The Total Dissolved Gas Abatement Plan

For the

Columbia River and Lower Snake River Corps Projects

March 2010
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I. Introduction

In its operation of the Federal Columbia River Power System (FCRPS) projects, the U.S. Army Corps of Engineers (Corps) is responsible for providing for the authorized project purposes consistent with applicable laws and regulations. The operation of the Corps FCRPS projects has effects on water quality and Endangered Species Act (ESA) listed fish. Accordingly the Corps considers the ecological objectives of the Clean Water Act and the ESA, and complies with the applicable water quality standards to the extent practicable as well conducting operations consistent with applicable Biological Opinions.

The 2008 NOAA Fisheries Federal Columbia River Power System (FCRPS) Biological Opinion (2008 BiOp) relies on spill operations at Corps mainstem projects for listed juvenile salmon and steelhead passage. Currently, the spill operations during the juvenile fish passage season (generally early April into August) at Corps dams are consistent with court-ordered operations and the adaptive management provisions in the 2008 NOAA BiOp as implemented through the Adaptive Management Implementation Plan (AMIP). The intent of the spill operations is to help meet juvenile fish survival performance standards identified in the 2008 BiOp. These fish passage spills may result in the generation of total dissolved gas (TDG) supersaturation in the Columbia and lower Snake rivers at levels above current state and federal water quality standards. The states of Washington and Oregon have authorized exceptions to these standards as long as the elevated TDG levels provide for improved fish passage through the spillway without causing more harm to fish populations than through other passage routes. The purpose of this document is to summarize past, present, and future structural and operational TDG abatement measures as requested by the State of Washington for their water quality standard criteria adjustment.

The Total Dissolved Gas Abatement Plan (TDG Abatement Plan) presents a holistic picture of the Corps’ past and potential efforts in TDG abatement for the Columbia and lower Snake River projects. This report includes an overview of the TDG Exchange Evaluation, operational and structural TDG abatement accomplishments, and identifies future opportunities for further TDG abatement. A TDG Exchange Evaluation was completed for Bonneville, The Dalles, John Day and McNary dams on the lower Columbia River and Ice Harbor, Lower Monumental, Little Goose, and Lower Granite dams on the lower Snake River. Each evaluation includes a series of estimates of TDG exchange properties in the Columbia and Snake rivers as a function of alternative structural configurations, operational policies, total river flow rate, background TDG properties and powerhouse capacity. This comprehensive set of conditions provides a summary of past, present, and potential configurations at each dam and the associated TDG generation and abatement through Corps efforts.

Although significant TDG abatement actions have been implemented, reducing TDG generation through structural and operational alterations can result in greater flexibility in managing spillway releases for improved fish passage. The current emphasis of spilling
water for improved fish passage during the spring and summer migration seasons has resulted in increased spill volumes afforded by recent TDG abatement measures while maintaining the Oregon and Washington TDG water quality standards as defined by the waiver and criteria adjustment. This focus is consistent with the Total Maximum Daily Load (TMDL) reports, addressing TDG in the lower Snake River and the Mid-Columbia River and Lake Roosevelt, which include the Washington Department of Ecology (WDOE) TDG criteria adjustments for fish passage. The Lower Columbia River TMDL, however, targeted fish passage spill in accordance with the waiver and rule adjustment for the first 5 years, and then for the last 5 years, targets 110 percent TDG year round as expressed by the delta total dissolved gas pressure.

II. Background

Actions taken by the Corps to reduce the amount of spill and TDG supersaturation predate the TDG abatement program with the expansion of powerhouse capacities and installation of spillway flow deflectors at many of the projects beginning in the 1970’s. A review of historic operations prior to the completion of upstream dams reveals large amounts of spill were routinely scheduled at projects due to the higher peak system flows with limited power plant capacity.

The Dissolved Gas Abatement Study (DGAS) was initiated in 1994 to examine potential methods for reducing TDG supersaturation produced by spillway operations on the Corps’ dams on the lower Snake and Columbia rivers. Some of the alternatives were promising including the addition or modification of spillway flow deflectors, powerhouse/spillway separation walls, submerged spillway gates, and additional spillbays. These actions were considered to achieve both acceptable fish passage and provide for TDG abatement benefits at significantly less risk and cost than the other alternatives. These other alternatives were found to be detrimental to fish and were therefore not included in recommended future actions. The redesigned baffled chute spillway, side channel spillway, and submerged conduit alternative were found to have the greatest potential of achieving state and federal water quality standards for TDG saturation. However, these alternatives are untested at the large discharges required of mainstem dams and thereby contained an unreasonable degree of uncertainty regarding TDG exchange and safe fish passage conditions. Considering the cost of design and construction of these structures, these alternatives were not considered for further development.

Since 1994, many of the feasible alternatives have been constructed and implemented for TDG abatement at the Corps projects. A summary of these efforts are included in the Accomplishment Section presented later in the report.
III. Water Quality Standards

The Washington State TDG water quality standards criteria states that the TDG saturation shall not exceed 110 percent at any point of collection. However, a TDG criteria adjustment for the Columbia and Snake rivers is also specified to aid fish passage at dams. The criteria adjustment allows TDG saturations based on a moving 12 hour average to not exceed 120 percent in the tailwater of a dam, 115 percent in the forebay of the next downstream dam. A maximum one-hour average TDG saturation of 125 percent is also prescribed.

The Washington Administrative Code also contains other qualifications to the criteria for TDG saturation for natural and irreversible human conditions as contained in Section 173-201A-260. This section identifies the role of natural conditions constituting the water quality criteria where they exceed the numeric criteria.

The natural Columbia River contained several waterfalls and cascades, the most prominent being Celilo Falls, which were natural sources for TDG supersaturation impacting the entire river every day of the year. The bathymetric features of Celilo Falls compares favorably with the natural falls (see footnote) and likely resulted in TDG levels well above 110 percent. These natural sources of TDG supersaturation should be considered in assessing the TDG standards in the Columbia and Snake rivers when the TMDL(s) are revised in the future.1

IV. Flow Frequency Analysis and TDG Exchange Evaluation

In order to provide a comprehensive description of the Corps past and proposed TDG abatement measures in the Columbia and lower Snake rivers, a series of estimates of TDG generation have been developed describing the TDG exchange properties as a function of alternative structural configurations, operational policies, total river flow rate, background TDG properties and powerhouse capacity. This comprehensive set of conditions provides a summary of past, present, and potential future configurations at each dam and the associated TDG exchange properties. This type of analysis also provides a comprehensive comparison of TDG exchange conditions for a controlled system. The estimated TDG exchange for a range of flows up to the seven day moving average with a ten year return period (7Q10) were determined. The base conditions for

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1 Two separate studies have been conducted recently in the Columbia River Basin that quantified the TDG exchange associated with the Willamette Falls on the Willamette River in Oregon and the Kootenai Falls on the Kootenai River in Montana. The TDG levels below the Willamette Falls were found to exceed 130 percent of saturation and at Kootenai Falls the TDG levels were observed to exceed 120 percent of saturation. In both cases, the TDG levels in the free flowing river were observed to remain well above 110 percent for 50 to 90 miles downstream. The bathymetric features of Celilo Falls compare favorable with the Willamette and Kootenai falls.
each project were the structural configurations in 1994 at the beginning of the Total Dissolved Gas abatement program managed by the Corps Portland and Walla Walla Districts. The evaluation of observed TDG data as the sole basis for assessing the progress of a TDG management program is problematic because of the influences from many uncontrolled sources such as the variation in runoff hydrographs, upstream sources of TDG supersaturation, and structural configuration of the dam. This section describes the critical components and associated assumptions used to generate TDG estimates and a summary of key findings from the evaluation. A more detailed description of the evaluation and a series of tables that quantify the TDG exchange properties at each of the dams for past, present, and future structural and operational configurations are contained in the Appendices A-H.

**Powerhouse Capacity**

The powerhouse discharge is an important component in this evaluation because powerhouse releases do not change the TDG content from conditions in the forebay as a general rule. Therefore, a project could be operated without altering the TDG loading in the river up to the hydraulic capacity of the powerhouse. The TDG content of powerhouse releases are generally less than the TDG content generated in spillway releases and can act to dilute the TDG levels in spill outside of the zone of highly aerated flow. The evaluation considered the maximum powerhouse capacity to consist of either all turbines (N) or all turbines less one (N-1) operating at the upper limit of one percent of peak efficiency. The difference between the 7Q10 flows and powerhouse capacity flows determines the largest spillway discharge or critical spillway flow rate for which water quality standards apply. This critical spill discharge ranged from a maximum of 255 kcfs at McNary Dam to a minimum of 92 kcfs at Little Goose Dam. Measures taken to increase the hydraulic capacity or reliability of individual turbines will reduce the magnitude and frequency of the spill discharges and the associated TDG loading.

**7Q10 Flow Evaluation**

The water quality standards for TDG are not applicable for river flows higher than the seven day, ten year frequency flood flow abbreviated as 7Q10. The 7Q10 is the average peak annual flow based on a seven day average flow with a recurrence interval of once every ten years. River conditions associated with flow greater than the 7Q10 flow are exempt from the Washington State water quality standards since it is impossible for dam operators to abate TDG saturation of these natural origin flows.

The 7Q10 flow rate was updated using the data from 1975-2009 and methodology as applied in the Lower Columbia River TMDL for TDG. These analyses determined the mean 7Q10 flows on the Columbia River to be 13 kcfs less than determined in the Lower Columbia River TMDL for TDG. The Snake River 7Q10 flows were estimated to be about 11 kcfs less than previously determined in the Snake River TMDL for TDG. The 7Q10 flow rate identifies the upper flow limit for which Washington State TDG standards are applicable and therefore represents the “worst case” conditions for TDG generation at main stem dams in this analysis. The high river flow conditions generate
high spill events across the entire hydrosystem resulting in the elevation of background TDG pressures generated at upstream dams. These high flow events are both infrequent and short lived and represent only a very small portion of the TDG loading generated by the dams considered in this report. Measures that increase fish survival by reducing the dependence on voluntary spill during most of the fish passage season can result in more sizable reductions in TDG loadings.

**Critical Spillway Discharge**

The evaluation of TDG exchange characteristics for a broad range of conditions can be further characterized by the frequency of occurrence of river flow conditions within and outside of the fish passage season for flows up to the 7Q10 discharge. The critical spillway discharge required to meet Washington State water quality standards for TDG was determined by subtracting the maximum powerhouse hydraulic capacity and auxiliary project flows from the updated 7Q10 discharge for each project as listed in Table 1. McNary Dam has the highest critical spillway discharge of 254.8 kcfs of the four lower Columbia River projects. However, the large length of the spillway at McNary Dam results in a critical specific discharge of 11.6 kcfs/spillbay or only slightly larger than conditions at Bonneville. John Day Dam has a small critical discharge of 110.4 kcfs due to the large powerhouse capacity and the smallest critical specific discharge of 5.5 kcfs/spillbay. The critical discharges on the Snake River were fairly similar ranging from 92.1 kcfs at Little Goose Dam to 109.8 kcfs at Ice Harbor Dam. The critical specific discharges on the Snake River projects were similar to conditions at McNary Dam. The TDG production at all projects except The Dalles Dam is directly proportional to the specific spillway discharge.

**Table 1**

**Critical Spillway Discharge for Lower Columbia and Snake River Projects**

<table>
<thead>
<tr>
<th>Project</th>
<th>7Q10  (kcfs)</th>
<th>Qphmax (kcfs)</th>
<th>Qspcr (kcfs)</th>
<th>Spillbays</th>
<th>Qspcr/Spillbay (kcfs/Spillbay)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BON</td>
<td>454.3</td>
<td>251.9</td>
<td>190.8</td>
<td>18</td>
<td>10.6</td>
</tr>
<tr>
<td>TDA</td>
<td>448.3</td>
<td>284.3</td>
<td>158.1</td>
<td>23</td>
<td>6.9</td>
</tr>
<tr>
<td>JDA</td>
<td>441.4</td>
<td>329.6</td>
<td>110.4</td>
<td>20</td>
<td>5.5</td>
</tr>
<tr>
<td>MCN</td>
<td>433.4</td>
<td>173.9</td>
<td>254.8</td>
<td>22</td>
<td>11.6</td>
</tr>
<tr>
<td>IHR</td>
<td>203</td>
<td>92.4</td>
<td>109.8</td>
<td>10</td>
<td>11</td>
</tr>
<tr>
<td>LMN</td>
<td>203</td>
<td>97.6</td>
<td>105.4</td>
<td>8</td>
<td>13.2</td>
</tr>
<tr>
<td>LGS</td>
<td>203</td>
<td>110.9</td>
<td>92.1</td>
<td>8</td>
<td>11.5</td>
</tr>
<tr>
<td>LWG</td>
<td>203</td>
<td>108</td>
<td>95</td>
<td>8</td>
<td>11.9</td>
</tr>
</tbody>
</table>

7Q10 = The seven day moving average high discharge with a return period of 10 years  
Qphmax = All turbines in operation (kcfs)  
Qspcr = 7Q10 – Qphmax-Qaux  Critical spillway discharge subject to WDOE TDG standards  
Spillbays = Number of spillbays  
Qspcr/Spillbay = Specific Discharge (kcfs/spillbay)
**Excursions Above 110 Percent Saturation**

All projects in this evaluation, assuming fully configured structural and operational TDG actions in place, produce TDG saturations in excess of 110 percent saturation during the 7Q10 river flows which occur during the fish passage season. The critical spill discharge at the 7Q10 flow requires sizable spillway flows (Table 1) generating aerated flow conditions throughout the stilling basin and into the tailrace channel. The estimated spill discharge resulting in tailwater TDG levels of 110 percent were far below the estimated critical spill discharge and below the voluntary fish spill flows.

The critical peak river flows outside of the fish passage season infrequently exceed the maximum powerhouse capacity and require spill discharge which generates TDG levels in excess of 110 percent.

**Excursions Above 120 Percent Saturation**

With the exception of John Day Dam, the critical spill discharge during the 7Q10 flow event generate TDG levels in excess of 120 percent of saturation in the tailwater of each dam for fully configured future structural and operational scenarios in the evaluation. The estimated TDG saturation in spillway releases for the fully configured future scenarios for each project during the 7Q10 spill with powerhouse capacity minus one turbine ranged from 120 percent at John Day Dam to 129.6 percent at Bonneville Dam. The favorable conditions at John Day Dam can be attributed to the large powerhouse capacity and wide spillway with an additional spillway chute. For comparison purposes, all the projects were forecast to achieve a flow weighted average TDG saturation of less than 120 percent at the 7Q10 flow for the fully configured future structural configuration assuming forebay levels of 110 percent.

**Project 2009 Structural Configuration TDG and Flow Summary**

The flow and TDG saturation in the Columbia and Snake rivers at each project was estimated for the 2009 structural configuration for a range of flow conditions, forebay TDG conditions of 115 percent saturation, and with a uniform spill pattern over the spillway with flow deflectors. The frequency of exceeding river flows with forced spill conditions with TDG saturations greater than 110 percent were determined by adding the powerhouse hydraulic capacity (all turbines operating at upper end of 1 percent of best gate efficiency) to the spill capacity as limited by 110 percent saturation in spillway flows within and outside of the fish passage season. The higher river flows are contained within the fish passage season as shown in Figure 1 where the frequency of TDG levels in spillway flows exceeding 110 percent ranged from a low of 5 percent at John Day Dam (JDA) to a maximum frequency of 28.5 percent at McNary Dam. The influence of the limited powerhouse capacity at McNary Dam causes the higher frequency of TDG levels above 110 percent while the large hydraulic capacity at the John Day powerhouse caused the low frequency of TDG levels above 110 percent. The frequency of exceeding 110 percent drops off significantly outside of the fish passage season where the frequency of exceeding 110 percent ranged from 0.3 percent at John Day Dam to 3.8 percent at McNary Dam. Although spillway flows can generate TDG levels in excess of 110
percent outside of the fish passage season at all projects, the frequency of occurrence is low, the duration is limited, and the magnitude of spill will be much smaller than spill during peak river flows.

Figure 1. Frequency of TDG Saturation in Spillway Flows exceeding 110 percent of saturation assuming historic river flows at maximum powerhouse capacity with 2009 structural configuration. (Total River Flow summary 1974-2009)

The frequency of exceedance of river flows with forced spill conditions with TDG saturations in spillway flows greater than 120 percent were determined by adding the powerhouse hydraulic capacity to the spill capacity as limited by 120 percent saturation in spillway flows within and outside of the fish passage season. The flow and TDG saturation in Columbia and Snake rivers at each project were estimated for the 2009 structural configuration for a range of flow conditions, forebay TDG conditions of 115 percent saturation, and with a uniform spill pattern over the spillway with flow deflectors. The higher river flows are contained within the fish passage season as shown in Figure 2 where the frequency of TDG levels in spillway flows exceeding 120 percent ranged from a low of less than 1 percent at The Dalles Dam (TDA) to a maximum frequency of 4.5 percent at Bonneville Dam (BON). The frequency of exceeding 120 percent of saturation in spillway releases at Bonneville, McNary, and Lower Granite dams were similar at about 4 to 4.5 percent which averages out to be about 7 days per year. The frequency of exceeding 120 percent in spillway flows drops off significantly outside of the fish passage season. Bonneville Dam is the only project where the likelihood of TDG levels in spillway flows exceeding 120 percent was clearly greater than zero.
Summary of the TDG Evaluation Findings

Through the TDG exchange evaluation process, several conclusions emerged related to the past and future TDG generation at the lower Snake and Columbia rivers:

- TDG management measures are currently in place for limiting Columbia and Snake River environments to acceptable TDG criteria levels for fish during most of the fish passage season.
- Significant TDG abatement has been accomplished through structural and operational improvements, but limited opportunities are available for further TDG reduction during flood flow conditions.
- Structural and operational alternatives that reduce dependence upon spill to achieve fish passage objectives provide the best opportunities to further reduce TDG loading of the Columbia and Snake rivers.
- TDG abatement measures that increase the spill capacity can provide system-wide TDG abatement benefits when lack of market spill events must be scheduled.
- A spillway training wall can effectively reduce the TDG loading at projects where powerhouse flows are entrained into the aerated spillway when forebay TDG levels are less than TDG pressures generated in spillway releases.

V. TDG Abatement Accomplishments

The Corps is committed to providing fish spill at each main stem project while operating mainstem projects consistent with applicable state water quality standards for TDG
saturation. The general approach of both operational and structural TDG abatement activities focus on limiting the entrainment of air into the water column by project releases, limiting the effective depth of the entrained air, and limiting the water flow rate in direct contact with the bubble plume. Maximizing the powerhouse discharge is generally consistent with minimizing TDG generation but not with optimal fish guidance operations.

A. Operational Accomplishments
A number of operational alternatives have been identified and are currently an important component of managing the TDG levels throughout the Columbia River system. These operational alternatives involve daily spill management, spill patterns, water regulation, powerhouse operations, and system spill operations.

Daily Spill Management
The Total Dissolved Gas Monitoring Plan, submitted to WDOE on January 9, 2009, is a critical component in managing TDG supersaturation in the Columbia River Basin. It is critical that a monitoring system be maintained in both the forebay and tailwater of each dam to provide a comprehensive description of projects impacts on the TDG loading of the Columbia and Snake rivers, provide estimates of the quality of aquatic habitat throughout the fish passage corridor, and identify any excursions above the water quality standards. The location of several forebay fixed monitoring stations (FMS) have been moved to provide a more representative sample of TDG pressures approaching the dam by reducing the occurrence of thermally induced TDG fluctuations. The tailwater fixed monitoring stations have also been moved at several projects to provide a more accurate estimate of TDG exchange in spillway discharges. The TDG instrumentation has been improved and consequently the reliability and consistency of TDG measures have also improved. The quality assurance and maintenance of TDG instrumentation has been standardized and performance records are maintained. The water quality and project operations data have been used to develop a predictive mathematical model of TDG saturation called SYSTDG, which is used as a management tool to forecast TDG on the Columbia and Snake rivers and set daily spill caps.

Spill Patterns
The spillway discharge and distribution of spill over the spillway as defined by the spill pattern, is one of the most important determinants of TDG exchange. As a general rule, the application of a uniform spill pattern over spillbays with flow deflectors minimizes the TDG exchange during a spillway operation. A uniform spill pattern is often not the most effective or efficient operation for fish passage and is not achievable with spillway weirs in place for typical river discharges. For higher river flows spill patterns have been structured to transition to a uniform pattern to minimize TDG generation. The presence of irregular bathymetry directly downstream of the stilling basin may provide an opportunity to minimize TDG exchange by developing a non-uniform pattern.
Water Regulation

The management of water storage on a daily or weekly basis can influence the magnitude and frequency of both voluntary and involuntary spill at federal and non-federal dams on the Columbia and Snake rivers. The scheduling of large discharges from storage reservoirs during high tributary inflows can result in involuntary spill at projects throughout the Columbia River basin. The regulation of the receiving pool elevation can have a significant impact on the tailwater elevation at the upstream project, influencing the spill jet flow regime and depth of aerated flow. System wide water regulation activities are updated on an hourly and daily basis to manage both power generation and voluntary and involuntary spillway operations.

Powerhouse Operations

A number of operational measures associated with hydropower plant operation are available to help manage TDG generation from spill by maximizing powerhouse capacity and setting unit priorities. Scheduling routine turbine maintenance and repair activities during low-power demand and river flow conditions will enable more reliable powerplant operations during high river flows. The identification of priority turbine usage can influence the interaction of powerhouse and spillway flows. This guidance on powerhouse operations can directly influence powerhouse entrainment into the spillway or influence the habitat impacted within the mixing zone of project discharges. At low loading rates, the operation of turbines can in some cases result in the aspiration of air into the turbines resulting in the uptake of TDG. The ability to operate turbines at the upper capacity limits will maximize powerhouse flows and limit involuntary spill.

System Spill Operations

The Spill Priority List is a TDG management plan that has been developed for involuntary spill when river flows or lack of market require spill in addition to voluntary spill. This list calls for adding spill incrementally across all federally owned projects to prevent excessively high TDG levels from being generated in selected river reaches. Excess spill is spread evenly over federal projects to hold peak TDG levels to targeted TDG thresholds in 5 percent increments. This management practice utilizes abatement measures implemented across the system reducing the number of projects required to alleviate the involuntary spill and reduce the overall TDG production in the system. The joint operation of Chief Joseph and Grand Coulee dams has been proposed as a subset of operational measures to manage TDG levels in the Columbia River.

B. Structural Accomplishments

The Corps has constructed a number of structures that have resulted in TDG abatement benefits since the initiation of the TDG abatement evaluation program in 1994. TDG abatement projects on the Columbia and lower Snake rivers include the addition of spillway flow deflectors, spillway training walls, and fish passage improvements including spillway weirs and surface bypass structures. Spillway flow deflectors are recognized as being the most effective means of reducing the TDG production during spillway operations for a wide range of flow conditions. Spillway flow deflectors prevent the turbulent spill jet from plunging to the bottom of the spillway by creating a surface
oriented jet that entrains and transports air bubbles much closer to the water surface. In many cases, specific structural and operational modifications have been implemented in addition to TDG abatement measures to maintain dam safety, navigation, hydropower, flood control, and fish guidance functions. A general overview of the structural and operational TDG abatement improvements for each dam is listed below.

**Bonneville Dam** - Spillway flow deflectors on 6 of the 18 spillbays were designed and built in 2002 and new spill patterns developed to optimize TDG exchange and fish conveyance properties in the spillway exit channel. These updated spillway flow deflectors when coupled with original flow deflectors on spillbays 4-15 resulted in deflectors present in all 18 spillbays. The combined effect of these structural and operational actions resulted in a significant reduction in TDG exchange. Prior to the application of these TDG abatement measures, a spillway release of 100 kcfs generated a TDG saturation of 125 percent and higher compared to 118 percent for current conditions. Improvements to fish passage facilities such as the Bonneville 2nd Powerhouse Corner Collector (B2CC) and juvenile bypass outfall have improved fish passage and survival and reduced the amount of spill required to meet fish passage objectives. Additionally, the TDG fixed monitoring program at Bonneville Dam has been improved by relocating the tailwater monitoring station from a mixed river location to a station directly measuring the TDG levels in undiluted spillway flows.

**The Dalles Dam** – The Dalles Dam remains the only Corps project without spillway flow deflectors. Shallow bathymetry characteristics immediately below the spillway moderate TDG generation during spillway flows but also limit the potential effectiveness of spillway flow deflectors. The Dalles Dam is equipped with a spillway training wall between spillbays 6 and 7 and a newly constructed extended wall located between spillbays 8 and 9 was completed in 2010. Although the extended wall was primarily built to improve fish passage and survival, the impacts on TDG exchange were factored into the design and operation. Efforts to improve fish passage at The Dalles Dam have resulted in a reduction on the reliance of spill for fish passage from over 60 percent spill in years past to the current spill operations of 40 percent of the total river flow. This reduction in voluntary spillway flows has resulted in reductions in TDG saturation as measured at the tailwater fixed monitoring station from 120.0 to 116.9 percent saturation for a total river flow of 250 kcfs and background TDG saturation of 110 percent.

**John Day Dam** – A number of structural and operational alternatives have been implemented at John Day Dam to reduce TDG supersaturation in spillway flows. Construction of spillway flow deflectors was completed in 1998 on 18 of the 20 spillbays (2-19) and new spill patterns developed. Prior to the addition of spillway flow deflectors, spillway flows of 100 kcfs at John Day Dam generated TDG levels of 135 percent saturation compared to current levels of 118 percent when spilling 100 kcfs. The addition of spillway flow deflectors allowed for higher volume fish spills subject to the TDG criteria adjustments. A surface bypass program at John Day Dam is underway and includes the addition of two spillway weirs that are designed to improve fish passage while maintaining effective skimming flow throughout the tailrace channel for TDG abatement. An extended spillway flow deflector is also under construction at John Day
Dam in spillbay 20 and is scheduled for completion during the 2010 fish passage season providing additional TDG gas abatement improvements.

**McNary Dam** – A total of four new spillway flow deflectors were installed in spillbays 1, 2, 21, and 22 at McNary Dam in 2001 to complete the full installation of this TDG abatement measure. The development of spill patterns utilizing all 22 spillbays resulted in a reduction of TDG supersaturation during both voluntary and involuntary spill conditions. Distributing the spill uniformly over 22 spillbays, instead of 18, reduced the TDG generation associated with a spill of 100 kcfs from 114.6 percent to 112.8 percent. The spill capacity as limited by the tailwater TDG criteria increased by about 37 kcfs as a result of the adding four new flow deflectors. Four new gate hoists were also added to the spillway to allow automated gate changes to the entire spillway. The new flow deflector also included a turning radius to allow for a smoother hydraulic transition from the spillway to stilling basin. A surface bypass program at McNary Dam includes the addition of two spillway weirs that are designed to improve fish passage. The non-uniform spill pattern associated with these spillway weirs has not significantly influenced the spill capacity as limited by tailwater TDG criteria.

**Ice Harbor Dam** – Prior to the TDG abatement program, spillway flows of 50 kcfs at Ice Harbor Dam resulted in TDG saturations of 135 percent and higher. Spillway flow deflectors were installed on all ten spillbays over a three year period from 1997-1999 resulting in significant reductions in TDG generation. Spillway releases of 50 kcfs today can result in TDG saturations as low as 113 percent of saturation. Spillway flows as high as 95 kcfs can be maintained at Ice Harbor Dam subject to the TDG tailwater criteria adjustment of 120 percent. Additional structural modifications to the spillway and downstream lock approach were required in conjunction with spillway flow deflectors to provide for suitable flow conditions for navigation and fish passage concerns. A spillway weir was designed and put into operation in 2005 for the purpose of improving fish passage while maintaining effective TDG abatement flow conditions in the tailwater channel. Currently, voluntary spillway flows at Ice Harbor Dam generate the lowest TDG levels of the eight dams included in this study as a consequence of the efficient skimming flow caused by flow deflectors and the shallow tailrace channel properties.

**Lower Monumental Dam** – The original spillway at Lower Monumental Dam contained spillway flow deflectors on 6 out of the 8 spillbays. The spill patterns were revised during the TDG abatement program to restrict spill to spillbays with flow deflectors resulting in a doubling of the spill capacity as limited by the tailwater TDG criteria. Spillway flow deflectors were added to the end spillbays for the 2004 fish passage season. The addition of two new flow deflectors resulted in an updated spill patterns using the entire spillway causing a reduction in TDG saturations from 132.1 to 118.2 percent for a spillway discharge of 50 kcfs. A spillway weir was put into service at Lower Monumental Dam for the 2008 fish passage season. The “bulk” spill pattern resulting from the high discharge through the spillway weir and associated training spill does increase the TDG generation for voluntary fish spill but the influence of the spillway weir on TDG generation dissipates at high spillway flows.
Little Goose Dam – Two new spillway flow deflectors were built at Little Goose Dam in 2008-9 to complete spillway flow deflector development across the entire spillway. The updated deflector designs included a longer deflector with a 25 ft radius toe curve to support safe juvenile fish passage. The flow deflectors were built in conjunction with a spillway weir designed to support downstream fish passage. The additional spillway flow deflectors will provide for TDG abatement during involuntary spillway releases. The additional spillway flow deflectors and updated spill patterns are estimated to produce TDG saturations of 121.1 percent during an involuntary spill of 64 kcfs compared with 131.5 percent for a uniform spill without the end spillbay deflectors. The spillway weir was put into service for the 2009 fish passage season. The “bulk” spill pattern resulting from operation of the spillway weir at Little Goose Dam was found to generate higher TDG levels when compared to a uniform pattern over the seven spillbays with a spillway weir.

Lower Granite Dam – Lower Granite spillway was built with spillway flow deflectors designed to minimize the production of TDG supersaturation during spillway releases. Lower Granite Dam is unique in that the background TDG levels remain at 110 percent or less for all flow conditions. In 2001, a spillway weir and spill pattern were designed and implemented to effectively guide fish during voluntary spill events while minimizing the generation of TDG pressures during involuntary spill conditions. The introduction of the spillway weir reduced the dependence on spillway flows to aid fish passage. Previous fish spill policies at Lower Granite Dam called for spilling as much water as possible, generally 40 to 50 kcfs, without exceeding the tailwater TDG criteria. The current voluntary spill operation is a fixed discharge of 20 kcfs. The TDG loading impacts of this new spill operation change were significant reducing the average TDG saturations in the Snake River below Lower Granite Dam from as high as 115.4 percent to 110 percent.

Chief Joseph Dam - The Chief Joseph Dam total dissolved gas abatement report recommended that spillway flow deflectors be implemented in combination with joint operations with Grand Coulee Dam. The spillway flow deflectors were completed in October of 2008 on all 19 spillbays. The field evaluation of the TDG exchange performance was conducted in April and May of 2009 with the final report describing the test results and proposed joint operations policy scheduled to be completed during the summer of 2010. The spill capacity as limited by the tailwater TDG criteria of 120 percent was limited to 32 kcfs prior to the addition of spillway flow deflectors. The preliminary finding post flow deflector installation indicates a three to four fold increase in the spillway capacity as limited by the tailwater TDG criteria. The difference between the hydraulic capacity of the Chief Joseph Dam powerhouse and the 7Q10 flow was only about 41 kcfs. A spill of 41 kcfs uniformly distributed across the spillway was found to generate TDG levels that fell well below the TDG standards. The joint operating policy aimed at more effective management of TDG supersaturation at Grand Coulee and Chief Joseph dams can limit outlet works operations in favor of generation with additional spill scheduled at Chief Joseph Dam.
Results of Increased Spill Capacity Due to Implementation of Spill Deflectors

The addition of spillway flow deflectors has been the primary structural alternative employed to abate TDG generation at Corps projects on the Snake and Columbia rivers. Since the initiation of the Corps gas abatement program in 1994, 14 flow deflectors were added to the Snake River projects for a 70 percent increase in the number of spillbays with flow deflectors. On the Columbia River, a total of 29 flow deflectors were added for a 93 percent increase in spillbays with flow deflectors.

A summary of the spill capacity as limited by the tailwater TDG criteria of 120 percent before and after the installation of spillway flow deflectors is listed in Table 2. The conditions in 1995 assumed the structural configuration and spill patterns applied at that date. The updated conditions in 2009 reflect the application of a uniform spill pattern without the impacts of spillway weirs. This scenario reflects the ideal conditions upon which to minimize the generation of TDG supersaturation. The addition of these flow deflectors has increased spill capacity from 219 kcfs in 1995 to 815 kcfs in 2009.

<table>
<thead>
<tr>
<th>Project</th>
<th>Qsp @ 120%</th>
<th>Qsp @ 120%</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bonneville</td>
<td>0</td>
<td>120</td>
<td>6 new deflectors for a total of 18</td>
</tr>
<tr>
<td>John Day</td>
<td>65</td>
<td>150</td>
<td>18 new deflectors</td>
</tr>
<tr>
<td>McNary</td>
<td>140</td>
<td>190</td>
<td>4 new deflectors</td>
</tr>
<tr>
<td>Ice Harbor</td>
<td>23</td>
<td>95</td>
<td>10 new deflectors</td>
</tr>
<tr>
<td>Lower Monumental</td>
<td>34</td>
<td>60</td>
<td>2 new deflectors</td>
</tr>
<tr>
<td>Little Goose</td>
<td>25</td>
<td>60</td>
<td>2 new deflectors</td>
</tr>
<tr>
<td>Chief Joseph</td>
<td>32</td>
<td>100</td>
<td>19 new deflectors</td>
</tr>
<tr>
<td>Total</td>
<td>219</td>
<td>815</td>
<td></td>
</tr>
</tbody>
</table>

* Assumes uniform pattern without spillway weirs

IV. Future Opportunities for TDG Abatement

There are limited structural alternatives available to significantly change TDG levels in spillway flow below the dams during the 7Q10 flow event. Modification of spillway flow deflectors targeting these high flow events may provide for small improvements in TDG generation but would likely prove to be counter productive during voluntary spill conditions. The development of spillway training walls can impact the cross sectional average TDG pressures at some projects but have little impact on TDG levels generated in spillway flows. The expansion of the spillway capacity through additional chutes or
spillbays may also have relatively small impacts because of the large size of existing spillway structures compared to an additional channel. Measures taken to increase the hydraulic capacity of the powerhouses of any of the projects evaluated in this study may have a small impact on critical spill magnitude and the resultant TDG pressures. Any resources devoted to attaining TDG criteria adjustments at these projects during the 7Q10 flows must consider the infrequent nature of these events (once in ten years) and relative habitat impacts.

The prospects for lowering TDG pressures throughout the Columbia and Snake rivers during voluntary flow conditions appear to be more attainable and of potentially greater habitat value given the frequency of these events. The alternative that holds the greatest promise involves developing more efficient and effective fish passage conditions at each dam. These fish passage improvements include spillway weirs and alternative spillbays that are designed to reduce the reliance on spill to meet fish passage objectives without adversely changing the TDG exchange properties at a given project. The spillway flow deflector alternative can be considered fully developed with the completion of the extended deflector in spillbay 20 at John Day Dam in 2010. Any improvement in flow deflector performance may involve changing the toe curve to provide safer fish passage conditions or modifying the elevation of the deflector to optimize skimming flow conditions. A spillway training wall can provide significant improvements in the TDG loading released from projects where powerhouse flows are entrained into the aerated flow conditions in the stilling basin and adjoining tailwater channel. These improvements can reduce the TDG levels arriving at the next downstream dam which frequently limits spill level during spring flows.

**Spillway Flow Deflectors**

The effectiveness of spillway flow deflectors has been consistently demonstrated at nearly all the Corps projects on the Columbia and Snake rivers. Spillway flow deflectors commonly referred to as flip lips, redirect the spill jet from a plunging flow that transports air bubbles deep into the stilling basin to a horizontal jet that maintains entrained air much closer to the water surface. The effectiveness of spillway flow deflectors can be enhanced through altering the orientation, length, submergence, toe curve transition, flow distribution, and depth of the tailrace channel. The adjoining spillway weirs and training walls can have a significant impact on the developing flow field in the tailrace channel and resultant TDG exchange. The reduction in TDG generation associated with spillway flow deflectors may provide significant TDG abatement benefits during forced spill operations and provide for greater operational flexibility during involuntary river flows.

**Spillway Training Wall**

The powerhouse operations transport water from the forebay without altering the TDG content with few exceptions. The TDG content in powerhouse releases is often considerably less than generated in spillway releases. However, the TDG content of powerhouse flow can quickly change when it becomes entrained into the highly aerated
flow conditions in the stilling basin and adjoining tailwater channel. The TDG levels in this entrained powerhouse flow can quickly become indistinguishable from the TDG levels in spillway flows due to the abundance of entrained air and large applied hydrostatic pressures. The TDG abatement benefits of a spillway training wall involve preventing the entrainment of powerhouse flows into highly aerated and turbulent spillway releases. A training wall may preserve most of the lower TDG attributes of powerhouse releases to dilute the higher TDG levels generated in spillway flows as the mixing zone between these releases develop in the tailwater channel below the zone of bubbly flow.

The entrainment of powerhouse releases into aerated spillway flows has been observed at many of the main stem dams on the Columbia and Snake rivers. The entrainment volume can equal the entire powerhouse release as total river and spill flows increase. The entrainment of powerhouse flows is particularly important at the four Snake River dams. Complete entrainment of all powerhouse flows can be accomplished under some conditions while spilling as little as 40 percent of the total river flow at these projects. The TDG abatement benefits of a spillway training wall can be most evident in the cross sectional average TDG pressures in the river and in the residual TDG pressures arriving at the next downstream dam. However, this alternative may have little to no effect on the TDG levels observed in spillway flows and at the tailwater fixed monitoring station. The influence of a spillway training wall on TDG abatement can be effective at the Snake River dams when forebay TDG pressures are below TDG levels generated in spill. A large forebay to spillway TDG differential may present greater TDG abatement benefits associated with a spillway training wall when significant entrainment of powerhouse flows are present. A training wall may result in the largest TDG reduction at Lower Granite Dam where forebay TDG levels always remain less than 110 percent. The cumulative increase in TDG levels on the Snake River, where a significant component of the river is spilled at each dam, can incrementally lessen the benefits of a training wall.

Additional Spillways

The construction of additional spillbays or bypass chutes was determined to be a feasible alternative in the DGAS program. An added spillway could be designed to draw surface waters from the forebay and maintain a horizontal spill jet trajectory at a modest specific discharge in the tailwater. The added spillway capacity would allow for spill to be distributed over a wider distance in the tailwater at less energy and a smaller potential to entrain and transport air to depths in the stilling basin. These conditions can reduce the TDG pressures associated with spillway flows. Although this option has been considered viable for TDG reduction, it is an expensive alternative and justification would depend upon the added biological benefits for fish passage. Grant County PUD has designed and built an auxiliary spillway chute at Wanapum Dam with a 20 kcfs capacity that demonstrated moderate levels of TDG exchange safely below tailwater TDG criteria.
Fish Passage Improvements

Structural and operational measures designed to achieve BiOp biological performance standards may also result in a smaller commitment to spill in achieving the water quality standards. These potential changes in fish spill operations towards lesser spill may reduce the TDG loading and further minimize TDG effects on fish during voluntary flow regimes.

Surface passage facilities are increasingly used to provide more natural river passage conditions, improve juvenile fish survival, reduce fish delay in the forebay, improve water quality and potentially spill less water. Most juvenile salmon tend to stay in the upper 10 – 35 feet of the water column as they migrate downstream to the ocean. Spillway weirs use new technologies to provide more surface-oriented, less stressful passage routes for juvenile fish. Juvenile bypass systems guide fish away from turbines by means of submerged screens installed in front of the turbine intakes. As fish follow currents down toward the turbines, the screens guide the fish back up to channels in the dam. The fish are then either routed to the river below the dam or loaded into barges or trucks for transport. Although bypass systems are in operation at seven of the eight lower Columbia and Snake River dams, modifications to these systems are ongoing to improve fish survival.

Programs designed to improve fish survival through turbines, predatory removal programs, surface bypass improvements, tailwater egress operations or structural modification, and behavioral guidance barriers are just several of the areas where significant improvement to fish passage have been demonstrated. For example, fish spill operations at The Dalles Dam previously called for spilling over 60 percent of the instantaneous flow in the Columbia River during the fish passage season, as compared to the current operation of spilling 40 percent of the flow. Because the commitment to fish spill makes up the majority of the TDG loading produced at mainstem dams during the course of the year, small reductions in the reliance on spill to guide fish can translate into sizable reduction in the TDG loading when integrated over the entire year.

Future TDG Abatement Opportunities by Project

The prospects for further improvements in reducing the TDG loading at each project through structural and operational measures are discussed below.

A. Bonneville Dam

The modification of spillway flow deflectors for the interior spillbays 4-15 may have a small TDG abatement benefit by providing optimal performance over a wider range of flow conditions. Incremental improvements in fish passage facilities and operations can lead to a smaller reliance on spill to meet fish passage standards. Moving away from a fish spill operation determined by the spill capacity as limited by the tailwater TDG rule adjustment can lower the TDG loading to the Columbia River.
B. The Dalles Dam
The addition of the spillway training wall located between spillbays 8/9 and the revised spill pattern concentrating spill to the northern end of the spillway may modify the hydraulic flow field defining the TDG exchange characteristics at this project. The TDG exchange performance of this structure and spill patterns is scheduled to be evaluated and TDG management activities adjusted accordingly. The development of additional structural and operational actions improving fish passage can lead to a smaller reliance on spill. The implementation of system-wide TDG management practices (e.g. spill priority list) can reduce the scheduled spillway flows at high river flows given the large hydraulic powerhouse capacity at The Dalles Dam.

C. John Day Dam
The completion of a 19th flow deflector in spillbay 20 at John Day Dam is likely to result in an increase in the critical spill discharge generating TDG levels at 120 percent while providing improved juvenile egress conditions in the tailrace channel. The powerhouse at John Day Dam has the largest hydraulic capacity of any of the federal dams on the Columbia River and smallest critical spillway discharge at the 7Q10 river flow of 110 kcfs. The TDG exchange associated with uniform spill over 18 spillbays as high as 180 kcfs have been observed to generate TDG levels at 120 percent and less at John Day Dam. The model estimates of TDG generation at John Day with the additional completed spill deflector in spillbay 20 at the 7Q10 river flow were slightly above (4 mm Hg) the 120 percent criteria but fall well within the confidence limits of the TDG generation model. The TDG monitoring of future spill activities at John Day Dam with the new structural configuration should continue to document TDG generation and attainment of TDG standards.

D. McNary Dam
The powerhouse at McNary Dam has the smallest hydraulic capacity of any of the Federal Dams on the Columbia River and largest critical spillway discharge at the 7Q10 river flow of 255 kcfs. Increasing the hydraulic capacity of the McNary powerhouse through upgrading turbines can lower the forced spill at the 7Q10 river flow to about 189 kcfs with an estimated TDG saturation in spillway flow undiluted by powerhouse releases of 120.9 percent. It is reasonable to assume that this structural configuration of McNary Dam may consistently generate TDG levels at or below the WDOE standards given the uncertainty in the 7Q10 flows and the modeled TDG exchange relationship. Expanding the capacity of either the ice and trash sluiceway or powerhouse surface bypass channel would result in a small increase in TDG loading for voluntary spill conditions provided the commitment to spillway flows does not change. However, these measures can provide for a substantial reduction in TDG loading for voluntary spill operations if they result in a fish spill operation that relies on smaller volumes of spill.
E. Ice Harbor Dam

The spill capacity at Ice Harbor Dam as limited by the tailwater TDG criteria is the largest of the eight projects evaluated in this study when taking into account the spillway size. A component of the fish spill operation at Ice Harbor involves “spilling to capacity at 120 percent” which can result in spilling nearly the entire river during moderate to low river flows. The greatest potential to reduce the TDG involves reducing the reliance on spill to guide juvenile salmonids. Alternative structural configurations are being considered at Ice Harbor to provide for more effective and efficient fish guidance flows. A powerhouse surface bypass channel may generate TDG levels that are locally higher than existing conditions due to the higher specific discharges of these passageways. However, if this structure proves to be successful in safely and efficiently passing juvenile salmonids, the reliance on spill could be greatly curtailed. For a total river flow of 100 kcfs, reducing the reliance on spill from a “spill to capacity at 120 percent” to “spilling 45 percent” would result in reducing spill from about 90 kcfs to 45 kcfs and average TDG levels downstream from 117.6 percent to 113.6 percent. These structural measures may have minimal impact on TDG exchange during involuntary spill conditions.

F. Lower Monumental Dam

The critical spill discharge at Lower Monumental Dam is the largest of the eight project considered in this study when factoring the size of the spillway. The highly variable and non-uniform spill pattern at Lower Monumental Dam can produce TDG levels that approach and exceed TDG limits at the tailwater and downstream forebay monitoring stations for modest spillway discharges as low as 27 kcfs. The entrainment of powerhouse flows is an important component shaping the TDG loading at Lower Monumental Dam. The addition of a spillway training wall could provide significant reductions in the TDG loading (over 5 percent saturation) to the Snake River when forebay TDG levels are well below the TDG generated in spillway flows. The addition of a powerhouse surface bypass channel at Lower Monumental Dam will be an additional source of TDG supersaturation but can lower the TDG loading by reducing the reliance on spillway flows for fish passage. A change in fish spill operation away from spilling at capacity to 120 percent could reduce the TDG loading during voluntary spill operations at Lower Monumental Dam.

G. Little Goose Dam

The spill at Little Goose Dam was estimated to generate TDG saturations of 127 percent during the maximum spill during the 7Q10 river flow as currently configured with 8 deflectors with a spillway weir. A spillway training wall could be designed to eliminate most of the entrainment of powerhouse flows. This may significantly reduce the cross-sectional average TDG when forebay levels are significantly less than the TDG content in spillway releases. A spillway training wall could provide greater TDG reduction benefits at Little Goose Dam compared to the downstream projects because of lower background TDG levels and the strong interaction of powerhouse releases and aerated spillway flows.
The addition of a powerhouse surface bypass channel could reduce the reliance on spillway flows for fish passage.

H. Lower Granite Dam

The positioning of Lower Granite Dam on the Snake River far removed from potential upstream sources of TDG supersaturation results in low background TDG levels. The entrainment of powerhouse flows into aerated spillway releases are routinely observed below Lower Granite Dam. A training wall separating the powerhouse and spillway flows could have a large impact on TDG loading in the Snake River at Lower Granite Dam particularly during higher river flows requiring involuntary spill. For a 7Q10 river flow the training wall can cut the uptake in TDG saturation in half compared to current conditions if forebay levels are 110 percent or saturation or less. The current operation and configuration consisting of 8 deflectors and a spillway weir are estimated to generate TDG levels of 129 percent saturation when spill is required during the 7Q10 flood flow. The addition of a spillway training wall is not expected to influence the TDG content in spillway releases but will impact the average flow weighted TDG saturation released into the Snake River and the residual TDG saturation arriving at Little Goose Dam.

VII. Conclusion:

The implementation of structural and operational alternatives has steadily made headway over the past 15 years to reduce the impacts of project operations on TDG supersaturation in the Columbia and Snake rivers. Considering that significant TDG abatement has been accomplished through structural and operational improvements, limited opportunities are available for further TDG reduction. The Corps is committed to providing spill for ESA listed fish passage at the mainstem projects while operating the projects consistent with applicable state water quality standards for TDG saturation to the extent practicable. The future goals include seeking incremental reductions in TDG through continued development of structural and operational improvements for fish passage and survival that reduce the dependence upon spill. Through this evaluation these actions were demonstrated to provide the best opportunities for further TDG abatement.

In addition, the TDG exchange evaluation illustrated that achieving the TMDL(s) goal of 110 percent TDG outside of the fish passage season is not achievable during high flows, but meeting 115/120 percent TDG during fish passage season is feasible. The Corps of Engineers is committed to working with the states of Washington and Oregon to evaluate how the TDG abatement actions have aligned with the implementation plans identified in the three TMDLs addressing TDG in the Columbia River Basin and determine if additional actions are appropriate.