Proceedings of JPGC'01
2001 International Joint Power Generation Conference
June 4-7, 2001, New Orleans, Louisiana

JPGC2001/PWR-19032

INCORPORATE RCM INTO ACCEPTANCE TESTING TO DETECT LATENT DEFECTS

AVOID WARRANTY ISSUES AND PREMATURE FAILURE

Desi Dundics, P.E.
Equipment Links, Inc.
6345 S. Pecos Rd., Suite #202
Las Vegas, NV 89120
email: ddundics@equipment-LINKS.com

ABSTRACT

While traditional equipment acceptance criteria successfully define functional requirements and help to narrow down the list of qualified vendors and subcontractors, they are often ineffective toward eliminating future failures. These criteria stress functional performance, but rarely provide specific criteria that would indicate the presence of defects that are either latent from manufacturing or caused by poor installation practices. The result is premature system failure and all of the consequences associated with that failure. Regardless of whether the item fails before or after the warranty period, in all likelihood, the disruption in operation, the lost revenues, and the related recovery expenditures can all be avoided.

An approach using Reliability Centered Maintenance (RCM) containing Predictive Testing and Inspection (PT&I) can be very successful in helping to design equipment for optimum performance and identifying defects from installation. In several recent facility acceptance initiatives, PT&I was used to evaluate equipment performance during a traditional acceptance process, and the results were unbelievably disturbing. Even though functional performance was met, approximately 90% of all pumps and fans were either misaligned, improperly balanced, used improper sheaves, or had excessive vibration.[1] A myriad of other equipment demonstrated similar results.

This paper describes the need for RCM based technologies during acceptance, with examples from previous projects. It also develops the complete justification and model format for using RCM in the entire process from procurement through acceptance.

INTRODUCTION

In general, across the industry, the design community perceives themselves to be very good at equipment and system designs. This is certainly not a magic art, and there are volumes of engineering documents that explain the use of engineering calculations and example guidelines for modeling these systems. But even with this expanse of technical information, we continue to experience premature failure. Even over-design does not eliminate the problem. In fact, overdesign emphasizes the problem because the initial costs are higher yet the failures survive.

For the most part, these failures occur not because of bad design, but because the traditional equipment acceptance criteria are inadequate. These criteria usually define functional requirements of the user, and they help a purchasing agent to narrow down the list of qualified vendors and subcontractors. They are not particularly successful in identifying equipment that was mishandled during shipment or installed improperly. When a compressor is dropped off the truck, it is not usually the pressure or capacity that is effected, but rather there is damage to the bearing. This damage may not be evident during commissioning, but it will probably shorten the life of the bearing. Similarly, if the oil is contaminated during installation, there may be no apparent impact during the brief time that the compressor operates for acceptance, but the rotating elements have already started to wear and again will shorten their life. These are merely two simple examples that describe the problem. Had these failures caused personnel or environmental safety concerns, enhanced design and acceptance criteria would have been mandated by codes and regulations to prevent such failures. But when these failures are primarily economic, no such criteria are mandated and the burden of both design and operation rely upon internal measures.

When considering the maintenance community, we discover some organizations having made tremendous strides in techniques to extend the life of equipment. These efforts revolve around the efforts of Reliability Centered Maintenance (RCM), which is the process of generating the optimum mix of applicable and cost effective maintenance actions to improve equipment performance and extend its life. One of the elements of RCM is the use of sophisticated technologies (predictive maintenance) to assess equipment condition, and then to take further investigative or health restorative actions based on meeting specified criteria.

Interestingly enough, as an industry, we have been very slow in incorporating the knowledge from these RCM into the commissioning process.

This paper describes the gap between RCM and commissioning, and further describes how to eliminate the gap. It discusses three basic concepts:

- What is the current commissioning process, and where does it fall short,
- How can we use RCM to identify potential failures caused by defects from manufacturing and installation,
- How can we apply RCM knowledge to improve our acceptance criteria.

This paper will consistently use the example of a common motor driven centrifugal pump to help explain the concepts.

WHAT IS THE CURRENT COMMISSIONING PROCESS, AND WHERE DOES IT FALL SHORT?

In a traditional commissioning document, the typical definitions in a design and acceptance document might be:

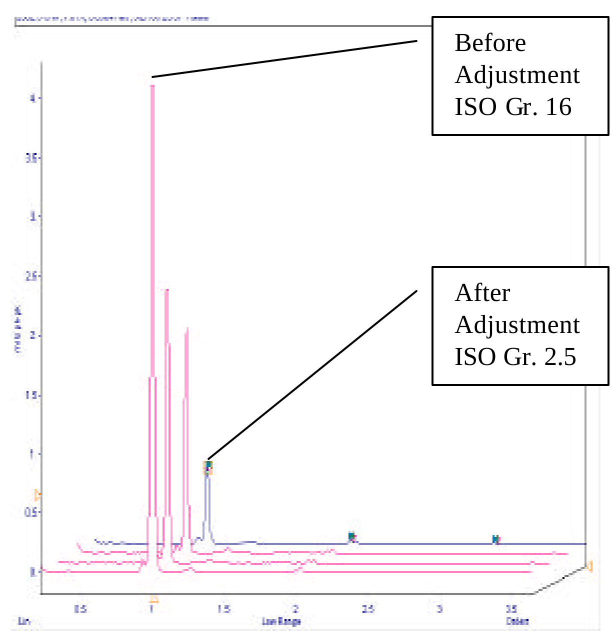
- flow requirements,
- pressure requirements,
- specifications for stages, size, etc.
- specifications for driver, voltage, phases, frequency, etc.,
- specifications for lubrication,
- specifications for any unique or customer requirements,
- specifications for instrumentation.

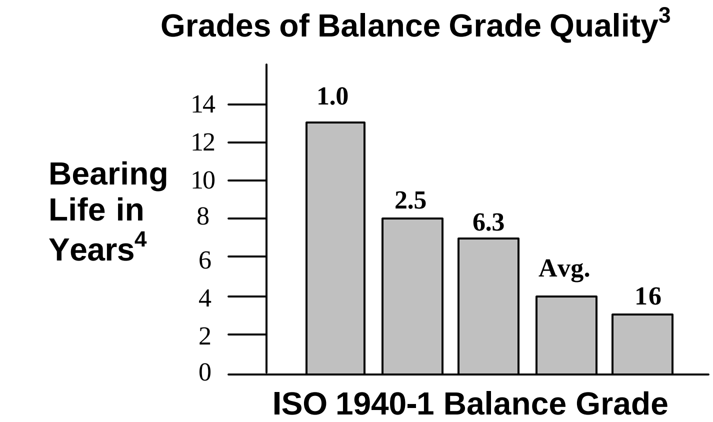
These specifications are sent out for bid, a manufacturer is selected, an installation contractor is selected, and the project is managed and accepted based on meeting the above specifications.

Focusing on the bearings, the specifications may include criteria for the type of bearings that are desired, and sometimes may also include the type of lubrication, but rarely includes criteria for balance and alignment. Experienced installers and inspectors can qualitatively identify when balance and misalignment are not satisfactory, but without specific criteria it may be impossible to enforce a contractor to make necessary adjustments. Any adjustments of this nature may depend entirely on a good working relationship between the two organizations. One way to measure imbalance and misalignment is with vibration analysis, and the bottom line is that if specific vibration criteria are not written into the specification, then there is little recourse by which to force a contractor to make the necessary adjustments.

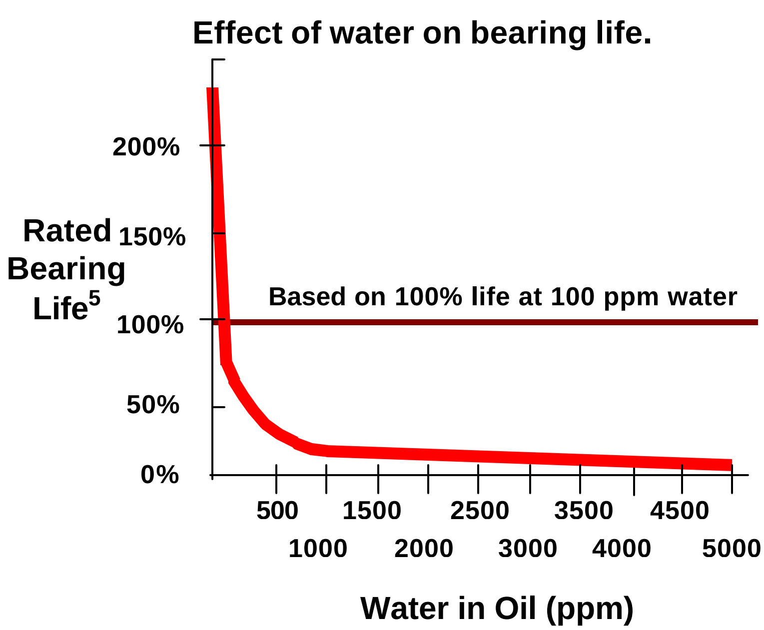
The impact of specifying a balance grade can be significant. In one recent installation, the initial measured grade level of the pump was calculated to be "16" and was adjusted to a grade level "2.5" when measured in accordance with ISO 1940-1[2]. From experience, this would effectively increase the bearing life from 3 years to 8 years. Had this been left unadjusted, the equivalent result is like saying that failure will occur soon after the warranty expires, and would occur three times as often. Although the initial acquisition and installation costs may stay low this way, future operations and maintenance costs will be much higher. The effective life cycle cost of the equipment will be high. The before and after vibration spectrum of the pump are shown below. In addition, the effect on bearing life as a result of balance grade is also shown.

Vibration, Before and After Balancing





In another example with the same pump, potential contamination of the oil with water would also contribute to significant shortening of life of the bearings. As demonstrated in the below graph, measured against a base limit of 100 ppm water, an additional 100 ppm water would reduce the life of the bearing by one half[5]. Unless maximum limits of various oil parameters are specified, this is another situation where the contractor cannot be enforced to comply with ASTM standards.



In the above examples, both vibration analysis and lubricating oil analysis demonstrated significant value in specifying a limit and requiring the installation contractor to adhere to those limits. In other words, these tests are applicable. However, it is not clear if either test is cost effective. If this is a 100 hp critical pump, and it's failure would result in safety consequences or high economic cost, then both tests would be easy to justify. If this was a non-critical 5 hp pump, the oil sample and analysis may be cost effective, but the added cost of vibration analysis would be unnecessary. This topic of cost effectiveness will be addressed later in this paper.

But for now, if these two tests indicated potential benefit in reducing failure and extending life, the question remains: "What other tests might be available that could address other potential failures."

HOW CAN WE USE RCM TO IDENTIFY POTENTIAL FAILURES CAUSED BY DEFECTS FROM MANUFACTURING AND INSTALLATION?

The RCM process is very adept at determining all the ways that equipment could fail by performing what is know as a failure modes and effects analysis (FMEA).

An FMEA contains the below listed four items of information and can be graphically depicted as follows:

FUNTIONAL FAILURE

↳ ***DOMINANT FAILURE MODE***

↳ ***FAILURE CAUSE / EFFECT***

↳ ***RECOMMENDED ACTION***

Step 1. In an FMEA, the analyst first identifies all the functions of the equipment. These functions include secondary functions in addition to the primary ones. Primary functions are those that are normally measured by parameters and can be easily observed during operation. Secondary functions are support related and also include containment. In an FMEA, the functions are reworded as descriptions of the failure to be able to meet that function (i.e. functional failure).

Step 2. Once the functional failures are defined, the FMEA lists all possible <u>observable</u> ways that the equipment would fail to meet those functions. These observations are general in nature, and do not yet identify the actual part or mechanism contributing to these observations. These observations are called dominant failure modes. There can be multiple dominant failure modes for each functional failure.

Step 3. Once the dominant failures modes are defined, the FMEA attaches to each mode the <u>specific mechanisms</u> that could cause those observations to occur. These mechanisms are defined as failure causes. An analysis of each of the failure causes will determine the risk associated with each failure cause, and leads to an assessment of the possible consequences that would occur should a failure happen as a result of that cause. This analysis is called the failure effect.

Step 4. Whenever a failure cause results in an effect that creates more risk than the organization desires, then the risk must be mitigated with some sort of action. This action must be both applicable and cost effective. If no applicable or cost effective action can be defined, and if the risk must be mitigated, then the organization needs to consider redesign that could eliminate or reduce the effects of that failure cause.

The above description of an FMEA is very basic. Further details about developing FMEA's can be obtained from a number of RCM books in the industry.

An analysis of our example pump might lead to the failure tree structure as shown below.

SAMPLE PUMP FAILURE TREE STRUCTURE

Functional Failure	**Dominant Failure Mode**	**Failure Cause**
Low/Inadequate Pump Flow		
	Low pump discharge pressure	
		Casing not completely filled with water
		Partial pump suction blockage
		Pump impeller or wearing rings are worn
	Mechanical seal leaks excessively	
		Seal faces are damaged or not flat
	Pump leaks excessively at stuffing box	
		Defective or improper packing
		Shaft sleeve worn or scored
No Pump Flow		
	Pump does not start	
		Defective motor
		Impeller binding against casing
	Pump fails while running	
		Bent or broken drive shaft
		Improper/inadequate pump bearing lubrication
		Lack of pump bearing cooling water
		Misalignment
		Motor bearing improperly lubricated
		Motor rotor failure
	Excessive noise or vibration	
		Unstable foundation, cracks or mounting not tight
		Cavitation caused by impeller wear
Containment breached		
	External leakage	
		Corrosion of pump casing, fittings, appurtenances
		Defective or improper packing
	Internal leakage	
		Pump impeller or wearing rings are worn
		Internal casing leaks

This failure tree is general for most pumps of the type in our example, and depicts the functions, failure modes and failure causes. It does not yet depict associated consequences of those failures. The next step of the process would be to determine the likelihood that such a failure cause would occur, and to determine the specific consequences that would result. Based on those likelihoods and consequences, the failure causes are ranked in terms of risk and a further determination can be made as to which failure causes are worth trying to eliminate or at least reduce their consequences. Failure causes that have a relatively high or medium level of risk must be mitigated with a cost effective action.

To demonstrate assessment of risk, consider our example pump in a auxiliary water service where there is an installed spare. When the primary pump fails, the spare pump starts automatically and function is preserved. Consider, alternately, that the same pump is installed in an oil service for the main turbine where there is no spare. Should that pump fail, the entire turbine must be removed from service and revenues are jeopardized. It is the same pump in both situations, yet they have two completely opposite consequences. The amount of time, resources and money invested to maintain the pump should be consistent with the consequences when that failure cause occurs.

HOW CAN WE APPLY RCM KNOWLEDGE TO IMPROVE OUR ACCEPTANCE CRITERIA?

The above process primarily describes how the FMEA pertains to the operations and maintenance community, and the resultant actions are those that are performed during the continued and long-term operation of the equipment. The same process is adapted for design and acceptance purposes to identify immediate defects that need to be eliminated, and also to identify future maintenance requirements that must be part of the design.

- Consider that each failure cause is not one that develops over time, but rather that it occurs during installation. If our example pump was dropped off the edge of the truck but does not look damaged, how can we find the defects that might not impede immediate performance, but will definitely shorten its expected life?

  Examples of acceptance actions that are designed to look for the above could include the following:

  - <u>vibration analysis</u> to verify balancing, alignment and bearing related defects. Alignment can also be verified using laser alignment techniques.
  - <u>sample</u> and <u>analyze the lubricating oil</u> to verify that the oil is correct and not contaminated,
  - perform <u>performance (pump) test</u> to ensure proper flow, pressure and efficiency,
  - <u>infrared thermography</u> to verify motor connections and hot bearings
  - <u>power factor and insulation resistance tests</u> to verify acceptable levels of power loss through insulation that could also be due to dirt and moisture,
  - <u>high voltage test</u> to verify windings and connections,
  - <u>motor tests</u> such as motor circuit or flux analyses to verify the condition of the complete motor circuit.

- Use the FMEA and future maintenance actions to ensure that the design allows those actions to be performed.

  - if future maintenance actions require vibration analysis, then ensure that the design identifies the required vibration sensor points and that appropriate sensors and vibration pads are included in the equipment specification,
  - if oil analysis is a requirement, then ensure that there is an accessible oil port for taking the samples.

WHEN DOES USING PT&I FOR ACCEPTANCE MAKE SENSE ?

Design engineers should understand that considerations during design can benefit the later stages of maintenance and operations. The acceptance criteria and the associated acceptance documents provide significant benefit toward integrating the design community with the O&M community. These technologies will define what technologies will be required to verify a defect free acceptance, what technologies will be required for equipment condition assessment and maintenance, who will be involved in supporting those technology initiatives, and when during the entire process will those technologies be required.

Design engineers should also understand that enhanced design features may increase the cost of acquisition and installation, so those additional features should only be included when it is cost effective over the entire life-cycle of the equipment to do so. It is not the intent of the acceptance criteria to unnecessarily drive up the cost of equipment installations and contractor work. If the cost of the added inspections and the cost of enhanced equipment designs outweigh their performance and life-cycle value, then obviously requiring overly restrictive acceptance criteria should not be used. The acceptance criteria should define the “minimum” limits essential for a good, quality installation.

SUMMARY

The process elements of RCM and predictive technologies can be very helpful in supporting the “forward-thinking” vision that value and cost span the entire life of equipment. Recognizing that installation defects play a critical role in shortening the desired life of our equipment, we need to be better at identifying those defects and enforcing installation contractors to eliminate them. Even though the extra identification of the defects may cause acquisition costs to rise, the benefits could be tremendous, extending the life of equipment, increasing equipment reliability and effectively mitigating risk of failure.

An additional benefit of proactively integrating RCM with the design process, is that an organization effectively bridges the gap between design and O&M to create an optimum solution for system productivity. Communication is improved, and the entire culture of the organization becomes one step closer to the vision of a cohesive work group service team.

REFERENCES

[1] “Reliability Centered Building and Equipment Acceptance Guide”, National Aeronautics and Space Administration, January, 2001

[2] ISO 1940-1:1986 Mechanical Vibration – Balance Quality requirements of Rigid Motors – Part 1: Determination of permissible residual balance.

REFERENCES (Continued)

[3] ISO 1940-2: 1997 Mechanical Vibration – Balance Quality Requirements of Rigid Motors – Part 2: Balancing Errors

4 "Balanced Parts, Waking to Reality", M. Span, *SMRP Winter Newsletter*

[5] "Clean Up Your Oil And Keep It Clean!", Dave Whitfield, *Orbit*, 4th Qtr 1999

ABOUT THE AUTHOR

Desi Dundics, P.E. is President and Founder of Equipment Links, Inc. He is a 1975 US Naval Academy graduate, naval nuclear plant qualified Chief Engineer, and has been providing consulting, RCM, CMMS and maintenance optimization support to utilities and general industry for over 20 years. He can be contacted at (702) 454-1939.