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ROOT CAUSE ANALYSIS INCREASES LOCOMOTIVE RELIABILITY AT AMTRAK

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ABSTRACT

In 2006, Amtrak instituted a program that coupled Reliability Centered Maintenance (RCM) with Root Cause Analysis (RCA) to increase rolling stock reliability. The RCM-RCA program at Amtrak combined features of RCM and RCA into a unique methodology to achieve success. A case study of the High Horsepower electric locomotive (HHP-8) power module failure RCA project is described in this paper. The initial focus of the RCA was a persistently high failure rate of power modules. Power modules are expensive to purchase and labor intensive to replace. Additionally, power module failures take locomotives out of revenue service.

Partially as a result of the HHP-8 Power Module RCA project, and the implemented recommendations, the availability of the HHP-8 locomotive fleet has improved by 80%. Changes were made to the maintenance, condition monitoring, and troubleshooting procedures for HHP-8 as a result of the RCA project. The physical, human, and latent root causes for the high failure rate of HHP-8 Power Modules, were determined and addressed during this six month effort. A cross-functional team of AMTRAK personnel worked closely with reliability consultants and the original equipment manufacturers to determine the various root causes. This case study is a valuable example of how the hands-on nature of a rigorous RCA coupled with the methodology of RCM can result in significant improvements to reliability and availability.

Figure 1: An ECO-B2 Power Module

BACKGROUND

AMTRAK, determined to decrease costs and improve reliability, instituted a program that coupled Reliability Centered Maintenance (RCM) with Root Cause Analysis (RCA). AMTRAK issued a Corporate Maintenance Policy that directed the implementation of Condition-Based Maintenance (CBM) throughout the corporation. In support of the CBM effort AMTRAK is now using RCM techniques to evaluate maintenance practices and produce improvements to eliminate ineffective maintenance processes and focus necessary preventive maintenance to increase the reliability of systems. RCM describes the three types of maintenance as preventive maintenance, corrective maintenance or alterative maintenance. Preventive maintenance, as the name implies, is intended to prevent system failures, corrective maintenance then restores a function lost due to a failure, and alterative maintenance improves capability or system performance. RCM is used to develop all three types of maintenance, but RCA is the tool that is used to determine which type of maintenance is required. The RCM process dictated that a special RCA team be empowered to determine maintenance needs and possible causes. Outcomes from RCA events may result in preventive maintenance procedures which are developed using the RCM methodology.

RCA is used as a supporting tool for the RCM initiatives and, at AMTRAK, is part of the integrated solution. RCM is being accomplished using the Reliability Center Inc (RCI) methodology and their PROACT® software. RCA is a post failure evaluation method to identify the most important causes for equipment failures. RCA is predicated on the belief that problems are best solved by correcting or eliminating root causes, as opposed to merely addressing the immediately obvious symptoms. By directing corrective measures at root causes the likelihood of problem recurrence will be minimized or eliminated. Each RCA will be accomplished on specific troubled systems or components identified by the RCM process or as requested by AMTRAK and will identify design, material, or process changes necessary to improve reliability. Process changes are in turn incorporated into the RCM program to develop preventive measures to eliminate or reduce disruptive failure events.

HHP-8 Power Modules

The HHP-8 locomotive was an AMTRAK asset with such low reliability that the idea of taking the entire fleet out of service was seriously considered. AMTRAK directed the T-Solutions Reliability team to perform an RCA of the HHP-8 power module failures. Figure 1 shows an ECO-B2 power module removed from the locomotive. A Pareto analysis was performed and it was found that of the top twelve systems on an HHP-8, the Power Modules had the highest failure rate as shown in Figure 2. Power module problems originated with the delivery of the HHP-8 locomotive units. It was thought that resolution of this issue alone would bring a substantial positive impact to the reliability of the HHP-8 fleet.

The Alstom designed power system utilized on the HHP-8 locomotive is a complicated system with multiple potential failure modes resulting in a locomotive power loss. The primary power module function is to convert single phase alternating AC power from the main transformer to a constant voltage DC power source and inversion of the DC power to a variable voltage, variable frequency three phase power supplies to each synchronous traction motor.

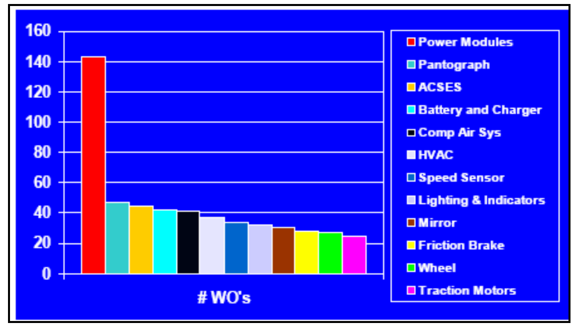

Figure 2: Failure data for HHP-8 fleet

The locomotive control system constantly monitors the performance of each power chain as well as each of the two Gate Turn-Off Thyristor (GTO) semiconductors on every module. If the locomotive detects a problem the power chain is "isolated" and the locomotive will continue to operate without power to the traction motor in that problem chain. The operating engineer's first indication of a propulsion problem is usually a power chain isolation which is reported to the operator as reduced dynamic braking capability or a 25% power loss. This in turn results in speed limitations and potential service schedule delays.

An isolated chain must be investigated and reset by a technician using an external laptop computer loaded with diagnostic software. It is not uncommon for an isolation event to occur randomly, however continued events over a period of time usually indicate an impending propulsion failure.

The term "Power Module" is a general term used to identify the Alstom propulsion components designated ECO-B2, ECO-P2 and ECO-RH2. These components are utilized in the propulsion circuit for traction motors and could be considered the heart of the Electric locomotive. These units have the dual roll of converting Alternating Current to Direct Current and inverting it back to AC. There are four traction motors with five power circuit chains on the HHP-8 locomotive. The fifth power circuit supplies Head End Power (HEP) for the train consist.

On the HHP-8 each power chain contains 5.5 power modules. The half module is the ECO-RH2 module which is shared by two chains and used for dynamic braking. There are 10 modules which are used as Forced Commutation Rectifier Bridges (FCRB) to convert the incoming single phase AC from the main transformer to a 2750V DC source on a common buss referred to as the "DC LINK".

Three modules for each traction motor (one for each phase on each motor totaling 12 modules per locomotive) then invert the DC to a 3 phase variable frequency, variable voltage synchronous AC source used to drive the synchronous traction motors. The frequency and voltage is controlled by the power system control units which turn on and turn off the GTO semiconductors to convert or invert the power current. The control circuit includes the Main Power Unit (MPU) and the Advanced GEC Alstom Traction Electronics Unit (AGATE), the Gate Driver (located on the ECO-B2), and the A613 control power supply. Each HHP-8 locomotive consists of two MPU's, five AGATE's, fifty-four Gate drivers (two per ECO-B2 and ECO-RH2 module), and five A613 power supplies. Each A613 supplies power to one AGATE and the five power modules in that chain.

There is no ECO-RH2 module utilized on the HEP power chain. Each ECO-B2 module has a corresponding ECO-P2 module connected to it. For the purpose of discussion and data analysis this report considers the combination of an ECO-B2 and ECO-P2 module as one power module. The RH modules do not utilize a P2 module. For the HHP locomotive there are a total of 25 ECO-B2/P2 units and 2 ECO-RH2 units.

The ECO-B2 and ECO-RH2 units are water/glycol cooled and utilize the same components within the power circuit, including GTO devices, diodes, and liquid cooled heat sinks (Cooling Devices). The ECO-P2 unit contains capacitors used in the FCRB "H" bridge circuit. Additionally, there are inductors (snubber coils or di/dt coils) and snubber resistors which are located separately from each module.

The Power modules have the following specifications:

- Rated Voltage- 2800V
- Output Current -1300A
- Peak repetitive cut-off current – 2600A
- Weight – 102 lbs

APPROACH

The RCA was conducted using the RCI PROACT® analysis approach. This process seeks to find the "true" root causes of the events being analyzed. According to RCI, the analysis technique has been field-proven and replicates the tasks involved in any investigative occupation. The analysis was conducted to determine the physical, human and latent root causes associated with the events at hand. Below is a quick overview of the RCA process:

1. Preserve Event Data - Outline the measures taken to collect the Parts, Position, People, Paper and Paradigms data.
2. Order the Analysis Team - Delineates the formation of the team and its associated structure.
3. Analyze the Event Data - The use of a disciplined, logical thought process to draw accurate and comprehensive conclusions based on facts.
4. Communicate Findings and Recommendations - The effective and efficient means of getting RCA recommendations implemented through proper communication.
5. Tracking for Bottom-Line Results - Ensuring the sustainability of successful outcomes by monitoring performance of implemented recommendations.

Initial RCA Event Investigation

A cross-functional team of AMTRAK personnel coupled with reliability consultants and the original equipment manufacturers was formed to begin the RCA process for the HHP-8 Power Modules. The first failure event investigated by the RCA team occurred on a locomotive that was shopped as a result of a glycol leak in the central propulsion block. The RCA team conducted a visual inspection of locomotive, performed analysis of all onboard monitoring systems recorded data as well as other data gathered from interviews and activities. All failed power modules were sent to the Wilmington Maintenance Facilities Electric Shop, where a thorough teardown inspection was planned. The power modules were replaced the locomotive was tested and inspected and was returned to Service. Subsequently, the locomotive suffered a second glycol leak in Auxiliary Block, which was found during a planned maintenance cycle. Figure 3 shows a failed ECO-B2 power module from the first investigation.

Figure 3: Failed power module

Prior to April Failure Event AGATE 5, which controls the Auxiliary Block power modules, reported GTO command faults, intermittent DC ground faults followed by over current faults. This pattern was recorded as far back as September of 2005 with reoccurrences in January of 2006 and March of 2006. The unit was shopped in March of 2006 for 92-day planned maintenance, no discernable failure was found. The locomotive was returned to service where this fault pattern continued, until finally on April 10 2006 the unit was shopped for a propulsion system power failure and reported explosion in the power module cabinet. Initial inspection indicated a large glycol leak in the 1-2 Power chain block. Power module 83 in location MOCV-22 was found to have what appeared to be an exploded cooling device component. Glycol leakage was determined to originate from this device. Two other modules were damaged by arcing as a result of the leaking glycol. The modules were replaced and the locomotive was returned to service. Within several days of returning to service the locomotive's sensors indicated DC Link ground faults. The AGATE's were downloaded and analyzed, where it was again noted that there were several instances of intermittent DC link grounds faults. Again no discernable failure could be found, therefore, the locomotive continued to operate in revenue service. On Sunday May 28, after sitting idle for two days, the locomotive was powered up and immediately went into fault with DC link ground faults and power module isolations.

Based on the information available, there were no clear indications as to what was causing the failure, and as a result there were continued attempts to power the locomotive. A more thorough inspection on Tuesday found a glycol leak in Auxiliary block due to an exploded cooling device in IRT-25. Two other power modules, IRT 15 and IRT 25, were replaced as a result of collateral damage.

At this time the locomotive was shopped for its 92 day planned maintenance where repairs were made and the opportunity was taken to perform the DC ground fault investigation procedure as provided by Alstom (Acela Technical bulletin 101 for DC ground faults). The traction motors were checked individually by disconnecting motor leads and checking each for grounds. Prior to returning the locomotive to service the RCA team assisted with checking of all power modules on for DC grounds in accordance with Acela procedure. No grounds were found, however three ECO-B2 modules and two ECO-P2 modules were removed. The ECO-B2 modules had leaking adapters and the ECO-P2 module had damage from the Auxiliary block failure.

The Acela procedure recommends checking all cabling and buss bars, however, the discrepancies between the Acela and HHP-8 configuration prevented this without further evaluation of the proper cables and components to be disconnected. The locomotive was powered up and all system downloads were analyzed for faults by the RCA team. Several problems were noted from the data downloads which required further inspection. These problems were not related to the initial failure. They were corrected and the locomotive was returned to service.

This investigation and series of incidents gave proof to the notion that DC grounds, over current faults, and power chain isolations or any combination of these are justification for removing the locomotive from service. At that time the locomotive will undergo a detailed evaluation and a series of tests and inspections.

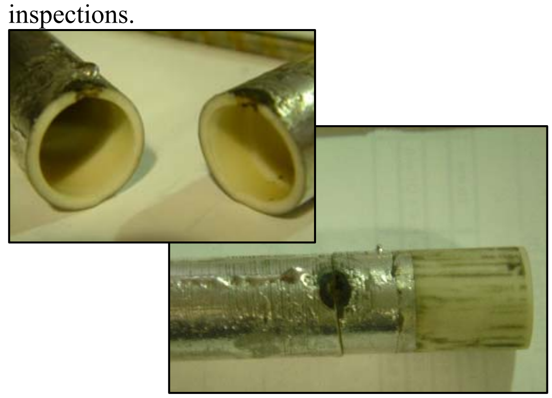

Figure 4: Cooling Device failed Ceramic tube

Intervention during earlier planned maintenance would have been a prime opportunity to investigate the intermittent faults recorded in the onboard data, and could have adverted corrective maintenance required in April and May. Performing the new DC ground investigation procedure during repairs to the April failure event may have adverted the May failure and corrective maintenance. The results of this initial event investigation led the RCA team to conduct further detailed inspections of other locomotives in the fleet. The following recommendations came from the initial RCA event. These recommendations were followed to address and remedy root causes of fleet failures.

1. Continue RCA efforts to determine Cooling device failure root causes
2. Adopt DC ground investigation procedure created for HHP-8 locomotives
3. Replace cooling plate adapters with RCA recommended fittings and Dowty washer
4. Increase the frequency of locomotive systems download and analysis to daily periodicity
5. Establish HHP-8 troubleshooting procedures and protocols to prevent unnecessary damage and maintenance effort

FINDINGS

The PROACT® software and the RCI methodology were utilized to identify potential root causes and track the results of the investigations as they were completed and to verify or eliminate suspected root causes.

Power module functional failures were determined to result from two modes, electrical and mechanical. Electrical failures are generally evident given the functional description noted and are usually represented by non-functioning semiconductors (GTO's or diodes). Mechanical failures include findings of a physical nature. For example, leaking coolant or loose fasteners. Generally a mechanical failure will lead to an eventual electrical loss of function.

Two primary physical root causes were identified from failures of components internal to the power module assembly.

1. Cooling device – Failure of a cooling device sub component was found to be primarily due to small holes in the ceramic cooling tube wall. These tubes pass through the cooling device body (heat sink) and allow the glycol/ water coolant to draw heat from the device and semi-conductors while maintaining an electrical isolation of the coolant. Figure 4 shows a failed ceramic cooling tube that has been disassembled from the power module. The device body is connected to the 2,750V DC bus. The identified holes result in power module electrical failures from DC link ground faults, producing internal arcing and localized flashing of coolant. Over time this will result in power module mechanical failures in the form of ruptured cooling devices (explosion from flashing in clogged tubes) and coolant leakage into the high voltage power module cabinet. Figure 5 is an image of a ceramic cooling device that is arcing due to pinhole leaks.

2. Gate driver assembly – The housing design permits the ingress of water, coolant, and cleaning liquids under the front cover resulting in GTO failures as well as grounded power module assemblies.

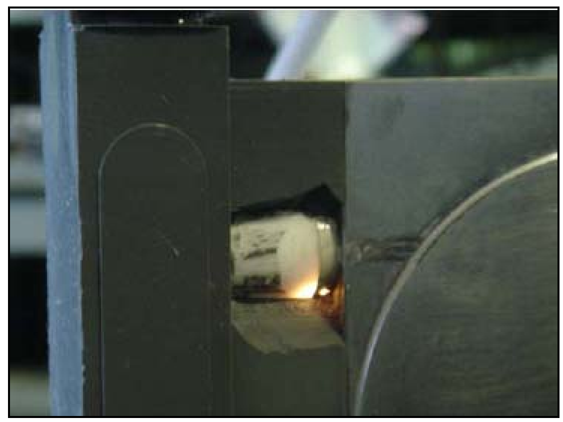

Figure 5: Cooling device with sidewall leakage

GTO failures developing from excessive current were found to be the common result of the identified root causes. The design of the locomotive power circuit and safety features of the operating software will utilize the power modules as the weak link and will sacrifice the GTO's to protect the traction motors.

The RCI method using the PROACT® software was utilized for the RCA to determine the true underlying causes which result in physical failures of components or systems and to organize the data and results in a concise package. These underlying root causes are identified as Human roots which are normally a result of what PROACT® characterizes as Latent Roots. These latent roots are usually findings related to procedures, training, specifications, and/or processes. The Human and

Latent roots that were identified for the Power Module RCA are listed as follows.

1. Quality assurance of ceramic tubes.
2. Insufficient review and actions taken on control system faults, which resulted in continued operation with HV DC link grounds. The daily Preventive Maintenance procedures have been changed to ensure that maintenance events recorded by the HHP-8 condition monitoring system are downloaded and reviewed daily. This data is used to predict imminent failures and allow for scheduled maintenance to be performed prior to failure.
3. Propulsion system isolation reset practices, which contributed to GTO failures from excessive current. Operational and troubleshooting procedures have been updated to prevent GTO failures due to improper reset.
4. Power module cleaning practices, which resulted in fluid ingress into gate driver housings. The 92-Day and Annual Preventive Maintenance procedures have been modified to eliminate excess residual moisture in the central block. Original PM Procedures did not caution maintainers to be aware of standing water left in the central block.
5. OEM repair procedures, which did not correctly identify potential problems and resulted in faulty power modules being returned to service. AMTRAK has worked with OEM and identified requested changes to the process.
6. Shipping and handling methods and containers, which resulted in damage to power module units, normally undetected until placed into service. AMTRAK has changed their packaging and handling to prevent damage during shipping.

CONCLUSION

The availability of the HHP-8 fleet has been increased by approximately 80%, partially due to the recommendations implemented as a result of the HHP-8 RCA project. Changes were made to the maintenance, condition monitoring, and troubleshooting procedures for HHP-8 because of the RCA project. The physical, human, and latent roots causing the high failure rate of HHP-8 Power Modules were determined and a process of addressing those roots was started during this six month effort. Also as a result of the RCA investigation an HHP-8 Oversight Team was formed to continue the process of implementation of the RCA recommendations. This case study is a valuable example of how the hands-on nature of a rigorous RCA coupled with the methodology of RCM can result in significant improvements to reliability and availability.

RCA findings directly resulted in inputs to the RCM review of PM procedures. Daily, 92-Day, and Annual maintenance procedures are being or have been modified using RCM methodology based on the finding of the RCA. Specifically, the use and analysis of the locomotive’s condition monitoring system has been made a daily requirement. The 92-Day and Annual procedures for cleaning power systems equipment have been modified.

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