SAYANO-SHUSHENSKAYA HYDROPOWER PLANT DISASTER

LESSONS TO BE LEARNT

September 2022

engineering new zealand
te ao rangahau

CONTENTS

This document summarises the webinar by Don Erpenbeck, vice-president of Stantec. Don serves as Stantec's global sector lead for the dams and hydropower business. He's a licensed mechanical engineer in Illinois and a technical expert in large rotating machinery, with over 30-years' experience working on some of the largest hydro units in the world.

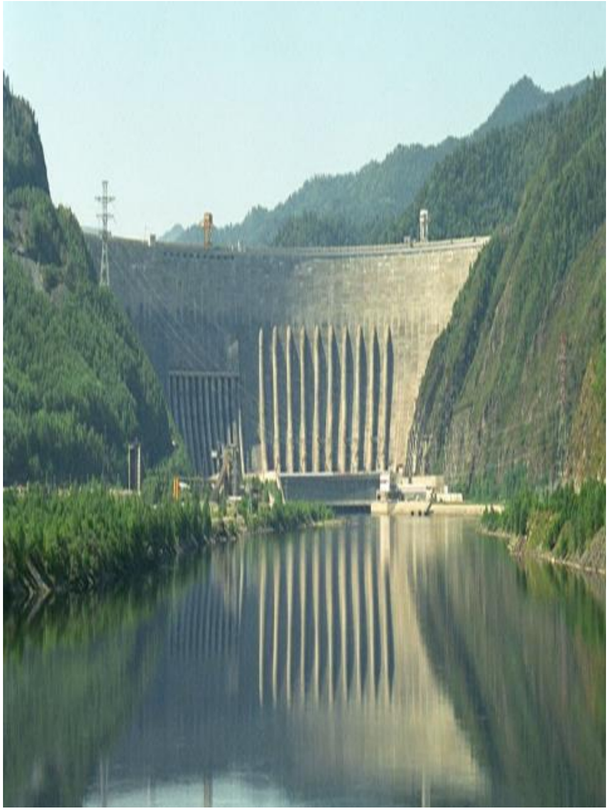
Don is chair of the New Zealand Hydropower Group, a technical interest group of Engineering New Zealand. Established in June 2021, this is 'a forum for hydropower professionals working in this multidisciplinary field of engineering. It supports professionals in this area to share experience and knowledge across New Zealand and internationally, as well as acting as a voice for the local hydropower sector' [1].

[1] https://www.engineeringnz.org/join-us/groups/new-zealand-hydropower-group/

1: INTRODUCTION

The Sayano-Shushenskaya hydro power plant is the largest plant in Russia, located on the Yenissei River, Siberia. It's the sixth largest hydropower plant in the world.

On August 17th, 2009, there was a catastrophic failure of unit 2 of the plant. This resulted in the death of 75 workers.



In addition, 6500 megawatts (MW) of power went off-line for six-seven years while repairs were completed.

As the plant powered a high proportion of the aluminium industry in Russia, the price of aluminium almost doubled overnight.

Exploring this failure – what happened and why and lessons learnt - helps us as engineers avoid future mistakes in our work and profession.

ACKNOWLEDGEMENT

The information presented in the following was obtained from the public domain and RUS Cold presentation. The opinions expressed are solely those of the presenter.

Don featured on a science channel show called, Deadly Engineering where he was interviewed on the Sayano-Shushenskaya Hydro Power disaster[2].

[2]https://www.sciencechannel.com/video/deadly-engineering-science/power-plant-catastrophes

2: WHAT HAPPENED

This section describes what happened in the hydropower plant failure and explores reasons why, including the characteristics of the plant, and the sequence of events that led to the disaster.

BACKGROUND

This hydropower plant was massive. At the time of accident, the Hydro Power Plant (HPP) operational parameters were:

- 4140 megawatts (MW) of power being generated.
- Eight of the ten units were operating (one unit was offline and Unit 6 was in a scheduled outage).
- It was running in Automatic Generation Control (AGC) mode for the control of frequency and power.

There was a huge amount of water flow.

- The water inflow into the reservoir was 2,350 cubic metres per second (2350 m3/s).
- The water was discharging through the turbine units at 2,250 cubic metres per second (2250 m3/s) and discharging through the spillway at 0 m3/s.

There was also a lot of head. This is the height difference between where the water enters the hydro system and where it leaves it, measured in metres.

- The upstream water level, in the upper reservoir, was at an elevation of 537.11 metres.
- The downstream water level was at an elevation of 325.07 metres.

That's about 200 metres of difference. And as the turbines were set low in the plant, it was closer to 230 metres of head.

WHAT HAPPENED

The water (which normally flows from the dam through the generators) surged and damaged one of the electrical generators and flooded the vast machine hole which housed all the electrical equipment. The turbine was destroyed by the 'so-called' hydraulic impact of the surge.

The plant was badly damaged, with the roof blown off and water shooting out. With the water flowing through to the lower elevations, all the electrical equipment shorted out in the transformers and substations.

- All the power supply, including back up for all the auxiliaries, was lost for the entire facility.
- All the units went offline within 49 seconds (from 8:13:25 to 8:14:14).
- The wicket gates were not fully closed, and so the units went into various states of runaway/overspeed.
- The intake gates did not close, are they were not capable of automatic closure as they were wheel gates.

IMMEDIATE RESPONSE

One of the operators grabbed two janitorial staff, climbed 240 metres of stairs in the dark, to shut off the intake gates.

- At 9:20 AM (one hour seven minutes after the event) they were finally able to shut off the water to the unit 2 intake gate and stop the flooding into the powerhouse through the destroyed unit.
- At 10:00 AM (one hour 47 minutes after the event) they shut down all the other nine units' intake gates.

But after turning off all the water flowing through the turbines, the water level in the reservoir began to climb, as there was no power to the spillway gates.

- At 11:00 AM (two hours 47 mins after the event) an emergency diesel generator was delivered to the dam to power a gantry crane. This crane was used to begin opening the spillway gates.
- At 11:40 AM (over three hours after the event) the spillway gates were opened and the balance between water inflow into the reservoir and water discharge downstream of the hydro power plant was restored.

The situation at the dam stabilised.

The hole from Unit 2 in the powerhouse gallery.

PRE-INCIDENT PLANT CHARACTERISTICS

Relevant plant characteristics

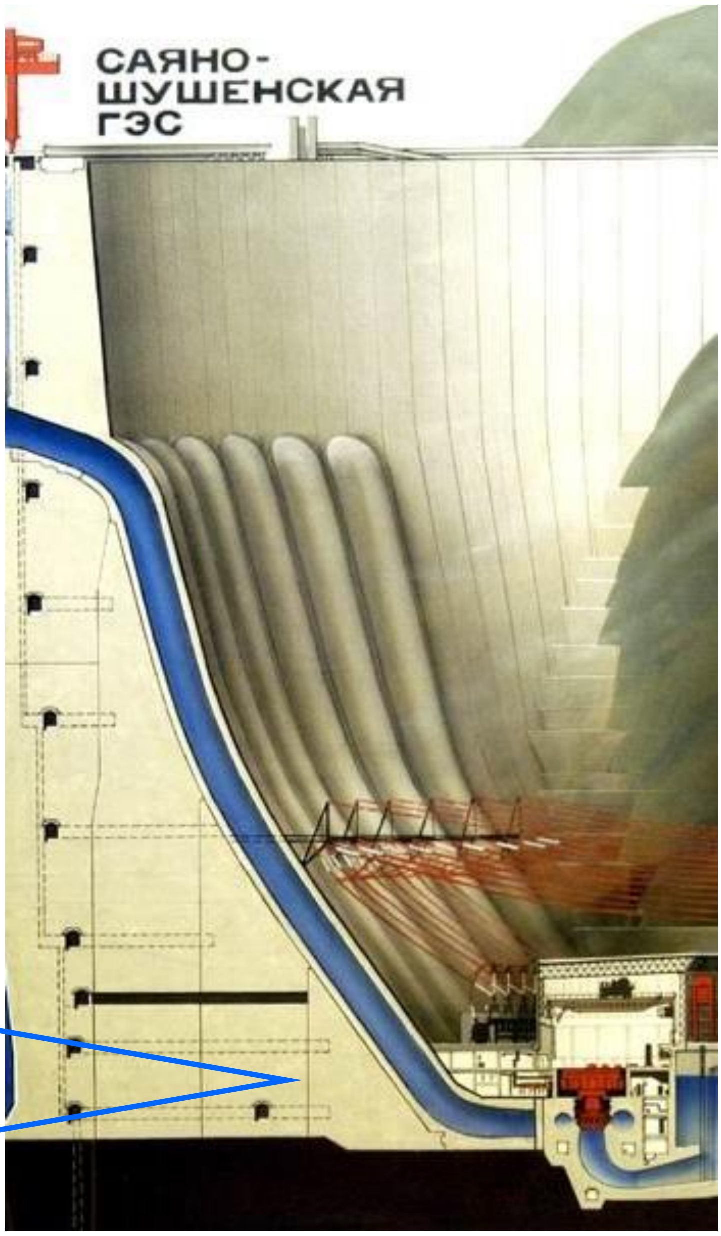
Sayano-Shushenskaya hydro power dam is 233 metres tall, with a reinforced concrete arch dam and a crest length of 1,000 metres.

Originally built in 1971, at the time of the failure it was a little under 40 years old. Other details are:

- The ten 650 MW units have a nominal plant capacity of 6500 MW.
- 1070m long crest at EL. 247, TOE at EL. 14.
- There is 9 million m^3 (319 million ft^3) of concrete.
- Reservoir storage: 31.3km^3 (25.4M acre-ft).
- Live storage to 40m depth: 15.3 km^3 (12.4 million acre-ft).

This cross section of the plant shows the transformers and the power transmission lines coming off the plant.

And as the water came through, all the transformers and electrical lines shorted out.



3 The information presented in the following was obtained from the public domain and RUS Cold presentation. The opinions expressed today are solely those of the presenter. The information presented in the following was obtained from the public domain and RUS Cold presentation

Generator hall

Here is a photo of the generator hall before the failure.

The row of windows and the different turbine units. In the background is the powerhouse crane, which is the main way of servicing these units.

Unit Characteristics

Francis turbine

The turbines in the dam were Francis turbines. The maximum power of the Francis turbine is 735 megawatts (MW), and it is rated at 650 MW. At minimum water levels it can still produce 550 MW.

The wheel of the turbine runner is 156 tons.

	MINIMUM	RATED	MAXIMUM
HEAD (M)	175	194	220
FLOW (m^3/s)	335	360	358
OUTPUT (MW)	550	650	735
RUNNER DIAMETER	6.25 m		
NO. OF BLADES	16		
RUNNER WEIGHT	156 tons		
ROT. SPEED	142.8 rpm		

Generator

The generator weighs 900 tons on the rotating parts and the stationary part of the generator is 500 tons. That's a lot of mass!

This is very relevant because of the design.

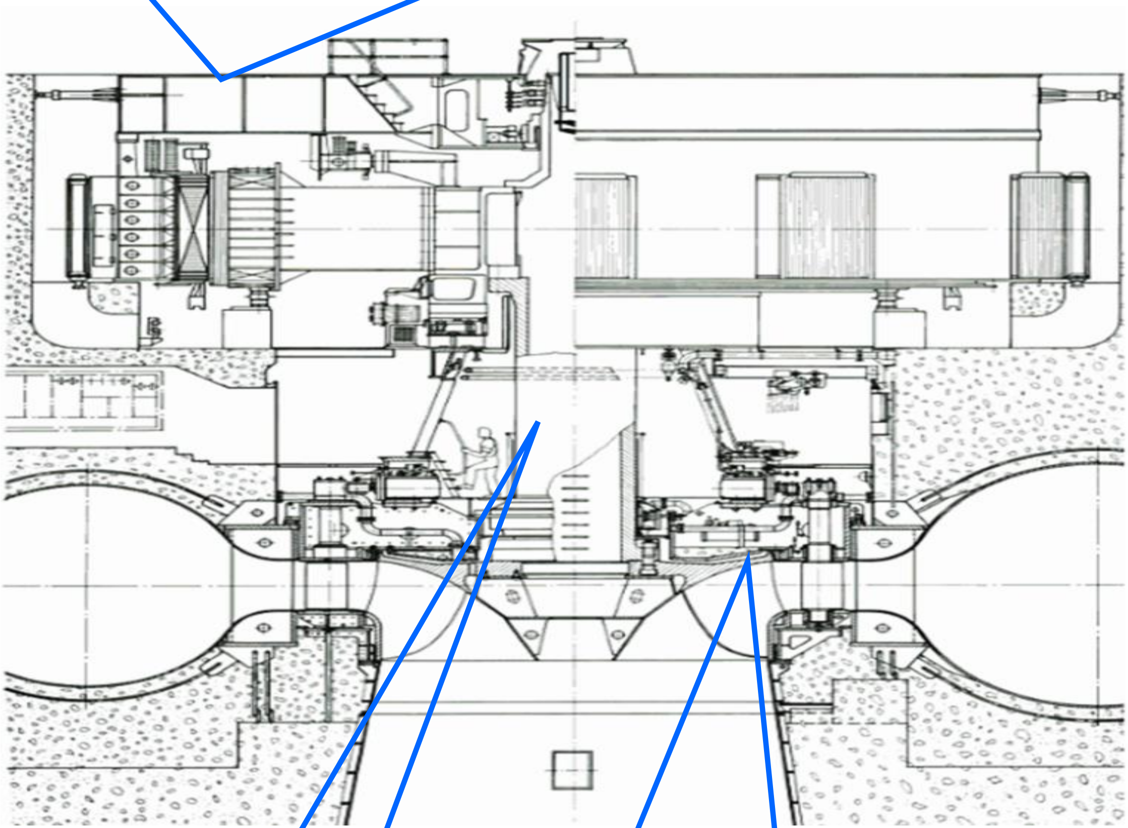
The speed was 142 rpm synchronized for a 50 Hertz (Hz) frequency power system.

RATED CAPACITY	640 MVA / 736 MVA
POWER FACTOR	0.9
RATED VOLTAGE	15.75 kV
FREQUENCY	50 Hz
SPEED/POLES	142.8 rpm/42 POLES
Close-coupled umbrella type with single guide bearing above rotor	
Direct water-cooled stator winding	
Rotating exciter with rectifier	

Unit cross section

The diagram below shows a cross section of the turbine that failed. The unit was of massive scale. The runner weighed 160 tons. And 730 megawatts of torque needed a large shaft, which was rolled out of plate or forged out of a ring.

The lowered thrust bearing wasn't connected to the concrete at all at this level, but went down to the head cover, which was bolted with a series of bolts to the 'stay ring flange'(a stationary ring).

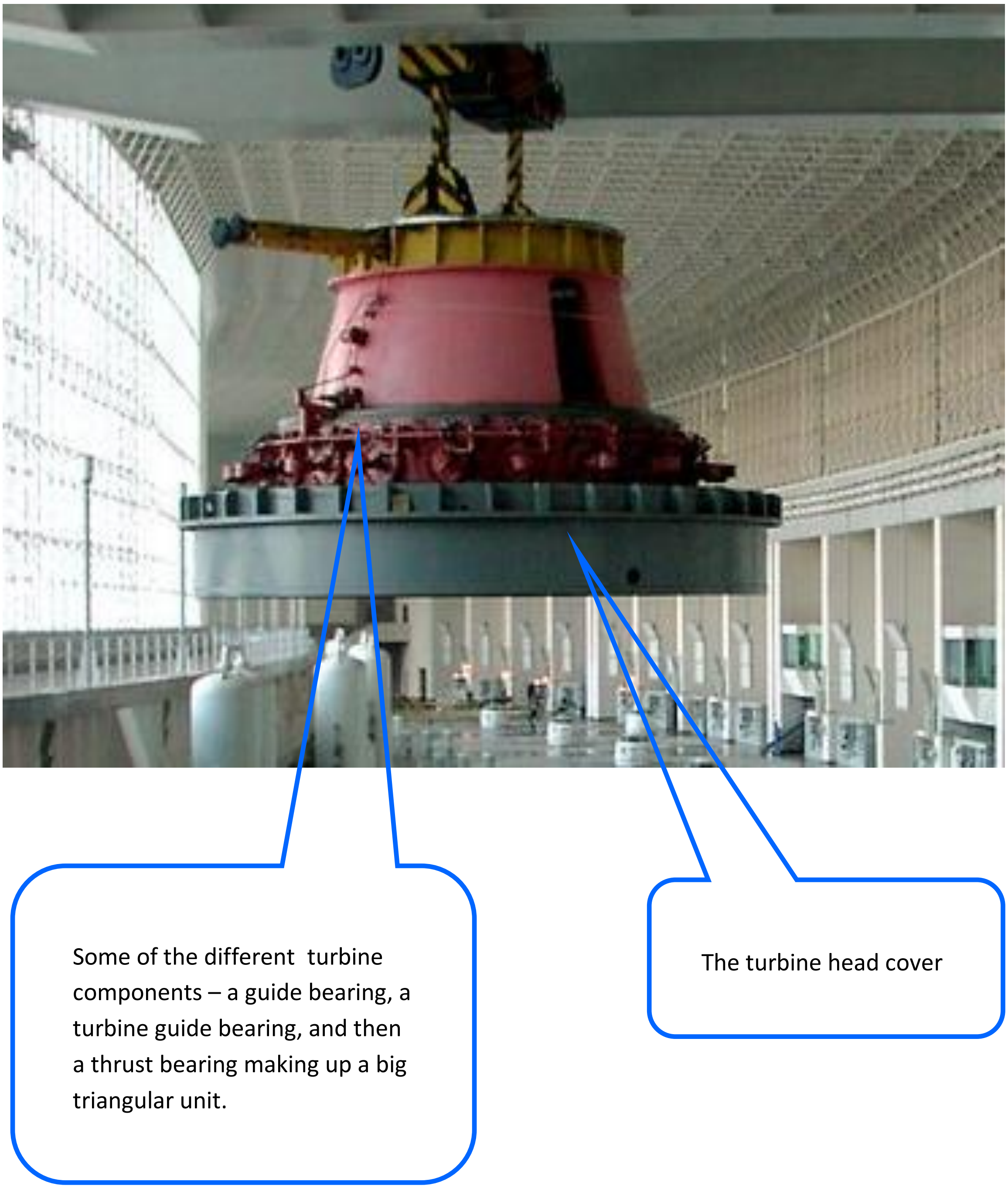


The shaft was hollow with a set of stairs inside. Note: the person shown standing is on the head cover which contains the pressure.

What is different about this machine is the thrust bearing up under the generator. A big cone carries the weight of the generator and rotating parts and puts pressure on the head cover. It uses the weight of the machine itself to counteract the hydraulic pressure underneath.

Headcover and Thrust Cone During Installation

This is the generator. The picture below shows the thrust-bearing bracket being suspended from the crane when it was being installed. (Note we will later see what it looked like after the explosion.)



MULTIPLE ISSUES AND MISTAKES (PRIOR TO THE INCIDENT)

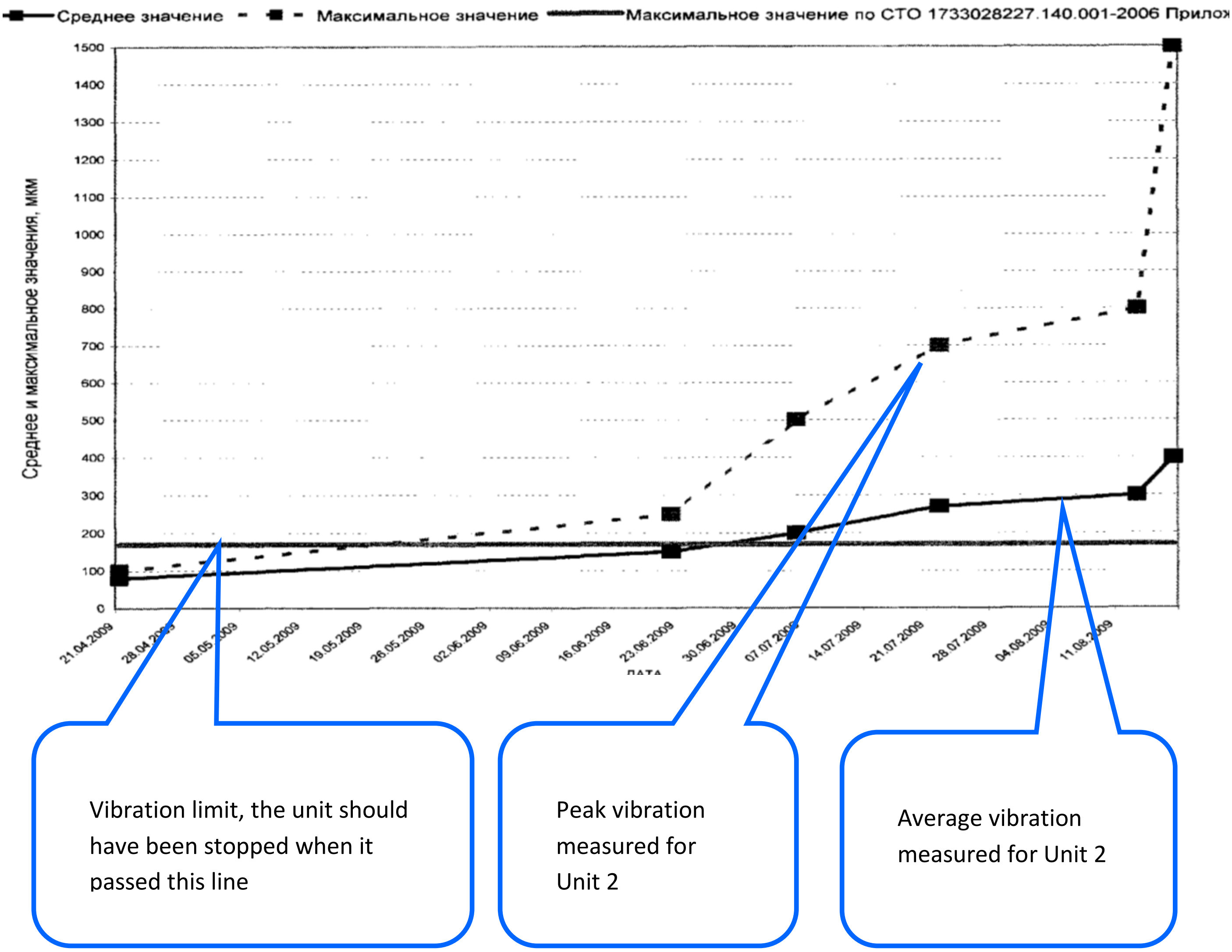
Most critical accidents that occur, don't happen because of just one thing, when you get to this level of catastrophic failure they happen because of multiple mistakes. There were multiple issues and mistakes leading up to the failure.

Increase of Unit 2 turbine bearing vibration from April 2009 to August 2009.

Although Unit 2 had been refurbished earlier in the year in April, a month after this refurbishment the unit started to show an increasing rate of vibration in the machine.

The solid line in the graph below shows the vibration limit and the unit should have been stopped when it passed this. This is at a little under 200 micrometres, which is the peak amplitude vibration.

As you can see in the graph, in August, the vibration amplitude started climbing quickly. (In fact, many of the 75 people who died were part of an engineering team investigating the increasing vibration.)



Plant Loading by unit (just prior to accident)

The table below shows the loading on each unit just seconds prior to the accident and indicates that things were going wrong.

- The amplitude of the vibration of Unit 2was at 840 micrometres. The next closest unit is at 200 micrometres, and some units were down at 50 micrometres (at really low power).
- Unit 2 was at 475 MW, yet the wicket gates which control how much water goes into the turbine were 69% open. Compare this to Unit 1, where the wicket gates were 70% open and was at 570 MW. And similarly for Unit 4 and Unit 5.

• Unit	GA -1	GA -2	GA -3	GA -4	GA -5	GA -6	GA -7	GA -8	GA -9	GA -10
MW	570	475	570	575	570	In the repair	85	585	570	100
Q, m3/s Flow	298	256	298	302,5	298		75	305	298	83
Wicket Gate %	70	69	75	71	69		12	71	71	24
R pressure MPa [MNU]25-2/63-3	In the assigned limits						In the assigned limits			
Amplitude of Turbine Guide Bearing Vibration	200	840	175	160	160		50	200	170	50
R, kgf/cm2 DT Pressure	0,5	1,2	0,6	1,2	0,1		1,1	0,5	0,6	1,1
R, kgf/cm2 Head Cover Pressure	3,2	3,5	3,6	3,3	1,1		2,0	3,5	3,1	2,3

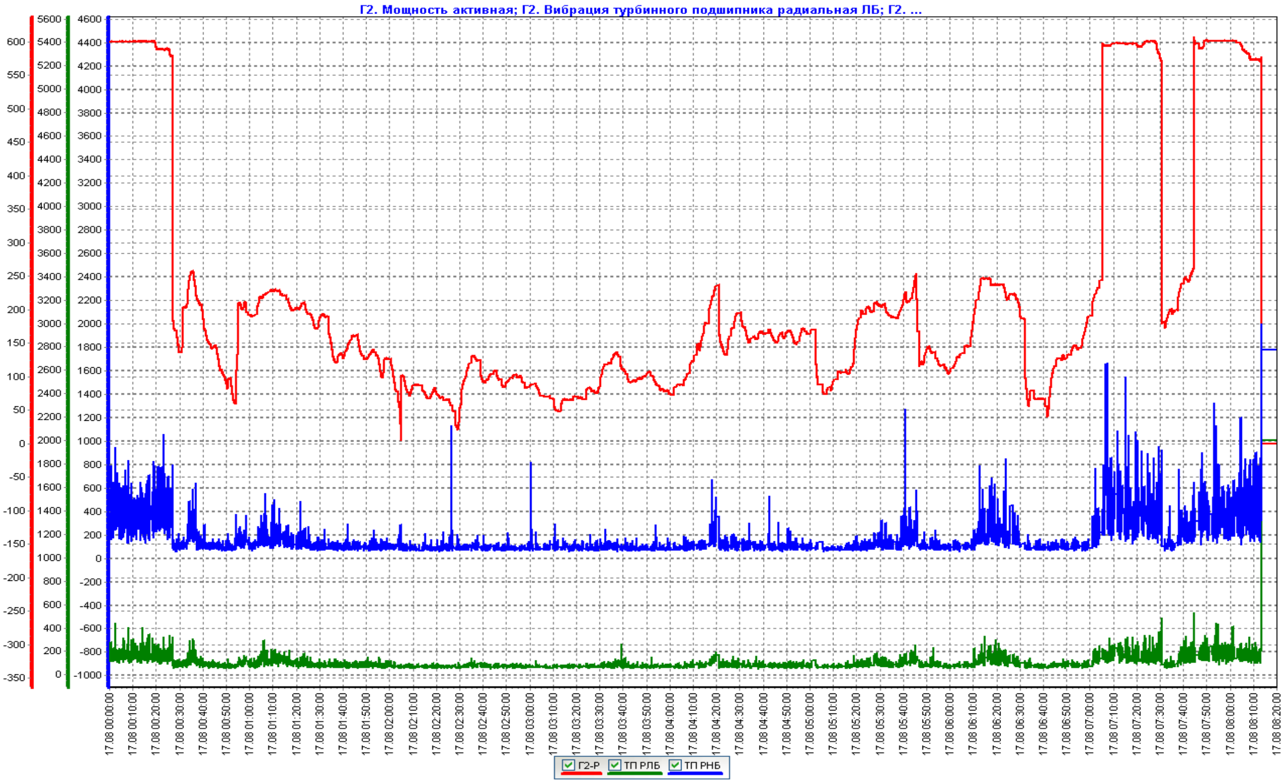
Unit 2 loading (8-hour period prior to accident)

Eight hours before the accident, there was a fire in control room at a nearby plant. And in another plant, the System Operators primarily used the automatic generation control (AGC) to raise and lower the power being generated (to maintain the frequency at 50 Hertz in the transmission system).

The System Operators selected Unit 2 as the first responding unit in AGC, the reason for this selection is not known.

With the vibration issues in Unit 2, it should have been the last responding unit. The operators should have picked a different unit. But the operators assumed that since Unit 2 had just been refurbished, it was in the best shape, and turned off the vibration alarms that were continually going off.

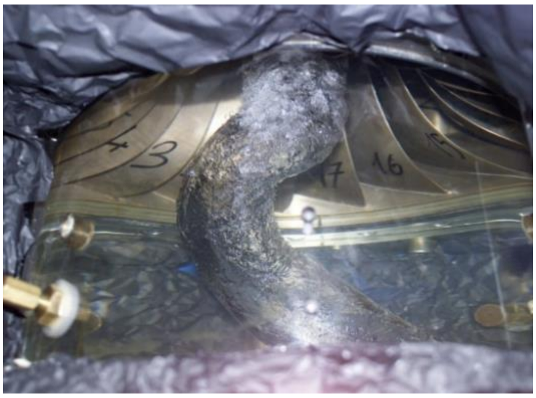
So, starting at midnight Unit 2 was operating at 600 MW, then dropped down in AGC mode to between 250 and 50 MW all night long, to a lower operating regime. For this type of turbine, it should not run all over this full range like this. It was than ramped up in the following morning to 600 MW, dropped back, came back up, and then dropped back down in the failure.



Part load Rough Zone & Low Power Operation

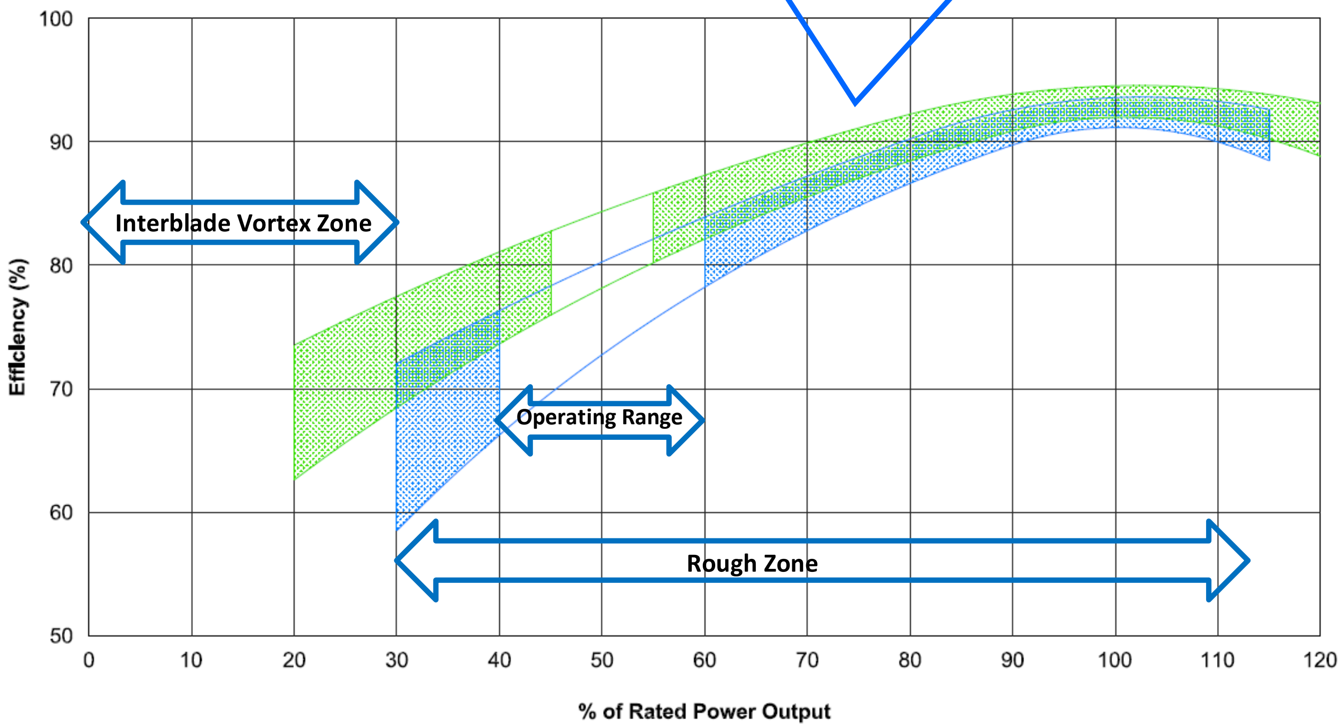
The graph below shows the operating regime for a hydro power turbine and what happens when it is run in a rough zone. The blue represents the efficiency curve of a typical Francis turbine, and the rough zone that occurs in the middle of the curve occurs between about 40 and 60% power. It's called a part-load rough zone but it's **not** a little bit rough, and it feels like an earthquake when the turbine moves through this zone! if you're in the powerhouse, every time the turbine ramps up (in this case it would've been from about 300 megawatts, to about 450 megawatts) it would go through this rough zone.

This is called a von Kármán vortex. It is essentially making all 1800 tons of rotating equipment bounce upward, inducing a vibration. Every machine goes through a rough zone. We try to go through it as fast as we can, and not too often.



von Kármán vortex – this photo is of what happens inside a turbine while it is in the rough zone

The blue shading shows the vibration on the turbine bearing and the green is the generator bearing for Unit 2.
The graph shows how the different vibration levels began to climb – and yet the System Operators kept running Unit 2 and didn't trip the machine and switch to a different one.



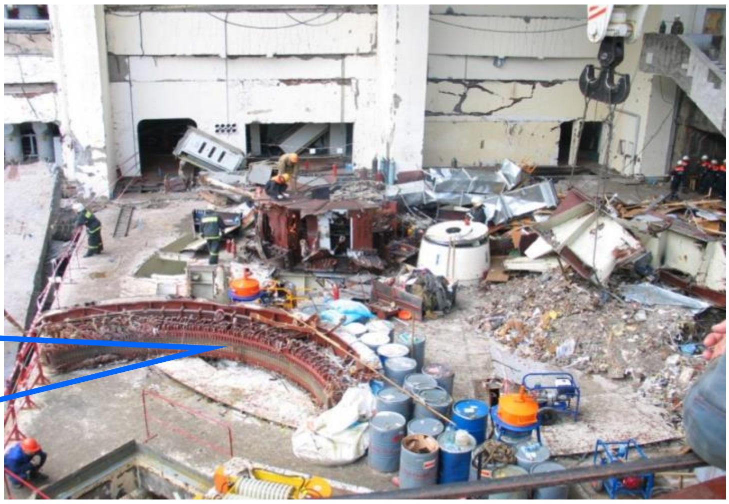
Unit 2, during the 8 hour period prior to the accident went through the rough zone four times in a one-hour period - twice up and twice down. It was also sitting down at the low power range, at below 250 MW, which isn't as bad of a vibration regime as the rough zone, but it is a very tough place to operate because of the angles of the flow that happen.

At this power range, little vortexes form between every blade and the runner as it goes by. Any inefficiency goes into destroying your machine! Running down at 200 MW, the efficiencies were down at 50 to 60%, so running at 200 megawatts and at 50%, 100 megawatts then goes into destructive inefficiency. They were running at this level continuously, all night long.

DAMAGED UNITS

What happened to each of the units?

Unit 1 ended up with lots of the different parts of Unit 2 sitting on top of it, but it was not terribly damaged.



In **Unit 2** you can see the damage to the cone (that we previously saw hanging from the crane.

Also, the arms of the generators were ripped right off - in the direction of motion.

Note the rotor rim and the stator of the generator have gone (500 tons of steel and copper). All you can see is some foundation pedestals of where it used to sit.

The cover of **Unit 3** was ripped off, and parts of Unit 2 and the crane landed on it.

Unit 4 and **5** weren't too badly damaged.

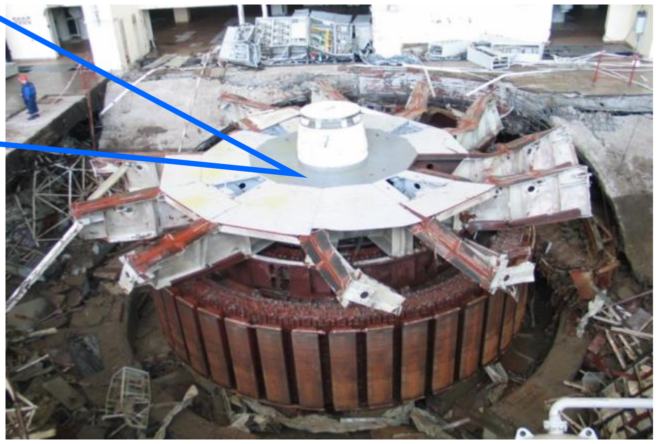
Unit 6 was shut down for maintenance at the time of the failure.

They were able to get it up and running about three months after the failure.

Unit 7 had a lot of damage.

The bearings and the stator were completely gone (note the arms and the torsional pattern that it came off in) with the bracket sitting on top of the stator.

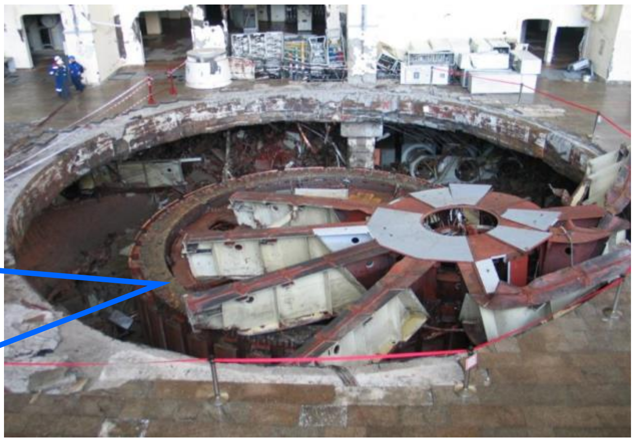
The other interesting thing is that all the copper was gone from the rotor poles.



Unit 8 looked OK.

In **Unit 9** the stub shaft was completely gone, and the upper bearing bracket completely shifted off.

And again, the stator was completely gone, and the copper gone on the rotor poles.



Unit 10 looks ok.

OTHER DAMAGE

The transformer area and the area between the powerhouse and the dam.

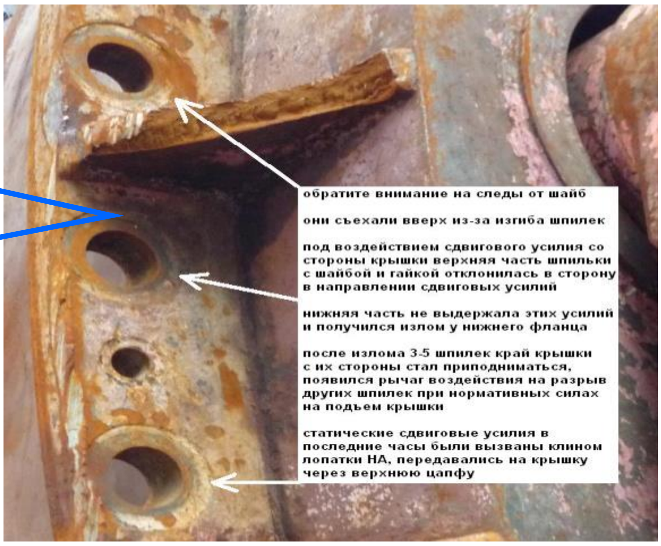
This is where a lot of the shorting out probably occurred (when the water started to shoot out through the roof).

Parts of the tail race deck.

The head cover, note the damage to the wicket gate stems (which control the flow of water into the turbine). The stems of the wicket gate shafts, which were about 25 or 30 centimetres in diameter, were completely sheared off inside the upper head cover piece. Most probably as a result of the torsional failure on the wicket gates.

You can also see the head cover flange that failed. This had been bolted down to where that thrust cone connects on to the concrete section of this flange.

Another view of the damaged wicket gate and sheared off steel (from the other side). Note the sheared off pins.



The wicket gate torn in half. This is the bottom half of the wicket gate. The top half is still in the head cover.

A collection of bolts - that were the main cause of the failure.

The flange embedded in the concrete.

If you look closely, you'll see the sheared bolts still in the holes.

There were six studs that didn't fail and weren't even damaged, which shouldn't even be possible!

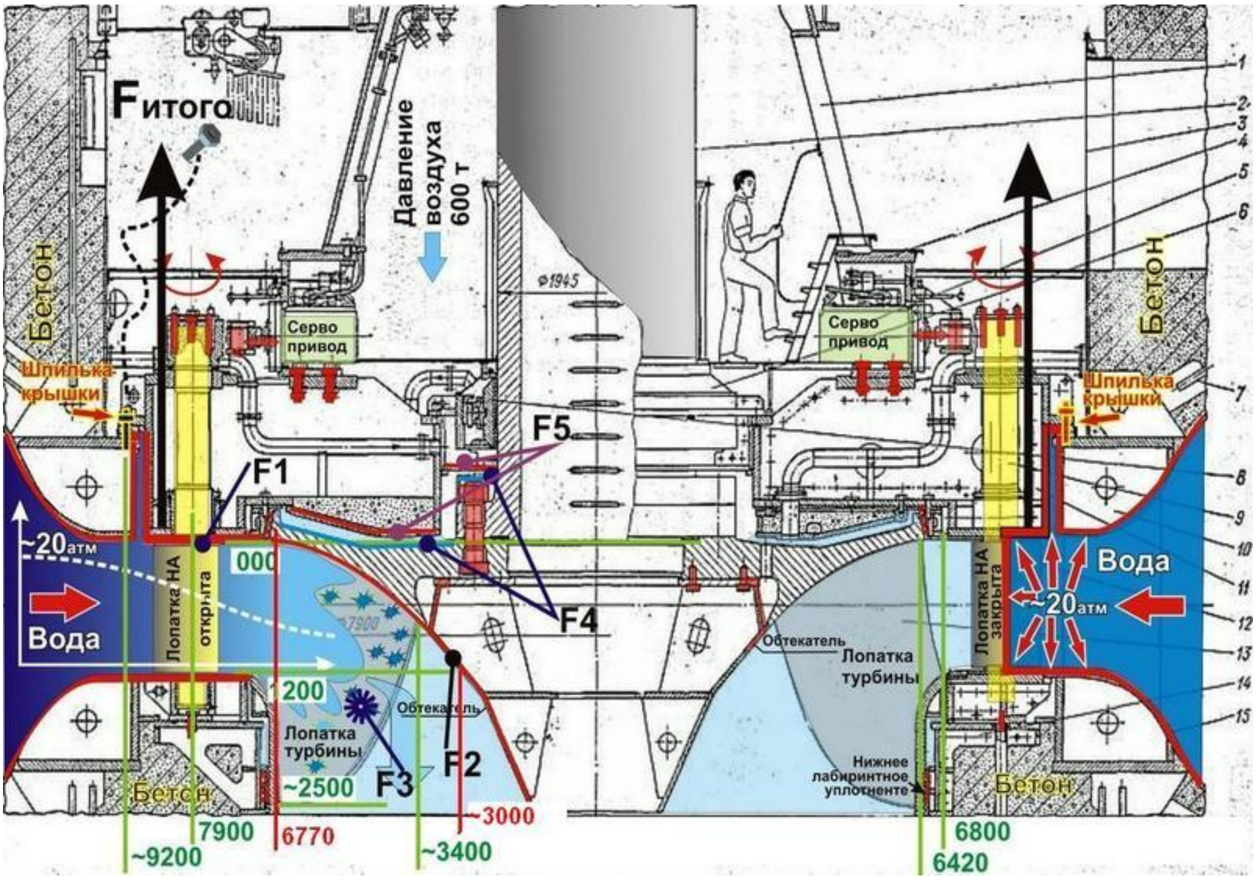
The stator core windings of Unit 7.

.

3: SEARCHING FOR THE CAUSE

The wicket gate pieces (yellow in the diagram below) control the flow of the water in and out of the turbine. Even with the wicket gates closed the pressure outside the wicket gate's 8.4m diameter outer circle, creates an uplift force of about 1,600 ton on the head cover.

The head cover (F1 to the left in the diagram below), was subject to high pressure from the upper reservoir at 230 metres of water pressure. At a rated 200m head, the uplift force on the 9m diameter head cover in the area outside the entrance of the 6.25m runner could be up to 6,500 ton. The head cover flange, and the flange bolts held it down.



The turbine is 6.2 metres in diameter. It can produce a down thrust of 6,500 tons on that head cover if it wasn't counteracted and the seals weren't working right. With the wicket gates closed, it still has 1600 tons of thrust on it. And the bolt circle is 8.4 meters in diameter.

The 900-ton rotor weighs as much as 4 large locomotives. The dead weight of rotating parts on the head cover mounted thrust bearing about 1800 tons (shaft, runner, thrust bearing and cone, head cover).

A unit spins at 142.8 rpm. This isn't so fast, but the large radius gives increased velocity and power - for a rotor peripheral speed of 93 m/s, this is **equivalent to 209 mph (350 kph).**

FUNDAMENTAL ROOT CAUSE

The fundamental root cause was the fatigue failure of the head cover bolts.

- Prior to the event it was reported that Unit 2 had an unusual vibration.
- Unit 2 was operating in the rough zone and the vibration levels continued to increase.
- Of the 80 head cover bolts, 41 had fatigue fracture.
- The threads on 6 of the 80 bolts were found to have no damage –there were no nuts on them.

While there is no doubt that the failure was fundamentally a fatigue failure of these stationary bolts, there remains the question ‘what was the triggering event’?

Unit 2 shouldn't have failed. In spite of the fatigue failure of the bolts, there was still a lot of strength in them. And there is not normally a catastrophic failure like this, particularly when there are 80 bolts in a circle. To fail in shear is very strange, all things considered.

Example of a fatigued headcover fastening stud.

Рис.4

There are a range of hypothesis.

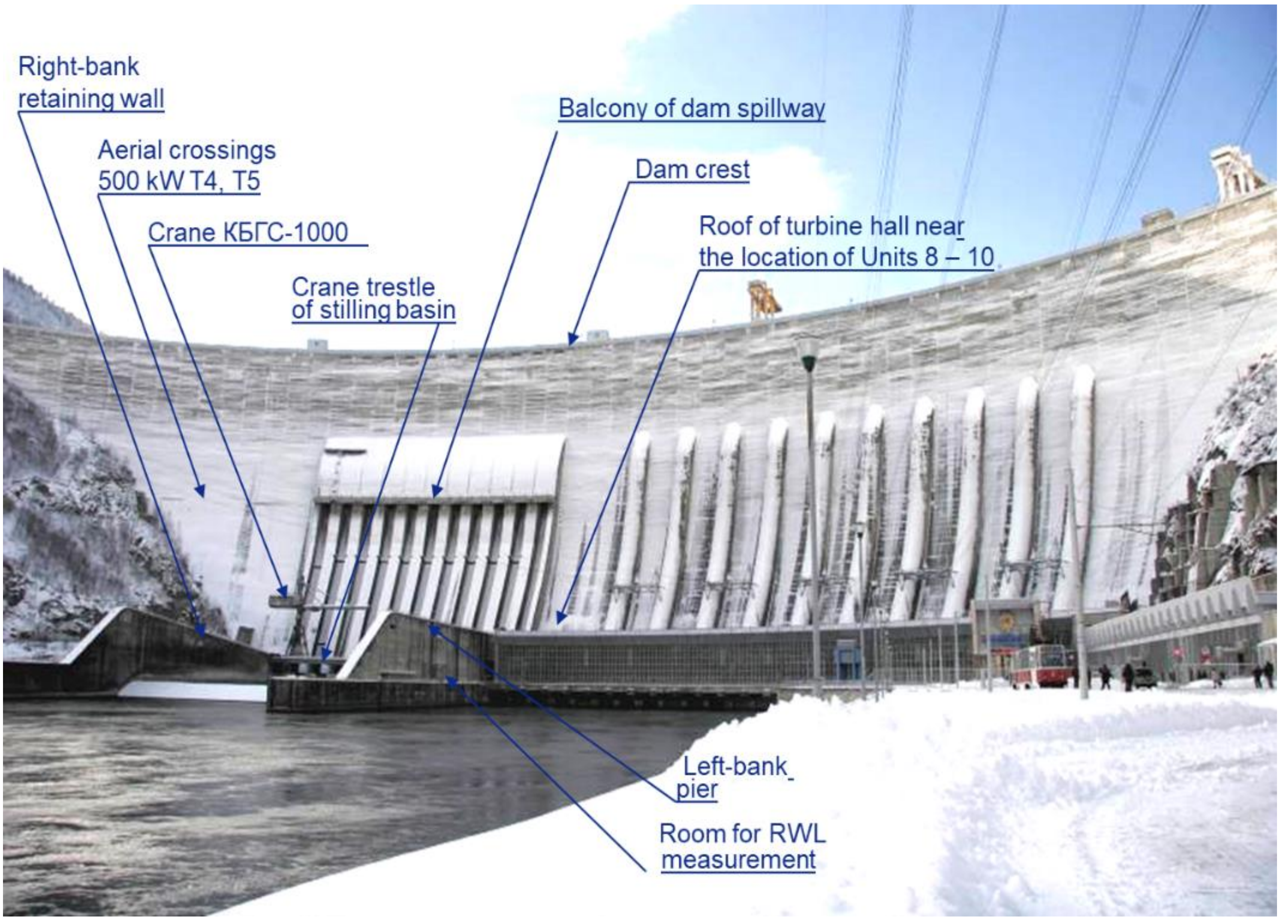
1. **Hydro-mechanical cause hypothesis.** One of the things that happens when you trip a turbine off, if you don't have a catastrophic failure, is the wicket gates are closed. Typically, it takes about 10 or 15 seconds to close off the flow. The water tries to separate underneath the turbine as it's going out the draft tube. This could have created:
   - water hammer from penstock
   - reverse water hammer from draft tube.
2. **Electrical cause hypothesis.** The other event that could have caused the failure it is a short circuit event in the generator or the transformer or stator.
3. **Electrical-mechanical combined hypothesis.** The third possibility is a combined event that could have happened in the generator. Once you synchronise the generator, its motor acts a giant electrical magnetic bearing, and tries to centre the stator and rotor inside the electrical centre of the stator. And so, the machine can move from a mechanical centre to an electrical centre. And if it had tripped off for any reason, and the grid load dropped suddenly, the air gap can suddenly become unstable. Then the machine wants to go to mechanical centre - and the rotor is pulled into the stator and there can be a small ‘kiss rub’ between the rotor and the stator of the generator.

CONSEQUENCES – UNINTENDED PROBLEMS

After the failure, there wasn't even power to open the spillway gates . And with most of the power plant offline for about seven years, and during the time the dam was offline, they had to release the water coming down through the dam.

The dam being located in the cold conditions of Siberia, meant there was a constant battle during winter to stop the freezing on the spillway.

Below is a picture of the dam, with the spillway shoots on the left.



At these temperatures it was a battle to minimize the icing and keep the spillway open. Also the air intakes needed heating, as they kept freezing, and air is a crucial to any water flow.

There was a lot of routing to do everyday (and damage occurring from the icing and anti-icing agents used).

Measures on safe operation of the spillway in Winter 2012

Overall, spillway operation was limited to a maximum discharge of 1200 m3/s:

- to ensure the reservoir drawdown
- to minimise icing of both the structures and gates
- to exclude cavitation of water discharge and minimise load on the stilling basin.

Other measures included the following.

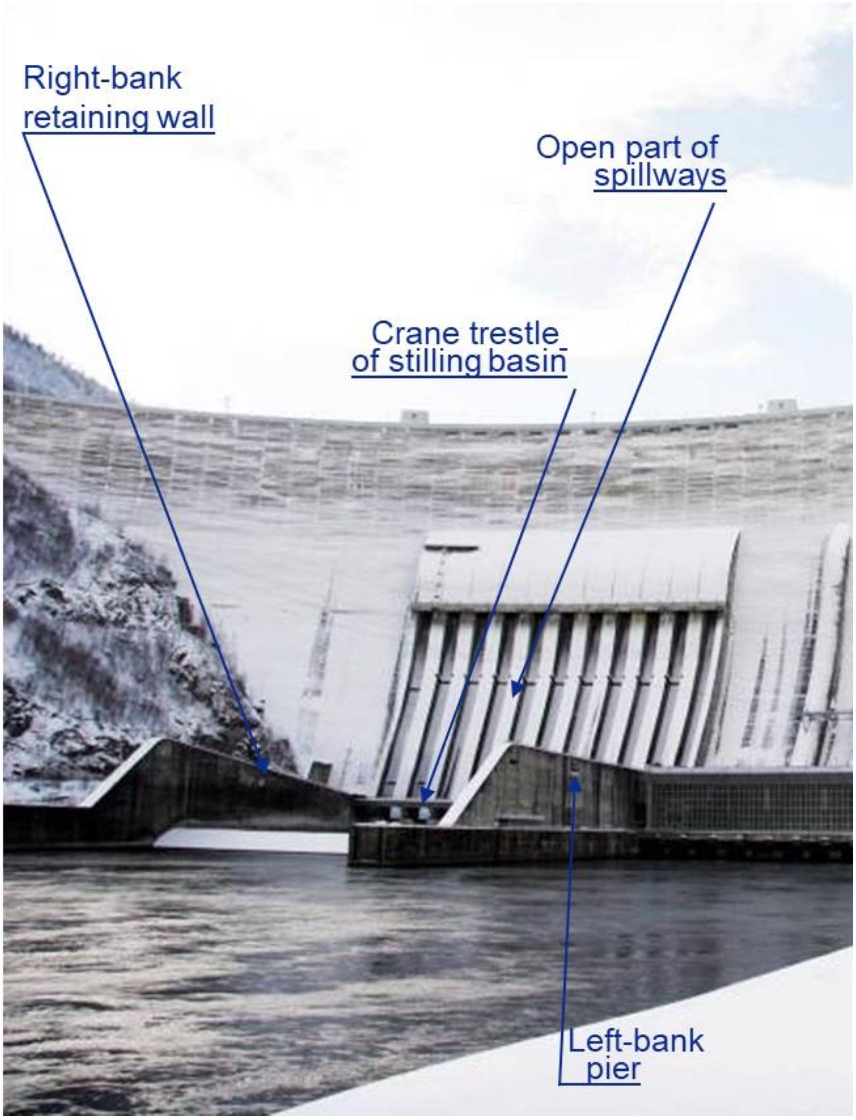
- Air Intakes were covered by heat insulation screens.
- Grouting of visible leakage points on the spillway were fulfilled.
- The surfaces suffered from icing were regularly cleaned by anti-icing reagent.
- The powerhouse cover, water-intake cones and spouting chute were heated.
- Everyday cleaning of formed snow and ice was carried out.
- The powerhouse and structures within the ice formation zone were monitored every day.

Main zones of ice build up

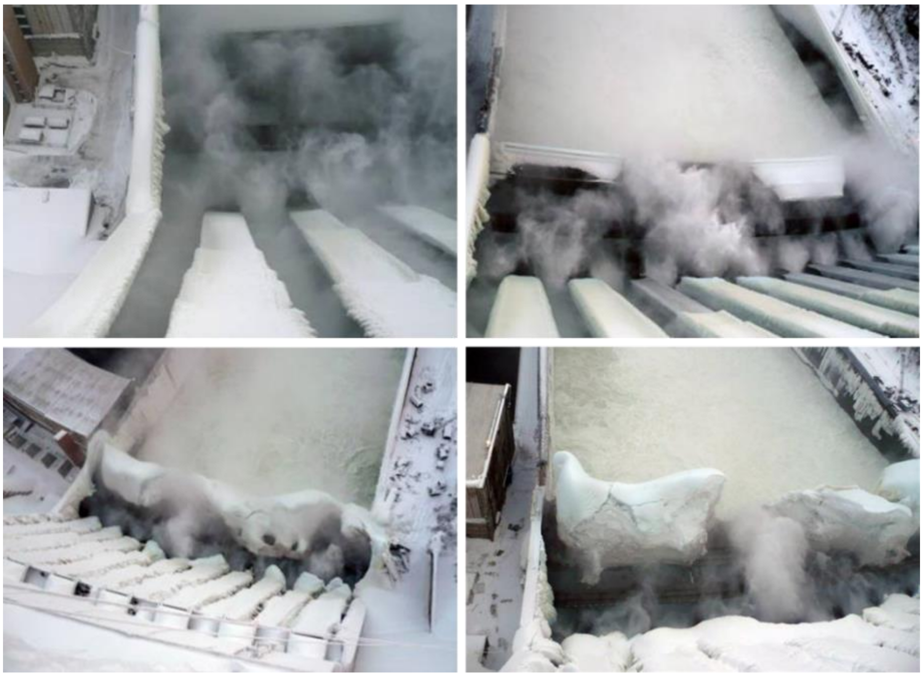
During dam operation the main zones of ice formation were identified as:

- open part of spillways
- crane trestle of Stilling Basin
- the left-bank pier
- the right-bank pier.

Following are some pictures showing the issues occurring due to ice build up.



Crane trestle of Stilling Basin.



Controlling the ice build-up by using pneumatic jacks.

4: LESSONS TO BE LEARNT

Lessons from the failure at the Sayano – Shushenskaya plant have influenced the design, maintenance, operation and safety approach to hydropower plants across the world. Lessons are summarised into the following points.

Listen and feel your units

- If something changes in the way a unit is performing, investigate it immediately. For example, if you can feel the powerhouse vibrating differently, or if there is suddenly a different noise, call the control room and 'ask what's changed'?
- When vibration or noise doubles, the rule of thumb is to shut it down until you know what's going on (unless you know why).

Stationary Parts ARE subject to fatigue

A lot of the Sayano-Shushenskaya fatigue design used in the hydropower turbines ignored the stationary bolts and anchor bolts. No one was checking them.

After the event, there was a worldwide callout to check head cover bolts. Many projects found major fatigue cracks in their stationary bolts.

In addition, it came to light that larger bolts have a tendency to become loose (as the number of threads per millimetre are not that much and it doesn't take much of a rotation for them to lose their bolt stretch).

The unit is ONE integral machine (turbine and generator). Do not separate it into two.

A unit is not just a turbine or a generator but one machine. You must understand how it works and how the bearings work.

At the Sayano–Shushenskaya plant, the thrust bearing configuration used was sitting on the turbine, which was not very common. And it was not fully understood that all the loads from the vibration that were going to those bolts.

Know your operating limits

Know your unit operating limits, and that when you change how you operate (for example using AGC mode, with low power operating and high ramp rates) there is a consequence (energy is neither created or destroyed).

- Only equipment designed to bear dynamic loads (i.e. loads from mechanical and electrical frequent start-ups and stops, a number of transitions through the non-recommended zone of the turbine operation, and so on) should be used in this regime. Unit 2's operating limits were violated over a few days, in terms of the number of hours spent in the rough zone and the number of stack ramp ups and ramp downs.

- The Original Equipment Manufacturer (OEM) and designers of equipment should define limits for its use and define supplementary requirements to its Operations and Maintenance (O&M).
- Operate the best performing unit, **not** the worst (which was unit 2 in this disaster).

Take into account water retaining structures and dam safety

Operation spillways should take into account the possibility of long-time continued usage from plant outage, including winter operation. For example, the addition of an Overflow Emergency spillway.

Automatic, protective and control systems must be well designed

- In the design of control and protection system, consider **extreme** events. In this situation, once they lost power, they couldn't do anything about it. Not only couldn't the turbines be shut, but they also couldn't close the emergency devices off. They couldn't even handle the normal shutdown sequences.
- Intake gates must be capable of closure against full flow. **They should be considered as part of the safety of the dam.** And they need to be tested and inspected. RUShydro has now implemented a two-minute closure time system wide.
- Backup power systems above flood levels should be provided for in the intake and spillway. The spillway designs need to consider that the entire plant can go down for long durations and also be able to be put into full time, operational use 24/7, for years on end. One of the things that they've changed at Sayano, is adding a massive overflow spillway at the top of the dam that doesn't require gates in order to get the flow down and around. They've also added a second spillway.

Minimise the number of people at the lower elevations

Minimise the number of people working at the lower elevations of a plant.

In the plant disaster, 75 people were in the lower elevations. This was at a time when no units were really torn down or in major outage. (Unit 6 was shut down, but there wasn't much work on it that day.)

Operators must be trained on emergency response

Operators must be trained to be able to respond to emergency situations.

5: QUESTIONS AND ANSWERS

Don Erpenbeck concluded the webinar with the following question and answer session.

Was there a working high-pressure jacking system on the thrust bearing for unit start and stop, prior to the event?

It is assumed that units of this size normally have a high-pressure lift system just to do spinning and rotation for normal maintenance.

What is AGC mode?

AGC mode is automation generator control mode. It is a mode of frequency control that you put a unit in so that it automatically ramps the MW up and down to keep the power grid in perfect balance. It is based on real-time supply and demand, and the system has about one to two seconds to make corrections, to keep the system running at 50 Hz frequency. If the frequency deviates, which happens at about half a Hz, the breakers of the system will begin tripping. So at about 50.5 Hertz and 49.5 Hertz, the rest of the system will begin to disconnect from the grid to protect itself.

Hydropower machines are the best machines for running in AGC mode as it follows the load and tries to maintain 50 Hertz. And if the frequency begins to go up or down, it adjusts the power output either up or down to match.

Why did the penstock head gate not automatically trip?

Power was lost to the head gate, and it wasn't set up to automatically trip in the event of a failure. There was a push-button closure option from the control room, but they lost power and weren't able to implement it (with no power). The battery room was completely flooded and there was no supervisory control or power. Even to lower the wicket gates needed dedicated hydraulic cylinders.

Was the two-minute close time on the intake gates based on all that the intake gates can handle when closing under full flow or was a full redesign required for the gates?

Two minutes is fast for gates of this size and this type of flow and head.

We normally tell turbine designers that they're supposed to design for up to 30 minutes of these types of high-speed events. And a normal closure is about a metre per minute. So at 10 metres you'd be looking at 10 minutes to close an intake gate like this. We might close it a little bit faster and do more, but these are massive amounts of force and you've got to be careful how fast you stop it. It also needs to link with the turbine design and the turbine has to be able to take that speed for a certain amount of time.

So many failure investigations show the operating team silencing alarms as part of the cause. Operators deal with nuisance alarms daily, which creates a habit of silencing these, which one can imagine can be very annoying. These false alarms should be minimised to prevent this. Have you an opinion on this?

This situation was more than just turning off the alarm. I've been in powerhouses in a unit that's vibrating like this, and you can feel it in the parking lot - which the Russians talked about. Every time it started and stopped it went through the rough zone.

They should have shut unit 2 down, not run it with this type of vibration. And probably months before that, they should have put it in only very limited operation and run it at best efficiency point - where there's almost no destructive power and it's well balanced and no vibration. Because there are points that you can run these machines and they don't really vibrate at all.

What destroyed unit 7 and 9 ? Was it just from the runaway or a delay in closing the water flow?

We believe it was a short-circuit event in the generator and it torqued right off. Just after the explosion, fountains of water can be seen pouring from the facility. There appears to be electrical flashes silhouetted in the windows. The blast killed 12 people and more than 60 are still missing.

The first report actually showed that it was a transformer failure that started this, which is possible. If it started in the generator, they had a transformer failure or some type of major trip out like we said. That combined theory would explain what could have happened. But there's no doubt the bolts were already weakened and were ready to fail.

Are there any safeguards that need to be put in place to protect workers from such events as this, outside of design considerations? Should it be covered at emergency management plans or something else?

A safety lesson for our internal team is, unless you belong in the lower elevations in a power plant like this 6,500 MW one, and unless you're a competent person, don’t go there. And the 75 people who died included many people who didn't need to be down at those lower elevations.

And another lesson it to make sure the control rooms are up high and machines such as generators are above water level.

What is a recommended frequency of checking head cover bolts for integrity after this event?

I would say five-year annuals, with some spot checks in between for regular things such as head cover bolts.

If it’s a head cover mountain or a thrust bearing, it should probably be annually.

It's pretty easy to do a UT shot down the bolts which will tell you quickly if there is an issue. Or even tapping bolts with a hammer helps to find cracks sometimes.

What happened to the copper? I think you said your presentation, it was all gone. Any ideas?

Because of the over-speed event and short circuiting, the copper came off the end of the rotor. The rotating parts of the rotor just ripped the stator and the foundation. The bearings twisted off and the stator just went.

We did a calculation on the torques and found there could have been a 400-ton force on each of the 12 plates in a short-circuit event.

This is a big number, and most people don't realize all the forces can transfer in that air gap. You don't need physical contact. The electromagnetic forces that happen in the air gap are tremendous.

One of the things that happened was the battery room was flooded, forcing the batteries to the other side of the room, compromising the DC tripping supplies. Did they relocate the battery room in the rebuild?

I don't have any information on what they would've done, but I hope so. They relocated the things they could, and they definitely put some diesel generators on top of the dam - at a higher elevation.

What's the usual gap in meters between the rotors and the stators?

The typical air gap is between 19 millimetres and 24, 25 millimetres. For the floating rim it might be a little bit bigger, but not much. 25 millimetres is typically the largest, but it tends to be more 17, 18 millimetres. The bigger the air gap, the less efficient the generator is. So, they tend to make it smaller.

Was there an automatic intake gate trip system that just didn't work because of the lack of power. Or did they not have one?

It was initiated by command from the control room, and not set to automatically trip and close the intake gates.

Now it is set as an automatic trip closure, with two or three different sensors - where two or three of them have to trip. It's got a double redundancy on it, so that there's not an accidental trip of a head gate.

5: REFERENCES

The information presented in the following was obtained from the public domain and RUS Cold presentation. The opinions expressed today are solely those of the presenter. The information presented was obtained from the public domain and RUS Cold presentation.

Sites referred to in the presentation are:

https://www.engineeringnz.org/join-us/groups/new-zealand-hydropower-group/

https://www.sciencechannel.com/video/deadly-engineering-science/power-plant-catastrophes