Lifetime Reliability • Solutions

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# How to Change RCM2 to Get Really Useful Maintenance Strategy

This is a tutorial that shows you how to get greater reliability with a better maintenance strategy than what typical comes from using Reliability Centered Maintenance (RCM) methodology.

Though the logic of RCM is faultless and the maintenance strategy recommendations that result seem sound and sensible—the final result is not effective in delivering real reliability improvement to its Users. In this tutorial you will see how to combine Physics of Failure Analysis and Operational Risk Management with RCM to produce reliability creating and cost reducing maintenance strategy.

Reliability Centered Maintenance started as the MSG-1 (Maintenance Steering Group) process in the USA aircraft industry during the 1960s and progressed through stages 2 and 3 to what is now called in non-aircraft industries as RCM. Along the way RCM has had many variants from attempts to simplify the methodology, including RCM2, Lean RCM, RCM Turbo and more.

RCM2 was made famous by the late John Moubrey in his books on Reliability Centered Maintenance. It is a structured methodology using logic to arrive at reliability maintenance strategy for physical assets. The logical question set used in RCM2 is shown in Figure 1.

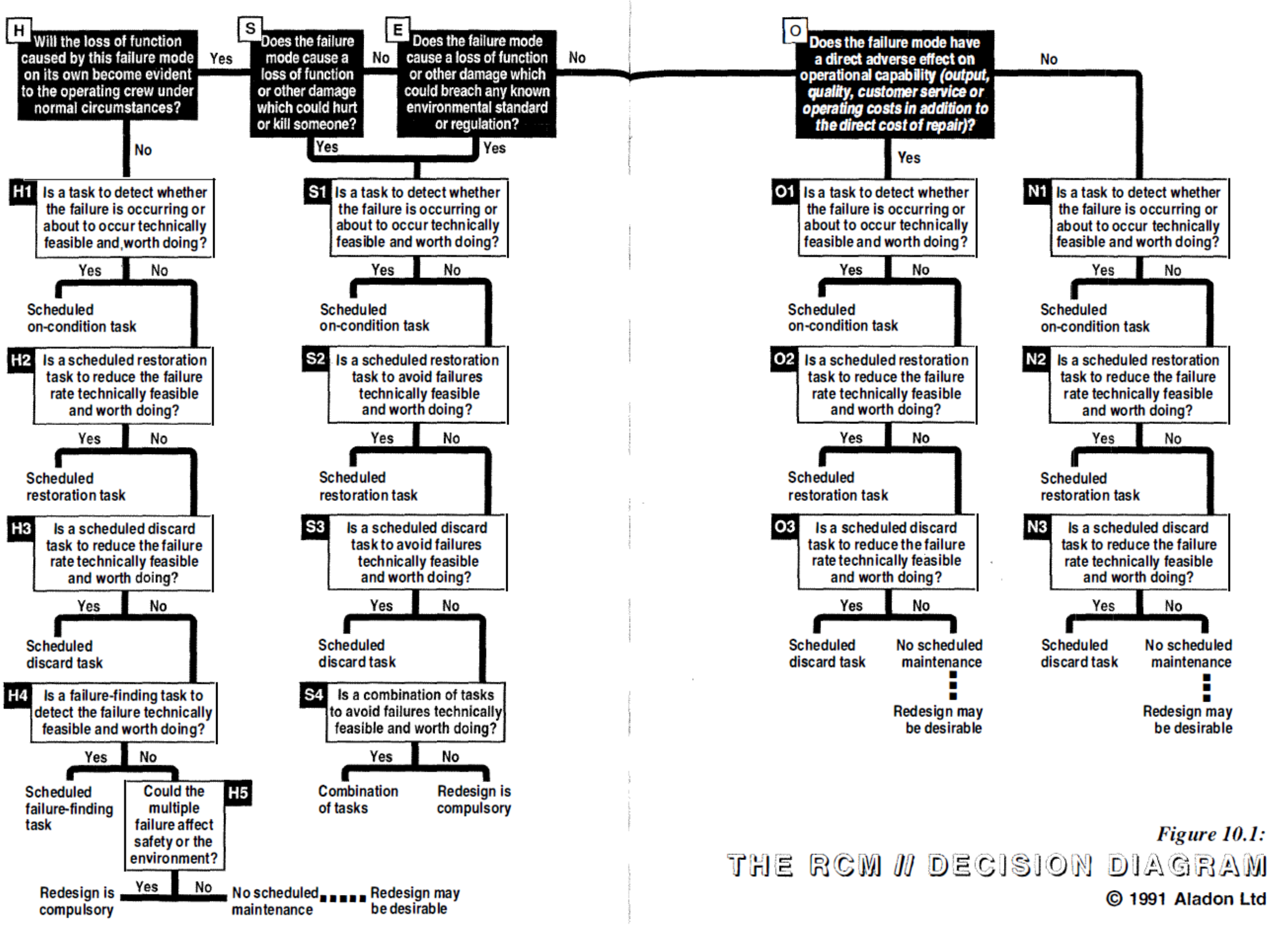


Figure 1 RCM2 Decision Logic Diagram

We will take an example of a standard RCM analysis and turn it into outstanding RCM analysis. A portion of the results from a standard RCM of the boiler feedwater pump in Figure 2 is shown in the resultant spread sheet of Table 1.

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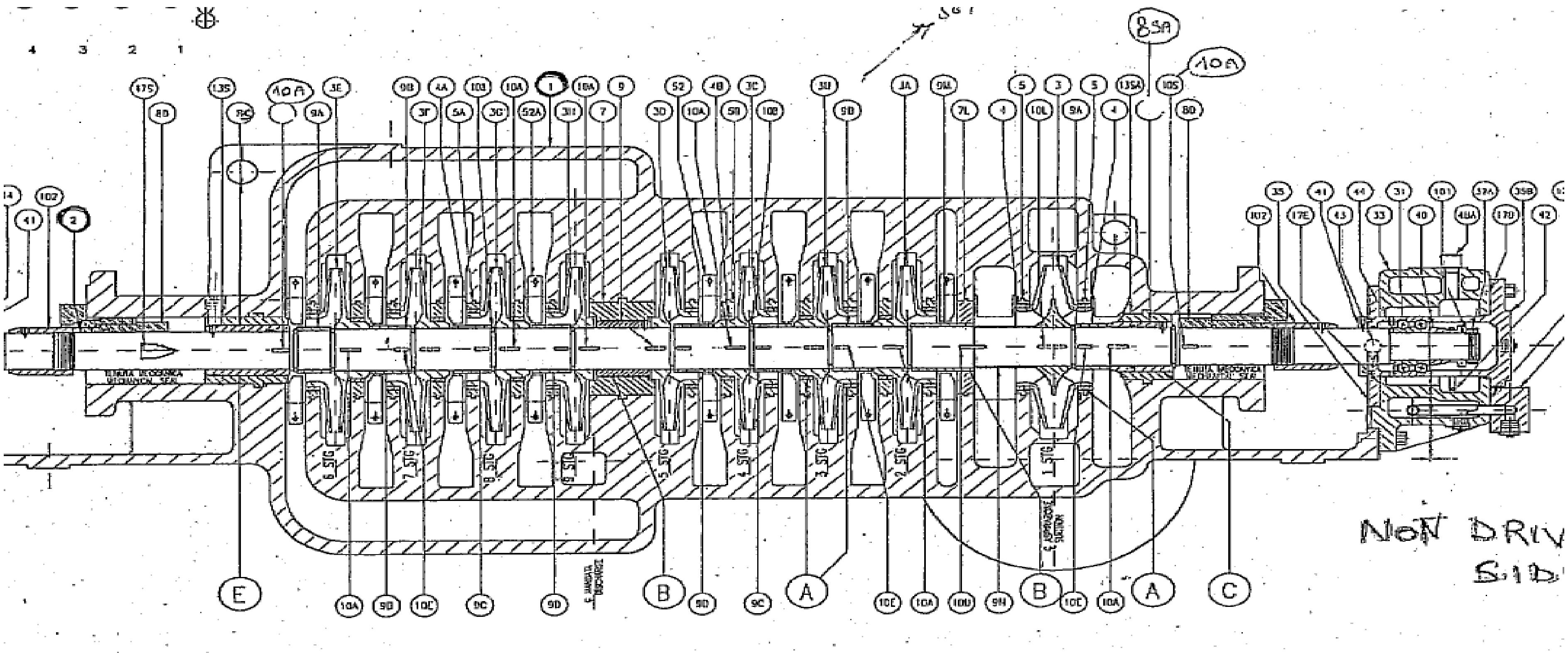


LISTA DELLE PARTI – LIST OF PARTS

| MARCA ITEM | DESCRIZIONE | DESCRIPTION | MARCA ITEM | DESCRIZIONE | DESCRIPTION | MARCA ITEM | DESCRIZIONE | DESCRIPTION |
|---|---|---|---|---|---|---|---|---|
| 1 | CORPO POMPA | CASE | 8A | CAMICIA ALBERO TENUTA MECCAN. | SHAFT SLEEVE SEAL | 32A | DADO BLOCCAGGIO | LOCKNUT |
| 2 | ALBERO | SHAFT | 9 | CAMICIA INTERMEDIA ALBERO | INTERMEDIATE SHAFT SLEEVE | 33 | SUPPORTO CUSCINETTI | BALL BEARING HOUSING |
| 3 | GIRANTE 1° STADIO | IMPELLER 1ST STAGE | 9A | CAMICIA DISTANZIATRICE ALBERO | INTERMEDIATE SHAFT SLEEVE | 35 | COPERCHIO SUPPORTO | BEARING COVER |
| 3A | GIRANTE 2° STADIO | IMPELLER 2ND STAGE | 9B | CAMICIA DISTANZIATRICE ALBERO | INTERMEDIATE SHAFT SLEEVE | 35A | COPERCHIO SUPPORTO | BEARING COVER |
| 3B | GIRANTE 3° STADIO | IMPELLER 3RD STAGE | 9C | CAMICIA DISTANZIATRICE ALBERO | INTERMEDIATE SHAFT SLEEVE | 35B | COPERCHIO SUPPORTO | BEARING COVER |
| 3C | GIRANTE 4° STADIO | IMPELLER 4TH STAGE | 9D | CAMICIA DISTANZIATRICE ALBERO | INTERMEDIATE SHAFT SLEEVE | 40 | ANELLO CENTRIFUGATORE | OIL RING CARRIER |
| 3D | GIRANTE 5° STADIO | IMPELLER 5TH STAGE | 9M | CAMICIA INTERMEDIA ALBERO | INTERMEDIATE SHAFT SLEEVE | 41 | ANELLO PARAOLIO | BEARING SHIELD – INNER |
| 3E | GIRANTE 6° STADIO | IMPELLER 6TH STAGE | 9N | CAMICIA DISTANZIATRICE ALBERO | INTERMEDIATE SHAFT SLEEVE | 41A | ANELLO PARAOLIO | BEARING SHIELD – OUTER |
| 3F | GIRANTE 7° STADIO | IMPELLER 7TH STAGE | 10 | LINGUETTA GIUNTO | COUPLING KEY | 42 | ANELLO DI LUBRIFICAZIONE | OIL RING |
| 3G | GIRANTE 8° STADIO | IMPELLER 8TH STAGE | 10A | LINGUETTA GIRANTE/CAMICIA | IMPELLER KEY/SLEEVE KEY | 43 | OLIATORE A LIVELLO COSTANTE | COSTANT LEVEL OILER |
| 3H | GIRANTE 9° STADIO | IMPELLER 9TH STAGE | 10D | LINGUETTA CAMICIA INTERN. | KEY–INTERMEDIATE SHAFT SLEEVE | 44 | ANELLO DI SPALLAMENTO | BEARING SHOULDER RING |
| 4 | ANELLO USURA GIRANTE | IMPELLER WEAR RING | 10E | LINGUETTA CAMICIA INTERN. | KEY–INTERMEDIATE SHAFT SLEEVE | 48A | FILTRO ARIA | AIR FILTER |
| 4A | ANELLO USURA GIRANTE | IMPELLER WEAR RING | 10L | LINGUETTA GIRANTE 1° STADIO | IMPELLER KEY 1° STAGE | 52 | FRANGIFLUSSO – MANO DESTRA | SPLITTER – RIGHT HAND |
| 4B | ANELLO USURA GIRANTE | IMPELLER WEAR RING | 10S | LINGUETTA CAMICIA | KEY SLEEVE | 52A | FRANGIFLUSSO – MANO SINISTRA | SPLITTER – LEFT HAND |
| 5 | ANELLO USURA CORPO | CASE WEAR RING | 13S | BUSSOLA DI FONDO | THROTTLE BUSHING – SEAL | 80 | TENUTA MECCANICA | MECANICAL CEAL |
| 5A | ANELLO USURA CORPO | CASE WEAR RING | 13SA | BUSSOLA DI FONDO | THROAT BUSHING – SEAL | 101 | ROSETTA DI FERMO | LOCKWASHER |
| 5B | ANELLO USURA CORPO | CASE WEAR RING | 17D | GUARNIZIONE COPERCHIO SUPPORTO | GASKET BEARING COVER | 102 | CAMICIA ALBERO | SHAFT SLEEVE |
| 7 | ANELLO DI SEPARAZIONE CORPO | CASE SEPARATING RING | 17E | GUARNIZ. SERPENT. DI RAFFRED. | GASKET HEAT EXCHANGER | 102A | CAMICIA ALBERO | SHAFT SLEEVE |
| 7L | ANELLO DI SEPARAZIONE CORPO | CASE SEPARATING RING | 17S | GUARNIZIONE CORPO POMPA | GASKET – CASE SPLIT | 108 | ANELLO DI SPALLAM. GIRANTE | LOCATING RING – IMPELLER |
| 8 | CAMICIA ALBERO TENUTA MECCAN. | SHAFT SLEEVE SEAL | 31 | CUSCINETTO A SFERE | BALL BEARING | 134 | ASS. SERPENTINA RAFFR. | HEAT EXCHANGE ASSEMBLY RADIAL |

| Rev. | Descrizione – Description | Prep'd | Cont–Chk'd | App–Appr'd | Data – Date |
|---|---|---|---|---|---|
| 1 | REVISIONE DEI BOLLINI "VALORI GIOCO"-REVISED "VALUES CLERANCE" | DPF | [illegible] | [illegible] | 23/12/99 |
| 0 | EMISSIONE – ISSUE | DPF | FEBBRILE | [illegible] | 24/10/99 |

Titolo – Title: SECTION CENTRIFUGAL PUMP TYPE : Y 3x9 WMSNDH9/Sig.

**Nuovo Pignone** BARI

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Lavoro – Lang.: I — Foglio – Sheet: 1/1

Figure 2 Multistage Centrifugal Boiler Feed Water Pump for RCM2 Maintenance Strategy Analysis

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| | FUNCTION | | FUNCTIONAL FAILURE ( Loss of Function) | | | FAILURE MODES ( Causes of Failures) | | FAILURE EFFECTS | Consequencies | | | | H1 S1 O1 N1 | H2 S2 O2 N2 | H3 S3 O3 N3 | DEFAULT ACTION | | | Proposed Task |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Modes | Causes classification | | H | S | E | O | | | | H4 | H5 | S4 | |
| 1 | To Supply water to Boilers | A | Unable to flow water at all | 1 | Impeller failure | Impeller adrifts due to mounting nut/key | assembly errors | The loose impeller will damage the pump diffuser area and downtime will be 1 week | N | N | N | N | Y | | | N | | | Train Millwright and verify the impeller and shaft interference fit area duringoverhauling |
| | | | | | | Cavitation | operational upset | 1st stage Impeller will be damaged. Downtime will be 1 day | N | N | N | N | | | Y | N | | | Continuously monitor the flow condition upstream of pun |
| | | | | | | Improper clearnaces in overhauling/ bent shaft | assembly errors | The impeller will be damaged and complete overhaulng will be required. Downtime will be 1 week | Y | N | N | Y | Y | | | | | | Train Millwright and Verify these readings in Overhauling |
| | | | | 2 | Shaft fails | Shear due to fatigue failure | Wear mechanism | Shaft will be damaged .Downtime will be 1 week | N | N | N | N | | | Y | N | | | Replace the shaft after suitable time depending upon failu history |
| | | | | | | Overload Failure | operational upset | Shaft will be damaged .Downtime will be 1 week | Y | N | N | N | Y | | | | | | Continuously monitor the flow conditions of pump |
| | | | | | | | Unbalance/ Misalignment | | N | N | N | N | Y | | | N | | | Monitor the vibration of pump for unbalance and misalignment |
| | | | | 3 | Valves fail open | Valves left open | Operational error | Standby pump will be driven in reverse direction | Y | N | N | Y | | | | Y | | | Check the condition of upstream and downstream valves |
| | | | | | | Valve spindle seized due to corrosion | Corrosion mechanism | Standby pump will be driven in reverse direction | Y | N | N | Y | | | | Y | | | Check the condition of upstream and downstream valves |
| | | | | 4 | Valves fail closed | Valves left shut | operating error | High pressure build up damage pump parts and casing.Down time will be one week | Y | Y | N | N | | | | Y | | | Check the condition of upstream and downstream valves |
| | | | | | | Valve spindle seized due to corrosion | Corrosion mechanism | High pressure build up damage pump parts and casing.Down time will be one week | Y | Y | N | N | | | | Y | | | Check the condition of upstream and downstream valves |
| | | | | 5 | Bearing failure | Normal wear and Tear | Wear mechanism | Bearing will produce high vibration and noise. Downtime will be one day | Y | N | N | N | Y | | | | | | Monitor the vibration signature for abnormality |
| | | | | | | Electrostatic damage | Static charges | High vibration due to pitting of bearing.Downtime will be one day | N | N | N | N | Y | | | N | | | Monitor the vibration signature for abnormality |
| | | | | | | Overload Failure | Operational upset | Bearing wll be damaged .Downtime will be one day | Y | N | N | N | Y | | | | | | Continuously monitor the flow conditions of pump |
| | | | | | | | Misalignment/ Unbalance | | N | N | N | N | Y | | | N | | | Monitor the vibration of pump for unbalance and misalignment |
| | | | | | | Lubrication Failure | Lack of lubrication | High vibration and noise and siezure of bearing.Downtime will be one day | N | N | N | N | Y | | | N | | | Monitor the vibration signature for abnormality |
| | | | | | | | Over Lubrication | High temperature of bearing housing and pump will overload. Downtime will be one day | Y | N | N | N | Y | | | | | | Monitor the vibration signature for abnormality |
| | | | | | | | Lubrication degradation | High vibration of bearing.Downtime will be one day | N | N | N | N | Y | | | N | | | Monitor the condition of lube oil for abnormality |
| | | | | | | Wrongly installed | Assembly errors | Sudden seizure of bearing after start up.Downtime will be one day | Y | N | N | Y | Y | | | | | | Train Millwright and verify the interfernce fits in Overhauling |
| | | B | Low Flow | 1 | | Valves partially open | Operational upset | High overload stresses on pump parts and temperature rise . | Y | N | N | Y | Y | | | | | | Continuously monitor the flow conditions of pump |
| | | | | 2 | | Low NPSH availabe | | | Y | N | N | Y | Y | | | | | | |
| | | | | 3 | | Cavitation | | | Y | N | N | Y | Y | | | | | | |
| | | C | Insufficient Pressure | 1 | | Internal wear | | High power demands and impeller damage due to high flow | Y | N | N | Y | Y | | | | | | Continuously monitor the flow conditions of pump |
| | | | | 2 | | choking | | | Y | N | N | Y | Y | | | | | | |

Table 1 RCM2 Analysis Table for Boiler Feed Water Pump Maintenance Strategy

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The RCM strategy recommendations on the right hand side are shown again in Table 2.

| Proposed Task |
|---|
| Train Millwright and verify the impeller and shaft interference fit area duringoverhauling |
| Continuously monitor the flow condition upstream of pump |
| Train Millwright and Verify these readings in Overhauling |
| Replace the shaft after suitable time depending upon failure history |
| Continuously monitor the flow conditions of pump |
| Monitor the vibration of pump for unbalance and misalignment |
| Check the condition of upstream and downstream valves |
| Check the condition of upstream and downstream valves |
| Check the condition of upstream and downstream valves |
| Check the condition of upstream and downstream valves |
| Monitor the vibration signature for abnormality |
| Monitor the vibration signature for abnormality |
| Continuously monitor the flow conditions of pump |
| Monitor the vibration of pump for unbalance and misalignment |
| Monitor the vibration signature for abnormality |
| Monitor the vibration signature for abnormality |
| Monitor the condition of lube oil for abnormality |
| Train Millwright and verify the interfernce fits in Overhauling |
| Continuously monitor the flow conditions of pump |
| Continuously monitor the flow conditions of pump |

Table 2 Resultant RCM2 Strategy

## RCM recommendations do not get reliability

Most companies would take those recommendations at face value and put them directly into a work order, thinking that because they came from RCM analysis they must produce reliability. It is an easy trap to fall into.

The outcomes are sensible—yes, as the top recommendation states, impellers must have the right fit and tolerance and the shaft must be straight. But those RCM outcomes will not get you reliability—they do not tell you how precise the fit must be, or how straight the shaft needs to be, to get a highly reliable impeller/shaft life.

The RCM recommendations are incomplete, and if used in a work order as described that are flawed because they provide no guidance on how to create reliability. They do not contain the important information that causes reliability.

What should have been written for the first recommendation is, “Train the Millwright to verify the impeller bore and shaft interference is a sliding H6/h6 fit, with a form of IT 7, and with a lathe-turned surface finish of Ra 3.2 micrometre.” Once the impeller bore is at those conditions you will get a reliable service life.

If an activity is to ‘check the condition’ you must also give specific detail on when the condition is acceptable and when it is not acceptable, along with what to do to get it right if it is wrong.

Identifying the necessary specifications needed for reliability cannot be done with standard RCM recommendations. The recommendations from an RCM analysis merely get you considering what is important to control in order to get reliability. You then must specify the exact conditions that produce the reliability you need.

## RCM Condition Monitoring inspections give you high maintenance costs

It is a natural human nature to be risk adverse. An RCM Team will keep adding inspection tasks to check equipment condition as the RCM analysis progresses. You can see in Table 2 that the added tasks are nearly all for inspections. Bear in mind that the pump is already in service and has been operating for years. Never before had those inspections been necessary, but during the

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RCM analysis they were included as required additional work that will make the pump more reliable. Really; will the pump actually become highly reliable because it is inspected more often? What a load of rubbish! RCM condition monitoring recommendations cause you to increase man-hours on pointless maintenance inspections that add maintenance costs.

To protect against false decisions and unnecessary costs each RCM recommendation must be economically justified to prove that its use will make money. Start doing Profit-Centred Maintenance and financially model the benefits a RCM suggestion brings the operation. If there is no money in doing the suggested maintenance task then do not do that recommendation.

There is another financial problem in accepting RCM outcomes to do condition monitoring. A maintenance strategy to 'Monitor the vibration signature for abnormality.' will not bring reliability. To get reliability you must not have abnormal vibration. By the time you detect high bearing vibration it is far too late—the bearing is already failed. RCM will get you doing hundreds of bearing vibration checks that incur high maintenance costs while your equipment will still be out-of-service; though not from breakdowns: but from doing maintenance to replace bearings before they breakdown. Your breakdowns will fall and your corrective maintenance and inspection costs will rise.

If your equipment is reliable extra RCM-justified condition monitoring is an unnecessary and expensive maintenance strategy. In reliable operations you would apply PMO (Preventive Maintenance Optimisation) and rationalise the maintenance tasks to those that protect the operation from high operating costs.

The above explanations (RCM does not bring reliability but adds more inspections that increase maintenance costs) are why RCM has failed most users at delivering reliability and lowering maintenance expense. RCM practised as it is championed in RCM2 books does not bring you great reliability or markedly lower maintenance costs because it cannot deliver those outcomes.

There is a supplimentary solution to use with RCM that will let you draw the right maintenance strategy conclusions. You can pick the right life cycle asset management strategy to get high reliability and low cost maintenance.

**Physics of Failure Analysis**

Physics of Failure Analysis (POFA) examines why the materials-of-construction fail. Not only do you identify what can fail, you also identify what occurrences, situations and events to prevent so there will be no failure. POFA focuses you on what destroys reliability. Instead of reacting to operating risk with added inspections to find a failure that has started, you are challenged to act proactively and prevent the causes of a failure starting in the first place. You must still justify the new work with financial modelling to prove that it brings added profits and not added costs. In POFA you use a16x13 risk matrix to immediately prove that your recommendation will make more operating profit.

We start the POFA by selecting a component to be analysed and the location to be investigated. The circle on Figure 3 indicates the POFA will be for the final 9th stage impeller bore-to-shaft position.

Unlike RCM, in POFA we do not require a team of knowledgeable people to brainstorm the failure modes and their numerous causes. POFA relies on using a table of all known causes of

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material-of-construction failure. This table is a 'live' document and is continually updated with the corporate learning and knowledge from the organisation and its people.

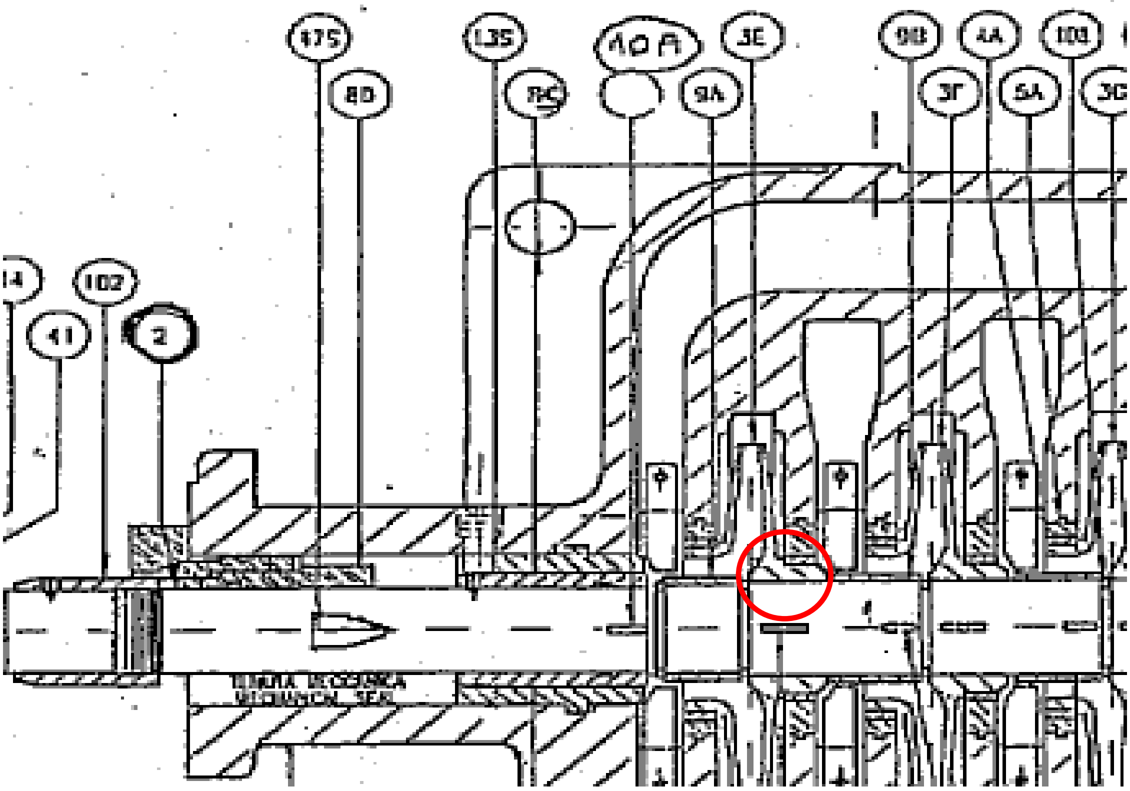


Figure 3 Location for Pump Impeller Physics of Failure Analysis

Table 3 shows a portion of a company's POFA table with its lists of dozens and dozens of known causes of materials failure. From the POFA table we only select the causes of materials-of-construction failure that can happen to the component at the chosen location.

Table 4 is the final list of causes to be taken into the RCM analysis for the 9th Stage Impeller. You can see that the impeller can be failed by more than the three reasons noted in the standard RCM2 table.

Unlike RCM, which addresses operational service, a POFA considers the life-cycle of the component. You consider when and where failure can be initiated throughout its life. The POFA guidewords table makes possible to consider multitudes of scenarios that lead to failure of component materials-of-construction never thought of in RCM Analysis.

The next step is to rationalise which failure causes will be taken into the final analysis. Though failure can be initiated during design, chemical formulation, smelting, ingot making, and original manufacture, you do not normally consider them in a pump impeller RCM/POFA as they are out of your control.

What remains of the POFA list that is controllable is noted in Table 5. Included are both the causes of failure and the situations during its service life when they can arise.

The RCM table is lengthened to cater for the greater number of failure causes. Once the causes are listed the RCM is continued through to its natural conclusion using the standard set of logic questions. The depth of understanding gained on impeller bore failure allows one to pick a combination of operational and maintenance controls over the causes of impeller failure.

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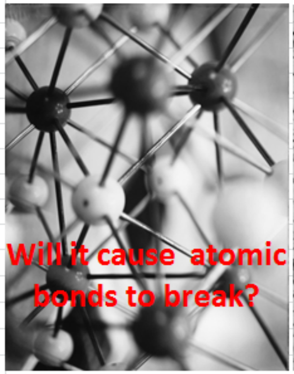
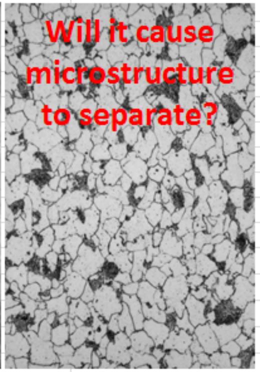
| Physics of Failure Guidewords | | | | | |
|---|---|---|---|---|---|
| **Factors that cause Atomic or Microstructure Failure** | **Component Manufacturing Events** | **Component Operational Stress Events** (Horizontal, Vertical, Axial) | **Component Environmental Events / Conditions** | **Electronic / Electrical Effects** | **Component Life Cycle Situations** |
| Compressive force overload | Metallurgy error | Pressure | Thermal high | Electrical discharge | Conception |
| Tensile force overload | Formulation error | Under-loaded | Thermal low | Electromagnetic | Feasibility |
| Shear force overload | Process conditions error | Interference fit tight | Microbial/bacterial attack | Electrostatic | Approval |
| Cyclic stress fatigue | Chemical composition error | Interference fit loose | Erosion | Metal migration | Final Design |
| Shock force overload | Interference fit tight | Insufficient load (looseness) | Corrosion (pitting, galvanic, crevice, etc) | Threshold Voltage Shift | Project Management |
| Punch hole in molecular structure | Interference fit loose | Physical deformation (bend, twist, squash) | Density gradient | Leakage current | Installation |
| Melt molecular structure | Misalignment | Pressure hammer | Thermal gradient | Power dissipation | Manufacture |
| Crack in molecular structure (dislocation) | Foreign inclusion | Shrinkage | Radiation | Stray electrical current | Assembly |
| Material missing from molecular structure | Thin cross section | Expansion | Diffusion | Ionisation | Operation |
| Material ripped from molecular structure | Weld penetration | Misalignment | Humidity | Tin Whiskers | Maintenance |
| Wrong atoms in molecular structure | | Unbalance | Contaminant ingress | Electromigration | Overhaul / rebuild |
| Electromagnetic radiation | | Punch (Impact load on small area) | Moisture ingress | Time Dependent Dielectric Breakdown | Transport |
| Chemical reaction | | Hydraulic shock | Product ingress | Hot Carrier Injection | Storage |
| Crystal lattice attack | | Vibration shock | Chemical reaction | Negative Bias Temperature Instability | Restitution |
| Depolymerisation | | Abrasion (wear material away) | Rate of change of event | | |
| | | Hammer impact | Lubrication degradation | | |
| | | Gouge | Oxidisation | | |
| | | Impingement (jet of fluid) | Dissimilar materials | | |
| | | Foreign inclusion in material-of-construction | Hygro-mechanical (moisture absorption) | | |
| | | Detach-debond-delaminate | Inclusions in contacting process | | |
| | | Acts-of-God/Acts-of-Nature | Crystal lattice attack | | |
| | | Fracture | Elasticity degradation | | |
| | | Buckling | Vibration | | |
| | | Yield | Shock | | |
| | | Creep | Temperature Testing | | |
| | | Material fatigue | »»Operating – High and Low Temperature | | |
| | | Physical abuse | »»Storage and Transportation – High and Low Temperature | | |
| | | Vehicle impact | »»Temperature Shock | | |
| | | Soft material of construction (ease of wear) | Humidity – Condensing and non-condensing | | |
| | | | Altitude | | |
| | | | »»Operational/Storage/Transportation | | |
| | | | »»Temp/Altitude | | |
| | | | Rapid Decompression/Explosive Decomp | | |
| | | | Combined Environments | | |
| | | | Solar Radiation – actinic and thermal effects | | |
| | | | Salt Fog | | |
| | | | »»NaCl | | |
| | | | »»Artificial Seawater | | |
| | | | Sand and Dust | | |
| | | | Rain | | |
| | | | Immersion | | |
| | | | Explosive Atmosphere | | |




PoF Strategy Development | PoF Guidewords | Risk Matrix | Taken into POFA

Table 3 Physics of Failure Analysis Guidewords Table

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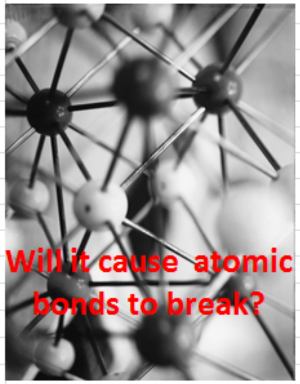
| | B | C | D | E | F | G |
|---|---|---|---|---|---|---|
| 1 | **Physics of Failure Guidewords** | | | | | |
| 2 | **Factors that cause Atomic or Microstructure Failure** | **Component Manufacturing Events** | **Component Operational Stress Events** (Horizontal, Vertical, Axial) | **Component Environmental Events / Conditions** | **Electronic / Electrical Effects** | **Component Life Cycle Situations** |
| 3 | Compressive force overload | Metallurgy error | Pressure | Thermal high | | |
| 4 | Tensile force overload | Formulation error | | | | |
| 5 | Shear force overload | Process conditions error | Interference fit tight | | | |
| 6 | Cyclic stress fatigue | Chemical composition error | Interference fit loose | Erosion | | Final Design |
| 7 | Shock force overload | Interference fit tight | Insufficient load (looseness) | Corrosion (pitting, galvanic, crevice, etc) | | |
| 8 | Punch hole in molecular structure | Interference fit loose | Physical deformation (bend, twist, squash) | | | Installation |
| 9 | Melt molecular structure | Misalignment | Pressure hammer | Thermal gradient | | Manufacture |
| 10 | Crack in molecular structure (dislocation) | Foreign inclusion | | | | Assembly |
| 11 | Material missing from molecular structure | Thin cross section | Expansion | | | Operation |
| 12 | | | Misalignment | | | Maintenance |
| 13 | Wrong atoms in molecular structure | | Unbalance | Contaminant ingress | | Overhaul / rebuild |
| 14 | | | | | | |
| 15 | Chemical reaction | | Hydraulic shock | Product ingress | | |
| 16 | Crystal lattice attack | | Vibration shock | Chemical reaction | | |
| 17 | | | Abrasion (wear material away) | | | |
| 18 | | | | | | |
| 19 | | | Gouge | Oxidisation | | |
| 20 | | | | Dissimilar materials | | |
| 21 | | | | | | |
| 22 | | | Detach-debond-delaminate | Inclusions in contacting process | | |
| 23 | | | Acts-of-God/Acts-of-Nature | | | |
| 24 | | | Fracture | | | |
| 25 | | | | Vibration | | |
| 26 | | | Yield | Shock | | |
| 27 | | | | | | |
| 28 | | | Material fatigue | | | |
| 29 | | | Physical abuse | | | |
| 30 | | | | | | |
| 31 | | | Soft material of construction (ease of wear) | | | |
| 32 | | | | | | |
| 33 | | | | | | |
| 34 | | | | | | |
| 35 | | | | | | |
| 36 | | | | Combined Environments | | |
| 37 | | | | | | |
| 38 | | | | | | |
| 39 | | | | | | |
| 40 | | | | | | |
| 41 | | | | Sand and Dust | | |
| 42 | | | | | | |
| 43 | | | | | | |



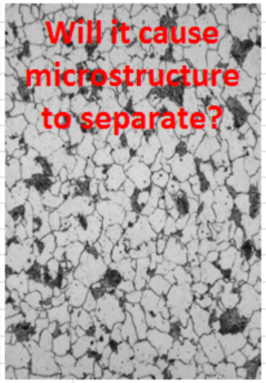




Table 4 initial Physics of Failure Guidewords Used in Boiler Feed Water Pump Impeller RCM Analysis

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| | A | B | C | D | E | F | G |
|---|---|---|---|---|---|---|---|
| 1 | | **Physics of Failure Guidewords** | | | | | |
| 2 | | **Factors that cause Atomic or Microstructure Failure** | **Component Manufacturing Events** | **Component Operational Stress Events** (Horizontal, Vertical, Axial) | **Component Environmental Events / Conditions** | **Electronic / Electrical Effects** | **Component Life Cycle Situations** |
| 3 | | | | | Thermal high | | |
| 4 | | | | | | | |
| 5 | | | | Interference fit tight | | | |
| 6 | | Cyclic stress fatigue | | Interference fit loose | | | |
| 7 | | | | | Corrosion (pitting, galvanic, crevice, etc) | | |
| 8 | | Punch hole in molecular structure | | Physical deformation (bend, twist, squash) | | | Installation |
| 9 | | | | Pressure hammer | Thermal gradient | | |
| 10 | | | | | | | Assembly |
| 11 | | | | Expansion | | | Operation |
| 12 | | | | Misalignment | | | Maintenance |
| 13 | | | | Unbalance | Contaminant ingress | | Overhaul / rebuild |
| 14 | | | | | | | |
| 15 | | | | Hydraulic shock | Product ingress | | |
| 16 | | | | Vibration shock | Chemical reaction | | |
| 17 | | | | | | | |
| 18 | | | | | | | |
| 19 | | | | Gouge | Oxidisation | | |
| 20 | | | | | | | |
| 21 | | | | | | | |
| 22 | | | | | Inclusions in contacting process | | |
| 23 | | | | Acts-of-God/Acts-of-Nature | | | |
| 24 | | | | Fracture | | | |
| 25 | | | | | Vibration | | |
| 26 | | | | | Shock | | |
| 27 | | | | | | | |
| 28 | | | | Material fatigue | | | |
| 29 | | | | Physical abuse | | | |
| 30 | | | | | | | |
| 31 | | | | | | | |
| 32 | | | | | | | |
| 33 | | | | | | | |
| 34 | | | | | | | |
| 35 | | | | | | | |
| 36 | | | | | | | |
| 37 | | | | | | | |
| 38 | | | | | | | |
| 39 | | | | | | | |
| 40 | | | | | | | |
| 41 | | | | | Sand and Dust | | |
| 42 | | | | | | | |


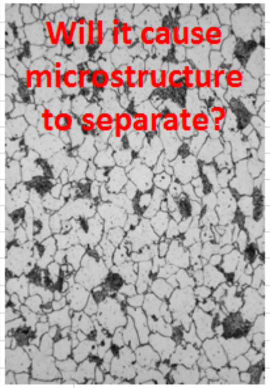


Table 5 Final Physics of Failure Guidewords for Pump Impeller RCM Analysis

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| No | Item | Function | Functional Failure | Failure Mode | Failure Cause | Cause Classification | Failure Effect | Consequences H | S | E | O | H1 S1 O1 N1 | H2 S2 O2 N2 | H3 S3 O3 N3 | Default Action H4 | H5 | S4 | Proposed Task |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Impeller | Eject pressurised water | No water ejected | Impeller does not turn | No key in keyway | Assemble error | Pump out of service | Y | N | N | Y | N | N | N | | | | Take photo of key in keyway upon assembly |
| | | | | | Shaft does not turn | Shaft broken | Pump out of service | | | | | | | | | | | Start stand-by pump |
| | | | | | | No drive power | Pump out of service | | | | | | | | | | | Start stand-by pump |
| | | | | Impeller slips on shaft | Key sheared | Metallurgical failure | Pump out of service | | | | | | | | | | | Specify key size and material in procedure |
| | | | | Key sheared | Soft key material | Assemble error | Pump out of service | | | | | | | | | | | Check key material against parts list and confirm correct in job history |
| | | | | | Fit loose | Assemble error | Pump out of service | | | | | | | | | | | Specify key dimensions in procedure; confirm actual measurements and record in job history |
| | | | | | Overload | Operational upset | Pump out of service | | | | | | | | | | | Specify how to achieve correct running duty in operational procedure and record actions taken |
| | | | | Impeller disintegrated | Physical deformation (bend, twist, squash) | Assemble error | Pump out of service | | | | | | | | | | | Specify bore and shaft cylindricity, circularity, tolerances in procedure; measure and record in job history |
| | | | | | Pressure hammer | Operational upset | Pump out of service | | | | | | | | | | | Specify how to achieve correct running duty in operational procedure and record actions taken |
| | | | | | Expansion | Operational upset | Pump out of service | | | | | | | | | | | Specify how to achieve correct running duty in operational procedure and record actions taken |
| | | | | | Misalignment | Assemble error | Pump out of service | | | | | | | | | | | Specify shaft straightness in procedure and measure and record in job history |
| | | | | | Unbalance | Assemble error | Pump out of service | | | | | | | | | | | Specify impeller maximum unbalance in procedure and measure and record in job history |
| | | | | | Hydraulic shock | Operational upset | Pump out of service | | | | | | | | | | | Specify how to achieve correct running duty in operational procedure and record actions taken |
| | | | | | Vibration shock | Operational upset | Pump out of service | | | | | | | | | | | Specify how to achieve correct running duty in operational procedure and record actions taken |
| | | | | | Gouge | Assemble error | Pump out of service | | | | | | | | | | | Specify surface finish in procedure and take photo of bore and shaft prior assembly |
| | | | | | Material fatigue | Metallurgical failure | Pump out of service | | | | | | | | | | | Include full internal and external dye penetrant inspection of surfaces for cracks |
| | | | | | Fracture | Metallurgical failure | Pump out of service | | | | | | | | | | | Include hammer ring test in procedure and perform and record result during assembly |
| | | | | | Physical abuse | Assemble error | Pump out of service | | | | | | | | | | | Specify surface finish in procedure and take photo of bore and shaft prior assembly |
| | | | | | Thermal high | Operational upset | Pump out of service | | | | | | | | | | | Specify how to achieve correct running duty in operational procedure and record actions taken |
| | | | | | Thermal gradient | Operational upset | Pump out of service | | | | | | | | | | | Specify how to achieve correct running duty in operational procedure and record actions taken |
| | | | | | Contaminant ingress | Operational upset | Pump out of service | | | | | | | | | | | Specify how to achieve correct running duty in operational procedure and record actions taken |
| | | | | Impeller corroded | Inclusions in contacting process | Assemble error | Pump to be rebuilt | | | | | | | | | | | Specify cleanliness in procedure and take photo of bore and shaft prior assembly |
| | | | | | Corrosion (pitting, galvanic, crevice, | Corrosion | Pump to be rebuilt | | | | | | | | | | | Include full internal and external dye penetrant inspection of surfaces for corrosion |
| | | | | | | | | | | | | | | | | | | Insure materials are galvanically compatible and specified by correct part numbers in the procedure |

Table 6 Pump Impeller RCM Analysis with Operational and Maintenance Strategy Proposals

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It is opportune to realise that a cause of impeller bore failure at the high pressure end of a multistage pump has been left out of the guideword list—liquid recirculation through the bore from the high to low pressure sides of the impeller. That cause now needs to be added back into the POFA guideword table so it is not forgotten in future. It would also be reasonable to develop POFA guideword tables that apply to individual types of equipment on a site instead of using only one table to address all equipment. Much would be repeated from table to table, but the equipment lists would be shorter that a using a global guideword list.

In Table 6 the causes of impeller failure are listed and after careful consideration of the options actionable proposals are made to address each with practical solutions that can be readily undertaken. In the proposals the necessary activities and measurements needed to confirm impeller condition and compliance are specified. Still to be done is to write operational and maintenance procedures that clarify how and who will do the necessary tasks.

**Maintenance Cost Reduction using a Risk Matrix**

The extensive checks identified in the RCM incur high costs. Many of the proposals are not worth doing every time the pump is overhauled. Yet they are all vital factors that must be achieved if the pump is to be highly reliable. We are in the dilemma of needing to reduce maintenance costs while improving reliability. It is time to introduce a means to pick what maintenance is worth doing and what can be dropped.

We are now in a risk management situation and need to make choices that carry a degree of operational risk. If we get the decisions wrong there will be expensive failures. To make risk decisions for operational plant and equipment it is best to use a risk matrix to plot the effects of our choices. Table 7 is a risk matrix calibrated for a Low total business-wide risk of $10,000 per year. This company accepts an item of equipment can be allowed to fail (i.e. not deliver its service duty) provided total business-wide costs stay below $10,000 for the year.

To locate the point on the risk matrix for a failure scenario you first calculate the total business cost of the failure. This identifies the consequence column on the risk matrix. Secondly you identify the likelihood of the event actually happening in your operation. Where the two factors cross on the risk matrix is the failure event risk rating.

Each RCM proposed task is assessed on the assumption that it is not done. The total costs of failure (DAFT Costs—Defect and Failure Total Costs) from not doing the task are calculated. This identifies the financial consequence of our decision on the risk matrix. Should a catastrophic 9$^{th}$ stage impeller failure occur the pump may be totally destroyed. The cost to the business would be a total pump replacement, plus all business-wide losses from the downtime needed to replace the pump.

If a stand-by pump was available it would be put into service and the total business-wide costs would be far less than if there was no pumping redundancy.

For example, if in a redundant 2-from-3 boiler pump arrangement a high pressure impeller disintegrated and destroyed a duty pump the stand-by pump would be started. The business-wide failure cost for a boiler feed water circuit with a stand-by pump might total $100,000. This cost locates the column on the risk matrix.

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| Probability (per Opportunity) | Sigma Level | Event Count per Year | Likelihood of Equipment Failure Event per Year<br>Time Scale | Descriptor Scale | Historic Description | DAFT Cost per Event | $30 | $100 | $300 | $1,000 | $3,000 | $10,000 | $30,000 | $100,000 | $300,000 | $1,000,000 | $3,000,000 | $10,000,000 | $30,000,000 | $100,000,000 | $300,000,000 | $1,000,000,000 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | 1.5 | 2 | 2.5 | 3 | 3.5 | 4 | 4.5 | 5 | 5.5 | 6 | 6.5 | 7 | 7.5 | 8 | 8.5 | 9 |
| | | 100 | Twice per week | | | 2 | 3.5 | 4 | 4.5 | 5 | 5.5 | 6 | 6.5 | 7 | 7.5 | 8 | 8.5 | 9 | 9.5 | 10 | 10.5 | 11 |
| | | 30 | Once per fortnight | | | 1.5 | 3 | 3.5 | 4 | 4.5 | 5 | 5.5 | 6 | 6.5 | 7 | 7.5 | 8 | 8.5 | 9 | 9.5 | 10 | 10.5 |
| 1 | | 10 | Once per month | Certain | | 1 | | 3 | 3.5 | 4 | 4.5 | 5 | 5.5 | 6 | 6.5 | 7 | 7.5 | 8 | 8.5 | 9 | 9.5 | 10 |
| 0.3 | 2 | 3 | Once per quarter | | | 0.5 | | | 3 | 3.5 | 4 | 4.5 | 5 | 5.5 | 6 | 6.5 | 7 | 7.5 | 8 | 8.5 | 9 | 9.5 |
| 0.1 | 3 | 1 | Once per year | Almost Certain | Event will occur on an annual basis | 0 | | | | | 3.5 | 4 | 4.5 | 5 | [illegible] | [illegible] | 6.5 | 7 | 7.5 | 8 | 8.5 | 9 |
| 0.03 | | 0.3 | Once per 3 years | Likely | Event has occurred several times or more in a lifetime career | -0.5 | | | | | | | 4 | 4.5 | 5 | 5.5 | 6 | 6.5 | 7 | 7.5 | 8 | 8.5 |
| 0.01 | 4 | 0.1 | Once per 10 years | Possible | Event might occur once in a lifetime career | -1 | | | | | | | | 4 | 4.5 | 5 | 5.5 | 6 | 6.5 | 7 | 7.5 | 8 |
| 0.003 | | 0.03 | Once per 30 years | Unlikely | Event does occur somewhere from time to time | -1.5 | | | | | | | | | 4 | 4.5 | 5 | [illegible] | 6 | 6.5 | 7 | 7.5 |
| 0.001 | | 0.01 | Once per 100 years | Rare | Heard of something like it occurring elsewhere | -2 | | | | | | | | | | 4 | 4.5 | 5 | 5.5 | 6 | 6.5 | 7 |
| 0.0003 | | 0.003 | Once per 300 years | | | -2.5 | | | | | | | | | | | 4 | 4.5 | 5 | 5.5 | 6 | 6.5 |
| 0.0001 | 5 | 0.001 | Once per 1,000 years | Very Rare | Never heard of this happening | -3 | | | | | | | | | | | | 4 | 4.5 | 5 | 5.5 | 6 |
| 0.00003 | | 0.0003 | Once per 3,000 years | | | -3.5 | | | | | | | | | | | | | 4 | 4.5 | 5 | 5.5 |
| 0.00001 | | 0.0001 | Once per 10,000 years | Almost Incredible | Theoretically possible but not expected to occur | -4 | | | | | | | | | | | | | | 4 | 4.5 | 5 |

| Note: | Risk Level | |
|---|---|---|
| | | 1) Risk Boundary 'LOW' Level is set at total of $10,000/year |
| | Red = Extreme | 2) Based on HB436:2004-Risk Management |
| | Amber = High | 3) Identify 'Black Swan' events as B-S (A 'Black Swan' event is one that people say 'will not happen' because it has not yet happened) |
| | Yellow = Medium | 4) DAFT Cost (Defect and Failure Total Cost) is the total business-wide cost from the event |
| | Green = Low | |
| | Blue = Accepted | |

Table 7 Risk Matrix Used to Make Risk Based Decisions

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We still need to identify the likelihood of such an event. Quantitative risk assessment (i.e. mathematically calculated risk probability) is unnecessary, as historical frequency of the event occurring on your site (or in your industry) are sufficiently accurate to identify the likelihood row on the matrix.

Disintegrating high pressure boiler pump impellers are not common, but they have occurred. On the risk matrix the row with the description ‘Event does occur somewhere from time to time’ matches our risk scenario. The cell where consequence and likelihood meet is marked with a black dot containing the number ‘1’. It is in the acceptable risk zone. You can choose to do nothing to prevent catastrophic high pressure impeller failure.

If you choose to do nothing more to prevent failure you are counting on 1) the pump being manufactured correctly, 2) the pump being overhauled and rebuilt correctly, and 3) the stand-by pump being fully operational when it is needed. As an added precaution you might use the RCM proposals as quality management criteria on the company doing the pump overhaul/repair.

However, if the pump arrangement is 2-from-2 and there is no stand-by pump, the cost of a catastrophic failure and the consequential loss of boiler steam supply and production knock-on for the duration of the repair might be $10,000,000. This cell on the risk matrix is marked with a black dot containing the number ‘2’. Because of this massive failure cost it is now a business imperative that on non-redundant systems all POFA / RCM proposed tasks are done correctly every time.

We have not yet totally exhausted our options to drive maintenance costs lower and still have outstanding reliability.

Recall that by using POFA we gain a life cycle perspective not available in a standard RCM analysis. Many of the risk management tasks can be delegated to more appropriate parts of the life cycle than during the overhaul of an operating unit. The balancing of impellers is done during manufacture. It should be unnecessary to redo individual impeller balance in an overhaul, provided the impeller has not gained weight from product build-up or lost weight from corrosion/erosion. You would remove the impeller balance requirement from the overhaul and replace it with visual inspection for build-up and removal of material from the impeller and ask for photographic evidence of good impeller condition. Only if there has been removal or addition of material would you justify a rebalance.

Metallurgical failures of high pressure boiler pump impellers should have been addressed by the pump impeller manufacturer and ought never to cause operational problems. It should be unnecessary to do die penetrant testing and/or ultrasonic inspection of in-service impellers unless there is clear evidence of a problem. Instead of stipulating metallurgical examination you instead request visual inspection for corrosion/cracks/gouges/cavities and photographic evidence of acceptance. You would do a dye penetrant test if visual inspection showed concerns.

Once this level of analysis is done for one impeller much of the work and decision making would repeat for all other high pressure stage impellers. Only the first and second stage impellers would be different since they can suffer cavitation damage and are the first to be affected by solid particles and materials entering the suction of the pump.

**Conclusion**

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We have done all the above with the use of just one person knowledgeable in the engineering design and process application of the equipment. With the 16x13 risk matrix the financial modelling took seconds and the right Profit-Centred Maintenance answers were obvious.

The thorough coverage POFA affords RCM by combining them with the use of a Risk Analysis allows you to optimise your choices and greatly improves the odds of equipment being built with good condition parts, properly installed with good condition parts, and correctly operated to maximise service life and minimise maintenance costs.

My best regards to you,

Mike Sondalini
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