October 15, 2008

Ms. Erica M. Hamilton
Commission Secretary
British Columbia Utilities Commission
Sixth Floor – 900 Howe Street
Vancouver, BC V6Z 2N3

Dear Ms. Hamilton:

RE: Project No. 3698500
British Columbia Utilities Commission (BCUC)
British Columbia Hydro and Power Authority (BC Hydro)
F2009/F2010 Revenue Requirements Application (F09/F10 RRA)

Further to BC Hydro’s response to BCUC IR 3.186.1.2 filed on July 22, 2008, and Exhibit B-25 filed on October 6, 2008, BC Hydro submits the attached Contributing Factors and Recommended Actions report on the GM Shrum Generating Station Generator 3 Runner Failure.

For further information please contact the undersigned.

Yours sincerely,

[Signature]

Joanna Sofield
Chief Regulatory Officer

Enclosure

c. BCUC Project No. 3698500 Registered Intervenor Distribution List
Generator 3 Runner Failure

BC Hydro GM Shrum Generating Station

Contributing Factors
Recommended Actions
Introduction to Tripod Beta Analysis Methods

The information presented in this report follows the Tripod Beta model for investigative analysis of events. The reader should have, at minimum, a basic understanding of the model and how the different analytical components combine to provide an overall description of causal factors associated with the event.

The Tripod Beta Tree depicting the events and associated missing, failed and effective barriers provides the reader with a graphical representation of how the end result occurred. The active failures, preconditions and latent failures provide the understanding of why barriers are missing or have failed.

The opportunity for improvement is found in addressing the failed barriers and latent failures.

In simple terms, Tripod Beta uses a trio model of identifying what happened (event), what caused the event (agent) and who or what (target) was involved in the event.

Once that has been done, then the process is to identify what allowed the event to occur. That is, what barrier failed or was missing that allowed that event to occur.

Once the failed or missing barriers are identified, then the work begins on understanding the cause of those failed barriers. Active failures are identified. That is, what was done or not done that resulted in the failed or missing barrier. An active failure can be a sub-standard act by a person or a sub-standard condition.

The next step in the process is to determine what motivated the active failures – the preconditions. That is, determining the reasons why a person or condition was substandard. It should be noted that the relationship between active failures and preconditions is not deterministic but probabilistic. Once the preconditions have been determined, the remaining issue to identify is the underlying causes, or latent failures. Latent failures are often common causes of problems and can be described as systemic problems.

Underlying causes or latent failures are deficiencies that create the preconditions resulting in the immediate causes or active failures in incidents. In order to implement long lasting change, organizations must look beyond correcting failed barriers. Addressing underlying causes, or latent failures, provides the opportunity to have a widespread positive influence on the organization.

The analysis of a business loss usually results in the identification of a number of preceding events and associated agents and targets. The Tripod Beta Tree provides an overall view of how these multiple trios combine sequentially resulting in business losses.

This commentary is not intended to be a primer for Tripod Beta but is provided to make the reader aware of the methodology used to produce this report. Familiarity with the methodology will result in a better understanding of the findings and recommended actions.
Generator G3 Runner Failure – BC Hydro GM Shrum Generating Station

Acknowledgements

This report was prepared under BC Hydro contract No. 00034154 to provide a report incorporating data gathered through subject matter experts, onsite technical staff and management. Analysis of this event was to be done using BC Hydro’s preferred analysis tool – Tripod Beta.

Thanks to the many individuals at BC Hydro who openly and willingly contributed to this report, its findings and recommendations.

Submitted by:

R.A. (Bob) Bernard
Bernard and Company

Accepted by:

Richard Brittin
Manager, Technical Services
BC Hydro
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A. Executive Summary

GM Shrum (GMS) Generating Station is located 23 km upstream of the Peace Canyon Dam on the Peace River and is BC Hydro's largest generating station with ten generating units and a total installed capacity of 2730 MW. The first five generating units (G1 – G5) went into service in 1968. They have CGE 275 MVA Generators and Mitsubishi 261 MW Turbines.

The Mitsubishi turbine runners are prone to cracking. Extensive engineering studies, over 40 years, have identified probable design and manufacturing contributors including runner natural frequencies, high principle stresses, low fatigue strength and defects in the original manufacturing. Historically, BC Hydro has successfully managed the cracking through regularly scheduled inspections and welding repairs; although, defects and residual stresses have been introduced by multiple weld repairs.

On March 2, 2008, Generator 3 runner experienced blade failure during which large pieces of trailing edge material broke away from three runner blades.

A shear pin failure of one of the water passage wicket gate control arms resulted in a cascading shear pin failure over four wicket gates. The water pressure imbalance behind the four closed wicket gates caused the runner to be forced to one side. The runner struck the stationary seal ring. The excessive stresses experienced by the runner resulted in blade failure.

The primary contributing factors to the runner failure were:

1. The wicket gate design introduced operating interferences between a closed wicket gate arm and adjacent wicket gate arm if the wicket gate is open greater than 20.5°. This design limitation was not known. Historically, the unit had not experienced a wicket gate shear pin failure with the wicket gates open greater than 20.5°.

2. The wicket gate linkage design subjected the shear pins to shear, bending and torsional stresses. The shear pins functioned as both shear pins and link pins. Unit 3 experienced between 1 to 3 shear pin failures annually.

3. The runner had natural frequencies that were integer multiples of the blade passing frequency. This may have allowed one of the natural frequencies to be excited by the runner striking the stationary seal ring.

4. The runner design had inherent high dynamic stresses, low fatigue strength and defects in the original manufacturing.

5. The runner had defects and residual stresses introduced by multiple weld-repairs.

6. The unit was not equipped with a shear pin detection system to provide unit control alarm and shutdown capability for single/multiple shear pin failure. As a result, the unit continued to operate with four wicket gates closed.

7. While the Unit had been retrofitted with a vibration monitoring system in the early 1980's, the vibration monitor was not capable of detecting the runner striking the stationary seal ring or the vibrations experienced on March 2nd.

Secondary contributing factors to the runner failure were:

1. There was no analysis of historical shear pin failures which may have identified that shear pin #11 had a disproportionate number of failures. Records show that, of the 24 shear pins on unit 3, shear pin #11 experienced ≈25% of the shear pin failures. Shear pin #11 was the first shear pin to fail on March 2nd.

2. When Unit 3 shear pins were replaced as part of regular maintenance, Shear pin #11, the first shear pin to fail, was taken from a box of shear pins marked, “Do not use, emergency use only.”
3. There was no analysis of the impact that a significant increase in start/stop operation could have on Unit 3. Prior to 1994, Unit 3 experienced less that 50 start/stop cycles per year. In 2005, the Unit experienced > 300 start/stop cycles; in 2006, > 400 start/stop cycles.

4. A number of relevant technical reports were prepared by, or commissioned by BC Hydro Engineering; some recommendations were acted on while some were not.

This report includes recommendations for the prevention of future similar events. Included are recommendations for the addition of shear pin failure detection, improved shear pin failure analysis and record keeping, and review of vibration monitoring systems and improvement in the application of asset management practices, including root cause analysis of equipment failures, oversight of maintenance, documentation and continuous improvement. The recommendations can be found on pages 17 to 23.
B. Sequence of Events

Incident Date: March 2, 2008
Incident Time: 05:05 – 05:39 am
Incident Place: BC Hydro GM Shrum Generating Station

The following sequence of events was developed by subject matter experts examining physical evidence on site, documenting unit operating conditions at the time of failure, gathering data from the Operational Information (OI) system and calculating forces experienced as the events unfolded. The detailed analysis can be found in the Generation Engineering Report E653, "GM Shrum Generating Station G2 Runner Failure", September 2008.

Prior to the failure of the first shear pin the unit was operating under normal conditions on automatic generation control.

1. At 5:05 am (times are approximate), Sunday, March 2nd, 2008, wicket gate shear pin #11 on GMS G3 failed. The wicket gates were open to 21.5°.

2. The G3 wicket gate shear pins also act as link pins. With a shear pin failure, the wicket gate arm is disengaged from the servomotor operating mechanism. As a result of shear pin #11 failing, wicket gate #11 was forced closed by water pressure in the water passage. The failure of shear pin #11 and sudden closure of the wicket gate with the adjacent wicket gate #12 open to 21.5° resulted in the wicket gate #11 arm striking the arm of wicket gate #12. Prior to March 2nd, there had not been a shear pin failure on G3 with the wicket gates opened to 21.5°. The interference between adjacent wicket gate arms had not been known.

3. The resultant force impact on the wicket gate #12 arm was enough to cause wicket gate #12 shear pin to fail and wicket gate #12 closed. It is important to note that this resultant force was within the range of breaking strength of the shear pin but did not exceed that breaking strength by a large enough margin to ensure a shear pin failure. However, in this case, the shear pin did fail. The wicket gate servo-motors continued to open the remaining synchronized wicket gates to compensate for wicket gates #11 and #12 being closed.

4. Wicket gate arm #12 struck the arm of wicket gate #13. The engineering analysis of this event is not conclusive. However, the evidence supports the theory that the resultant force exerted on the wicket gate #13 arm was not enough to cause the shear pin to fail immediately. Eventually, wicket gate #13 shear pin did fail and its wicket gate arm struck wicket gate #14 arm. This impact caused shear pin #14 to fail and wicket gate #14 rapidly closed. Now, wicket gates #11 to #14 were closed. The servo-motors continued to open the remaining wicket gates to compensate for the four closed wicket gates.

5. Wicket gate #14 arm struck the wicket gate #15 arm. The resultant force exerted did not cause the wicket gate #15 shear pin to fail. The cascading shear pin failures stopped at this point. Approximately 6 minutes had passed since shear pin #11 failed.

6. Wicket gates #11 to #14 were closed creating a low pressure zone in the runner/wicket gate cascade. This forced the runner toward the low pressure zone. The runner struck the stationary seal ring. The runner experienced excessive stresses likely due to one or more of the natural frequencies of the runner being excited and/or an accumulation of stresses due to the radial displacement of the runner.
7. Runner blades #4, #11 and #14 failed. One piece was ejected into the draft tube (the piece was found intact in the draft tube). Two pieces were forced into the runner/wicket gate cascade (numerous small pieces of runner blade were found around the turbine). The blade pieces struck the trailing edge of the open wicket gates breaking the shear pins. The remaining wicket gates were probably closed during one revolution. Approximately 12 minutes had elapsed between the time the four wicket gates were closed and the remaining twenty wicket gates were forced closed.

8. The turbine continued to run with the blade pieces trapped in the runner/wicket gate cascade. The runner blade leading edges, wicket gate trailing edges and skin plates, head cover and seal ring as well as other turbine components were damaged.

9. The operator, in consultation with the control centre (SCC), initiated an emergency shutdown. Because the wicket gates were inoperable, the operator closed the head gate to drain the penstock and bring the unit to a final stop.

The total time between shear pin #11 failing and final stop of the unit was ≈ 34 minutes.
C. Events Analyzed

The following event(s) have been used in the analysis:

<table>
<thead>
<tr>
<th>Event</th>
<th>Title</th>
<th>Summary</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Shear pin 11 failure initiates cascading shear pin failures</td>
<td>Because the shear pin also acts as a link pin, its failure resulted in the wicket gate arm separating from the servomotor linkage. The rapid closure of wicket gate #11 resulted in the arm striking the adjacent wicket gate #12 arm. A cascading effect resulted in wicket gates #11 - #14 being closed.</td>
</tr>
<tr>
<td>2.</td>
<td>Closing of wicket gates results in runner striking seal ring</td>
<td>The low pressure zone downstream of the closed wicket gates caused the runner to shift toward the direction of the closed wicket gates. The runner impacted the stationary seal at the location of the closed wicket gates.</td>
</tr>
<tr>
<td>3.</td>
<td>Runner blades fail damaging turbine components</td>
<td>Hydraulic forces from the closed or partially closed wicket gates plus the mechanical impact of the runner against the stationary seal at each revolution increased the stresses on the runner. Blades #4, #11 and #14 failed and pieces of the runner blades were forced into the runner/wicket gate cascade damaging turbine components.</td>
</tr>
<tr>
<td>4.</td>
<td>Further damage to unit (avoided)</td>
<td>The operator successfully executed an emergency shutdown preventing more damage to the unit.</td>
</tr>
</tbody>
</table>

The Tripod Beta Tree developed to analyze these events is on page 25.

The following section of the report provides an analysis of these events.
D. Results of analysis

Evidence provided by subject matter experts, site technical personnel and management forms the basis for this analysis. In addition, where definitive events cannot be fully supported by physical evidence, the most likely scenarios are provided.

Event 1
The Tripod Beta Subtree for this event can be found on page 26.

Event Information
Description: Shear pin 11 failure initiates cascading shear pin failures

Engineering calculations performed by subject matter experts provide key findings supporting this event. The forces exerted have been calculated and possible failure sequences analyzed. The following description represents the most likely scenario for the shear pin failures.

The initiating event was wicket gate shear pin #11 failing and wicket gate #11 closing. This resulted in the servomotors responding to open the wicket gates to meet load demand.

Shear surface analysis of wicket gate #11 shear pin indicates failure due to torsional fatigue and shear overload. Wicket gate #11 rapidly closed. Physical evidence on the wicket gate arm and failure analysis of wicket gate #12 shear pin supports the finding that the rapid closing of wicket gate #11 resulted in the wicket gate arm striking the arm of wicket gate #12. This caused shear pin #12 to fail under shear overload.

Physical evidence also supports the finding that the wicket gate #12 arm struck the arm of adjacent wicket gate #13. Engineering analysis of the fracture surface of shear pin #13 is inconclusive. The wicket gate servomotor position went from 72% open to 97.2% open over \( \approx 6 \) minutes. This indicates that the cascading shear pin failure experienced some time delay.

Wicket gate shear pin #13 eventually failed and the associated wicket gate arm struck the arm of wicket gate #14 shearing pin #14.

The cascading shear pin failures stopped at shear pin #14. The most likely explanation is that the resultant force experienced by the shear pins was within the range of breaking strength but did not exceed that breaking strength by a large enough margin to definitively cause shear pin failure (e.g., shear pin #15 withstood the impact of the arm of wicket gate #14 on wicket gate #15 arm).

Agent Information
Description: Unit operating conditions at 254 MW generator output power

Subject matter experts determined the operating conditions of May 2, 2008 positioned the wicket gates at 21.5° open. The gross head calculations and generator output measurements confirmed the unit was operating normally (e.g., all wicket gates were in proper operating position).

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1 The description of this event is fully detailed in Generation Engineering Report E653, “GM Shrum Generating Station G2 Runner Failure”, September 2008
The barriers involved for this Agent are:

1. **Wicket gate linkage design (an inadequate barrier)**
   
   **This Barrier failed because:**
   
   **Latent Failure:** Linkage geometry introduces interference between adjacent gates
   
   When a wicket gate shear pin fails, hydraulic pressure forces the wicket gate closed. If the remaining wicket gates are opened less than 20.5°, the stroke of the rapidly closing wicket gate is limited by a mechanical stop on the head cover.
   
   However, if the wicket gates are open greater than 20.5°, the arm of the rapidly closing wicket gate will contact the arm of the adjacent wicket gate.
   
   This condition was not known prior to the March 2, 2008, failure. Previous shear pin failures occurred with the wicket gates opened less than 20.5°. This resulted in the wicket gate arm striking a mechanical stop rather than the adjacent wicket gate arm.
   
   **Latent Failure:** Linkages have one pin for both shear pin and link pin functions
   
   Dual duty for the shear pins causes the pins to be subjected to shear, bending and torsional stresses associated with the operation of the wicket gates.

2. **Shear pin failure analysis (a failed barrier)**
   
   **This Barrier failed because:**
   
   **Active failure:** Historical and recent shear pin failures did not raise concerns
   
   There were no Unit 3 shear pin failures from 1985 to 1988. Since 1988, records show Unit 3 has experienced 1 to 3 shear pin failures per year, averaging 2 per year, except for 2005. In 2005, Unit 3 experienced 5 shear pin failures.
   
   Prior to March 2, 2008 there had been no apparent adverse effect as a result of running units with a single broken shear pin. BC Hydro had a practice of continuing to run units with a failed shear pin until an opportune time for repair was available.
   
   **Precondition:** Impact of changes to unit operation was not understood
   
   Site engineers were not familiar with the history of Unit 3, including historical head cover issues associated with the major overhaul in 1985. The wicket gate shear pins experienced increased stresses due to the misalignment of wicket gate bores after the major overhaul. Increased start/stop cycles would exacerbate the condition by increasing the wicket gate open/close operations.
   
   Although the servo-differential tests are included in the maintenance program for the unit, the significance of the test for this unit is not identified. This is contrary to Generation’s documented RCM practices which require the reason for tests and inspections to be documented in the Maintenance Instructions so the persons completing and reviewing work understand the reason for each task.
   
   **Latent Failure:** Oversight did not determine impact of operational changes
   
   Prior to 1994, Unit 3 experienced less than 50 start/stop cycles per year. In the time frame from 1994 to 1999, Unit 3 experienced, on average, 79 start/stop cycles per year. From 2000 to 2003, the start/stop cycles remained relatively low at an average

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of 57 per year. Then, beginning in 2004 there was a significant increase in start/stop cycles. There were 143 start/stop cycles in 2004, 243 in 2005 and 219 in 2005. Unit 3 was equipped with synch condense capability in 2005. Including start/stops and sync condense operations, the unit experienced cycles in excess of 300 in 2005 and over 400 in 2006.

Unit commitment at GMS is driven by a number of factors. The operating objective is to minimize water use while meeting unit and plant operating constraints. Decisions are driven by efficiency curves, operating ranges and capacity as well as current availability.

With respect to the significant operating changes at GMS (and specifically Unit 3), three key events have driven an increase in stop/start cycles.

1. In late 2003, improved unit commitment decision support software (EULR) enabled dynamic updates of the unit commitment table recognizing current unit outages, operating ranges and constraints.

2. With the turbine upgrades to units G6, G7 and G8 between 2003 and 2005 the commitment table became more biased to avoiding the operation of the less efficient G3 during mid-range plant generation.

3. The introduction of synch-condense capability to G3 in mid 2005 resulted in synch-condense operations being added to the increased stop/start cycles already introduced. The purpose was to enable less plant generation and maximize imports and accept increased IPP supply.

Although the increase of cycles is commented on in the Facility Asset Plans, there is no indication of mitigation of risk associated with the additional stresses imposed on the unit as a result of the increased cycles. In addition, there was no evidence that preventive maintenance instructions were modified as a result of the changed operation, as required by Generation’s RCM process.

An increase in management and skilled resource changes coupled with organizational restructuring has resulted in loss of unit knowledge (expertise and documentation) and experience. There was a failure to recognize the impact of operational changes due to the increase in starts/stops.

Further, programs such as Equipment Health Rating (EHR), Reliability Centered Maintenance (RCM) and Back to Basics result in increased process and time requirements. These programs require additional resources.

**Latent Failure:** Maintenance planning needs improvement

As time has elapsed, operation and maintenance has focused more on outage availability in lieu of addressing risks associated with increased unit stop/start cycling and limitations on maintenance activities.

Annual preventive maintenance plans are based on completion of the work defined in Passport less work that was considered not achievable in the fiscal year. Deferred work is considered by GMS staff to be a lower priority. Subsequently, the annual preventive maintenance plans have moved to completion of work based on what could be achieved. For shutdowns, the addition of resources, optimization of work plans and efficient use of downtime appear to be less than ideal. Additionally, resources are pulled away from preventive maintenance activities for dealing with forced outages as well as support for onsite capital work projects.

GMS Facilities Asset Plan for Fiscal 2009, 2010 and 2011 provides some historical information on maintenance expenditures. From F2004 to F2007 preventive maintenance expenditures declined from $2.5M to $1.76M and condition based maintenance increased from $0.98M to $1.26M, resulting in overall planned...
maintenance decreasing from $3.48M to $3.02M. During the same time period, corrective maintenance expenditures increased from $0.28M to $1.67M.

The inspection frequency for G3 runner repairs was annual. Records show that the schedule was met in most cases. However, one inspection was missed in calendar year 2005 during the installation of synch-condense capability on Unit 3. Site personnel interviewed could not provide insight into why the inspection was missed. The subsequent inspection in March 2006 found blades 1 and 8 with missing pieces of their trailing edge and another 8 blades with cracks. This was the first instance of pieces of blades missing. PowerTech was contacted for assistance with welding procedures. At the time, the practice of failure analysis was not universal. Presently, BC Hydro’s practice is to analyze all forced outages.

New spare shear pins were not available when required and a shear pin marked as “Do not use, emergency use only.” was used for routine maintenance. This shear pin was the first to fail on March 2, 2008.

**Precondition:** Shear pin failure modes analysis was not done

Risks associated with shear pin failure were not fully recognized. Failure modes and trending were not conducted while shear pin failures continued through to March 2008.

In addition, servo-differential tests were conducted in accordance with maintenance standards but maintenance engineers confirmed that trending and analysis of data was not performed. Such analysis would provide insight into changes associated with the forces exerted by the wicket gate servo-motors to open and close the gates.

A review of historical shear pin failures following the turbine failure identified all but two of the failures were during transitions - generate to shutdown, shutdown to generate, generate to synch condense and synch condense to generate.

Two shear pin failures were at steady state operation. However, in both cases wicket gate opening was significantly less than the 21.5° experienced during this event.

**Latent failure:** Records of shear pin failures and analysis are limited

Historical records of shear pin repairs, replacement and analysis have limited detail. Maintenance personnel have become accustomed to shear pin failure with little, or no, impact on unit condition. A number of work orders do not identify which shear pins were replaced. There are indications that the practice of stamping newly installed shear pins with the installation date is not consistent.

Recent failure modes analysis and trending have not been conducted. A cursory review of shear pin failure records show shear pin #11 experienced a disproportionate number of failures representing ≈25% of shear pin replacements since 1988.

**Latent failure:** Generation Engineering involvement has decreased

The following table shows approximate levels of Request for Services (RFS) for Generation Engineering approved during the fiscal years 2001 to 2009 and actual costs billed to GMS.
The table indicates significant variances during the fiscal years 2004 to 2006. For fiscal years 2005 and 2006 completion was well below RFS approved levels. Fiscal 2005 shows a dramatic reduction in approved RFS levels. The reasons behind the reduction in engineering support and the effects of the reduced support are uncertain.

In 2004, Generation’s Technical Services group, which was historically a “free service” for generating stations was moved to Generation Engineering and renamed Generation Engineering Maintenance Services (GEMS). The Technical Services budget was split amongst the generating stations to be used as funding for a “fee for service” structure.

Subsequently, the annual runner inspection for the unit was missed in 2005 and the March 2006 runner inspection found 2 blade pieces missing. This was the first time the runner had experienced a failure. It is plausible that reduced GEMS support may have contributed to less unit oversight.

It is important to note that GEMS involvement has increased during the past two fiscal years. What level of GEMS support is preventive versus post failure needs further examination.

**Target Information**

**Description:** Wicket gate linkage arms and shear pins

The barriers involved for this Target are:

<No barriers involved>
Event 2
The Tripod Beta Subtree for this event can be found on page 27.

Event Information
Description: Closing of wicket gates results in runner striking seal ring
When the wicket gate shear pins failed, the runner shifted toward the direction of the closed wicket gates (due to the low pressure zone behind the closed wicket gates). The runner impacted the stationary seal at the location of the closed wicket gates.

Agent Information
Description: Shear pin 11 failure initiates cascading shear pin failures
Reported as Event 1 above
The barriers involved for this Agent are:
3. Broken shear pin detection (a missing barrier)
This Barrier failed because:
Latent failure: Broken shear pin detection system not installed
The Generation Engineering Report MEP165 titled, "Guidelines for the Design of Hydroelectric Generator Protection" (April 1996) outlines the philosophy to be applied to the application and design of generator protection at BC Hydro hydroelectric power plants. It defines the use of on-line shear pin failure detection systems and their application to generator control systems. The report provides direction for the design of generator protection when existing unit protection is upgraded and new units are purchased.

Unit 3 is not equipped with a shear pin detection system.

In 2000 the "GMS G1-G10 Vibration Monitors Replacement Project Definition Phase" was initiated, which included shear pin failure detection. However, the project was not implemented.

Target Information
Description: Wicket gates 11 to 14
The barriers involved for this Target are:
<No barriers involved>
Event 3
The Tripod Beta Subtree for this event can be found on page 28.

Event Information
Description: Runner blades fail damaging turbine components

When the wicket gate shear pins failed, the runner shifted toward the direction of the closed wicket gates (due to the low pressure). The runner impacted the stationary seal at the location of the closed wicket gates. This impacting may have excited some of the natural frequencies of the runner.

In addition, historical studies found that runner cracking was a result of high dynamic stresses, low fatigue strength and defects in the original manufacturing. These issues along with the natural frequencies have been well documented.3

Further to these matters, there have also been defects and residual stresses introduced by multiple weld-repairs.

Hydraulic forces from the closed or partially closed wicket gates plus the mechanical impact of the runner against the stationary seal put destructive energy into the runner.

The trailing edge of runner blades #4, #11 and #14 failed. Physical evidence indicates one piece was ejected into the draft tube. Two pieces were ejected into the runner/wicket gate cascade striking the open wicket gates, shearing the remaining intact shear pins and damaging turbine components.

Agent Information
Description: Closing of wicket gates results in runner striking seal ring

Reported as Event 2 above

The barrier involved for this Agent is:
4. Vibration Monitoring (a missing barrier)

This Barrier failed because:
Latent failure: Vibration monitoring not to current standards

Generation Engineering report No. MEP165 titled, "Guidelines for the Design of Hydroelectric Generator Protection" outlines the philosophy to be applied to the application and design of generator protection at BC Hydro hydroelectric power plants. It defines the scope of detection systems and their application to generator control systems. The report provides direction for the design of generator protection when existing unit protection is upgraded and new units are purchased.

In 2000 the "GMS G1-G10 Vibration Monitors Replacement Project Definition Phase" was initiated. However, the project was not implemented.

Latent failure: Application of Engineering Report recommendations needs improvement

An inspection of the Unit 3 runner in March 2006 found blades 1 and 8 had portions of their trailing edges missing. With the assistance of PowerTech (providing welding

3 Generation Engineering Report PSE303, “GM Shrum Generating Station Units 1 to 5 Runner Blade Cracking Study”, December 2000
procedures), GMS repaired the failed blades.

Additionally, a report commissioned by Generation Engineering and produced by Hydro Performance Processes Inc (Report BCH_HPP1) in June 2007 highlighted key issues to be addressed. It made recommendations in three key areas.

- First, in the area of design and operations, the report recommended detailed performance analysis using operational data to determine production increases achievable through improved optimization, the adequacy of measured performance data, the extent of avoidable losses, rough zone operations, rough zone crossings, start-ups, shut-downs and other operations affecting maintenance.

- Second, in the area of maintenance and metallurgy, the report recommends improved welding procedures (e.g., patch welding), streamlined procedures to minimize outage time and allow for more frequent inspections of the runner. In addition, a modified "back-up" runner is recommended with optimized inserts designed for the problematic regions of the runner blades. Note that the idea of runner blade inserts was proposed in Generation Engineering Report PE303 issued December 2000.

- Third, the Hydro Performance Processes Inc report of 2007 makes recommendations associated with mechanics and fluid mechanics. These recommendations focus on verifying and/or calibrating unit performance through independent reviews of acoustic flow measurements and, if warranted, installation of additional instrumentation.

Additionally, the report recommends detailed strain monitoring tests and additional vibration monitoring. GMS considered the welding recommendations of the report and undertook to train the welders. Scheduling prevented implementation of the training. No other actions were taken with respect to the 2007 report recommendations prior to the runner failure in March 2008.

Improved vibration monitoring was proposed in the mid 1990's by Generation Engineering with extensive studies and recommendations presented in 2000\(^4\).

**Target Information**

**Description:** Runner

**The barrier involved for this Target is:**

5. Runner replacement (a missing barrier)

*This Barrier failed because:*

**Latent failure:** Runner inspection and repair in lieu of replacement

As early as 1997 Engineering recommended proceeding with replacement of the runners on GMS units 1 - 5. At that time, technical advice was that the cracking could be managed through maintenance and the annual cost of repairs was relatively low. As well, the turbines were of a high efficiency design for their vintage; replacement could not be justified on efficiency gains. The decision was made to continue managing the cracking of the runner through annual inspection and repair.

**Latent failure:** Runner replacement project deferred

In 2004 an assessment was initiated for upgrading the GMS units 1 to 5 turbines to improve efficiency and resolve runner blade cracking problems. This was part of a

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\(^4\) see Generation Engineering Reports PSE295, March 2000 and PSE308, May 2000
Strategic Partnering Agreement with GE Canada. Work progressed on model testing of new turbine runners, water passages and other turbine components based on a design developed by GE. Fixed components of the existing turbines and water passages were also modeled. With the completion of the modeling work, the scope of work proposed for the turbine upgrades included new turbine runners, new wicket gates, modified stay vanes, removal of the draft tube tripod air admission systems, refurbishing or replacing of the head covers and resurfacing of all the water passage components not being replaced.

In the fall of 2005, the project was discontinued and the turbine upgrades deferred. The reasons for not proceeding included substantial cost increases, lack of satisfactory guarantees on expected efficiency gains, uncertainty of the assumed efficiency of the existing turbines (there was no modeling done) and general concerns with recent experiences with GE on other turbine upgrade projects (Cheakamus and GMS Units 6 - 8).

It is important to note that replacement does not always result in better and trouble free equipment.
Event 4
The Tripod Beta Subtree for this event can be found on page 29.

Event Information
Description: Further damage to unit

Continued operation of the unit would have likely caused additional runner blade failure and turbine component damage.

Agent Information
Description: Runner blades fail damaging turbine components

Reported as Event 3 above

The barriers involved for this Agent are:
6. Emergency Shutdown (an effective barrier)

The operator, in consultation with the control centre (SCC), initiated an emergency shutdown of the unit. Because of loss of control of the wicket gates, the head gate was closed to drain the penstock. The unit experienced an over speed condition then coasted to a final stop.

Target Information
Description: GMS G3 Generator

The barriers involved for this Target are:
<No barriers involved>
E. Barriers and Recommended Actions

Recommended actions are provided by the author, subject matter experts and site technical personnel.

**Barrier 1**

**Wicket gate linkage design (an inadequate barrier)**

**Category:** Physical  
**Failure:** Linkage design weaknesses include adjacent wicket gate linkage interference under certain operating conditions and shear pins acting in dual capacity as shear and link pins.  
**Action:** The inherent design weaknesses on units 1 to 5 raise significant challenges. Introduction of friction devices on the wicket gate operating mechanisms and redesign of the wicket gate linkages to eliminate the dual duty of the shear pins should be examined.

**Barrier 2**

**Shear pin failure analysis (a failed barrier)**

**Category:** Physical  
**Failure:** Welding of re-configured baffles in 1985 caused distortion of the head cover. The wicket gate bore distortion made it impossible to install the head cover over the wicket gates. The new bushings had already been installed. There was insufficient time to re-order new bushings so it was decided to machine on the bushings and rebuild the wicket gate matching journals to suit the new bushing diameters. The results were less than adequate. The mis-alignment caused increased stresses on the shear pins. The significance of not re-aligning all of the bores was not evident until the runner was dismantled after the catastrophic failure in 2008.

Management of operational changes and maintenance activities were less than adequate.

Analysis of shear pin failures and trending has not been done. However, historically, the unit operated successfully with a single broken shear pin. Automatic governor adjustment maintained power output.

**Action:** Although the other units did not experience the same modifications, gathering and analysis of servo-differential test data for remaining units 1, 2, 4 and 5 should be undertaken to determine if excessive forces are experienced in operating the wicket gates.

A better understanding of the interaction between changes to operations and the resultant maintenance activities is required. Site management and technical resources along with Generation Engineering should determine appropriate levels of monitoring and maintenance for effective risk mitigation for remaining units 1, 2, 4 and 5.

Additionally, the stresses imposed on the units by the operational changes, most notably the increase in stop/start cycles and the synch-
condense function, should be better understood. If warranted, operational controls may be a consideration.

The December 2000 report issued by Generation Engineering titled, "GM Shrum Generating Station Units 1 to 5 Runner Blade Cracking Study" (report PSE303) provides insight into safety factors and the impact of operations on the life of the runner. GE Canada provides runner fatigue data and Goodman Diagram comparisons to identify allowable stress amplitudes. This, and other specialized analyses in the report, should be communicated to site. The report is technical and requires interpretation for understanding.

Analysis of shear pin failures in remaining units 1, 2, 4 and 5 should be undertaken to identify trending and determine possible abnormal conditions.

**Barrier 3**

**Broken shear pin detection (a missing barrier)**

**Category:** Physical

**Failure:** Control room alarms and/or unit trips on broken shear pin detection are not in place.

**Action:** Shear pin detection and associated operational control schemes should be implemented in accordance with pertinent engineering standards and guidelines. The fact that a single shear pin failure was the initiating event for the runner failure in March 2008 should be taken into consideration when options are being evaluated for an effective risk mitigation strategy with respect to shear pin detection and unit control.

Work is presently underway for implementation of broken shear pin detection on GMS units 1 – 5.

**Barrier 4**

**Vibration Monitoring (a missing barrier)**

**Category:** Physical

**Failure:** The control room did not receive vibration alarms during the March 2008 G3 runner failure.

**Action:** Whether or not the currently installed vibration monitors adequately protect the units should be investigated and remedial action taken in accordance with pertinent engineering standards and guidelines.

In addition, alarm and trip levels for units 1-10 should be reviewed and revised, as required, by subject matter experts to ensure the equipment is adequately protected. A formal process of approving changes to settings should also be implemented.

**Barrier 5**

**Runner replacement (a missing barrier)**

**Category:** Physical
Failure: The risk of runner failure was not understood leading to the runner not being replaced.

Action: Runner replacement is underway. Unit 3 runner is being replaced as part of this forced outage. Remaining units 1, 2, 4 and 5 runners are scheduled for replacement.

Evaluation of interim measures to mitigate the risks of resonance conditions should be undertaken.5

Barrier 6

Emergency shutdown (an effective barrier)

Category: Physical

Failure: N/A

Action: N/A

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F. Latent Failures and Recommended Actions

Recommended actions are provided by the author, subject matter experts and site technical personnel.

**Failure 1**

**Description:** Linkage geometry introduces interference between adjacent gates

With wicket gates opened to 20.5°, a shear pin failure can result in the wicket gate arm contacting the adjacent wicket gate arm.

**Recommended action:**

Fleet wide assessment of similar conditions should be carried out and risk mitigation strategies implemented.

**Failure 2**

**Description:** Linkages have one pin for both shear and link pin functions

Shear pins are subjected to shear, bending and torsional stresses.

**Recommended action:**

Fleet wide assessment of similar conditions should be carried out and risk mitigation strategies implemented.

**Failure 3**

**Description:** Oversight did not determine impact of operational changes

Although the increase of start/stop cycles is commented on in the Facility Asset Plans, there is no indication of mitigation of risk associated with the additional stresses imposed on the unit as a result of the increased cycles. In addition, there was no evidence that preventive maintenance instructions were modified as a result of the changed operation, as required by Generation’s RCM process.

An increase in management and skilled resource changes coupled with organizational restructuring has resulted in loss of unit knowledge (expertise and documentation) and a failure to recognize the impact of operational changes.

**Recommended action:**

A better understanding of the interaction between changes to operations and the resultant maintenance activities is required. Fleet wide identification of significant operational changes and needed maintenance adjustments should be undertaken.

BC Hydro, as with many organizations, will have challenges associated with hiring and retaining skilled resources at its facilities. A structured approach to transferring institutional knowledge is required.

When taking a new management or technical position an individual should be provided with a facility history, current challenges, key contact information and critical issues at hand. Records and reporting mechanisms with easily accessible and accurate information are essential to the ability to assess asset and business conditions.

Management should ensure there is alignment between needed knowledge and skills and people selected for the role or to oversee the work.
**Failure 4**

**Description:** Maintenance planning needs improvement

Identification and scheduling of maintenance activities, allocation of skilled and technical resources, tracking of maintenance issues and adequate spare parts inventory need improvement.

**Recommended action:**

BC Hydro has made considerable investment in its engineering and maintenance programs. There remains opportunity for improvement in a number of areas to further reduce risk to its fleet.

Asset risk exposures are not well understood. Responsible Generation departments, site technical resources and management should refine the approach to asset management. Improvements in asset tracking, data analysis and recordkeeping should be sought. Resources intended for the implementation of programs such as Equipment Health Rating (EHR) and Reliability Centered Maintenance (RCM) programs should not be taken off this work to meet other day-to-day site duties. When practical, dedicated resources should be allocated to implement key initiatives.

Alignment of maintenance activities with the aging fleet and increased operational demands, which is part of Generation’s RCM practices, needs to be implemented.

All critical spare parts need to be tracked in BC Hydro’s spare parts system. This enables automatic re-ordering of critical spare parts when spare parts are used for maintenance. The system captures re-order points and delivery lead times so that an adequate quantity of spares is on hand at all times.

Evaluation of skilled trades’ resources and alignment with site demands for preventive, condition and corrective maintenance, as well as capital project support should be reviewed. Are sufficient resources available for the defined work?

Opportunities for improved monitoring of aging assets should be examined (e.g., does asset condition require more extensive tracking?).

Decisions on capital investment should not deter maintenance efforts. A planned turbine upgrade in 5 years should be met with a determination to ensure the existing turbine will be able to withstand the operational demands of another 5 years. The planned capital investment should not diminish the focus on maintenance.

**Failure 5**

**Description:** Records of shear pin failures and analysis are limited

Records of shear pin repairs and replacement are not complete. No trending and failure mode analysis was conducted in recent years.

**Recommended action:**

Organizational commitment to recordkeeping of equipment operational changes, failures and analysis is critical.

Organization wide “best practices” in recordkeeping should be identified and modeled to benefit those groups of individuals responsible for the operation and maintenance of the fleet assets.

Regular scheduled reviews of shear pin failures in the fleet should be conducted to identify trending and failure modes. Findings should be shared with other sites.
Failure 6
Description: Generation Engineering involvement has decreased
Records for fiscal years 2004 to 2006 show a significantly reduced level of GEMS service at GMS.
Recommended action:

The apparent reduced service levels may have been associated with adapting to a new organizational structure and the associated changes to billing and tracking processes.

The increase in the use of GEMS in recent years is a positive trend. A review of the type of GEMS service being provided to the generating stations should be undertaken to understand the focus of GEMS services; preventive or condition based support.

Evaluation of benefits and unexpected consequences associated with the current practice of interdepartmental billing should be undertaken with an objective to further interaction between site personnel and GEMS.

Failure 7
Description: Broken shear pin detection system not installed
Shear pin detection on units 1 to 5 is not installed.
Recommended action:

Work being undertaken for installation of shear pin detection should include capability for detecting individual shear pin failures.

Risks of operating a unit with a single failed shear pin should be evaluated and consideration given to minimizing, or avoiding, operation of a unit under that condition.6

Failure 8
Description: Vibration monitoring not to current standards
In 2000 the "GMS G1-G10 Vibration Monitors Replacement Project Definition Phase" was initiated. However, the project was not implemented.
Recommended action:

Fleet wide review of vibration monitoring and control schemes should be undertaken to identify opportunities for mitigating risks associated with aging equipment. Where appropriate, vibration monitoring systems should be upgraded.

Failure 9
Description: Application of Engineering Report recommendations needs improvement
The decision making process for implementation of engineering recommendations is not clear. Some of the benefits of large investments in engineering research and studies are not being realized.

Recommended action:

Risk assessment models and decision making processes should be reviewed to determine their effectiveness in dealing with fleet asset conditions.

Consideration should be given to dedicating resources to interact with Generation Engineering to fully understand the proposals being brought forward. Management involvement in defining the intent and application of standards and guidelines should be considered.

Consideration should be given to implementing a formal process for “accepting” the recommendations of Engineering technical reports, determining at which facilities the recommendations should be applied, and tracking that the recommendations have been implemented.

Failure 10

Description: Runner inspection and repair in lieu of replacement

Runner replacement could not be justified on efficiency gains or reduction in annual cost of repairs. Technical advice was that known runner problems could be adequately managed through a maintenance program.

Recommended action:

Asset maintenance planning, implementation and recordkeeping should be emphasized to enable support needed for extending asset life, including from Generation Engineering.

Failure 11

Description: Runner replacement project deferred

In 2004 an assessment was initiated for upgrading the GMS units 1 - 5 turbines to improve efficiency and resolve runner blade cracking problems. This was part of a Strategic Partnering Agreement with GE Canada. Work progressed on model testing of new turbine runners, water passages and other turbine components based on a design developed by GE. In the fall of 2005, the project was discontinued and the turbine upgrades deferred. The reasons for not proceeding included substantial cost increases, lack of satisfactory guarantees on expected efficiency gains, uncertainty of the assumed efficiency of the existing turbines (there was no modeling done) and general concerns with recent experiences with GE on other turbine upgrade projects (Cheakamus and GMS units 6 - 8).

Recommended action:

No recommendations are provided.
G. Conclusion

A number of factors contributed directly to the failure of the runner. The unit has operated since 1968 without these factors aligning to provide the conditions experienced on March 2\textsuperscript{nd}.

The primary contributing factors were:

1. Wicket gate design introduced operating interferences between a closed wicket gate arm and adjacent wicket gate arm if the wicket gate is open greater than 20.5°.
2. Wicket gate linkage design subjected the shear pins to shear, bending and torsional stresses.
3. The runner design had weaknesses including,
   - natural frequencies that were integer multiples of the blade passing frequency
   - high dynamic stresses, low fatigue strength and defects in the original manufacturing
4. The runner had defects and residual stresses introduced by multiple weld-repairs.
5. The unit was not equipped with a shear pin detection system.
6. The unit was not equipped with vibration monitoring schemes capable of detecting the vibrations experienced on March 2\textsuperscript{nd}.

Secondary contributing factors were:

1. There was no analysis of shear pin failures which may have identified the underlying causes of ongoing shear pin failures and that shear pin #11 had a disproportionate number of failures.
2. Spare shear pin inventory was not maintained. A shear pin taken from a box labeled, “Do Not Use – For Emergencies Only” was installed on wicket gate #11 as part of routine maintenance.
3. There was no understanding of the impact that a significant increase in start/stop operation could have on Unit 3.
4. A number of relevant technical reports were prepared by, or commissioned by BC Hydro Engineering; some recommendations were acted on while some were not.
Tripod Beta Tree
The tree is broken down by event in the following pages.

Event 1

Event 2

Event 3

Event 4
Tripod Beta Sub Trees

*Event 1 - Shear pin 11 failure initiates cascading shear pin failures*

- Oversight did not determine impact of operational changes.
- Maintenance planning needs improvement.
- Records of shear pin failures and analysis are limited.
- Generation Engineering involvement has decreased.
- Shear pin failure modes analysis was not done.
- Historical and recent shear pin failures did not raise concerns.
- Wicket gate linkage arms and shear pins.
- Linkage geometry introduces interference between adjacent gates.
- Linkages have one pin for both shear and link pin functions.
- Wicket gate linkage design.
- Shear pin failure analysis.
- Unit operating conditions at 51% NAW generator output power.
- Shear pin 11 failure initiates cascading shear pin failures.
Event 2 – Closing of wicket gates results in runner striking seal ring
Event 3- Runner blades fail damaging turbine components
Event 4 – Further damage to unit (avoided)
System Event Recorder Trace

Shear pin 11 fails and wicket gate is forced to the closed position

During this timeframe shear pins 12, 13, 14 fail and wicket gates are forced to the closed position (≈ 6 minutes)

Piece of runner blade is ejected into draft tube

Operator initiates emergency shutdown

Remaining wicket gates are forced closed by pieces of runner blade ejected into runner/wicket gate cascade

Unit comes to a full stop

Emergency shutdown; unit spins ≈ 11 minutes

Unit operates with runner pieces in runner/wicket gate cascade (≈ 6 minutes)

Unit operates with 4 wicket gates in closed position (≈ 12 minutes)
Photographs

Blade #14 Missing Section
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