Sayano-Shushenkaya Hydro Power Project

Pat Regan

- On August 17, 2009 the Sayano-Shushenkaya Power Plant in Siberia suffered a catastrophic failure in a turbine-generator unit
- 75 people lost their lives in the accident


Norilsk
Yenisei
Nizhnyaya Tunguska
Podkamennaya Tunguska
Angara
Sayano
Krasnoyarsk
775 km
Bratsk
Lake Baikal
Abakan
775 km
Irkutsk
Ulan-Ude
Selenge
Ulaanbaatar


Sayanogorsk
Mayna
Cheremushki
Sayano
© 2009 Geocentre Consulting
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Image © 2009 TerraMetrics
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Imagery Dates: Sep 22, 2005 - Aug 31, 2007
52°57'06.35" N 91°26'20.34" E elev 2536 ft
Eye alt 31.59 mi
©2009 Google

Basic Data

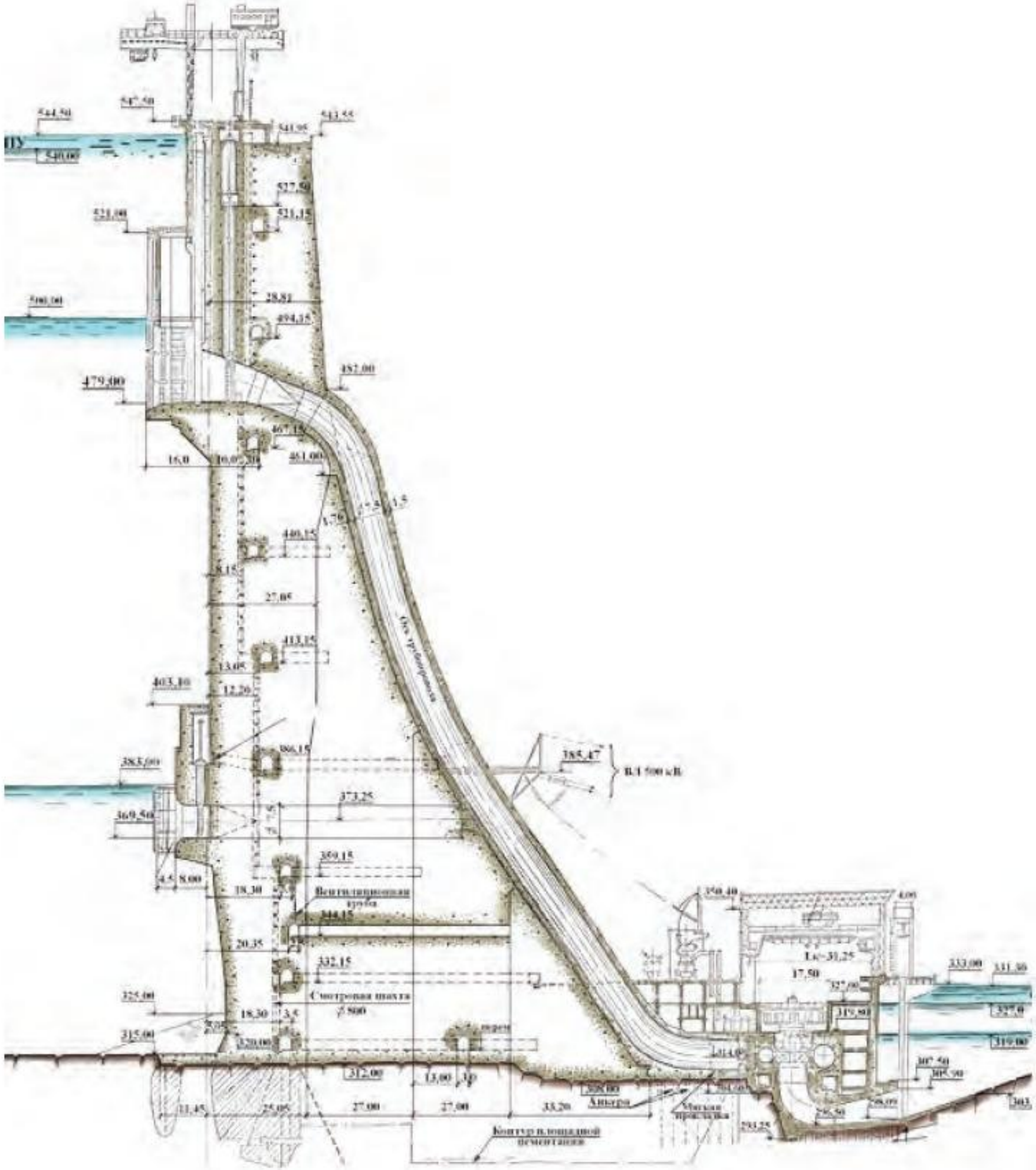
- Dam
  - Concrete Gravity-Arch
  - 242 m maximum height (794 ft)
  - 1,074 m crest length (3,524 ft)
  - 25 m crest width (82 ft)

САЯНО-ШУШЕНСКИЙ ГИДРОУЗЕЛ НА р. ЕНИСЕЕ

ГЕНПЛАН

Basic Data

- Spillway
  - 11 spillway outlets 8.2 m x 5.4 m (26.9' x 17.7')
  - Spillway inlet sills are 61 m (200') below NWL
  - Spillway control is by flat roller gates
  - 2 traveling cranes (500 ton capacity) are used to move the gates
  - Discharge velocity up to 55 m/s (180 ft/s; 123 mph)
  - Specific flow rate 120 $m^3/s/m$ (1292 cfs/ft)



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543.55
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500.00
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482.00
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467.15
461.00
440.15
413.15
403.10
386.15
385.47
ВЛ 500 кВ
383.00
373.25
369.50
359.15
350.40
Вентиляционная труба
344.15
332.15
Смотровая шахта
325.00
315.00
312.00
Анкера
Контур площадной цементации

Basic Data

- Powerhouse
  - 289 m long (948')
  - 10 Francis turbine-generator units
    - 640 MW each
    - 194 m rated head (636')
    - 358.5 m^3/s (12,659 cfs)
    - 6.44 m turbine diameter (22.2')
    - 156 metric ton generator weight (343,980 lbs)


(C) 4044415

Basic Data

- Penstocks
  - Composite steel liner / reinforced concrete
  - Trashrack in front of submerged intake
  - Slots for inserting maintenance bulkhead
  - Penstock shut-off gates operated by dedicated hydraulic cylinders
  - There are no turbine shut-off valves

Construction History

- Construction began in 1963 and the first unit was commissioned in 1978.
- In 1979, while the dam was still under construction, the seasonal flood could not be passed through the spillways and operating units and therefore overtopped the dam. The powerhouse was flooded.

Construction History

- The overtopping resulted in:
  - Cracking of the concrete in the upstream monoliths
  - Cracking at the dam-foundation interface
- Seepage through the dam was 18.4 cms and through the foundation 19.4 cms
- In response to these problems the cracking was grouted and a decision was made to reduce the normal water level 1 meter.

Construction History

- A flood in 1985 resulted in a discharge of 4500 m^3/s through the spillway
- The discharge resulted in destruction of the stilling basin bottom concrete
- Reportedly (from a source other than the official report) the spillway stilling basin also sustained damage in 1998
- An additional tunnel spillway was contemplated as early as 2000. The tunnel had been started but was not complete.


17.07.86г.

Construction History

- Unit Commissioning
  - HU-1 Dec 1, 1978
  - HU-2 Nov 5, 1979
  - HU-3 Dec 1, 1979
  - HU-4 Oct 1, 1980
  - HU-5 Dec 1, 1980
  - HU-6 Nov 1, 1981
  - HU-7 Sep 1, 1984
  - HU-8 Nov 1, 1984
  - HU-9 Dec 1, 1985
  - HU-10 Dec 1, 1985

Construction History

- Full scale tests by the turbine manufacturer identified zones of head-flow combinations that produce excessive vibrations
  - "Zone II – Under the runner there is a powerful central whirl with a rotation frequency of 0.4-0.8 Hz. This frequency determines the frequency of turbine bearing vertical vibration, axial force, and pressure fluctuations in all points of the turbine's flow duct (except from fluctuations under the turbine cover, where along with whirl frequency other determinant frequencies are 4.76 and 200-300 Hz."

Construction History

- "Operation of the turbine is coincident with strong hydraulic shocks in the flow area and loud noises."
- "The amplitudes of pressure fluctuations in the scroll case and draft tube reach 15-22 m of water column, and under the turbine cover – 36 m water column, vertical vibration of the turbine bearing 230 micro-meter, generator power oscillations 18-20 MW, axial force fluctuations – 150 ton-force"

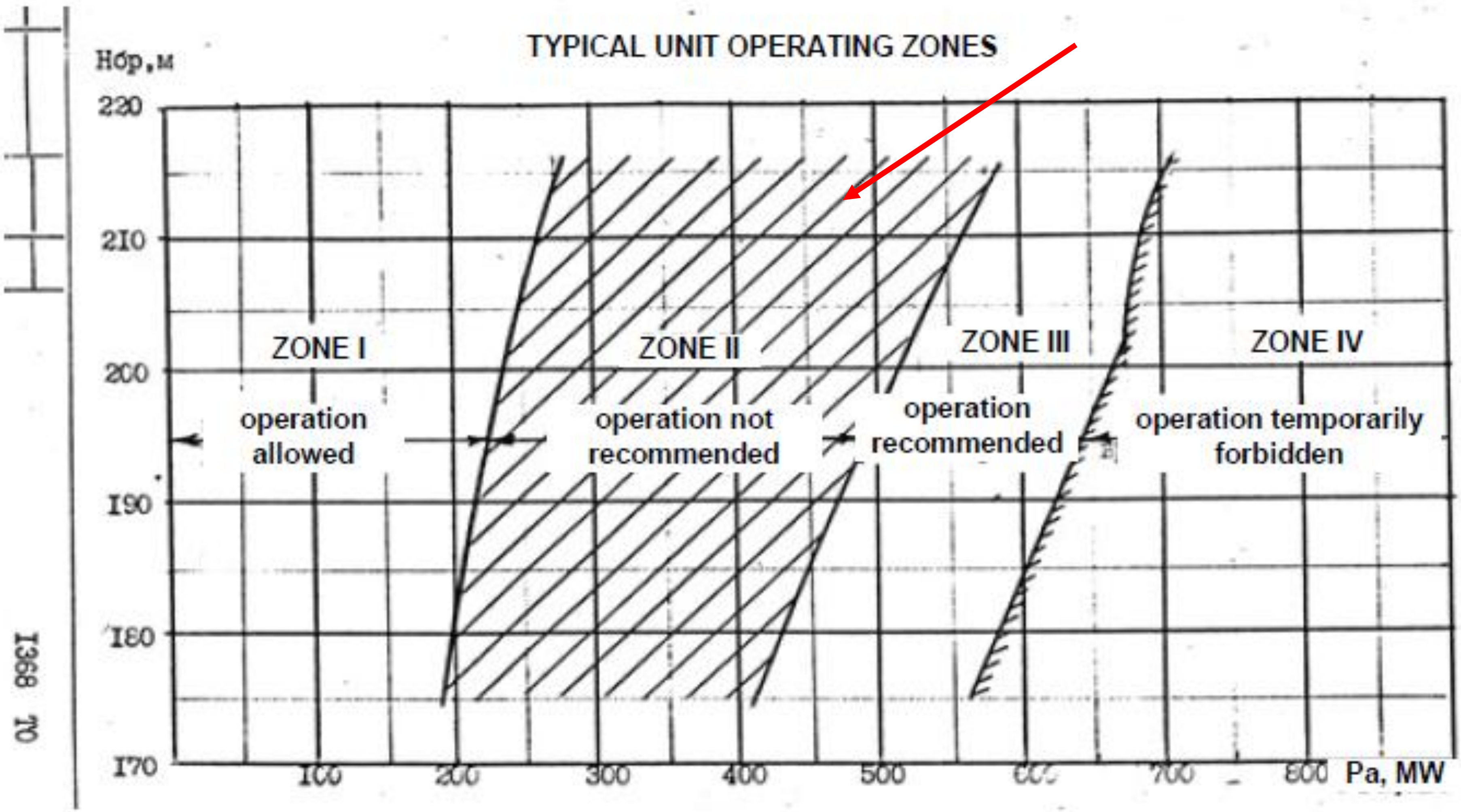


Fig. 4.5.1. Performance Parameters of a Hydroelectric Unit with a RO230/833-V-677 Turbine

Operation History

- Operations have noted flaws in the turbine manufacture resulting in cracking of turbine blades
- The control system does not provide for wicket gate closure under loss of power

Unit 2 Operational History

1979-11-05	Unit 2 commissioned
1980-03-13	Increased shaft wobble of up to 1.3 mm, significant leakage through the turbine bearing sealing (cracks on the shaft surface, rubber tear-outs on the segments, damaged upper and lower gaskets of the turbine bearing), and hydraulic unbalance of the removable runner.
1980-04-24	Oil leakage in the control system's pressure pipeline at the tie-in of the pipeline from the oil pressure unit pumps to the pressure pipeline through a crack, resulting from incomplete penetration of the weld joint on the pressure pipeline
1980-06-28	Same issues as above
1980-08-01	Increased water leakage through the top gasket of the turbine bearing – the joints of the rubber ring broke loose due to poor workmanship
1980-09-08	Same issues as above
1981-09-13	Damaged rubber surface and fastening bolts of the turbine bearing's segment dowels, destruction of the lower static ring of the runner labyrinth controls. Runner cone break.

Unit 2 Operational History

1981-10-02	Increased shaft wobble from 1.9 mm (increased gap to 1.7 mm between bearing segments and shaft liner).
1981-11-29	Increased shaft wobble to 1.5 mm – break of segment dowels’ fastening bolts due to hydraulic unbalance of the runner.
1981-12-14	The same wobble of up to 2 mm.
1982-01-18	The same wobble of up to 2 mm – detachment of rubber on Segments 7 and 11; break of turbine bearing shell pins; damaged shaft liner
1982-01-25	Wobble increased to 1.9 mm (increased gap, damaged shaft liner, damaged surface of the segment rubber)
1982-02-01	Same issues as above
1982-03-24	Increased shaft wobble to 0.95 mm and increased bearing shell vibration. Break of two pins fastening the bearing shell to the turbine cover – hydraulic unbalance of the runner.
1982-05-03	Increased wobble to 1.9 mm (break of turbine bearing shell pins, increased gap to 1.85 mm)

Unit 2 Operational History

1982-05-14	Increased wobble to 1.5 mm (displacement of the turbine bearing shell up to 1 mm, a crack on the shaft liner, pin break
1982-05-28	Same issues as above
1982-06-26	Same issues as above
1982-07-09	Same issues as above
1982-09-03	The same, wobble of up to 1.6 mm
1982-09-08	Damaged rubber coating of the segments. Increased shaft wobble due to hydraulic unbalance of the runner
1982-10-01	Runner cone break
1982-10-27	Oil leakage on the pressure pipeline supplying oil from the oil pressure unit pumps at the tie-in with the pressure pipeline of the wicket gate servomotors.
1982-11-10	Same issues as above
1982-11-28	Increased shaft wobble to 1.6 mm – hydraulic unbalance of the runner

Unit 2 Operational History

1983-01-23	Increased shaft wobble to 1.6 mm – hydraulic unbalance of the runner
1983-03-10	Same issues as above.
1983-03-24	Break of the turbine bearing shell fastening. Turbine bearing shell vibration of up to 0.7-0.6 mm with shaft wobble of 0.95 mm due to hydraulic unbalance of the runner
1983-07-27	A turbine bearing shell crack resulting from turbine bearing shell vibration increase to 0.4 mm with shaft wobble of 1.44 mm, significant water leakage onto the turbine cover, break of the stiffener angles on the additional fastening of the shell to the turbine cover – hydraulic unbalance of the runner.
1983-08-18	Break of the stiffener angles on the additional fastening of the turbine bearing shell. Turbine shell vibration up to 0.65 mm with the shell wobble of 1.3 mm due to hydraulic unbalance of the runner.
1987-11-30	Loss of water pressure in the left line of the service water supply due to weld failure of the plug installed on the pipeline of the system's pump feed due to poor weld workmanship of the installation company.

Unit 2 Operational History

1987-09-27	Oil leakage along the weld joint on the pressure oil line of Servomotor 13 due to poor weld workmanship
200-03-27 to 2000-11-12	Overhaul of Unit 2 with complete disassembly. Items noted include: 1) cavities up to 12 mm deep on the back side of the turbine blades close to the entrance edge and cracks in the upper part of the exit edges of Blades 1 and 7 (130 mm long Blade 1, 100 mm long Blade 7) – the cracks were repaired but the cavities were not eliminated. 2) the turbine bearing had worn rubber coating on the segments, cracks in the segments' support plates and worn seals and fastenings. 3) the turbine shaft had indications of wear from the upper flange seal 47 mm high and 4mm deep around the entire shaft diameter. This was repaired by build-up welding and grinding to the design profile.
2009-01 to 2009-03	Scheduled repairs and modernization. A new electro-hydraulic regulator was installed.

Unit 2 Operational History

2005-01-29 to 2005-12-29	Overhaul of Unit 2. Items noted include: 1) elimination of cavities on the runner blades, measuring and adjusting shaft bias, centering of unit on labyrinth seals
2009-01-01 to 2009-03-16	Heavy maintenance on Unit 2. Items noted include: 1) a 1.0 m long crack in the weld joint of the annular plug in the place where the wicket gate bottom ring adjoins the turbine stator lower belt in the area of wicket gate 10 2) cavities up to 15 mm deep on the entrance edge of the turbine blades and up to 12 mm deep on the upper ring Accepted for operation on April 15, 2009 with a final grade of “Good”

Privatization of SSHPP

- In 2000 the Russian utility monopoly was broken up into regional power companies who operate as investor owned companies.
- The condition assessment report prepared for the transfer noted:
  - “There is a need for turbine replacement”
  - “as soon as reasonably possible, start construction of an additional spillway”

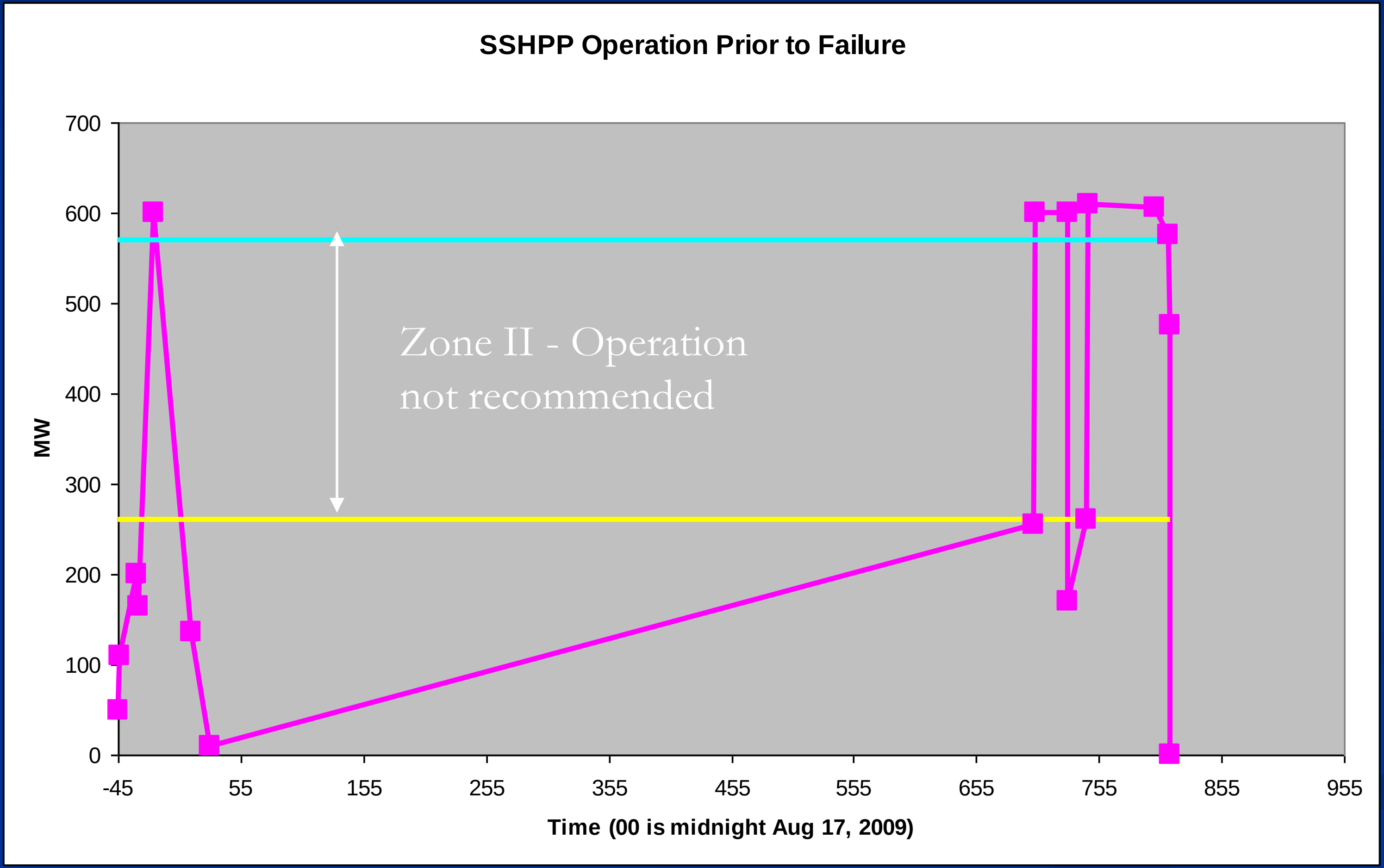
Events Leading to Failure

- Beginning at 00 hours 00 minutes on August 16, 2009:
  - The Bratskaya HPP was operating under Automatic Frequency and Power Control of the Inter-Regional Dispatch Office
  - The SSHPP was operating under local control in a normal operations schedule to ensure the planned daily flow requirements
  - At 2020 hours a fire at the Bratskaya HPP interrupted communications with the dispatch office

Events Leading to Failure

  - At 2031 the system transferred automatic control to the SSHPP
  - At 2314 Unit 2 was started up and placed under automatic power control
- At 0813 on August 17, Unit 2 failed

Events Leading to Failure



Events Leading to Failure

Date/Time	Power Output	Vibration amplitude of turbine bearing	Pressure under Head Cover (kgf/cm^2)
Manufacturer allowable	600 MW	0.160 mm	
2009-03-12 After maint.	601 MW	0.137 mm	
2009-08-17 0800	600 MW	0.200 mm	3.4
2009-08-17 0813	475 MW	0.840 mm	3.5

Events Leading to Failure

- Standard Operating Procedures required a unit to be shut down if vibration increased above 0.16 mm. This was not done.

Technical Causes of Accident

- Unit 2 had a design life of 30 years according to the manufacturer
- At the time of the accident, the turbine was 29 years, 10 months old.
- The turbine had a narrow acceptable operating range and had to move through an area labeled "operation not recommended" to reach its normal operating area.

Technical Causes of Accident

- The Active Power Control system did not take individual unit limits on power and areas not recommended for operation.
- Over the course of operation, the vibrations associated with transition through, and operation in, the "not recommended" zone resulted in fatigue induced cracking in the bolts holding down the turbine head cover.

Technical Causes of Accident

- Post-failure investigations found evidence that six of the bolts holding down the head cover had no nuts at the time of failure.
- Management did not follow procedures regarding maintenance and replacement of turbine runners.
- The operator did not follow standard operating procedures regarding unit shut-off when vibrations exceeded design limits.

Technical Causes of Accident

- The continuous vibration monitoring system had not been commissioned and was not taken into account during plant operation.
- From the completion of the overhaul in April 2009 to the failure there was a four-fold increase in unit vibrations.

Technical Causes of Accident

- Ultimately the failure was caused by failure of the bolts holding down the head cover.
- Post-failure investigations discovered:
  - 41 of the 80 bolts showed evidence of fatigue cracking with an average fracture area of 65%
  - 2 bolts failed without evidence of fatigue cracking
  - 6 bolts were in tact and showed no evidence of stripped threads. This is interpreted to indicate there were NO nuts on these bolts

Technical Causes of Accident

- In a group of seven adjacent bolts, 4 showed no evidence of having nuts at the time of failure, 2 had fatigue cracking over 95% of their area and the last had fatigue cracking over 35% of its area.
- Essentially, over a 51 degree section of the headcover, there was only 6% of the design clamping force.

Grand Rapids
Manitoba Hydro

- Failed headcover in 1992
- 77 of 120 bolts either completely or partially fractured prior to failure
- 27 bolts failed by fast fracture
- 10 bolts failed under the nuts
- 6 bolts failed by stripping the threads
- Most of previously fractured bolts were in the same half of the headcover in an area here pipes had been welded to the stay vanes

Investigation Recommendations

- Hydraulic Units
  - Arrange for examination (as appropriate full-scale tests) of the hydroelectric units
  - Develop a turbine with a broad active power control range
  - Upgrade the governor system providing for closure of the wicket gates under loss of power
  - Use NDT diagnostics on flange coupling components and head cover bolts.

Investigation Recommendations

  - Equip units with continuous monitoring of vibration and temperature and integrate into the control system with implementation of alarms and automatic shutdown
- Powerhouse and Dam
  - Assure protection from flooding of control systems and communication lines
  - Provide video surveillance and wireless communications

Investigation Recommendations

- Do not place administrative, maintenance or auxiliary building below the level of the afterbay
- Install autonomous power supplies on the crest of the dam for operation of cranes, penstock gates and spillway gates

Investigation Recommendations

- Protection Systems
  - Modify APCS to ensure safe operation and reliable shutdown in emergency situations
  - Implement an emergency penstock gate closure system to guarantee closure under emergency situations and on demand from the control room
  - Adopt a procedure to make decisions based on vibration monitoring data

Investigation Recommendations

- Operations
  - Work with the manufacturer to develop a control algorithm for the units accounting for their condition and operation limits
  - Develop and implement procedures to prevent loosening of the nuts on water conduit couplings

Investigation Recommendations

- Penstocks
  - Examine the technical condition of the composite reinforced concrete penstocks. Eliminate surface crack growth

Investigation Recommendations

- Reservoir Operation
  - Operate the reservoir in accordance with modes established by the local Water Directorate
  - Develop design and technical measures to ensure safe operation of the spillway and stilling basin taking into account limits on evacuating and filling the reservoir

Investigation Recommendations

- Develop and submit to the local Water Directorate measures to ensure safe operation of the dam and stilling basin when water is not discharged through the powerhouse
- Develop procedures to assure safe operation in winter taking into account ice entering the spillway, gate frosting, spillway discharge restrictions, etc.

Investigation Recommendations

- Arrange for observation of the condition of the stilling basin's slabs
- Arrange for instrument-based observation of the stylus inclination and settling of heavy part of the collapsible abutment of the stilling basin

Investigation Recommendations

- Emergency Action Planning
  - Calculate according to established procedure, potential damage in case of an accident at SSHPP
  - Develop and submit to the authority a declaration of safety of the hydraulic safety of the SSHPP spillway
  - Examine instrumentation and determine need for additional instrumentation

Investigation Recommendations

- Obtain from the Ministry of Emergency Situations the conclusion of readiness to contain and respond to emergencies, protect the population and the territory in case of accident

Spillway Concerns

- The spillway capacity is reportedly 12,870 m^3/s
- The flood of record is reportedly 24,000 m^3/s
- The SSHPP assumed that the units would be available to pass flow (3,500 m^3/s total)

Spillway Concerns

- The spillway was damaged by high flow releases in 1985 (4,500 m^3/s), 1988 (flow unknown) and 1998 (flow unknown)
- These flows were for a limited duration – passage of specific flood waters.
- Heavy snowpack in the watershed indicated the potential for a new flood of record in 2010

Spillway Concerns

- The need for additional spillway capacity has been recognized for a long time.
- A tunnel spillway/bypass is being constructed but may not be completed until after the 2010 runoff period
- The spillway has not been used over a long period of time to pass large flows.

Spillway Concerns

- The powerhouse was unable to be usable to pass flow until after the runoff.
- The spillway was be the only way to pass water in 2009. Heroic efforts completed a new spillway in time for the 2010 runoff season.
- Given the damage the spillway sustained during other large discharges, for a limited time, this was a BIG concern.

How Could a Dam Failure Occur? Part 1 - Reality

1) Under Normal Operation
2) A fire at a remote power plant causes the system dispatcher to transfer load-following responsibility to SSH hydro plant
3) SSH staff start Unit 2 and place in load following mode
4) Operation of Unit 2 over the course of 30 years causes partial to complete fatigue failure of the bolts holding down the turbine head cover

How Could a Dam Failure Occur? Part 1 - Reality

5) In load following mode Unit 2 transitions through the rough operating region on several occasions
6) The fatigue failure of the head cover bolts reaches a critical state
7) The turbine head cover tears loose ejecting the turbine through the generator

How Could a Dam Failure Occur? Part 1 - Reality

8) The open head cover allows water to flood into the powerhouse
9) The flooding water knocks out station power cutting power to the penstock intake gates
10) Water flows for half an hour until the gates can be closed using manual operators
11) The flooding damages the powerhouse to the extent that all 10 units are forced off line and only two units will be available to help pass flow in the coming runoff season

How Could a Dam Failure Occur? Part 1 - Reality

12) Damage to the powerhouse results in the majority of inflow passing through the spillway for an extended period
13) Operation through the winter results in icing over the spillway and collapse of a crane used to access the stilling basing for repair

How Could a Dam Failure Occur? Part 2 - Hypothetical

14) Higher than normal snowfall in the watershed may lead to larger than normal runoff (assume flood of record)
15) The high runoff requires the spillway to run full
16) The excess inflow rapidly fills the reservoir
    - 19 days if one tunnel spillway and two units are available
    - 12 days if only two units are available
    - 7 days if the service spillway becomes inoperable
17) The excess inflow overtops the dam reinitiating the crack at the dam foundation interface
18) High spillway flows destroys the stilling basin bottom and begins to undercut the dam toe
19) Undercutting continues as the spillway passes flow.

How Could a Dam Failure Occur? Part 2 - Hypothetical

20) Cracking of the dam-foundation interface leads to increased uplift under the dam
21) The combination of continued toe undercutting and increasing uplift under the dam leads to a sliding failure of the dam

How BIG is BIG?


Hoover Dam
Height – 726.4’
Crest Length – 1244’
Res. – 28.5M ac-ft

Sayano-Shushenskaya
Height – 794’
Crest Length – 34984’
Res. – 25.4M ac-ft


How Big is Big?