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Understanding the Multiple Roots of Machinery Failures

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Looking at the newspapers we frequently see statistics on the cause of some group of failure events shown as a pie chart or other chart adding up to 100%. Also, we frequently hear television announcers citing the latest study where they say things like “X percent of all home accidents are caused by poor lighting” or “Y percent of deaths are caused by cigarette smoking”. The idea that an accident occurred or a piece of equipment broke down because of the error of a single person or a simple design error would be nice – but usually it doesn’t hold up to scrutiny in the real world. Certainly, it would simplify preventing future equipment and machinery failures if they did occur in that “once cause vacuum” but the real roots are usually much deeper than a single metallurgical problem or one error on the part of the maintenance mechanic or even the fact that the machine is being run at far above the design load. When all the human errors and management system deficiencies are included, the typical machine breakdown is generally the result of somewhere between five and ten significant contributors.

The depth of the analysis into the roots of the failure is the key to accurately unearthing all of the sources. Looking at machinery breakdowns one finds that there are:

- **Physical Roots –** The physical reasons why the parts failed.
- **Human Roots –** The human errors of omission or commission that resulted in the physical roots.
- **Management System (Latent) Roots –** The deficiencies in the management systems or the management approaches that allow the human errors to continue unchecked.

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The more detailed the analysis, the better we can understand all the events and mechanisms that contribute as the roots of the problem.

These analyses are usually divided into three categories in order of complexity and depth of investigation. They are:

- **Component Failure Analysis (CFA) –** Conducted in a laboratory and looks at the piece of the machine that failed, for example, a bearing or a gear, to determine that it resulted from a specific mechanism such as fatigue, overload, or corrosion and that there were these x, y, and z significant influences.

- **Root Cause Investigation (RCI) –** Includes a field investigation in addition to the CFA and is conducted in much greater depth than the CFA. The RCI goes substantially beyond the physical roots of a problem, but is usually stops at the major human causes and doesn’t involve the latent system deficiencies.

- **Root Cause Analyses (RCA) –** Includes everything the RCI covers plus the minor human error causes, and more importantly, the management system that allows the human errors and other system weaknesses to exist.

Although the cost increases as the analyses become more complex, the benefit is a much more complete recognition of the causes. Using a CFA to solve the causes of a component failure answers why the specific part or machine failed and can be used to prevent similar future failures. However, conducting a RCA and correcting the major causes, the system weaknesses, will eliminate huge groups of problems.

An example of the benefits of an RCA can be seen in those situations where the failure relates to replacement components. While we were part of a large corporation, the corporate reliability group, using a Root Cause Analysis, determined that improper replacement parts were contributing to a significant portion of our maintenance problems. As a result, in our plant (and several others) we began a receiving inspection program for the materials used in maintenance. In the first year this found that more than 20% of the materials received were not what was specified on the purchase orders. With time the vendors initiated their own inspections and we corrected our purchasing specifications and the number of improper components decreased. Over six plants the average eventually leveled out at about 4%. Certainly this was a huge improvement, but think about the production and maintenance affects of installing that 4% if they were not detected.

In our company we get involved in all three levels of analyses but most of our work is centered around CFA's and RCI's. In an attempt to better understand the specifics and the interactions between the various causes we decided to look at three years' of our project reports and sort for what the major failure contributors were. (The source of our data was the reports sent to our clients. In these reports the technique we use to discover the failure roots generally involves the use of a logic tree. In developing these trees the contributions of the site operating and maintenance personnel are critical for an accurate analysis.)

Over the three years there were a total of 131 RCI's that we were involved with and we list the primary failure mechanisms below.

Corrosion	18%
Fatigue	44%
Wear	10%
Corrosion Fatigue	13%
Overload	15%

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(Note: These are the primary failure mechanisms and frequently there is more than one mechanism involved.)

In defining these five categories there is the possibility of confusion between corrosion fatigue and fatigue. What we did was to assign fatigue as the mechanism in those cases where the component would have eventually failed and corrosion was not needed to effect the failure. In those situations where the component would not have failed without the action of the corrosion, i.e., there was cyclic loading but it was not severe enough to cause cracking without corrosion, the cause was considered as corrosion fatigue.

After analyzing those failures for the mechanisms we then looked at them to determine the major human error causes. These are defined as those causes that were readily apparent from the component inspection, field analysis, and discussions with plant hourly and salaried personnel. Based on experience we selected six error categories, operational, design, maintenance practice, situation blindness, manufacturing, and original equipment installation, and sorted the causes.

In sorting for these causes we used the follow definitions:

Operational Errors – These are situations where the machine or process was operated beyond the normal or accepted design boundaries. Two examples are:

- The machine was not cleaned properly and the resultant corrosion reduced the thickness of the structural members to the point where significant distortion occurred.

- The specified operating practice for the perforating machine called for three sheets at a time, but the operators ran up to six sheets in an effort to get more productions. This contributed to a failure that destroyed the perforating machine drive system in about three months operating time.

Design Errors – There were two categories of design errors. The most common occurred when the design of the machine or the system did not meet the needs of the operation. However there were also situations where the machine performance requirements were changed without a sound design review.

Before citing the examples we should note that these were not all the result of errors committed by engineers. There were examples where the “design” of a piece of equipment was the work of a maintenance planner or a vendor sales representative and the equipment was installed without competent oversight review. There were also situations where the machine operating rate was increased by plant personnel with tacit engineering approval but no realistic design analysis.

Three examples of design errors are:

- The dryer felt roll failed from fatigue that originated at a stress concentration where a stiffener was welded into position. The design oversight yielded a high stress concentration at the site of significant residual stresses and the parts fatigued.

- The pump impeller failed from cavitation, a corrosion mechanism. The cavitation resulted from poor piping design and the rapid failure from the use of a material that was not cavitation resistant. The system design had the pump operating at well below the minimum NPSH.

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- The paper machine operating speed was increased by 5% without a serious engineering review. Consequently, some components were operating at resonant frequencies and failed repeatedly with the result that the total production capability remained constant while maintenance costs increased tremendously.

Maintenance Errors – The maintenance mechanics did not properly repair or properly install the machine or component after a repair. Examples:

- The pump shaft had loose bearing resulting from poor fitting practice. The resultant fretting corrosion reduced the fatigue strength of the shaft and the shaft fractured rapidly.

- A crankshaft on a large reciprocating compressor failed from bending fatigue. The crankshaft was supported by three plain bearings and the bearing alignment was not checked prior to crankshaft installation. Several months later the shaft failed as a result of the loading.

Manufacturing Errors – The components were improperly manufactured and as a result failed prematurely. Examples:

- The manufacturer of large vertical shaft pumps used in waste treatment plants had torsional resonance in both the drive shafts and the pump bases. As a result the drive shafts would fracture from torsional fatigue after 4000 to 8000 operating hours.

- The manufacturer of an expansion joint specified for use at 180 psi actually supplied one designed for use at 120 psi. (There were errors in their internal procedures.) The joint failed during operation shortly after startup.

Original installation errors – At the time of the installation a properly manufactured piece of equipment was installed incorrectly and, as a result, failed prematurely. Two examples are:

- A vertical pump motor that was misaligned, causing stress on the shaft and directly contributing to the shaft failures.

- The copper water line that was installed without the specified dielectric union, resulting in corrosion that caused a leak approximately 15 months later.

Situation Blindness – A situation where plant personnel, supervisors and hourly, recognize the severe problems exist, but no action is taken and the result is a significant failure. Two examples are:

- A supercalender drive failures that occurred when the reducer ran out of oil. This critical 2000 hp reducer had been leaking for 18 months but no corrective action had been taken. The gears melted when it was allowed to run out of oil and a spare was not readily available.

- A critical bearing that failed when the lubricant supply system failed. There was a monitoring system on the lubricant line and, even though the machine diagnostic report noted that the monitoring system had failed several months earlier, it had not been repaired. As a result, when the lubricant supply failed the bearing was destroyed and substantial downtime resulted.

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In developing these categories the first five were relatively straightforward. However “Situation Blindness” was created during the review when we decided that another category was needed to categorize those failures where the gross neglect of a relatively minor problem allowed it to grow into an expensive and catastrophic failure. The supercalender drive failure is an example of this lack of action. It was in a plant where every operator was responsible for checking the lubricant level on every machine on every shift. The reducer was located in an area that was remote from the control room and awkward to get to, down a flight of stairs, across the operating floor, and up a ladder. It had been leaking heavily for more than a year and both the area around the reducer and the sides of the pedestal were saturated with oil. Certainly the direct cause was the leaky seal, but we felt there had to be some recognition of the general lack of problem awareness on the part of both plant supervision (failure to schedule the repair of a serious oil leak) and the operators (failure to replenish the oil in a known critical operation).

There were a total of 276 major human errors and hundreds of minor contributory causes listed in the reports over those three years. The values below indicate the number of times the specific human error caused occurred. Note that there is almost always more than one contributory cause and a typical example is the calciner shell failure that was caused by pitting corrosion. The pitting resulted from the combined effects of a welding error during fabrication and an operating error.

The total number of major errors in each category shows:

34	Operational Errors
90	Design Errors
93	Maintenance Errors
28	Manufacturing Errors
20	Original Installation Errors
11	Situation Blindness

Recognizing that the distribution of the failures wasn't uniform we then looked at the actual number of failures affected by each category, i.e. we sorted to see how many failures involved design errors, maintenance errors, or operating errors. This showed:

59%	Design Errors
38%	Maintenance Errors
24%	Operating Errors
16%	Installation Errors
12%	Manufacturing Errors
10%	Situation Blindness

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During this same period we were also deeply involved with several true Root Cause Analyses. These generally indicate that when an industrial failure is taken to the point where all the possible causes are examined there are somewhere between 6 and 12 roots. The distribution generally falls along the same lines of what we saw in the RCI's except there seemed to be more situation blindness.

We don't have a good explanation of the apparent inconsistency between the general public practice of showing a single cause for accidents or failures and the reality that there are almost always multiple contributors. Looking at well-studied situations such as airplane crashes, one sees that the NTSB states that there are generally 12 and 14 events that have to coincide before a failure occurs. Yet the general public (and many of us) tends to believe that a failure is the result of a single individual's actions. If this erroneous thought process is used in conducting failure analyses, it results in the detection and elimination of only one contributing cause and the frequent recurrence of the failure.

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