

**Independent Expert Engineering Investigation and Review Panel**

**Report on Mount Polley**

**Tailings Storage Facility Breach**

**Appendix I: B.C. Tailings Dam Failure Frequency  
and Portfolio Risk**

**January 30, 2015**

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## Independent Expert Engineering Investigation and Review Panel

### APPENDIX I: B.C. TAILINGS DAM FAILURE FREQUENCY AND PORTFOLIO RISK

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## 1.0 INTRODUCTION

The purpose of the work described in this Appendix was to determine the historic failure frequency of tailings dams in British Columbia. To this end, a database was compiled from Ministry of Energy and Mines (MEM) records of the number of failures, the number of dams, and the number of years these dams were in operation during the 46-year period from 1969 to 2015.

These numbers are used to derive the historic failure frequency as failures per dam per year. Failure frequency is distinct from failure rate. The former accounts for the lifetime of dams in the population, and the latter does not. Failure frequency is used to evaluate the government's portfolio risk for tailings dams under its jurisdiction and strategies for reducing this risk.

## 2.0 DATA SELECTION

### 2.1 ACTIVITY STATUS

Previous catalogues of tailings dam incidents have shown the activity status of tailings dams to have a dominant influence on the prevalence of failures.<sup>1,2</sup> The number of reported failures for tailings dams that do not contain ponded water is small compared to those that do. To control for this effect, operational duration for only the subpopulation of "active" tailings dams—dams whose impoundments contain surficial water—was considered. This was to avoid biasing the database by including dams with intrinsically low propensity for failure.

The activity status of a tailings dam is not to be confused with that of the mine it serves. An active mine will ordinarily have at least one active tailings dam to receive the tailings produced by its mill.

But a closed mine may still have one or more active tailings dams if they continue to retain ponded water after cessation of milling. This may be the case for impoundments that have not yet been reclaimed, for those without structural measures to prevent surface water accumulation, or for those that intentionally retain a water cover as part of their closure plan. In any event, once water is removed from the impoundment surface, the dam's period of active operation ends.

Accordingly, the activity status of a given tailings dam may change over time. The compilation tracked the activity status of each dam to obtain its duration of active operation over the designated period of record.

<sup>1</sup> USCOLD, 1994, Tailings Dam Incidents, U.S. Society on Dams (formerly U.S. Committee on Large Dams), Denver, 82 p.

<sup>2</sup> ICOLD, 2001, Bulletin 121, Tailings dams risk of dangerous occurrences. International Commission on Large Dams, Paris, 144 p.

## 2.2 PERIOD OF RECORD

Prior to 1969, the Province had no requirement for tailings dam permits. To achieve a degree of uniformity in data quality and completeness, only the operational period of those structures permitted in 1969 or later was included. Similarly, only failures during and after 1969 were considered, whether or not the failed structure was permitted. This results in a 46-year period of record from the beginning of 1969 to the beginning of 2015. This period is generally reflective of modern tailings dam technology.

## 2.3 MULTIPLE STRUCTURES

A given mine may have multiple tailings impoundments, and any one impoundment may be confined by multiple dams. Each tailings dam was treated as a separate entity, regardless of these factors.

## 2.4 STRUCTURE CHARACTERISTICS

MEM records contain information on mine-related impoundments of several types in addition to tailings dams. For purposes of this compilation, tailings dams were considered to be only those structures that confine impoundments for permanent retention of solid mineral processing wastes. Mine water reservoirs, emergency storage facilities, settling ponds, treatment ponds, or temporary storage facilities were not included. No restriction was placed on dam height or impoundment size.

## 2.5 INCIDENT TYPES

For purposes of this compilation, “failure” is defined as breach of the dam resulting in release of tailings and/or water. Incidents meeting this definition were considered failures regardless of volume released, run-out distance, or whether released materials were contained on the mine site.

MEM records contain a number of incidents of various types that do not conform to this definition. Some involved release of tailings or water from spills without dam breach, others involved only partial breach, and yet others were for potentially dangerous occurrences that involved no release at all. Such incidents were not included in the compilation.

## 2.6 DEFINITIONS

Key definitions are summarized as follows:

- **Tailings dam:** A structure that permanently retains solid mineral-processing wastes.
- **Active tailings dam:** A tailings dam whose impoundment contains surface water.
- **Failure:** Breach of the dam resulting in release of tailings and/or water.

## 3.0 DATA SOURCES AND COMPILATION

Data were compiled from MEM files in Victoria during October 2014. The basis of the compilation was provided on two spreadsheets previously prepared by MEM. These spreadsheets included all tailings dams in B.C. known by MEM to exist, including operating, closed, abandoned, and historic structures. The two spreadsheets were combined into one list referred to as the inventory. The inventory included physical attributes (location, maximum height, dam crest length and elevation) but did not include dates associated with commissioning, construction, or closure. The principal objective was to establish a timeline of active operation for each tailings dam. This focused on establishing a construction start date and an end date of water storage for each impoundment. Information was generally found with the Mine Permit files and may have included, but was not limited to, any of the information sources listed below. In a few cases, additional information was obtained from MEM's off-site storage facility.

Estimated "construction start" dates were determined using the following procedures in descending order of precedence:

- Specific reference to initiation of construction (either written or photographic)
- Inferred reference to beginning of construction
- Permit date
- Estimated mining operation dates, as further explained below

Estimated "end of water storage" dates were determined using the following procedures in descending order of precedence:

- Specific reference to end of water storage (either written or photographic). Google Earth Pro was used as the main tool in determining if an impoundment was currently holding water
- Where Google Earth was inconclusive, and no specific reference to impoundment closure could be found, it was assumed that the impoundment was still containing water
- Where Google Earth indicated no water storage, but no specific reference to impoundment closure could be found, an estimate was made based on the available file information

Estimated "mining operation" dates were determined using the following procedures in descending order of precedence:

- Specific reference to mining operation dates
- The BC MEM MINFILE mineral directory database

Years in active operation for each dam were determined by subtracting the estimated construction start date from the estimated end of water storage year. Impoundments that were determined to still be holding water were assigned an end of water storage year of 2014.

Information from the following sources was reviewed:

- Mine permits and addendums
- Drawings and maps
- Photographs (with captions)
- Reports on construction
- Construction record reports
- As-built reports
- Design reports
- Reclamation inspection reports
- Annual reclamation reports
- Environmental and reclamation reports
- Letters from and to MEM Senior Geotechnical Engineer
- Reports/letters to and from the Chief Inspector of Mines
- Internal correspondence from MPMC
- Report of Inspector of Mines
- Technical memoranda
- MEM office memoranda
- Report of Inspector of Mines, Geotechnical Inspector
- Tailings dam annual review of operation reports
- Annual reviews of tailings dam reports
- Annual reviews of tailings management facility
- Annual tailings dam performance reviews
- Dam safety review reports
- Formal annual dam inspection reports
- Annual geotechnical reviews
- Operation maintenance and safety manuals
- Geotechnical assessment reports
- Environment Canada regional pollution incident reports
- Mine seepage review reports
- Investigation on leakage from dam reports
- Closure reports
- Closure cost estimate reports
- BC MEM MINFILE mineral directory
- Google Earth Pro

Impoundment location data, tailings dam inventory data, and research data are included as Attachments I1 through I3.

## 4.0 RESULTS

### 4.1 FAILURES

Seven incidents met the definition of failure. These are briefly described in **Table I 4.1.1** from information in MEM files and supplemental published references.

**TABLE I 4.1.1: FAILURES OF ACTIVE TAILING DAMS IN B.C., 1969 - 2015**

MINE NAME	TAILINGS DAM OR IMPOUNDMENT DESIGNATION	FAILURE DATE	DESCRIPTION
Mount Polley	Perimeter Embankment	8/4/14	This report.
Red Mountain	Jumbo	6/5/99	Several sinkholes developed on the surface of the Jumbo Creek Tailings Impoundment. The sinkholes were triggered by failure of the surface water diversion culvert beneath the storage facility. Failure of the culvert resulted in discharge of tailings into the water reclaim pond downstream of the impoundment and into Little Sheep Creek. Remediation activities were completed on June 29, 1999, by Granite Mountain Excavating Inc. Dam failure resulted in the release of 5,000-10,000 m <sup>3</sup> tailings.
Sullivan	Active iron dyke	8/23/91	300 m rotational failure of 1.500 m long ring dykes during dam raise construction over tailings 40 years old. Dam had been built upon the foundation of older tailings that were placed as beach below water (BBW) material. The initiation of shear stresses that exceeded their shear strength in the upstream constructed facility led to a rise in pore pressures that led to static liquefaction. <sup>3,4,5</sup>
Mineral King	Mineral King	3/20/86	Dam breach by spring freshet; water diversion channel blocked by ice. Water flowed into impoundment via the emergency spillway (flowing opposite the intended direction), impoundment flooded, and dam overtopped eroding the dam. Tailings spilt out through dam but were almost completely contained by the emergency pond downstream of the dam. Initial reports were that seepage through the dam led to the collapse of the dam (a view that is now discredited) <sup>6</sup> .
Churchill Copper	unknown	12/1/79	Seepage and piping with release of 10,000,000 gallons of supernatant.
Churchill Copper	unknown	1975	Charged and convicted for spill between Feb 12 and 25; failures since 1976 and during operations; July, 1975 floods and breaches in 3 places.
Phoenix Copper	Twin Creek	9/12/69	Dam constructed by the upstream method. Piping failure occurred 25 years after closure with a release of 9 million gallons of tailings and supernatant.

<sup>3</sup> Davies, M.P., Martin, T., and Lighthall, P., 2000. Mine tailings dams: when things go wrong. Proc. Tailings Dams 2000, pp. 261-273, Association of State Dam Safety Officials, Lexington Kentucky. [www.infomine.com/library/publications/docs/Davies2002d.pdf](http://www.infomine.com/library/publications/docs/Davies2002d.pdf)

<sup>4</sup> Davies, M.P., McRoberts, E.C., and Martin, T.E., 2001. Static liquefaction – fundamentals and case histories. Proc. Tailings Dams 2002, Association of State Dam Safety Officials, Lexington Kentucky. [www.infomine.com/library/publications/docs/Davies2002c.pdf](http://www.infomine.com/library/publications/docs/Davies2002c.pdf)

<sup>5</sup> ICOLD, 2001, Bulletin 121, Tailings dams risk of dangerous occurrences. International Commission on Large Dams, Paris, incident 196

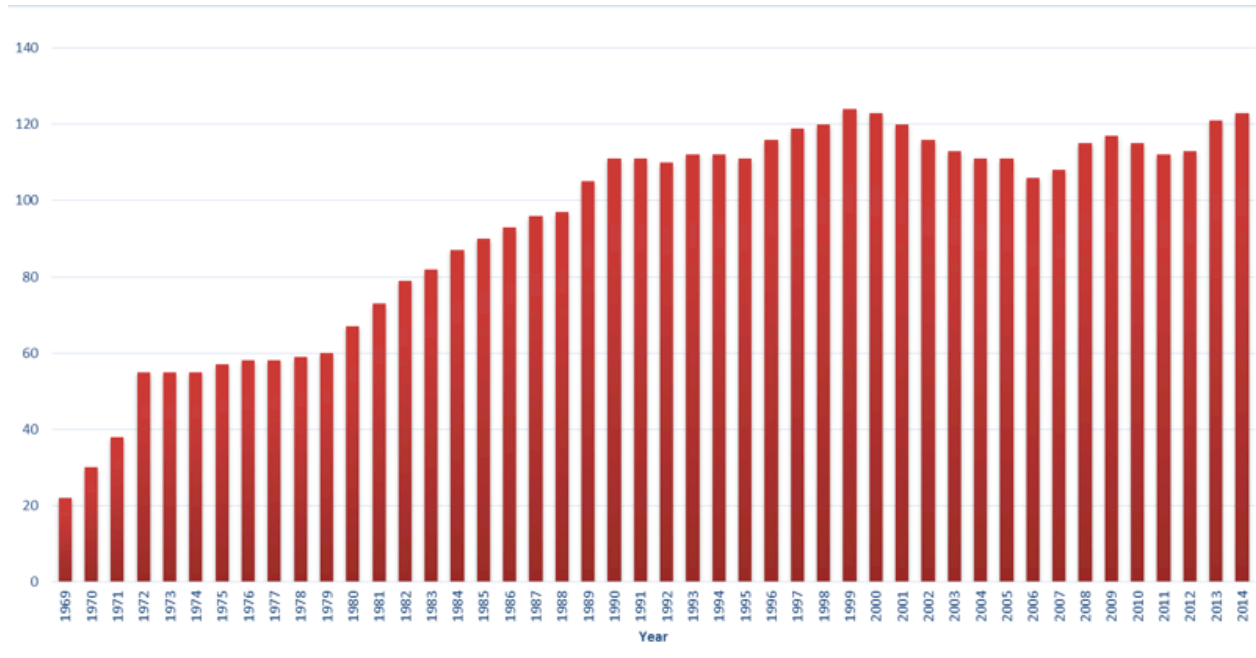
<sup>6</sup> ICOLD, 2001, Bulletin 121, Tailings dams risk of dangerous occurrences. International Commission on Large Dams, Paris, incident 188



4.2 INVENTORY

The number of tailings dams in the inventory has varied with time, with new dams coming into active operation and old ones relinquishing their active status once surface water has been removed. The annual inventory of active tailings dams throughout the period of record is shown in **Figure I 4.2.1**.

FIGURE I 4.2.1: INVENTORY OF ACTIVE TAILING DAMS IN B.C., 1969 - 2015



**Figure I 4.2.1** shows that the number of active tailings dams has fluctuated within a relatively narrow range between 110 and 120 for about the last 15 years. Over the period 1969-2015, there were a total of 4,095 dam-years of active operation for the complete inventory.

4.3 FAILURE FREQUENCY

Failure statistics are provided in **Table I 4.3.1**.

TABLE I 4.3.1: FAILURE FREQUENCY OF ACTIVE TAILINGS DAMS IN BRITISH COLUMBIA, 1969 – 2015

NUMBER OF FAILURES	DAM-YEARS OF ACTIVE OPERATION	AVERAGE REPORTED MAXIMUM DAM HEIGHT	FAILURE FREQUENCY
7	4,095	34.2m	1.7x10 <sup>-3</sup>

It is important to note that the failure frequency of 1.7x10<sup>-3</sup>/dam-year applies to the reference population of tailings dams, and not to any one in particular. It can be viewed as the probability of failure for a typical or “statistically average” dam in the population.

4.4 BENCHMARK FAILURE FREQUENCY

It is useful for comparison to benchmark the B.C. tailings dam failure frequency to that for related structures, in this case, conventional water dams. There are no known such statistics for water dams in B.C. or in Canada as a whole. Hence, data compiled by the U.S. Bureau of Reclamation (USBR) is used for benchmarking to water dams elsewhere under related physiographic, hydrologic, and technological conditions.<sup>7</sup> USBR failure statistics on U.S. dams through 1979 are separated into the following categories:

- **Location:** western U.S. and eastern U.S.
- **Height range:** <50 ft., 50-100 ft., 100-300 ft., and >300 ft.
- **Year built:** <1930, 1930-1960, >1960
- **Dam type:** earthfill, rockfill, buttress and gravity, and arch

B.C. conditions are more similar to the western U.S. The average reported height of the B.C. tailings dams of 34.2 m (112 ft.) borders the two intermediate USBR height categories, and these are combined due to this and sample-size considerations. The USBR post-1960 category corresponds approximately to the post-1969 period of record for the B.C. tailings dams. And B.C. tailings dams may be composed of both earthfill and rockfill, so these categories are combined as well. Corresponding failure statistics for this subpopulation of water dams are provided in **Table I 4.4.1**.

**TABLE I 4.4.1: FAILURE FREQUENCY FOR WESTERN U.S. WATER DAMS, 50-300 FT., POST-1960**

DAM TYPE	NUMBER OF FAILURES	DAM-YEARS OF OPERATION	FAILURE FREQUENCY
Earthfill	4	4961	-
Rockfill	0	306	-
Total	4	5267	7.6x10 <sup>-4</sup>

To evaluate the variation in this failure frequency for other subpopulations, **Table I 4.4.2** gives comparable data for all U.S. water dams.

**TABLE I 4.4.2: FAILURE FREQUENCY FOR ALL U.S. WATER DAMS, 50-300 FT., POST-1960**

DAM TYPE	NUMBER OF FAILURES	DAM-YEARS OF OPERATION	FAILURE FREQUENCY
Earthfill	13	20450	-
Rockfill	0	525	-
Total	13	20,975	6.2x10 <sup>-4</sup>

Despite differences in regional characteristics and sample size, **Table I 4.4.2** shows only a small variation between the western U.S. and total U.S. water dam subpopulations.

Comparison of **Tables I 4.3.1** and **I 4.4.1** shows that the failure frequency of 1.7x10<sup>-3</sup> for B.C. tailings dams is about twice the benchmark value of 7.6x10<sup>-4</sup> for western U.S. water dams. This difference is not disproportionately large in light of the differences in design, construction, and operation between the two types of structures.

<sup>7</sup> von Thun, J.L., 1985, Application of statistical data from dam failures and accidents to risk-based decision analysis on existing dams. U.S. Bureau of Reclamation Engineering and Research Center, Denver, 38 p.

## 5.0 PORTFOLIO RISK

The Panel has been mandated in its Terms of Reference with making recommendations “to ensure that a similar failure does not occur at other mine sites in B.C.”

Since Government has jurisdiction over all tailings dams in the province, this statement can be viewed in terms of its portfolio risk, or the risk posed by the total inventory of tailings dams in B.C. To the extent that failures affect the B.C. mining industry as a whole, it too bears the same portfolio risk.

The language of the Panel’s Terms of Reference also gives rise to the following inferences:

- The aim is to prevent future failures, where all such failures are equally undesirable. Accordingly, risk is taken here as the probability of future failures regardless of the nature or magnitude of failure consequences.
- Ensuring that no future failures occur can be expressed as some sufficiently high probability of experiencing no failures over some applicable evaluation period.
- The evaluation period can be taken as some reasonably foreseeable future duration, given current industry technology and levels of activity.

### 5.1 QUANTITATIVE SAFETY GOALS

“Ensuring that a similar failure does not occur” starts with quantifying this statement. Quantitative safety goals provide the guideposts for determining the measures required to achieve this objective.

It is axiomatic that nothing, in engineering or in life, can be assured with 100% certainty. Even so, 95% confidence limits serve as a proxy for statistical certainty in many areas of scientific research. Recognizing that there may be preferences for higher or lower degrees of assurance, a range from 90% to 99% probability of experiencing no failures is evaluated here. Confidence levels as low as 75% were considered. However, the verbal descriptor “probable” that can be associated with this value is incompatible with Panel’s mandate to “ensure.”<sup>8</sup>

Similarly, the period over which failures are to be prevented must be specified. Ideally, this would be forever. But again, engineering and life share the undeniable fact that nothing can be forever. This notwithstanding, a decade and a generation are readily conceptualized durations over which no failures should occur. Corresponding 10-year and 30-year evaluation periods have been used to reflect these time spans.

### 5.2 HISTORIC CONDITIONS

Portfolio risk can be calculated from the number of dams in the inventory, their failure frequency, and the period over which it is evaluated.

<sup>8</sup> Reagan, R., Mosteller, F., and Youtz, C., 1989, Quantitative meanings of verbal probability expressions. *J. Applied Psychology*, v. 74, no. 3, pp. 433-442.

Let:

$P_{nf}$  = probability of no failures during the evaluation period

$t$  = duration of the evaluation period in years

$n$  = number of active tailings dams in the inventory

$p_i$  = annual failure frequency of active tailings dams in the inventory

$n_f$  = expected number of failures during the evaluation period

If individual tailings dams are probabilistically independent, and both  $n$  and  $p_i$  are constant, then:

$$P_{nf} = (1 - p_i)^{nt} \quad [1]$$

And if the probability of at least one failure is designated  $P_f$  then:

$$P_f = 1 - P_{nf} \quad [2]$$

The mathematical expectation, or the expected value, for the number of failures during the evaluation period is given by:

$$n_f = nt(p_i) \quad [3]$$

Given the historic failure frequency of  $1.7 \times 10^{-3}$ /dam-year for active B.C. tailings dams, and assuming the current inventory of 120 dams remains unchanged, **Table I 5.2.1** gives the probability of at least one failure and the expected number of failures for 10- and 30-year evaluation periods.

**TABLE I 5.2.1: PORTFOLIO RISK FOR CURRENT INVENTORY AND HISTORIC FAILURE FREQUENCY**

EVALUATION PERIOD, $t$ (YEARS)	PROBABILITY OF AT LEAST ONE FAILURE, $P_f$	EXPECTED NUMBER OF FAILURES, $N_f$
10	0.87	2
30	0.99	6

Such high probabilities and numbers of future failures are incompatible with safety goals for either evaluation period. The Province's portfolio risk is clearly excessive for ensuring that similar failures do not occur at other mine sites in B.C.

## 5.3 RISK REDUCTION STRATEGIES

The terms in equations [1] through [3] contain two basic strategies for reducing portfolio risk: reduce failure frequency, or reduce inventory. Both are evaluated below.

### 5.3.1 Reduction in failure frequency

From section 5.1, the quantitative safety goal for reasonably assuring against future failures is taken as  $P_{nf}$  in the range of 0.9 to 0.99. The reduction in failure frequency  $p_i$  needed to meet this goal can be obtained from equation [1]. This is shown on **Tables I 5.3.1** and **I 5.3.2** for 10-year and 30-year evaluation periods, again assuming a constant inventory of 120 active dams.

**TABLE I 5.3.1: REQUIRED REDUCTION IN FAILURE FREQUENCY FOR 10-YEAR EVALUATION PERIOD**

PROBABILITY OF NO FAILURES, $P_{nf}$	FAILURE FREQUENCY $P_i$	$P_i$ REDUCTION FACTOR
0.9	$9 \times 10^{-5}$	20
0.99	$8 \times 10^{-6}$	200

**TABLE I 5.3.2: REQUIRED REDUCTION IN FAILURE FREQUENCY FOR 30-YEAR EVALUATION PERIOD**

PROBABILITY OF NO FAILURES, $P_{nf}$	FAILURE FREQUENCY $P_i$	$P_i$ REDUCTION FACTOR
0.9	$3 \times 10^{-5}$	60
0.99	$3 \times 10^{-6}$	600

Together, these tables show that meeting safety goals would require reduction in historic failure frequency of more than one to two orders of magnitude for 10 years and triple this reduction for 30 years. This would require that failure frequencies be reduced well below the benchmark values for water dams in section 4.4.

### 5.3.2 Reduction in inventory

Reducing the number of active dams can also be considered as a means for meeting the same safety goals. For the historic failure frequency of  $1.7 \times 10^{-3}$ /dam-year, **Table I 5.3.3** provides the necessary reduction to achieve a 90% to 99% probability of no failures in 10 years.

**TABLE I 5.3.3: REQUIRED REDUCTION IN INVENTORY OVER 10-YEAR EVALUATION PERIOD**

PROBABILITY OF NO FAILURES, $P_{nf}$	REQUIRED NUMBER OF ACTIVE DAMS, $n$	REDUCTION IN $n$
0.90	6	120 → 6
0.99	0	120 → 0

For a 10-year evaluation period, **Table I 5.3.3** shows that achieving safety goals solely by inventory reduction would require all but eliminating active tailings dams. The same would be true for a 30-year period.

### 5.3.3 Combined approach

The limited efficacy of either failure frequency or inventory reduction alone suggests that both are needed to meet safety goals. One such combined approach might consist of:

- reducing the historic failure frequency by a factor of 10 to  $1.7 \times 10^{-4}$ , somewhat below water-dam benchmark values.
- halving the active dam inventory from 120 to 60.

The effects of such a strategy are shown in **Table I 5.3.4**.

**TABLE I 5.3.4: EFFECTIVENESS OF COMBINED FAILURE FREQUENCY AND INVENTORY REDUCTION**

EVALUATION PERIOD (YEARS)	PROBABILITY OF NO FAILURES, $P_{nf}$
10	0.90
30	0.74

**Table I 5.3.4** demonstrates in principle that reducing both failure frequency and inventory will be necessary to meet or approach safety goals inferred from the Government's charge to the Panel. This, in turn, will require changes in both practices and technologies for tailings management.

Reducing failure frequency will require a variety of improvements in tailings management practices as they pertain to the corporate, professional, and regulatory spheres.

Reducing the current inventory of active tailings dams can be brought about from attrition by eliminating surface water at closure. Restricting future growth of the inventory can be achieved through tailings technologies that avoid water storage in the first place.

The historic failure frequency provides clear evidence that past practices and technologies have failed to provide acceptable levels of tailings dam safety in the province from a portfolio risk point of view. Equally clearly, then, both best practices and best available technology provide the dual cornerstones of an effective tailings dam safety strategy for the future.

### Appendix I: Attachments

- **Attachment I1:** Impoundment Location Data
- **Attachment I2:** Tailings Dam Inventory Data
- **Attachment I3:** Permit Research Data