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Hydrolink

SAYANO SHUSHENSKAYA 2009 ACCIDENT UPDATE

BY FRANK A. HAMILL

17 August 2019 marked the tenth anniversary of the catastrophic accident at RusHydro's Sayano-Shushenskaya Dam and power station (Figure 1). The accident destroyed or severely damaged all the hydraulic turbines contained in the large powerhouse located at the toe of the dam (Figure 2). The Project is located on the Yenisei River in the village of Cheryomushki, which is near the city of Sayanogorsk, Khakassia in southern Siberia. In the ten years since the event, numerous writers have expressed opinions as to the probable cause of the accident. The owner of the plant, RusHydro, and the national industrial safety agency, Rostekhnadzor, have both issued findings as to the probable cause. None of the official reports or findings have discussed the governor wicket gate closure time or its possible relation to the accident.

In November 2010, this writer prepared an article for the magazine International Water Power and Dam Construction in which he presented an hypothesis as to the direct cause of the accident. The hypothesis was that a very fast governor time resulted in a quite sudden wicket gate closure upon the unit shut down due to total load rejection. This caused water column separation to occur in each of the affected turbine draft tubes. When the resulting vapor cavities collapsed, there was an extremely large draft tube pressure rise in each case as the water column collided with the underside of the turbine head cover, causing it to rise several meters and destroying the turbine and generator supported by the head cover. Unit 2 failed first and showed the most extreme damage. The writer's hypothesis was based on the published data in the Rostekhnadzor report of 3 October 2009. Neither Rostekhnadzor nor RusHydro mentioned this hypothesis as a possibility. It was possible that neither operations personnel nor management were sufficiently familiar with the fluid mechanics of unsteady flow in closed conduits to entertain the idea of such a phenomenon [1].

Nothing has appeared since then to change the writer's opinion as expressed in that article.

That reinforces the lesson from this disaster that the design limitations of the plant MUST be respected. Operator training should emphasize design limitations with particular emphasis on the operation of turbine governors, and younger operators replacing retired experts should undergo a detailed examination of the behavior of the equipment under all conditions. If necessary, manage-

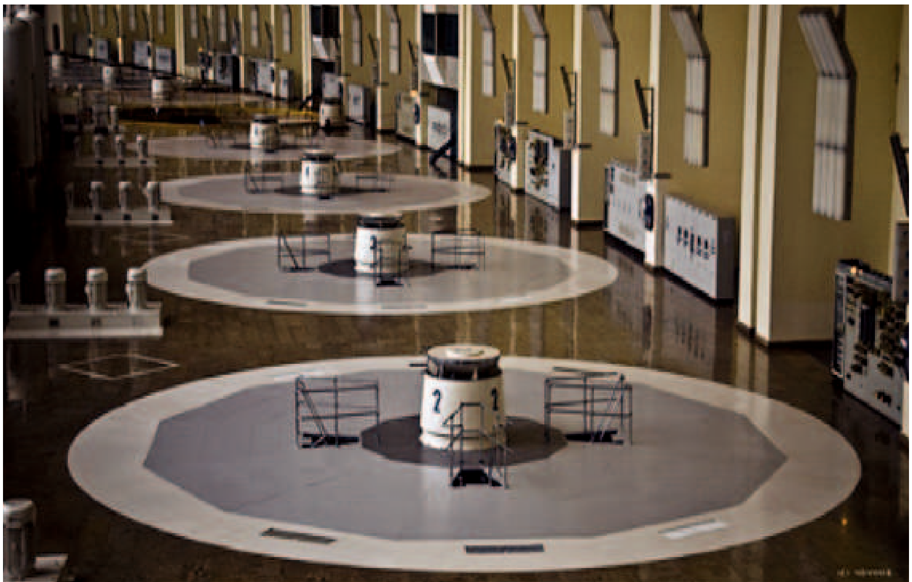


Figure 1. Sayano-Shushenskaya powerhouse machine hall operating floor prior to accident.

Figure 2. Part of the damage to the powerhouse after the 17 August 2009 accident. Unit 2 as seen on 3 September 2009 after dewatering.

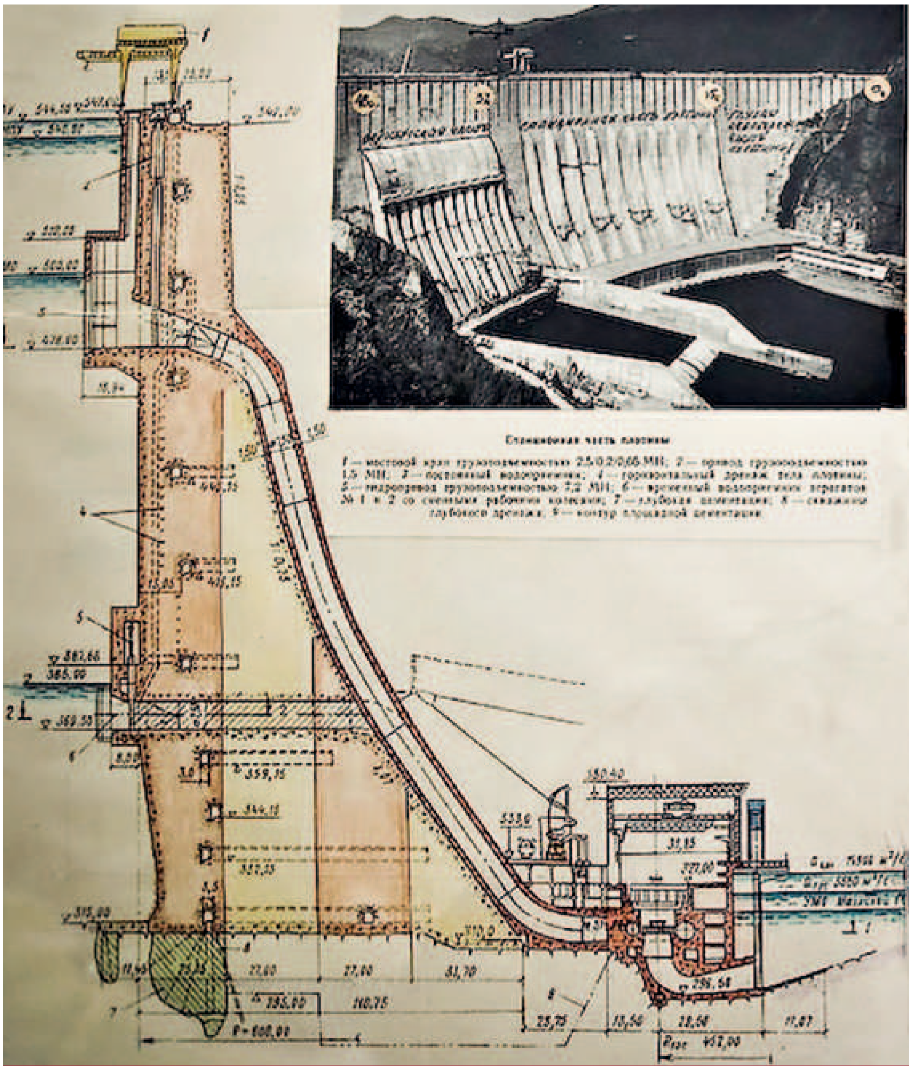


Figure 3. Cross section through dam, penstock and powerhouse.

ment personnel should also undergo detailed training. If an operator is ordered to perform unsafe actions, he or she must be permitted to refuse such an order.

Background

The Sayano Shushenskaya installation (Figure 3) was and remains the largest hydroelectric power station in the Russian Federation. It was the sixth largest in the world at the time of the accident with 6400 MW installed capacity. The powerhouse contained ten turbine generating units rated at 640 MW each. The turbines were of the Francis type (Figure 4) with a rated net head of 194 m and a rated discharge of 358.5 m^3/s. The rotational speed of each unit was 142.86 rpm [1].

The primary loads served by the Sayano Shushenskaya power station were a series of aluminum smelters located in the region of Siberia served by the regional electrical grid. This type of load is significant to the failure condition since such smelters are known to have rapid and unpredictable load changes. This is due to the loads having no significant inertia. The result is that the generating station must be able to adjust to load changes very rapidly to maintain electrical frequency stability. Sayano Shushenskaya had normally served as a base-load plant, with frequency control coming from other stations. Unfortunately, a fire at the Bratskaya station, which normally provided frequency control in the same service area, the night before the accident required that the Sayano plant shift to frequency control duties, for which it was not suited [5].

At 08:13 and 25 seconds on the morning of 17 August 2009, Unit 2 in the plant suffered a total load rejection. This was followed by a violent eruption of water in the draft tube lifting the turbine head cover, turbine runner, shaft, turbine and generator bearings upward several meters (a witness estimated three meters rise). This destroyed the generator rotor spider and permitted water to flood the turbine pit and spill out into the powerhouse operating floor (Figure 5). The sudden failure of Unit 2 was followed immediately by similar failures of Units 7 and 9. In all, nine of the ten operating units were either destroyed or severely damaged. Only Unit 6, which was out of service at the time, was spared from severe damage, although it was flooded by water from the other failed units. In all, 75 people died and 13 were injured in the power-house as a result of the flooding, which raised the event to the level of a national scale disaster.

The accident was studied by Rostekhnadzor, which issued a preliminary report on 3 October 2009. The tentative conclusion was that the studs which attach the head cover outer flange to the unit stay ring failed due to fatigue related to the observed severe vibration of Unit 2. The report did not address the failures of the other units in the station, nor did it attempt to explain the source of the very large upward force necessary to cause the damage that was observed. It was expected at the time the report was issued that it would be expanded later. In fact, the report, which included a significant amount of technical data such as turbine loads versus time for each unit leading up to the failure, was withdrawn a few months later [5].

Update post reconstruction of the station

Repairs commenced as early as November 2009. In 2010, the four least damaged units (Units 3,4,5, and 6) were put into operation on a temporary basis. In December 2011, the first new unit (Unit 1) was launched, with repairs and replacements taking place over the next three years. By the end of 2014, all 10 units were replaced with new ones and the new ones were in operation. By 2017, new control and safety equipment was installed and put in operation [3], [4], [6], [7].

Technical studies

The technical aspects of the failure were discussed by several writers since the accident, although none drew definitive conclusions.

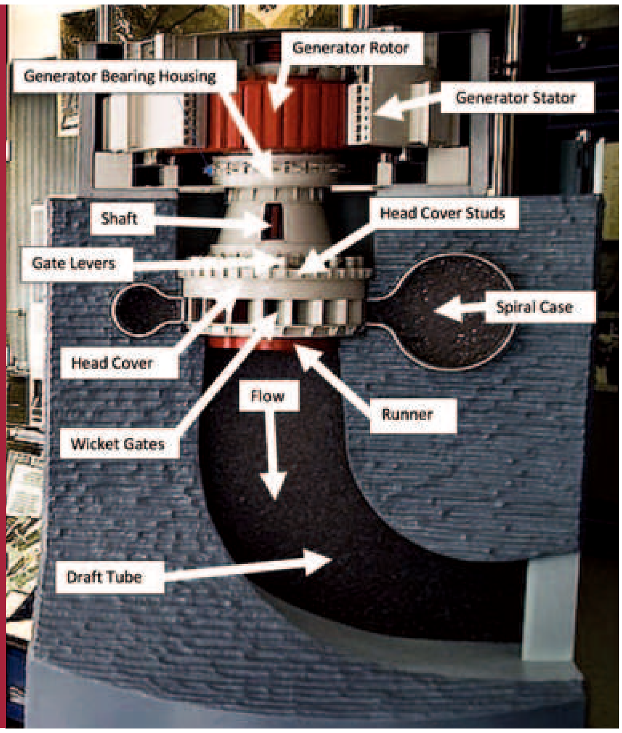
In March 2010, the magazine Hydro Review published an article that quoted Donald Erpenbeck, a vice president of MWH Americas, Inc., who agreed with the conclusion of Rostekhnadzor that fatigue failure was one of several causes of the accident. He rejected the possibility of water-hammer from a governor closure, stating that "there are other things in the system that should not have allowed the wicket gates to close that fast." He theorized that a possible generator short circuit may have been involved but did not explain the similar failures of Units 7 and 9 [2].

In an extensive article in Power Magazine dated 1 December 2010, Alexander Boyko and Sergey Popov, both relay protection engineers with EKRA-Sibir Ltd., and Nemanja Krajisnik, a power systems consultant for Siemens Transmission and Distribution Ltd. described the events that occurred immediately prior to and during the accident. They described the 1860 ton head cover being blown off leaving the Unit 2 turbine in its pit with no turbine mountings but with its wicket gate and head gate opened. The claim was made that the 212 m water head ejected the turbine rotor from the pit. This explanation is not convincing in light of the type and extent of the damage [5].

Some writers have suggested that something else other than simply the fatigue failure of the studs must have been involved in order to lift the head cover of Unit 2. An article in Engineering and Technology Magazine published on 11 July 2011 suggested that the studs connecting the head cover to the stay ring were primarily there to effect a water and air tight seal, while the main upward force that was expected during operation would be resisted by the large downward thrust caused by the weight of the generator and turbine supported by the thrust bearing, which, in turn, was supported by the head cover. The article proposed that the studs could not have been expected to resist the expected upward thrust even if they had been in pristine condition. The article also noted that the turbine, generator and thrust bearing, weighing nearly 1600t were thrust vertically several meters in the air flooding the powerhouse. The article did not speculate as to the cause of the waterhammer pressure that lifted the head cover, however [8].

An article dated 19 December 2014 in Hydro Review by Enes Zulovic of Hydro Tasmania discussed several cases where failures were experienced due to hydro knowledge transfer deficiency. This was shown to be related in part to the retirement of experienced hydro personnel leaving young engineers with fewer opportunities to gain experience. The Sayano Shushenskaya accident was an example used in Zulovic's article. Unlike many other writers, Zulovic accepted the premise that draft tube water column separation was a likely cause of the accident [12].

Figure 4. Cutaway turbine-generator model.



In May 2015 at a World Hydropower Congress held in Beijing, a group of representatives of RusHydro made a presentation which concluded that the accident was NOT caused by a shock or hit, but rather attributed the accident to the destruction of the studs due to the long term influence of high frequency vibration. This finding is very strange, given the evidence in the Rostekhnadzor report, and the failures of the other units in the station. No mention was made of the effects of a rapid governor shut down on load rejection [13].

A brief article in Tayga Info dated 22 November 2017 reported that the power station had been restored to full operation. The article referred to the Rostekhnadzor finding that the accident had been caused by destruction of the studs in the head cover but indicated that many experts believed that the conclusions were incomplete and inaccurate since a complete study of the reasons was not carried out. Moreover, the fact that the break of the head cover mounting and pushing the multi-tonne unit upwards contradicts all physical principles of operation of a hydraulic turbine [14].

The tenth anniversary of the accident gave rise to several articles about the incident. Of these, there were both technical and historical presentations [9],[10],[11],[16],[17].

In an emotionally moving article in Siberia Realities dated 16 August 2019, journalist

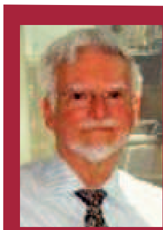
Figure 5. Unit 2 several hours after failure.

Julia Starinova interviewed several of the people who had been affected by the accident ten years previously. She reported that a number of the affected people remained quite bitter about the accident and about the reaction of the officials in the years that followed. The title of the story was a quote from journalist Mikhail Afanasyev, who in 2009 was charged with libel by the local prosecutor for his coverage of the story: "The true culprits will never be punished." In general, the technical claims of the officials were not believed by the people who were there [15].

A more technical evaluation of the failure was discussed by power engineer Gannady Rassokhin in a brief article in the Russian website ProAtom dated 16 August 2019 recognizing the tenth anniversary of the accident. He looked at the plots of pressure in the spiral case and in the draft tube at the time of the accident. His conclusion was a rather complex event involving flow around the rotor rim deflecting flow into the station's engine room. Although this analysis appears to be closer to the true conditions, it still fails to define the source of the enormous upward thrust that caused the massive rotating turbine to be projected several meters into the air. The large cover of the generator air housing was observed by a witness to have been blown up to the roof by the water column (geyser). The roof was blown off the building by the event [18].

Legal investigations and findings

Legal investigations into the causes of the accident were started as early as October 2009, when the regional Investigative Committee at the Prosecutor's Office for the Republic of Khakassia opened a criminal case under a provision of the Criminal Code of the Russian Federation that governed labor protection rules. This was quickly transferred to the Main Investigative Department of the Investigative Committee under the Prosecutor's Office of the Russian Federation. The investigation centered on the increase in the amplitude of vibration of the turbine bearing supported on the head cover of Unit 2. This was reported to be a significant factor in the hours immediately preceding the failure. The conclusion was that the studs holding the head cover to the stay ring failed due to fatigue caused by the serious vibration. In June 2013 the Main Investigative Department completed an investigation into the criminal case of the accident. As a result, seven managers and engineering workers of the station were tried at the Sayanogorsk City Court of the Republic of Khakassia. A verdict was reached on 24 December 2014. The director of the station and the chief engineer were both sentenced to six years in prison. Two deputy directors were sentenced to over five years imprisonment each. Employees responsible for monitoring equipment in the station were given 4.5 years probation. Another employee was sentenced to 4.5 years but was released under an amnesty [19]. Apparently, none of the legal investigations fully evaluated to the technical aspects of the incident. Both the failures of the other units (particularly Units 7 and 9) and the unexplained source of the very large upward force that was necessary to cause the type of failure that occurred were not pursued by the courts.



Frank Hamill has worked 50 years for Bechtel Corporation as technical advisor, project manager and project engineer for concept planning and design of water supply and hydroelectric projects, powerhouses, dams, tunnels, penstocks, canals, large diameter pipelines and pumping stations. Expertise in site evaluation, project concept development, feasibility studies, licensing, economic analysis, planning, hydraulic analysis and design of dams, hydroelectric facilities, and pumping stations. He has been recognized as Bechtel Distinguished Engineer.

Tentative conclusions remain unchanged

In reviewing these articles and several other short pieces recognizing the tenth anniversary of the accident, this writer has not found any reference to the original or to the present-day turbine governor settings. Of particular interest would have been the wicket gate closure time when the governor was saturated due to a full load rejection. There was also no reference to the extent, if any, of a "cushion stroke" in the final stage of gate closure between the speed-no-load setting and fully closed. Such cushion stroke settings are slowed-down gate movements usually used to prevent extreme waterhammer pressure changes in the zone where flow rate changes very rapidly in response to relatively small gate position changes. Since this normally applies only in the zone where there is no load on the machine (near shut-down), it does not affect the machine's response to load changes. Thus, the governor may have had two speeds: a fast one for load changes, and a slow one for the last stage of shut down. The fast speed is the one of significance to this event, and the record seems not to indicate what it was.

A very significant point was made in the March 2010 Hydro Review article, wherein the author indicated that "There are other things in the system that should not have allowed the wicket gates to close that fast." If these "other things" had been adjusted to permit faster responses to load changes, this could have caused the accident. This had been the tentative conclusion reached in this writer's December 2010 article in International Water Power and Dam Construction. As mentioned above, nothing in the literature since the 2010 article has surfaced to cause a change in this conclusion [1], [2].

This issue remains very important for designers, builders, operators, and owners. The physical limitations of any hydro power installation cannot be ignored regardless of the short-term economic benefits that may be expected by managers or operators who may be unfamiliar with the fluid mechanics of unsteady flow in closed conduits. There may be an opportunity to start a conversation among interested technical personnel on this vital issue. It is hoped that this can make the issue more transparent to the industry. ■

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