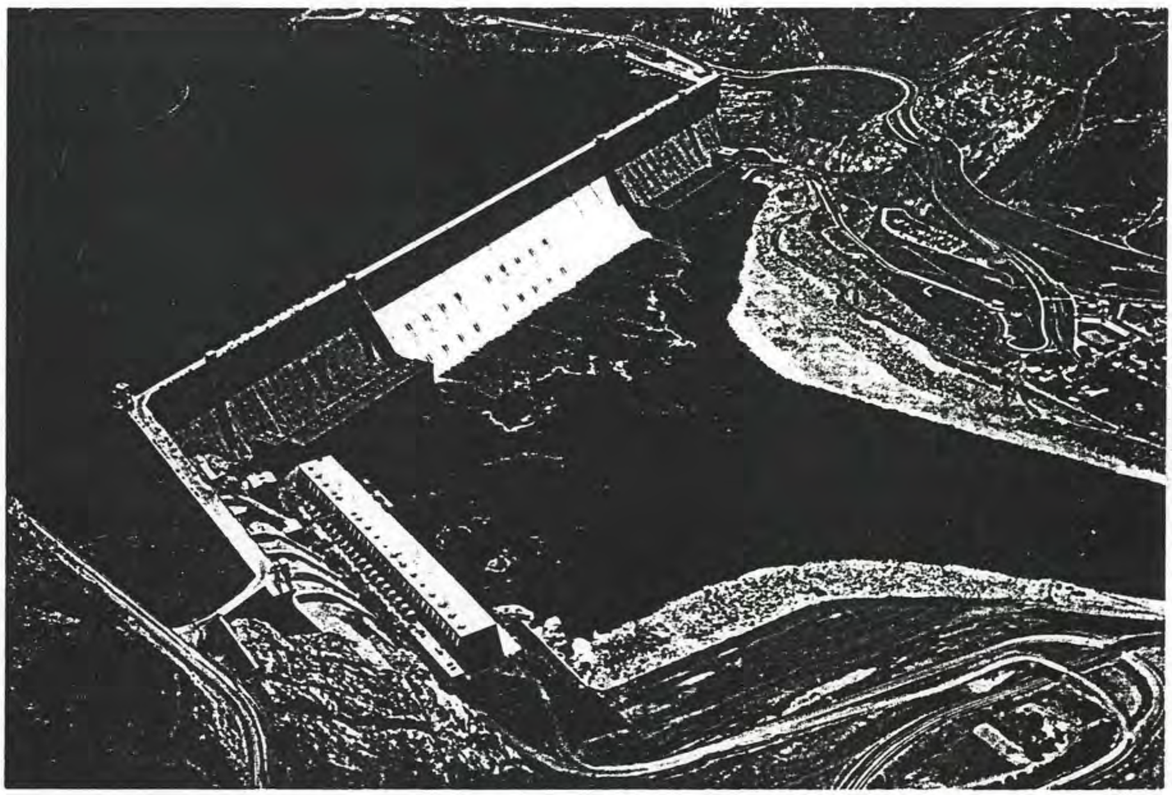
PAP-724

DISSOLVED GAS SUPERSATURATION

STUDY

FOR GRAND COULEE DAM



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Introduction

Salmon recovery efforts are ongoing on the Columbia and Snake River systems. The National Marine Fisheries Service (NMFS) has issued biological opinions on ways to aid the salmon recovery. NMFS has recommended increasing releases from dams on the river systems, lowering reservoir levels, and reducing barging of fish. These methods would keep more fish in the rivers; however, increasing releases raises concern for increasing dissolved gas levels which may also endanger fish populations. In addition, powerplant flows may need to be reduced because of power lines out of service or fewer requests for power. In these cases, spillway releases would be needed to pass water from the dam.

Total dissolved gas levels have been monitored in the Columbia and Snake River systems since the 1960's. State water quality standards require levels to be below 110 percent at all times. Monitoring of the rivers has shown these levels are routinely exceeded during spill seasons. High dissolved gas levels may be as hazardous to salmon as barging or bypass structures. Therefore, increasing spills may increase hazards to the salmon populations downstream. If spills will be required, there is a need to investigate operational or structural modifications to aid fish recovery that would minimize dissolved gas levels.

The State of Washington, Department of Ecology, has granted NMFS a temporary variance to exceed the total dissolved gas criteria of surface water to aid fish passage on the lower Snake and Columbia Rivers. The temporary variance is reviewed annually. The total dissolved gas standards may only be exceeded for certain time periods. The total dissolved gas level shall not exceed an average of 120 percent as measured in the tailrace of each dam. The maximum capacity is 125 percent total dissolved gas for any 2 hours during the 12 highest hourly measurements per day. This temporary measure will allow the investigation of benefits gained by having more water in the river versus possible stress produced by the potentially higher levels of total dissolved gas introduced by spillway releases.

Purpose

The purpose of this study is to conduct a dissolved gas supersaturation analysis using existing field data for Grand Coulee Dam, Washington. The analysis is needed to determine the best way to operate the dam's spillway, outlet works, and powerplants to reduce the potential for gas supersaturation downstream. Gas supersaturation has been shown to be responsible for severe fish kills in the downstream reaches of the Snake and Columbia Rivers. Efforts to reduce total dissolved gas levels at Grand Coulee Dam will assist with minimizing the problems faced by operation of the downstream dams. Most of the downstream dams are run-of-the-river dams and are spilling daily. The gas supersaturation problem is cumulative, so minimizing the levels in the upstream portion of the Columbia River would be helpful throughout the system.

Scope

The investigation includes tracking dissolved gas levels in Lake Roosevelt upstream of Grand Coulee Dam and the effect of subsequent releases from the dam on the Columbia River's dissolved gas supersaturation problem. To accomplish the investigation, the following tasks were performed:

- Gathered, consolidated, and reformated existing field data that included total dissolved gas levels, temperature, barometric pressure, dam releases, and reservoir and tailwater elevations.

- Summarized general trends of the dissolved gas supersaturation levels both upstream and downstream of the dam based upon existing dissolved gas data.

- Determined the frequency of required spillway and outlet works discharges during the past 15 years since bringing the Third Powerplant on line. The frequency analysis excluded releases made for the tourist visitor's show. This analysis will assist with the decision on whether some action, either operationally or structurally, is warranted based upon the expected frequency of operation.

- Predicted dissolved gas supersaturation levels for potential release options for Grand Coulee Dam. The predictions will use gas transfer theory and semi-empirically based relationships. A transfer efficiency for the structure was developed from existing dissolved nitrogen data. A range of historical reservoir dissolved gas levels was used with a full range of spillway, outlet works, and powerplant releases and accompanying tailwater levels for the investigation.

- Determined what the affects of Canadian dam releases in the upper reaches of the Columbia River are on the dissolved gas levels entering the United States at the upper end of Roosevelt Lake.

Grand Coulee Dam

The geometry of the hydraulic structures, discharge capabilities, reservoir and tailwater elevations, reservoir stratification, barometric pressure, and temperature are all important when considering dissolved gas levels and potential operational or structural modifications. The hydraulic height of Grand Coulee Dam makes addressing the dissolved gas issue more complicated than at many of the other dams on the Columbia River system.

Grand Coulee Dam was constructed from 1933 to 1942, with the forebay and additional powerhouse constructed from 1967 to 1974. The dam is located on the Columbia River, 28 miles northeast of Coulee City, Washington, and forms Franklin D. Roosevelt Lake which stretches to the Canadian border. The dam has a hydraulic height of 350 ft. The hydraulic structures are a 1,650-ft-wide gated spillway, an outlet works comprised of 40 conduits through the dam in 2 tiers of 20 each, left and right powerplants, and the pump-generating Third Powerplant located approximately parallel to the right dam abutment. An elevation and spillway section are shown on figure 1.

The spillway is located in the center of the dam with eleven 28- by 135-ft drum gates controlling releases up to a maximum water surface of El. 1291.5. The spillway capacity is 1,000,000 ft^3/s. The spillway has a submerged roller bucket energy dissipator, at El. 874.4, discharging onto the rock surface downstream.

The outlet works conduits discharge onto the downstream face of the spillway, also utilizing the roller bucket dissipator. The outlet works has a capacity of 191,920 ft^3/s at reservoir El. 1290. The outlet works are generally used to lower the lake level in the spring when high runoff is expected and the lake level is below the spillway crest (El.1260).

The powerplants and pump-generators have a total capacity of 280,000 ft^3/s and discharge from the reservoir to the tailrace under submerged conditions.

The geometry of the hydraulic structures has a major influence on the gas transfer characteristics at the dam and could allow operational flexibility.

Existing Data

Existing dissolved gas data for Grand Coulee Dam were collected as early as 1965 because of concerns about the relationship between dissolved gas levels and fish mortality. Reclamation's involvement increased in the early 1970's when efforts were made to determine the levels of dissolved gas throughout Lake Roosevelt and its tributaries and the effects of passing water through the hydraulic structures at the dam on the downstream gas levels. During 1972 and 1973, many stations in the lake and its tributaries and downstream from the dam were monitored. Numerous reports from the 1970's summarizing dissolved gas levels and resulting effects on fish populations have been obtained and reviewed.

The U.S. Army Corps of Engineers (COE) is by far the most involved party in the dissolved gas issue because of the great number of dams they have on the Columbia, Spokane, and Snake Rivers. Total dissolved gas data on these river systems are continually collected and entered into a fortran-based spreadsheet by the COE in their Portland, Oregon office. These data contain random hourly data of temperature, barometric pressure, total gas pressure, gas concentrations, operations, and reservoir and tailwater elevations. These data have been converted to Lotus spreadsheet format. Data stations pertaining to Grand Coulee are now limited to the international boundary with Canada on the Columbia, 6 miles downstream of Grand Coulee Dam, and downstream of Chief Joseph Dam. These data are available, with varying degree of completeness, from 1965 through 1994. Prior to the 1994 - 1995 season, data have only been available for reservoir forebay-to-forebay analysis.

Daily operational data for the spillway and outlet works from the dam and average monthly operational data from Reclamation's Policy Analysis Office (PAO) have been obtained. These data were used for the release frequency analysis and for predicting dissolved gas levels produced by outlet works releases.

A literature search has revealed a semi-empirically-based method to use in predicting dissolved gas levels produced by flow through the spillways and outlet works.

Summary of Results

The results include the trends determined by analysis of the data gathered in the early 1970's, an example of the increase in downstream dissolved gas levels as a result of spillway discharge, the frequency of spillway discharges post-1981, and the potential for gas transfer at the structure for various operating conditions and initial reservoir gas saturation levels.

The data from the intense studies in 1971 to 1973 primarily focused on identifying the origins of the dissolved nitrogen concentrations (figure 2), how the concentrations varied throughout the reservoir and downstream of the dam, and the effect of temperature and pressure on the saturation levels. A small portion of the study dealt with controlled flows through the spillway and outlet works. Throughout the study, the powerplants were almost continuously operated.

The following are the summarized results from the existing data:

- The major source of dissolved nitrogen in the reservoir enters from the Columbia River, with high nitrogen concentration levels present by the time the river reaches Trail, British Columbia, at the international border. The Spokane River tributary contributes a significant, but much lower level of dissolved nitrogen, with none of the other tributaries adding to the system (figure 3).

- Reservoir nitrogen levels fluctuate seasonally with the highest levels present in the spring and early summer (figure 4).

- Saturation percentages increase with temperature, to a maximum in late June and July, even though the actual concentrations remain essentially constant.

- The reservoir is thermally stratified from July through August. The temperature is higher at the surface than the bottom, but the nitrogen concentrations at the surface are less, thus resulting in lower dissolved gas saturation levels. Throughout the rest of the year, the reservoir mixes and there is not much temperature effect on gas saturation levels.

- The dissolved nitrogen level in the reservoir forebay has historically exceeded saturation levels of 120 percent. This level alone exceeds Washington State standards for water quality.

- Powerplant releases do <u>not</u> increase dissolved nitrogen levels.

- Outlet works releases under controlled conditions produced inconclusive results on dissolved gas levels. It would be natural to assume that these releases would increase dissolved nitrogen levels downstream; however, the test releases and/or duration were probably not high or long enough to adequately judge the results. Outlet works releases could be predicted similarly to spillway releases if enough existing discharge and dissolved gas data are available.

- Data from spillway releases in 1966, 1971, and 1972 show that the percent saturation level increased up to 28 percent with variations in spillway discharge and water temperature. This indicates spillway releases will, in general, increase or exacerbate the dissolved gas problem (figure 5).

- Analysis of a short spillway discharge in 1993 (figure 6) indicated an increase in dissolved gas percentage downstream from the dam from 119.6 percent, the level measured in the river prior to the spillway release, to 139.9 percent or a percentage difference of 17 percent. These results also show that the powerplants simply transfer the saturation level from the reservoir. It also shows that the lake saturation level at the dam is close to that at the border. These results confirm the previous analyses performed in the 1970's.

Frequency of spillway releases:

- Daily releases from the spillway and outlet works were analyzed for the 15-year period after placing all units of the Third Powerplant on line. These results show that daily spillway releases are most frequent in June, occurring 17.6 percent of the time (figure 7). Fall and early winter releases have not occurred in the last 15 years. These results exclude flows made for the tourist show. These are based upon the operational condition of releasing through the powerplants to meet power demands prior to making spillway or outlet works releases.

The percent gas saturation downstream of the dam can be predicted using the presented method with the gas transfer efficiency for the structure computed from existing data.

General predictive results of gas transfer caused by spillway releases:

- This method was used with spillway discharges ranging from 2,500 to 990,000 ft^3/s, 1 to 11 spillway gates operating, and 0 to 280,000 ft^3/s through the powerplants. The reservoir saturation level was varied from 90 to 140 percent. The standard barometric pressure associated with the elevation of the spillway stilling basin was used in all cases. For example, with the reservoir 100 percent saturated, and no powerplant flow, a discharge of 30,000 ft^3/s results in a downstream saturation varying from 123.5 percent with 1 gate open to 103.1 percent when passed through all 11 gates. All gates would be used to release a discharge of 990,000 ft^3/s and the downstream saturation would be 160 percent. The results for the entire flow range are shown on figures 8-19.

- The downstream dissolved gas level will always be increased by spillway flows if the reservoir dissolved gas level is less than 100 percent. For saturated or supersaturated reservoir levels ($\geq$ 100 percent), some small flow rates ($\leq$ 30,000 ft^3/s) may be passed with various gate combinations that will maintain or slightly reduce downstream gas levels.

- The additional tailwater provided by powerplant releases increases the gas supersaturation level in the stilling basin because the jet penetration depth is greater. The influence of tailwater decreases when the spillway flow is passed by the maximum number of gates. Mixing of the powerplant and spillway flows farther downstream in the river will lower the saturation level.

Results of outlet works flow investigation:

- Limited data on the dissolved gas levels downstream from the dam were compared before, during and after outlet works releases. The results showed an increase in downstream dissolved gas levels with outlet works releases compared to the downstream level before operating. The percentage increase in dissolved gas levels with flow are; less than 10,000 ft^3/s, 1-7 percent; 25,000 ft^3/s, 13 percent; and 50,000 ft^3/s, 26 percent. This conclusion should be tempered by the fact that the monitoring station measures the mixed outlet and powerplant flows. The outlet works flows were only a small portion of the powerplant flows.

Recommended operation:

- Spillway flows may be spread over the entire 1500 ft width of the gates, whereas the outlet works flows are more concentrated. As a result, in the normal operating range of the dam, the spillway should be used for operations whenever possible. If, however, the reservoir level is high to use the spillways for releases, a large spill, needed for flood releases, could be hazardous to downstream fish populations.

Influences of Canadian dam releases:

- Nitrogen levels could be lowered with the addition of a powerplant on Hugh Keenleyside Dam in Canada. The addition of a powerplant has been approved, but there is no schedule for construction at this time. However, BC Hydro, the owner of the dam, has stated that the dissolved nitrogen levels in their lake are also high. If this is the case, the most that could be expected would be to decrease the dissolved gas levels entering Lake Roosevelt to those of the reservoir at Hugh Keenleyside Dam.

Theory

The rate of gas transfer across an interface is directly proportional to the difference between the dissolved gas concentration in the water, C, and the saturation concentration in the water at atmospheric pressure and temperature, C_s. This relationship is given by:

$$\frac{dC}{dt}=K_L a\,(C_s-C) \quad \textbf{(1)}$$

where K_L is a liquid film coefficient, and a is the ratio of the total bubble surface area to total air-water mixture volume.

Essentially, the resulting gas level below a hydraulic structure depends on the dissolved gas level in the reservoir, the potential dissolved gas level in the stilling basin, the length of time that the gas is being dissolved into the flow, and a constant that is specific to the geometry of the structure and the operating condition. The dissolved gas potential in the stilling basin depends on the basin depth, water temperature, barometric pressure, and the characteristics of the jet entering the tailwater.

Typically, this analysis has been accomplished using Reclamation report, "Prediction of Dissolved Gas at Hydraulic Structures" (Johnson, 1975). This approach uses the site geometry, temperature, pressure, an assumed reservoir dissolved gas level, and graphical methods to determine the constant, K, which includes assumptions regarding the diffusion of the jet in the tailwater. This method was used to analyze the previously collected dissolved gas data at Grand Coulee Dam.

Nitrogen and oxygen are the major components of the atmosphere (78 and 24 percent, respectively). Nitrogen, being relatively inert, will remain fairly constant for quite some time and will not be as affected by changing biological action. Nitrogen concentrations are, therefore, a better predictor of dissolved gas levels than oxygen.

The gas bubble will try to come to equilibrium in solution. Under pressure the bubble will dissolve into the surrounding water. Near the surface, the pressure will be significantly less and the gas will transfer out of the water into the atmosphere.

<u>Monitoring Stations</u>

The monitoring station locations downstream from the dam were varied during the test period in the 1970's. Data were gathered directly downstream from the powerplant tailraces. These data would give accurate information regarding powerplant releases due to the layout of the structures and the river channel. The closest data station used for determining the spillway and outlet works releases was located 1.5 miles downstream for the tests in 1971. The downstream data station is currently located 6 miles below the dam. Because of the geometry of the river channel, this will give results for only mixed flows, whether spillway and powerplant, or outlet works and powerplant are operating. Therefore, the <u>actual</u> dissolved gas levels produced by spillway or outlet works operation would be diluted by powerplant flows by the time the measurement is taken downstream. This measurement will be giving a dissolved gas level somewhere between that of the reservoir, transferred directly by powerplant operation, and the maximum produced locally by the operation of the other structures. This makes computations of the direct effect of spillway or outlet works operation on the total dissolved gas levels difficult.

Recommended additional monitoring - To truly determine the effect of either outlet works or spillway flows on the total dissolved gas levels in the river, river transects would need to be taken without the powerplants operating. This data would greatly assist with the accuracy of the predictive analysis that is reported herein. It would be unrealistic to expect measurements be taken directly downstream of the spillway/outlet works stilling basin with the powerplants operating, given the high flows and the close proximity of the powerplants. It would also be necessary to measure dissolved gas levels immediately upstream of the dam to get real time information on the lake levels. This would allow better predictions of gas transfer, because the boundary levels might not be the same as those at the dam.

Discussion of Dissolved Gas Data Analysis From the 1970's

Extensive investigations of Grand Coulee Dam dissolved gas potential were conducted in 1972 and 1973. A summary of that work is provided based upon reports from that time (Seattle Marine Laboratories, 1973 and 1974). The data gathered during the early 1970's provide excellent insight into the dissolved gas situation both upstream and downstream of Grand Coulee Dam on the Columbia River.

Data were collected at nine stations in 1972 (numbered locations on figure 2), primarily to track dissolved gas levels through the reservoir and immediately downstream. During the 1973 monitoring, the tributary locations were deleted and stations downstream from the dam were added. These data were gathered to allow year-round analysis of the dissolved gas levels.

The analysis compared concentration levels and partial pressures or percent saturation. Concentration levels show the actual amount of dissolved nitrogen and are not significantly influenced by temperature as are saturation percentages based upon partial pressures. However, state standards are based upon acceptable percent saturation levels. Therefore, the results will be discussed in terms of percent saturation.

The dissolved gas saturation problem at Grand Coulee Dam can be divided into two parts: the saturation level in the reservoir, and the effect of spilling water through the spillway, outlet works, or powerplant.

Lake Roosevelt - The nitrogen concentrations and temperatures vary with depth and longitudinal location throughout the reservoir. The Columbia River provides the major contribution of water to Lake Roosevelt (80 to 85 percent) and therefore, most significantly influences the dissolved gas content. The dissolved gas levels of the Columbia River entering Lake Roosevelt are measured at Northport (11), figure 2. This measurement station takes into account the influence from the Kootenai and Pend Oreille Rivers and operation of the Canadian reservoirs. Influences from the other four tributaries, the Kettle River (9), the Colville River (10), the Spokane River (7), and the Sanpoil River (5), were measured just before each entered Lake Roosevelt. The effect of the dissolved gas levels as each tributary entered the lake and approaching the dam was determined. The station closest to the dam is Pine Tree Point (4). The dissolved gas levels at Pine Tree Point are representative of all influences in the lake. The data from Pine Tree Point are then used to determine the influence of powerplant, spillway, or outlet works releases on the river downstream from Grand Coulee Dam.

The tributaries of the Kettle, Colville, and Sanpoil Rivers produce little or no effect on the saturation levels in Lake Roosevelt. For the most part, temperatures are slightly higher in the tributaries than in the lake, but dissolved gas levels were, in general, near or below saturation. Only during May and June did gas levels exceed saturation to 103 to 113 percent on the Kettle River.

The Spokane River is the largest tributary into the lake contributing about 10 percent of the flow. Dissolved gas levels were considerably higher than for any of the other minor tributaries. Samples were taken below two COE dams during the study period and at the confluence of the Spokane River with the lake. Below the dams, the partial pressures exceed saturation levels reaching 128 percent in May and June, then declining to about 100 percent from July through October. The measurement station at the confluence was very similar to the lake level readings at Castle Rock (6) upstream of the Spokane, indicating that dilution occurs in the main body of the lake.

Further studies were performed on September 7 and 8, 1972, of the surface waters of the lake from the dam at Pine Tree Point upstream to Northport near the Canadian border. These studies showed a slight, but steady increase in gas saturation level and dissolved nitrogen concentration from Pine Tree Point upstream toward the border. The dissolved gas levels at Pine Tree Point are actually less than levels upstream in the reservoir indicating some loss of dissolved gas or more likely a dilution with the pure volume of water in the lake. Water temperatures were highest at the dam and slightly decreased toward the border. The high water temperatures at the dam produced a supersaturated condition (120 percent) even though the concentrations were lower than at Northport at the upstream end of the lake. A plot of the dissolved gas levels at the various tributary measurement stations in the reservoir during June of 1972 is shown on figure 3.

At Pine Tree Point, thermal stratification does play a role in the dissolved gas levels. Prior to July, there are few variations in temperature or concentrations with depth. From July through August, thermal stratification occurs from the dam upstream to the Castle Rock station. During stratification, the temperature is substantially higher at the surface (epilimnion), but the concentrations are significantly lower, resulting in lower dissolved gas supersaturation levels at the surface compared to the depths of the reservoir (hypolimnion). The decrease in nitrogen levels in the summer may be due to wind waves on the surface causing degassing. The concentrations near the middle and bottom decrease from July through the fall until the concentrations are again constant throughout the depth, indicating that mixing has occurred by September. The gas saturation levels increase from acceptable limits in April and early May, to exceeding the 110 percent limits throughout depth from mid-May through August. Throughout the fall, the gas saturation levels decrease to acceptable limits again. This trend shows the importance of temperature on the dissolved gas levels. Relatively constant concentrations and rising temperatures produce a reasonably wide fluctuation of gas supersaturation levels (figure 4).

In summary, the Spokane River water contributes to the dissolved gas problem in the late spring; the other tributaries are minor contributors. Monitoring of dissolved gas levels in Canada indicates that most of the dissolved gas enters Lake Roosevelt from the Columbia River.

Downstream of Grand Coulee Dam - Dissolved gas measurements were taken 6 miles downstream from the dam (station 1), and in the left and right powerplant tailraces (stations 2 and 3). The measurement station 6 miles downstream includes the effect of all flows, powerplant, outlet works, and spillway, and, as such, is showing average diluted gas supersaturation levels. Measurements in the powerplant tailraces show basically the same saturation level as the upstream reservoir at Pine Tree Point. The station 6 miles downstream shows higher concentrations of dissolved gas and higher saturation values due to high spillway flows and temperature increases in the river (figure 3). The dissolved gas saturation levels exceeded 140 percent from May into early July. These results are shown on figure 5 for the measurement locations at the powerplant tailraces and 6 miles downstream from the dam. In general, these historical data indicate that spillway releases will increase dissolved gas supersaturation downstream of the dam.

The controlled flow tests performed in April of 1973 using the two levels of outlet works discharge tubes produced inconclusive results. In general, the dissolved nitrogen levels increased from those in the forebay; however, the test discharges were so small compared to the powerplant flows that accurate detection of the true nitrogen levels was difficult with the limited sampling performed.

Dissolved Gas Analysis for a Typical Low Flow Year (1993)

The outlet works operated briefly in the spring and the spillways operated only for a 4- day period in May of 1993. The remainder of the flows was through the powerplant or for the visitor tours at the dam. Existing total dissolved gas data were analyzed to show the effect of this minor spillway release and to compare to earlier results from the 1970's. The international boundary total percent saturation and nitrogen concentration data, the releases from the dam, and the data in the river channel downstream from the dam are shown graphically on figure 6.

In general, the nitrogen concentration downstream from the dam closely tracks that of the level at the international boundary with Canada. The percent saturation levels at both locations increase throughout the spring and summer as the water temperature increases, then begins decreasing in the fall. The percent nitrogen saturation at the boundary is usually above 110 percent and spikes in late April and late June to above 130 percent. The gas saturation in the river below the dam is continually above 110 percent, because the high dissolved gas levels in the reservoir are passed by the powerplant releases. The short duration spillway release, with a maximum of 57,000 ft^3/s, quickly increases the dissolved gas supersaturation level to 139.9 percent or about a 17 percent increase over the existing level of about 119.6 percent before the release. This increase was typical of those recorded in the early 1970's and consistent with the finding that the Columbia River upstream of Lake Roosevelt is the major contributor to the dissolved nitrogen problem.

Canadian Dissolved Gas Influence

Past and current monitoring of the dissolved gas levels at the upper end of the Columbia River (Northport Station) have shown high levels of dissolved nitrogen concentration and percent saturation. Past monitoring programs through Lake Roosevelt have shown that minimal nitrogen is added by other lake tributaries. Thus, the dissolved gases entering the lake from Canada are the primary contributors to the saturation level in the reservoir at Grand Coulee Dam. Until the dissolved gas levels in the Columbia River upstream of the lake can be reduced, the lake will have dissolved gas supersaturation problems that will be transferred downstream of the dam by current operations.

BC Hydro is the owner of the major dams in the Upper Columbia River basin. BC Hydro is currently investigating ways to mitigate or minimize dissolved gas levels on its dams on the Columbia River. This includes monitoring gas levels to further understand the problems and looking to mix Columbia River system water with the Kootenai and Pend Oreille Rivers. The dam owners on these other tributaries have agreed to monitoring and trying operational changes or augmenting flows, but do not have funds for structural modifications including badly needed maintenance. The Pend Oreille River enters the Columbia River at the United States/Canadian border. Sampling conducted at Waneta Dam indicates that the Pend Oreille River is not a major contributor to the dissolved gas levels. Sampling at Trail, British Columbia, indicates dissolved gas levels slightly higher than those at the Northport Station at the upstream end of the lake, indicating that the dissolved gas levels in the Columbia River in Canada are the major factor in the problem.

BC Hydro has a draft document with a computer model for predicting beneficial operations at Keenleyside Dam. This document is not finalized, but does give guidance for operations at Keenleyside. The lake formed by Keenleyside Dam has a supersaturation level of about 107 percent occurring naturally. Operation of the low level sluiceways is limited by problems with cavitation damage, which requires releases be made from a higher structure. Also, the riverbank is unstable near the low sluiceways, thus limiting some uses. Use of the higher level outlets increases the dissolved gas saturation problem. Construction of a powerplant has been authorized by the provincial government and would alleviate the problem of increasing gas saturation levels by releases from Keenleyside. However, there is no schedule for this construction.

All agencies and dam owners are members of a committee addressing the dissolved gas level problem in Canada. These organizations must approve the use of the predictive model and agree to implement operations recommended by the draft document which was prepared by a consultant. The time frame for the document to be finalized and accepted is not known at this time, but it does appear that progress is being made in Canada to address the levels of dissolved gas being transferred to the United States.

Frequency Analysis of Spillway and Outlet Works Releases

The decision regarding operational or structural modifications to Grand Coulee Dam to reduce the supersaturation potential during spillway and outlet works releases will partially be based upon the expected frequency of the releases.

If releases are expected to occur frequently, perhaps modifications could be justified.

This analysis was based upon data received from the PAO and the Operations Office at Grand Coulee dam. Data from the PAO were in a spreadsheet and identified as bypass flows. In other words, these were discharges passed through the dam spillway and/or outlet works, not through the powerplants. Data from the dam were in total daily flows from the spillways and outlet works and hourly outlet works operation. These two data sources were compared for any discrepancies. The PAO data included the tourist spill information, but in the daily flow records it was easily identified and omitted before performing any frequency analysis. Often the only spillway use was for the tourist spill, which occurs from May through September of each year. Prior to 1987, the tourist spill amounted to a fairly large volume of water released in a month. In 1987, the tourist spill was reduced to between 100 to 200 $ft^3/s/day$. In 1992, the tourist spill was reduced even further, to less than 100 $ft^3/s/day$.

Data from 1981 to 1995 were used because the Third Powerplant went entirely on line in 1981. This gives a database of 15 years for analysis. Currently, the powerplants pass the majority of the flow from the dam, but additional flows may be required to enhance downstream riverflows.

To determine the frequency of expected releases for each day, the records were searched for any spill in excess of the tourist spill and simply counted. The total number of days the spillway or outlet works were used in each month is shown in table 1. The probability that the spillway will operate on any given day of each month was determined by dividing the total number of days operated by the number of days in the month and the 15 year period (figure 7). Most releases have been in June, but then only 17.56 percent of the time or 1 out of every 5.7 days. The spillways have not been used in the fall or early winter, as indicated by the 0.0 percent frequency shown.

In general, the results show that spillway and/or outlet works use is infrequent, but during wet years is used almost continually. When releases are required, they are generally more frequent during the spring and summer months, then much less frequent during the fall and winter.

The data are heavily skewed toward years of high flood flows (1981, 1982, and 1983) during which time the spillway and outlet works began operating almost daily in the spring and operation continued to some degree throughout the summer. In contrast, no releases have been made for 5 of the last 10 years, 1985 to 1995.

Method Used to Predict Dissolved Nitrogen Saturation Potential

The method used to predict dissolved gas levels below Grand Coulee Dam combines a gas transfer efficiency determined for the dam from known saturation data with bubble penetration and mass transfer theories.

The potential for transfer of dissolved gases with spillway and outlet works releases has been performed. The analysis used is based upon determining an effective depth and saturation concentration, which is a function of the bubble depth and mass transfer. The analysis uses the depth of bubble penetration given the spillway angle of inclination, and the velocity and depth of the jet at impact with the tailwater pool level. This penetration depth is then used with a semi-empirically derived relationship to predict an effective depth that accounts for tailwater levels and the characteristics of the bubble swarm. The theory has been developed by John S. Gulliver, Associate Professor, Saint Anthony Falls Hydraulic Laboratory, University of Minnesota (Hibbs, in press; Geldert, 1996).

Table 1. - Daily Spillway and Outlet Works Operating Information

YEAR	Jan 31 days	Feb 28 days	Mar 31 days	Apr 30 days	May 31 days	June 30 days	July 31 days	Aug 31 days	Sept 30 days	Oct 31 days	Nov 30 days	Dec 31 days
1981	2	0	0	8	9	30	27	17	0	0	0	0
1982	1	4	28	28	27	16	12	0	0	0	0	0
1983	0	9	30	8	13	1	4	0	0	0	0	0
1984	0	0	0	1	0	18	6	2	0	0	0	0
1985	0	0	0	0	0	0	0	0	0	0	0	0
1986	0	0	5	18	1	10	0	0	0	0	0	0
1987	4	0	0	0	2	0	0	0	0	0	0	0
1988	0	0	0	0	0	0	0	0	0	0	0	0
1989	0	0	0	0	0	0	0	0	0	0	0	0
1990	0	0	0	0	0	4	0	0	0	0	0	0
1991	0	0	0	0	5	0	0	0	0	0	0	0
1992	0	0	0	0	0	0	0	0	0	0	0	0
1993	0	0	0	0	4	0	0	0	0	0	0	0
1994	0	0	0	0	0	0	0	0	0	0	0	0
1995	0	0	0	0	0	0	0	0	0	0	0	0
Total number of days operated	7	13	63	57	61	79	49	19	0	0	0	0
Probability (%) of operating	1.51	3.1	13.5	12.67	13.12	17.56	10.5	4.1	0	0	0	0

A Lotus spreadsheet was developed to allow a significant amount of flexibility with regard to varying discharge, barometric pressure, temperature, reservoir saturation levels, and depth of the basin as a function of tailwater for total spillway, outlet works, and powerplant discharge. Discharge increments were chosen for investigation and then divided among the number of gates used.

A water surface profile program was used to determine the flow depths and velocities at the location of impact with the tailwater for discharge condition investigated (Falvey, 1990). Flows were assumed to not spread laterally across the face of the spillway, producing a more concentrated jet than expected and conservative results.

The penetration depth of the jet in the tailwater pool was determined from the following equation by using the depths, d_o, and velocities, U_o, calculated from the water surface profile program:

$$Y_p = d_0 \left[\frac{U_0/u_b + \sqrt{(U_0/u_b)^2 - 41.73\tan\alpha_2/\sin^2\theta}}{6.46\tan\alpha_2/\sin^{3/2}\theta} \right]^2 \quad \textbf{(2)}$$

with u_b=0.25 m/s, α_2=0.14°, θ=51.34°. This equation computes the jet penetration depth as a function of the jet travel down the spillway slope, the expansion of the jet in the tailwater pool, and the bubble rise velocity.

The non-dimensional effective depth is then calculated from:

$$\frac{1}{(d_{eff}/TW)} = \frac{1}{\beta(y_p/TW)} + \frac{1}{(d_{eff}/TW)_{\max}} \quad \textbf{(3)}$$

with $\{d_{eff}/TW\}_{max}$= 2/3 as per Johnson, β=0.32. This equation computes the effect of tailwater on the mass transfer characteristics of the bubbles in the tailwater. It is the sum of the average bubble depths for low and high flows. The bubble depth may be less than y_p for low flows, and may be limited by the depth of the basin or structure for high flows. The coefficient, β, has been determined empirically from measurements of aerated plunging jets.

The effect of the hydrostatic pressure on the submerged bubbles in the stilling basin is then determined by computing the effective saturation concentration:

$$C_{se} = C_s\left(1 + \gamma\frac{d_{eff}}{P}\right) \quad \textbf{(4)}$$

with C_s=saturation concentration (mg/l) and γ=specific weight of water (atm/m), and P=atmospheric pressure at the site (atm).

The downstream percent saturation for various operating conditions is then computed by utilizing the effective depth or effective saturation concentration and a gas transfer efficiency, E, with the upstream or reservoir saturation percentage. The downstream saturation potential is computed from:

$$Y_d = Y_u + E\left[100\left(\gamma\frac{d_{eff}}{P}\right) + 1\right] \quad \textbf{(5)}$$

where Y_d and Y_u are the downstream and upstream percent saturations. The gas transfer efficiency, E, was computed from existing dissolved nitrogen concentration data for both the spillway and outlet works. The effective depth was chosen to use in the downstream saturation equation because it is not influenced by temperature. The total dissolved gas monitoring station downstream of the dam does not allow direct evaluation of spillway or outlet works flows because mixing has occurred with the powerplant flows. The local dissolved gas saturation is more likely greater than computed because the efficiency is computed from mixed flows. This should be adequate given the geometry of the river channel, powerplant operations and downstream requirements.

Prediction of Gas Transfer from Spillway Releases

The dissolved gas potential for spillway releases was computed using this method. All possible spillway gate opening combinations were investigated. For instance, with a total maximum spillway discharge of 1,000,000 ft^3/s, each of the 11 gates is capable of passing 90,900 ft^3/s each. So, for a discharge of 90,900 ft^3/s or less, 1 gate or all 11 gates may be used to pass the flow. In general, increments of 90,000 ft^3/s were used in the spreadsheet with three levels of powerplant flow, thus three tailwater levels. The tailwater elevation was varied from that associated with 0, 140,000, and 280,000 ft^3/s in addition to the spillway flow.

Predictions of downstream dissolved gas levels as a result of spillway releases were made by choosing initial values for the forebay percent saturation between 90 to 140 percent and the standard barometric pressure corresponding to the stilling basin elevation. Computations were then made for spillway discharges ranging from 2,500 to 990,000 ft^3/s, assuming the three levels of powerplant flows. The number of spillway gates used to pass the flow was then varied from 1 gate (assuming 1 gate can pass about 90,000 ft^3/s) to all 11 gates. The effective depths for each case were computed.

The ability of the structure to transfer gas, or the transfer efficiency, E, was determined from the data collected in 1971. The efficiency, E, was computed to be 0.2 for the spillway. The downstream percent saturation was then computed using the computed effective depths, the efficiency, and the standard barometric pressure from the elevation of the stilling basin and the various chosen upstream percent saturations. The results cover the full operational range of expected reservoir saturation levels, spillway and powerplant discharges, and tailwaters (figures 8-19).

In general, the saturation potential decreases as the number of gates used to pass a flow rate is increased. For example, with the reservoir saturation level at 120 percent, and 280,000 ft^3/s being passed by the powerplants, a discharge of 90,000 ft^3/s results in a downstream saturation varying from 162.1 percent with 1 gate open to 135.7 percent when passed with all 11 gates. This is appropriate because the thinner jet causes less penetration into the tailwater and sooner diffusion of the bubble swarm.

The downstream dissolved gas level will always be increased by spillway flows if the reservoir dissolved gas level is less than 100 percent. If the reservoir level is greater than 100 percent, some small flow rates ($\leq$ 30,000 ft^3/s) may be passed with various gate combinations that will maintain or slightly reduce downstream gas levels.

Prediction of Gas Transfer from Outlet Works Releases

The same analysis was performed to determine the effect of outlet works discharge on the total dissolved gas levels downstream. The outlets discharge onto the face of the spillway and use the same stilling basin. It was assumed that the

102- in -diameter outlets each operate fully open. A discharge rating table was obtained from the dam operators for the upper (El. 3136.67) and middle (El. 3036.67) outlets. (The lower outlets were only used during dam construction and are no longer operable.) The outlets are generally only operated once the reservoir drops below El. 1260. For the analysis, it was assumed that the outlets could be operated at maximum reservoir El. 1290. For reservoir El. 1260 the discharges are 3,855 and 5,032 ft^3/s, for the upper and middle outlets, respectively. For reservoir El. 1260, the discharges are 4,260 and 5,336 ft^3/s, for the upper and lower outlets, respectively.

The first step in determining the characteristics of the outlet works jets was to compute the depth and velocity at the point of entry with the tailwater. During this process, it became apparent that there was no significant difference in the depth or velocity of the jets with the two reservoir and outlet elevations investigated. Also, it was noted from the operation data that the upper and middle outlets were always operated together. Therefore, the discharges, depths, and velocities were averaged for both reservoir elevations and outlet works levels. This produced one penetration depth, y_p, but varying effective depths, d_{eff}, depending upon the tailwater produced by the number of outlets operating and the powerplant discharge. Comparison of the effective depths to the tailwater depths over the full operational range of 1 to 40 outlets and 0 to 280,000 ft^3/s powerplant flows indicated that the jets from the outlets would never dive to the bottom of the stilling basin. Shallower penetration would create turbulent flow conditions downstream. Project personnel have stated that the downstream river channel is very turbulent when the outlet works are releasing.

The remaining aspect of the analysis was to determine the gas transfer efficiency of the outlet works. The outlet works release data were sorted to determine what years the outlet works had been operated for a significant amount of time. These times were then compared to the reservoir elevation (less than El. 1260) to make sure that the spillway was not operating. The dissolved gas data were then searched for upstream and downstream data for these years of outlet works operation only. This narrowed the possibilities significantly. Because of a combination of missing data, data not collected early enough in the year, or the reservoir not dropping below El 1260, there were only two instances where the efficiency could be computed, 1986 and 1991. The upstream and downstream percent saturations for both these years were computed using boundary data and the monitoring station 6 miles downstream from the dam. The downstream saturation percentages were less than the upstream values producing a negative gas transfer efficiency. However, the dissolved gas level at the dam may be different than that measured at the boundary for the same day. This could be the reason for the negative efficiency. With an unreliable efficiency, no predictions can be made for gas transfer with outlet works operation as were made with the spillway flows.

The recent dissolved gas data with the outlet works operating was then investigated. A comparison was made between downstream data before, during, and after outlet works releases. The boundary data was not used in the analysis because of the uncertainty in the travel time through the reservoir to the dam. Review of the downstream data showed an increase from a baseline level of about 110-111 percent when any significant flows were passed. Flows less than 10,000 ft^3/s produced increases of from 1 to 7 percent. Flows of about

25,000 ft^3/s produced increases of about 13 percent, and flows of 50,000 ft^3/s increased the baseline saturation level by 26 percent.

This conclusion should be tempered by the fact that the monitoring station measures a mixture of outlet and powerplant flows, with the outlet works flows only a small portion of the powerplant flows.

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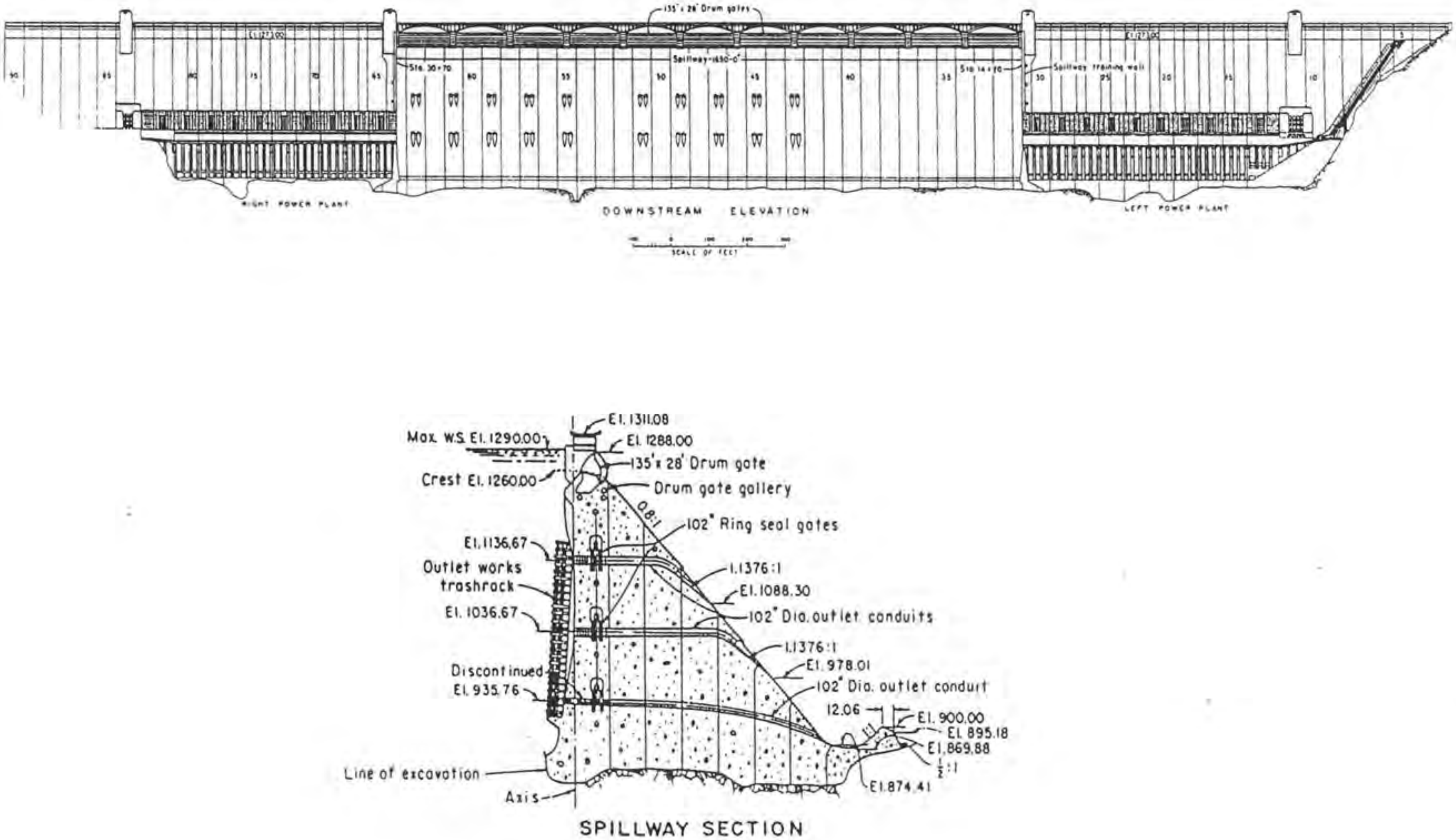

Figure 1. - Downstream section of Grand Coulee Dam and sectional view of the spillway.

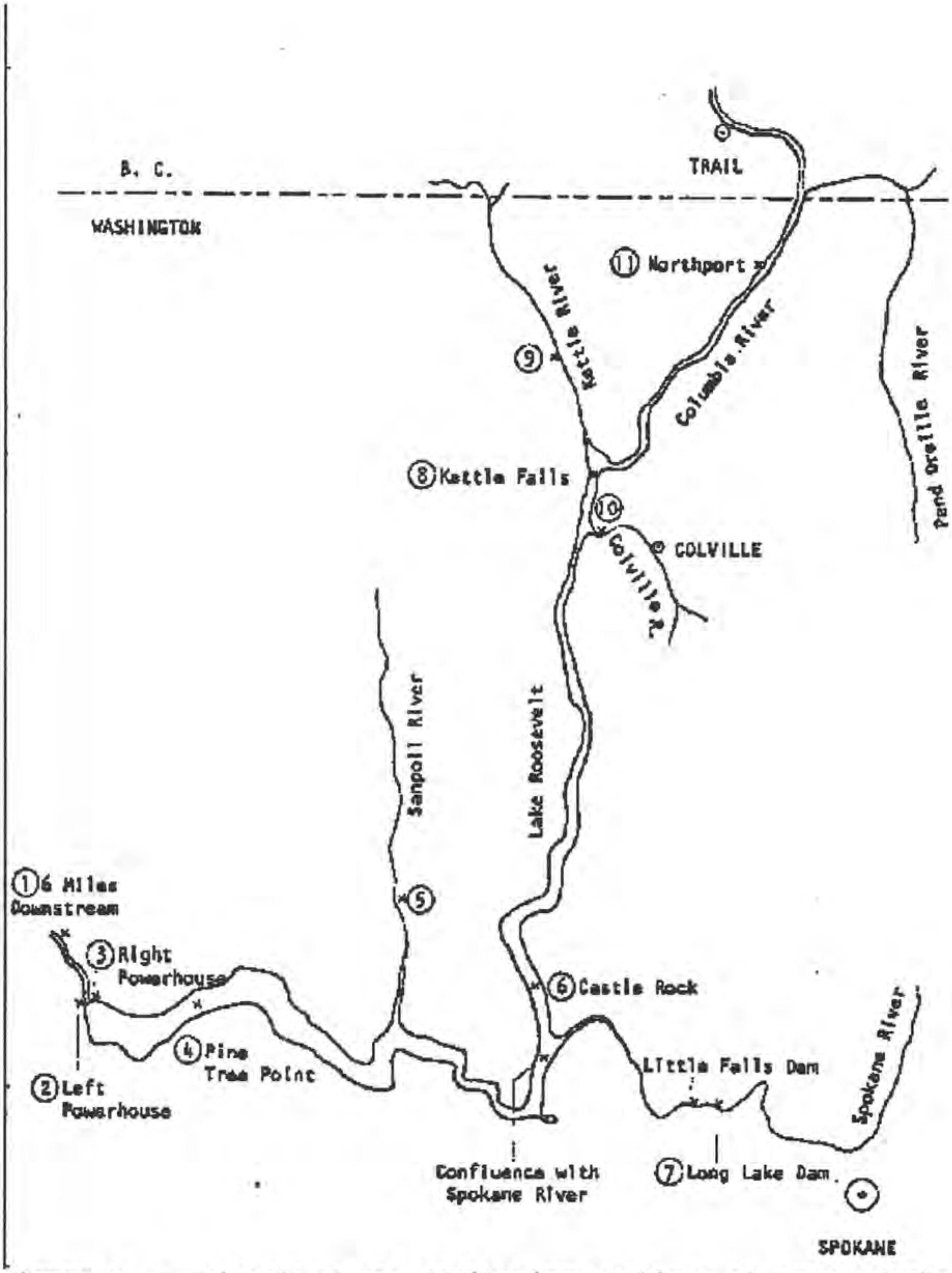

Figure 2. - Dissolved gas monitoring stations at Grand Coulee Dam and on Lake Roosevelt.

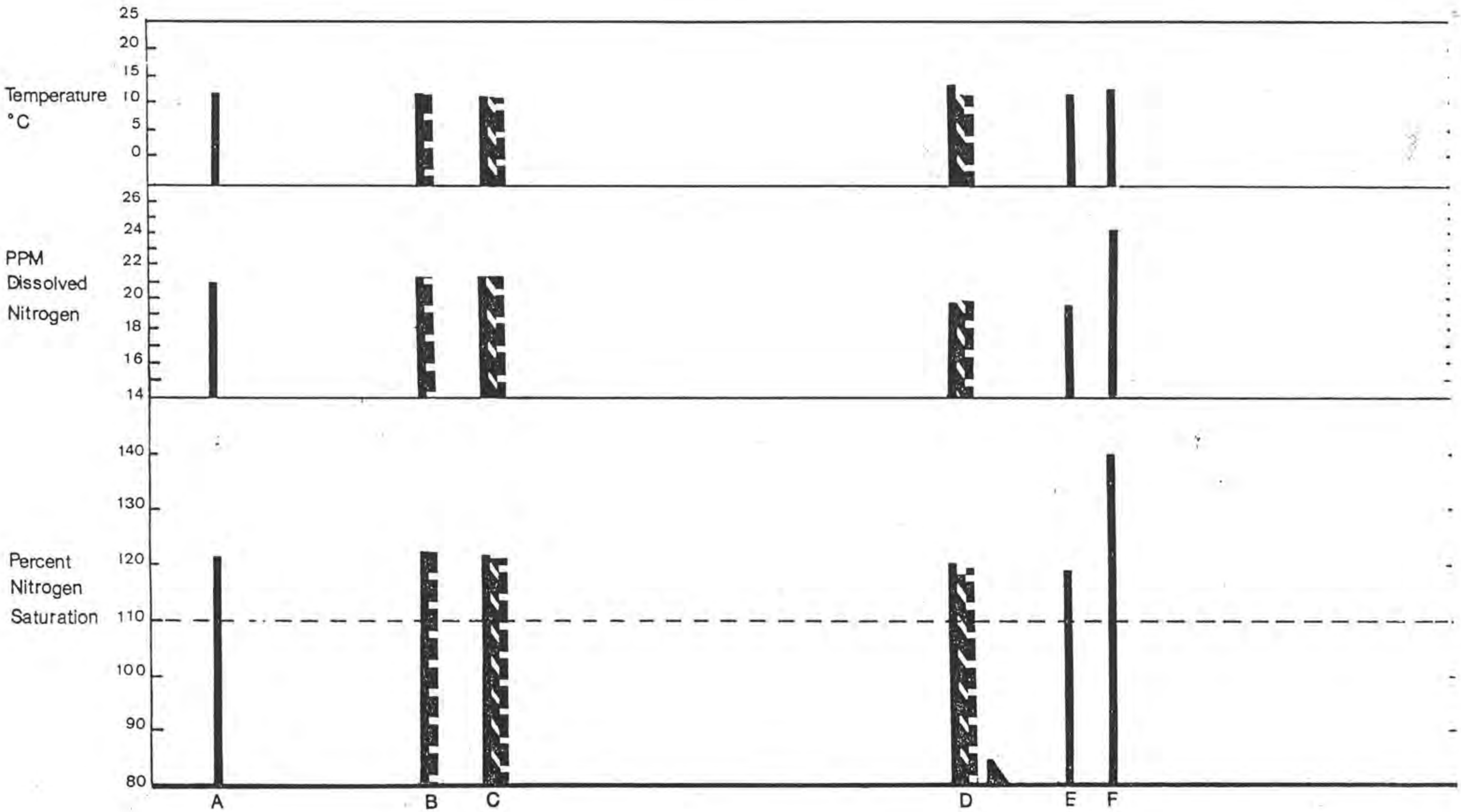

Figure 3. Average dissolved nitrogen parameters in Lake Roosevelt during June, 1972 as sampled at Northport (A), Kettle Falls (B), Castle Rock (C), Pine Tree Point (D), Powerhouse (E), and below Grand Coulee (F). Surface, Mid-depth, and Bottom. Dam Location.

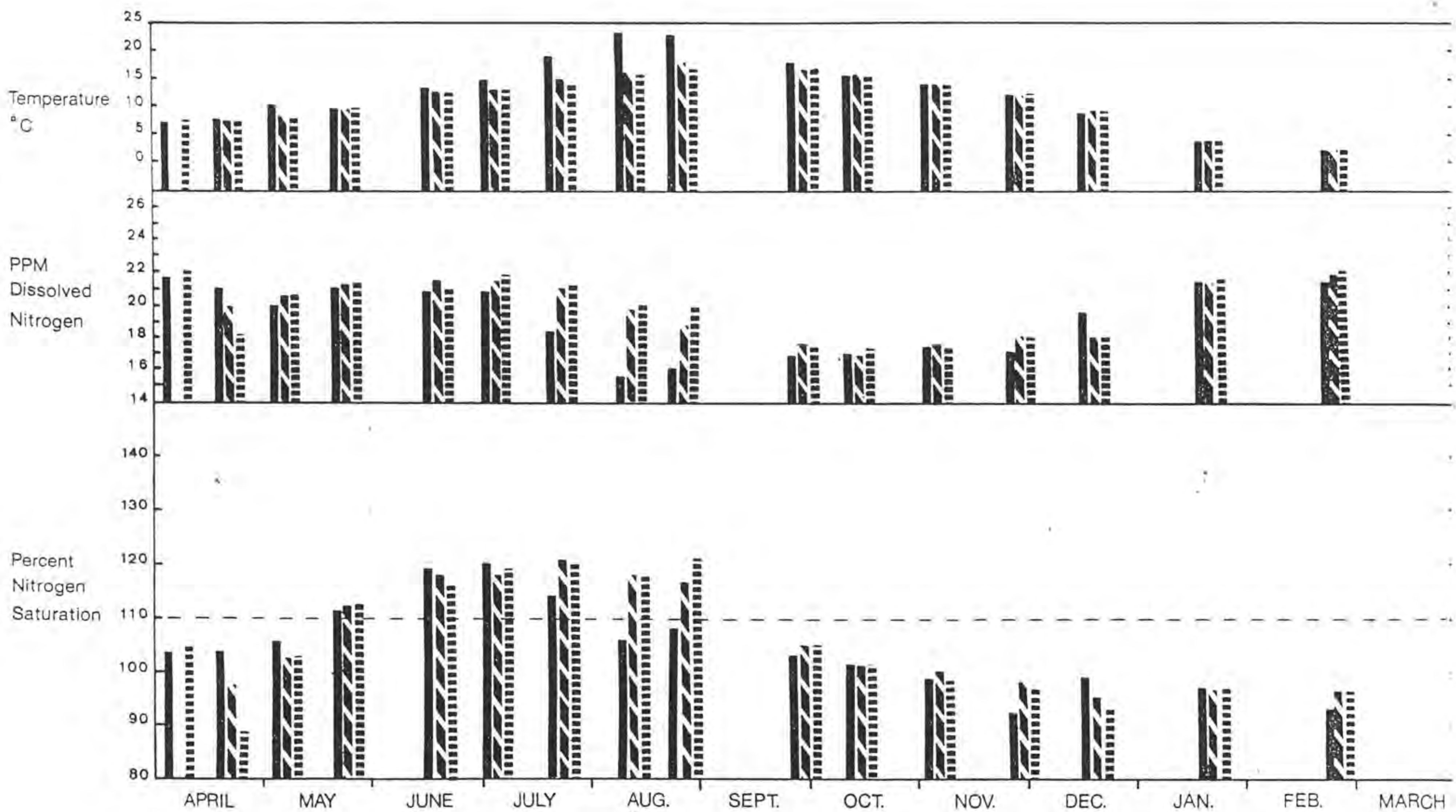

Figure 4. Pine Tree Point, average water temperatures, dissolved nitrogen concentrations and nitrogen partial pressures from April 1972 to March 1973. Surface, Mid-depth, and Bottom.

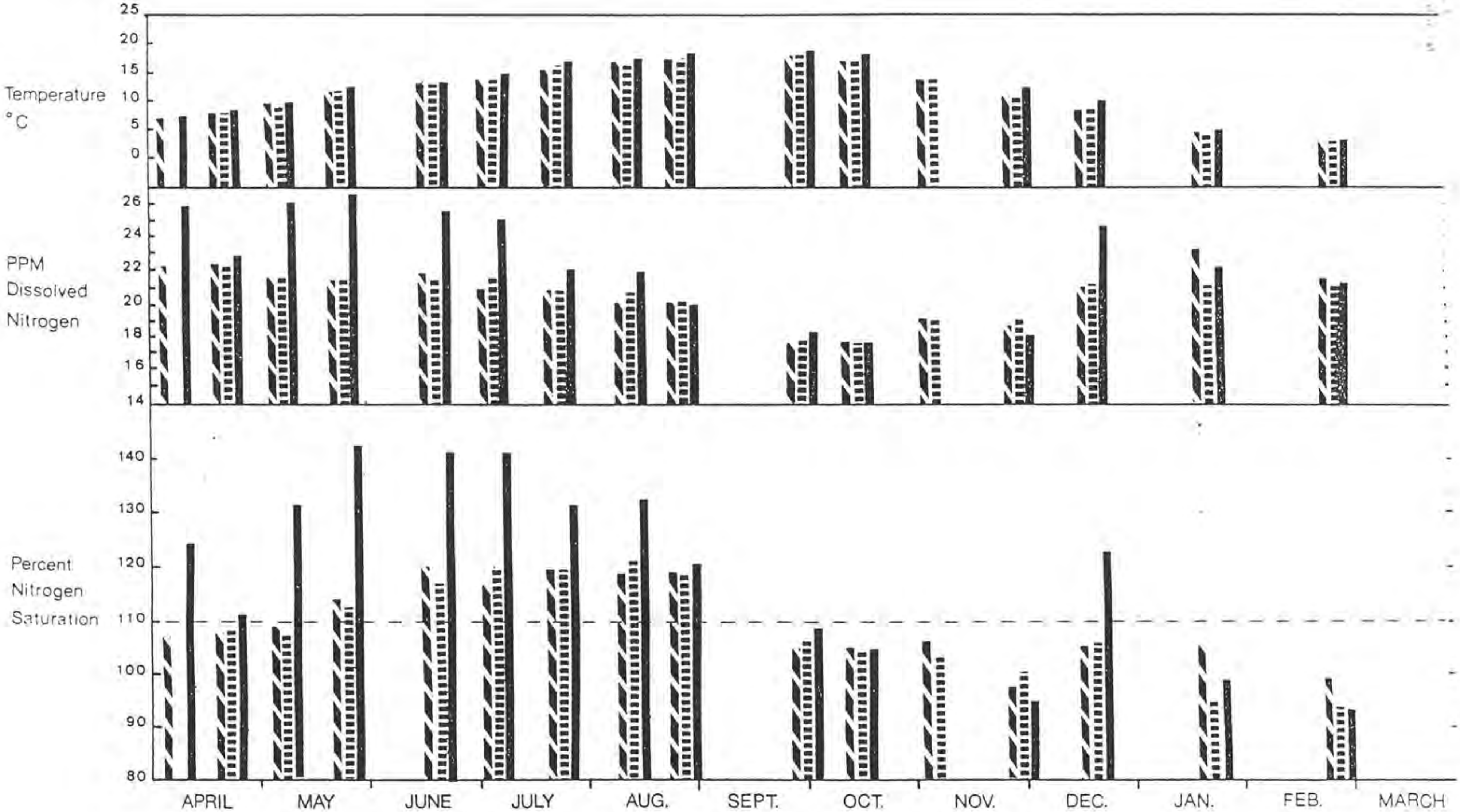

Figure 5. Downstream from Grand Coulee Dam, average water temperatures, dissolved nitrogen concentrations and nitrogen partial pressures from April 1972 to March 1973. Left Powerhouse, Right Powerhouse, Below Grand Coulee Dam.

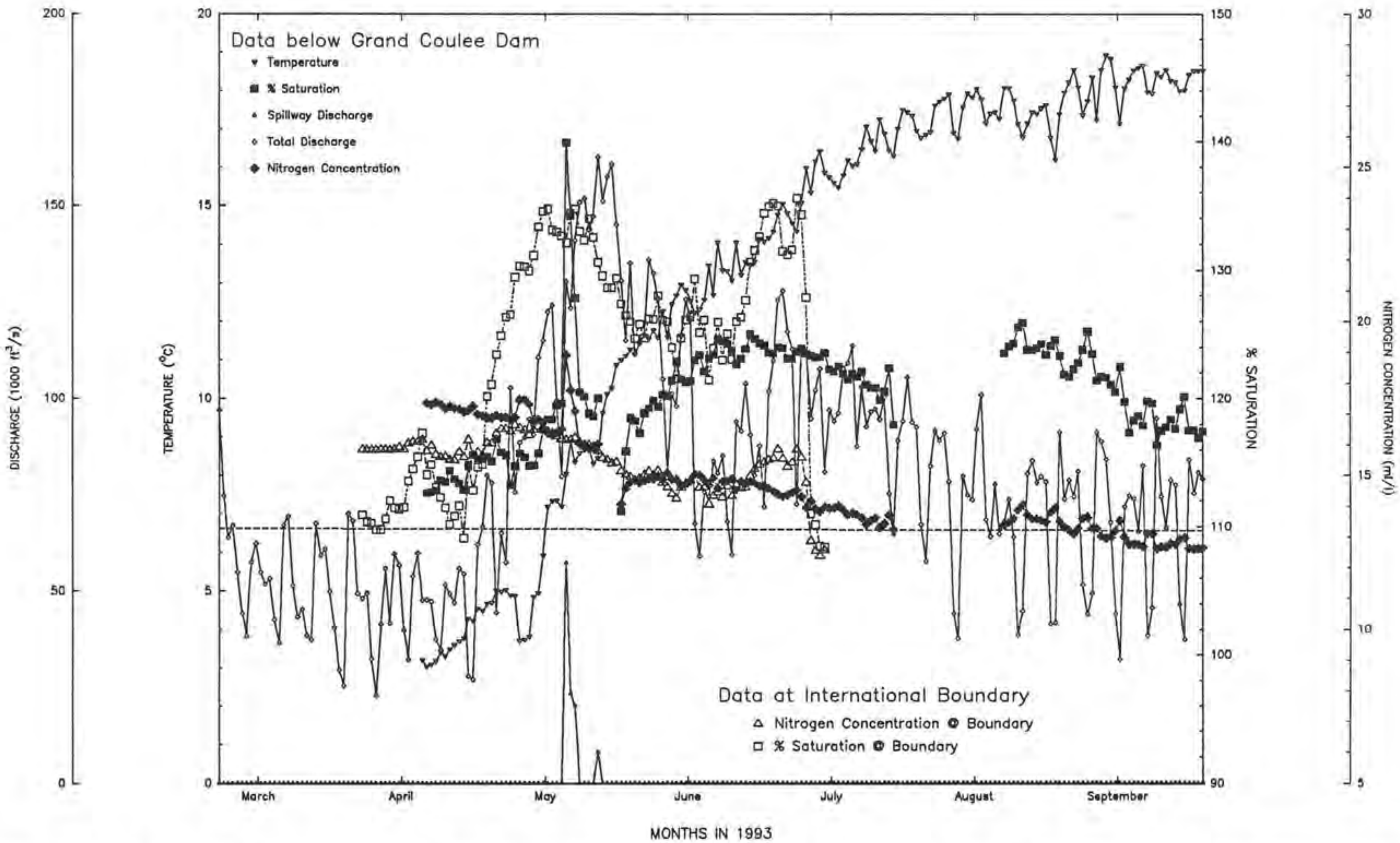

Figure 6. - Dissolved gas analysis for 1993 showing data from the international boundary and downstream of the dam.

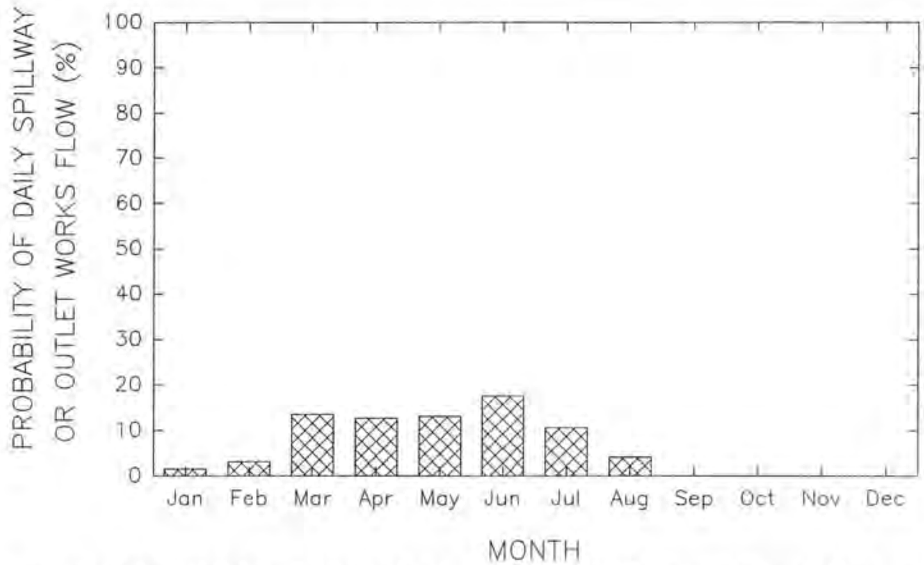

Figure 7. - Probability (%) that the spillway or outlet works will be operated any given day based upon the previous 15 years of data (1981-1995).

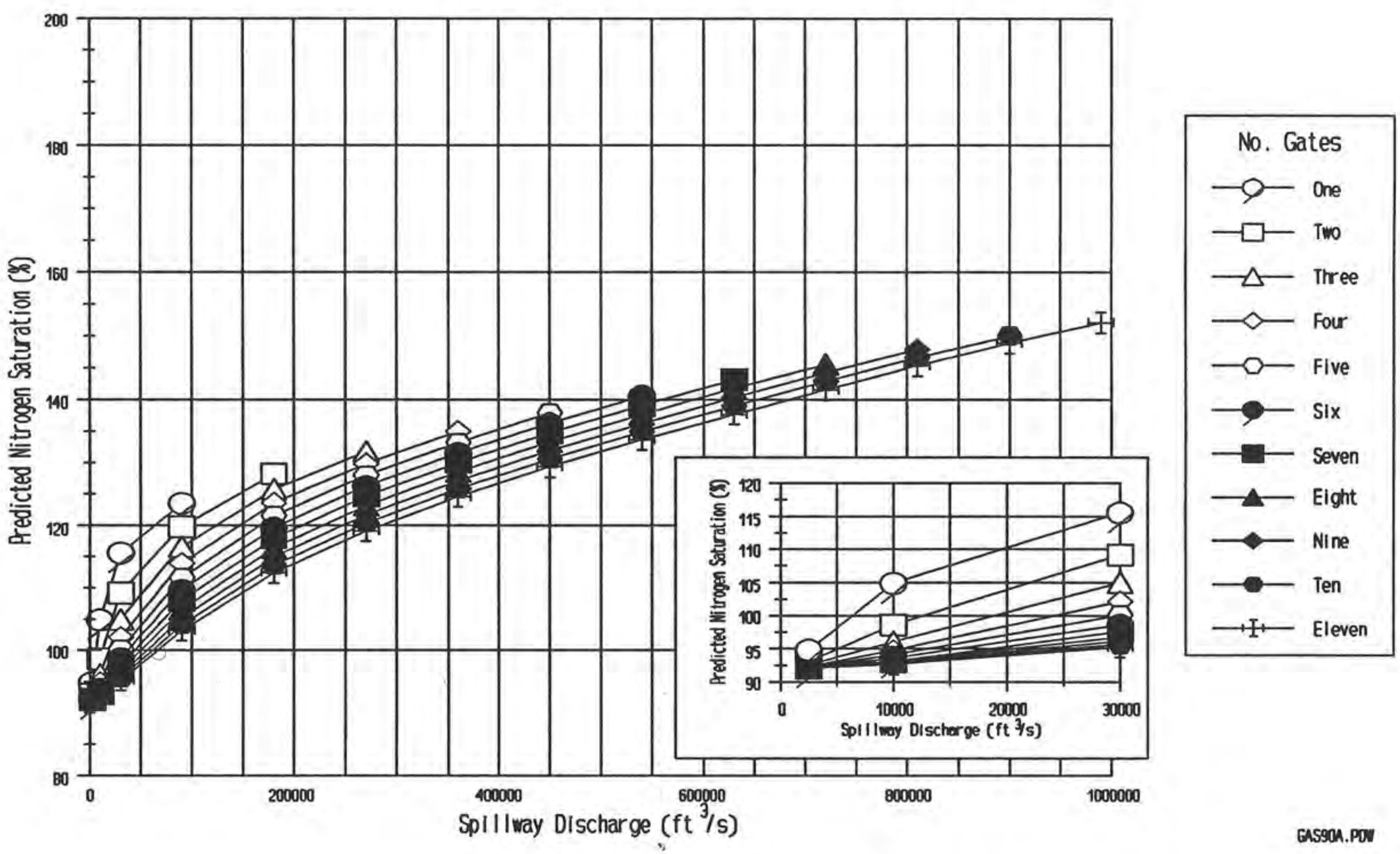

Figure 8. - Predicted dissolved nitrogen saturation for Grand Coulee Dam with the reservoir at 90% saturation and spillway discharges only.

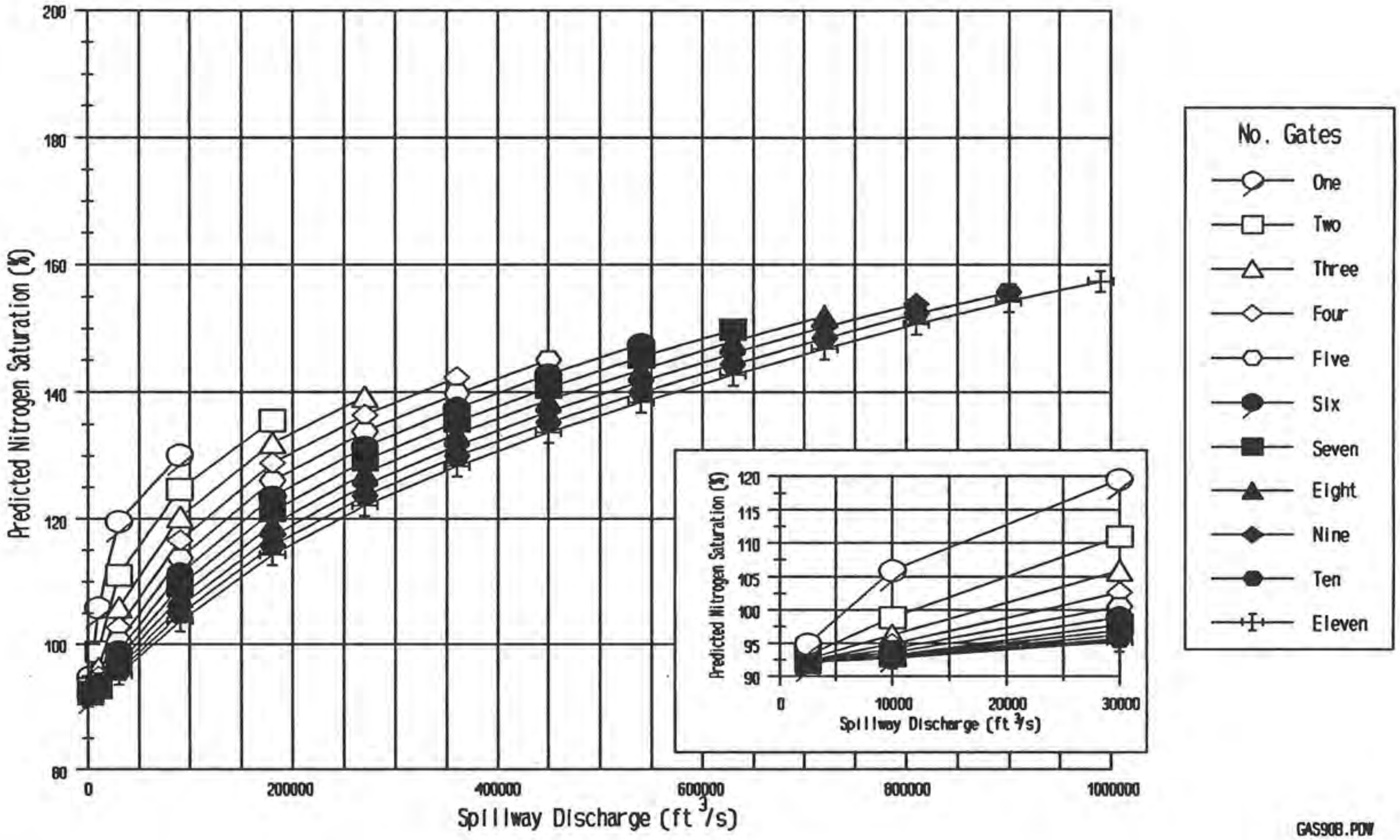

Figure 9. - Predicted dissolved nitrogen saturation for Grand Coulee Dam with the reservoir at 90% saturation and spillway discharges with 280,000 ft^3/s through the powerplants.

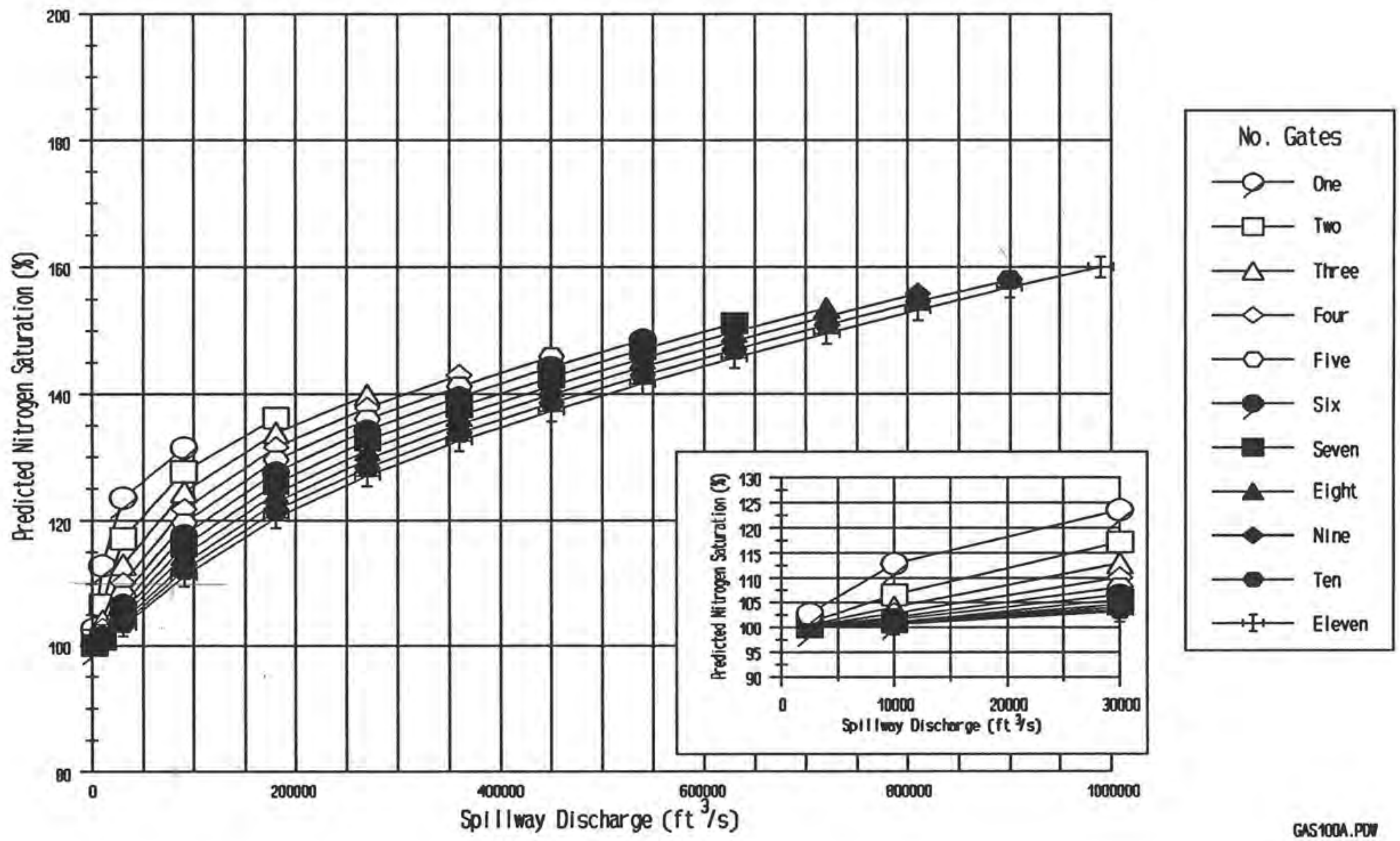

Figure 10. - Predicted dissolved nitrogen saturation for Grand Coulee Dam with the reservoir at 100% saturation and spillway discharges only.

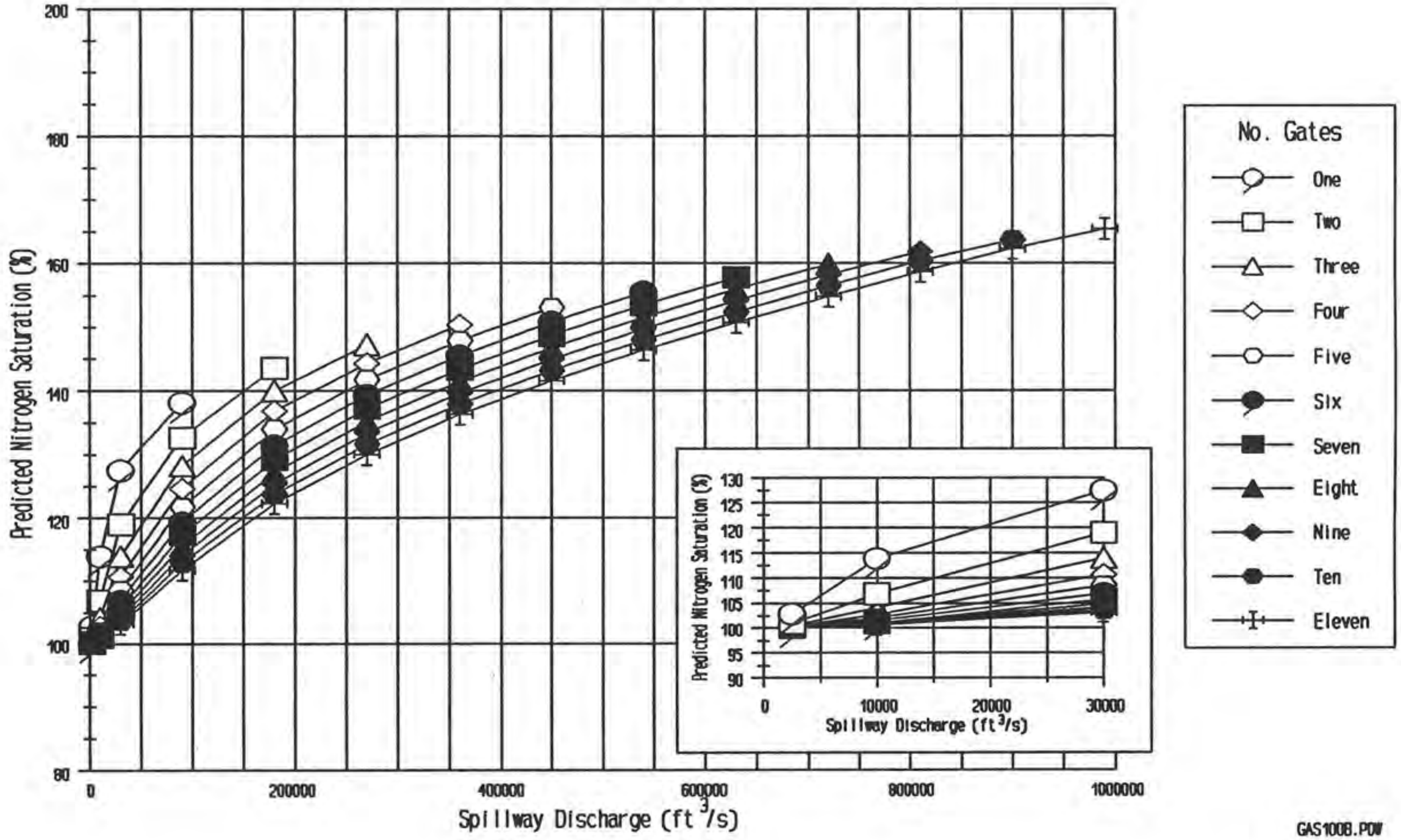

Figure 11. - Predicted dissolved nitrogen saturation for Grand Coulee Dam with the reservoir at 100% saturation and spillway discharges with 280,000 ft^3/s through the powerplants.

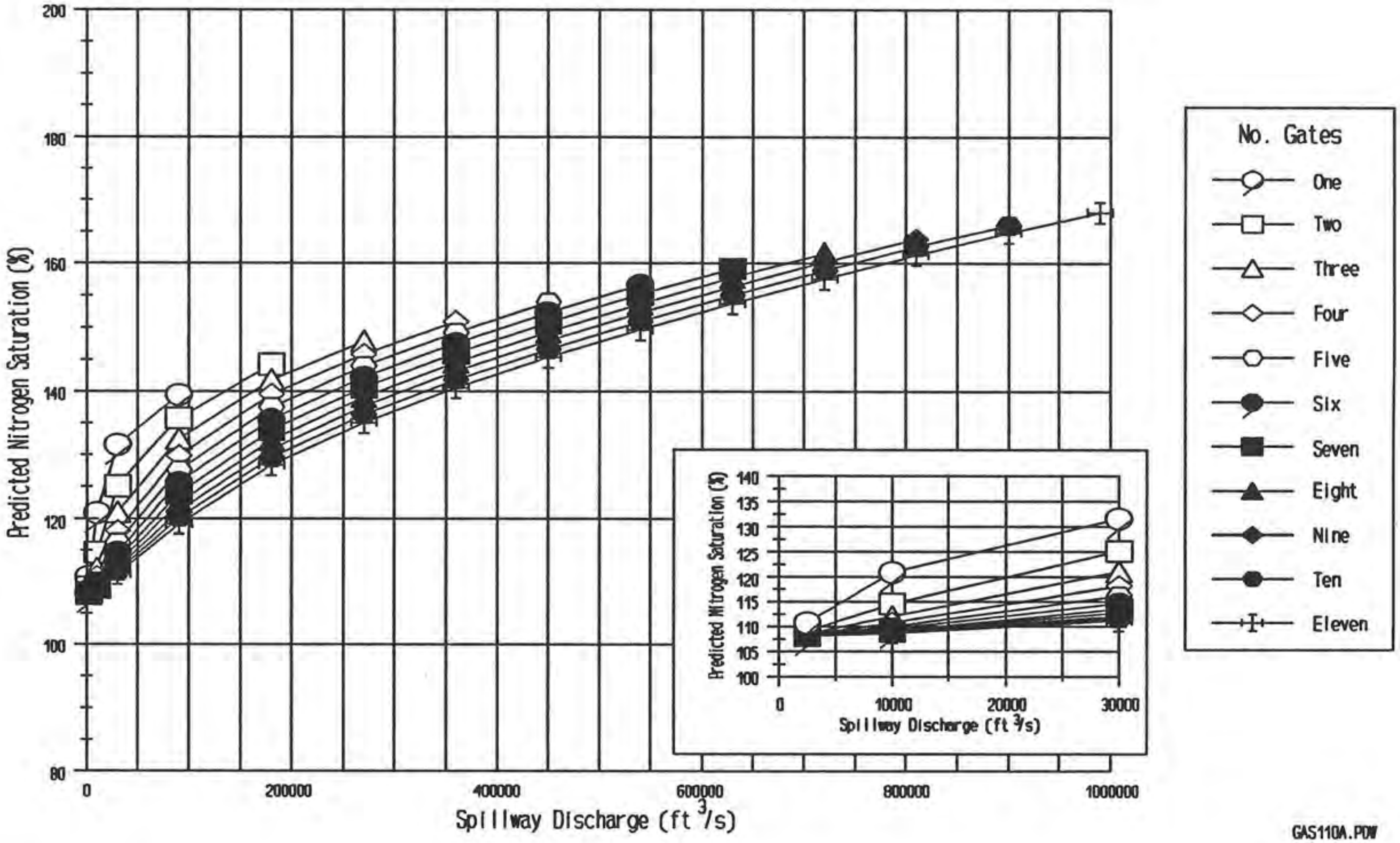

Figure 12.- Predicted dissolved nitrogen saturation for Grand Coulee Dam with the reservoir at 110% saturation and spillway discharges only.

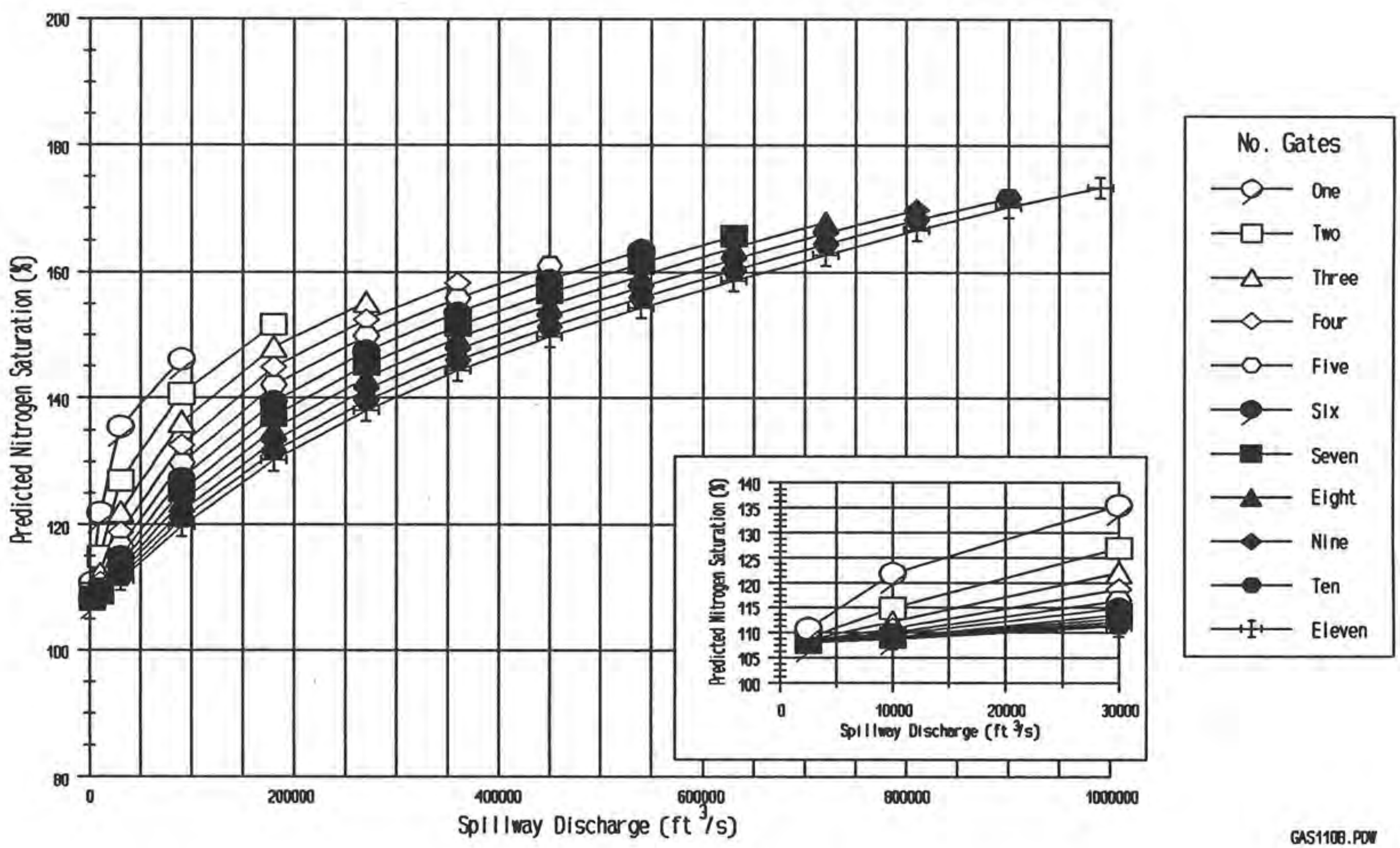

Figure 13. - Predicted dissolved nitrogen saturation at Grand Coulee Dam with the reservoir at 110% saturation and spillway discharges with 280,000 ft^3/s through the powerplants.

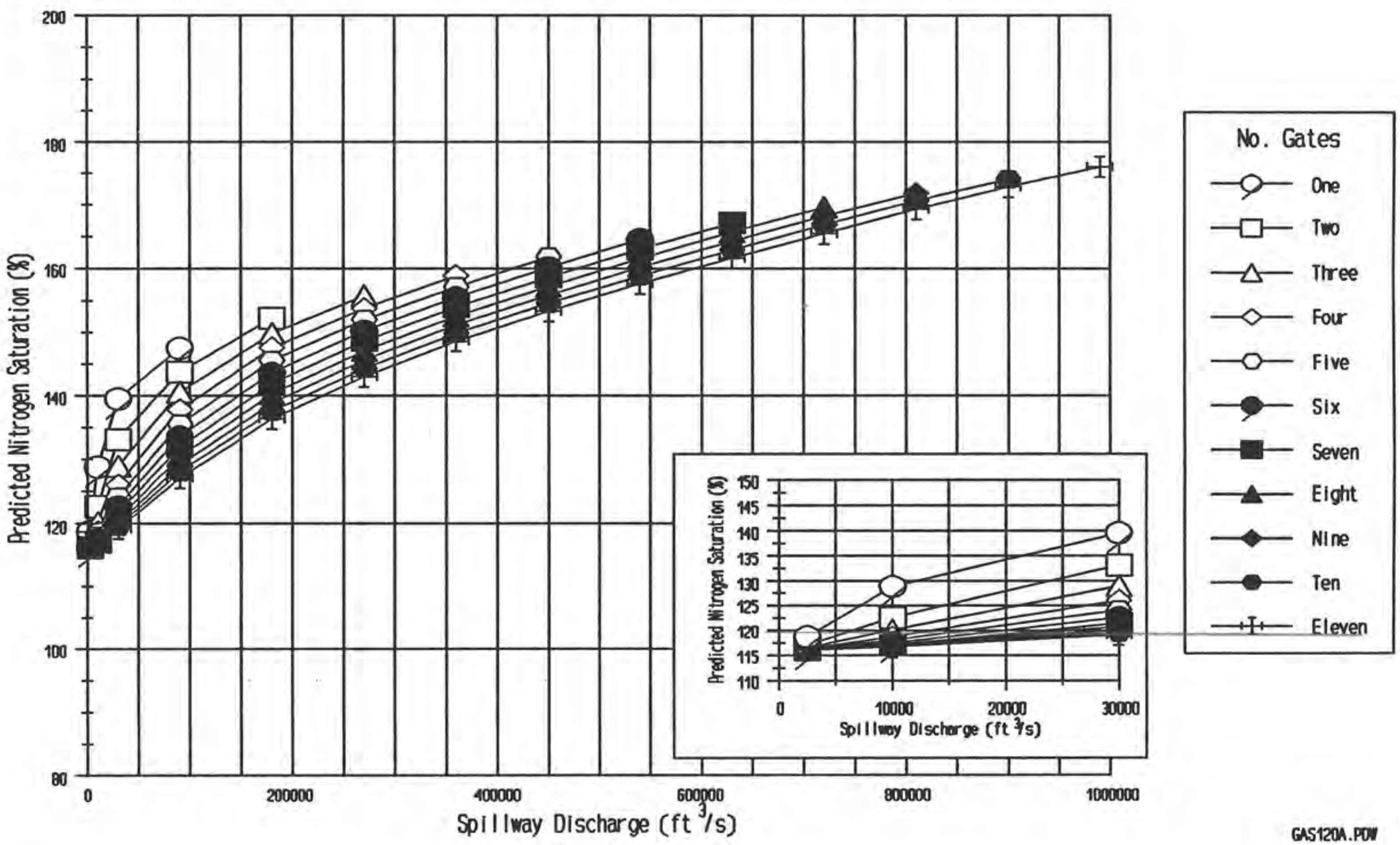

Figure 14. - Predicted dissolved nitrogen saturation for Grand Coulee Dam with the reservoir at 120% saturation and spillway discharges only.

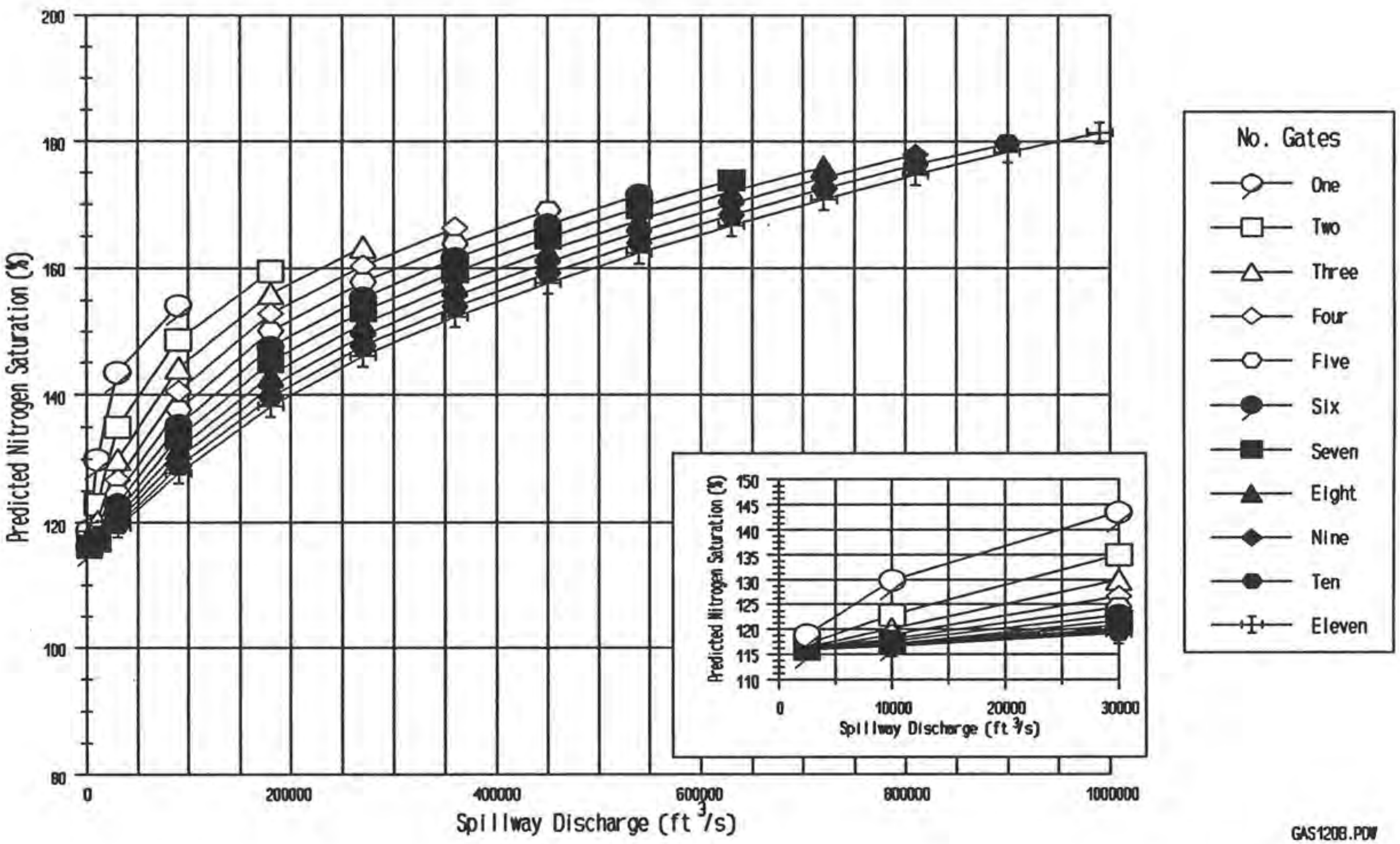

Figure 15. - Predicted dissolved nitrogen saturation for Grand Coulee Dam with the reservoir at 120% and spillway discharges with 280,000 ft^3/s through the powerplants.

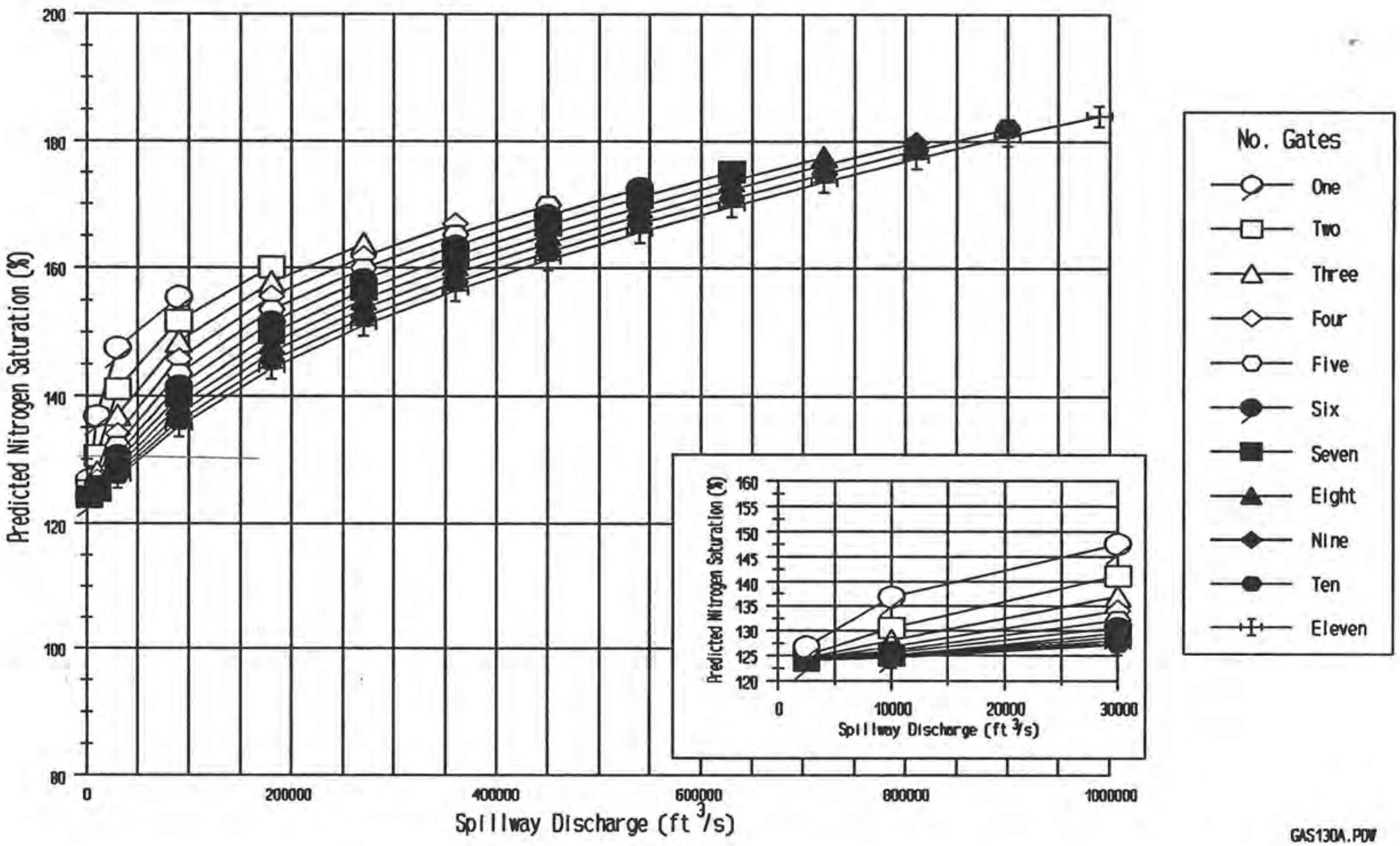

Figure 16. - Predicted dissolved nitrogen saturation for Grand Coulee Dam with the reservoir at 130% saturation and spillway discharges only.

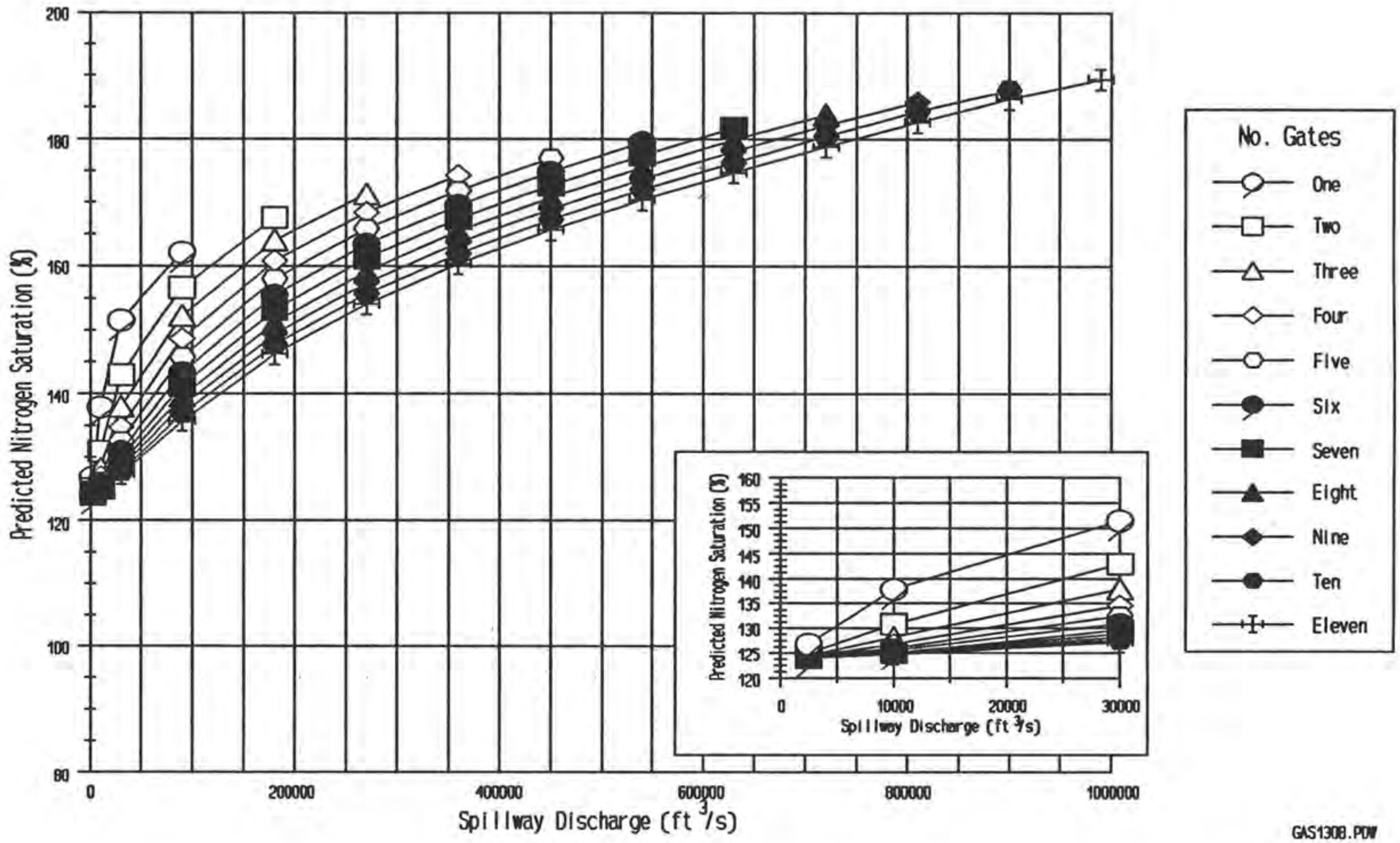

Figure 17. - Predicted dissolved nitrogen saturation for Grand Coulee Dam with the reservoir at 130% saturation and spillway discharges with 280,000 ft^3/s through the powerplants.

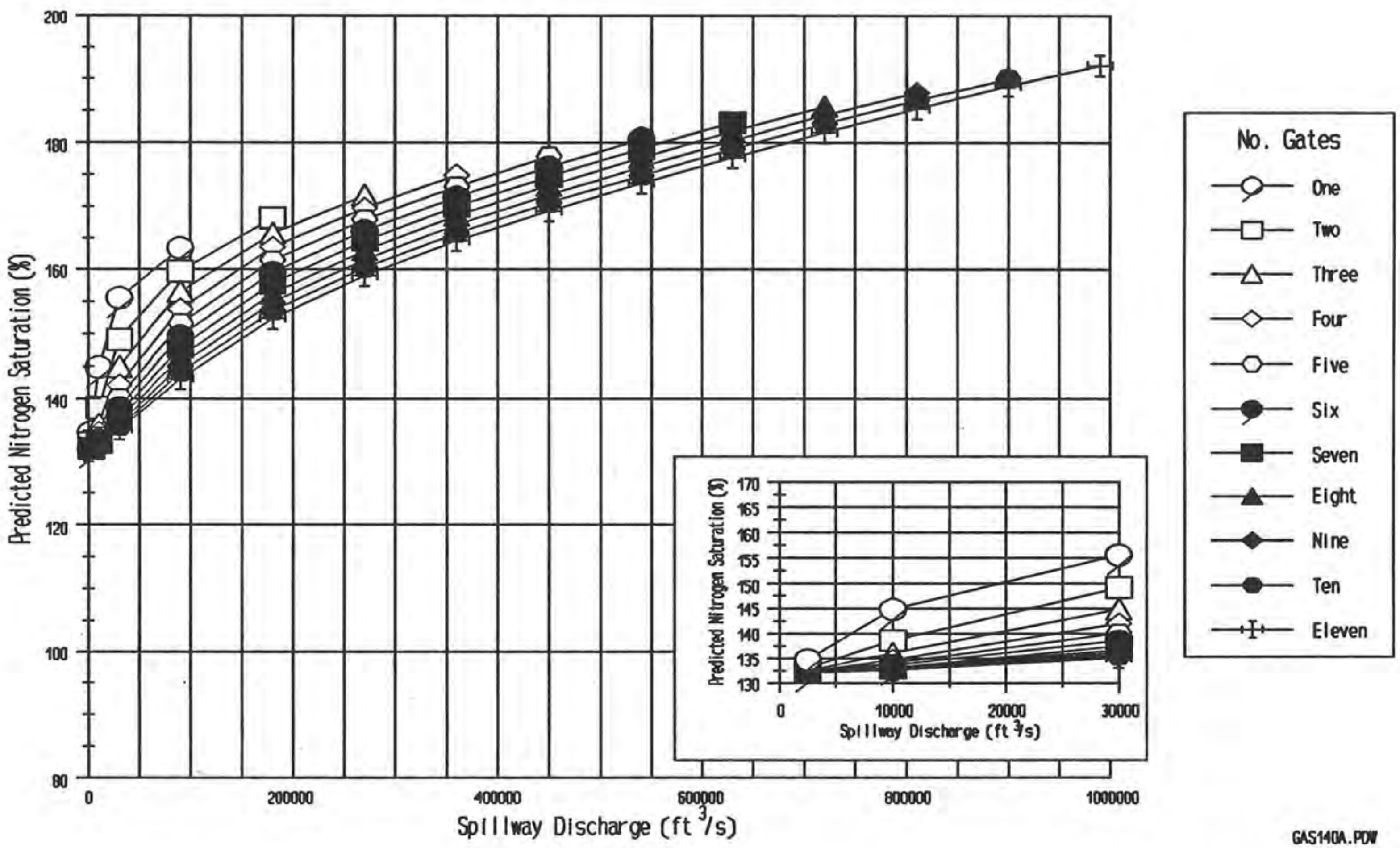

Figure 18. - Predicted dissolved nitrogen saturation for Grand Coulee Dam with the reservoir at 140% saturation and spillway discharges only.

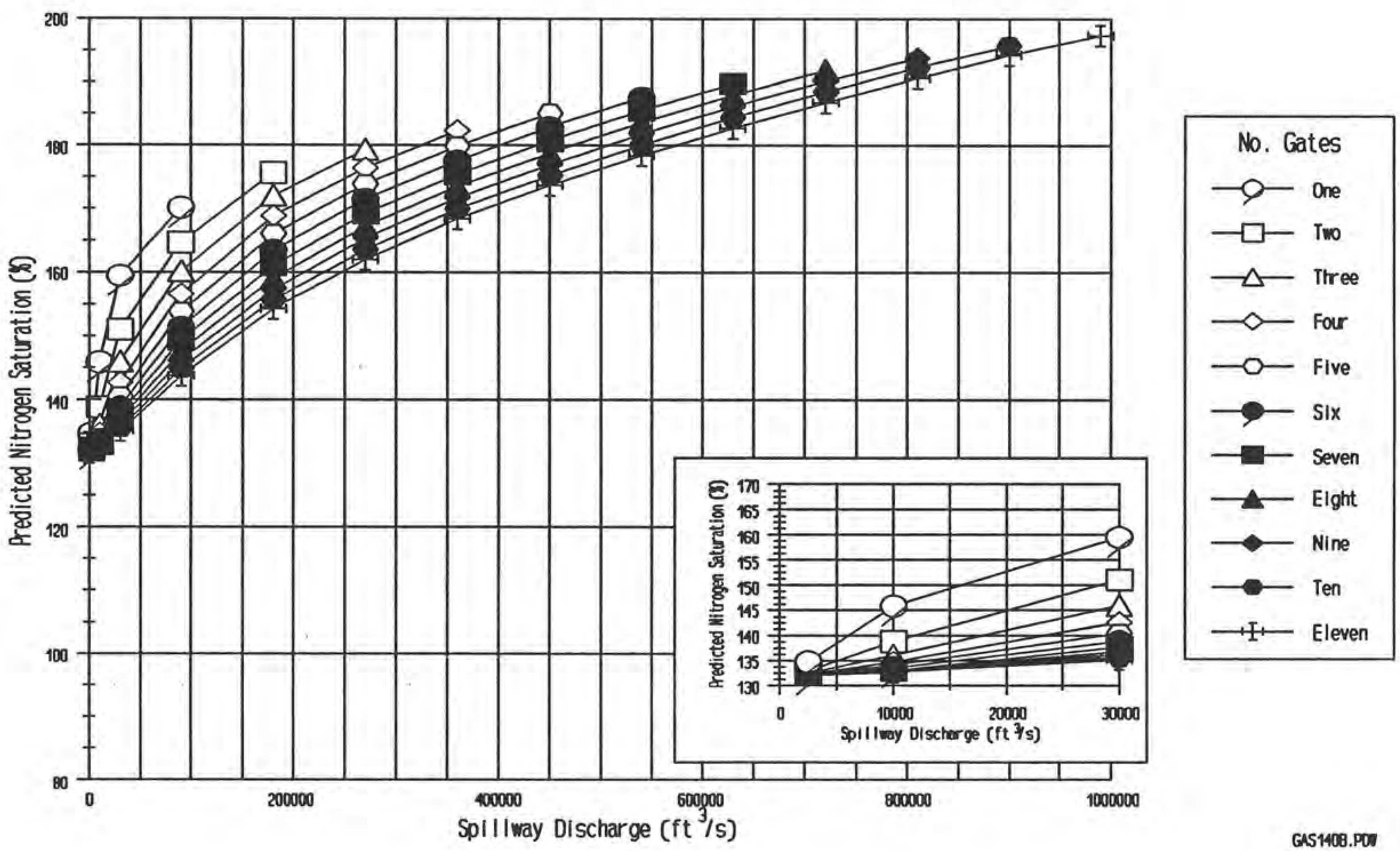

Figure 19. - Predicted dissolved nitrogen saturation for Grand Coulee Dam with the reservoir at 140% saturation and spillway discharges with 280,000 ft^3/s through the powerplants.