MARSHFIELD STATION REHABILITATION

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ABSTRACT

The focus of this Technical Paper will be to describe the mechanical overhaul and the subsequent troubleshooting of a vertical Francis turbine and its ancillary mechanical components at the Marshfield No. 6 Hydroelectric Station. Not only will this paper describe the mechanical overhaul's fast track progression and lessons learned concerning post-rehabilitation vibration and bearing challenges, but it will also describe an innovative turbine bypass designed to manage the station's discharge requirements during project delays.

INTRODUCTION

Green Mountain Power's 350 ft. head Marshfield Station, located on Molly's Brook in Marshfield, Vermont, has a single 8,300 ft long wood stave and steel penstock leading to a single 1977 rehabilitated 5 Mw vertical Francis turbine. Since the unmanned powerhouse, shown below, encloses only this single unit the turbine's operation is critical for headpond control and station generation especially considering that discharge of flows over the spillway during very cold weather could and occasionally has caused ice jams in the stream just below the spillway.

In June of 2003 the single Francis turbine (see Figure 1) tripped offline due to a vibration level fault detection. The station operator reset the unit and attempted to bring it back online. However, as the unit approached speed no load, the operator again observed extreme turbine vibration just prior to the vibration switch tripping the unit again. The obviously substandard conditions prompted a forensic investigation which placed the station temporarily out of commission unit the root cause was determined and a remedial procedure enacted.

PHOTO 1 MARSHFIELD STATION

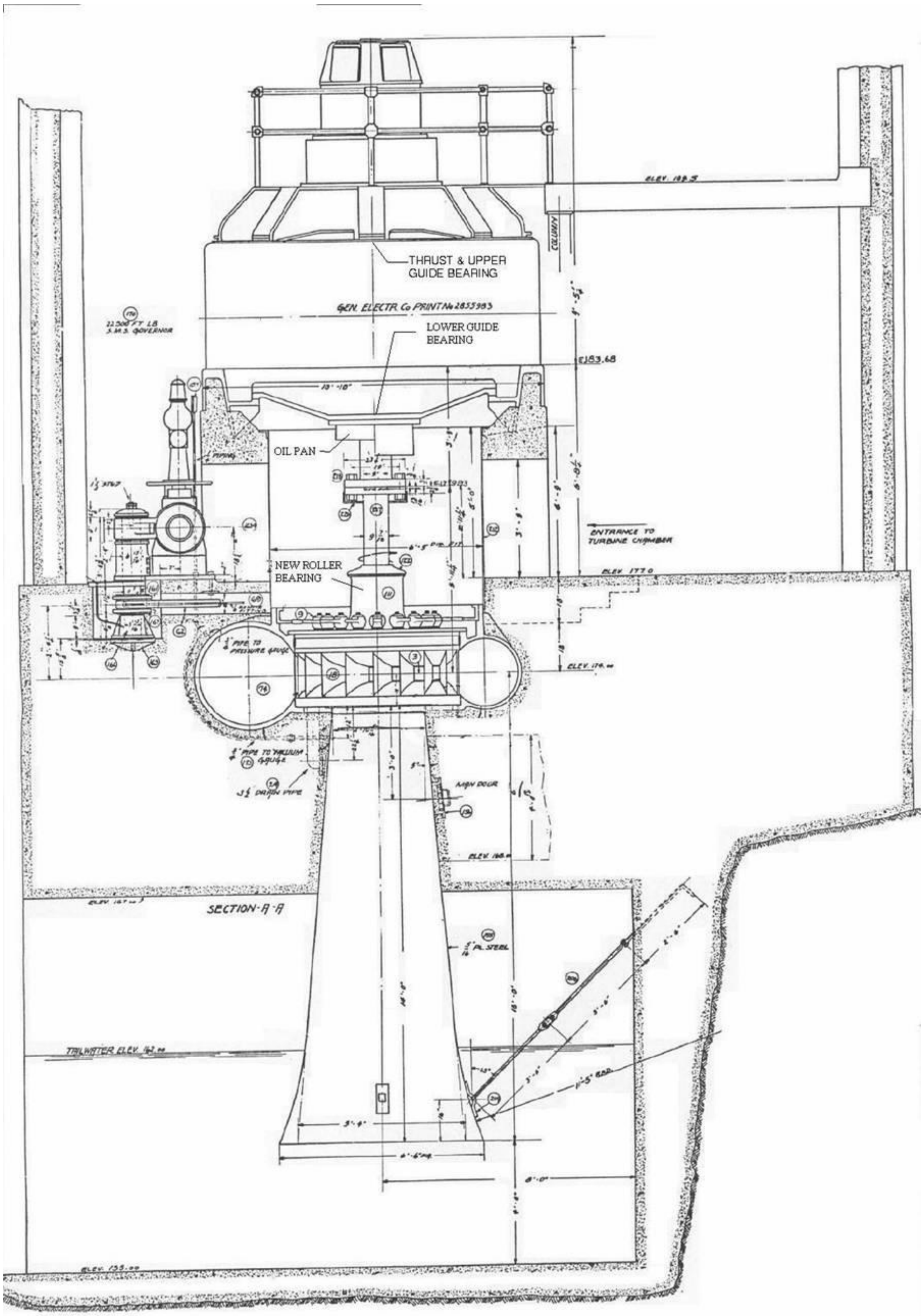

FIGURE 1 POWERHOUSE CROSS SECTION

INITIAL TURBINE INSPECTION

Within two days of the occurrence and after dewatering the 8,300 ft long penstock, Kleinschmidt and GMP personnel were able to inspect the high pressure side of the turbine from the scroll case and the low pressure side of the runner and the discharge ring from a draft tube maintenance platform. The initial observation was that runner cavitation had not only produced the characteristic surface pitting or "frosting" on the runner's low pressure trailing edge but had been so prolonged and excessive that it precipitated the complete penetration of the buckets on almost all blades as shown in Photo 2.

The uniform cavitation indicated that there was an initial design problem with the runner and that the condition was not due to local manufacturing or casting imperfections. However, with this type of wear it becomes more difficult to isolate the fundamental cavitation source whether it be the operation of the unit, operating heads, or blade profile. Historical investigation disclosed that the original equipment had been intended for another site, but after the original site's construction was postponed the unit had been installed at Marshfield and operated under slightly different operating conditions. This appears to have been a contributor to the cause of cavitation.

PHOTO 2 RUNNER BUCKET EROSION

One "rule of thumb" states that runner cavitation repair should be undertaken when damage is approaching 20 percent of the blade thickness or 1/2" in depth although most owners elect to perform the repairs when the damage reaches a maximum depth of around 3/8" which is the depth that can be filled with two weld passes.[1] Since this was a bronze based runner the weld filler would typically be an Ampcotrode 10 aluminum bronze filler which would provide a significant improvement in cavitation resistance.[2] However, since the damage had obviously exceeded those conditions and since modification of the existing profile to prevent future cavitation would be somewhat a trial and error procedure, it appeared best to replace and not repair the runner.

[1] Electric Power Research Institute EPRI-4719 "Cavitation Pitting Mitigation in Hydraulic Turbines, Volume1 Guidelines and Recommendations." Section 4, Copyright 1986.

[2] Thomas Spicher, "Hydro Wheels, A Guide to Maintaining and Improving Turbine Runners." Page 13 Copyright 1991.

Furthermore, conversation with the station personnel (which is critical to the success of a rehabilitation project) indicated that "nuisance" vibration trips had occurred over time but had been "solved" by adjusting the vibration trip levels. The vibration was explained in part by the observed loss of several balancing weights located within the runner's discharge cone. The loss of the balancing weights did not appear to have been recent and thus did not appear have caused the latest vibration alarms, but had, along with the increasing cavitation damage, steadily elevated the dynamic instability.

PHOTO 3 DETACHED SEAL RING

PHOTO 4 DISCHARGE RING CONDITION

As with other stations, an annual vibration monitoring program or, if financially justified, permanent vibration trending equipment could have been advantageous in this situation for trending the increased vibration and in scheduling planned inspection and maintenance outages as opposed to a costly emergency shutdown. The new ISO 7919-5 Vibration Evaluation criteria for Hydraulic Turbines, issued in 2005, suggests that a 25% increase in magnitude over the limits suggested by ISO 7919-5 is grounds to inspect the unit.[3] Advanced notice of the runner's deterioration would have prevented significant damage to both the runner and other components; therefore it is recommended that all hydroelectric units have established limits based on ISO 7919-5 by which to evaluate their condition without expensive dewatered inspections.

The additional vibration mentioned previously and the condition of the generator shaft mentioned later had also forced the runner's rotating bronze seal ring to wear against the stationary seal ring to the point that the rotating ring had worn completely through at one location. Correspondingly, the seal ring pins had become so corroded that the combined effects of the worn ring and the weakened pins caused the seal ring to detach (see Photo 3 above) creating tremendous equipment vibration. Not only had the failure created vibration but, because of the increase seal clearance, high pressure water was able to bypass the runner buckets. The bypassed

[3] ISO 7919-5 "Mechanical vibration – Evaluation of machine vibration by measurements on rotation shafts—" Part 5: "Machine sets in hydraulic power generating and pumping plants" 2nd ed. 2005-04-15.

water cavitated because of the abrupt change in pressure causing 5/8" deep cavitated pockets in the embedded discharge ring and in some locations completely penetrating the steel ring and eroding the foundation's concrete (Photo 4). It is recommended that periodic inspections (not necessarily annually) of the runner's seal clearance be performed to prevent such damage and to maintain efficiency.

TURBINE REHABILITATION

These findings compelled GMP to immediately retain Kleinschmidt to prepare a Technical Specification for a complete mechanical turbine overhaul. Subsequent to the review of the proposals, GMP awarded a contract to one of three bidders and thus instigated a complete turbine replacement and auxiliary equipment refurbishment.

PHOTO 5 LOWER CURB RING

As the unit was disassembled the extent of the damage became more evident. The stainless steel wicket gate facing surface of the lower curb ring appeared to be in excellent condition from the scroll case vantage point (Photo 5); however, as seen in Photo 6, the cast steel lower base, which had been hidden by the runner's lower band, was extremely eroded to such an extent that the wicket gate bearing journals were exposed thus damaging the wicket gate stems. Therefore the stainless steel portion was retained while a new lower base was to be supplied.

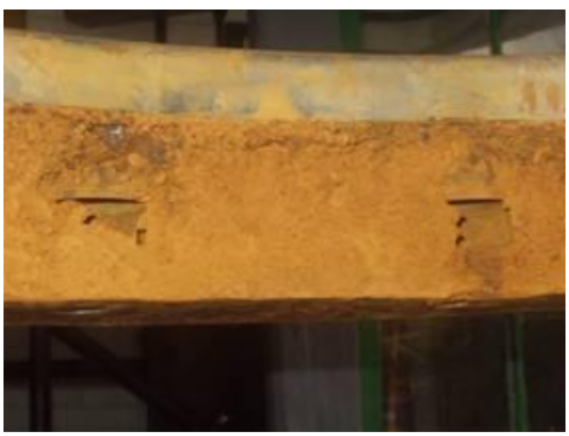

PHOTO 6 EXPOSED WICKET GATE BUSHINGS

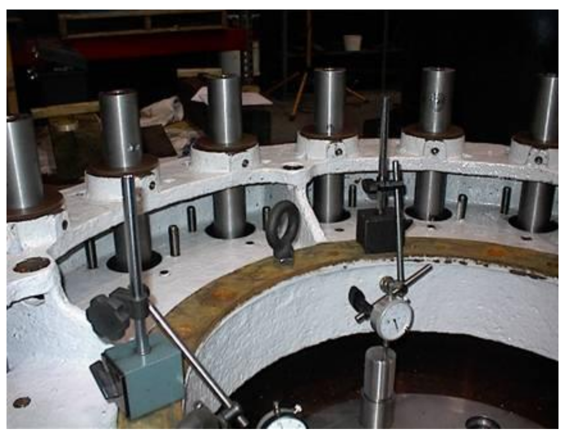

PHOTO 7 NEW ASSEMBLY

To begin repairing the unit, the voids in the concrete behind the discharge ring were filled with a cementous grout. Then the remaining gusset brackets and the remaining circumferential material were machined to sound material; whereupon weld overlays were built up concentrically with new gussets installed. This process was found to be, in this instance, less expensive and far quicker to incorporate than machining and installing filler pieces.

Due to the wicket gate bushing condition, new wicket gates were supplied and the original bronze bushings were replaced by Tenmat FEROFORM® T814. This material consists of a cured phenolic resin matrix carrying reinforcing fibres and which has been advertised as being used in over 1,500 turbines. The operating linkage/wicket gate thrust rings and all linkage bushings were replaced with Delrin AF, which according to its engineering data has a 13,000 psi compressive strength, a Rockwell hardness number of R120, and a dynamic coefficient of friction of 0.14. Both materials have operated successfully to date, but have not been disassembled for inspection.

Additionally all Babbitt guide bearings and the spring based thrust bearing were damaged, with large pieces of Babbitt missing from the guide bearings and 40% to 50% of the Babbitt not bonded to the base of the thrust bearing. GMP elected to install a new Craft roller bearing to replace the previous oil-lubed Babbitt bearing to simplify both the system and its maintenance. The new Craft bearing, which is rated for operation in a submerged environment, has performed remarkably well considering the vibrations that occurred after the unit was re-commissioned (discussed below). Had a Babbitt bearing been installed, the bearing surface would have needed to have been remachined as was necessary for the generator's lower guide bearing and would have added significant time to the turbine repairs.

PHOTO 8 ORIGINAL TURBINE GUIDE BEARING INSTALLATION

PHOTO 9 NEW CRAFT BEARING

Finally, a new lube oil tank and pumping system was furnished to replace a system that required constant attention.

TURBINE BYPASS

The project team encountered a significant schedule delay in the refurbishment. The generator shaft had been removed during the disassembly but had not been set up in lathe to measure the shaft runout. Once the runout readings were taken, the shaft was found to have a 10 thousands bend which, along with the loss of the balance weights, had been the root cause of the misalignment and thus the seal ring failure. It was evident from inspection that the shaft had once been heated and bent back to its original tolerance, but had not been able to maintain its straightness. This discovery required that a new shaft be forged and machined, thus prolonging the project through mid-spring. The prolonged and costly delay made it evident that all components should be measured regardless of whether they were to be replaced or refurbished.

The schedule delay required to furnish a new generator shaft also perpetuated a secondary problem. The problem was that the project's wood penstock had to remain watered to avoid having the wood slats dry and shrink. Upon rewatering, this condition would have created extensive leakage. A watered, stagnant penstock, however, was as much problem as a dry penstock since the stagnant water in an exposed penstock would freeze in the cold Vermont winter climate. Kleinschmidt therefore began to compute the required discharge necessary to maintain only a limited ice layer on the interior of the penstock. These calculations were based on the work of Ioan Sarbu and Francisc Kalmar as published in the Journal of Hydraulic Research.[4]

Additionally, the extension of the project not only forced the penstock to remain watered through the winter it became more apparent that prolonging the project into mid-spring. This created a serious concern of bypassing the headpond's spring runoff inflow without discharging the full inflow over the spillway and through Molly's Brook, which likely would have caused residential flooding.

A turbine bypass at the powerhouse was required to address both the freezing and flooding concerns. The bypass had to be extracted upstream of the turbine's butterfly valve, located inside the powerhouse, to allow continued work on the unit, but had to be discharged within the footprint of the powerhouse to comply with state permit concerns. Thus the exposed steel penstock was to be tapped and bifurcated just upstream of the powerhouse. A valve would be installed just downstream of the bifurcation with the discharge pipe angled down a newly cored 18" diameter hole through the powerhouse foundation.

[4] Ioan Sarbu, Francisc Kalmar, "Numerical Simulation and Prevention of Water Freezing in Outdoor Penstocks" Journal of Hydraulic Research, Vol. No. 4

Typically the valve downstream of the bifurcation would have to be a Multiple Orifice Valve designed to dissipate the full 350 foot of potential energy; however, this type of valve required an unacceptable delivery time. Therefore, Kleinschmidt located the most readily available surplus ball valve and, using a finite element vibration analysis and detailed flow calculations, designed an energy diffusing chamber capable of reducing the potential free discharge velocity from approximately 95 fps to 30 fps. This diffusion chamber was bolted to the furthest downstream portion of the pipe underneath the powerhouse and discharged into the same bay where the conical draft tube discharged (Photo 10).

PHOTO 10 TURBINE BYPASS

The bypass performed very well within the time constraints and provided sufficient discharge to avoid any discharge over the reservoir's spillway.

TURBINE TROUBLESHOOTING

After installation and alignment of the bearings, wicket gates, shafting, and stainless steel runner, the unit was commissioned in May of 2004. During the startup there were some unacceptable grinding noises from the runner pit as the unit began to roll. The wicket gates also had to be opened to a greater percentage than was typically required to breakaway and start the turbine rotating. Once the unit was up to speed it generated significantly more power than had been realized at that station for some time; however the unit had slightly higher vibration and temperature readings than was expected.

Runner clearance readings were then taken in June of 2004 and some modifications to the packing, oil flow, and the addition of a roller bearing pedestal (to allow for easier access to the turbine packing) were performed. Vibration levels were monitored and confirmed to be within reasonable levels but there was still some continued concern as to the performance of the machine (independent of the power generated). No realignment checks were made to confirm the unit's alignment since it was reasoned that the roller bearing's new pedestal had been installed in the same exact location. This, however, proved to be a problem.

After operating through the summer and fall of 2004, the unit again began tripping between January and March of 2005. These shutdowns were due to a combination of high vibration pickups and high temperature alarms on the lower generator bearing. Thus in March of 2005, the unit was inspected and the lower generator guide bearing was found to have no clearance on the land side of the unit and had to be re-machined to open up the bore to a RC 8, fit even though a

RC5 and RC7 medium to free running fits for a 600 RPM machine would have been acceptable according to Mark's Engineering Handbook. More importantly the lower guide support spider had to be moved 0.004" to make the bearing concentric with the shaft. The vibration and startup noise diminished after these modifications, but the unit still experienced higher than expected vibration; therefore during June of 2005, GMP selected another contractor to work with Kleinschmidt to determine the cause of the vibration.

Kleinschmidt, GMP, and the second contractor jointly reran the original alignment and found that the shaft was significantly out of plumb and that there was no clearance between the runner and the curb ring; even though the shaft was within the USBR's recommended concentricity tolerance at the lower guide bearing (because of the previous 0.004" adjustment). Startlingly, the shaft was out of plumb by a factor of 4.6 times the USBR's recommended plumbness tolerance of 0.00025"/ft and there was no runner clearance on one side of the unit even after rotating the shaft 180 degrees. This indicated that the shaft was being held to one side.

The subsequent removal of the roller bearing and the corresponding jump of the bearing housing as it was released from the forced stress against the shaft absolutely proved that the roller bearing had been holding the shaft to one side, causing the runner to make contact with the curb ring. It was the contact with the curb ring that created extra vibration in the system and damaged the lower guide bearing. The machining of the generator's lower guide bearing and the adjustment of the spider were only modifications that treated the symptom, because the spider had to be moved back in the original direction by the same quantity after the roller bearing was installed properly.

PHOTO 11 MARSHFIELD REFURBISHED TURBINE

The analysis of the new unit's lower guide bearing failure and the re-verification of the four wire vertical alignment enabled Kleinschmidt to determine that the unit had been installed outside of acceptable alignment tolerances during the installation of a roller bearing pedestal modification. This reinforces the fact that after any major modification a full alignment test with complete documentation should be undertaken to avoid any future problems or costly repairs.

Since June 2005 the Marshfield hydroelectric generating unit continues to operate without any restrictions or problems and continues to provide greater power production that had been possible before the rehabilitation.

LESSONS LEARNED

- It his highly important that the condition of the equipment be verified and documented on a regular basis so as to preclude any emergency shut downs.
- Temperature and vibration trending data are extremely useful to track and plan maintenance activities.
- All hydroelectric units should have established vibration limits based on ISO 7919-5 by which to evaluate their condition.
- Periodic inspections (not necessarily annually) of the runner’s seal clearance and the watered equipment’s condition should be performed.
- The condition of all components whether planned to be refurbished or not must be closely evaluated as soon as they are disassembled to avoid delays.
- Installation of the runner must follow a written and engineer approved checksheet and have written documentation of the alignment.
- The alignment form must be completed prior to final commissioning.
- After any change no matter how innocuous the alignment should be checked to verify that noting has shifted.
- The installation alignment and commissioning plan must be submitted to the owner’s engineer for review and approval or the owner’s engineer must develop a protocol for which the unit is to be commissioned.

AUTHOR

Matthew Dunlap, is a mechanical engineer at Kleinschmidt. He was the lead engineer responsible for Kleinschmidt’s involvement with the Marshfield Project Rehabilitation.