LIBBY DAM TOTAL DISSOLVED GAS MANAGEMENT STUDY INITIAL APPRAISAL REPORT

Libby Dam
Libby, Montana

30 September 2005

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ACRONYMS AND ABBREVIATIONS

BiOp	Biological Opinions
BPA	Bonneville Power Administration
CEERDC	[U.S. Army] Corps of Engineers, Engineer Research and Development Center
CENPD	[U.S. Army] Corps of Engineers, North Pacific Division (now Northwestern Division)
CENWP-NWW -NWP -NWS	[U.S. Army] Corps of Engineers, Northwestern Division, Engineer District Portland, Engineer District Walla Walla, and Engineer District Seattle
cfs	cubic feet per second
DEQ	Montana Department of Environmental Quality
DGAS	Dissolved Gas Abatement Study
^{o}F	degrees Fahrenheit
Forebay	The area of a reservoir immediately upstream of a dam
GBT	gas bubble trauma
kcfs	1,000 cubic feet per second
NGVD	National Geodetic Vertical Datum
PMF	Probable Maximum Flood
Sluiceway	low level regulating outlets through a dam
Spillway	A structure that facilitates flow over a dam
Stilling basin	The apron at the toe of a dam designed for dissipating spillway/sluiceway flow energy
T/E	threatened or endangered [species]
Tailrace	The area of river immediately downstream of a dam
Tailwater	Refers to the elevation of the water surface below a dam
TDG	total dissolved gas
USACE	U.S. Army Corps of Engineers
USBR	U.S. Bureau of Reclamation
USFWS	U.S. Fish and Wildlife Service
USGS	U.S. Geological Survey
VARQ	Variable Discharge Flood Control Operation
WES	(Corps of Engineers) Waterways Experiment Station (Now CEERDC)

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EXECUTIVE SUMMARY

The Libby Dam Project is a multi-purpose project authorized to provide both local and system-wide flood control, power generation, and other uses including recreation. The project powerhouse has five installed generating units with a maximum discharge capacity of approximately 25,000 cfs. In addition, the powerhouse has three unused penstocks/skeleton bays where turbines are installed without the electrical power generating components. The project also has three low-level regulating outlets and a two-bay spillway. The powerhouse and sluiceways are available for use at all operating-range pool levels while the spillway is usable at pool levels above elevation 2,405 feet.

Under normal operation, water can be discharged through the powerhouse without appreciably adding to the total dissolved gas (TDG) level of the reservoir forebay. All discharges through the powerhouse are generally well below the Montana water quality maximum for TDG of 110 percent saturation. When either the sluiceways or the spillway are used, the flow through or over these structures becomes highly aerated. The plunging action of these flows into the stilling basin causes TDG levels below the project to rise to levels which exceed the Montana maximum level of 110 percent saturation. Given this, the project is operated such that use of the sluiceways and/or the spillway is minimized.

The U.S. Fish and Wildlife Service (USFWS) 2000 Biological Opinion (BiOp) (USFWS 2000) recommends, at RPA 8.2.a, that the Seattle District, U.S. Army corps of Engineers (Corps) release up to 5,000 cfs in addition to the maximum powerhouse discharge, resulting in a total project discharge of approximately 30,000 cfs, while staying under a TDG saturation level of 110 percent. The BiOp further recommends at RPA 8.2.a.6 that, by spring of 2007, the Corps be prepared to release 10,000 cfs of additional flow for a total project discharge of approximately 35,000 cfs. Under existing conditions, this would require use of the spillway or sluiceways at Libby Dam, which leads to TDG supersaturation in the river below the project exceeding Montana state standards and the 2000 USFWS BiOp criterion of 110 percent.

In response to the 2000 BiOp RPA, the Corps initiated this study to identify and evaluate a comprehensive group of structural and operational alternatives. This study presents a preliminary overview of possible options for providing this additional flow while managing TDG levels; it does not evaluate whether additional flows of this magnitude are sufficient and necessary, nor does it determine that it is reasonable and prudent to provide such flows.

This initial appraisal of potential total dissolved gas (TDG) management alternatives for Libby Dam indicates that should additional flows of the magnitude described in the USFSW BiOp be determined to be reasonable and prudent, those alternatives which pass flow through the dam under a pressurized flow regime, such as occurs currently through the powerhouse, should be explored further. Assuming that air entrainment can be minimized and forebay levels of saturation are below 110 percent, this type of flow regime appears to provide the most certain means of keeping dissolved gas levels in the river below the dam within the Montana water quality standard maximum of 110 percent saturation. Controlling discharge temperatures of powerhouse releases via the project's selective withdrawal system has been an important part of project operations, and the pressure-flow alternatives which utilize one or more of the unused penstock/skeleton bay structures would merit further study in the event additional flow were determined to be warranted. This study evaluated three pressure-flow alternatives. Two of these alternatives involve commissioning two additional turbines to transmit electrical energy to either the grid or to onsite load banks. The third alternative involves the conversion of one or more of the unused penstocks to regulating outlets.

Alternatives which involve modification of the spillway and/or sluiceways might warrant further study if the point of compliance for dissolved gas levels was located some distance downstream of the project or if the 110 percent saturation standard was relaxed. Such alternatives include the installation of flow deflectors on the sluiceways and/or spillway.

Finally, alternatives that do not reduce the amount of dissolved gas generated but may allow higher degassing rates, improved dilution, or shorter mixing zone length than the existing condition are evaluated.

The alternatives considered in this study are as follows:

Alternative 1: Existing Condition (no changes)

Alternative 2: Spillway/sluiceway flow deflectors

Alternative 3: Spillway/sluiceway flip bucket

Alternative 4: Tailwater mixing structure

Alternative 5: Side channel and spillway

Alternative 6: Baffled chute spillway

Alternative 7: Raised stilling basin floor

Alternative 8: Raised tailrace channel

Alternative 9: Modification of sluiceway outlets

Alternative 10: Siphon/dedicated pressure flow system

Alternative 11: Penstock/draft tube conversion to a regulating outlet

Alternative 12: Additional generating units transmitting power to grid

Alternative 13: Additional generating units using load banks

Alternative 14: Extension of right (west) stilling basin wall

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INTRODUCTION

The operation of Libby, Hungry Horse, and Grand Coulee dams for flood control and hydropower benefits has altered the natural river hydrology of the Columbia River Basin. These reservoirs are drawn down in the winter to provide space for spring runoff. The filled reservoirs provide a water source for power production in the fall and winter, as well as recreational activities. According to the U.S. Fish and Wildlife Service (USFWS), Kootenai River white sturgeon require high spring flows, which historically were provided by spring snowmelt runoff. The USFWS has recommended changes in water control policy providing for higher spring flows for the conservation and recovery of Kootenai River white sturgeon, as outlined in their 2000 Biological Opinion (BiOp) for operation of the Federal Columbia River Power System (USFWS 2000).

Currently, depending on the April to August forecast inflow volume to Lake Koocanusa, a variable volume of water is allocated for sturgeon flows each year. In a year with a low April to August inflow forecast, there might be no volume available to be allocated for sturgeon. Through a System Operation Request (SOR), the USFWS coordinates the start date and duration of these releases each spring before the sturgeon flow operation commences. Historically the maximum flow provided for sturgeon has been the maximum flow that can be provided by the powerhouse, which is roughly 25,000 cfs. Flows for sturgeon have been provided in this manner since 1991, and since this time there apparently has not been any increase in the recruitment of juvenile sturgeon.

The 2000 USFWS BiOp directed the Corps to be prepared to release, by spring 2004, up to 5,000 cfs in addition to the maximum powerhouse discharge, resulting in total project discharge of approximately 30,000 cfs, while staying within a total dissolved gas saturation level of 110 percent, as required by the Montana Department of Environmental Quality (DEQ). By the spring of 2007, the BiOp recommends that the Corps be prepared to release up to 10,000 cfs for a total project discharge of approximately 35,000 cfs. With the current powerhouse capacity at Libby Dam of roughly 25,000 cfs, the only existing options for physically discharging an additional 10,000 cfs would be to send the water over the spillway and/or through the lower elevation sluiceways. However, discharges of more than about 1,600 cfs via either the spillways or the sluiceways would result in total dissolved gas saturations exceeding the 110 percent criteria (Schneider 2003) downstream of the project's stilling basin.

During spillway or sluiceway releases at Libby Dam, highly aerated flow conditions are generated on the spillway face or in the sluiceways that, upon entering the stilling basin, result in the absorption of atmospheric gases which cause total dissolved gas (TDG) supersaturation, where TDG levels are above 120 percent. TDG supersaturation can cause potentially harmful gas bubble trauma (GBT) in fish and aquatic insects, resulting in direct or indirect morbidity and mortality. Symptoms of GBT generally include the internal or external formation of bubbles in the impacted organism, similar to decompression sickness or "the bends" in human divers. The bubbles damage tissue or block blood flow.

In the summer of 2002, a spill test was conducted at Libby Dam to determine dissolved gas levels resulting from various combinations of powerhouse and spillway outflow. That year was a high runoff year where peak inflow to the project prior to the spill test had exceeded 71,000 cfs. The test commenced on June 24, 2002. On June 25th, continued high inflows in excess of 60,000 cfs, coupled with a reservoir elevation slightly above 2,450 feet (full pool is 2,459 feet) and rising, resulted in the test being switched to a flood control operation. This resulted in total project discharges exceeding 40,000 cfs, including a maximum spill of over 15,000 cfs. Involuntary spill continued through July 7th. While the flood event was unplanned, monitoring and evaluation throughout the event resulted in a wealth of valuable information. One finding was that the threshold spillway flow for 110 percent TDG saturation (as measured approximately 200 feet downstream of the stilling basin) is about 1,600 cfs (Schneider 2003).

The Corps initiated this study to identify a comprehensive group of structural and operational alternatives that would allow 10,000 cfs of additional flow to be passed at Libby Dam and examine the impact they might have on TDG management in the Kootenai River below the project. This study describes Libby Dam and current operations; it identifies TDG exchange characteristics for present powerhouse, sluiceway, and spillway operations; and it discusses effects of project operations on release temperatures. The study first discusses the physical processes that cause or contribute to dissolved gas during dam operations. Following that is a discussion of alternative operations and an assessment of the impacts of the alternatives on TDG and release temperatures.

This initial appraisal does not assess the feasibility or advisability of passing an additional 10,000 cfs over Libby Dam, nor does it address other environmental or water quality issues related to such action. This is simply a discussion of structural and operational alternatives that would allow the additional flow.

OBJECTIVE AND SCOPE

As discussed above, in response to USFWS 2000 BiOp Reasonable and Prudent Action (RPA) 8.2.a.6, Seattle District, U.S. Army Corps of Engineers (USACE, Corps) initiated this study to identify and evaluate a comprehensive group of structural and operational alternatives that would allow 10,000 cfs of additional flow to be passed at Libby Dam. This study is a preliminary overview of possible options for providing such flow, recognizing that more detailed engineering analyses would be required to make a determination of technical, economic, and environmental feasibility. This study considers the impact which identified alternatives might have on TDG management in the Kootenai River below the project, but does not attempt to consider a full array of environmental, flood control, water quality (other than TDG and to a degree temperature) and other impacts additional flow or these alternatives would have. These and other issues would need to be evaluated to determine feasibility. The study also does not evaluate the benefit or lack of benefit additional Libby Dam releases might have on Kootenai River white sturgeon or any other aquatic species. Furthermore, it is recognized that Congressional authorization and appropriation would be required for all alternatives.

PROJECT DESCRIPTION

Libby Dam, pictured in Figure 1, and the Lake Koocanusa Project is a multi-purpose Federal project for flood control, water storage, and other purposes, located in northwestern Montana near the town of Libby. The project is operated by the U.S. Army Corps of Engineers, and is located on the Kootenai River at river mile 221.9. Its reservoir is the fourth largest, in terms of storage, in the Columbia basin, and the seventh largest in the United States (US Society on Dams 2004, USACE 2002). At maximum pool, the reservoir is 90 miles long, 48 miles of which is in the United States and the remaining 42 miles in Canada. The project was authorized for flood control, power generation, irrigation, and other uses, including recreation (USACE 1984).

A concrete gravity dam, Libby is 2,887 feet long and 432 feet tall. Five of eight 20-foot diameter penstocks deliver water to the turbines for power generation. The project has an upper spillway, three low-level sluice outlets, and a stilling basin to dissipate the large amount of energy present in spillway and/or sluice discharges. The capacity of the spillway is 145,000 cfs at full pool and the capacity of the sluiceways is 60,000 cfs at full pool. This allows for a maximum project discharge of 205,000 cfs. The

Bonneville Power Administration (BPA) markets power generated at the dam. Table 1 lists some pertinent data regarding the project.

Construction of the dam was started in 1966, filling of the pool commenced in 1972, and power generation was brought on line in 1975. Figure 2 shows both pre- and post-project summary hydrographs at the USGS gage at Leonia, downstream of the project on the Idaho-Montana border, to illustrate hydrologic/hydraulic changes as a result of the project. The project was originally designed and built to accommodate eight generating units. By 1975 four generating units had been commissioned. Plans called for installation of the remaining four units along with construction of a re-regulation dam downstream of Libby Dam which was intended to smooth out fluctuating discharges resulting from power peaking at Libby. The re-regulation project was eventually abandoned and a fifth generating unit, the last to be placed in service, was installed in 1984. Units 6-8 were manufactured, the turbines installed, and the balance of the components placed in storage on site. Maximum powerhouse discharge is about 27,000 cfs when the pool is at about elevation[1] (el) 2,420. A profile view of a penstock through the dam is shown in Figure 3.

The two spillway bays and three sluiceways (sometimes called "regulating outlets") allow water from the reservoir to bypass the generators. The spillway releases water from the upper levels of the reservoir by raising two 48-foot-wide by 59-foot-high tainter gates above the crest of the spillway, located at elevation 2,405. The face of the spillway attains an angle of 54 degrees from horizontal, with the upper portion divided by a center pier. The invert elevation of the sluiceway inlets is at elevation 2,201. Each sluiceway conduit is 10 feet wide and 22 feet high and exits onto the spillway face near the spillway base. The conventionally designed stilling basin has a length of about 275 feet from the toe of the spillway to the end sill, and a width of 116 feet with training walls on both sides. The top elevation of the training walls is 2,142 feet. The stilling basin apron elevation is 2,073 feet, resulting in an average depth of flow of about 52 feet for a project discharge of 35,000 cfs, where tailwater is at approximately 2,125.5 feet. A 12-foot-high sloped end sill defines the end of the stilling basin. Figure 4 shows spillway, sluiceway, and stilling basin details. The trapezoidal tailwater channel is armored with rock, and extends downstream below the stilling basin and discharges into the natural river channel. The design elevation of the tailrace area is 2,110 feet. However, tailrace bathymetry indicates the overall elevation is actually higher than 2,110 feet, as high as about 2,117 feet in some locations. Since power generation came online at Libby Dam, the sluiceways and spillway have seen infrequent use.

To control temperature in the river below the project, Libby was designed with a selective withdrawal system to withdraw water from various reservoir elevations during power operations. The selective withdrawal system consists of 14 vertical slots, each with

[1] Elevations are in feet and referenced to the National Geodetic Vertical Datum (NGVD).

22 ten-foot-high gates or bulkheads. Adding or removing the bulkheads to control the elevation of the withdrawal of water to each of the five active penstocks provides temperature control within its limits of operation. This water management system provides the project with the flexibility to adjust outflow temperature to benefit the downstream fishery. The effectiveness of the selective withdrawal system is largely dependent on the vertical temperature gradient present in the forebay.

WATER QUALITY CRITERIA

The State of Montana considers water in the main stem Kootenai River to be class B-1, which is suitable for drinking after conventional treatment. It is also suitable for recreational use, growth and propagation of aquatic organisms (including salmonids), and agricultural and industrial uses. In Circular WBQ-7, which lists the state of Montana’s Numeric Water Quality Standards, a total dissolved gas level above 110 percent saturation is identified as a toxic condition with an aquatic life standard designation of “acute.”(Montana DEQ 2004) The acute designation precludes the application of Montana mixing zone provision as stated in statute 17.30.507, which reads “acute standards for aquatic life for any parameter may not be exceeded in any portion of a mixing zone.”

Under the Montana water quality standards for temperature of a class B-1 water body, discharge temperatures cannot exceed 67 ºF (statute 17.30.623). The rate and degree of deviation from naturally occurring water temperatures is also specified in the Montana water quality standards. A 1 ºF maximum increase above naturally occurring water temperature is allowed within the range of 32 ºF to 66 ºF. A 2 ºF per hour maximum decrease below naturally occurring water temperature is allowed when the water temperature is above 55 ºF. A 2 ºF maximum decrease below naturally occurring water temperature is allowed within the range of 55 ºF to 32 ºF. As a means of assuring project release temperatures are compatible with downstream aquatic species, the project has established downstream temperatures it tries to target by using the selective withdrawal system. These temperatures vary throughout the year.

WATER QUALITY COMPLIANCE

Water temperatures are managed through the operation of selective withdrawal bulkheads that control the elevation, or depth, from which water is withdrawn from Lake Koocanusa for the powerhouse. This provides some degree of control over release temperatures when Lake Koocanusa thermally stratifies. The selective withdrawal system is configured such that 10-foot-high bulkheads can be placed starting at elevation 2,222 feet, the invert of the penstock intakes. Twenty-two of these bulkheads can be stacked, resulting in a maximum bulkhead crest elevation of 2,442 feet. The releases from Libby Dam have generally been in compliance with the state of Montana water quality standards for temperature since the completion of the powerhouse in 1975.

The Corps maintains a fixed dissolved gas monitoring station located on the left (east) bank of the Kootenai River at the location of the USGS gauging station, about one half mile downstream of the project. While this location is historically the location where compliance has been determined, some other location(s) could be selected by the state of Montana in the future. Due to the physical exchange processes occurring (degassing, mixing, etc.) as flow with elevated levels of dissolved gas moves downstream, a formal determination by the state of Montana as to compliance location could have a bearing on the ultimate feasibility of a particular dissolved gas management alternative. The TDG saturation of releases from Libby Dam has generally complied with state water quality standards due to the low frequency of spillway/sluiceway releases since the project powerhouse was completed in 1975. Based on project flow data, the portion of days when the regulating outlets or the spillway were in use at Libby Dam from 1977 to 2003 has been only about 0.8 percent.

Given the current configuration of Libby Dam, discharging an additional 10,000 cfs above powerhouse capacity would require releases over the spillway or through the sluiceways. Using either of these release mechanisms, as currently configured, produces dissolved gas levels in excess of 110 percent saturation. With a 10,000 cfs spillway/sluiceway discharge, and a 25,000 cfs powerhouse discharge, a lateral TDG level gradient is established in the river below the project until such time that the two flows are completely mixed. This lateral gradient is manifested by a scenario where the right side of the river is comprised essentially of the powerhouse flow with lower TDG levels while the left side experiences higher TDG levels driven by spillway flows.

Depending on the vertical reservoir temperature gradient, releasing water over the spillway or through the sluiceways may complicate temperature management at Libby Dam. Typically, during the May-June timeframe (generally the period when the spring freshet occurs), the sluiceways withdraw cold water from deep in the pool, while the powerhouse releases warmer water from higher in the pool via the selective withdrawal structure. During the spring, depending on forebay temperatures, selective withdrawal bulkhead placement, and reservoir elevation, spillway releases have the potential to be warmer than powerhouse releases. The selective withdrawal system's ability to control downstream water temperature is dependent on the vertical temperature gradient present in the forebay, whether it is the sluiceways or spillway releasing any additional water, and the amount of spillway/sluiceway flow. Under a combination powerhouse and sluiceway/spillway flow scenario (especially a powerhouse/sluiceway combination), lateral temperature gradients likely will persist for some distance downstream of the project, as the mixing zone between powerhouse and spillway and/or sluiceway flows develops, similar to the one described above with respect to dissolved gas.

GENERAL TDG EXCHANGE DESCRIPTION

This section describes general processes governing TDG exchange at dams, based primarily on studies at main-stem dams on the Columbia and Snake Rivers. Comparisons are made between observations of these processes at Columbia and Snake River projects and the likely TDG exchange characteristics at Libby Dam.

The TDG pressure in water is composed of the sum of the partial pressures of atmospheric gases dissolved in the water. The primary gases making up TDG pressure in water are oxygen, nitrogen, argon, and carbon dioxide. The atmospheric compositions of these gases are 20.95, 78.09, 0.93, and 0.03 percent, respectively. Henry's Law is an equation of state that relates the solubility of a given gas to the partial pressure. The constant of proportionality is called Henry's constant or the Bunsen coefficient. This equation relates the mass concentration of a constituent gas to the partial pressure at equilibrium. The constant of proportionality is a function of barometric pressure, temperature, and salinity. The mass concentration of dissolved gases in water can be determined from estimates of the TDG pressure, water temperature, and barometric pressure assuming atmospheric composition of gases in solution. Thus, for constant temperature and pressure conditions, the TDG can be represented as either a concentration or pressure in conservation statements.

The solubility of a gas in water is dependent on the ambient pressure of the gas, water temperature, and salinity. The total pressure experienced by entrained air bubbles in the water column is composed of barometric pressure and hydrostatic pressure. Thus, the solubility of gas in water doubles at a depth of about 33 feet in response to a doubling of the total pressure. The compensation depth is where the total pressure is equal to partial pressure of the TDG. At this depth, the saturation concentration is equal to the ambient concentration in the water. The solubility of gas in water is inversely proportional to the temperature. If the total dissolved gas concentration of 30 mg/l (907 mm Hg, 110.0 percent) is held constant in a water sample at one-atmosphere of pressure, and the temperature is raised from 20º to 21º C, the TDG pressure will increase by 17 mm Hg (924 mm Hg, 112.0 percent). Under these conditions, an increase in temperature of one degree will result in an increase in the TDG saturation of 2 percent.

The gas exchange characteristics of a dam are closely coupled to the system hydrodynamics and entrainment of air. Without the entrainment of air bubbles, the exchange of atmospheric gases at a hydraulic structure is restricted to the water surface, where gas exchange tends toward equilibrium at 100 percent of saturation. With aerated flow at a dam spillway due to surface aeration, plunging action, or induced aeration, entrained bubbles quickly dominate the gas exchange process (Wilhelms and Gulliver 1994). If bubbles in spillway flow are transported to depth in a stilling basin (even as little as 3 to 4 feet), the hydrostatic pressure compresses the bubbles thereby increasing their gas concentrations above atmospheric. This allows the transfer of atmospheric gases between entrained air and the water column to levels above atmospheric, causing total dissolved gases supersaturation. These elevated total dissolved gas pressures cannot be maintained in a non-aerated flow environment, where gas transfer at the water surface tends to reduce supersaturated conditions back to equilibrium at 100 percent saturation.

There are two general principles applicable to total dissolved gas management alternatives at dams: 1) eliminate or reduce the entrainment of air (aeration of flow) and 2) minimize the depth to which entrained air is transported. The first principle may be accomplished by passing flow through a closed conduit, such as a penstock, which operates under a pressurized flow regime. Unless air must be introduced for some reason, such as to mitigate cavitation[2], a pressurized flow system will generally not entrain air. The second principle may be accomplished by the use of flow deflectors which reduce the depth to which highly aerated spillway flow plunges. Because of a lack of additional closed conduits by which to reduce or limit aeration of flows, and the great expense of constructing such conduits, minimizing spillway plunge flow depth via flow deflectors has been the primary tool used to manage dissolved gas levels below Corps projects on the Columbia and Snake Rivers during spill events.

The following description of TDG exchange at different components of a project is based in part on the near-field TDG studies conducted during the Dissolved Gas Abatement Study (DGAS) program (USACE 2002). This discussion focuses upon the

[2] A potentially structure-damaging condition that can develop locally when the pressure within a body of water drops to below that of the vapor pressure of water. As fluid in these areas vaporizes, cavities can form, which, when moved by flow to areas of higher pressure, collapse. The collapsing of these cavities has the potential to damage (in some cases severely) the surfaces of hydraulic structures.

hydrodynamic and gas exchange characteristics in five regions of a dam: forebay, spillway/sluiceway, powerhouse, stilling basin, and tailwater channel.

Forebay

The TDG properties in the immediate forebay of a dam are generally uniform, when no thermal stratification is present, although they can change rapidly in response to operations of upstream projects (not a factor at Libby), tributary inflows, and meteorological and limnological (i.e., relating to ponds or lakes) conditions. A small vertical temperature gradient of several degrees near the water surface can limit the influence of gas exchange at the water surface to the near-surface layers of a pool. Additionally, heating of an impoundment can cause total dissolved gas pressure responses (e.g., higher temperatures can result in higher TDG levels) that result in changes to supersaturated conditions (Colt 1984). Although not likely significant in Lake Koocanusa, biological activity involving the production or consumption of oxygen may also influence TDG pressure. Thus, depending on the vertical temperature gradient in the forebay, and the placement of selective withdrawal bulkheads, the initial TDG level of water entering the spillway intake may be different from the TDG level of water entering the powerhouse intake.

The flow under a spillway gate or into a turbine intake may spawn vortices or other local hydraulic conditions that provide a vehicle for air entrainment. In general, however, TDG contributed by these local phenomena is insignificant and has not been a problem at Libby.

For most hydropower projects, powerhouse intakes are deep in the pool, resulting in releases from the hypolimnion (cold bottom water), essentially at 100 percent saturation. The selective withdrawal structure at the Libby Dam powerhouse allows withdrawal from different levels in the reservoir. Current project operations generally require a minimum submergence on the upper selective withdrawal bulkheads of 20 to 30 feet, resulting in withdrawal from the upper part of the hypolimnion. An intake at this level can also allow the withdrawal zone to extend upward into the warmer surface water, called the epilimnion. This can result in warmer release temperatures and, perhaps, slightly elevated TDG concentrations, compared to the usual bottom withdrawal.

The depth of the sluiceway intakes results in the withdrawal of cold water from the hypolimnion. At this depth TDG levels would likely be near atmospheric equilibrium at 100 percent. However, air entrainment facilitated by the high-velocity flow in the sluiceway, and the plunging of these flows to depth in the stilling basin, dramatically increases the TDG level of releases associated with the sluiceways.

SPILLWAY/SLUICEWAY

The highly turbulent flow that is characteristic of spillway or sluiceway flow serves to entrain large amounts of air in the flow. The depth of flow and water velocities change rapidly as flow passes under the spillway gate onto the face of the spillway. The roughness of the spillway piers and gates may generate surface turbulence that entrains air. Flow on the spillway may become aerated for low specific discharges[3] as a consequence of the development of the turbulent boundary layer. On a spillway, the turbulent boundary layer starts developing due to the interaction of the flow with the spillway floor. As the flow progresses down the spillway, the thickness of the turbulent boundary layer increases to the point where it encompasses the entire depth of the spillway flow. On many spillways, the point at which the turbulent boundary layer encompasses the entire depth of spillway flow can be seen as the sudden appearance of milky or frothy water. The photograph of the Libby spillway during a spill of approximately 2,000 cfs, shown in Figure 5, illustrates this. The distance required for the turbulent boundary layer to develop depends on factors such as specific discharge, spillway slope, and spillway roughness (USACE 1990). Falvey (1980) indicates that no air entrainment is occurring prior to the full development of the turbulent boundary layer. Once the turbulent boundary layer becomes fully developed, the water surface becomes irregular, consisting of surface waves of varying amplitudes and frequencies, which serve to trap bubbles of air. If the local velocities generated by the turbulence (not to be confused with the overall flow velocity) are greater than the terminal velocities[4] of the air bubbles, the bubbles will then be diffused or entrained in the flow (Falvey 1980). In addition to the turbulence resulting from a fully developed turbulent boundary layer, the presence of the spillway piers and spray walls may generate surface turbulence that entrains air (Falvey 1980). The short time of travel down the spillway will limit the exposure of water to entrained air bubbles to only a few seconds and tend to limit the absorption or desorption of TDG (Rindels and Gulliver 1989, Wilhelms 1997). At some projects, where forebay TDG levels were elevated (Schneider and Wilhelms 1997), it has been found that the entrained air, shallow flow on the spillway, and stilling basin conditions combined to reduce dissolved gases from above 120 percent down to about 116 percent.

The physical exchange processes in the stilling basin and tailrace – that is, the forcing into solution of entrained air in the stilling basin and the stripping of dissolved gas in the tailrace – ultimately dominate resulting TDG levels associated with spillway or sluiceway discharges, making the ultimate release TDG level essentially independent of forebay TDG levels, or the amount of air entrained in spillway flow. In general, it is thought that the extreme turbulence of spillway flow entrains more air than can be forced

[3] Discharge per unit width, cfs per foot
[4] Defined as the rate of rise of a air bubble in water in which the effects of turbulence, adjacent structures, etc. are negligible

into solution for a given water temperature, flow rate (volume), stilling basin depth, and barometric pressure. Given these factors and the typical forebay dissolved gas levels found at Libby, the resulting dissolved gas levels attributable to spill are probably influenced very little by dissolved gas levels found in the forebay.

POWERHOUSE FLOWS

There is little opportunity for entrained air to be introduced into the confined flow path through a turbine, except during inefficient turbine settings when air is aspirated into the turbine (Wilhelms, Schneider, and Howington 1987). During normal turbine operation, there is essentially no change in TDG pressure between the forebay and the tailwater as power generation flows pass through the powerhouse. Since turbine discharges generally do not entrain air, resulting downstream dissolved gas levels are not increased appreciably above those found in the forebay (USACE 1998).

The proximity of powerhouse releases to the high-energy environment in the stilling basin can result in a strong interaction of these project discharges. If the powerhouse flows are sufficiently isolated from the stilling basin action, then the fate of powerhouse releases is to dilute (due to lateral downstream mixing) TDG pressures produced by spillway releases. However, if the powerhouse releases are completely or partially entrained into the violent flow conditions of the stilling basin, then their normally low TDG levels may be gassed up to stilling basin levels, reducing or eliminating the potential for downstream dilution. This occurs because there is typically more entrained air in the spillway flow than can be forced into solution given the volume of spill, hydrostatic pressures, temperature, etc. The presence of powerhouse flows, with low dissolved gas levels, provides the additional volume of water for the excess entrained air. Data from the 2002 spill test seems to indicate that this may happen at Libby to some degree.

If powerhouse flow entrainment is occurring to some degree, the presence of stilling basin training walls at Libby are the likely reason that entrainment of powerhouse flow into spillway/sluiceway flow is not as significant as observed at other projects. In order to accurately assess the degree of powerhouse flow entrainment, another spill test would be required. During the 2002 test, the sensor placed in the stilling basin failed. This resulted in no dissolved gas data being collected for the stilling basin. It is unknown if the readings obtained from two sensors placed approximately 150 feet downstream of the stilling basin end sill are representative of dissolved gas levels generated in the stilling basin. If they are in fact representative, then, given other dissolved gas data obtained during the test, it would seem that powerhouse flows are providing additional water for dissolved gas uptake. If the values recorded are actually lower than actual dissolved gas levels generated in the stilling basin, then some de-gassing and/or dilution type mixing is occurring between the stilling basin end sill and the sensor location. A new test with stilling basin dissolved gas readings would be required to verify this.

Stilling Basin

The flow conditions in the stilling basin are often highly three-dimensional and are shaped by tailwater elevation, project head, spillway geometry, and the presence of spillway piers, sidewalls, baffle blocks, and/or an end sill. In general, however, the flow conditions downstream of a spillway are characterized by highly aerated spillway flow plunging to the bottom of the stilling basin. A bottom current directs flow out of the stilling basin, while a surface roller returns flow back to the plunge point. The end sill redistributes the bottom-oriented discharge current throughout the water column (Figure 6–not specific to Libby). Because of the high air entrainment and the transport of entrained spillway flow air to full stilling basin depth, a rapid and substantial absorption of atmospheric gases present in the spillway flow takes place in the stilling basin. These flow conditions typically result in the maximum TDG levels experienced below a dam.

Based on observations at other projects, it appears that stilling basin TDG levels at very low specific discharges may be relatively low, around 120 percent, but rapidly climb with increasing discharge to asymptotically approach a maximum that depends upon the stilling basin depth. Unfortunately, because of failure of the dissolved gas sensor placed in the stilling basin during the 2002 spill test, no data was recorded regarding maximum dissolved gas levels generated in the stilling basin.

Tailwater Channel

A rapid and substantial desorption of supersaturated dissolved gas takes place in the tailwater channel immediately downstream of the stilling basin (Schneider and Wilhelms 1996). As entrained air bubbles are transported downstream, they rise above the compensation depth[5] in the shallow tailwater channel. Above the compensation depth, the air bubbles strip dissolved gas from the water column, and the entrained air content decreases as the flow moves downstream and the air bubbles rise to the surface and escape into the atmosphere.

Dissolved gas desorption appears to be quickly arrested by the loss of entrained air within 200 to 500 feet of the stilling basin. The depth of the tailwater channel appears to be a key parameter in determining TDG levels entering the downstream pool (Schneider 2003). If a large volume of air is entrained for a sufficient time period, the TDG saturation will approach equilibrium conditions, dictated primarily by the depth of flow. Thus, mass exchange in the tailwater channel has a significant influence on TDG levels delivered to the downstream pool during high spill discharges. TDG absorption in

[5] Compensation depth is the depth at which the ambient TDG concentration would be at 100 percent saturation relative to the absolute pressure at that depth. For example, for TDG = 110 percent, relative to atmospheric pressure, the compensation depth is approximately 1 meter, where the absolute pressure is about 1.1 atmospheres.

the stilling basin and this process likely account for the upper limit on TDG observed at many Corps projects at high spillway discharges.

The rapid exchange of TDG pressures ceases downstream of the zone of bubbly flow. The exchange of atmospheric gasses continues at the air-water surface, driving conditions toward 100 percent of saturation. The TDG pressures generated at a dam can also change rapidly throughout a downstream river reach as the mixing zone develops. As discussed previously, hydropower releases entrained into the aerated spillway flows will often be exposed to similar levels of TDG exchange as experienced by spillway releases, thus influencing the amount of hydropower flow available for downstream dilution in the mixing zone. An understanding of the development of the mixing zone is critical to the interpretation of point observations of TDG pressure in the river. In regions where the mixing between powerhouse and spillway releases are incomplete (an example of this at Libby is between the Thompson Bridge and the USGS gage under spill conditions), lateral gradients in TDG pressure will be present, and point observations of TDG pressure will reflect some degree of mixing of project flows. The properties of the mixing zone will be dependent upon the tailwater channel features, the location of powerhouse and spillway structures, hydrodynamic conditions in the river, spillway and powerhouse operations, and the entrainment of powerhouse flows into the aerated spillway flows.

There are a number of processes that can further influence the TDG characteristics in a river reach below a dam. The re-aeration process in the river will continue to restore TDG levels toward 100 percent saturation. The mass exchange at the water surface can be greatly accelerated where surface waves increase the air-water interface, entrain bubbles, and promote the movement of water to the surface layer. The roughening of the water surface can be generated by surface winds or channel features such as rapids or local flow obstructions. The inflow from tributaries to the main stem can change the water quality properties in the study area through transport and mixing processes. The heat exchange within the river systems can result in rising or falling water temperatures that influence TDG pressures. The interaction of nutrients, algae, and dissolved oxygen can impact TDG concentrations in a river. The diurnal cycling of photosynthesis and respiration is chiefly responsible for fluctuations in dissolved oxygen (DO) concentrations.

RESERVOIR ELEVATION & SPILLWAY RELIABILITY ANALYSIS

VARQ (Variable discharge) is an alternative flood control operation implemented at Libby and Hungry Horse Dams. VARQ is intended to provide better project refill reliability during years when flood control flexibility allows. This increased refill reliability will in turn allow more flexibility to provide flow augmentation for the benefit of endangered Kootenai River white sturgeon, threatened bull trout in the Kootenai and Flathead rivers, and various listed stocks of salmon and steelhead in the main stem Columbia River. VARQ allows for Libby and Hungry Horse outflow to vary during the spring refill period based on the water supply forecast. Because the reservoir is not drafted as deeply during lower runoff years, there is less flood storage space during those years. By contrast, during the refill period under standard flood control policy, project outflows were held to minimum levels, resulting in the storage of water that might otherwise be passed downstream under VARQ (USACE 2002b, USACE 2004).

In order to evaluate the impacts of VARQ flood control operation, as well as the impacts of providing sturgeon flow releases of up to 10,000 cfs over powerhouse capacity, the Corps' Seattle District conducted a hydro-regulation model study (USACE 2004). The Corps' Streamflow Synthesis and Reservoir Regulation numerical computer model (SSARR) and the Autoreg pre/post-processing program were used to perform the model simulations for this study. This study used daily average project inflows from water years 1948 through 1999 to compute daily average discharges and pool elevations given both base flood control operations and VARQ operations as well as various fish flow augmentation scenarios.

The numerical model used in the VARQ study is based on a mass balance approach, where Lake Koocanusa storage is estimated as a function of daily inflow, outflow, and target pool elevation (rule curve). Daily project inflows, along with the difference between actual and desired pool elevations, determine the volume of water that should be released that day. From this volume, the daily required discharge is estimated, subject to constraints such as minimum or maximum discharge, rate of change in discharge, rate of change in pool elevation, and downstream local inflow. Reservoir simulation modeling gives an indication of what might be expected in terms of pool elevations and project discharges over a long period of time (in this case longer than the project has been in existence) for a given set of project operational rules. This study assumed historic inflows from 1948-1999 would be representative of project inflows in the future.

Libby Dam primarily provides flood control benefits during the spring snowmelt season. As such, the project provides varying levels of reservoir space to capture spring runoff that is dependent on the estimated, or forecast, volume of April to August runoff. When runoff is estimated to be high, the reservoir will be drafted deeper to ensure required flood control space is present. Runoff forecasts are generated starting in December and refined throughout the winter. These forecasts dictate the target pool elevations of the project throughout the winter. Figure 7 shows the Libby storage reservation diagram base flood control operation. Figure 8 shows the Libby storage reservation diagram for VARQ operation. The storage reservation diagram shows the empty reservoir volume to be targeted for flood control operations at a given time during the winter, based on the April-August runoff forecast. As forecasts change throughout the winter so does the empty volume target (or reservoir elevation) for spring flood control operations. The storage reservation diagram for base flood control (Figure 7) applies to project flood control operation prior to 2002. The storage reservation diagram for VARQ operation (Figure 8) applies to project flood control operation starting in 2002.

Figure 9 shows the Libby spillway gate-rating curve for one gate (USACE 1984). According to this figure, for the upper spillway to deliver 10,000 cfs, the forebay elevation should be above elevation 2,418 feet. This pool elevation is required to provide the design discharge of 5,000 cfs per spill bay, or 10,000 cfs total. The design discharge of 10,000 cfs could be also attained at a pool elevation of 2,415, but this would require free-overflow (uncontrolled) at the spillway gates, which is not as desirable a condition for accurately regulating the spillway discharge as is spill under a gated condition. In addition, flow instabilities could be expected (as indicated by Figure 9) in the zone between free-overflow and gated flow. These hydraulic instabilities could arise due to wave action in the forebay. At gate settings that result in a low submergence of the gate lip, waves could cause the flow to oscillate from gated flow to free overflow. From a hydraulic standpoint it would be preferable to start spilling under a gated condition and not transition back and forth, as might happen if inflows drop below 35,000 cfs during the operation at a pool of less than 2,418 feet or excessive wave action occurs in the forebay.

For the purposes of this study, additional flows for sturgeon are assumed to start sometime between 15 May and 15 June. Historically, during years when sturgeon flows have been requested, the start dates have fallen during this period in all but two years. Based on historical data (1948 to 1999) and reservoir modeling using VARQ flood control operation, the frequency of the Lake Koocanusa water surface being above elevation 2,418 feet ranged from 16 percent on 15 May to 88 percent on 15 June. The frequency of pool elevation exceeding elevation 2,418 feet for inflow conditions from 1948-1999 is shown in Figure 10. R PA 8.2.a.4 of the 2000 USFWS BiOp states that the spillway shall be considered a viable long-term option for passing additional flow only if the project is operated in such a manner that, in 80 percent of years, the pool elevation is above the spillway elevation by the time sturgeon flows are required. As per Figure 9, the reservoir elevation needs to be at approximately elevation 2,418 to pass 10,000 cfs.

With respect to the flood control aspect of Libby operation, the pool is drafted during the January through April time period in order to create space for the spring snow melt runoff. For years where the April to August runoff is forecasted to be low, the pool is not drafted as deeply (because not as much space is required for the expected runoff) to ensure the pool will be filled. For years where the April to August runoff is forecasted to be high, the pool is drafted to a lower level during the winter to ensure there is enough storage to contain this volume or at least mitigate downstream flooding. This causes significant variability in the spring portion of the Libby elevation rule curve, which must be considered when evaluating the filling schedule for the reservoir. Years where the reservoir is deeply drafted (high spring runoff forecast) can have an impact on the pool being at a level that would facilitate passing an additional 10,000 cfs over the spillway, especially if sturgeon flows would be required earlier in the 15 May-15 June time period. In addition to the variable spring rule curve, there is a requirement that outflows from Libby Dam must be such that Lake Koocanusa is not drafted until the spring freshet at Kootenay Lake is declared.

While the reservoir simulation model is useful for decision-making purposes, it does not capture the uncertainty that is inherent with real-time operation of the project. Real-time flood control operations are based on operational responses to a variety of factors. Some of these factors include water supply forecasts, short-term and long-term inflow forecasts, short-term and long-term weather forecasts, current weather conditions, current project inflows, local inflows below the project (and associated forecasts), project operational rules, communication, and any other unique circumstances within the system. Many of these factors are dynamic, forcing water managers to constantly make operational adjustments in response to these changing conditions. All of this adds some amount of uncertainty to the results of the modeling, including the data in Figure 10.

To illustrate the variability in project inflow, inflow hydrographs for selected years with higher than average April to August runoff volumes are illustrated in Figure 11. Clearly, even for years with similar inflow volumes, the reservoir does not receive this volume in a consistent manner. This variability makes it difficult to use the inflow volume forecast to predict what the pool elevation might be on a given day during the 15 May to 15 June period.

Depending upon the requested starting date (particularly if it is in the middle part of May) of the additional 10,000 cfs, the modeling indicates that the reservoir might not be at a sufficient elevation to pass 10,000 cfs flow above powerhouse capacity over the spillway. In addition to the reservoir elevation requirement, reservoir inflows would need to be at a sufficient level to prevent drafting of the reservoir in the event the pool is at or slightly above elevation 2,418. Based on the results of the numerical modeling effort,

Table 2 shows the date each spring (for the years 1948 to 1999) where the pool reached elevation 2,418 feet, along with the reservoir inflow on this date. These dates are shown for both VARQ operation and a non-VARQ operation. In addition, the date the reservoir actually reached elevation 2,418 for the period 1976 to 1999 is included for comparison. The date the pool reaches elevation 2,418 is a function of how deep it is drafted during the winter (this depends on the April-August snowmelt volume forecasts which are being updated monthly throughout the winter), the actual snowmelt inflow volume, the timing of the snowmelt, and any significant springtime precipitation that occurs. The years where the reservoir does not reach elevation 2,418 feet until sometime after the first of June tend to be the years where the April-August inflow volume forecast was high. The years where the reservoir reaches elevation 2,418 earlier in May tend to be the years where the April-August volume was forecast to be lower than average. The spillway is available for use sooner in these years, but because these are lower inflow volume years, it is questionable as to whether a 10,000 cfs over powerhouse capacity flow can be supported this early due to low inflows. Inflows above approximately 35,000-37,000 cfs would be required or the pool would draft, reducing spillway and/or powerhouse capacity. In addition, the drafting of Lake Koocanusa is only allowed in the spring once the spring freshet for Kootenay Lake has been declared.

The pool elevations under VARQ flood control operation at the requested starting dates of the sturgeon flows play an important role in evaluating the timing of flow augmentation above the current powerhouse capacity and the availability of the spillway to deliver these flows. Some of the alternatives in this report involve using the spillway as the mechanism for providing the additional flow from the project. This discussion was intended to address the viability of the spillway to provide these flows. In the event that additional flows are determined to be warranted and are pursued at Libby, the reliability of the spillway to provide additional flows would have to be addressed in feasibility studies.

EXISTING POWERHOUSE CAPACITY

The discharge capacity of Libby Dam powerhouse will vary according to the project head, maximum generating limit, and cavitation potential. The maximum generating limit for Libby Dam turbines is 120 MW. At a pool elevation of 2,420 (turbine head of 302 feet), the maximum discharge is 5,406 cfs per turbine for a maximum total discharge of 27,030 cfs through the powerhouse. For pool elevations below 2,420, the maximum discharge is reduced because it is constrained by the available head on the turbine. Above elevation 2,420, maximum discharge is also reduced, because of the maximum power output limits of the generators. Figure 12 shows the discharge-rating curve for one generating unit. If the pool is at elevation 2,420 feet when an additional 10,000 cfs sturgeon flow is requested, then the maximum possible outflow from the project would be approximately 37,000 cfs (27,000 cfs powerhouse plus 10,000 cfs spillway). Likewise, if the pool were above or below elevation 2,420 by some amount, then it is possible the project outflow would be less than 35,000 cfs.

The hydraulic capacity of the Libby powerhouse will vary as Lake Koocanusa is filled during the spring and early summer period. Based on the reservoir modeling using VARQ flood control operation (flow data 1948-1999), the exceedance probability for the hydraulic capacity of the Libby powerhouse is shown in Figure 13 for each day of the proposed sturgeon operation window. Based on this data, the hydraulic capacity of the Libby powerhouse (based on the 20 percent and 80 percent exceedance discharge) ranged from 23,600 cfs to 26,700 cfs. The first few days in June produce the highest probability of maximizing flow through the powerhouse.

EXISTING TEMPERATURE AND TDG CONDITIONS

The thermal stratification in the forebay of Libby Dam influences the vertical distribution of TDG pressure. The TDG saturation in the warmer surface water of Lake Koocanusa can violate the Montana state water quality standard for TDG of 110 percent when the rate of surface heating is high, particularly during the summer months. However, most of the water stored in Lake Koocanusa below the surface layer contains TDG levels that are close to saturation (Schneider 2003). The passage of water through the Libby powerhouse generally does not change the TDG pressures in the Kootenai River when turbines are operated near design discharges. The TDG saturation of powerhouse releases from Libby Dam typically ranges from 102-104 percent during hydropower operations (Schneider 2003). Based on April to September data from 2003 and 2004, dissolved gas levels of powerhouse releases ranged from a low of about 96 percent to a high of about 106 percent. The withdrawal of warmer surface water from Lake Koocanusa through the selective withdrawal system is likely responsible for the mildly supersaturated conditions in project releases.

Discharges through the spillway or sluiceways at Libby Dam have historically created elevated total dissolved gas levels in the Kootenai River below the dam. Before power generation came online, all day-to-day regulation of the project was accomplished with releases through the sluiceways. The TDG saturation resulting from sluiceway releases were measured extensively during 1972-1975 (Graham 1979, Battelle 1974), the early years of project operation. TDG below the dam during regulating outlet operation ranged from 128-150 percent, with an average value of 138 percent (Figure 14). Based on documentation (Battelle 1974), it is believed this dissolved gas data was recorded at the Thompson Bridge, below the dam. During the period these readings were taken, discharges would have been entirely from the sluiceways since the powerhouse was not yet online. A lateral dissolved gas gradient as seen presently with combined powerhouse and spillway operation would not have been present. The TDG saturation associated with sluiceway discharges was generally higher than TDG levels observed during comparable spillway discharges prior to hydropower operation at Libby Dam (Figure 14). The higher rates of TDG exchange associated with sluiceway outlets, when compared to spillway releases, have also been observed at Dworshak Dam during the 2003 season (CENPD 2003). The higher TDG saturation levels associated with sluiceway releases can likely be attributed to the higher specific discharge and air content of these discharges.

The Libby sluiceways operate with an open channel flow regime downstream of the service gates. As with the spillway, the high velocity open channel flow regime and the resulting turbulent flow provide the opportunity for air to be entrained in the sluiceway flow. In addition, aerators, intended to mitigate cavitation issues, also add to air entrainment in sluiceway flows. In the past, cavitation near the sluiceway service gates has caused damage to sluiceway floor surfaces. The dynamic effects of water flowing over a surface discontinuity (a step, surface roughness, etc.) at high velocities can cause the pressure in localized areas of the flow to fall to the vapor pressure of water for the given temperature of the flow. Vapor cavities can occur in these areas, and when transported to higher-pressure areas, these cavities collapse. This collapsing of vapor cavities can in turn damage adjacent surfaces. In the case of the Libby sluiceways, this problem was addressed by adding aeration slots to the sluiceway invert, which are vented to the atmosphere (McGee 1984). This venting to the atmosphere inhibits the formation of vapor cavities in the vicinity of the aeration slot, and thus helps mitigate cavitation damage.

As discussed previously, in June 2002, the Corps conducted a TDG exchange study (spill test) at Libby Dam to determine how TDG levels in the river would be affected by discharges over the spillway (Schneider 2003). For various spillway discharges up to about 15,000 cfs, with concurrent powerhouse discharges of about 25,000 cfs, TDG was sampled across a fixed array of automated logging sensors located above and below Libby Dam. TDG levels below Libby Dam varied widely in response to changing project operations, location of sample, and natural river processes. According to information from the monitors during this study, the highest TDG pressures were observed several hundred feet below the spillway outside of the highly aerated flow regime, but prior to complete mixing with powerhouse discharges. The TDG in spillway releases increased as an exponential function of the spillway discharge (Figure 15), ranging from 104 percent during a 700 cfs spill to 134 percent during a 15,600 cfs spill. Measurements of TDG in spillway releases of 10,600 cfs reached 132 percent. It should be noted that, although not measured during this study, higher TDG levels likely occurred in the stilling basin, judging from what happens at other dams. For example, TDG measured in the stilling basin at Chief Joseph Dam on the upper Columbia River approached 175 percent compared to a peak level of 137 percent downstream of the bubbly flow (Schneider and Carroll 1999). The flow-weighted cross-sectional average TDG in the Kootenai River increased incrementally as a function of the percent of total river flow spilled. The average TDG saturation in the Kootenai River generally declined with distance below the project due to gas exchange with the atmosphere. The cross-sectional average TDG saturation in the Kootenai River reached a peak level of 116.9 percent during the 15,600 cfs spill event. However, for spill discharges up to 4,000 cfs, the average TDG saturation in the Kootenai River remained below 110 percent. The average TDG saturation in the Kootenai River at the tailwater fixed monitoring station (USGS gage location) for a 10,600 cfs spill and a powerhouse release of 25,000 cfs was slightly above 115 percent (Figure 16).

During the 2002 spill test, the increase in the total dissolved gas levels in the Kootenai River at the USGS gage location attributed to spillway releases from Libby Dam were observed to be larger than the product of spillway discharge and the TDG pressures observed immediately below the spillway and shown in Figure 14 (Schneider 2003). In order to calculate the flow-weighted average TDG pressures observed in the Kootenai River at the tailwater gaging station during spillway releases, an additional source of TDG pressure was required in the form of an effective entrainment discharge equal to the lesser of $0.84Q_{sp}$ or 4.72 kcfs. This additional source of TDG pressure is likely attributed to the interaction of spillway and powerhouse flows downstream of the stilling basin but prior to the initial observations of TDG pressure collected below the spillway during the 2002 field investigation.

The characterization of TDG saturation in the first six miles of the Kootenai River below Libby Dam was dominated by the development of a mixing zone between powerhouse and spillway flows. At the David Thompson bridge, just downstream of the dam, during a powerhouse discharge of 25,000 cfs and a spillway discharge of 10,600 cfs, the TDG levels near the left, or west bank (the side of the river most influenced by spillway flows) were about 125 percent of saturation, but along the right or east bank (the side of the river most influenced by powerhouse flows) were only about 103 percent saturation (Figure 16).

It was also observed in the June 2002 spill test that Kootenai Falls caused a significant increase in TDG saturation of the Kootenai River during powerhouse operations only or with combined powerhouse and spillway operations. The TDG levels below the falls were always greater than levels just upstream of the falls and were apparently independent from the TDG concentrations produced just by spillway operations at Libby Dam during the study period. The TDG saturation below the falls ranged from 116 to 121 percent throughout the study period. Prior to the initiation of spillway releases, the TDG levels in the Kootenai River were observed to be 103 percent saturation upstream of the falls and 116.1 percent downstream of the falls. The TDG exchange caused by Kootenai Falls is a function of river discharge and, as a consequence, river stage (Schneider 2003). Clearly, even under natural conditions without Libby Dam, TDG below Kootenai Falls exceeds the Montana state standard of 110 percent.

The project tries to operate the selective withdrawal system in such a manner that, when possible, downstream temperature objectives can be met. Figure 17 is a plot of the temperature targets throughout the year. The ability to meet these target temperatures during the elevated sturgeon flows for existing conditions depends upon the pool elevation and thermal stratification in Lake Koocanusa. Under current operations, with all flow going through the powerhouse, the downstream temperature targets are not always met. The releases are sometimes colder than the target values. Typically the selective withdrawal bulkheads are set to withdraw warmer water from high in the pool, in the upper or epilimnetic layer. However, because of submergence requirements to prevent vortex formation, the withdrawal elevation has been historically set 40 to 50 feet below the water surface. In 2004 the project operated with a submergence of 30 feet without problems and is looking at trying a submergence of 20 feet in 2005. Thermal stratification above the elevation of the bulkhead opening sometimes will limit the withdrawal of warmer epilimnetic surface water.

In some years, a thermal stratification begins to form at the time of sturgeon releases. In those years, if the upper spillway is used to pass the additional sturgeon flow, water temperatures in spillway release water may be warmer than powerhouse flows, especially if the selective withdrawal bulkheads are below the elevation of the spillway crest. For sluiceway operations, the release water temperature would be colder than the powerhouse discharge water, making it more difficult to meet spring/summer release target temperatures in the Kootenai River. Temperature data from 2000 through 2002 indicates that from 15 May to 15 June, the water temperature at the level of the sluice intakes was about 40 ^{o}F compared to the 50 to 55 ^{o}F at the spillway crest elevation. Figure 17 indicates that during the 15 May to 15 June time period, the minimum desired water temperature downstream of the dam ranges from 45 to 49 ^{o}F.

If the sluiceways were used to pass the additional flow, prominent lateral temperature gradients in the Kootenai River would be expected. As much as a 10 to 15 ^{o}F lateral temperature differential could occur until the river becomes completely mixed. If the sluiceways were to be used to pass additional flows, a more gradual scheduling of sluiceway releases may need to be considered given the potential thermal shock associated with the release of this cold water.

In recent years investigations have been carried out regarding retrofitting existing dams with temperature control structures. At some projects, such as Shasta Dam in northern California, complex temperature control systems have been installed. It is worth noting that temperature control curtains have been used successfully to adjust outflow temperatures at two Bureau of Reclamation projects not equipped with formal temperature control structures in the Sacramento and Trinity River basins (Vermeyen, 1997).

ALTERNATIVES

In a study of TDG abatement on the Lower Snake and Columbia Rivers (USACE 1996), 43 alternatives were initially identified as potential measures for TDG abatement at dams on the Snake and Columbia Rivers. Many were quickly eliminated because of constructability, operational, or hydraulic concerns. For this study, fourteen individual alternatives (including the existing condition for purposes of comparison) were identified as having potential to meet or partially meet the operational and release objectives as outlined above. They are as follows:

1. Existing condition (base condition, no changes)
2. Spillway/sluiceway flow deflectors
3. Spillway/sluiceway flip bucket
4. Tailwater mixing structure
5. Side channel and spillway
6. Baffle chute spillway
7. Raised stilling basin floor
8. Raised tailrace channel
9. Modification of sluiceway outlets
10. Siphon/dedicated pressure flow system with auxiliary stilling basin
11. Penstock/draft tube conversion
12. Additional generating units
13. Additional generating units using load banks
14. Extension of right (west) stilling basin training wall

Congress authorized the Libby Dam Project in 1950 in part to handle the Probable Maximum Flood (PMF) in that location. The outlet capacity of the spillway and the three sluiceways (at full pool the sluices and spillway can discharge about 205,000 cfs) are an integral part of insuring Libby can handle a large flood and maintain the integrity of the structure. Any modifications to the spillway or sluiceways must not permanently reduce this capacity. This requirement must always be considered when examining alternatives to pass additional flow. In many cases, physical model studies are required to verify that an alternative does not negatively impact the design outlet capacity and hydraulics of the project.

A detailed description of the various alternatives follows; Table 3 provides an abbreviated summary of each.

ALTERNATIVE APPRAISAL

1. EXISTING CONDITIONS

There would be no project modifications for this alternative. The spillway or sluiceways would be used to deliver the additional 10,000 cfs of flow. Based on historical records and the June 2002 field study (Schneider 2003), the powerhouse can deliver release water at TDG levels of less than 103-104 percent. The spillway and the sluiceways will deliver water to the tailrace channel at much higher TDG levels that, especially in the case of the sluiceways, could exceed 140 percent saturation. However, a combination of the powerhouse with spillway/sluiceway can mitigate the effects of spillway or sluiceway releases on TDG when the flows become fully mixed.

Typically the powerhouse is operated at the published turbine cavitation limit in order to maximize sturgeon flows. TDG production from the spillway should be minimized by distributing the total spill uniformly over both spill bays (Schneider and Wilhelms 1997). The spillway was operated in this manner during the 2002 spill test and would be operated in this manner in the event of any future spills. The BiOp recommends a first additional flow increment of 5,000 cfs by 2004. The resultant maximum and average TDG saturation in the Kootenai River can be estimated using the production relationship for spillway flows shown in Figure 15, and by applying mass conservation principles with the effective entrainment discharge to compute a flow-weighted average. During the 2002 field study (spill test) at Libby (Schneider 2003), the TDG levels released through the powerhouse were approximately 103 percent. For discharges from the spillway of 5,000 cfs, the maximum TDG saturation in spillway releases was approximately 131 percent (Figure 15). Although in violation of the state TDG criteria throughout the stilling basin and downstream mixing zone, a flow-weighted averaging of powerhouse releases of 25,000 cfs and spillway releases of 10,000 cfs results in an estimated TDG level of 111.6 percent.

If the spillway cannot be operated, or could not provide the entire additional flow needed, then the sluiceways would be needed to deliver all or part of the additional flow. The sluiceways would generate TDG at a level that, according to Figure 14, can range up to 144 percent saturation. Using flow-weighted averaging and assuming the same formulation for the effective entrainment as determined for spillway flows, the average TDG saturation would be about 113.7 percent, once well-mixed conditions are achieved several miles downstream of the dam.

If the additional flow were to be passed with the current project configuration, the spillway is preferable to the sluiceways as the mechanism to accomplish this, based on an objective of minimizing dissolved gas production. To accommodate the additional flow, 10,000 cfs would be spilled (generating 132 percent TDG) and 25,000 cfs would be released through the powerhouse (103 percent TDG). The flow-weighted average TDG would be approximately 115 percent. If 10,000 cfs were released through the sluiceways (generating about 138 to 140 percent TDG according to Figure 14), the flow-weighted average TDG is estimated to equal approximately 118 percent, assuming an effective entrainment discharge of 4.72 kcfs (refer to page 22).

Based on these estimates, discharging an additional 10,000 cfs from Libby Dam, as currently configured, will result in the elevation of TDG saturation in the Kootenai River to levels well above state water quality standards for either spillway or sluiceway releases. The dissolved gas saturation in some areas of the river will likely exceed 110 percent as far down the Kootenai River as Kootenai Falls. Since TDG levels in the Kootenai River would exceed the 110 percent standard in the stilling basin and throughout portions of the tailwater channel, a water quality exception would likely be required from the state of Montana to proceed with sturgeon flow operations under these conditions.

The operation of the spillway may allow a warmer release than with only powerhouse operation that would more closely meet temperature objectives. Depending on weather conditions at the time of a sturgeon flow operation, the warmer spillway release could either help or hurt efforts to meet temperature objectives below the project.

Operation of the sluiceways would reduce release temperatures, compared to powerhouse releases only, significantly impacting the ability of the project to maintain target release water temperatures. Because temperatures are much colder at the sluiceway intake level than the powerhouse flows, a lateral temperature gradient, similar to the lateral dissolved gas gradient, would likely be present for some distance downstream of the project until powerhouse and sluiceway flows could be fully mixed. This temperature differential would apply to any alternative using the sluiceways.

The cost of adopting the revised operational scheme called for in the 2000 BiOp without modifying the project is minimal. Operations and Maintenance (O&M) costs would increase. Both the spillway and the sluiceways (along with the stilling basin) are maintained for an infrequent level of use. Use of either of these components of the project for one to three weeks each year would increase the costs associated with maintaining these systems. In addition, increased use of the spillway/sluiceways would likely increase stilling basin maintenance. The Libby stilling basin suffered major damage during the years when the sluiceways were used to regulate the project. A more detailed study should be conducted to determine the hydraulic, hydrologic, and ecological effects of integrating spillway and/or sluiceway and powerhouse discharges for sturgeon flows.

2. SPILLWAY AND SLUICEWAY FLOW DEFLECTORS

Spillway flow deflectors have been the primary method for TDG management on lower Snake and Columbia River dams (CENWP-NWW 2002). Flow deflectors at these projects have reduced TDG production at spillways to 120 percent[6] or below for discharges up to 7,000 to 10,000 cfs per spill bay (specific discharges of 140 to 200 cfs per foot) depending upon the specific project. These projects operated under water quality waivers with the state when spilling water for the benefit of fish. Spillway deflectors have not reduced TDG levels to the state standard of 110 percent.

Flow deflectors are concrete structures mounted on the spillway face (Figure 18), generally at an elevation slightly below that of the design tailwater condition. They usually span the full width of the spill bays and normally extend horizontally 8 to 15 feet out from the spillway face with some type of curved transition from the spillway face to the horizontal portion of the deflector. Flow deflectors turn the highly aerated spillway flow to produce a surface-skimming water jet that has a horizontal instead of a vertical direction. This type of flow tends not to plunge to the bottom of the stilling basin, thus keeping the entrained air exposed to lower hydrostatic pressures and resulting in lower TDG levels. Flow deflector designs are based on the results of physical model studies. Details such as length, elevation, and transition curve radius are fine-tuned during this process to produce the desired surface jets for a wide range of spillway discharges. During very high flows, the spillway jet overrides the deflector, allowing the stilling basin to operate as designed.

In the early 1970s, through physical model studies, flow deflectors for Libby Dam were investigated for the sluiceway outlets to reduce TDG levels, and the results documented in a report (CENPD 1983). At that time, flow regulation at Libby Dam was accomplished with the sluiceways. Based on the physical modeling results, the deflectors proposed for the sluiceways did not produce the desired skimming flows for a wide discharge and tailwater range. Since the powerhouse would be operational in about three years, drastically reducing use of the sluices, development of the proposed deflectors was abandoned. However, photographs in the report show that 10,000 cfs divided among the three sluices with flow deflectors, produces a desirable, surface skimming flow.

The spillway at Libby is configured differently than the spillways on the lower Snake and Columbia projects in that sluice outlets are located on the lower face of the spillway. The sluiceway outlets are located at approximately the same elevation that flow deflectors would be installed, complicating the deflector design. This would leave three 10-foot-wide sections in the spillway face without a deflector to help turn the flow.

[6] The 120 percent TDG level has been adopted as maximum TDG standard at the fixed monitoring stations for the Snake and Columbia Rivers, when spilling to aid fish migration. Additional TDG criteria must also be met. Waivers from the 110 percent standard have been granted by appropriate state agencies.

Bridging these sections with the deflectors might help reduce plunging of spillway flow but likely would not be as efficient as the sections mounted directly to the spillway face. Bridging the sluice outlets could also interfere with the hydraulic performance of the sluiceways. The sluiceways are an integral part of the project design outlet capacity and any alterations affecting sluiceway flow capacity would violate the existing project authorization. A potential remedy might be installation of an "eyebrow" deflector over the top of the sluice outlets to prevent spillway discharge from flowing over the outlets (CENPD 1983). However, the hydraulic performance of such a design and its impact on the spillway and stilling basin are highly uncertain.

The bridge over the stilling basin is in close proximity to the spillway face and the sluiceway outlets. The bridge's impact on deflector operation (or deflector impact on the bridge) would have to be considered.

If the sluiceway deflectors produce a desirable surface jet flow pattern (CENPD 1983), a combination of spillway and sluiceway deflectors might provide TDG reduction benefits similar to those observed at other spillways. The sluice deflectors may be able to deflect the portion of spillway discharge that flows over the outlets. This combination would allow use of the upper spillway when the pool elevation is above 2,418 and the sluices, or some combination of the sluiceways and upper spillway, when it is lower. A physical model study would be required to verify this.

In order to provide insight as to possible TDG reduction at Libby Dam with spillway deflectors, TDG production data at Lower Granite Dam on the Snake River was examined. Lower Granite has a stilling basin with a depth that is about the same as the Libby stilling basin. Additionally, it is the most upstream project on the Lower Snake River (there are projects much farther upstream on the Snake River but they should have a minimal impact on Lower Granite dissolved gas levels) and it should experience forebay TDG levels that are unaffected by an upstream project, similar to Libby. In addition, the geometry of the Lower Granite deflectors should be similar to the geometry of deflectors that would be used on the Libby spillway. The TDG production relationship (Figure 18) for Lower Granite Dam as presented in CENWP-NWW (2002) expresses the increase in TDG level as a function of the tailwater depth and specific spillway discharge for various spill patterns.

At a spillway discharge of 10,000 cfs, the discharge per unit width of the upper spillway at Libby is about 86 cfs/ft. At Lower Granite, this specific discharge equates to a flow per spillway bay of 4300 cfs (4.3 kcfs). From Figure 19, for a flow of 4300 cfs per bay, atmospheric pressure of 745 mm Hg, and tailwater elevation of 636 feet (stilling basin depth of 56 feet), TDG production at Lower Granite Dam results in a downstream (estimated to be at a point between the stilling basin and the Thompson Bridge) saturation of about 113.5 percent. The yellow, or "STD" spill pattern data is used from Figure 19 for this comparison. For this production level at Libby, using flow-weighted averaging, the mixed TDG level would be approximately 106 percent for combination of 10,000 cfs of spillway flow (with deflectors) and 25,000 cfs of powerhouse releases with TDG of 103 percent. Complete mixing of powerhouse and spillway releases would occur within approximately five miles of the dam. There are two significant differences between Lower Granite and Libby that add uncertainty to this estimate. First, total project head for Lower Granite, at about 110 feet, is lower than Libby, which has a maximum head of about 340 feet. While unit discharge and stilling basin/tailwater depth are the dominant factors that determine TDG generated by a spillway, the impact of the very high head lends some uncertainly to these estimates. Second is the hydraulic performance of spillway deflectors that are interrupted by the sluiceway outlets. At these locations spillway flow would most likely not be turned as efficiently as in other locations along the width of the upper spillway. These performance issues would have to be investigated in a physical hydraulic model of the Libby spillway.

A similar approach can be used to estimate the TDG exchange associated with a sluiceway discharge of 10,000 cfs with flow deflectors. The higher specific discharge of the sluiceways, and a somewhat different deflector geometry, will create an additional level of uncertainty in applying the Lower Granite TDG production formulation. The unit discharge for the sluices operating at a total flow of 10,000 cfs would be about 333 cfs per foot. For a spill of 333 cfs/ft, atmospheric pressure of 745 mm Hg, and stilling basin depth of 56 feet (tailwater elevation of 636 feet), TDG production at Lower Granite Dam results in a dissolved gas saturation of 130.1 percent. The higher TDG pressures, compared to spillway flows, are caused by the higher specific discharge of the sluiceways. With a Libby powerhouse discharge of 25,000 cfs at 103 percent, flow weighted averaging gives a downstream TDG of 110.7 percent. Uncertainty is also significant in this estimate, because of the undefined performance of the sluiceway deflectors. At Lower Granite, a specific discharge of 333 cfs is likely beyond the flow rate at which the deflectors were designed to produce a skimming flow. At Lower Granite, it is thought at this specific flow is beyond the design range for the deflectors to produce a skimming flow. Given the skimming flow was apparently observed in the earlier physical model study (USACE 1983) at 10,000 cfs, it is likely that Libby sluiceway deflectors would produce lower levels of dissolved gas than the comparison with Lower Granite indicates.

The addition of spillway or sluiceway deflectors to Libby may significantly change the circulation patterns in the stilling basin and adjoining tailwater channel. Because of the high velocity skimming jet coming off the deflectors, a low-pressure region is created in the stilling basin that can entrain flow from outside of the basin. When the spillway is adjacent to the powerhouse, a portion of this entrainment flow can be supplied directly from powerhouse releases. This entrained flow is exposed to the highly aerated flow in the stilling basin, causing some degree of dissolved gas uptake if no structure is present to separate spillway and powerhouse flows. In the case of Libby, the presence of training walls running the entire length of the stilling basin would help prevent such entrainment. Assuming the training walls are effective at preventing the deflector generated low pressure region from entraining powerhouse releases, the water surface at the upstream end of the stilling basin would likely be somewhat lower with deflectors than it would be without deflectors. This is because there would not be any additional water to feed this low-pressure area. This would be an important consideration when determining a deflector elevation.

The fate of powerhouse discharges will vary from project to project and will depend upon structure configuration, operating conditions, and stilling basin hydraulics. Recent findings from the Little Goose spillway performance test (Schneider and Wilhelms 1998) showed that nearly all of the powerhouse flow was entrained into spillway releases and gassed to comparable levels. Observations of flow conditions in the field and laboratory physical models have indicated that powerhouse releases are also entrained at Ice Harbor Dam. As estimated in physical model measurements and from observations taken during near-field spillway performance tests, entrainment has ranged from 4,000 to 40,000 cfs depending upon flow conditions (Fuller 1998). As discussed earlier, it is unknown to what degree powerhouse flows are entrained at Libby. It is thought the training walls along the entire length of the stilling basin play a major role in preventing this entrainment. A new spill test would be required to address the entrainment issue at Libby.

The addition of spillway flow deflectors will not change the ability to meet release water temperature objectives as described for spill with the existing dam configuration. Release temperatures would depend upon the thermal stratification in the reservoir and the elevations of withdrawal. In general, for spillway operations, the water would be withdrawn from the warmer surface waters of the epilimnion. For sluiceway operations, the water would be cold, withdrawn from the lower depth, or hypolimnion. As discussed earlier, lateral temperature gradients could be quite large through the downstream mixing zone.

To finalize flow deflector design, two physical model studies would be required to develop the spillway flow deflector, define potential entrainment of powerhouse releases, and assess impacts on dam safety. This effort would use a sectional spillway/stilling basin model to determine optimum deflector placement elevation and geometry to produce skimming flows. The overall flow patterns in the tailrace, including entrainment of powerhouse flows, would be investigated in a general project model. Both models would be used to verify that the project operates as designed for large flood events.

While flow deflectors have not demonstrated the ability to reduce dissolved gas levels to below 110 percent, they do have a couple of advantages over some other alternatives. One is that the Corps as an agency has a great deal of experience retrofitting projects with deflectors. Secondly, dewatering of the Libby stilling basin is relatively easy (a bulkhead is provided for this purpose) and would allow construction in the dry without cofferdam construction.

Installing spillway and sluiceway flow deflectors should significantly reduce the TDG levels in the Kootenai River resulting from spill at Libby Dam, compared to spill under the existing spillway/sluiceway configuration. However, TDG levels would still exceed the 110 percent standard in the stilling basin and portions of the river downstream. A water quality exception would likely be required from the state of Montana in order to proceed with sturgeon flow operations under these conditions.

The design and construction of flow deflectors would cost \$8-\$12 million with funding contingent upon Congressional support. As discussed earlier, given the spillway configuration, deflectors would probably be required on the sluiceways as well as the spillway to minimize dissolved gas production from spillway use.

3. SPILLWAY/SLUICEWAY FLIP BUCKET

A type of energy dissipation system at some dams involves using a spillway flip bucket (also known as a ski jump or flip lip) to direct and disperse the high velocity spillway jet away from the dam. While a small amount of energy is dissipated through bucket friction and the interaction of the water and air during the jet's trajectory, most of the excess energy is dissipated due to the impact and dispersion of the jet at the impact area. A conceptual sketch of a flip bucket on the spillway at Libby Dam is shown in Figure 20.

Flip bucket design varies from project to project. Bucket invert elevation, curve radius, alignment, cross sectional geometry, and lip angle all play a role in trajectory distance, angle of jet impingement on the tailwater surface, and the amount of jet dispersion achieved. Typically flip bucket systems direct the spillway jet away from the project to a location where scour and erosion cannot occur (possibly an existing hard rock area or a specially designed receiving basin), or if scour or erosion in unpreventable, to a location where the impact poses no real negative consequences of such streambed degradation. Where conditions permit, a flip bucket energy dissipation system can eliminate the need for a costly hydraulic jump-type stilling basin.

Given the lack of any sizeable hard rock area in the Kootenai River immediately downstream of the dam, the composition of the Kootenai River substrate and the large amount of head, Libby is more suited to a hydraulic jump-type stilling basin for dissipating excess energy. At very high (and infrequent) spillway flows (as indicated by the physical model study at flows greater than 100,000 cfs), the Libby stilling basin effectively operates as a very large flip bucket, producing a very large rooster tail which impacts well downstream of the stilling basin end sill. With very large flows, downstream riverbed and infrastructure damage could be expected (USACE 1984).

The effectiveness of the flip bucket energy dissipater on total dissolved gas exchange depends upon having a shallow receiving basin as an impact point for the high velocity jet. With regard to Libby, an armored basin with a depth of 10 feet or less (floor elevation 2,116 feet) would likely provide an environment where the effective depth of bubbles would limit the amount of TDG exchange to 110 percent or less.

Seven Mile Dam, located on the Pend d'Oreille River in British Columbia, Canada, demonstrates the potential effectiveness of a flip bucket spillway discharging into an adjoining shallow trajectory basin. Seven Mile Dam has been observed to lower TDG levels in the Pend d'Oreille River when forebay conditions exceed 110 percent of saturation. The net reduction in TDG saturation has been attributed to the flip bucket, or "flip lip" spillway, and associated shallow receiving basin. The powerhouse at Seven Mile Dam can pass elevated TDG levels to the downstream river, while water discharged through the spillway generally reduces TDG levels to 110 percent of saturation (RL&L 2002).

As part of a Libby Dam dissolved gas reduction investigation, a variant of this design for modifying just the sluiceway outlets with a flip bucket chute was experimentally evaluated in a 1:50 scale physical model of the Libby sluiceway and stilling basin (USACE 1983) in the early 1970's. The flip bucket chute had a circular transition toe curve to a 30-degree exit angle, discharging at el 2,127.7. The radius of the bucket was not disclosed but photographs indicate that it must have been rather large as the bucket extended well under the stilling basin bridge, with the bucket terminating just downstream of it. The walled chute maintained a rectangular cross section with the exception of a wedge located at the flip bucket lip on the center sluiceway to spread the jet. The impact zone was observed to occur on the run out slope downstream of the stilling basin (meaning the jet just cleared the stilling basin) for a discharge of 10,000 cfs, pool elevation of 2,459 feet (full pool), and tailwater elevation of 2,121.5 feet. The flip bucket concept was considered as part of a solution of anticipated elevated TDG levels associated with sluiceway releases. This specific design was abandoned because of the potential scour of material making up the run out slope and the severe waves generated by design flow conditions. The report gave no indication as to how the presence of the flip buckets impacted the hydraulic performance of the spillway and stilling basin. Given sluiceway flip buckets with the same radius, elevation, and geometry as those in the seventies' study, and the lower head and higher tailwater conditions that would be experienced with a sturgeon flow operation, the trajectory of the high velocity jet would likely be shorter, possibly plunging the jet into the deep stilling basin where high levels of dissolved gas could be generated. The governing equation for flip bucket trajectory distance (USACE 1990, Equation 7-6 used for preliminary design computations; a physical model study is usually required to verify a design) indicates that under conditions that could be expected during a sturgeon flow operation, the trajectory of the sluiceway flow could be about 35 feet less in horizontal distance than the trajectory seen in the physical model study. Increasing the exit angle to 45 degrees could possibly increase trajectory distance but at a lower than full pool head. The impact location of the jet may still be in the stilling basin.

Spillway flip buckets would likely function much differently from sluiceway flip buckets. The much larger specific discharge of the sluiceways would result in a much thicker jet per unit width for a given total discharge than would be produced by the spillway on a unit width basis. Intuitively, it would seem that the jet fraying (considered to be spray that diverges from the core jet in the air) which would take place during the spillway jet's trajectory would represent a much larger portion of the total flow volume than would be represented by jet fraying of the sluiceway flow due to the spillway's much larger width. It would then seem that this difference in frayed volume would leave much less spill volume (given the same sluiceway and spillway flow) to make up a cohesive jet that would plunge to depth in the stilling basin. It is unknown as to whether there would be a significant generation of dissolved gas from this frayed portion of the spillway flow impacting (essentially raining on) the deep water of the stilling basin. Intuitively, it would seem that the overall resulting depth of plunge of the frayed portion of the flow (and resulting dissolved gas levels) would be less than the portion making up the coherent jet. A literature search did not turn up any studies dealing with dissolved gas generation resulting from the dispersion of a high velocity jet. If the frayed portion of spillway flow which is passed over a flip bucket is significant, the equations used to estimate trajectory length might not be applicable. It would seem that the more fraying that occurs, the shorter the trajectory distance.

A cursory analysis of literature dealing with the dynamics of turbulent water jets in air (Blevins 1984) seems to support the above discussion of flip bucket performance of the sluiceways versus the spillway, assuming the spillway/sluiceway jet is analogous to the "turbulent jet" described. The above referenced text gives a relationship (equation set 9-74) that has jet breakup length essentially as a function of jet diameter (assumed to be analogous to jet thickness in this case) and the Weber number (a ratio of the inertial force of a fluid element to the surface tension of the liquid) of the flow. The Weber number of sluiceway and spillway flow would be close to the same, leaving the jet thickness as the predominate variable. Since the depth of spillway flow would be much less than the depth of sluiceway flow, it would be expected from the above referenced turbulent jet breakup length equation that a larger volume of spillway flow would be attributable to fraying than might occur with sluiceway flow.

Adding a structure such as a flip bucket to a dam spillway could affect the hydraulic performance of the spillway and stilling basin. Based on experience with Snake and Columbia River projects, the addition of flow deflectors to spillways has not posed any hydraulic issues that have precluded deflector installation. This might or might not be the case with flip bucket installation. The geometry of the deflectors has allowed spillway flow of low to moderate spills to be effectively turned to produce a desirable skimming flow while at the same time allowing large spillways flows to override the deflector (or plunge as if there were no deflector). The ability of large flows to override the deflector allows the spillway and stilling basin to function essentially as designed in terms of energy dissipation for large spillway flows. This would be a key issue with regard to either flip bucket or flow deflector installation at Libby. What happens hydraulically on the spillway, in the stilling basin, and in the tailrace during the transition from spills that are flipped to spills that override the flip bucket would need to be examined closely. As with flow deflectors, just how the sluiceway outlets would affect a flip bucket operation are unclear. Most likely, sluiceway flip buckets would need to be configured such that they would aid in flipping spillway flow while at the same time providing acceptable sluiceway operation. The stilling basin bridge could interfere with spillway operation with flip buckets, requiring removal of the bridge. Spray from spillway operation and its affect on adjacent structures would need to be considered. Structurally, the large forces on a bucket from spillway flow would need to be evaluated.

A typical horizontal length (parallel to the direction of flow) of installed flow deflectors has been about 12.5 feet, based on successful experience at other projects. Assuming that installing this “typical” structure on the Libby spillway would not produce undesirable hydraulic characteristics, given current flip bucket design guidance, a flip bucket could be designed for Libby within the dimensions of flow deflector structures that have been successfully (i.e., with no adverse hydraulic characteristics) installed at other projects. A graphical analysis indicates that within a 12.5-foot-long deflector, and given the slope of the Libby spillway, the maximum bucket radius would be six feet. Design guidance (USACE 1990) indicates that minimum bucket radius should be at least four times the flow depth in order for the bucket to effectively turn the flow. Estimating the depth of flow is difficult. It is expected that spillway hydraulic losses would be quite low, resulting in very high velocities due to the high head. Given the width of the spillway, this would indicate a very small pure water depth (possibly something like 0.75 feet) normal to the spillway face. However, the depth of flow would be greater than this due to air entrainment, which causes bulking. What this depth might be is unclear, and so is the function of a flip bucket with a six-foot radius given the hydraulic conditions on the spillway face. Available literature suggests that a mixed flow depth is largely a function of spillway slope. Given the analysis in Hager (1991), it would follow that the air-bulked flow depth could be expected to be approximately 2.5 times the theoretical pure-water depth, or about 2 feet. It would seem the spillway flow with this type of air concentration reaching the flip bucket would not have as coherent of a jet as would the sluiceway flow due to the smaller depth of flow and the associated air bulking. If this were indeed the case, a spillway flip bucket probably would not have a very large, well-defined trajectory, but would instead disperse the flow out over a rather large area in front of the dam. As stated earlier, it is unknown whether this would be good or bad for managing dissolved gas levels.

Assuming a six-foot radius bucket is adequate, and that a well-defined trajectory could be achieved (i.e., design criteria applies), the trajectory distance would be estimated at about 270 to 300 feet for a bucket mounted at elevation 2,126 feet and a discharge angle of 45 degrees. This distance would put the jet at about the location of the stilling basin end sill. This location would make construction of a permanent shallow receiving basin difficult and could still leave the deflected flow vulnerable to plunging. Construction of such a structure would likely interfere with stilling basin operation during high spillway discharges as well. It would effectively create a shorter stilling basin with a much higher end sill. It is thought that this would have a dramatic effect on the hydraulics of the stilling basin and tailrace.

Assuming flip buckets could be configured that allow for acceptable operation of the stilling basin, one possible option might be to utilize some type of temporary structure to serve as a receiving basin. One such possibility might be a structure that would be floated into position (similar to the bulkhead used to dewater the stilling basin but on a much larger scale) at the downstream end of the stilling basin and somehow secured in place by tethering or submerging and securing. This structure could be re-floated and towed out of the stilling basin in the event large spills were required. It is unknown whether such a system would be structurally practicable. It is unclear how large this structure would need to be to provide an impingement point for deflected flow. It would have to span the width of the stilling basin (116 feet) and probably be at least 50 feet long. The required submergence is also unclear. It would seem, given the TDG performance and configuration of Seven Mile Dam, that the surface of such a structure would need to be at the tailwater elevation or slightly below. If sinking were required for stability, and a 10-foot submergence required, this would mean the structure would have to be about 42 feet high given the 52-foot deep stilling basin. An end sill of an undetermined height might also be required at the upstream end of this structure to prevent a secondary plunge off the back of the structure into the deep stilling basin. This would likely be a very large structure. Moving it in and out of place could be a large effort. It is unknown what type of equipment would be required.

Probably a better option than the floating structure would be construction of a "fusible bridge" at the downstream end of the stilling basin. This bridge would serve as the shallow receiving basin on to which spillway or sluiceway flow would be deflected. The deck of this bridge would be placed at approximately elevation 2,116 feet, span the width of the stilling basin, and be designed to break apart and exit the stilling basin at a predetermined spillway and/or sluiceway discharge. As with the "barge" option, some type of end sill might be required to direct flow downstream and prevent a secondary plunge into the stilling basin. One of the critical aspects pertaining to the practicability of such a structure would be achieving a design that would be able to withstand the hydraulic forces of the deflected flow but at the same time break apart and exit the stilling basin at some higher flow so the stilling basin could function as designed. It is unclear as to whether either the "barge" option or the "fusible bridge" option would be acceptable from a dam safety point of view. Sketches of both these concepts are shown in Figure 21.

Given the dissolved gas performance of Seven Mile Dam, properly designed spillway/sluiceway flip buckets, and associated receiving basin, would likely provide TDG levels in the Kootenai River that meet the 110 percent standard outside the region of aerated flow. However, it is possible that the TDG levels within the receiving basin could exceed the standard. Thus, a water quality exception could be required from the state of Montana to proceed with sturgeon flow operations under these conditions.

To finalize the flip bucket and receiving basin design, two physical model studies would be required to develop flip bucket and basin geometry and assess impacts with regard to dam safety. This effort would use a sectional spillway/stilling basin model to determine optimum flip bucket features and the location, extent, and shape of the receiving basin. The overall flow patterns in the tailrace would be investigated in a general project model. Both models would be used to verify that the project operates in an acceptable manner for large flood events.

The additions of a flip bucket(s) to the spillway and addition of a receiving basin will not change the ability to meet release water temperature objectives as described for existing conditions. Release temperatures would depend upon the thermal stratification in the reservoir and the elevations of withdrawal. In general, for spillway operations, the water would be withdrawn from the warmer surface waters of the epilimnion to mix with cooler powerhouse water. The addition of flip buckets to the sluiceways would, as discussed earlier in this document regarding sluiceway operation, result in overall colder downstream temperatures compared to spillway use. In addition, lateral temperature gradients could be quite large through the downstream mixing zone.

Some of the considerations regarding a flip bucket system at Libby are:

- Bucket geometry. Can both sluiceway and spillway flip buckets be designed to allow adequate deflection of spillway and sluiceway flow (including the portion of spillway flow over the sluiceway outlets) while allowing satisfactory hydraulic performance at higher flows?
  It seems that a rather compact bucket geometry would be required to allow the bucket to be overridden during large flows. The hydraulics resulting from operation in the transition between pure flipping and structure overriding would be of concern.

- Receiving basin. Given the configuration of Libby Dam, constructing a dedicated receiving basin for deflected flow would be problematic. Two suggestions for a remedy include a “barge” and a “fusible bridge”, both positioned at the downstream end of the spilling basin, at approximately elevation 2,116, to serve as the shallow receiving basin. It is unknown as to what volume of flipped or deflected flow would be frayed. From available research on turbulent water jets in general, it is reasoned that the spillway would produce a larger volume of frayed flow than the sluiceways. It is unknown if there is any reduction in dissolved gas uptake with the frayed portion of the flow impacting downstream versus the main spillway jet impacting the downstream water surface. If the frayed portion of the flow impacting the water surface results in acceptable levels of dissolved gas, and flip buckets could be designed that fray most of the flow, then it is conceivable that a receiving basin might not be needed.

- Downstream infrastructure. Given the close proximity of the stilling basin bridge to the spillway, this structure might interfere with flip bucket operation. The increased spray associated with flip buckets could impact other structures, such as the powerhouse and transmission infrastructure, as well.

Given the many uncertainties with this alternative that would need to be resolved, it is difficult to estimate a cost. It would seem that at a bare minimum for flip buckets only to be designed and constructed, the cost would start at $10 million. Cost would rise depending on what was needed in terms of a receiving basin and other infrastructure modifications. Physical model studies would likely be required to verify hydraulic performance (at both design flow and large flood flows) and assess dissolved gas improvement potential.

4. Tailwater Mixing Structure

A tailwater mixing structure is an alternative that would reduce lateral gradients in TDG and temperature below Libby Dam caused by the joint operations of the spillway/sluiceways and the powerhouse. It would not prevent the production of high dissolved gas levels in the stilling basin. This alternative reduces the TDG level by dilution of high concentrations of TDG in spillway/sluiceway water with hydropower releases. For this alternative, in-stream structures would be constructed to mix spillway/sluiceway and powerhouse flows. These structures would likely take the form of stone dikes, groins, submerged weirs and channel re-contouring as shown in Figure 22. The spillway or sluices would still produce the same levels of TDG, but the submerged structures in the tailrace area would induce more mixing with powerhouse flows to reduce the length of the mixing zone and reduce the area over which the Montana TDG standard is exceeded.

With successful mixing structure(s), the downstream TDG across the entire river would be closer to the flow-weighted averages previously described for existing conditions. For example, with a 10,000 cfs spill (no deflectors, generating 131 percent TDG) and 25,000 cfs powerhouse flow (103 percent TDG), the flow-weighted average TDG is 115.0 percent after complete mixing. This would still leave the reach upstream of the structure with high dissolved gas levels. This alternative might be more effective when used in conjunction with flow deflectors, since the spillway TDG with deflectors (~114-115 percent) is significantly less than spillway TDG without deflectors (~130 percent).

There are no known cases where in-stream mixing structures have been used for TDG management. Thus, the locations and design of the structure(s) would most likely have to be evaluated in a general physical model of Libby Dam and the downstream river reach where the structure(s) would be located. The evaluation of in-stream mixing structure might also show that this alternative is not practicable.

As with all of the downstream alternatives, the addition of in-stream mixing structures will not change Libby Dam's ability to meet release water temperature objectives as described for spill under the existing project configuration. Release temperatures would depend upon the thermal stratification in the reservoir and the elevations of withdrawal. In general, for spillway operations, the water would be withdrawn from the warmer surface waters of the epilimnion to mix with cooler powerhouse water. For sluiceway operations, the water would be withdrawn from the hypolimnion and therefore be colder than powerhouse water. If the sluiceways were used, it would be expected that the lateral temperature gradient downstream would not be as extreme downstream of the mixing structure(s).

The cost for this alternative could be highly variable, depending on the type and number of structures needed. Further study would be required to develop a design and obtain a cost estimate.

5. Side Channel and Spillway

This alternative was evaluated for the lower Snake and Columbia River projects during TDG management studies (CENWP-NWW 1996). It would require constructing a gated intake structure upstream of the dam at the reservoir that transitions into a channel to transport flow around the dam. Upon reaching the spillway location, this channel would transition into a variable geometry channel with one side forming the ogee crest of the spillway. The variable geometry channel is required for the length of the spillway crest to insure even discharge across the spillway face. The spillway itself would be about 330 feet long to achieve a unit discharge of about 30 cfs per linear foot. The spillway would terminate in a stilling basin with a depth of less than 10 feet to minimize plunge depth followed by a transition channel returning the flow to the river.

Figure 23 shows a profile schematic of a concept level design for this alternative, which lends an idea of the magnitude of such a system and the extent of excavation required. Figure 24 shows a plan view of the same concept design. It assumes that such a system would be designed to the same year-to-year reliability level as the current spillway. The area adjacent to the west (right side, looking downstream) side of the dam would probably be the most suitable location. The main transport channel shown in Figure 23 and Figure 24 is trapezoidal in shape, rock-lined, has side slopes of 1:1, a bottom width of about 20 feet, and a top width of about 67 feet. It is placed on a constant slope of 0.2 percent. With a flow of 10,000 cfs, the velocity would be about 11 feet per second and the depth of flow would be 22 feet. The intake structure would have an invert at elevation 2,405 and contain two 48 x 59 foot radial gates identical to the existing spillway. To maintain the same elevation-discharge relationship as the existing spillway, these new gates would need to sit on top of a similarly shaped spillway crest that operates in an unsubmerged condition. Since the depth of water in the trapezoidal channel would be about 22 feet, in order for the intake gate to be able to operate under unsubmerged conditions, the invert of this channel would need to be placed at least 22 feet below the intake invert (in reality this distance would likely be greater), or below elevation 2,383.

From Figure 9, a pool elevation of about 2,415 is required to discharge 10,000 cfs under free-flow conditions. If the invert of the trapezoidal channel were placed at a higher elevation, then the rating curves shown in Figure 9 would not be the same. A higher pool elevation or a wider intake structure would be needed to produce the same flow for a given gate opening when the intake structure crest is submerged. Given the initial design requirement of maintaining the same reliability as the existing spillway, given the choice of intake structure used, and given that the surrounding topography in the area of the right abutment is about elevation 2,480 feet, an excavation of about 100 feet deep would be required. A much larger intake structure might allow this depth to be decreased by some amount, but probably no more than 10 to 15 feet. If a level of reliability greater than the current spillway were required, then the depth of excavation would increase as well. The crest elevation of the side channel spillway is dependent on the selected location for the spillway, the slope of the channel, the distance from the intake location to the spillway location, and the hydraulic head required to provide the needed flow. For the last 330 feet of the system, the spillway crest would be the left side of the channel. In order to obtain a uniform flow along the spillway face, the channel geometry and/or the crest elevation in this area would have to be variable.

While this alternative appears conceptually capable of producing relatively low levels of TDG, there are numerous other items that would require consideration, including, as mentioned earlier, the extent of excavation needed to get the channel around the dam. Such an excavation would likely require relocation of the visitor’s center, parking lot and access road. Geotechnical and dam safety issues with regard to the integrity of the right abutment of the dam would also need consideration. Once around the dam, the channel would then be built on a steep hillside, requiring very large amounts of fill and possibly complex retaining structures. The channel, from the intake structure to the downstream spillway, would be at least 2000 to 3000 feet long, probably longer, depending upon a suitable location for the spillway. The spillway would be constructed into the side of the hill leading down to the river.

On the Snake and Columbia River projects, this alternative was expected to limit TDG levels to less than 110 percent. When applied to Libby, similar results could be expected. While the spillway would be higher than at any of the Snake or Columbia River projects, the very low flow per unit width and the very shallow stilling basin should limit the amount of gas forced into solution. Release temperatures through the side channel spillway would be similar to the temperatures released through the existing spillway. The water would be withdrawn from the warmer surface waters of the epilimnion.

For Lower Granite Dam, the cost of this alternative was estimated to be $302 million (1996 dollars) (USACE 1999). While the Lower Granite system would have a much higher capacity (96,000 cfs vs. 10,000 cfs), the costs associated with the required excavation, construction of the channel on the hillside, and the very high spillway at Libby would likely be much higher. Additionally, this alternative would require extensive hydraulic and geotechnical investigations. The variable geometry channel approaching the spillway would require a physical model study to ensure that the design performs adequately. A more detailed study would also be needed to develop a cost estimate for this alternative.

6. Baffled Chute Spillway

A baffled chute spillway dissipates energy on impact blocks as flow moves down the spillway (Figure 25 presents a conceptual sketch not specific to Libby). Thus, at the downstream end of a baffled chute spillway, little energy is remaining that requires dissipation in a stilling basin or plunge pool. Peterka (1978) gives design information for a baffled chute spillway, the dimensions of which depend upon the unit discharge. If used as a stand-alone alternative, like the side channel spillway, a baffled chute spillway would require construction of a gated intake structure with a rock-lined channel leading to the baffled spillway. With a unit discharge of 100 cfs per foot of width, the spillway would be 100 feet wide to pass the 10,000 cfs discharge. The spillway would consist of a straight chute with offset rows of vertical baffle blocks, leading to a shallow discharge apron. A connecting channel would deliver spillway releases to the river. Essentially all the infrastructure for this alternative, up to the actual spillway would be the same as the previous alternative and be subject to the same design process.

As a stand-alone alternative, a baffled chute spillway suffers the same issues as the side channel spillway. Deep excavation for a gated release structure would be required. A lengthy channel would be needed to transport release water to the spillway location. Operation of the baffled chute spillway would also be limited to those periods with high pool elevations, if the intake structure were constructed at the existing spillway elevation of 2,405. The advantage of this alternative over the Side Channel and Spillway is that the baffles allow for a much narrower spillway.

Measurements of dissolved gas transfer at a baffled chute spillway (Klohn, Leonof 1991) showed that about five rows of baffle blocks were needed for dissolved gas to reach an equilibrated state when discharged to the shallow spillway apron. Additional analysis would be required to estimate the equilibrium level of dissolved gas for a Libby Dam structure, but it would likely be below the state criteria of 110 percent TDG (Wilhelms 1991). Release temperatures through the baffled chute spillway would be similar to the temperatures released through the existing spillway or the Side Channel and Spillway alternative. The water would be withdrawn from the warmer surface waters of the epilimnion. Lateral gradients in temperature would likely occur downstream of the confluence of the baffled chute spillway tailrace and the Kootenai River.

This alternative is expected to be quite expensive, similar to the side channel spillway with extensive hydraulic and geotechnical investigations and a physical model study to ensure that the design performs adequately. A more detailed study would be needed to develop a more accurate cost estimate for this alternative.

7. Raised Stilling Basin Floor

The concept of a raised stilling basin was evaluated for application to lower Snake River projects (USACE 1996). Raising the stilling basin apron reduces the depth to which aerated spillway flow can plunge, thereby reducing the hydrostatic pressures that the air bubbles experience. As a consequence, TDG levels generated in the stilling basin are reduced. The idea behind raising the stilling basin floor is similar to the idea behind a flow deflector.

No examples of a stilling basin modification of this type could be found. In order to estimate changes in dissolved gas levels, comparisons of other projects with different stilling basin configurations are used. It is thought that the Ice Harbor project has a stilling basin that might represent Libby's current configuration, and The Dalles project stilling basin might represent a modified condition. The TDG levels monitored at the end sill of the Ice Harbor stilling basin prior to flow deflector installation reached as high 167 percent saturation with a discharge of 6,000 cfs per spill bay or 120 cfs per foot of spillway (Schneider and Wilhelms 1997) and a basin depth of 45 feet. In contrast, the TDG saturation at The Dalles stilling basin end sill, with a stilling basin depth of 25 feet, did not exceed 140 percent saturation during spill events with discharges as high as 15,000 cfs per bay or 300 cfs per foot of spillway (Schneider and Wilhelms 1996). With Libby Dam's stilling basin depth at approximately 52 feet, TDG levels higher than Ice Harbor could be expected in the stilling basin. The Libby stilling basin has a floor elevation of 2,073 feet, and at a total project discharge of 35,000 cfs, the depth of the stilling basin is about 52 feet.

To effectively reduce TDG production, it is thought that the stilling basin depth should be less than 20 feet at the design flow. This value is based on observations at The

Dalles Dam. Based on comparisons between the Ice Harbor and The Dalles spillway, a raised stilling basin would likely produce TDG levels in the stilling basin under the 140 percent observed at The Dalles. With degassing in the tailrace, the TDG exiting the tailrace will likely be in the range of 115 percent (Schneider and Wilhlems 1998) for a unit discharge of 100 cfs per foot of spillway width. For Libby Dam, the unit discharge for a 10,000 cfs spill is 86 cfs per foot. This suggests that the raised stilling basin alternative would produce similar results as spillway flow deflectors. This estimate should be used with caution. There is no known example of a stilling basin floor being raised with documented changes in dissolved gas levels.

This alternative would also likely reduce TDG from sluiceway usage. The higher specific discharge associated with the sluiceways makes comparison with other projects uncertain, but compared to spillway releases, higher TDG pressures would be expected from sluiceway use as compared to spillway use.

This alternative would require a physical model study to assess hydraulic performance of a modified stilling basin for the design flow of 10,000 cfs and for higher discharges up to the maximum probable flood flows. The present Libby stilling basin is approximately 275 feet long, 116 feet wide and has a floor elevation of 2,073 feet. As mentioned, at a total project discharge of 35,000 cfs, stilling basin depth is about 52 feet. The kinetic energy dissipation required to transition from the high velocity, supercritical spillway or sluiceway flow to lower velocity, subcritical tailwater flow is accomplished via a hydraulic jump. The stilling basin serves as a location for the formation of the hydraulic jump, and can withstand the forces generated by the extreme turbulence of the jump without any damage to the dam, tailrace, and/or related infrastructure.

An important aspect of stilling basin design is setting a floor elevation. In theory, the floor elevation must be such that the downstream tailwater depth (or elevation) is the same or slightly higher than the sequent depth of the incoming stilling basin flow depth. The relationship between incoming stilling basin supercritical flow depth and the corresponding downstream subcritical flow depth, or sequent depth, is given by a standard equation pertaining to hydraulic jumps in flat, rectangular channels (USACE 1990, Equation 2-26). If the floor elevation is too high, the jump can form downstream of the stilling basin, which can cause erosion and scour. Using standard hydraulic jump theory and stilling basin design guidance (USACE 1990) for a spill of 10,000 cfs and a tailwater elevation corresponding to a total project outflow of 35,000 cfs (25,000 cfs powerhouse and 10,000 cfs spill), the maximum stilling basin floor elevation would be about elevation 2,100 feet, resulting in a depth of about 26 feet. If the floor were placed at a higher elevation, so that the sequent depth of incoming flow was greater than the tailwater depth, then the jump would occur farther downstream. In theory, when the sequent depth is greater than the tailwater depth, the downstream position of the jump is primarily a function of this difference.

The present Libby stilling basin is designed to completely contain the hydraulic jump for spillway discharges up to 50,000 cfs. Above 50,000 cfs, the jump begins to form out of the stilling basin and into the tailrace area. At 90,000 cfs the jump forms downstream of the stilling basin. Above 50,000 cfs, energy dissipation outside of the stilling basin, in the tailrace, may cause tailrace erosion. However, events requiring spills of more than 50,000 cfs are very rare, and a longer stilling basin was not deemed necessary. If the apron were raised to an elevation of 2,100 feet, as shown in Figure 26, and given the discussion of the previous paragraph, the hydraulic jump would move out of the basin at discharges much lower than 50,000 cfs. In order to retain the energy dissipation of the original design, either length would have to be added to the existing basin or an additional downstream stilling basin would have to be added to dissipate the energy that would be exported from the stilling basin to the tailrace. The physical model study would address the revised apron elevation and the design of the secondary stilling basin, and develop other design modifications as needed to ensure the project operates properly at high flows.

Assuming the stilling basin floor could be raised to elevation 2,100 feet, the depth available for spillway/sluiceway flow to plunge would still be about 25 feet. Experience with flow deflectors indicates that for a design discharge, a properly designed flow deflector would result in an initial plunge of less than 25 feet. Downstream of the deflector, the skimming flow pattern generated by the deflector would help to reduce the depth and resulting hydrostatic pressures the highly aerated spillway/sluiceway flow would experience. While raising the stilling basin floor does result in a definite boundary that would reduce the depth of plunge for all spillway flows, it is thought that in reality, at a specific design flow, properly designed flow deflectors would produce dissolved gas levels that would be the same or better than this option with far fewer issues and much lower cost.

Elevating the existing stilling basin floor to elevation 2,103 (to produce a flow depth of approximately 23 feet at 35,000 cfs) would require approximately 40,000 cubic yards of material. As discussed above, requirements could include a secondary stilling basin and possibly raising and reinforcing the existing stilling basin training walls. These elements could pose major constructability problems. In addition, the stilling basin bridge could interfere with the different hydraulic conditions resulting from raising the floor elevation. An in-depth feasibility and physical modeling study would be required to determine the viability of this alternative and develop an accurate cost estimate.

A possible solution to the hydraulic issues presented by a higher stilling basin floor elevation and resulting high-flow hydraulic issues might be a structure that would serve as removable floor. This structure would utilize a floating “barge” that would “dock” against the spillway and either be tethered or submerged. Figure 27 shows a concept level sketch of this idea. Conceptually, this structure would prevent spillway flow from plunging to the bottom of the stilling basin. In the event that high flows would need to be passed over the spillway, the structure would be floated (if submerged) and removed from the stilling basin, allowing for normal stilling basin operation. There is no known example of this type of system being employed to reduce the depth of a stilling basin. Obviously, if the entire floor needed to be raised in this manner, a very large floating vessel, or group of vessels would be required. If only a portion of the floor were raised in this manner, it is unclear what the effect on dissolved gas levels would be. From just a hydraulic standpoint, this structure could be made long enough to contain just the hydraulic jump resulting from the design conditions. Using basic stilling basin design concepts (USACE 1990), for a design spillway flow of 10,000 cfs, and a tailwater elevation of 2,126.5 feet (corresponding to a total project discharge of 35,000 cfs), the floor elevation required to match up tailwater elevation with incoming flow sequent depth would be approximately elevation 2,100 feet.

Guidance regarding stilling basin length yields values of approximately 134 feet. This would be the estimated length and depth required to contain the hydraulic jump generated for the given flow and tailwater conditions entirely on the removable structure. While the initial plunge depth would be reduced, the “barge” dimensions would leave about 140 feet of stilling basin length that would still have 52-foot-deep water. From a dissolved gas standpoint, what improvement could be expected compared to the existing condition, or to other alternatives, is unclear. A concern is that the highly aerated water would just plunge, or roll, off the end of the structure, resulting in elevated dissolved gas levels. The flow would be subcritical at this point and there would not be a high velocity jet to drive a skimming flow pattern as with a flow deflector. The structure could be shortened to ensure a supercritical flow regime off the end in an attempt to generate a skimming flow. In this case it would seem much more practical to simply configure the spillway with flow deflectors. It would seem that for this option to be much of an improvement over existing conditions, the entire stilling basin floor would need to be raised in this manner. The practicability of restraining such a structure, such that it would be stable when subjected to the forces generated by the high-energy spillway jet, is uncertain. Probably some type of deflector (see Figure 27) would be required to insure the spillway jet does not impinge on the interface between the barge and the spillway, creating instability. Furthermore, the configuration of the sluiceway outlets in the spillway face would preclude a smooth barge-spillway interface over about 30 feet. Probably the sluiceway outlets would need to be configured with flow deflector type structures as well, to insure the spillway jet impacts the barge only on the top horizontal surface. It is not known how these structures would affect the hydraulic performance of the spillway and/or sluiceways during large flood events.

While a removable stilling basin floor might be a way around the hydraulic issues posed by raising the floor permanently, the cost of implementing and constructing this system is unknown. Studies would be required to determine if a practicable system could be developed. There are a myriad of issues that would need to be considered and resolved. Some of these include:

- Ultimate benefits. Permanently raising the entire floor might not provide dissolved gas levels below 110 percent or levels which are any better than would be realized with flow deflectors. Configuring a system that only raises part of the floor still leaves a portion of the stilling basin with deep water and the potential to generate high levels of dissolved gas.

- Structural issues. Whether a barge or system of barges could be utilized in a manner (either floating or submerged) that is structurally sound and does not pose a safety hazard to the dam or adjacent infrastructure is unknown.

- Logistics. What would be needed to safely remove these barges, how much time would be required to remove them, and where the barges would be moored after removal is unknown. Would a large tug be required? Is the tailwater deep enough for the draft of one of these vessels?

As discussed for other alternatives, release temperatures would depend upon the thermal stratification in the reservoir and the elevations of withdrawal. In general, for spillway operations, the water would be withdrawn from the warmer surface waters of the epilimnion. Because of the variability in spring inflow, the spillway may not be usable during the 15 May to 15 June time period. For sluice operations, the water would be colder, withdrawn from the hypolimnion. As discussed earlier, lateral temperature gradients could be quite large through the downstream mixing zone.

8. Raised Tailrace Channel

The concept of raised tailrace topography was evaluated for application to lower Snake River projects (USACE 1996) with particular emphasis on the Ice Harbor Dam (Schneider and Wilhelms 1998). For this alternative, the elevation of the channel bed would increase for a distance up to 250 to 500 feet downstream of the stilling basin as shown in Figure 28. It would not prevent the absorption of dissolved gases in the stilling basin, but would aid in the de-gassing of the spillway or sluiceway flow in the tailrace. This alternative is effective as long as entrained air bubbles are still in solution, but above the compensation depth. Thus, in general, this alternative is effective for only a short distance downstream.

The armored Libby tailrace was designed to be at a uniform elevation of 2,110 feet (USACE 1983). At a total project discharge of 35,000 cfs, the tailwater elevation is approximately 2,126 feet, providing a design tailwater depth of about 17 feet. This makes the Libby Dam tailrace very shallow compared to the projects on the lower Snake and Columbia Rivers. For the Ice Harbor Dam evaluation, a minimum depth of 10 feet was recommended. Filling the tailrace from elevation 2,110 to elevation 2,117 would likely reduce TDG levels downstream of the raised portion by only 1 to 3 percentage points, based on Schneider and Wilhelms' 1998 analysis for Ice Harbor. For spillway operations with 130 percent TDG production (as measured approximately 150 feet downstream of the stilling basin end sill), raising the tailrace channel could reduce the TDG exiting the tailrace to about 127 percent. For this spillway TDG and a powerhouse TDG of 103 percent, the flow-weighted average would be about 110 percent. Similarly, for sluiceway releases, the TDG levels could be reduced from about 138 percent to 135 percent, resulting in a mixed TDG level of about 112 percent, still above the Montana standard.

Elevation mapping conducted in the mid 1970s shows that the tailrace is actually higher than the design elevation of 2,110 feet in many locations. The mapping indicates that the tailrace topography reaches elevations as high as 2,117 feet between the end of the stilling basin and the Thompson Bridge (this high spot can be seen as a dark spot in the middle of the tailrace just upstream of the Thompson Bridge in Figure 1) and as low as elevation 2,100 feet along the eastern edge of the channel just upstream of the bridge. It is unknown how the rate of degassing of the existing tailrace condition would compare to the as-designed condition.

Raising the tailrace would provide some improvement in dissolved gas levels, but would not achieve TDG levels of 110 percent except when fully mixed with powerhouse flows. This alternative only aids in the de-gassing of supersaturated flows. It does not prevent the generation of high levels of TDG in the stilling basin, leaving many locations with TDG in excess of the state standard.

Release temperatures would depend upon the thermal stratification in the reservoir and the elevations of withdrawal. In general, for spillway operations, the water would be withdrawn from the warmer surface waters of the epilimnion. For sluiceway operations, the water would be colder, withdrawn from the hypolimnion. As discussed earlier, lateral temperature gradients could be quite large through the downstream mixing zone.

With a 10 ft/sec velocity and 10-foot minimum depth, the required channel width would be at least 350 feet. To raise the tailrace area by 7 feet for a 250- to 350-foot area (87,500 ft^2), nearly 23,000 yd^3 of material would be required. The fill would be protected by riprap, grout, or concrete cap to prevent erosion. For Ice Harbor Dam, the cost estimate to raise the tailrace by 9 feet for 250 feet in length was $5.4 million. For Lower Granite, the cost estimate to raise the tailrace by 14 feet and 350 feet in length was about $70 million. A more detailed study would be required to develop a cost estimate, but the cost for modification at Libby would likely be less than the Ice Harbor estimate. To develop an acceptable design for this alternative, a physical hydraulic model would be required.

9. Modification of Sluiceway Outlets

For this alternative, one or more of the sluiceways would be modified to submerge their outlets. The sluices would operate in a pressurized state, like the penstocks, thus not entraining any air and discharging below the surface of the tailwater. Grand Coulee is similar to Libby in that it has regulating outlets with outlets in the main spillway face. The Bureau of Reclamation investigated the installation of extensions to the sluiceways to discharge the flow below the tailwater surface (USBR 2000). The Bureau's design configured the outlet of each regulating outlet such that hydraulic control would be shifted from the upstream service gate downstream to the submerged outlet. This would change the flow regime in the conduit from one of open channel flow, which entrains air, to one of pressurized flow, which does not entrain air.

This concept was never implemented at Grand Coulee. Instead, it was proposed that dissolved gas management at Grand Coulee could be accomplished by a spill and power swap involving Chief Joseph Dam, downstream. It is anticipated that when Chief Joseph is configured with flow deflectors, the dissolved gas levels resulting from spill will be reduced. Under this proposal, Grand Coulee would produce some of Chief Joseph's power, reducing Grand Coulee spill, and thus Chief Joseph forebay dissolved gas levels. Chief Joseph would in turn spill water that Grand Coulee would have been required to spill at lower dissolved gas levels, thanks to flow deflectors.

As with the Grand Coulee concept, the modification of the Libby sluiceways would create a pressurized flow regime in the sluiceway conduits and discharge the flow completely below the stilling basin water surface, similar to the powerhouse discharges. A conceptual sketch is shown in Figure 29. In order to pressurize the sluiceway, flow control would be shifted from the existing service gate (when fully open) to the sluiceway outlet. The Grand Coulee study proposed to accomplish this by reducing the size of the outlet and creating a constriction. At Libby, the sluices are an integral part of providing outlet capacity for the probable maximum flood; so preserving this capacity is a pre-requisite for any modification. This might preclude the use of a permanent outlet constriction to shift hydraulic control.

One possibility might be the installation of a removable steel orifice plate over one or more of the sluiceway outlets. Since the sluiceway outlets are approximately halfway submerged by the tailwater at a project outflow of 35,000 cfs, the orifice(s) would be placed in the portion of the plate below the water surface as shown in Figure 30. If the plate reduced the hydraulic capacity of the sluiceway(s), it would have to be designed such that it could be easily and quickly removed in the event the design capacity of the sluiceway(s) was required. Although the sluiceways are used very infrequently, it is unknown as to the acceptability of a "quick removal" system. Calculations (based on published orifice head loss data (Miller 1990)) indicate that a plate could be designed for one sluiceway and provide a flow of about 15,000-20,000 cfs at a pool elevation of 2,420 feet. At a full reservoir elevation, initial calculations (using estimated head losses through a sluiceway) show that one sluiceway, under a pressure flow regime, could still deliver the design flow of 20,000 cfs.

The forces on such a plate would be very large. It is unknown if an anchoring system could be designed to anchor a plate to the outlets that would withstand these forces. The most likely scenario for such a system would be the addition of wing walls, which extend outward from the spillway face (shown in Figure 30) on either side of a sluiceway outlet. These walls would have a top cover and slots for a plate. This would likely be a very substantial gate, possibly weighing 50 tons or more. If the hydraulic capacity of the sluiceway could not be preserved, the system would need to be designed such that the plate could be quickly removed. It is unknown from a dam safety perspective if some type of "quick removal system" would be acceptable. The new plate housing walls would need to be designed so they did not adversely affect spillway operation or project hydraulics. The required plates would undoubtedly be very heavy. The practicability of using a mobile crane (and the local availability of such a crane) to remove them, if needed, is unknown. Probably the best location for crane removal would be the stilling basin bridge. Whether this bridge could support the weight of a crane and plate is unknown. Given the close proximity of this bridge to the spillway, it likely would interfere with the required modifications and need to be removed anyway.

As currently configured, the existing sluiceway service gate does not operate in a submerged condition. This alternative would cause the gate to be submerged. Ramifications of submerging the service gate(s) and the associated equipment would need to be investigated.

From a hydraulic standpoint, three major concerns are cavitation, the flow pattern out of the orifice(s), and system startup. The high head differential between forebay and tailwater, and the resulting high velocities through the orifice plate would make such a system a candidate for cavitation. If this were a problem, one or more additional plates could be required, adding to the complexity of designing a "quick removal" system. The characteristics of the flow out the orifice(s) and the required submergence would also need to be looked at. Depending on these flow characteristics, the high velocity jet from the plate could end up entraining air and adding to TDG levels. It is unknown whether the sluiceway outlet geometry and the tailwater elevation would allow for a plate configuration that would provide the required submergence to prevent additional air entrainment. If the 10,000 cfs of additional flow were spread out among all three sluiceways, the required orifice opening would be smaller and the resulting submergence greater. However, this may reduce the ultimate full-pool capacity of the sluiceways, requiring a system with gates that can be quickly removed. Based on approximate calculations, assuming a flow of 20,000 cfs through one sluiceway (this flow provided the best cavitation index value), a submergence of about five feet might be attainable.

Whether this value would be sufficient to prevent air entrainment in the stilling basin is unknown.

The other concern would be system startup. With simply an orifice, there would be a point where the flow regime would transition from open channel flow to pressure flow as the service gate approached the full open position. Typically this transition is not hydraulically stable. Also, as the service gate is opened, a hydraulic jump could form just inside the plate due to the backwater from the tailrace. For start up it would be preferable to have some type of valve (possibly a hollow-cone valve, capacity and operating head to be determined) on the plate. It would seem that a valve of some type would resolve the startup issues but how such a valve would be operated given its position close to the spillway face and how it might affect spillway operation is unknown.

Presuming no air entrainment and sufficient submergence of the high velocity jet from the plate by the tailwater, this alternative should function like the powerhouse and not appreciably add to forebay dissolved gas levels. As discussed elsewhere, with operation of the sluices, the sluice water will likely be colder than powerhouse releases, reducing the capability to meet the release temperature criteria.

A physical model study would be required to investigate the technical practicability of this alternative and arrive at a cost estimate. If a system could be configured (temperature issues aside) with one plate (or a minimal number of plates), this could be a relatively inexpensive alternative.

Some of the major issues that would require further investigation are:

- Does the required outlet (either valve or orifice) submergence to prevent air entrainment require modification of more than one sluiceway?
- Can one or more sluiceway outlets be modified and still provide the required outlet capacity under a pressure flow regime?
- Is a “quick removal” system acceptable and practicable from an operational and a dam safety point of view?
- Will modifications to facilitate this type of system still allow acceptable spillway operation?
- Hydraulic issues. Can the required outlet submergence be achieved? Would cavitation be an issue? Would the system be hydraulically stable from the point of startup through the point of becoming completely pressurized?

- Structural/mechanical issues. Can a system be structurally configured to withstand very large forces generated by a high hydraulic head? Will the stilling basin bridge interfere with the design? Can the existing service gate and associated equipment be operated in a pressurized state?

10. SIPHON/DEDICATED PRESSURE FLOW SYSTEM WITH AUXILIARY STILLING BASIN

One alternative suggested as a means of passing additional flow at Libby is the installation of a siphon over the top of the dam. This concept would involve some type of conduit(s) routed up and over the crest of the dam, with an inlet located in the reservoir and an outlet discharging at the downstream tailwater. When the crest of a siphon is completely filled with water, evacuating all the air, the gravity pull of water in the lower leg will maintain a continuous flow throughout the system. The siphon will continue to operate until air is introduced to the system. The major limiting factor in siphon design is the vertical distance from the hydraulic grade line to the top of the siphon conduit. When the elevation of a closed conduit rises above the elevation of the hydraulic grade line, negative pressures will be experienced in the conduit. If these negative pressures become too extreme, cavitation damage and/or conduit collapse can occur. The vapor pressure of water is the limiting factor for these negative pressures. If the pressure in the pipe drops to the vapor pressure of water for a given temperature, about negative 32 feet of head, the water will boil. Typically for design purposes, the maximum elevation between the top of the conduit and the hydraulic grade line is about two thirds of the vapor pressure of water or about 20 to 22 feet, depending on elevation (Street 1996).

Due to the fact that typical pool elevations at the time of sturgeon flow operations are in the vicinity of 2,400 to 2,420 feet, it would not be possible to configure a siphon that would follow a route up and over the top of the dam. For use at Libby, a siphon system would require boring or tunneling through the dam to maintain acceptable conduit pressures for a given minimum design reservoir elevation. If a minimum operating pool elevation of 2,400 feet were used, the maximum elevation the top of the siphon conduit could reach would be dependent on the hydraulic characteristics of the system. Realistically, this elevation would probably not be much greater than elevation 2,400 feet. If 10-foot-diameter conduits were used (probably five or six conduits would be required), approximately 45 to 50 feet of tunneling through the dam per conduit would be required.

Figure 31 shows a concept level design for a siphon-type bypass system. The system would take advantage of a pressure flow regime that, from a theoretical standpoint, would not entrain air. The minimum operating pool elevation is 2,400 feet. It would incorporate five, 10-foot-diameter concrete conduits with gated intakes and exits. The maximum design velocity is 25 ft/sec, which equates to a flow of about 2,000 cfs per conduit. The downstream gates would serve as the hydraulic control for the system.

Excess energy would be dissipated in a dedicated stilling basin about 80 feet wide and 180 feet long. The stilling basin floor would be at elevation 2,090. Due to negative pressures generated by the relatively high design velocity, the maximum elevation of the top of the conduit would be roughly elevation 2,400, meaning it would be submerged for the operating pool range. Reducing outflow via the downstream gates would decrease velocity, decreasing head losses, and decreasing pressures in the crest of the conduit. This would allow for a higher elevation placement of the conduit but additional or larger diameter conduits would be needed to make up for the reduction in flow.

Alternately, Figure 31 also shows a non-siphon variation of this alternative. It would be essentially the same but pass through the dam at a lower elevation, most likely the elevation of required intake submergence, elevation 2,365 for this concept-level case. This type of configuration would eliminate negative pressure drawbacks, and result in a shorter overall conduit length, but would require an additional 30 to 35 feet of tunneling per conduit.

Regardless of the configuration, cavitation and the discharge flow patterns would be of concern. Due to the high head, in order for the downstream gate valves to throttle the system to the design velocity, they would be operating with a relatively constricted opening. This is likely to set up a condition for cavitation in the vicinity of the gate. If this was indeed an issue, one possible solution might be the installation of one or more perforated plates upstream of each gate valve, allowing the gate valve to be operated with a larger opening. A system of perforated plates prior to the discharge gate valves could also reduce the size of the stilling basin. Depending on the flow characteristics out of the gates and into the stilling basin, it is possible that air entrainment would occur, possibly resulting in elevated dissolved gas levels. The stilling basin floor would need to be designed at an elevation such that the hydraulic jump formed by the flow out of a conduit would be submerged by the tailwater. The amount of submergence required to prevent air entrainment in the stilling basin is unknown. A gated intake structure at the conduit's entrances would be needed. Some type of structure(s) would be needed to facilitate operation of the intake gates. This would probably be a complex and expensive component of such a system.

Most likely a major hurdle for this alternative from a cost, technical, and dam safety standpoint would be the tunneling/boring through the dam. Tunneling through mass concrete has been done at Little Goose, John Day, and Lower Monumental dams (CENWW 1989). At Libby the shortest distance through the dam would be approximately 45 feet. Based on the above concept design utilizing five 10-foot-diameter conduits, the total volume of material to be removed would be about 655 cubic yards. Using the per-yard estimate for the Lower Monumental project (CENWW 1989), and adjusting for inflation (assuming 4 percent per year), the total concrete removal costs would be about $1.3 million. Dam safety concerns in tunneling through a dam would also have to be considered.

This concept-level design is intended to serve only as an illustration of the items that would have to be taken into consideration in the design of this type of facility. Some other variations of this concept could be explored, especially with regard to energy dissipation. A smaller stilling basin with a different configuration might be possible. Another possibility would be to investigate routing the conduits into the existing stilling basin through the left training wall. In any case, a physical model study would be required to determine the practicability, final design, and cost of this alternative. It is anticipated that the cost of this alternative would be greater than the average of the alternatives examined in this study.

11. Penstock/Draft Tube Conversion to Regulating Outlets

Only five of the eight power-generating units originally designed for Libby Dam were installed. Currently, units 6, 7, and 8 have the spiral case/wicket gate/turbine assemblies installed but not the generating units. This alternative would use one or more of the unused penstocks, or skeleton bays, to pass additional flow above the current powerhouse capacity. However, the large difference in elevation between the Libby reservoir water surface elevation and the tailwater provides a large amount of potential energy that must be extracted (via a hydropower turbine) or dissipated.

Berger/Abam Engineers, Inc., (Berger/Abam 2002) investigated the practicability of converting one or more of the unused penstocks/skeleton bays to regulating outlets. They considered two potential methods:

(a) Installing perforated orifice plates in the penstock to dissipate excess hydraulic head. They concluded that this would require numerous plates with structural design and installation issues.

(b) Replacing the turbine, wicket gate assembly, and the head cover with a custom head cover fitted with multiple energy dissipating valves that would discharge into the draft tube. They concluded that this unprecedented use of these valves would require substantial development and would not produce the needed additional flow.

The Berger/Abam report did not include any specific numbers to go along with its orifice plate analysis. A review of available texts dealing with fluid dynamics (Miller 1990, Blevins 1984) provided information for a more detailed investigation into energy dissipation using perforated orifice plates.

An orifice plate located inside a closed conduit is a common type of flow measurement device and as such, there is quite a bit of orifice plate head loss data available. An orifice plate dissipates energy by imposing a sudden change in boundary which causes an increase in turbulence in the vicinity of the plate. As a result, eddies are formed in the wake of the plate which spread downstream and eventually decay. Energy is dissipated via the viscous shear occurring within this turbulent flow downstream of the plate (Rouse 1946). Energy dissipation attributable to the orifice plate is complete when the intensity of the turbulence downstream of the plate is reduced to essentially the intensity of the turbulence of the flow approaching the plate. In addition, the development of turbulent flow downstream of the plate is marked by a reduction in pressure. Some of this pressure is recovered downstream of the plate (Rouse 1946). If the pressure drop created by the orifice plate is great enough, cavitation can occur. The ratio of orifice diameter to conduit diameter impacts the amount of pressure drop downstream of the orifice and the distance required for all of the energy to be dissipated. Smaller ratios (i.e. greater disturbance caused) produce a greater degree of energy dissipation but also result in a greater pressure drop, potentially causing a cavitation issue. This can result in the need to use multiple plates to dissipate the desired amount of energy.

From a cavitation standpoint, it appears that placing plates lower in the system would allow more energy to be dissipated per plate for a given cavitation index level. In addition, fitting the penstock with plates would logistically be difficult due to very limited access. This exercise looked at perforated plates placed in the draft tubes of two unused skeleton bays from purely a hydraulic perspective, using theoretical procedures coupled with available empirical data. No consideration was given to the structural aspects of using perforated plates. Some of the assumptions made for this analysis include:

1) Maximum flow through each penstock is 5,000 cfs. Without information about the structural forces for which the system was designed, there is concern that anything higher than the current maximum capacity with the turbines in place would increase the forces within the system to unacceptable levels. In addition, higher flows would likely make cavitation issues worse.

2) Design pool elevation is 2,420 feet.

3) Turbines are removed and the head cover is modified. It is unknown if the wicket gates could be left in place and be operational.

4) Hydraulic losses (due to bends, friction, etc.) within the system are negligible. No wicket gate energy losses were accounted for. Given the concept-level of analysis and the relatively low velocities associated with 5,000 cfs, these system losses would likely be small.

5) With regard to cavitation, incipient cavitation (cavitation parameter equal to about 2.5 (Blevins 1984)) is used for the level of design.

6) Flow evenly splits upon entrance to draft tube diffuser.

7) Orifice plates used are in the "thin plate, sharp edge" category. Given the high head and resulting forces generated within such a system, it is unknown what thickness plate would be appropriate and what type of anchorage would be required.

8) No consideration given to debris blockage.

Initial calculations indicate that six to eight plates would be required per draft tube. Each draft tube separates into two diffusers at a point downstream of the turbine location. Each of these diffusers would require three to four plates, with the first plate dissipating the most energy, and each subsequent plate dissipating a lesser amount of energy. Figure 32 is a schematic of the penstock/skeleton bay/draft tube system. For the concept level design described above, the plates would be placed in the draft tube starting just downstream of the divider pier nose.

Spacing of the plates poses a problem. In order to achieve the desired level of energy dissipation, the plates need to be spaced far enough apart such that the flow passing through the orifices has enough distance to fully expand before the next orifice. Likewise, the last orifice plate would need to be located such that the flow would fully expand before discharging into the tailrace area. Using sudden enlargement guidance (Blevins 1984), it was estimated that the jets exiting from the orifices would expand at a length to width ratio of about 9 to 1. This would mean the plates dissipating the most energy would require spacing farther apart. The estimated total required length for three plates is approximately 50 to 60 feet. There is only about 35 feet of space from the draft tube pier nose to the exit. This indicates that some type of extension structure might be required or further investigation is needed into the possibility of spacing the plates closer together within the existing confines of the draft tube. The concern is if the plates are spaced too close together, the required amount of energy dissipation per plate will not be achieved. Plates could be placed higher up, in the penstock, but this would require more plates to dissipate the same amount of energy due to higher cavitation potential. The first several plates that dissipate the most energy also have orifice area to total plate area ratios well below 0.5. Literature (Miller 1990) indicates that flow distribution problems can arise when this ratio is below 0.5. This could mean more plates are required. A physical model study would be required to sort out the spacing and flow distribution issues.

There would be structural concerns with this alternative. It is not known exactly how the forces each component of the system sees would change when operating without a turbine in a conventional manner. The forces on the head cover, spiral case, wicket-gate assembly, and the powerhouse structure itself would have to be examined closely. Vibration could be an issue. Substantial modification to the draft tubes would likely be required to anchor the orifice plates in place. It is unknown if the forces present would allow the use of plates that meet the "thin, sharp edge" definition. Thicker plates could lead to less energy dissipation, requiring more plates. Additionally, some type of extension structure could be required for the draft tube outlets to provide the required plate spacing.

The analysis described above was based strictly on available data from experiments and experience with other hydraulic systems. It appears this setup would be an unprecedented use of perforated orifice plates for a project with as much head as Libby and given the scale required. On several Snake River projects, skeleton bays were used as regulating outlets for a short period of time. Excess energy was dissipated via perforated bulkheads installed at the skeleton bay intake (CENPD 1984). Although data indicates TDG levels below 110 percent resulted, apparently this setup contributed to a very high mortality rate for fish passing through the system and the system was not used for long.

A physical model study would be required to even determine if this type of system is practicable at Libby, and if so, refine the design and determine a cost estimate. However, this model study might be less expensive than the studies required for the other alternatives. Since the powerhouse does not play a role in passing the Probable Maximum Flood (PMF), a general physical model would not be needed. Potentially, an existing turbine model with a configuration similar to that at Libby could be modified to investigate this alternative.

The TDG attributes of this alternative are very attractive. Operation of this alternative would not increase TDG levels above those present in the forebay. Additionally, the selective withdrawal system would be usable to help regulate downstream temperatures and the issue of sufficient pool elevation (as with the upper spillway) would be nonexistent.

12. Installation of Additional Generating Units

Originally the Libby project was planned to utilize eight generating units at the dam. These units were to be operated in a manner that would allow the project to closely match power demand, producing outflows that would fluctuate widely over short time intervals. A downstream re-regulation dam was proposed to smooth out these fluctuations to avoid problems associated with possible erosion or high flows downstream. Because of local opposition and ensuing litigation, the re-regulation dam was never built, and Libby has operated with only five units. This alternative looks at the possibility of commissioning two of the remaining generating units to meet the additional 10,000 cfs flow recommendation.

As discussed earlier, this alternative has very attractive attributes relative to dissolved gas levels and release temperatures. Forebay dissolved gas levels would be transported through the powerhouse essentially without increase. Also, using the generating units would allow withdrawal through the temperature control structure, improving the capability to meet temperature objectives. Further, the issue of sufficient pool elevation (as with the upper spillway) would be non-existent.

On the other hand, limitations in the existing transmission system and power market would need to be addressed in order to bring additional units on line. Currently, Libby typically operates a single unit for several months of the year. During the fall and winter months, when demand for power is high, and during periods of flow augmentation, all of the units may see use. Even with additional units beyond unit five, the project would not likely operate more than five units except during the sturgeon flow period due to downstream concerns about high flows. Thus, additional units would provide little benefit to project power reliability or be of any real benefit outside the sturgeon flow period.

The cost of commissioning two additional units is estimated to be between $54.5 and $200.5 million, depending on the needed transmission system upgrades (CENWS 2004). These costs include a $15 million per unit payment that would be required under debt repayment rules.

13. Additional Generating Units with Load Banks

This alternative would require the commissioning of two of the additional generating units, but instead of sending the generated power to the grid, it would be sent to a local load bank complex. The onsite load bank complex would address the transmission system and power market constraints by providing an onsite sink for generated electricity. As noted above, adding generating units has very attractive attributes relative to dissolved gases and release temperatures: forebay gas levels are transported through the powerhouse without increase, and using the generating units permits withdrawal through the temperature control structure, improving the capability to meet temperature objectives. Further, the issue of sufficient pool elevation (as with the upper spillway) would be non-existent. The Montana state standard of 110 percent could be reliably met with the required BiOp flow of 35,000 cfs.

The question of what to do with the generated electricity remains, however, in the absence of an upgrade to the transmission infrastructure. It appears the only readily available commercial load banks are units that convert electrical energy into heat and dissipate this heat into the air. This commercially available unit is rated at approximately five megawatts and can be used in multiple configurations when more energy dissipation is required. Given two additional units at Libby, 48 of these units would be required, which would create a substantial complex. A better alternative might be to investigate the development of a customized integrated system to function in the same manner on a larger scale.

Another possibility is a system that dissipates electrical energy in water, via a system of heating elements. While it is tempting to think that such a system would provide warmer water downstream of the project, calculations indicate that the net increase in river temperature would be virtually un-measurable once the heated water was mixed with the rest of the river water. Moreover, assuming some type of heating element system was used, there would likely be localized areas of very hot water, which would be problematic for aquatic habitat. Unlike the land-based load bank alternative, at this time there are no known commercially available units designed to dissipate electrical power into water on a scale that would be required here.

In addition to some type of commercially available or custom designed load dissipation system, another possibility might be an onsite operation that would utilize the generated electricity for some type of revenue producing venture. The downside to this alternative is that additional units would only be operating during the short period when sturgeon flows are required. BC Hydro is pursuing the use of generation at its projects during periods of low electricity demand to produce hydrogen for use in future hydrogen-powered vehicles (BC Hydro 2004). The hydrogen would be produced from water by electrolysis. Finding an enterprise of this sort to utilize additional generation at Libby might be possible but at this point seems speculative.

The estimated cost of commissioning two additional units, including $30 million under debt repayment rules, is $54 million (CENWS 2004). The cost of commercially available heat-air exchange load banks is estimated to be $8-10 million. Allowing for additional costs for the load bank complex infrastructure (foundations, fencing, controls, etc.) and transmission infrastructure from the powerhouse to the complex, the cost for this alternative would approach $70 million. Yearly operations and maintenance expenses could be expected for both the generating units and at the load bank complex.

A possible variation on this alternative would be to combine it with Alternative 11, where the empty penstocks are converted to regulating outlets. Initial calculations for Alternative 11 show that approximately six perforated plates per draft tube diffuser would be required. These calculations also show that the first plate would dissipate approximately 150 feet of head. Conceptually, this would indicate that if Alternative 13 were employed, and the draft tubes were fitted with the first plate (two plates required – one in each diffuser) shown in Alternative 11, then approximately 50 percent fewer of the commercially available load banks would be required because the plates would be helping dissipate the excess energy, leaving less energy for the turbine to generate electricity from. A physical model would be required to verify and refine the plate design.

14. Extension of Right (West) Stilling Basin Training Wall

As discussed earlier in this document, based on results of the 2002 spill test (Schneider 2003), it seems possible that some amount of powerhouse flow is being entrained in spillway releases. In order to verify this, a new spill test and/or physical model studies would be required. During the 2002 test, the dissolved gas sensor in the stilling basin failed, leaving no data on dissolved gas levels generated directly in the stilling basin. By comparing readings just downstream of the stilling basin end sill with dissolved gas readings at the USGS gauging station, it appears that weighted dissolved gas averages are higher than weighted averages using the powerhouse TDG sensor and the sensors located approximately 150 feet downstream of the stilling basin. One explanation for this is that some amount of powerhouse flow is being entrained in spillway flows. To fully test this hypothesis, and determine the degree of entrainment, a new spill test, which utilizes additional sensors, would be required. If it was determined that spillway flow was entraining powerhouse flows, extending the right stilling basin training wall might provide some dissolved gas benefits by keeping the flows separated until more of the excess entrained air is stripped from the spillway flow. Of course, if it were determined that in fact dilution-type mixing was occurring (discussed earlier as a possible explanation for the flow weighted average discrepancy), then extending the wall would probably not be beneficial. For the sake of evaluating this alternative, the following discussion assumes powerhouse flow entrainment is occurring.

Entrainment of powerhouse flows has been an issue at other Columbia/Snake River projects, but the process may be different than entrainment at Libby. At several projects, the addition of flow deflectors has made the problem worse. Evidently the modified circulation pattern in the stilling basin, brought about by the high velocity skimming flows produced by deflectors, has created a low-pressure region that increases the rate of entrainment (Citation NWW-NWP). The remedy for this has been to either build or extend a training wall between the stilling basin and the powerhouse. Since Libby has training walls running the entire length of the stilling basin, it is unknown if this low-pressure region (assuming deflectors were installed) would extend beyond the training walls and entrain powerhouse flows. It is unclear if entrainment at Libby (assuming this explains the dissolved gas value discrepancy discussed earlier) is precipitated by some type of low pressure region that develops as a result of hydraulic conditions at the stilling basin end sill or the flows are just mixing for some reason while there is still an excess amount of entrained air in the spillway flow. In any case, if testing determined entrainment was an issue at Libby, extending the right, or west, stilling basin training wall could help reduce downstream dissolved gas levels by limiting the volume of water available for dissolved gas uptake to just the spillway flow.

Further evaluation in the form of a spill test and/or physical model study would be required to arrive at a design length for a divider wall and evaluate its potential effectiveness at reducing dissolved gas levels. Evaluation of the entrainment issue at Lower Granite, Ice Harbor, and Lower Monumental Dams looked at divider walls ranging up to 150 feet in length beyond the stilling basin end sill (Citation NWW-NWP). While the existing training wall has a top elevation of 2,142 feet, an extension wall would likely only need to be no higher than elevation 2,130 feet. In the event project discharges higher than 35,000 cfs were required, the wall would be submerged.

More study would be required to arrive at a cost. It is unknown if a structure as simple as a sheet pile wall would work or if a wall similar to the existing training wall would be required. A general project physical model would be required to verify acceptable hydraulic performance. This is an alternative that might make the most sense when combined with another alternative such as flow deflectors.

RESULTS AND FINDINGS

A proposal from federal resource agencies to release flows ranging from 5,000 cfs to 10,000 cfs over current powerhouse capacity from Libby Dam during mid-May to mid-June was outlined in the 2000 USFWS Biological Opinion for operation of the Federal Columbia River Power System. Under the current project configuration, however, the scheduling of releases from Libby Dam in excess of powerhouse capacity to support the conservation and recovery of threatened or endangered species may result in degradation of water quality in the Kootenai River. A series of operational and structural measures designed to reduce the TDG supersaturation generated during project discharges greater than the current powerhouse capacity have been presented in this report. An operational objective of Libby Dam is to maintain project releases that meet the water quality standards of the state of Montana, which requires that no water sample exceed total dissolved gas saturation of 110 percent except in mixing zones. The Montana water quality standards for temperature in the Kootenai River limits release temperature to 67 °F or less, provided that naturally occurring water temperatures not influenced by human activity do not exceed this limit.

The complex spatial characteristics associated with the exchange and transport of TDG supersaturation at Libby Dam present a challenge in characterizing prospective project impacts. The entrainment and transport of air bubbles to depth in the stilling basin accelerates the exchange of atmospheric gasses into solution, resulting in TDG supersaturation. The maximum TDG pressures generally can be found in the zone of highly aerated flow where net absorption dominates the TDG exchange process. A rapid and substantial desorption of supersaturated dissolved gases takes place as the redistribution of the bubble cloud is vented back into the atmosphere. The description of TDG exchange at Libby Dam is characterized in terms of the peak and cross-sectional average conditions downstream of the zone of bubbly flow. Project releases containing different TDG pressures and water temperatures can remain distinct for up to several miles below the dam.

Discharges over the spillway or through the sluiceways at Libby Dam have historically created elevated total dissolved gas levels in the Kootenai River below the dam. Based on available data, the sluiceway operation will likely produce higher TDG pressures than a comparable spillway release. Reservoir modeling indicates that during a 15 May to 15 June timeframe (especially closer to the 15 May end of the range), the pool elevation may be insufficient to allow a spillway flow of 10,000 cfs. This would leave the sluiceways as the only means to pass all or part of any additional flow.

The TDG saturation associated with sluiceway discharges ranged from 128-144 percent with an average value of 138 percent, based on limited data from the 1970's taken in the vicinity of the Thompson Bridge. During the 2002 spill event, TDG saturation in spillway releases increased as an exponential function of the spillway discharge, ranging from 104 percent during a 700 cfs release to an upper limit of 134 percent during a spill of 15,600 cfs. At Libby Dam as currently configured, the TDG levels generated in spillway releases of 10 kcfs during capacity powerhouse operations will be 132 percent of saturation downstream of the zone of highly aerated flow. No direct measurement of the maximum TDG saturation within the zone of highly aerated flow has been conducted at Libby Dam although it is likely to exceed 150 percent based on observations at other projects. Spillway releases in excess of 1.6 kcfs are expected to generate TDG levels greater than 110 percent of saturation downstream of the zone of aerated flow.

Given the current configuration of the project, there are two main operational measures that can minimize the elevation of TDG saturation in the Kootenai River during project releases of 10,000 cfs over powerhouse capacity. Distributing the spillway discharge over both bays and sluiceway discharge over three conduits will minimize the TDG pressures produced for a given flow rate. The project has historically operated the spillway in this manner. The powerhouse turbines should be operated at their hydraulic capacity to minimize the amount of flow to be spilled. Again, during sturgeon flow operations (using maximum powerhouse capacity only), the powerhouse has historically been operated at the published cavitation limit for a given pool elevation.

The management of water temperatures released through the powerhouse at Libby Dam is controlled through a series of selector gates. These operations at Libby Dam allow releases to mimic natural thermal cycles in the Kootenai River. The release of additional water in excess of the powerhouse capacity at Libby Dam as currently configured will limit the capability to meet these release target temperatures. The ability to meet target temperatures during the elevated sturgeon flow for existing conditions will depend upon the pool elevation and thermal structure in Lake Koocanusa. The initiation of a sluiceway operation during sturgeon flows would introduce cold water at 40 °F into the Kootenai River. Typical water temperatures near the crest of the spillway range from 50 to 55 °F during the sturgeon flow time period.

The two general principles governing operational and structural measures aimed at minimizing production of TDG supersaturation in Libby Dam outflows are: 1) eliminate or reduce the entrainment of air; and/or 2) minimize the depth to which entrained air is transported. Most field investigations of dissolved gas exchange have shown that if air is entrained and transported to even small depths, TDG may exceed 110 percent, at least locally. If the point of compliance is interpreted to be anywhere in the river, including immediately below the dam, almost any alternative that allows the entrainment of air would violate the water quality standard of 110 percent TDG saturation. This would likely rule out alternatives that use the spillway and sluiceways to pass flows in excess of current powerhouse capacity.

The alternatives discussed in this report can be grouped into three main categories dealing with TDG production. The first group includes alternatives that release discharges with TDG at or below state standard of 110 percent. The second group has alternatives that release TDG that may exceed state standards but will provide an improvement in the initial generation of dissolved gas levels over the existing project configuration. The third group includes alternatives that do not initially reduce the dissolved gas levels generated but may provide some benefit through increased degassing or improved mixing with powerhouse flows.

The alternatives in each category may meet the Libby release temperature objective depending upon outlets through which water is withdrawn. Releases through a modified powerhouse will be similar in temperature to those under the current operation. For spillway releases from the warm surface water, release temperatures will be warmer than those released through the powerhouse, assuming reservoir temperature stratification is robust enough when sturgeon flows are recommended. Releases through the sluiceways will be cooler than the temperatures released under current operations. Although not considered in this study, further development of alternatives involving use of the sluiceways could include investigation into possible temperature control methods, depending on the degree to which temperature is determined to be a factor. The alternatives for which releases are expected to meet state standards for TDG are those where air is not entrained into the flow field or those where plunge depth of air entrained flows are kept very low.

The alternatives that should meet the state standard for TDG are as follows:

Alternative 9: Modification of sluiceway outlets

Alternative 10: Siphon/dedicated pressure flow system with auxiliary stilling basin

Alternative 11: Penstock/draft tube conversion to a regulating outlet.

Alternative 12: Additional generating units (electricity transmitted to grid)

Alternative 13: Additional generating units with load banks

Alternative 3: Spillway/sluiceway flip bucket

Alternative 5: Side channel and spillway

Alternative 6: Baffled chute spillway

Alternatives 9, 10, 11, 12 and13 release water through a closed system, providing the additional water at TDG levels of about 103 percent, which is the TDG level in Lake Koocanusa. For these alternatives, no mixing zone would be apparent, since the dissolved gas and temperature (extension of sluiceway outlets would produce colder temperatures, however) would be similar to the powerhouse releases. Alternatives 3, 5 and 6 will likely entrain air during the passage of water, but dissipate the energy in shallow water instead of allowing the discharge to plunge into a deep stilling basin and absorb dissolved gas. The dissolved gas resulting from implementation of one of the last three alternatives may range up to 110 percent, with mixed concentrations of about 106 percent. Lateral gradients in temperature could be noticeable for these three, depending on the temperature stratification of the reservoir and the configuration of the selective withdrawal bulkheads.

Some alternatives would provide an improvement in TDG levels over existing conditions but still exceed the 110 percent state standard. With these alternatives it would be expected that the length of river below the projects with dissolved gas levels above 110 percent would be shorter than under the existing project configuration. These alternatives are:

Alternative 2: Spillway/sluiceway flow deflectors

Alternative 7: Raised stilling basin floor

Spillway deflectors and a raised the stilling basin floor cause similar TDG release levels of about 113-115 percent for spillway releases. When mixed with powerhouse discharge, the average TDG should be less than 110 percent. For sluiceway releases, the higher specific discharge causes higher TDG ranging from 124 to 130 percent. Once sluiceway releases are mixed with powerhouse discharge, the TDG will be at 110 percent or lower. In addition to the TDG gradient, temperature gradients will also be present because of the warmer water being released through the spillway. With sluiceway releases, the water temperatures would likely be less than the hydropower flows. The cost of raising the stilling basin floor would be substantially more than the flow deflector alternative.

The last category includes alternatives that (with the exception of existing condition) do not reduce the amount of dissolved gas generated but may provide benefits downstream through higher degassing rates or improved dilution type mixing with powerhouse flows. These alternatives include:

Alternative 1: Existing conditions (base condition, no changes)

Alternative 4: Tailwater mixing structure

Alternative 8: Raised tailrace channel

Alternative 14: Extension of right (west) stilling basin training wall

The TDG generated in the stilling basin will likely exceed 145 percent, with 127-135 percent TDG exiting the immediate tailrace area. Even so, once spilled water is mixed with hydropower releases, downstream TDG will be close to 115 percent for spillway flows and 117.7 percent for sluiceway flows under existing conditions. Both the raised tailrace and existing conditions alternatives would cause significant lateral gradients in TDG and temperature. Although its impact on dissolved gas will likely be small, a tailwater mixing structure is included in this category since it could reduce the habitat impacted by peak TDG levels. By increasing the local mixing just downstream of the Libby structure, the mixing zone length could potentially be shortened. If entrainment of powerhouse flows is determined to be an issue, extending the right stilling basin training wall could provide improved downstream dissolved gas levels. This alternative might be most effective when combined with an alternative such as flow deflectors. Further study is required to determine if entrainment is in fact an issue.

Given the configuration of the project, the manner in which it is currently operated, and the lack of influence from other projects regarding dissolved gas levels, there appears to be little that can be done operationally to improve dissolved gas levels below the dam. Historically during sturgeon flow operations, the project has operated the powerhouse at the published turbine cavitation limit to maximize outflow. During spill events, both spill bays have been used to minimize dissolved gas levels.

This study is intended to serve as only an initial assessment of potential dissolved gas management measures at Libby Dam. It is not a feasibility study. From a total dissolved gas performance perspective, this initial appraisal of potential total dissolved gas (TDG) management alternatives for Libby Dam indicates that alternatives which might be worth exploring further, should additional flows of the magnitude described in the USFSW BiOp be determined to be reasonable and prudent, would be those which pass flow through the dam under a pressurized flow regime, such as occurs currently through the powerhouse. This type of flow regime (assuming air entrainment can be minimized) appears to provide the most certain means of keeping dissolved gas levels in the river below the dam, including immediately below the project, below 110 percent saturation, assuming forebay levels are below 110 percent. Controlling discharge temperatures of powerhouse releases via the project's selective withdrawal system has been an important part of project operations. When temperature control of outflows is also considered, it would seem that the pressure-flow alternatives which utilize one or more of the unused penstock/skeleton bay structures would merit further study in the event additional flow was determined to be warranted. Alternatives 11, 12 and 13 fall into this category.

In the event that a point of compliance for dissolved gas levels was determined to be at a location other than immediately below the dam, or if a standard less restrictive than 110 percent saturation were adopted, Alternative 2 and 3, which involve modification of the spillway and/or sluiceways, might warrant further study.

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TABLES

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TABLE 1. LIBBY DAM AND LAKE KOOCANUSA PERTINENT DATA

Project Location	
County	Lincoln
State	Montana
River	Kootenai
River Mile (above mouth of river)	221.9
Hydrologic Data	
Project Drainage Area	8,985 square miles
Design Inflow Peak	282,000 cfs
Spillway/Sluice Design Outflow Peak	206,000 cfs
Reservoir	
Name	Lake Koocanusa
Storage Capacity-US (gross)	4,877,175 acre-feet
Storage Capacity-Can. (gross)	992,217 acre-feet
Total Storage Capacity (gross)	5,869,392 acre-feet
Storage Capacity-US (usable)	3,987,251 acre-feet
Storage Capacity-Can. (usable)	992,217 acre-feet
Total Surface Area (full pool)	46,456 acres
Total Length (full pool)	90 miles
Maximum Pool Elevation…	2459 feet
Minimum Pool Elevation	2287 feet (regulated elevation)
Dam	
Type	Concrete gravity
Top Length	2,887 feet
Maximum height	432 feet (bedrock to top of structure)
Elevation of Top of Dam	2472 feet
Minimum Discharge	4,000 cfs
Tailwater elevation @ 4,000 cfs	2117 feet
Spillway	
Crest Elevation	2405 feet
Spillway Gates	2
Gate Type	Radial
Gate Dimensions	48 ft w x 59 ft h
Spillway width	116 feet
Sluice Regulating Outlets	
Number	3
Intake crest elevation	2201.5 feet
Tunnel Dimensions	10 ft w x 17 feet h
Service Gates	3, Radial type, hydraulically operated
Emergency Gate	1, tractor type, cable operated
Stilling Basin	
Type	Conventional, hydraulic jump energy dissipating
Floor Elevation	2073 feet
Length	275 feet (approx.)
Design Capacity	50,000 cfs spillway/sluice
Training Wall Elevation	2142 feet (top)
Powerhouse	
Generating Capacity (current)	600 mega-watts
Turbines (installed)	Five Allis Chalmers Francis type
Turbine Elevation	2118 feet (centerline)
Generating Units (installed)	Five Westinghouse 120 megawatt
Discharge Capacity (current)	27,000 cfs (approx) @ pool el 2420
Number of Generator Bays	8

Penstocks	
Number	8 (five currently in use)
Diameter	20 feet thru dam*
Penstock Intake Elevation	2222 feet
Temperature Control	Selective withdrawal system for powerhouse

Note: Data from Libby Dam and Lake Koocanusa Water Control Manual
All elevations are referenced to National Geodetic Vertical Datum of 1929

**Penstock diameter transitions to 17 feet just before entrance to turbine spiral case*

TABLE 2. DATES POOL ELEVATION REACHES 2418 FT. AND RESERVOIR INFLOW, 1948-1999

Year	Date Res. @2418 VARQ	Inflow	Date Res. @2418 Base FC	Inflow	Date Res. @2418 Actual	Inflow
1948	3 June	73000	3 June	73000	N/A	N/A
1949	17 May	49520	26 May	33138	N/A	N/A
1950	21 June	70637	21 June	70637	N/A	N/A
1951	13 June	40257	13 June	40257	N/A	N/A
1952	6 June	38105	13 June	37951	N/A	N/A
1953	5 June	53838	9 June	54659	N/A	N/A
1954	15 June	61099	15 June	61099	N/A	N/A
1955	4 June	25205	14 June	68042	N/A	N/A
1956	7 June	70836	6 June	77602	N/A	N/A
1957	18 May	45134	1 June	39976	N/A	N/A
1958	22 May	48446	30 May	50274	N/A	N/A
1959	12 June	42136	12 June	42136	N/A	N/A
1960	14 June	45714	16 June	46795	N/A	N/A
1961	2 June	74321	6 June	85175	N/A	N/A
1962	4 June	34091	17 June	44518	N/A	N/A
1963	1 June	52031	6 June	41745	N/A	N/A
1964	7 June	56074	13 June	59281	N/A	N/A
1965	21 June	54959	22 June	45728	N/A	N/A
1966	5 June	58437	9 June	45875	N/A	N/A
1967	20 June	72278	18 June	68340	N/A	N/A
1968	31 May	38872	11 June	47876	N/A	N/A
1969	4 June	52824	7 June	69096	N/A	N/A
1970	26 May	33901	30 May	30067	N/A	N/A
1971	4 June	55034	7 June	62096	N/A	N/A
1972	12 June	86412	10 June	77797	N/A	N/A
1973	24 May	29219	9 June	48411	N/A	N/A
1974	22 June	96909	20 June	104953	N/A	N/A
1975	15 June	42088	23 June	36233	N/A	N/A
1976	11 June	38687	18 June	34258	14 June	29400
1977	19 May	12214	23 May	13410	Never	N/A
1978	4 June	33120	15 June	37040	12 June	37200
1979	31 May	22191	4 June	36578	9 June	22800
1980	6 May	48211	13 May	30487	21 May	34300
1981	27 May	70965	30 May	51704	29 May	57300
1982	13 June	47481	16 June	61296	19 June	52800
1983	30 May	56399	11 June	35997	8 June	37600
1984	2 June	26383	13 June	33963	15 June	44500
1985	26 May	52231	4 June	29257	8 June	47500
1986	29 April	11565	2 June	81507	31 May	83400
1987	3 May	44972	12 May	46668	17 May	34000
1988	15 May	32471	14 May	35632	23 June	22600
1989	12 May	40847	6 June	43185	14 June	42000
1990	22 June	50282	20 June	49663	10 June	46000
1991	14 June	48194	13 June	59587	19 June	28800
1992	12 May	21792	2 June	27922	21 June	18700
1993	22 June	50693	19 May	46167	9 July	25800
1994	27 April	18449	9 May	26402	3 June	25300
1995	31 May	56215	1 June	57992	9 June	56400
1996	10 June	80580	9 June	82148	14 June	56000
1997	1 June	78839	6 June	69487	7 June	67500
1998	7 May	35716	12 May	34477	11 May	36700
1999	17 June	63569	19 June	65330	19 June	65330

TABLE 3. LIBBY TDG MANAGEMENT ALTERNATIVE MATRIX

*Estimate includes all required costs such as feasibility, physical modeling, design, etc.

Alternative	Description	Notes	Meet Montana Downstream TDG Level Standards?	Downstream Temp. Change?	*Implementation Costs	Operation and Maintenance Costs	Implementation Process	Advantages	Disadvantages	Reasonable and Prudent Considerations
Existing Condition	Under the existing configuration of the project, the upper spillway would be used to make additional releases above current powerhouse capacity of 24,000 to 27,000 cfs.	An analysis performed using numerical model results indicates that there are years in the 15 May- 15 June (more at the first part of this timeframe) where the spillway would be unavailable for use, or at least for flows less than 10 kcfs, due to pool elevation. For this and other alternatives that utilize the upper spillway to pass the BiOp flow, a determination would need to be made as to whether or not to use the sluices in these cases.	Yes for spill less than 1 kcfs, No for spill greater than 1 kcfs	No. Would not negatively impact downstream temperatures if the spillway is used. If the Sluiceways are used downstream temperatures would be negatively impacted.	None	These costs would be increased. Currently the upper spillway is maintained for a very limited level of usage.	A water quality exception would be needed from the State of Montana for spill in excess of 1 kcfs.	> No project modification req. > No implementation costs	> Does not meet W/Q requirements for TDG > Analysis indicates upper spillway is not always available for use due to pool elevation > Would negatively impact downstream temperatures if sluiceways used	Will not meet TDG objectives
Upper Spillway Flow Deflectors	Concrete structures placed on the spillway face, which help reduce the depth of plunge the spillway flow experiences.	Flow deflectors have never been installed on a dam with as much head as Libby. The sluiceway outlet configuration on the spillway face could impact performance. There would be some uncertainties here as to performance. A physical model study would be required to better assess performance potential. Most likely deflectors would be required on the sluiceways to enhance spillway deflector performance.	No. A comparative analysis with similar deflectors at other projects indicates that these structures would only achieve TDG levels of about 113 to 115%.	No. Would not negatively impact downstream temperatures.	$8 to $10 million	Increased O&M costs would be the result of the increased spillway use discussed with Alt. 1.	> Congressional authorization and appropriation required > Sectional and general physical model study required > Water quality exception required from Montana > Feasibility study	> Comparatively low cost relative to other alternatives > Would increase max spillway flow over existing that meets required TDG level >Could be constructed in the dry without construction of a cofferdam. >There is a significant amount of experience with flow deflectors. >Fewer unknowns than other alternatives	> Would not meet TDG requirement at BiOp flow > Analysis indicates upper spillway not always available for use > Some questions about ability to estimate performance due to sluice outlets > Flow deflectors have never been installed on a high head project like Libby	>Alternative will provide improvement in TDG but will still cause exceedance of the Montana TDG standard. >Lots of experience with deflectors at other projects to tap >May make sense with a simple missing structure and/or an extended training wall. >This alternative has fewer unknowns than others
Sluiceway Flow Deflectors	Concrete structures placed on the sluice outlets that help reduce the depth of plunge the sluiceway flow experiences.	Flow deflectors on the sluiceways were looked at in the early 1970's as a means of reducing TDG levels. During physical model tests, they did not produce the desired "skimming" flow over a wide range of discharges. However, they appear to have produced a skimming flow at a 10,000 cfs discharge. The sluiceways draw deeper water which is considerable colder than powerhouse or spillway flows.	No. Expected TDG performance would be worse (create higher TDG levels) than the spillway due to the sluiceways larger flow per unit width.	Yes. Due to the deep intakes, use of the sluices would make downstream temperatures colder than temperatures experienced from the powerhouse or spillway. Would likely cause a significant lateral temperature gradient in the river for some distance downstream.	$6 to $8 million	These costs would be increased. Currently the sluices are maintained for a very limited level of usage. Usage on an annual basis would increase these costs.	>Congressional authorization and appropriation required > Sectional and general physical model study required > Water quality exception required from Montana > Feasibility study	>Comparatively low cost relative to other alternatives > Sluices would be available for use in all years >See advantages for upper spillway	> Would not meet TDG requirement at BiOp flow > Would contribute to cooling the river downstream >Uncertainties regarding TDG performance estimates	>Alternative will cause exceedance of the Montana TDG standard. Also what impacts the lower temperatures would have on the system have not been fully explored. >Sluiceway deflectors likely required to improve the performance of spillway deflectors
Tailwater Mixing Structure	This would involve construction of some type of underwater structure(s) in the tailwater area that would enhance mixing of spillway/sluiceway and powerhouse flows. Would not reduce the amount of dissolved gas generated but would aid in reducing the length of the downstream mixing zone.	Mixing of powerhouse and spillway flows too early can result in increasing the TDG level of the powerhouse flow as well. Physical model studies required to determine feasibility.	No. Theoretically if complete mixing could be achieved at the structure and if this mixing was dilutional in nature, then 110% could be met. The length of the mixing zone would certainly be reduced. No example of this type of method being used has been found for comparison.	No if upper spillway were used. Yes if sluices were used. Use of the sluices would make downstream temperatures colder.	Unknown. Structures would probably be constructed of rock. Construction would probably be similar to riprap placement. A rough estimate would be between $5 to $10 million.	Would depend on final structure configuration. This alternative would probably not add much in the way of O&M costs due to the structure itself. Additional O&M costs would arise due to increased spillway/sluiceway use.	> Feasibility study > A physical model study would be required to estimate TDG performance, look at hydraulic issues at flood flows and finalize design > Water quality waiver most likely would be required > Congressional authorization and appropriation required	> If proven feasible could be cost effective > Might complement flow deflectors > Would improve TDG performance of both sluices and upper spillway	> TDG reduction potential unknown > Expensive physical model studies required to determine feasibility > Areas above structure (and probably for some unknown distance downstream of structure) would still experience high TDG levels > No prior use on this scale for TDG reduction	> For sure won't improve conditions upstream of structure > Downstream TDG effectiveness unknown > No mixing structures used for similar purposes at other projects > Expensive physical modeling required to determine feasibility >Might complement flow deflectors

Alternative	Description	Notes	Meet Montana Downstream TDG Level Standards?	Downstream Temp. Change?	*Implementation Costs	Operation and Maintenance Costs	Implementation Process	Advantages	Disadvantages	Reasonable and Prudent Considerations
Side Channel with Spillway	This alternative would involve construction of a channel around one side (probably the right side, or west side) of the dam that terminates at a 330-foot long side spillway that returns flow back to the river via a very shallow stilling basin.	This alternative would require an in-depth analysis to determine the elevation of the intake invert as well as the location of the various system components. Constructability is also of concern. If the intake invert were placed at 2405 ft, the same as the spillway, as discussed previously, there would be years when it might not be available for use when sturgeon flows are needed. At this elevation, an excavation about 100 feet deep and 70-80 feet wide would be required. Would likely displace some infrastructure in the vicinity of the dam.	Yes	No appreciable temperature change. Would be similar to using existing spillway.	Substantial. There are many unknowns. There would be a significant amount of earthwork required. Estimated at $200 to $500 million based on estimates at other projects. More study would be required to get an actual estimate for such a system at Libby.	There would be substantial O&M costs associated with this option.	> Feasibility Study > Congressional authorization and appropriation required > Physical model study	> If constructible would meet W/Q standard for TDG > Would not reduce downstream temperatures	> Constructability is questionable > Very high cost > Existing infrastructure would be severely impacted > Would probably have the same issue regarding system use as the upper spillway due to low pool elevations	> Very high cost > Extensive physical modeling required > Construction risks
Raised Stilling Basin Floor	This alternative would involve raising the elevation of the stilling basin floor to reduce the depth the spillway/ sluiceway flow plunges to. This results in less hydrostatic pressure to force entrained air into solution. This alternative tries to do essentially the same thing as flow deflectors try to do.	Raising the stilling basin floor would affect the basin's ability to contain the hydraulic jump generated during large flood events. If the floor were raised, the jump location would be moved farther downstream for a given flow. This could necessitate the need for a secondary stilling basin downstream. Also of concern is the height of the training walls. They may need to be raised.	No. TDG levels would most likely be reduced, and the length of the mixing zone reduced, similar to flow deflectors, but some of the entrained air will still be forced into solution.	If the upper spillway is used temperatures would not be any colder than they currently are. If the sluices were used downstream temperatures would be colder.	Unknown. Could be substantial. A secondary stilling basin could be required as well as modifications to the existing training walls.	Would be some additional O&M costs particularly if a secondary stilling basin is required.	> Feasibility study > Congressional authorization and appropriation required > Physical model study	> Would produce some improvement in TDG for both the spillway and sluiceways	> High cost > Might be some constructability issues > Possibly need second stilling basin and/or training wall modifications > Would not provide desired level of performance > Attempts to do the same thing as flow deflectors at a much higher cost	> Will likely still cause exceedance of Montana TDG standard > High cost if training wall and/or secondary stilling basin construction/mods required > Essentially does the same thing as flow deflectors at a much higher cost
Raised Tailrace	The elevation of the area about 350 feet downstream of the stilling basin would be raised to aid in forcing dissolved gas out of solution. It would not reduce levels of TDG generated but would speed up the degassing process.	The Libby tailrace was designed to be at a uniform elevation of 2110 feet. Given the tailwater elevation of 2127 feet at 35 kcfs, this make the Libby tailrace already pretty shallow. Of concern is how this alternative would alter the downstream hydraulics during large flows. Velocities would be increased resulting in an increased chance of erosion and scour.	No. The Libby tailrace, as designed, is actually pretty shallow so there probably would not be much room for improvement.	No for upper spillway use. Yes for sluice use. If the upper spillway were used temperatures would not be any colder than they currently are. If the sluices were used downstream temperatures would be colder.	$15 to $20 million, assuming tailrace is in the as-designed condition.	May be some increased O&M cost due to scour and erosion damage from higher velocities generated by the higher elevation tailrace.	> Congressional authorization and appropriation required > Feasibility study > Physical model study	> Would provide some improvement in downstream TDG levels. > Might enhance performance of flow deflectors	> Would not meet W/Q standard > Might cause severe erosion during large floods > Area in and around stilling basin would still experience high TDG levels	> Will not accomplish objectives
Installation of Additional Generating Units	Two of the additional generating units would be commissioned to pass the additional sturgeon flow.	Units 7 and 8 would be the likely candidates for commissioning. Unit 6 has been cannibalized for parts. The penstock would need to be accessed to inspect internal components such as the turbine, spiral case, and penstock liner.	Yes	This alternative would allow full use of the existing selective withdrawal system.	$54 to $200.5 million, depending on required transmission upgrades. Figures include $30 million required under debt repayment rules.	There would be additional O&M costs. These costs would depend on how much use the two additional units would see.	> Congressional authorization and appropriation required > Unclear if option could be paid for out of BPA fish program funding.	> TDG standard would be met with certainty > Project reliability at certain times of the year might be increased marginally > Selective withdrawal system would be available	> High cost of upgraded transmission infrastructure > May not be able to provide full BiOp flow in the event a unit is down > Source of spare parts lost > Another transformer would be required > Without the reregulation dam, Libby would not be able to efficiently use additional units except for passing flows above 25 kcfs	>Very high cost > In terms of technical unknowns and TDG performance potential, alternatives using turbines have an advantage over other alternatives.
Conversion of Unused Penstocks to Regulating Outlets	One or more of the three unused penstock/turbine/draft tube systems would be converted for use as regulating outlets.	The problem is how to safely dissipate 300-340 feet of head (the elevation difference between the reservoir and the tailwater) to avoid tailrace, draft tube, and/or powerhouse damage. Penstocks have been used as regulating outlets at Snake River projects with perforated plate modifications. However these projects are only have about 100-ft of head. From a hydraulic standpoint, energy dissipation appears to conceptually be possible with the use of perforated plates in the draft tubes. This scheme may require some type of draft tube extension to provide adequate plate spacing. Cavitation could be an issue as well. Many other unknowns, particularly structural, would have to be investigated.	Yes. If the conversion measures allowed the penstock to function with a pressure flow regime with no air entrainment, as currently happens with the penstocks in use, then this alternative should produce the desired results. If a lot of air has to be introduced to deal with cavitation then TDG performance may be compromised.	This alternative would utilize the existing selective withdrawal system as per current operation.	Unknown until physical model study is undertaken. May be a long-term cost of lost power generating potential if modifications do not allow the system to be returned to power generation use.	O&M cost would increase. Amount unknown due to unknown design.	> Physical model study required to determine feasibility and verify design > Feasibility study > Congressional authorization and appropriation required	> If pressure flow regime could be preserved option would most likely meet TDG standard > Selective withdrawal system could be utilized > Has the potential to be comparatively low cost, at least initially	> Physical model study required to determine feasibility > Cavitation may pose a problem > Needed modifications may make it impossible to return structures to use for electricity generation > May only be feasible to pass a portion of the BiOp flow > A scheme with perforated plates may not be fish friendly	> Has never been done before at a project with as much head a Libby > Expensive physical model studies required with the risk of finding this alternative is not feasible > Depending on modifications, returning system to use for power generation may be costly

Alternative	Description	Notes	Meet Montana Downstream TDG Level Standards?	Downstream Temp. Change?	*Implementation Costs	Operation and Maintenance Costs	Implementation Process	Advantages	Disadvantages	Reasonable and Prudent Considerations
Modifications to Submerge Sluice Outlets	This option would modify one or more of the existing sluiceway outlets, possibly with orifice plates, so that they discharge underwater. The outlet would be designed such that hydraulic control would be shifted from the service gate to the outlet. Conceptually this would allow the sluice(s) to operate in a pressurized state, thus not entraining air.	Modifications to allow hydraulic control to shift from service gate to outlet could reduce the conveyance capacity of the sluiceways. The sluiceways are an integral part of the projects ability to pass the Probable Maximum Flood, which is part of the project's authorization. It is unknown if a "quick removal" system would be allowed. Initial calculations indicate it might be possible to configure one sluiceway and still discharge 20 kcfs at full pool.	Yes, if the modifications would allow the sluice(s) to function in a pressurized state without the introduction of air.	Yes. Would make downstream temperatures colder with a lateral gradient until such time as powerhouse and sluiceway flows were mixed.	Unknown. Would require a physical model study to arrive at a cost. If a single orifice plate on only one sluiceway outlet was required, this could be a relatively inexpensive alternative.	These costs would be increased. Currently the sluices are maintained for a very limited level of usage. Usage on an annual basis would increase these costs.	> Congressional authorization and appropriation required > Feasibility study >Physical model study	>Could meet TDG standard if alternative functioned as envisioned >Could be low cost	> PMF issues unknown > Viability of "quick removal" system unknown > Cavitation, structural, and submergence issues need to be explored > Temperature issues >Mods could impact stilling basin bridge. >Hydraulics unknown as system is started-some type of valve may be required	>This alternative has a lot of issues that would need to be resolved. However, it is possible they could be resolved relatively easily.
Installation of Two Additional Generating Units with Onsite Load Banks	This alternative calls for installing two additional generating units and instead of transmitting the power, dissipating it as heat into the air at a nearby complex of load banks or possibly some type of system that involves heating reservoir and/or river water.	Alternative might be enhanced if another energy dissipation structure, such perforated plates, were also employed. This might significantly reduce the extent of the load bank system required. Alternatives involving the use of turbines appear to have the most certainty of achieving the TDG target and the least number of technical hurdles.	Yes. The system would function just like the five exiting turbines.	This alternative would allow use of the selective withdrawal system.	$30-40 million plus $30 million under debt repayment rules.	Unknown. Would depend on the type of load bank system determined to be most feasible.	> Feasibility study > Since this option generates power but does not distribute to grid, process is unclear > Congressional authorization and appropriation required	> TDG requirement would be met > Temperature issues would remain unchanged > Penstock/ Turbine system preserved for future generation to grid > Two additional units could possibly be used as backups outside of sturgeon flow season > Pool elevation not an issue >Use of turbines to pass additional flow has the fewest technical unknowns for an alternative that would meet the standard.	> High cost > Full BiOp flow may not be supplied in the event of a unit failure	>In terms of technical unknowns and TDG performance potential, alternatives using turbines have an advantage over other alternatives.
Siphon/Dedicated Pressure Flow System	This alternative calls for constructing bypass conduits over or through the dam. They would operate in a pressure flow regime as to not entrain any air.	Constructing conduits up and over the dam would require a very large pumping station-not very realistic. Boring through the dam would be required. A downstream gate and energy dissipation structure (stilling basin) would be required, as would a gated intake structure. If the system was configured to go up and over or up and through the dam, the intake structure would likely be more complex than if the conduits simply went through the dam. It might be possible to reduce the stilling basin size/need by installing perforated plates in the system and/or somehow using the existing stilling basin.	Theoretically the system would just transfer forebay TDG level to the tailwater as now happens with powerhouse operation.	Depends on intake elevation and whether or not some type of selective withdrawal system is configured.	Unknown. This would probably be a high cost alternative. The stilling basin, intake structure, and dam boring would all be significant costs.	Would depend on required design elements	> Feasibility Study > Physical Model study > Congressional authorization and appropriation required	>Would most likely meet TDG requirement	> Due to siphon conduit/ reservoir elevation constraint of ~20 feet very large assist pumps would be needed or would have to bore through dam > Boring through dam raises many safety/ constructability issues	>Very high cost >Many technical obstacles
Extended Right (west) Training Wall	Currently it is surmised that entrainment of powerhouse flows into spillway flows is a problem. This wall would keep these flows separated until dilution-type mixing could occur.	Currently it is surmised that entrainment of powerhouse flows into spillway flows could be a problem. This alternative might work well in conjunction with an alternative such as flow deflectors.	No	There would essentially be no change from current operation when the spillway or sluiceway is used.	Unknown. The type and length of wall would need to be determined.	Unknown. Would depend on the type of wall.	> Feasibility study >Spill test required to determine if entrainment is a problem > Congressional authorization and appropriation required	>Assuming entrainment is an issue, this alternative would provide some improvement in TDG levels by limiting the volume of water available for TDG generation to just the powerhouse flow.	>Would not reduce TDG levels below 110%	>More study would be required to determine if entrainment of powerhouse flows is actually a problem >Might be effective in conjunction with another alternative such as flow deflectors
Side Channel with Baffled Chute Spillway	This alternative is similar to the Side Channel and Spillway Alternative. Instead of a 330-foot wide spillway, this alternative would use a 100-foot wide spillway.	See notes for Side Channel with Spillway alternative	Yes	Similar to current operation using spillway.	Substantial. There would be a significant amount of earthwork required. $200 to $500 million.	There would be substantial O&M costs associated with this option.	> Congressional authorization and appropriation required > Feasibility study > Physical model study	> If constructible, would meet W/Q standard for TDG > Would not reduce downstream temperatures beyond that of spillway operation	>Constructability is questionable >Very high cost >Existing infrastructure would be severely impacted >Would probably have the same issue regarding system use as the upper spillway due to low pool elevations	>Very high cost >Extensive physical modeling required >Construction risks

Alternative	Description	Notes	Meet Montana Downstream TDG Level Standards?	Downstream Temp. Change?	*Implementation Costs	Operation and Maintenance Costs	Implementation Process	Advantages	Disadvantages	Reasonable and Prudent Considerations
Spillway Flip Bucket	This alternative would have flip buckets on the spillway and/or sluiceways to project flows over the stilling basin and onto a shallow receiving basin.	Flip buckets on the Libby sluiceways were part of a physical model study in the early 1970's. They were never implemented due to concerns over tailrace erosion. It appears configuring the shallow receiving basin would be difficult. Design guidance indicated flip buckets may have trouble deflecting flow beyond the stilling basin. A removable impact surface has been proposed but feasibility is unknown.	Based on the performance of flip buckets at other projects, this alternative would probably produce dissolved gas levels outside a shallow receiving basin below 110% saturation.	If they were installed on the sluiceways colder water would be discharged downstream. If they were installed on the spillway, there would probably be no change in temperature from current operation using spillway.	$14 million upwards	Increased O&M costs would be the result of the increased spillway use discussed with Alt. 1. Additional costs would depend on final configuration of system.	> Congressional authorization and appropriation required > Sectional and general physical model study required > Water quality exception required from Montana > Feasibility study	>Would most likely meet 110% TDG standard if proper configuration could be achieved.	> Pool elevation would need to be >2418 to use spillway > Use of sluices with this alternative would negatively impact downstream temperatures > Unknown if structures would impact outlet capacity of project-a physical model study would be required to verify >Stilling basin bridge may be impacted >Configuring a permanent receiving basin appears to be difficult >Flip bucket impact to hydraulics generated by large flows unknown	>Receiving basin configuration and alteration of project hydraulics are of concern >Many unknowns with floating or removable basin concept

FIGURES

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Figure 1. Aerial Photograph of Libby Dam

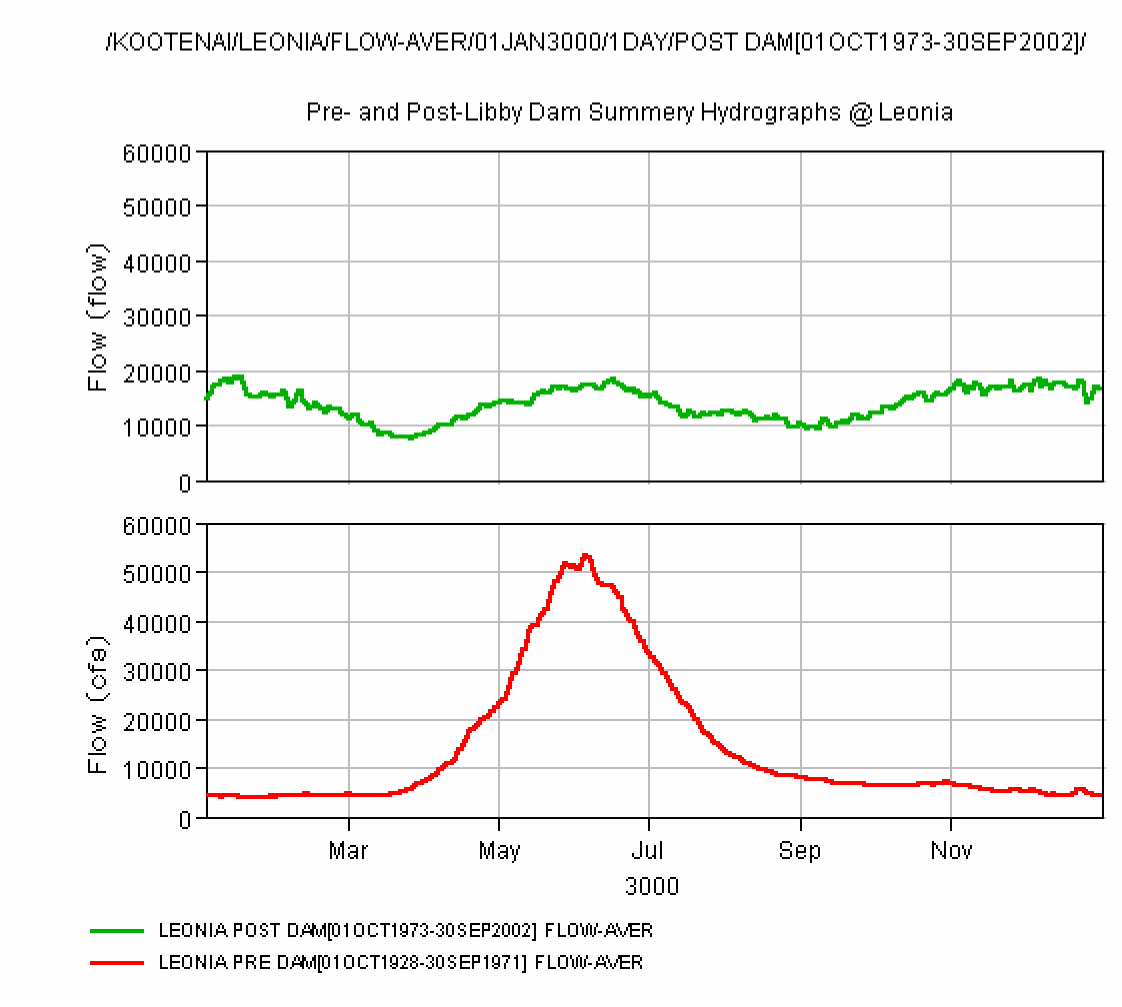

Figure 2. USGS Gage at Leonia Pre and Post Dam Summary Hydrographs

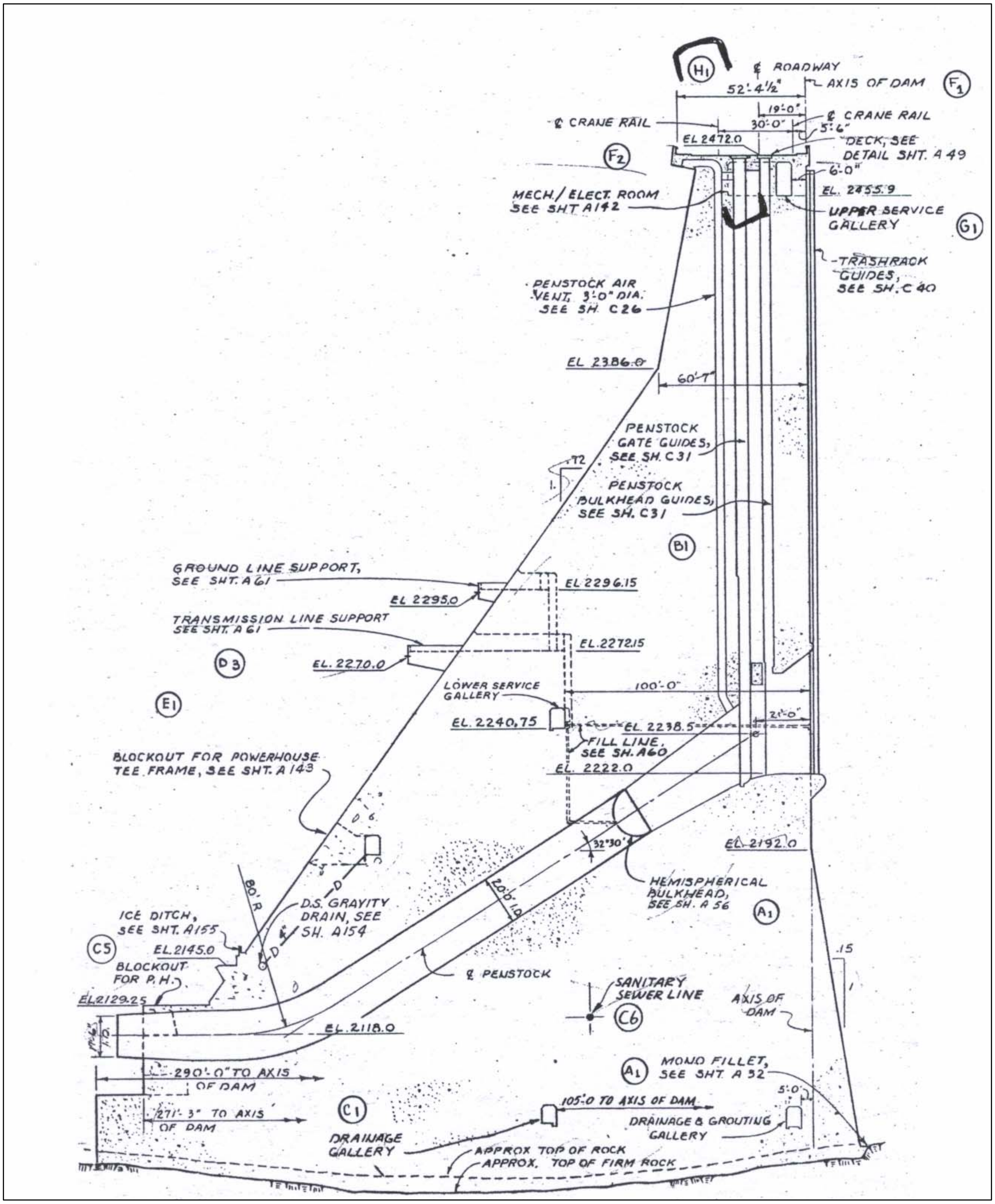

Figure 3. Cross Sectional Details of Penstocks

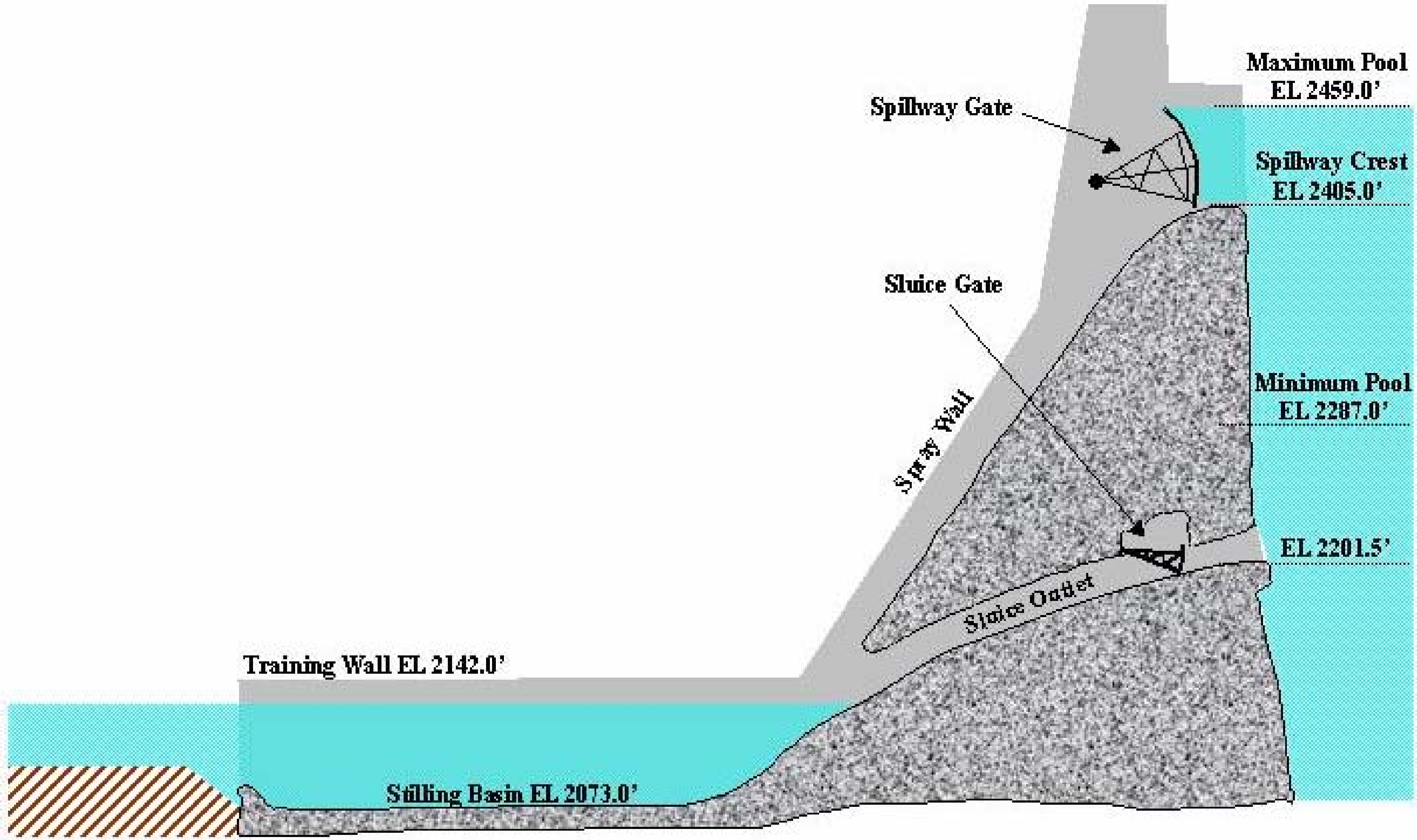

Figure 4. Cross Sectional Details of Spillway and Sluiceways

Figure 5. Turbulent Boundary Layer Development, Libby Dam Spillway

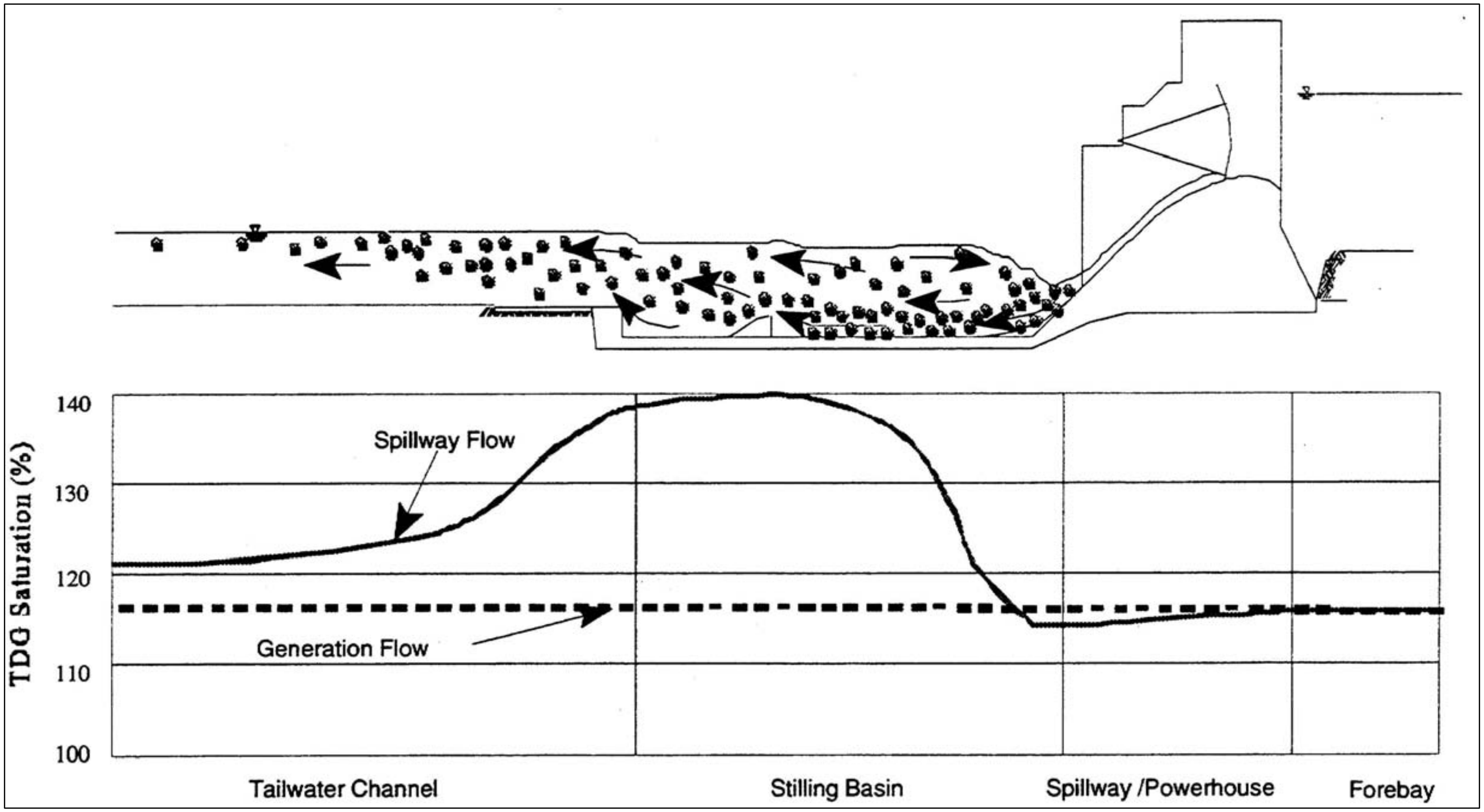

Figure 6. Dissolved Gas Exchange in Spillway Flows

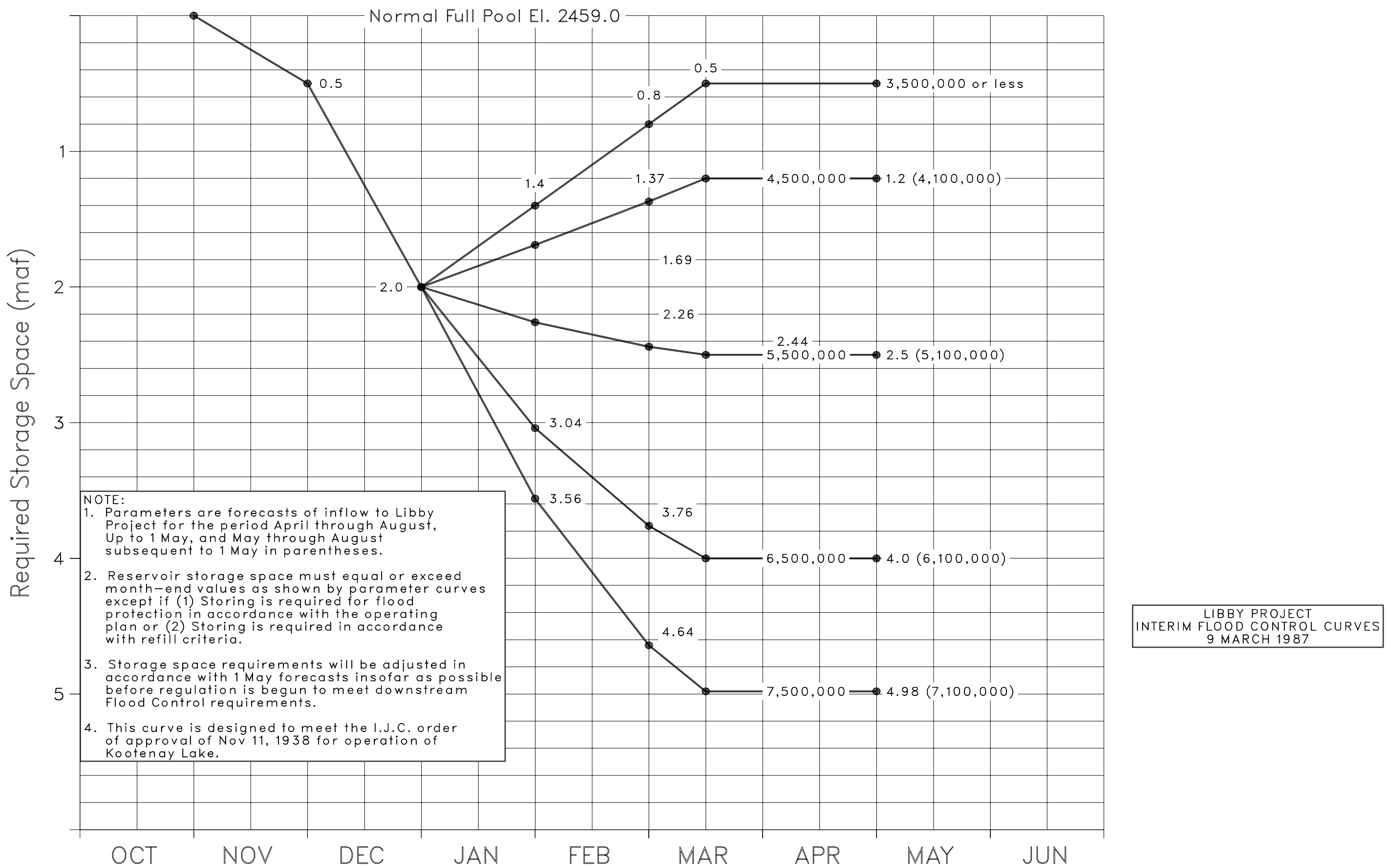

Figure 7. Base Flood Control Operation Storage Reservation Diagram (USACE 2002)

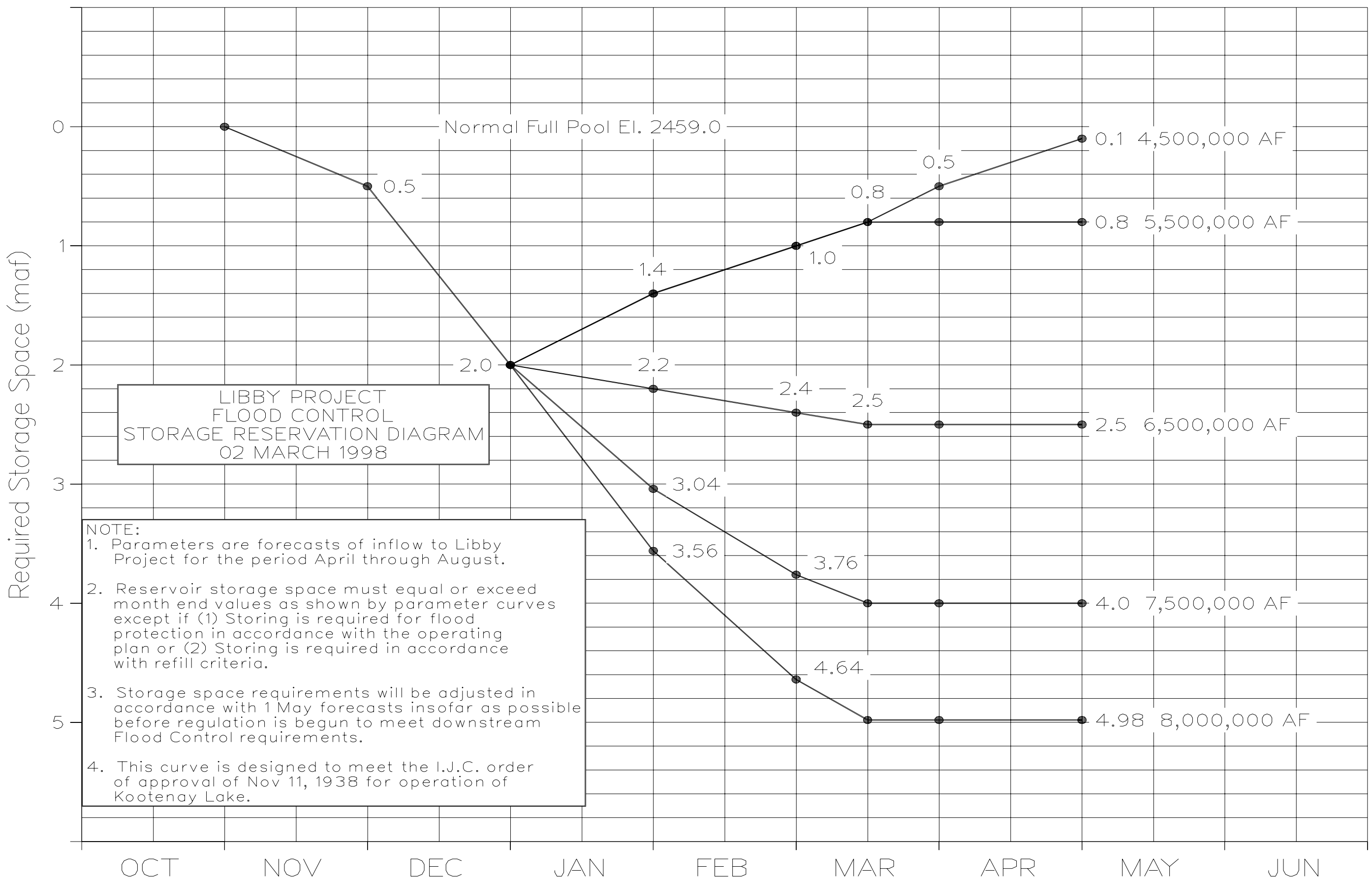

Figure 8. VARQ Flood Control Operation Storage Reservation Diagram (USACE 2002)

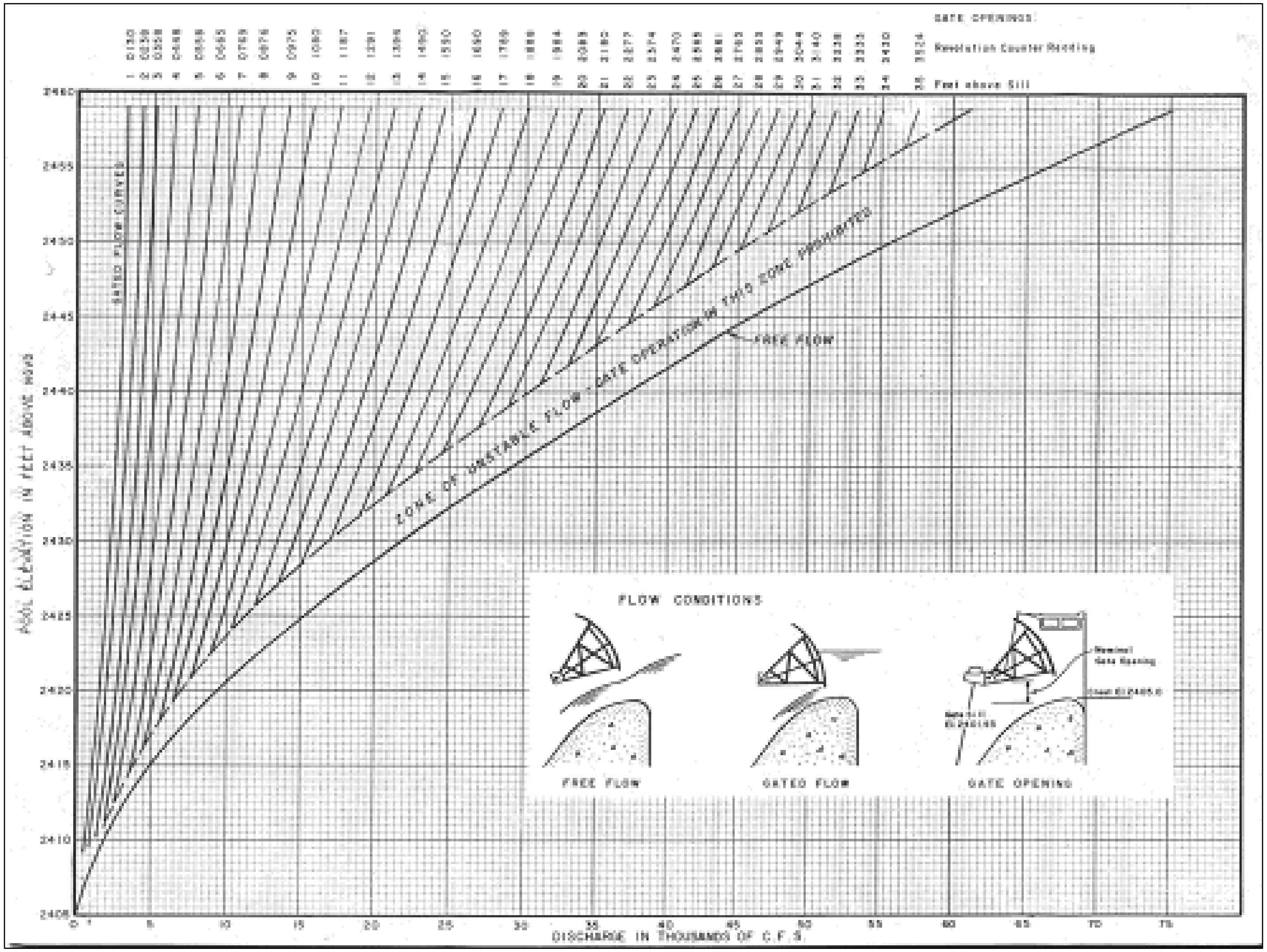

Figure 9. Spillway Rating Curve for One Gate (USACE 1984)

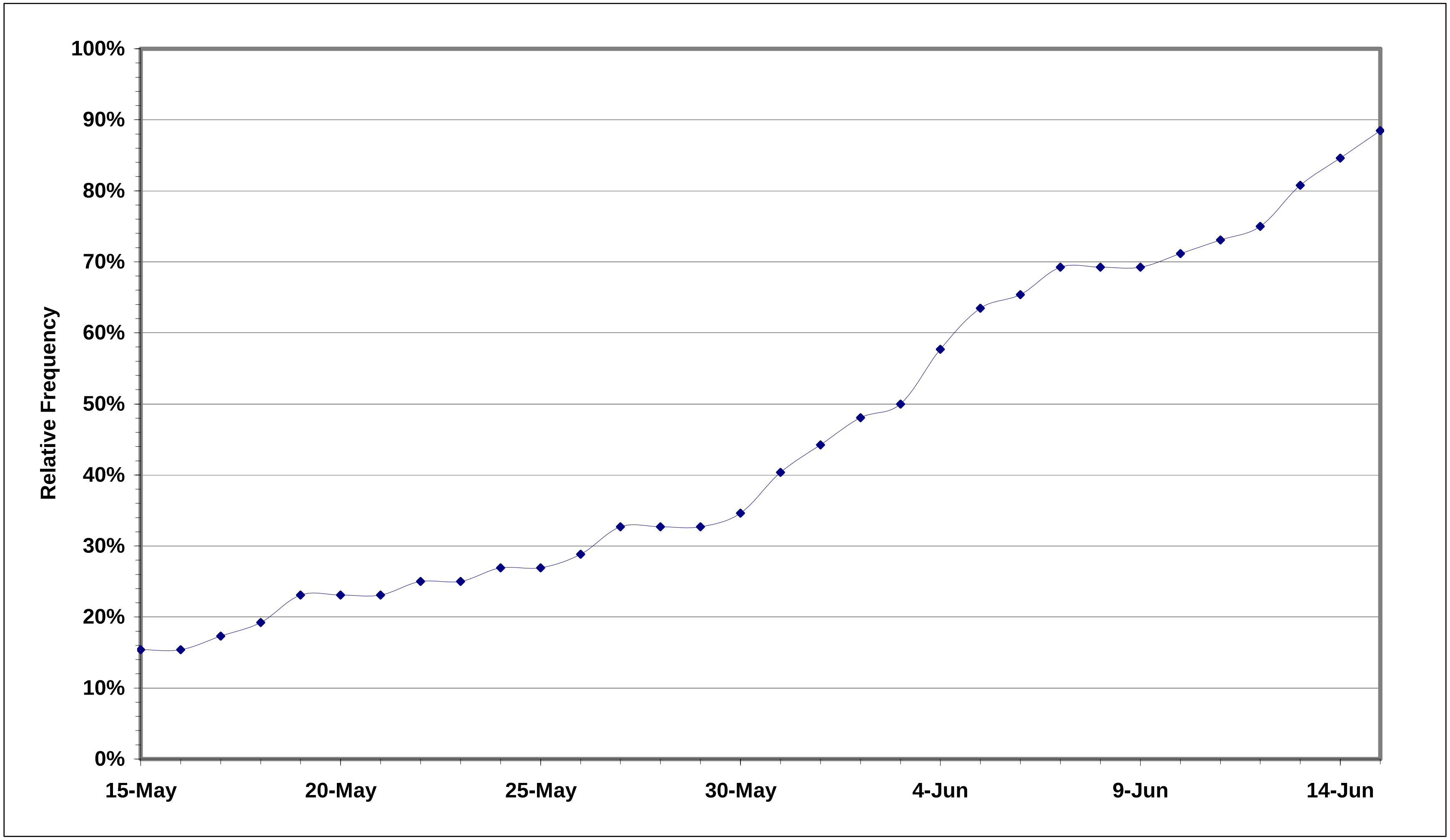

Figure 10. Relative Frequency of Libby Pool Being Greater than Elevation 2418 15 May- 15 June
(Plot generated from reservoir modeling using VARQ flood control operation)

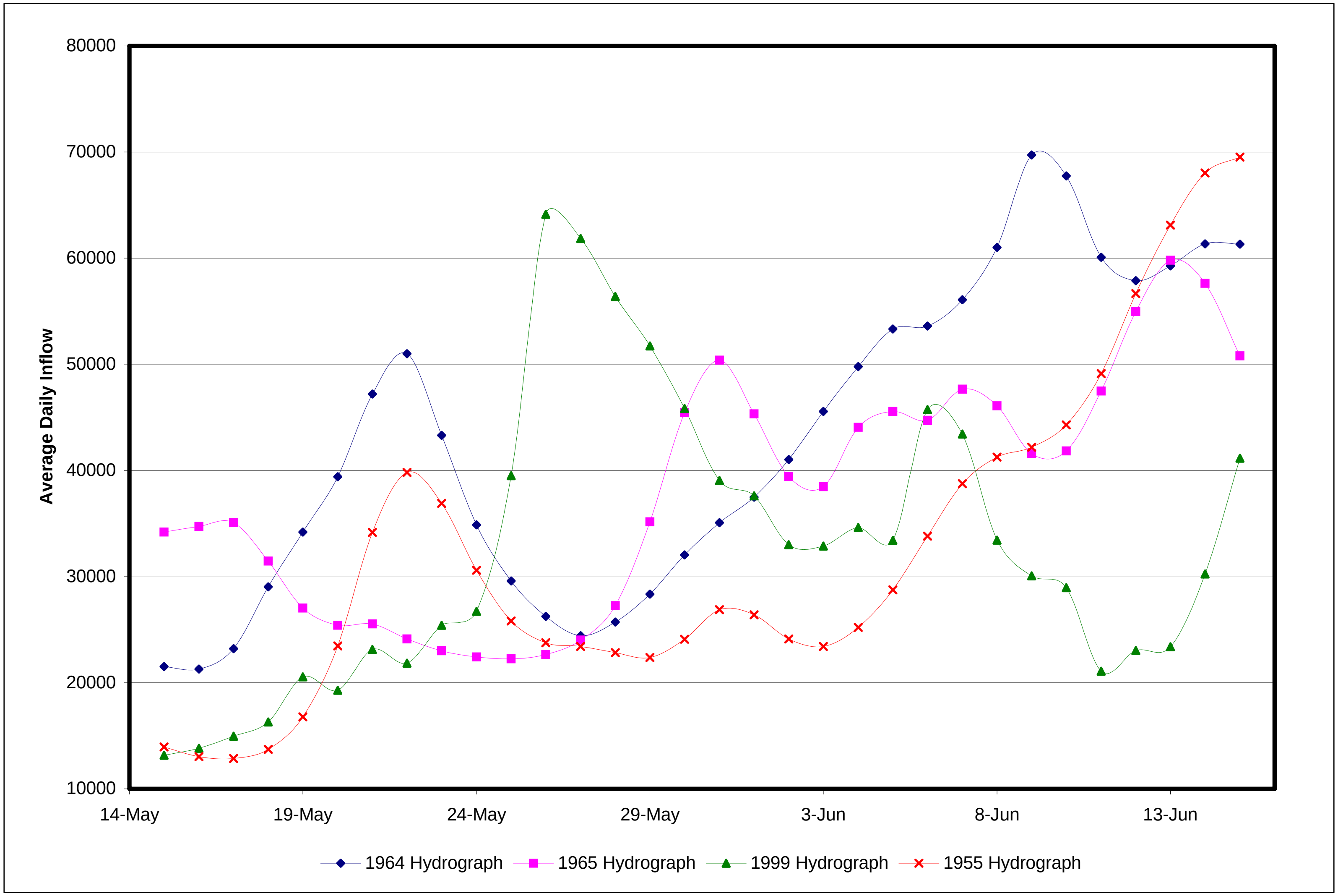

Figure 11. Lake Koocanusa 15 May-15 June Inflow Hydrographs for Selected High Runoff Years

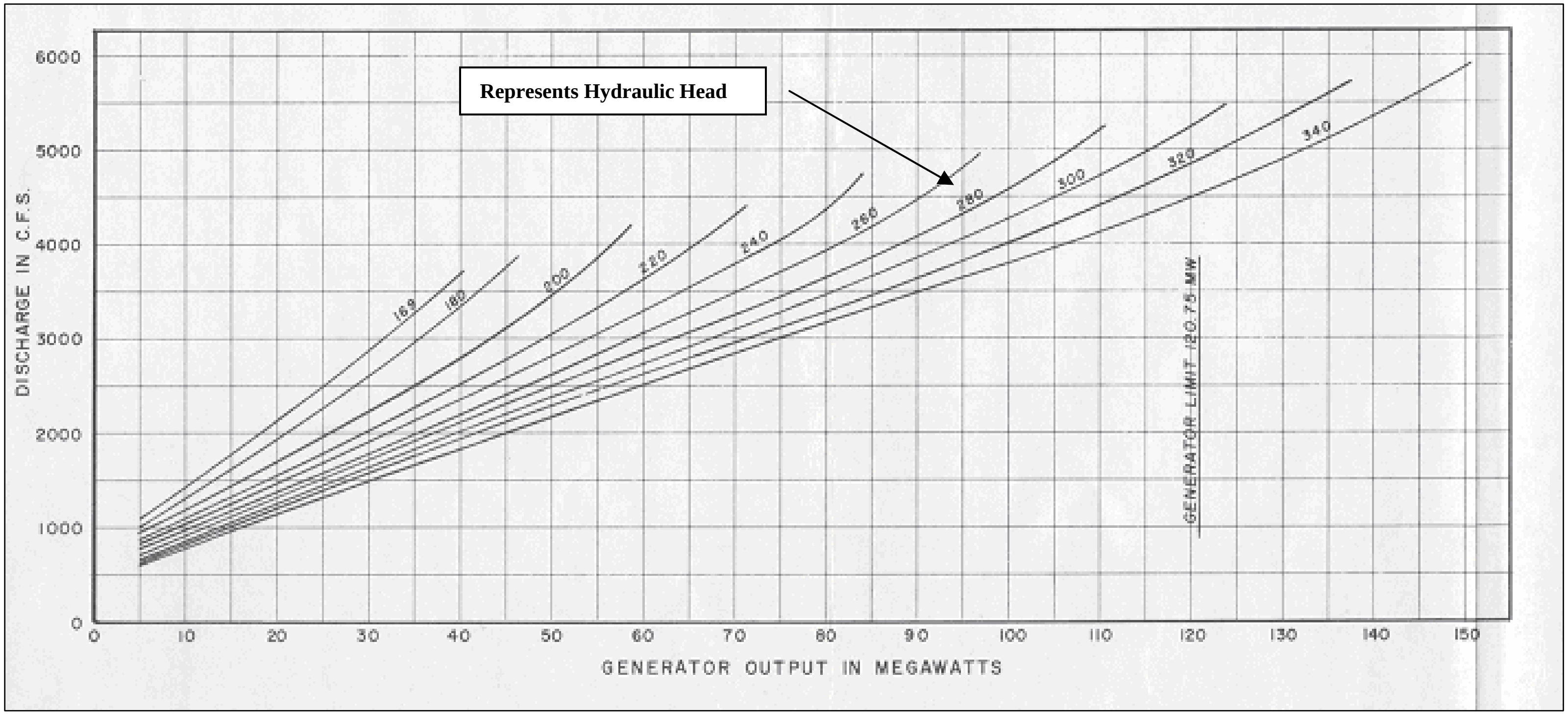

Figure 12. Libby Turbine Discharge Rating Curve

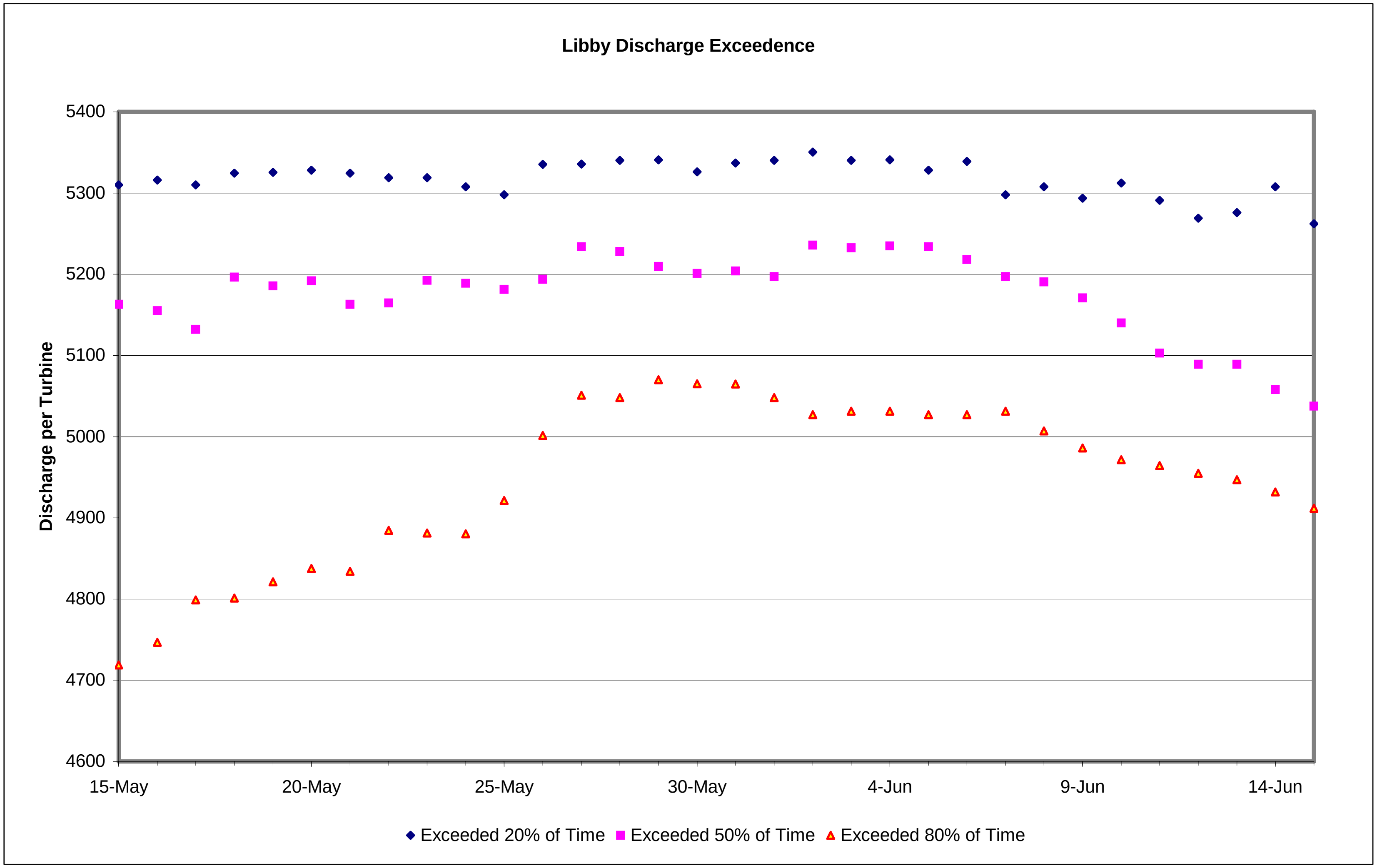

Figure 13. Libby Turbine Discharge Exceedance

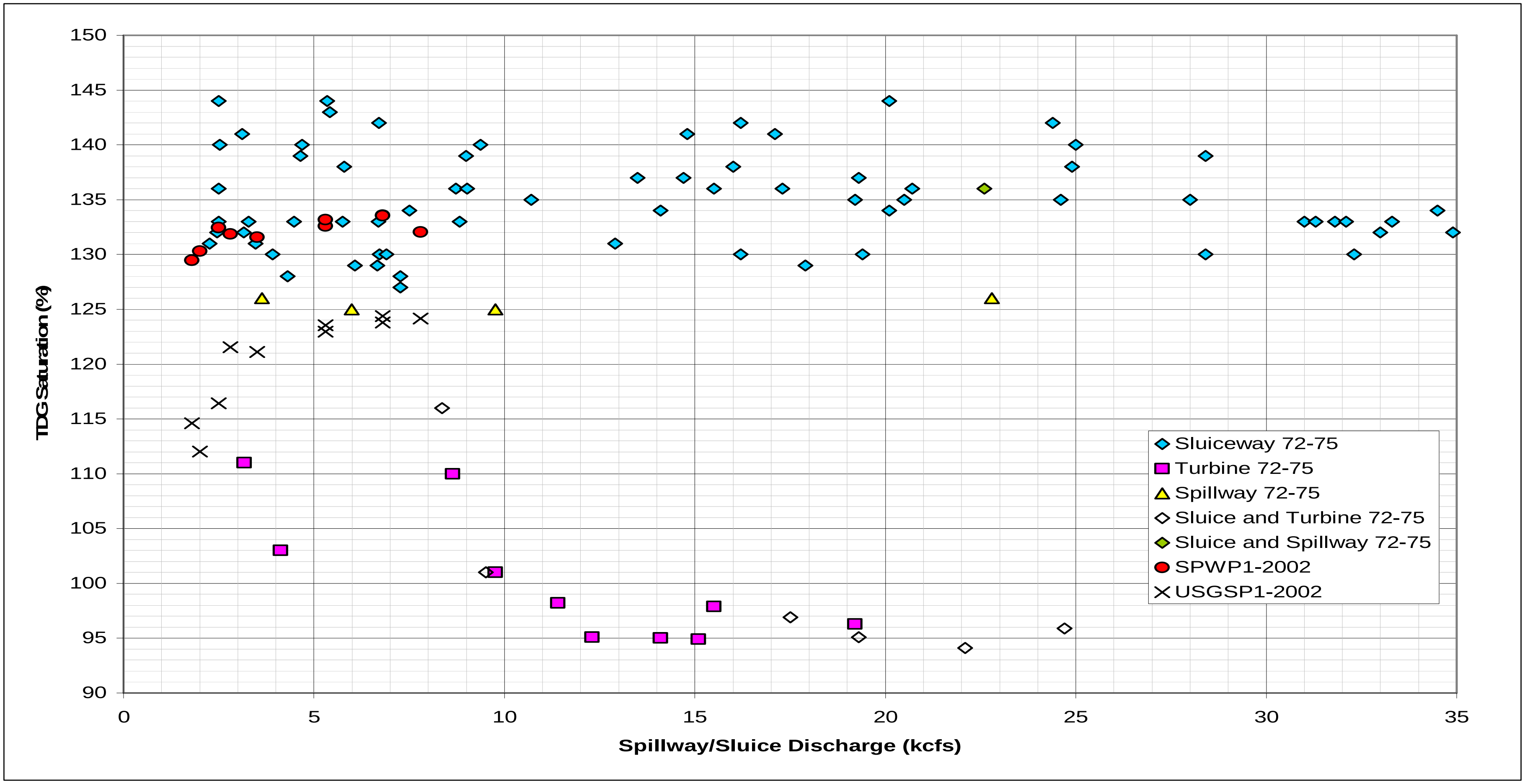

Figure 14. Total Dissolved Gas Saturation as a function of Spillway or Sluiceway Discharge, (1972-1975, 2002)

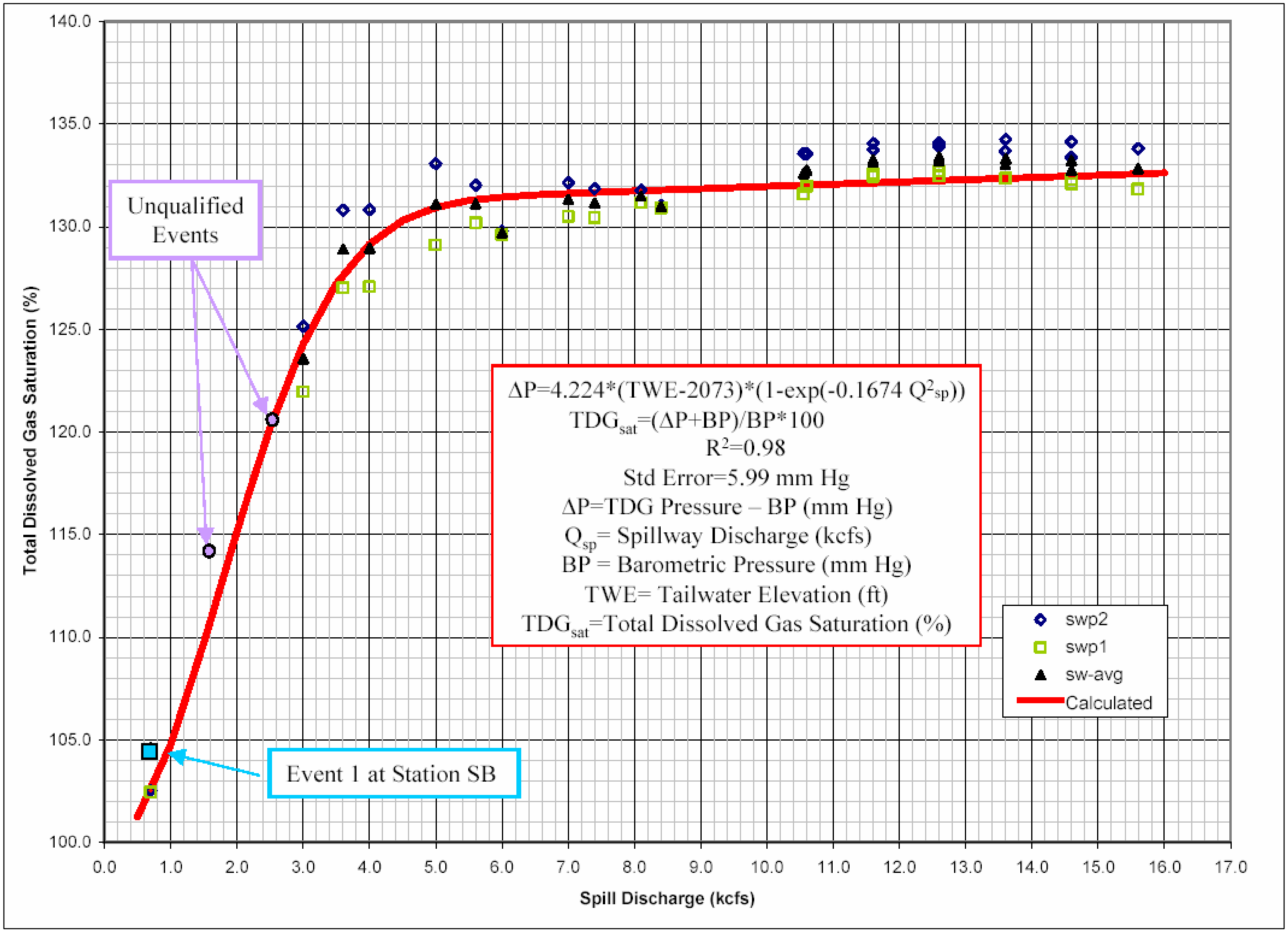

Figure 15. Libby Dam Total Dissolved Gas Saturation as a function of total spillway discharge.

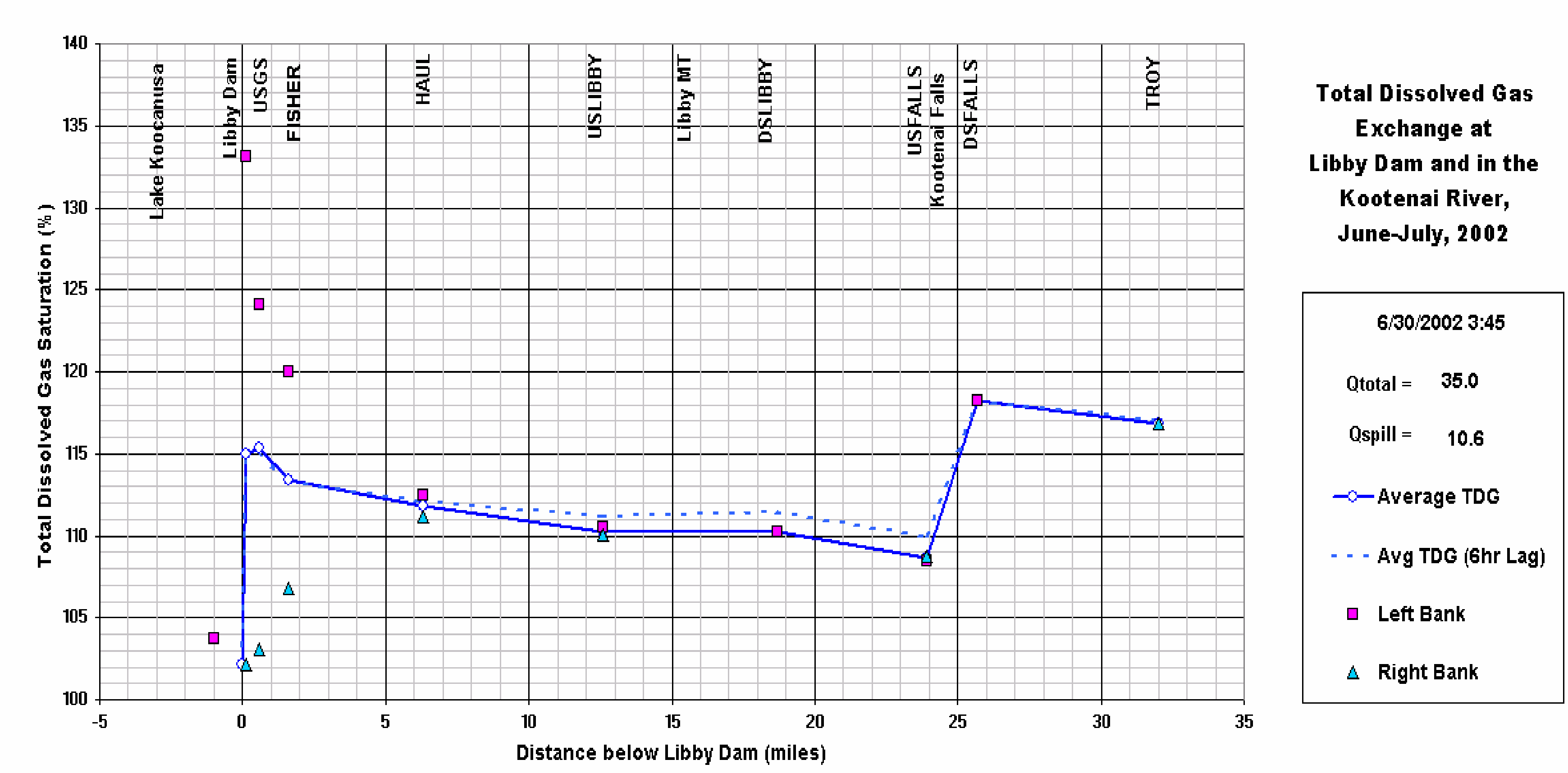

Figure 16. Total Dissolved Gas Saturation in the Kootenai River, June 30, 2002 3:45 hours, Qtotal=35 kcfs, Qspill = 10.6 kcfs

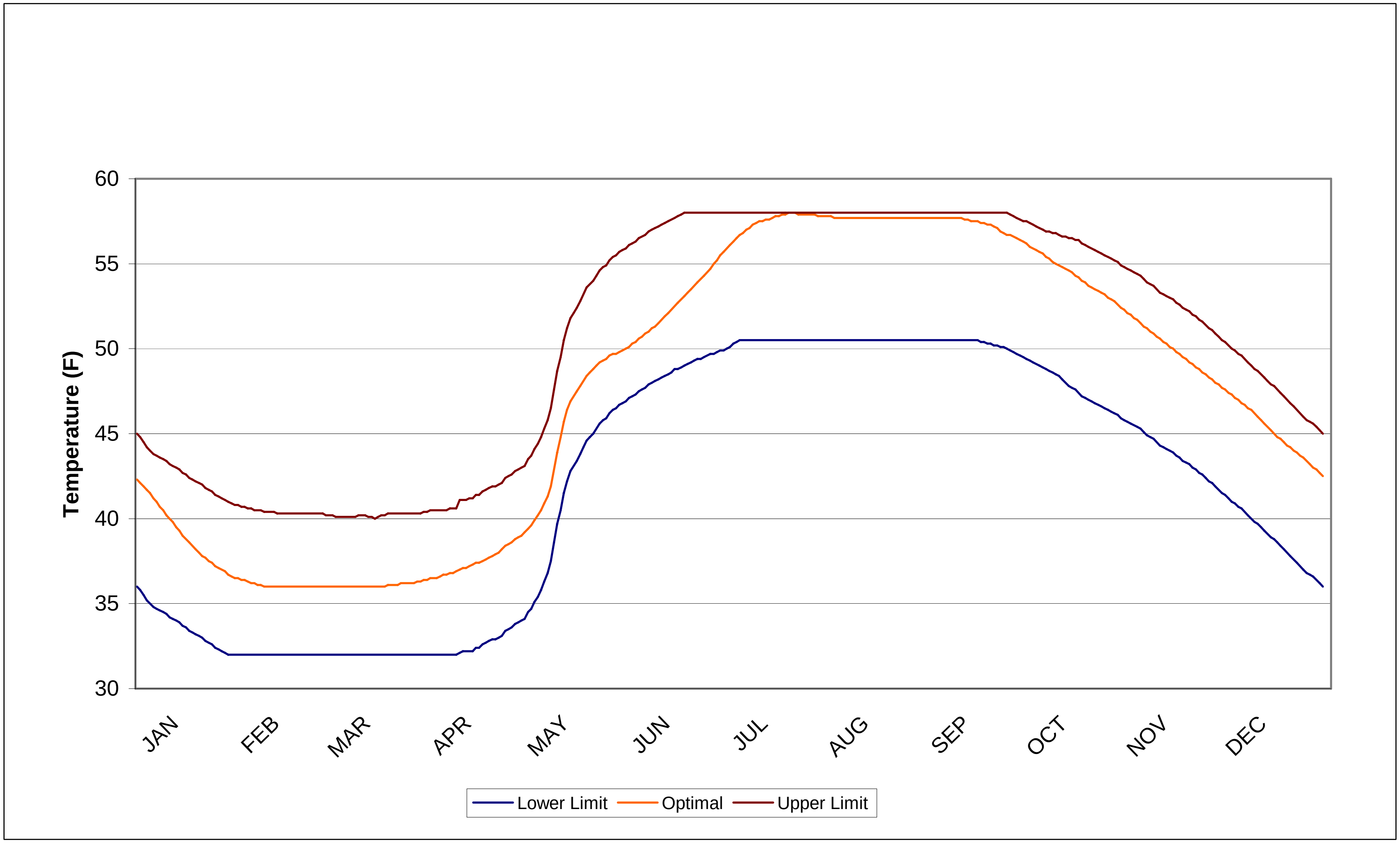

Figure 17. Libby Dam seasonal release temperature targets

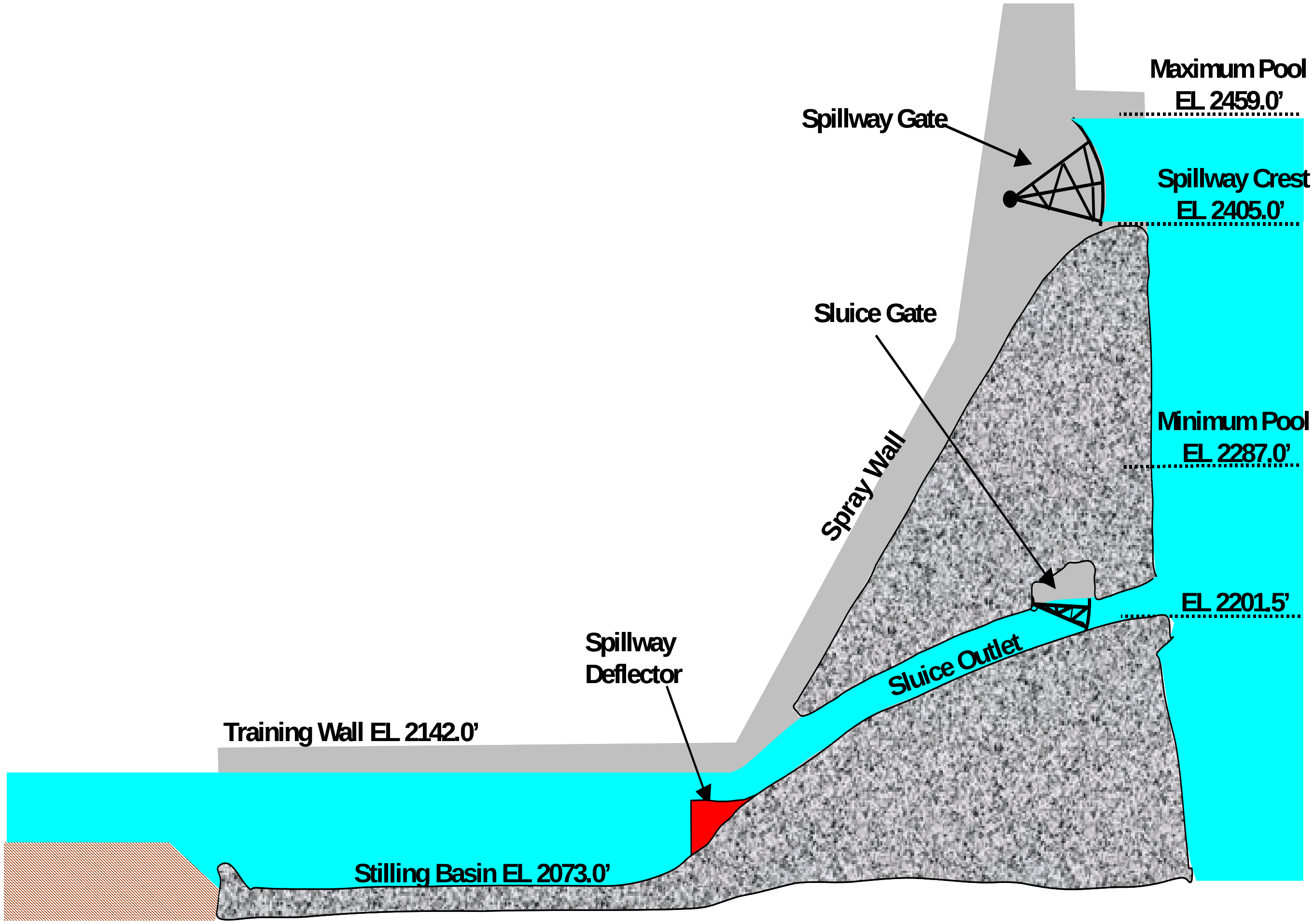

Figure 18. Spillway Flow Deflector Schematic

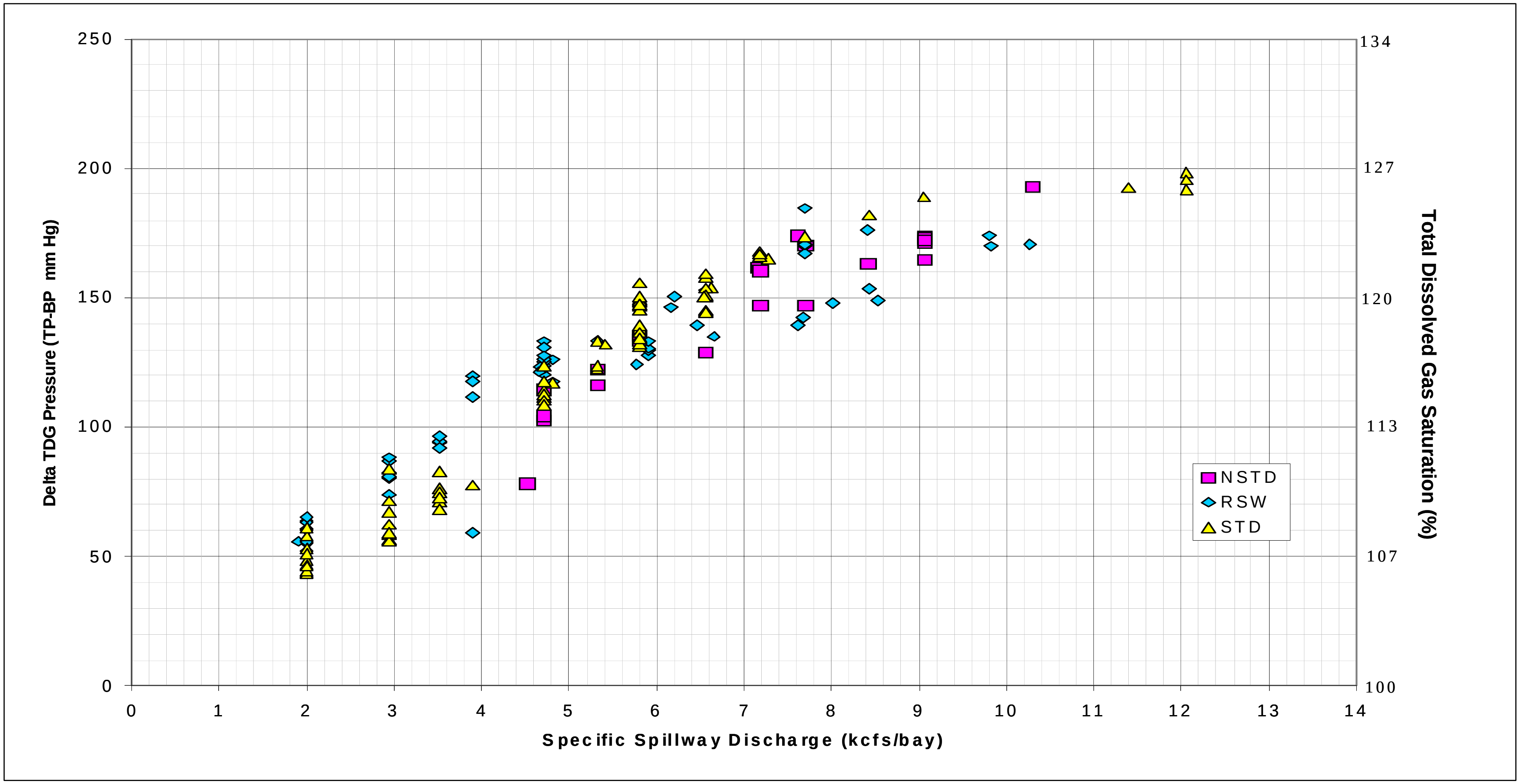

Figure 19. Lower Granite Total Dissolved Gas Production

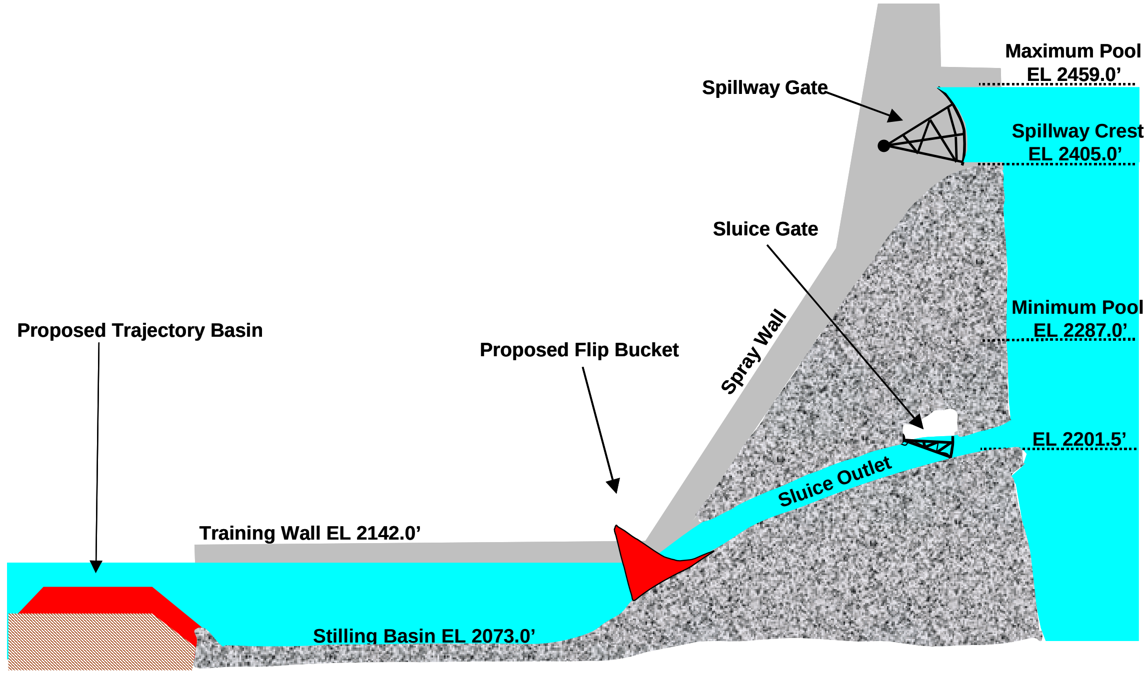

Figure 20. Spillway Flip Bucket and Trajectory Basin

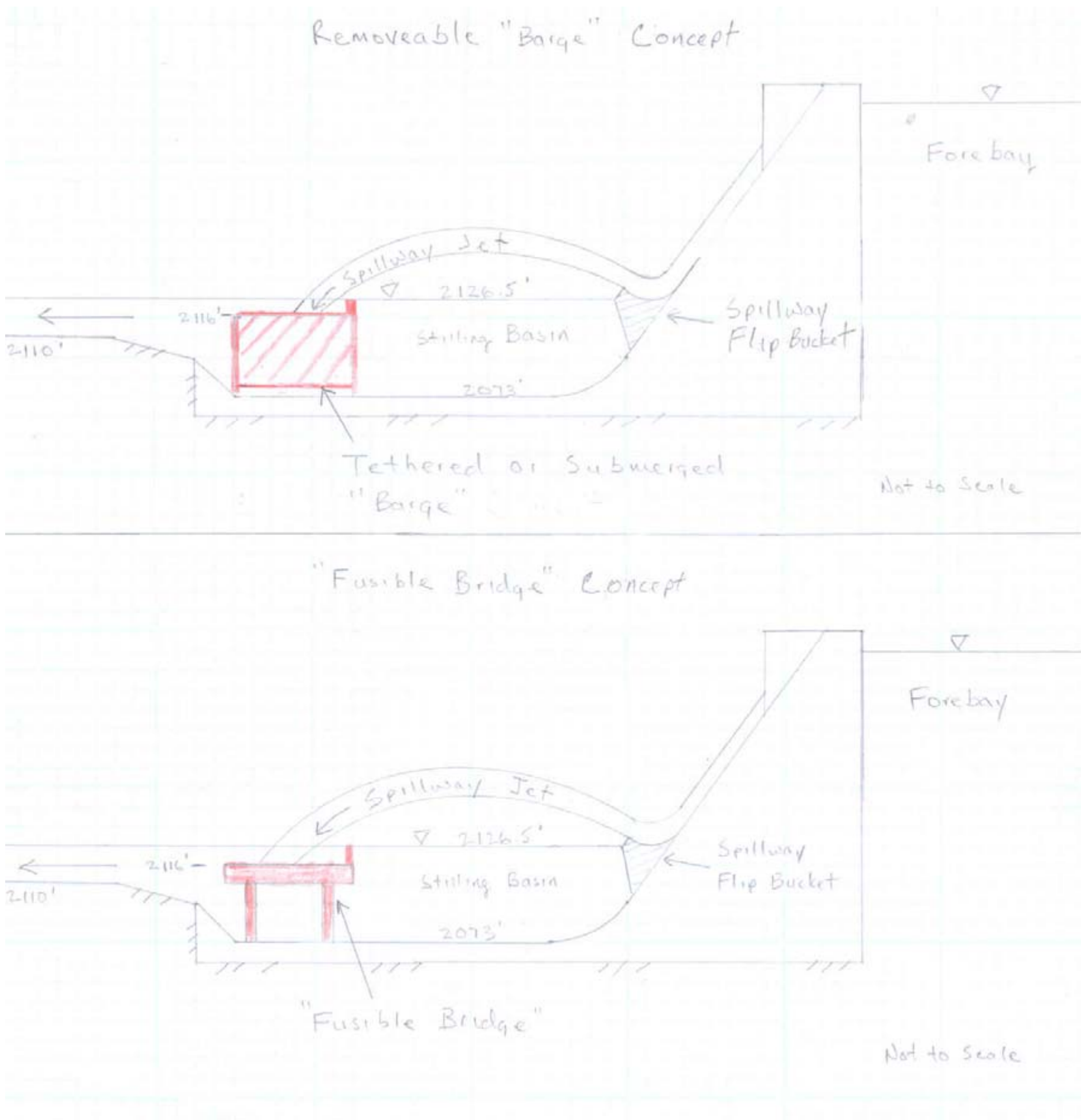

Figure 21. Removable Flip Bucket Receiving Basin Concept

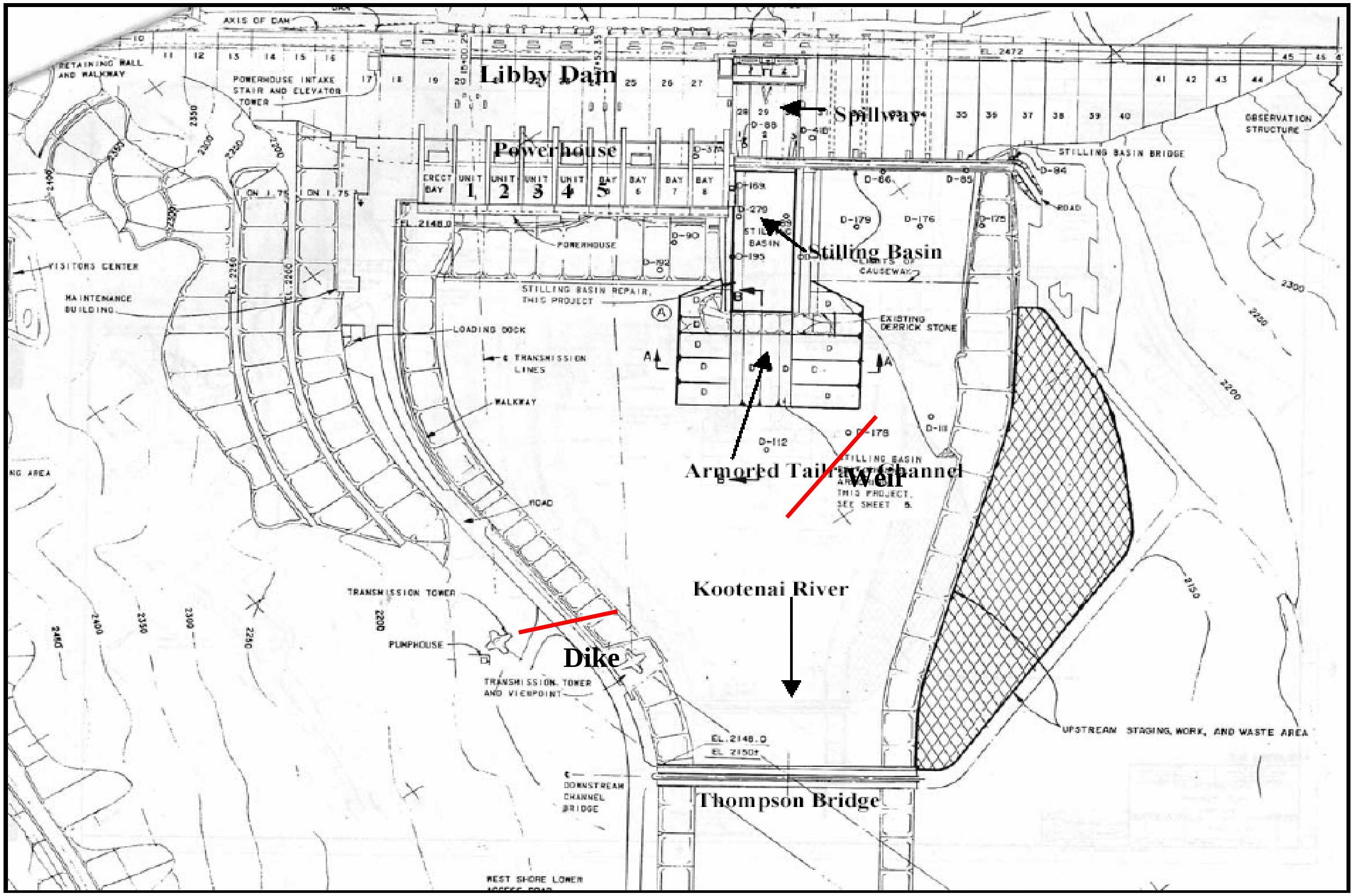

Figure 22. Libby Dam Tailwater Mixing Structure, Alternative 4

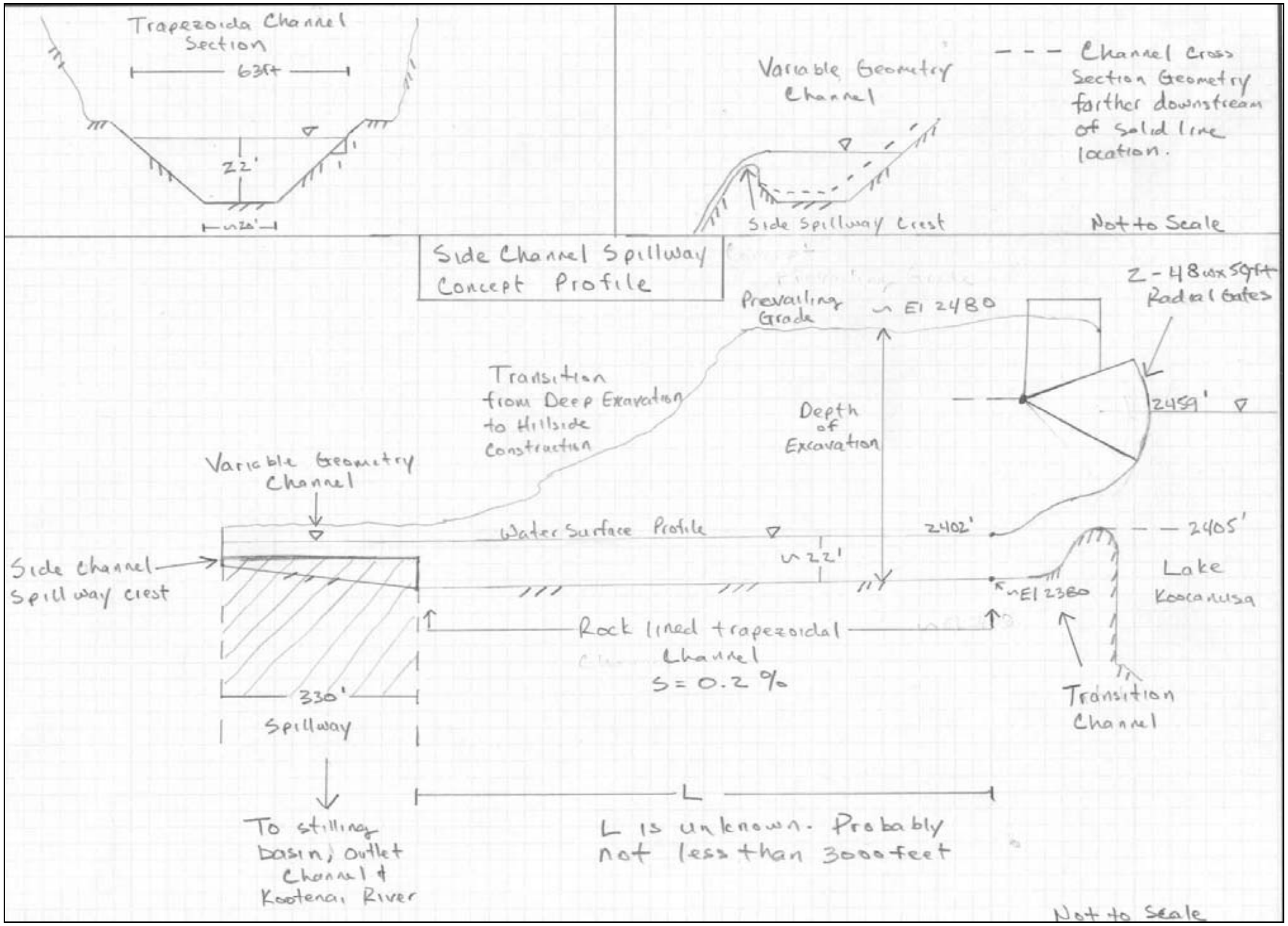

Figure 23. Side Channel with Spillway Concept Profile

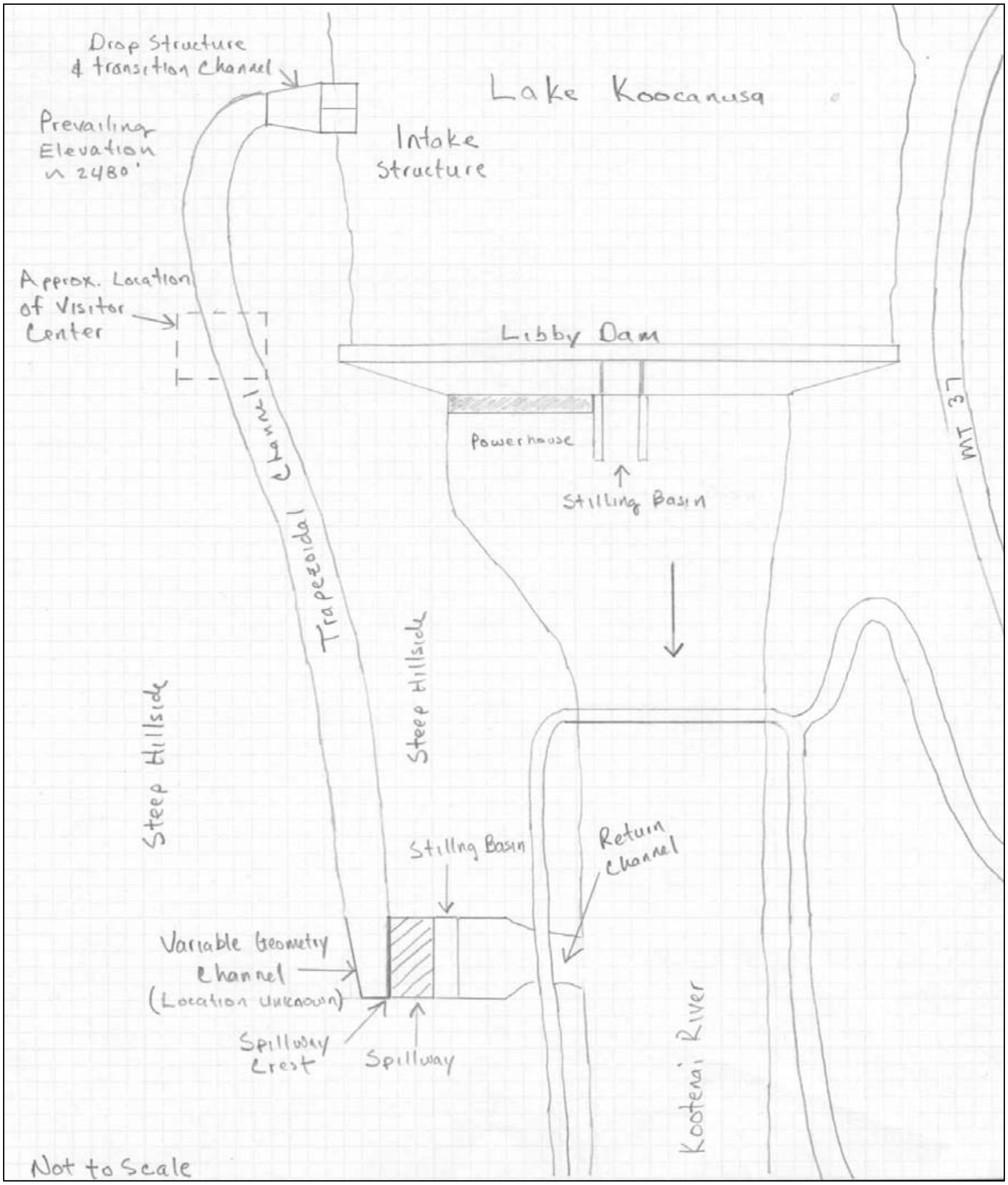

Figure 24. Side Channel with Spillway Concept Plan

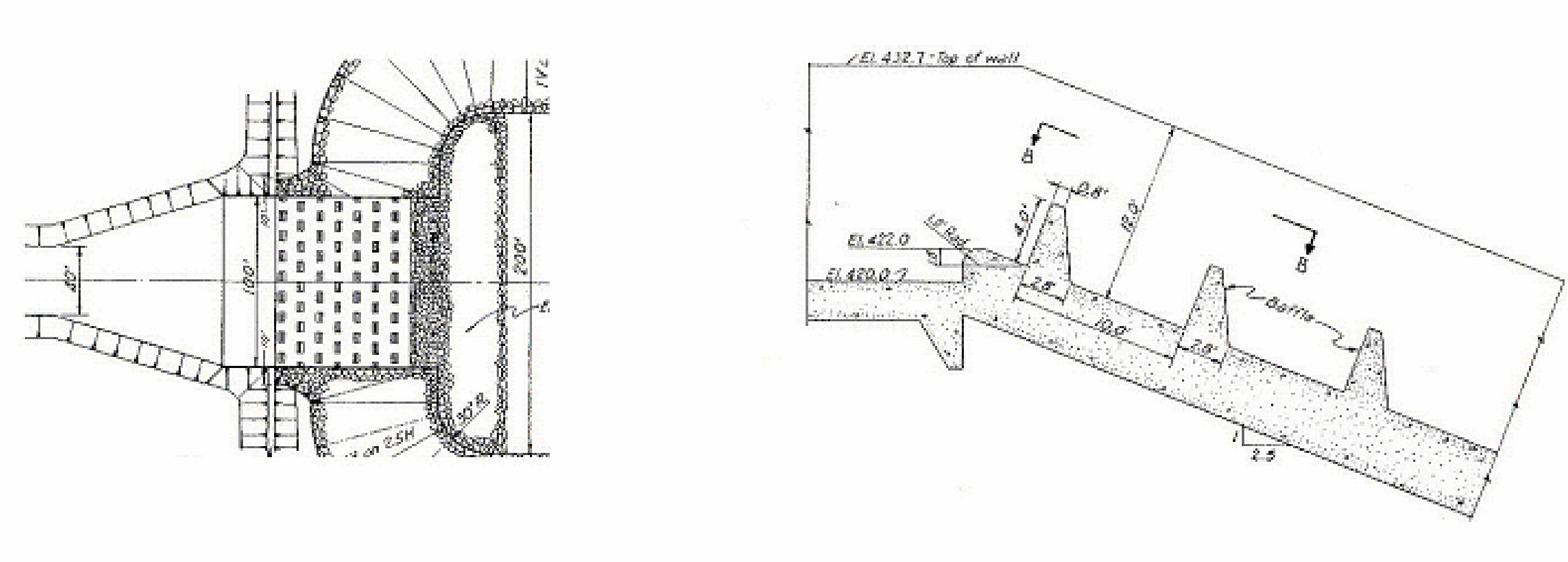

Figure 25. Libby Dam Baffled Chute Spillway, Alternative 6

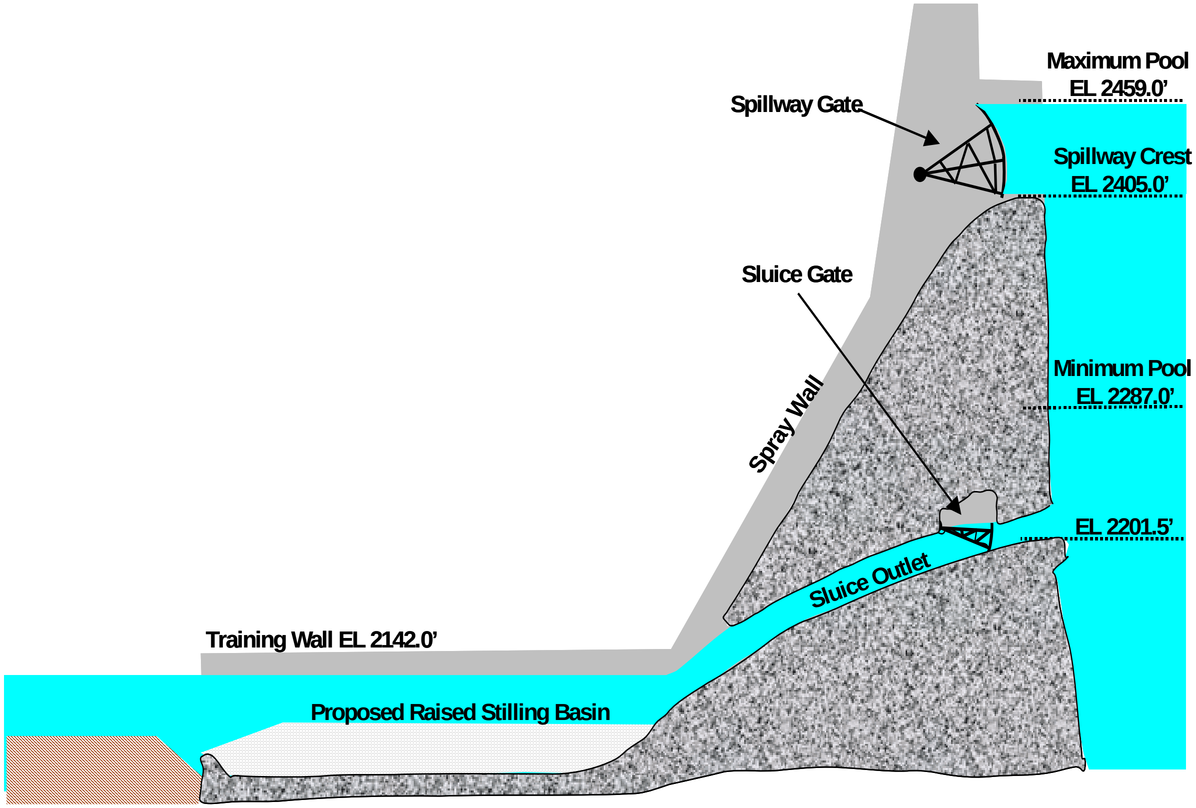

Figure 26. Raised Stilling Basin, Alternative 7

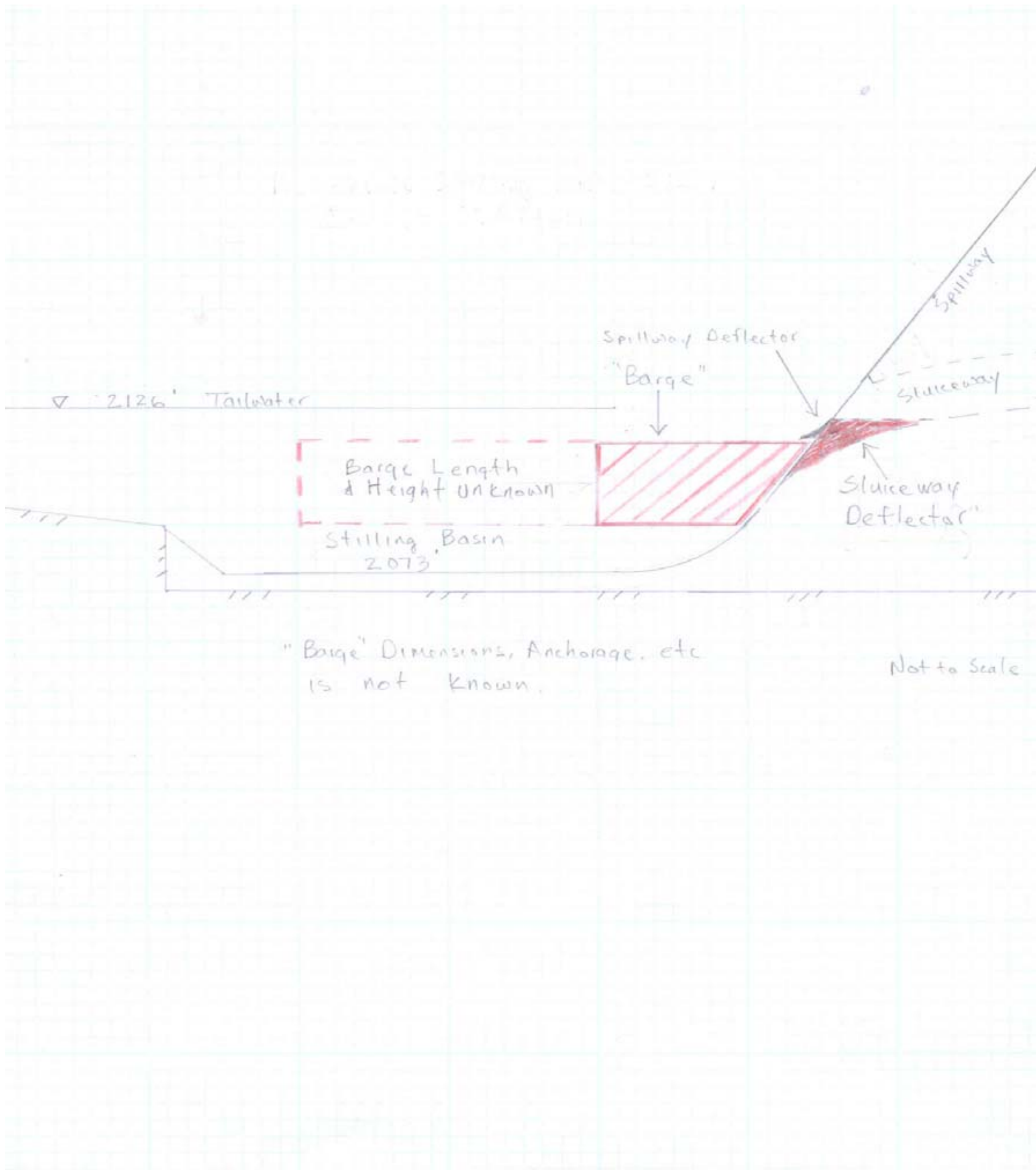

Figure 27. Removable Stilling Basin Floor Concept Sketch

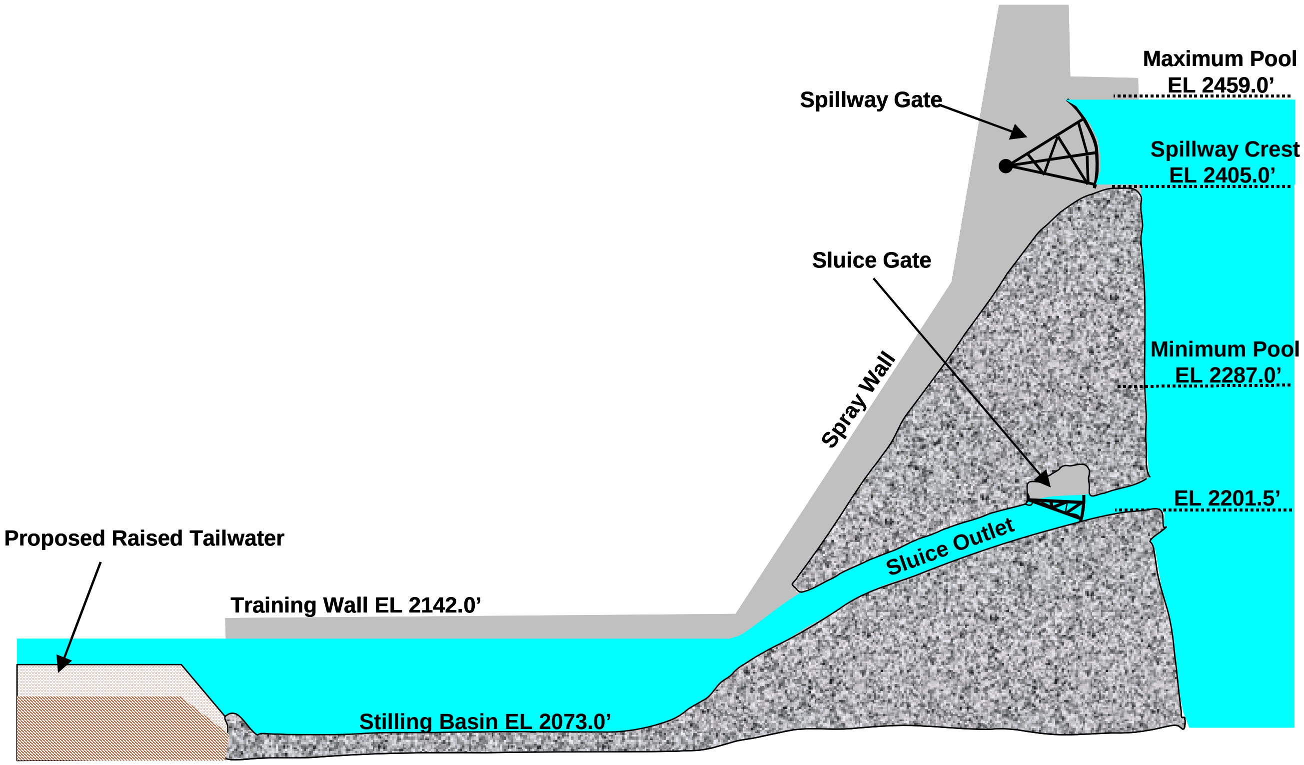

Figure 28. Raised Tailrace Channel, Alternative 8

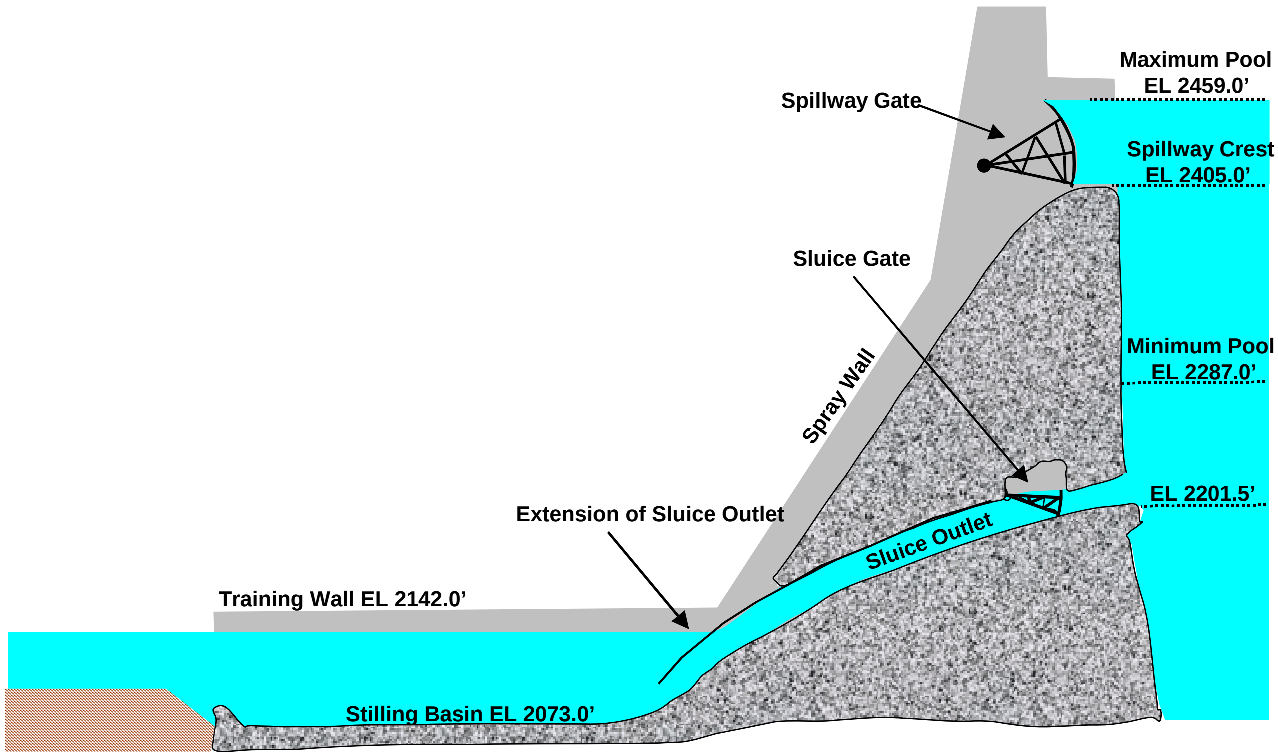

Figure 29. Extension of Sluiceway Outlets, Alternative 9

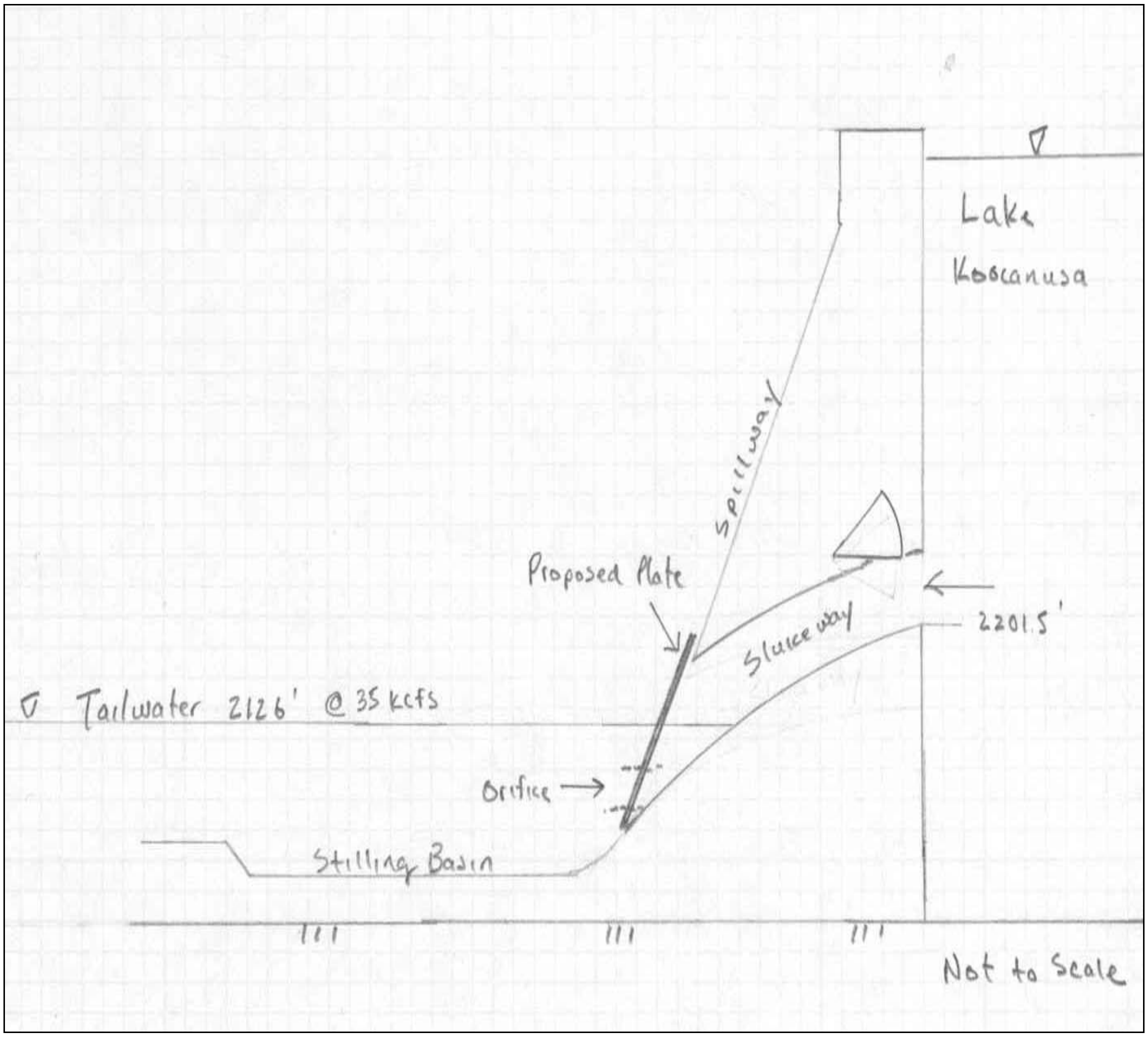

Figure 30. Sluiceway Outlet Orifice Plate

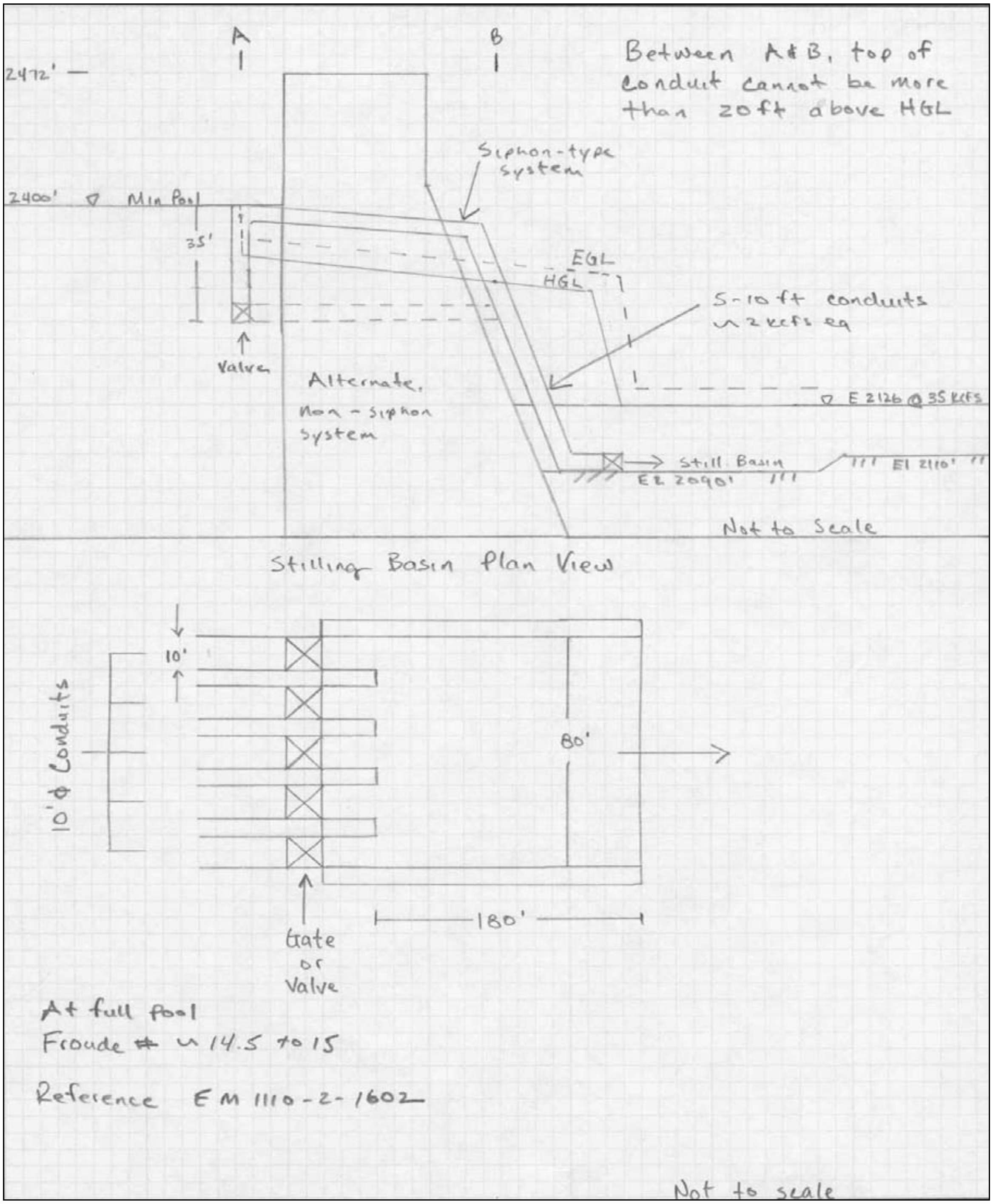

Figure 31. Siphon/Dedicated Pressure Flow System with Auxiliary Stilling Basin

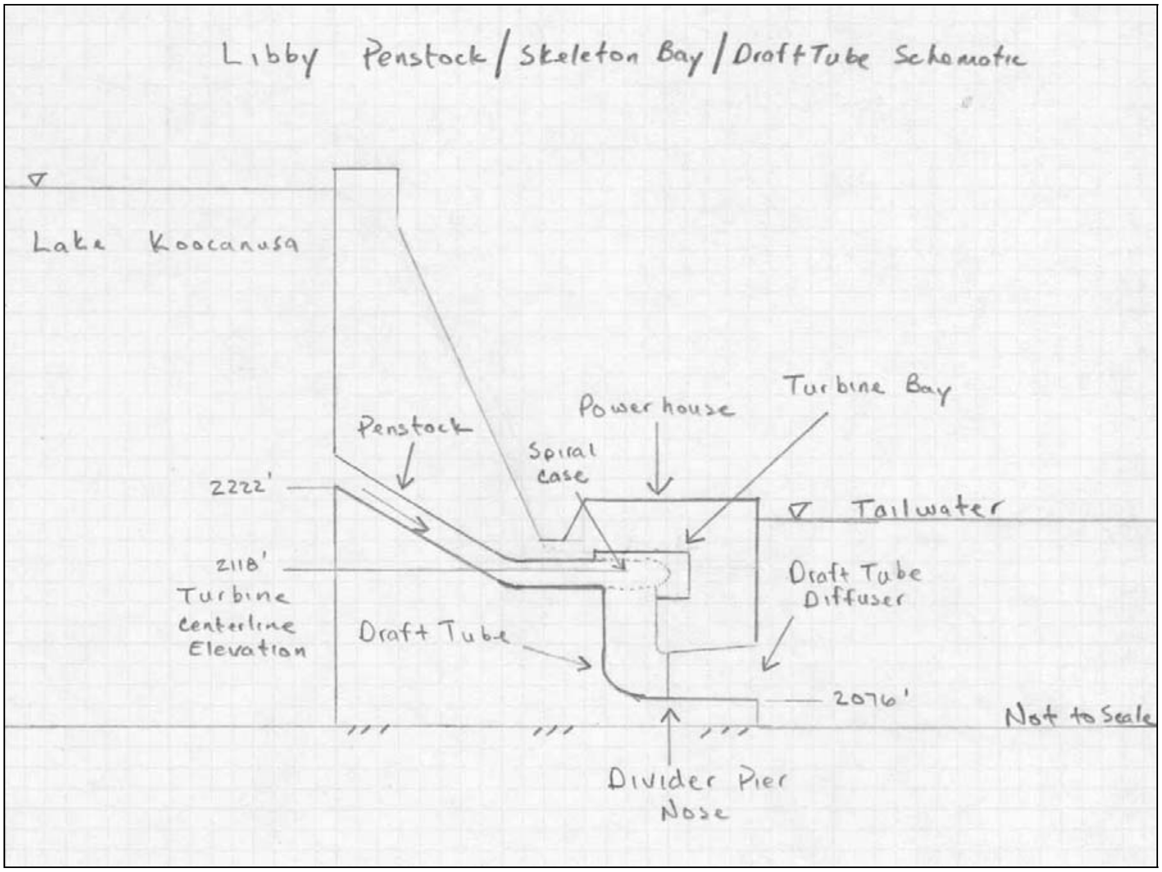

Figure 32. Penstock/Turbine Bay/Draft Tube Schematic