ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-WEPS80

LESSONS LEARNED FROM HARDWARE FAILURE DURING HL-LHC AUP CABLING*

E. M. Lee†, E. Buron, J.F. Croteau, A. Lin, T. Lipton, M. Naus,
C. Perez, I. Pong (*IEEE Senior Member*), Lawrence Berkeley National Laboratory, Berkeley, USA
A. Baskys, European Organization for Nuclear Research, Meyrin, Switzerland

Abstract

The production of cables for the High-Luminosity Large Hadron Collider Accelerator Upgrade Project at Lawrence Berkeley National Laboratory required a substantial increase in production rate at the superconducting cabling facility. Several critical components have experienced failure over the project's lifetime for reasons at least partly attributable to increased wear and tear on the hardware subsystems. This work analyzes three hardware failure case studies of varying severity and presents corresponding strategies to ensure operational readiness and uptime for legacy systems.

INTRODUCTION

The cabling machine at Lawrence Berkeley National Laboratory (LBNL) was intially built and further developed during the mid-1980s to early 1990s to support process development for the Superconducting Super Collider Project (SSC) [1]. The Nb-Ti cable production team at LBNL needed to acquire expertise in Rutherford cabling to produce cabler and Rutherford cable specifications for the SSC, so they developed an in-house prototype cabler. The machine initially functioned as a test bed to study cabling dynamics and cabler performance, but as LBNL research needs grew, the machine was incrementally updated to increase the spool capacity and machine power [2, 3]. Once the SSC project was cancelled, LBNL continued to use the cabler to support small scale R&D projects. The last major update to the machine was completed between 1992 and 1993 when the 60 spool bay and dual turkshead drive motors were added to the machine [4].

The LBNL cabling team has been using the cabler to produce a relatively high volume of Nb_3Sn cables in support of the LHC Accelerator R&D Program (LARP) which became a U.S. Department of Energy (DOE) 413.3b project, the High-Luminosity Large Hadron Collider Accelerator Upgrade Project (HL-LHC AUP) [5]. The annual production rate (in terms of cable length) for LARP and HL-LHC AUP is about an order of magnitude higher than the average rate over the last couple decades. The increased wear on mechanical components has contributed to a higher subsystem failure rate and underlined the need for system upgrades. This manuscript will present three case studies of hardware failure and their associated impacts to discuss suggested strategies for project execution and operational readiness for Rutherford cable manufacture.

* Work supported by by the Office of High Energy and Nuclear Physics, U.S. Department of Energy, under contract No. DE-AC02-05CH11231
† emlee@lbl.gov

CASE 1: ROLLER BEARING FAILURE

Synopsis

During the manufacture of Cable 1171, the operating team noticed that the cable mid-thickness had been increasing throughout the production run. The lead cabling machine operator made several attempts to stabilize the cable mid-thickness, but the keystone angle continued to decrease and the mid-thickness increased at an accelerated rate after each attempt. In the end, the cable was outside specification and rejected.

After the production run, disassembly of the drivetrain showed that the inner race of one of the drive rollers had been forced out of position by excessive journal pressure (Fig. 1). The roller assembly was therefore unable to hold its alignment in the vertical direction.

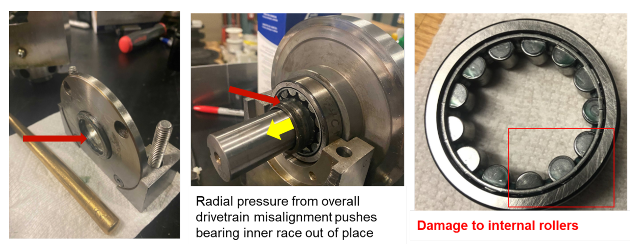

Figure 1: Roller bearing failure, Cable 1171.

Although the failure of Cable 1171 could be attributed to single point failure from a specific part (roller bearing wear), there are several risk factors and design issues that could contribute to a potential recurrence of this type of incident.

Turkshead Yoke Block Geometry

After the roller bearing failure, the turkshead vertical yoke blocks were disassembled to check for additional damage. The inner races of the SKF 206 ECJ cylindrical roller bearings are press fit onto the roller drive shaft, and the outer race of the bearing is constrained with a cap that provides radial pressure via two bolts into the block body. There are no additional features present to constrain the outer race and prevent axial displacement or separation from the inner race during operation (Fig.2).

For heavier loads and harsher operating environments, it may be important to re-design the yoke blocks to minimize risk to cabling materials and equipment. A future yoke block system may incorporate many improvements: alternate cap design to maintain positive retention of the bearing, weight reduction to reduce operator fatigue when handling

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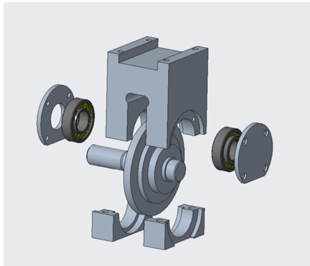

Figure 2: Turkshead yoke block assembly, showing no interference fit or shoulder constraint along around outer bearing housing.

the blocks and switching rollers, and additional instrumentation to monitor roll surface temperature and positional misalignment.

Engineering Analysis

The bearing failure provided two important opportunities for wider collaboration within LBNL that improved system understanding and cabler design tools. Consulting engineers from LBNL's Engineering Small Projects group re-analyzed the yield stresses on the drivetrain system and developed a spreadsheet calculator for the cabling team's internal use. The tool can calculate expected loads and maximum cable feed rates for various transmission configurations. Quick engineering calculations can help prevent unexpected system overloads and provide guidance for long term engineering improvements based on the target cable size.

The cabling team also hired an undergraduate intern to 3D model and reverse engineer the as-built turkshead assembly. The model is currently in use to design cable fabrication equipment for the High-Temperature Superconductor Cable Test Facility Magnet project [6]. Accurate as-built CAD data has provided a low risk, high reward test bed to explore new design concepts for cabler subsystems and is highly recommended for working facility system used in DOE 413.3b projects.

CASE 2: AIR BRAKE FAILURE

Synopsis

Approximately 335 m into the production run for Cable 1175, the emergency air brake for the cable bay fired and stopped the cable run. The sudden stop created a wire crossover at the 335th m and subsequent cable collapse. The cable did not meet the minimum length required for HL-LHC AUP coil winding and was therefore considered a failed cable.

For safety purposes, the air brake is normally closed and must be energized to stay disengaged and allow free rotation of the cable bay. There are four main scenarios under which the air brake would fire during a cable run: the broken-wire sensor is activated, the operator activates the brake using the brake control, pneumatic failure, or electromechanical failure. The operator did not fire the brake and no broken wires (strands) were found on the machine bay at the time of the trigger. The cabling team therefore initiated a hardware investigation to look for the root cause of the failure.

Pneumatic Investigation

The working team traced the existing air line to identify all components and discovered that the air brake had previously been modified without official documentation of the change: a gas spring was added to convert the bay brake to a normally closed system. Data and part numbers for the modification were subsequently recovered in personal records, and the team updated the as-built system description. No leaks were found, spare gas cylinders were ordered for all available part numbers to facilitate preventive maintenance, and the pneumatic system was determined to be operating normally and in good working condition.

Electromechanical Investigation

There are two contact triggers for the broken wire detector: a ring around the wire cone, and a floor detector for flying/broken wires that are spun outwards from the wire cone (Fig. 3).

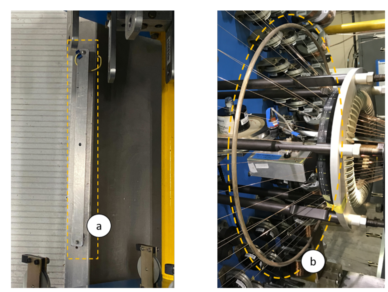

Figure 3: a) Floor switch and approximate trigger boundary b) Ring switch and approximate trigger boundary.

Because the cabling team had switched to a different dispensing pump before the production run, cabling operations took place under a much higher drip rate of lubricant than previous cable runs. The team was unable to reliably trip the sensor by applying excess lubricant on the sensor mount or its fittings; the lubricant itself was also found to be non-conductive via a multimeter continuity test, eliminating excess lubricant as a likely root cause.

During sensor testing, the team observed uneven oxidation across the surface of the broken wire ring detector. Minor cleaning/oxidation removal with Scotch Brite abrasive did not improve the sensitivity of the broken wire detector, which continued to trigger inconsistently. A qualified electrical worker (QEW) and a former cabling technical lead were brought in to assess the broken wire sensor subsystem for defects that could cause a system fault. No electrical shorts or damaged components were found in the relay control circuit for the air brake. The team ultimately proceeded by shutting off the broken wire detector due to its inconsistent behavior, and the issue has not recurred.

While the team implemented effective preventive action, the root cause was not conclusively established. Recovery

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of initial documentation and updates to as-built legacy systems may be preferable before the project execution phase to quantify and minimize project risks. Prioritizing improved maintenance access and assembly/disassembly features in the design phase, especially for systems with long expected working lifetimes, is recommended.

CASE 3: RESPOOLER GEAR FAILURE

Synopsis

In November 2021, the respooling machine (respooler)'s main transmission broke down due to increased wear and tear during LARP/HL-LHC AUP. After drivetrain inspection, the team quickly identified that the worm gear assembly and the rubber transmission wheel were damaged beyond repair (Fig. 4) and required replacement.

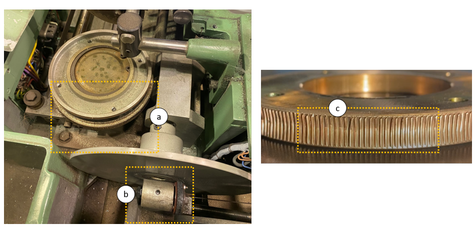

Figure 4: a) Worm gear location and brass debris b) Worn friction transfer wheel c) Detail, gear tooth damage.

It is important to note that the respooler used at LBNL was manufactured by a Swiss company sometime between the 1950's to 1960's. Although the company is still active and still manufactures linear winding machines, the replacement parts' long lead time was not compatible to HL-LHC AUP production schedule and no commercial off the shelf parts fitting the original manufacturer specification could be found.

Reverse Engineering

To put the machine back into service, the gear and mating worm from the transmission were sent to a specialty machine shop in Milwaukee, WI for reverse engineering and replacement fabrication. The shop determined the material of each component, measured the original mating geometry (pitch angle, etc.) and hobbed new gears. The LBNL main shop manufactured a new transmission wheel for the friction drive. Upon receipt of all parts and re-assembly, the technician team re-aligned all drivetrain components and identified areas for future preventive maintenance.

In total, the machine breakdown created a ~2 month delay for cable production at LBNL: respooling is an essential and upstream step for cable fabrication. The failure prompted the procurement for a modern winder with upgraded capabilities and wire capacity to replace the well-served winder.

ANALYSIS AND LESSONS LEARNED

During HL-LHC AUP cable production, the team recovered from every hardware failure because sufficient documentation and resources existed to support hardware repair during critical failures. The three cases present three important lessons learned regarding documentation. First, effective documentation practices and scheduled preventive maintenance are essential to prevent unexpected hardware failure and mitigate associated project risks. Secondly, for legacy systems, any gaps in documentation should be identified; corrective and preventive action to close such gaps should be performed before the project execution phase. Thirdly, documentation should be stored in a centralized, easily accessible location with back-up copies available.

If the team had lost access to key individuals with critical system information and documentation, recovery after hardware failure may have been much more difficult. System operators may also have extensive process or hardware information acquired from previous operators or their own experience. For legacy systems, it is crucially important to re-assess this information against engineering first principles, existing system documentation, or both. Re-assessment can help determine if the system's current baseline is off-normal relative to its original design intent and drive preventive action against unexpected hardware failure. It can also help identify which system changes, if any, are necessary for a legacy system to function reliably under expanded scope.

Appropriate planning and preparation are also key to prevent disruptions to project work and ensure successful task execution when working with legacy systems. Where resource constraints allow, procurement of critical tools and parts with long lead times during the planning or prototyping phases can mitigate schedule risks. Resource availability assessment would be a helpful exercise and is recommended: can the task at hand sustain diversion of personnel/schedule efforts if critical failures occur during the execution phase?

CONCLUSION

While the maintenance of legacy systems with long operational lifetimes poses unique challenges to team members and programs, these challenges provide many growth and learning opportunities. Upon the conclusion of discrete activities in April 2024, the HL-LHC AUP cabling yield was 96% - 6% higher than the targeted yield. The lessons learned have granted valuable insights into cabling hardware and processes at LBNL, and the team expects to further develop its Rutherford cabling technologies to improve the start of the art for superconducting cable manufacturing.

ACKNOWLEDGEMENTS

The authors thank Rick Bloemhard and Hugh Higley for their investigation into the pneumatic system malfunction on the cabling machine. The authors also thank Anjana Saravanan for her development of the turkshead 3D CAD model, as well as Jeff Takakuwa, Ryan Johnson, and Nick Wenner for their support in drivetrain analysis and hardware development. The work performed at Lawrence Berkeley National Laboratory was supported by the Office of High Energy Physics, U. S. Department of Energy, under contract No. DE-AC02-05CH11231.

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