT. Although data on these distributions are not yet available, (they appear to be skewed) it stands to reason that between 105 and 109-110% TGP, some fraction of the population at a given level of TGP will be found above the compensation depth, and therefore at risk. As chinook fry are known to occupy shallow waters, the fact that deeper waters may be available will not eliminate the risk of GBT occurring when excess TGP levels are present. Hence, where compensation depths are available the juvenile salmonid will not be free of risk from GBT. Therefore, we would expect chronic mortality to occur at levels of excess TGP in the chronic range, whether compensation depths are available or not.

For adult sockeye, Nebeker et al. (1976) estimated the lethal threshold to be near 114% saturation. Their fish were tested at 12°C in tanks with a water depth of 60 cm. In addition their method of expressing percentage saturation would be about 1% low compared with Colt's (1983) method of computation. A further question arises with reference to the position of the fish of Nebeker et al. (1976) in the 60-cm water depth. They mention that "survivors remained near the bottom of the tank ...". Knittel et al. (1980) found their results for steelhead juveniles were best explained if the test animals were assumed to be located at a volitional depth about 85-93% of the total depth. Applying these as correction factors to Nebeker et al. (1976), we may assume their lethal threshold, at a 50-cm depth, would be approximately (114+1-5) = 110% TGP (1% addition for water vapour pressure, 5% subtraction for hydrostatic pressure). Admittedly, the argument is tenuous but we suspect it provides a reasonable estimate of tolerable conditions for adult sockeye migration in the Nechako River.

TEMPERATURE REQUIREMENTS

Juvenile chinook. The physics of gas exchange, re-aeration and equilibration, and solar energy transfer are such that considerations of excess TGP are inextricably associated with temperature and discharge. In the period of maximum solar heating we recommend that temperatures in the Nechako from Cheslatta Flats to the Nautley confluence be restricted to the range of 12.5-17.5°C to provide for reasonable growth of juvenile chinook salmon on available food supplies. That is, water starting at 12.5°C at Cheslatta Flats should be discharged in sufficient quantity to maintain temperatures in the upper Nechako up to but not exceeding 17.5°C at the Nautley confluence. We suggest this cooling potential be provided by one of the following alternatives:

(1) That two outflow sources be provided at Kenney Dam, one to draw off hypolimnion water, the second to provide a source of surface water. The two sources could be combined and discharged through equlibration device(s) to provide a given volume discharge at a given temperature (e.g. 12.5°C).

(2) That two outflow sources be provided, a cold water outflow through an equlibration device at Kenney Dam, and a surface water outflow from Cheslatta Falls, the two sources to merge at Cheslatta Flats to provide a given volume discharge at a given temperature (e.g. 12.5°C).

The first of these alternatives is considered superior to the second with respect to expected TGP levels in the mixed water downstream from Cheslatta Flats. The first alternative (both sources at Kenney Dam) would provide a controlled volume at a selected temperature, the discharged water being essentially 100% saturated in dissolved gases. We assume that small adjustments could be made at Kenney Dam, if needed, to provide water close to 12.5°C at Cheslatta Flats. The need for discharge of water via Skins Lake spillway would be eliminated during the period of maximum solar heating.

The second alternative would require the building of a control structure to impound waters of the Murray Lake chain above Cheslatta Falls. Depending on the temperatures of the Kenney reservoir at depth (e.g. 6.0-7.2°C) and of the warmer water exiting by Cheslatta Falls (e.g. 18.0°C), the two sources could be combined to provide a given volume discharge at required temperature (e.g. 12.5°C) after mixing, at Cheslatta Flats.

Discharge by the first alternative would provide flow and temperature control and TGP near 100%. The second alternative would also provide flow and temperature control, but computations based on likely TGP levels at the base of Cheslatta Falls (O_2-105% saturation, N_2 + Ar - 110% saturation) indicate that the mixed flow would have an initial level of TGP of about 105-106% saturation. For example, at a total discharge of 4000 cfs (113.3 m^3/s), to provide a temperature after mixing of 12.5°C, would require 45.8% cooling water (at 6.0°C) and 54.2% warm water (at 18°C), or 50.9% cooling water (at 7.2°C) and 49.1% warm water (at 18°C). Using the second alternative, the initial TGP level in the mixed flow would be 105.5% saturation (with 6.0°C cooling water) or 104.8% saturation (with 7.2°C cooling water).

By either alternative the water leaving Cheslatta Flats at 12.5°C will be subject to heating as it proceeds downstream, resulting in a rise in TGP to a maximum (e.g. Servizi and Saxvik 1981, their Figs. 2, 3, 4) followed by a decline as re-aeration proceeds. The maximum TGP expected for water leaving Cheslatta Flats at 12.5°C is not known. The level should be somewhat less than that obtained for a 4000 cfs (113.3 m^3/s) discharge at 7.2°C (about 110% TGP, Table 7) or a 4340 cfs (123 m^3/s) discharge at 7.2°C (~115%) (Table 8) depending on the temperature of the Nautley inflow downstream and its TGP level. The near-saturation level of water arriving at Cheslatta Flats by the first alternative (compared with 105-106% TGP by the second alternative) is a distinct advantage in favour of the first. The chances of TGP levels rising into the acute range (110% or greater TGP) with subsequent solar heating downstream are substantially higher under the second alternative (starting TGP level of 105-106% saturation). We deem it essential that these two alternatives be investigated by modelling.

Adult sockeye. The temperatures of interest for sockeye adults range from a maximum for metabolic scope at 15°C to a lethal temperature of 21-22°C under field conditions (Servizi and Jensen 1977) to 24.8°C for juveniles in the laboratory (Brett 1956). Maximum swimming performance occurs at 15°C (Brett and Glass 1973), hence the cost of migration (per unit of track made good) would be optimized at that temperature. Reduced spawning success has been noted above 15.6°C. Increased susceptibility to infectious disease has been noted at temperatures above 15.6°C. We conclude that the 17.5°C upper temperature limit for chinook juvenile growth also is a reasonable upper limit for protection of adult sockeye salmon during migration. We recommend that temperatures in the Nechako River downstream from the Nautley River confluence not exceed 17.5°C for the well-being of adult migrating sockeye. Temperatures in the lower Nechako River currently do rise above 17.5°C and are likely to have done so prior to Kemano I construction. Hence migrant sockeye currently are at some risk from high temperatures. Recognizing the historical situation, we recommend 17.5°C as a maximum in the lower Nechako as dictated by the needs of the species, and further recommend that a currently achievable maximum be no greater than 20°C.

To summarize these arguments, modelling of the relations between temperature and TGP must be conducted to determine rates of discharge of hypolimnion water from Kenney Dam that will provide the biological requirements shown in the following table. The tabled levels of temperature and TGP provide a starting point for examination of discharge levels to be considered both for the upper and lower Nechako River.

Portion of Nechako River	Temperature (°C) Initial	Temperature (°C) Maximum	TGP (% saturation) Initial	TGP (% saturation) Maximum	Species
Cheslatta Falls to Nautley confluence	12.5	17.5	100	<110	juvenile chinook
Nautley confluence to Nechako at Pr. George	-	17.5-≯20.0	≯110	≯110	adult sockeye

DISCHARGE REQUIREMENTS

In the previous sections, recommendations have been made regarding the maximum TGP levels and temperature range for chinook juveniles on the upper Nechako, and for maximum acceptable temperatures during adult sockeye migration on the lower Nechako below the confluence of the Nautley River. Physically, both TGP level and temperature increases may be dampened by increased discharge. Therefore, we recommend that a series of simulation studies be performed to find optimum volume flows that would provide TGP levels and temperatures within the limits described earlier. We suspect that the range of flows of interest would range from 4000 cfs (113.3 m^3/s) to 8000 cfs (226.5 m^3/s), such flows being required during the period of maximum solar heating on the Nechako system.

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