PROSPECT MINI HYDRO: REMEDIATION THROUGH STAKEHOLDER ENGAGEMENT AND ROOT CAUSE ANALYSIS

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INTRODUCTION

Water utilities worldwide have adopted energy saving schemes, including the installation of embedded hydro turbine-generators to reduce fluctuations in the price of electricity, and provide benefits such as environmental stewardship and generating positive publicity.

An embedded hydro-generator is typically a modified, 'off the shelf' package, supplied by a designer/manufacturer, to a set of performance criteria, such as IEC 62006:2010. The standard design is modified for the application if necessary, with commissioning and performance testing performed under the design and construction contract.

This case study examines key failures of the Prospect mini hydro turbine three years after commissioning, despite achieving its performance guarantee, and passing its defect liability and warranty period. The case study focusses on the adopted methodology and innovative collaboration between Sydney Water and its renewable energy contractors Process Engineering Technologies (P.E.T.) and Stark Engineering Consulting (Stark) to develop a remediation strategy and execution plan for a sustainable, long-term solution.

YEAR CASE STUDY WAS IMPLEMENTED

2014 to 2015

CASE STUDY SUMMARY

This case study explores design, monitoring and operational improvements made to Sydney Water's largest renewable energy generator, the Prospect mini hydro turbine, after repeat failures and discontinued support from the Original Equipment Manufacturer (OEM).

It examines the process and methodology employed to meet the primary objective of improved asset availability. This case study illustrates how small, embedded generators, considered and sold as 'off the shelf', may still require extensive engineering effort prior to purchase, during construction and after commissioning, with a focus on materials selection, maintenance accessibility and asset longevity.

This case study further elucidates how a successful collaboration between asset owner, operation and maintenance (O&M) contractor and external consultants has not only provided a sustainable remediation for identified defects, but is in fact an exemplary framework for ongoing performance improvements and increased return on investment.

Key project actions highlighted in this case study include:

- Implementation of structured design review workshops with internal and external resources to identify root causes and best practice remediation strategies
- Design modifications to rectify identified root causes (incl. non-drive end bearing and mechanical seal failure)
- Material selection improvements for replacement components
- Improved datalogging and condition monitoring for long term outage planning
- Retention of knowledge from long term contractors

On completion of the remediation project, the turbine was successfully returned to operation. Since only part of the identified root causes were rectified, further work remediation work is planned for 2016-2017.

CASE STUDY DETAIL

Background

In 2007-2008 opportunities for renewable energy generation were identified by Sydney Water and its alliance partners. As part of the resultant Renewable Energy Program, a hydro turbine was installed in parallel with the existing hollow jet valves (HJVs) at the bifurcate outlet of the Warragamba pipeline within the Prospect Outlet works. The hydro consists of a double regulated Kaplan turbine, rated at 3.7 MW coupled to an induction generator, with a projected generation of 14.1 GWh p.a. The hydro turbine provides electricity at 11 kV for on-site usage, with the possibility to export to the public grid. Additionally, the generated power is considered 100% renewable and generates Renewable Energy Certificates through the Australian federal REC scheme. This represents financial benefits of approximately $1.5M per annum in avoided electricity, exported electricity and renewable energy certificates.

The control of the Prospect hydro turbine is unconventional, compared to other similar hydro turbine installations (Fasol, 2002). Water from Warragamba dam is delivered through the parallel valves and the hydro turbine. A flow controller issues setpoints to the valves and turbine based on the flow required by the Water Filtration Plant, the dam level and the specific discharge curves of each device. Feedback to the flow control PLC is that of valve and turbine position only. Feedback of actual flow is excluded to prevent flow oscillations and potential pipeline transients. Table 1 presents turbine and generator data.

Table 1: Turbine and Generator Detail

Turbine: Commissioned April 2011	
Type	Double regulating horizontal axis Kaplan Turbine Unit
Max. head/ flow	42 m / 12.9 m^3/s
Generator: Commissioned April 2011	
Brand & model	WEG 800A
Type	Air-water cooled Squirrel Cage Induction Generator
Max. electrical output	3,700 kW
Rated speed	431 rpm

Commissioning and early operation

Design, installation, testing and commissioning of the original project focused primarily on turbine performance points and pipeline transients, with significant effort expended on establishing the appropriate protection settings for pipeline protection and drinking water quality preservation. In May 2011, the turbine was considered fully commissioned and normal operation commenced. During its first year of operation, the turbine achieved approximately 8.2 GWh with approximately 70% runtime availability.

Early failures

In May 2012, after one year of operation, the hydro turbine suffered a non-drive end bearing failure, which was first evident through a high bearing temperature trip. The bearing was a sealed SKF dual row spherical bearing. The bearing’s design L_{10} life was in excess of 10^6 operating hours, greater than the design life of the machine.

Acting on the recommendation of the OEM, the bearing was replaced by external contractors under the OEM’s supervision at significant cost to Sydney Water. The cost was due primarily to the difficulty of turbine dewatering and isolation, access to the bearing and safe removal and reinstallation in-situ. Post-mortem review of the bearing by SKF revealed overheating and lubricant depletion of the bearing, likely due to excess axial load.

In July 2012, after less than 0.9 GWh of generation, the same bearing failed again. Once again, an identical bearing was installed. This time, by recommendation of SKF, an anti-fretting paste was applied to the bearing housing to facilitate the required sliding fit. Refer Figure 1.

In November 2013, a third bearing failure occurred, shortly followed by an identified defect on a high voltage capacitor. The hydro was left disabled, pending further investigation.

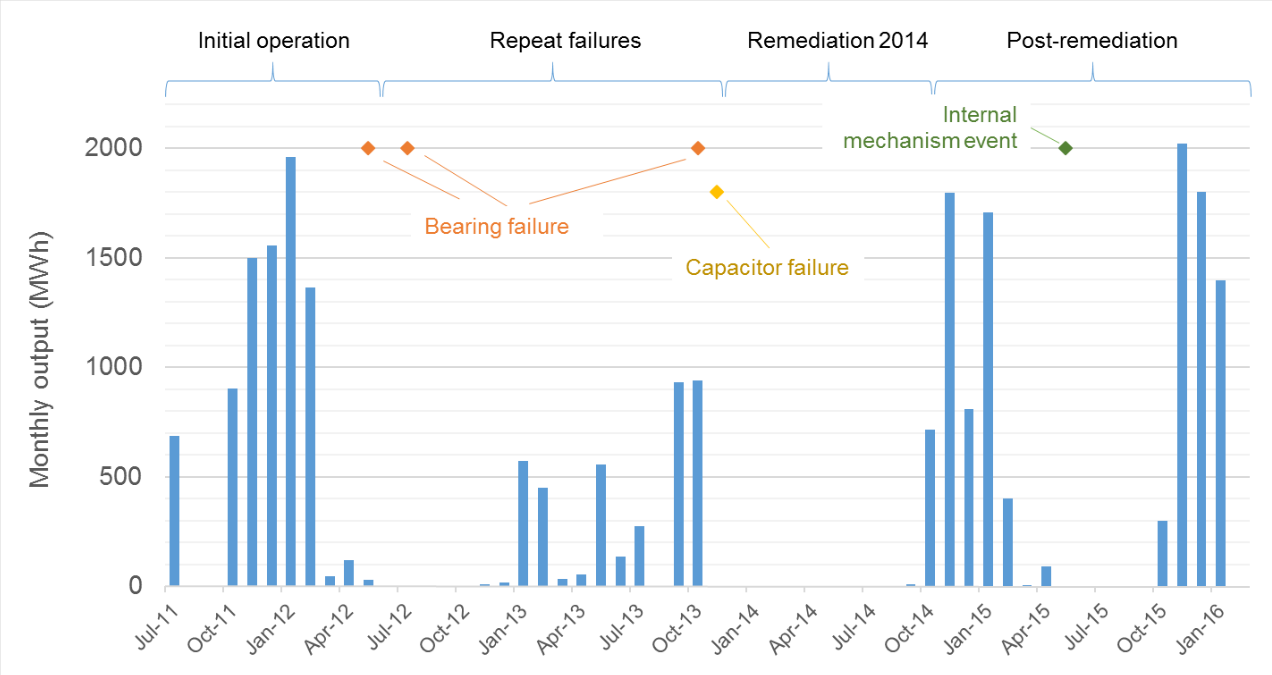

Figure 1: Mini hydro monthly performance since commissioning

Remediation: repeat bearing failures and severe corrosion

By late 2013, Sydney Water had incurred approximately $1,850,000 on lost generation, investigations and unsuccessful non-drive end bearing repairs. Protracted discussions with the turbine OEM and maintenance provider failed to address the root cause. In December 2013, Sydney Water handed over the operation and maintenance of its renewable energy portfolio to P.E.T., in cooperation with Stark. This provided the opportunity for a change in strategy at the Prospect plant. Furthermore, observed damage to a high voltage capacitor and the 6-month lead time of its replacement part provided a window of forced downtime for an extensive investigation and remediation.

A remediation project was initiated, with the intention to identify root causes of defects and implement a long-term strategy for cost-effective return to operation. The symptoms to be addressed, as perceived at the start of the project were categorised as follows:

- The primary symptoms:
  - The repeated failures of the non-drive end bearing
  - The failure and contamination of the mechanical seal
  - Widespread and significant corrosion around the Kaplan hub and guide vane actuators, as observed during outages for bearing replacement

- The secondary symptoms:
  - A cracked high voltage capacitor
  - Variance in Kaplan blade clearance (blade and casing)
  - Leaking generator heat exchanger, lack of leak detection
  - ‘Sticky’ electromechanical relays
  - Failure of high pressure hydraulic connections
  - Excessively worn rotary union anti-rotation pin

The Approach

Enabled by, and in cooperation with Sydney Water, P.E.T. and Stark adopted the following approach with a focus on a high degree of consultation and transparency.

1. A thorough internal review was conducted of historical trend data, bearing and mechanical seal design arrangements, chemical composition analysis of corrosion deposits, failure reports and past performance data. The initial findings were presented and discussed with Sydney Water, and summarised in a briefing paper as preparation for an in-depth workshop.

2. A team of P.E.T. and Stark engineers and technicians as well as independent non-OEM specialist hydro consultants was created with the emphasis on specialist skills from engineering and maintenance personnel alike.

3. Two external consultants were engaged to produce a desktop root cause review of the primary symptoms. An OEM-independent review ensured industry best-practice and un-biased conclusions. Figure 2 illustrates part of the identified fault tree presented in the desktop review.

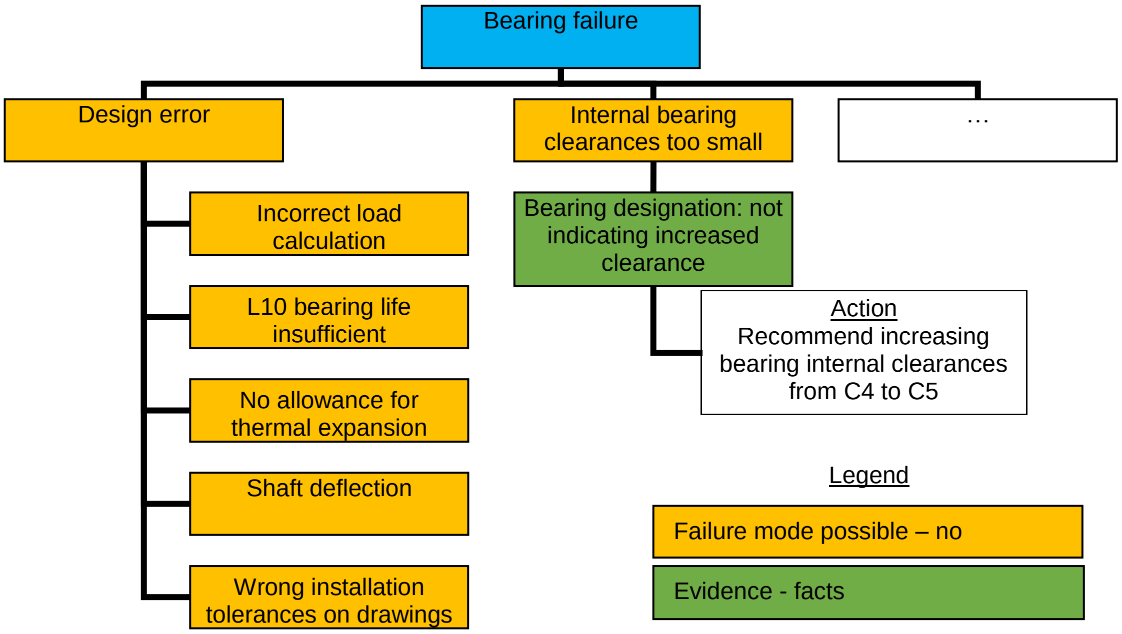

Figure 2: Part of root cause analysis tree

4. Following the desktop reviews, an extensive design review workshop and in-situ inspection was organised. The facilitated workshop aided in reaching consensus on the root causes of the primary symptoms, including an associated risk assessment. Table 2 illustrates a typical outcome from the workshop. The most likely root causes identified can be summarised as follows:

   a. Seizing of the non-drive end bearing outer race inside its housing results in loss of axial float and consequential axial overload, see Figure 3. The exact mechanism of the seizing of the bearing was found difficult to be established with certainty. Nonetheless, aggravating factors such as water ingress into the bearing housing and possibly bearing, surface corrosion of the mild steel bearing housing, insufficient internal bearing clearance and axial shaft movement during start-up and shut-down were believed to be factors that needed addressing.

   b. The existing mechanical seal was fitted with an atmospheric drain rather than a clean water injection line. As a result, raw water from the pipeline drains through the seal. In combination with prolonged shutdowns, corrosion deposits and silt are believed to contaminate and damage the seal, and possibly impact on the non-drive end bearing.

   c. Use of electroless nickel plating on the non-stainless steel turbine components was found to be unconventional. Minor scratches or defects in the coating are believed to lead to localised galvanic cells which result in the observed severe pitting of the underlying structure, see Figure 4.

5. Agreement on short-term and long-term remediation strategies was formally documented to Sydney Water, with recommendations on the options available for execution.

6. Based on the most likely root causes of the primary symptoms, the final approach for remediation of the plant was formulated as:

   a. Prior to return to service in 2014:
      i. Re-design of the non-drive end bearing arrangement to address the most likely root cause of excess axial loads, with a minimal modification to the original design
      ii. Re-design of the mechanical seal flushing mechanism to eliminate contamination with silt and corrosion deposits
      iii. In-situ treatment of corrosion with a suitable corrosion inhibitor and primer

b. After return to operation: define the options to address the internal corrosion in the medium to long term

7. A program was developed for implementation of the recommended rectification works. The program also included addressing the secondary symptoms, such as:

    a. Review of critical spares inventory for long lead items
    b. Replace electro-mechanical relays with solid state where appropriate for enhanced reliability
    c. Verification of high pressure hydraulic lines and installation of additional restraints to minimise the impact of connector failures
    d. Replacement of the anti-rotation pin for the rotary union
    e. Establish documented procedures for critical measurements

8. Execution of the works was completed by using specialist in-house P.E.T. and Stark resources. The involvement of the operation and maintenance (O&M) team throughout the implementation ensured optimal and pragmatic use of available knowledge, effectively reducing cost and minimising hand-over and training requirements.

9. The recommissioning of the mini hydro was approached with the same level of rigour as the original commissioning program. The hydro is located on the main drinking water supply to Sydney and each flow disturbance has the potential to cause an upset in the downstream water filtration process. At the same time, it was (and is) crucial to operate within the envelope of scenarios covered by the design transient studies to avoid any chance of pipeline damage due to over or under pressure scenarios. Engagement of external stakeholders such as the water filtration operators was critical for a successful completion of the recommissioning.

Figure 3: Non-drive end bearing failure, showing seizure and water ingress

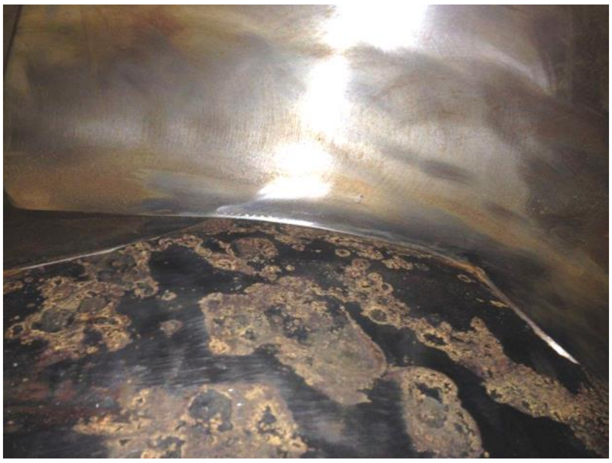

Figure 4: Kaplan hub showing failure of nickel plating and pitting corrosion

Summary of activities and their implementation
The execution of the works was carried out under the supervision of a P.E.T. O&M technician and a Stark engineer. The works can be summarised as:

1. In-house design modification of the non-drive end bearing arrangement. In the absence of OEM-provided manufacturing drawings, in-situ measurements were relied on. An aluminium bronze sleeve installed in a modified bearing housing carried a higher C3 clearance, open bearing, with externally lubricated H1 food grade grease. The design caters for bearing cavity seals on each side, including a stainless steel ‘flinger’ to prevent water ingress from the nearby mechanical seal. The assembly is replaceable in-situ. External greasing of the new bearing is performed using an automatic grease pack and an externally accessible grease line, see *Figure 5*.

2. ‘As found’ measurements were taken at key milestones to develop a baseline for later re-installation where the OEM had not provided ‘As-built’ clearances or drawings. A comprehensive Inspection and Test Plan was developed for this purpose. Components were match marked and scribed for repeatability of measurements.

3. The mechanical seal OEM was engaged to assist with developing a detailed procedure for an in-situ installation of the mechanical seal, to prevent installation damage. Additionally, a centrifugal pump was installed to provide clean, filtered water to the mechanical seal. The water filter includes a dual changeover filter arrangement to prevent downtime on the plant for filter clean-out.

4. In-situ corrosion abatement works included mechanical removal of the nickel coating were possible, in-depth cleaning of the corrosion pitting using dry ice blasting, treatment with corrosion inhibitor and coating with a suitable two-pack epoxy primer.

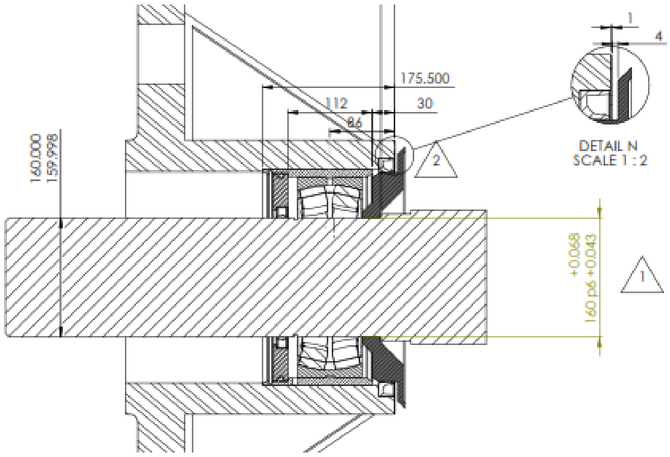

Figure 5: Redesigned bearing housing to prevent water ingress, provide external greasing and ensure axial float

5. Commissioning and performance testing included amongst others, a full suite of as-built measurements for the new bearing arrangement (run-out checks etc.), critical systems testing and a staged start-up and loading protocol. The commissioning findings were submitted and clarified to the stakeholders prior to return to normal operation.

Summary of outcomes and measurable impacts of the activities.

The main directly measurable outcome involves the turbine's runtime which returned to nearly 87% during high flow periods, with loss of runtime due primarily to external factors such as dam level and flow restrictions that place the hydro outside its permissible operating envelope.

A second direct outcome is that design modifications to the bearing and seal flush system have been proven reliable. The new bearing arrangement has now outperformed the previous design, with 16 months of operation without failure by the end of January 2016. On the other hand, an internal inspection in August 2015 has revealed that the in-situ corrosion abatement has only been partially successful, with signs of proceeding corrosion already visible again.

Indirect advantages of the project include increased skill level of the team involved, and knowledge within Sydney Water with regard to the plant's design. Historically the team had been reluctant to modify parts of the plant without the OEM's endorsement or approval, however the successful implementation of the project, specifically the workshops and design reviews, has improved system and process confidence.

The extent to which the outcomes are sustainable and were achieved in a cost efficient manner.

The modifications are designed to last for the life of the plant, with material selection chosen carefully to be compatible, and components re-usable (on turbine removal). The project exceeded the original budget allocation by approximately 30%, due to scope creep and program delays (primarily installation and engineering costs). However, the associated revenue since the turbine return to service has resulted in a pay-back time of the remediation works of less than 6 months.

Equally important as a sustainable technical outcome, was the adopted remediation approach. Since its return to operation, the hydro has incurred a number of minor defects and in each case a confident approach of rectification but also sustainable improvements has been adopted and supported by the stakeholders.

The most noteworthy of these was an event in May 2015 which eventually led to a further 5 month shut down period for inspection and remediation. During this period, root cause analysis and stakeholder management were again the key to further short-term and medium-term rectifications:

1. Immediate initiation of a new Remediation Project, to address the internal corrosion and suspected deterioration of the internal Kaplan mechanism in the medium and long term.

2. Upgrading of the vibration monitoring system to include reliable full-spectrum vibration monitoring.

3. Installation of enhanced data logging and remote access dashboard, allowing for customisable trends and reporting. More and accurate data as well as the instant access to it has already proven to be a key in assisting operators with diagnostics and accurate reporting to stakeholders. Typical turn-around after a trip event is now typically 4-5 hours, compared to previously 2-3 days. This has been a vast improvement in communication with stakeholders. Refer Figure 6.

4. Installation of two additional hydraulic oil accumulators for improved reliability and safe shutdown in the event of a complete hydraulic failure (eg. hose burst).

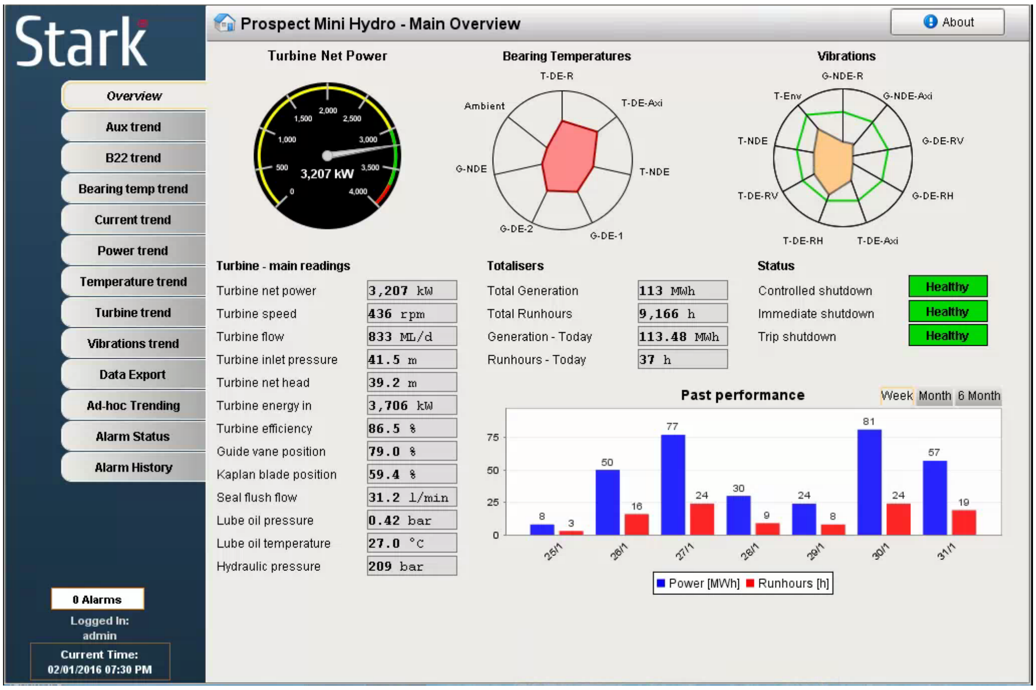

Figure 6: Remote access dashboard and datalogger

Important lessons learnt and critical success factors

The effectiveness of the root-cause analysis as well as extensive consultation with internal and external stakeholders proved key for the successful outcome of the remediation. Provided it is supported by the plant owner, this approach is particularly well-suited for non-OEM service providers and may in fact offer a better chance to cost-effective remediation in case of repeat or inherent machine failures.

The identified root causes of inappropriate material and component selection highlights the inherent risk associated with ‘off the shelf’ equipment for embedded generation. With the benefit of hindsight, it can be seen that seemingly insignificant design choices can have long-term impact on asset performance.

- Ease of access and maintenance is integral for fault finding and diagnosis, and in-situ repair.
- Material selection on submerged equipment is of paramount importance and should be thoroughly reviewed by both the owner’s engineer and a materials specialist.
- Performance testing and inspection should extend beyond the warranty period, or the warranty period be extended
- Engagement of operators in the design process, to provide a sense of ownership and understanding of the plant;

Finally, without the ongoing commitment from key stakeholders and plant owners to a long term remediation strategy, the Prospect mini hydro would not be able to return to operation.

<u>REFERENCES</u>

Fasol, K. (2002). A short history of hydropower control. IEEE Control Syst. Mag., 22(4), pp.68-76.

Table 2: Example of design review workshop synthesis. WS denotes Workshop agenda item

Discussion **(Short/medium term considerations)**	**Action closeout for bearing decision** **WSOA = Workshop Open Action**	**Design goal**	**Design synthesis (Options)**
Root cause possibility: Internal bearing clearances too small OR Incorrect shaft tolerance (oversize)			
WS: Given the low machine speed, consensus was reached that a higher clearance would not be a problem. Higher clearance would reduce the internal bearing stress.	**WSOA:** OEM to confirm the design bearing internal clearance. **WSOA:** OEM to confirm the design tolerance of the shaft, it seems like a typo compared to the ISO standard (0.086 vs 0.068). OEM to confirm the interference fit (shaft basis, ISO 286) **Stark EC:** Shaft measured to 6.3015-6.302", 160.06 - 160.071 mm which is within OEM drawing spec but outside ISO 286 for shaft interference fits – this provides further basis for a larger radial internal clearance OEM drawing shows shaft design surface finish is 1.6. µm Surface finish around 6 µm on (LHS) – not considered an issue **SKF:** Bearing supplied only comes as a normal fit. For the same sealed bearing C3, a special order must be placed. **Stark EC:** With the current (assumed p6) fit, the internal clearance 120-180 µm (normal), becomes 60-120 µm. **Stark EC/PET:** With a C3 fit the (assumed p6) fit, the internal clearance 180-240 µm, becomes 120-180 µm. For the given loads and speed of the bearing this is suggested.	Correct internal clearances	Bearing to have C3 internal clearance with p6 interference fit (shaft basis). Only open bearings facilitate this. Bearings are readily available from vendor