

# ROOT CAUSE FAILURE ANALYSIS FOR AC INDUCTION MOTORS IN THE PETROLEUM AND CHEMICAL INDUSTRY

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Austin H. Bonnett  
Life Fellow IEEE  
Emerson Electric, Retired  
Gallatin Missouri  
Austin.bonnett@emerson.com

**Abstract** - This paper is an abridgement and update of numerous IEEE papers dealing with Squirrel Cage Induction Motor failure analysis. They are the result of a taxonomic study and research conducted by the author during a 40 year career in the motor industry. As the Petrochemical Industry is revolving to reliability based maintenance, increased attention should be given to preventing repeated failures. The Root Cause Failure methodology presented in this paper will assist in this transition. The scope of the product includes Squirrel Cage Induction Motors up to 3000 hp, however, much of this methodology has application to larger sizes and types.

Index Terms – Electric motors, failure analysis, reliability based maintenance.

## I. INTRODUCTION

The failure survey data is helpful because it points to the most likely causes of failure based on which component has failed. Figure 1 also identifies the various motor components for a TEFC motor. The percentages in Figure 1 may vary by Industry and application.

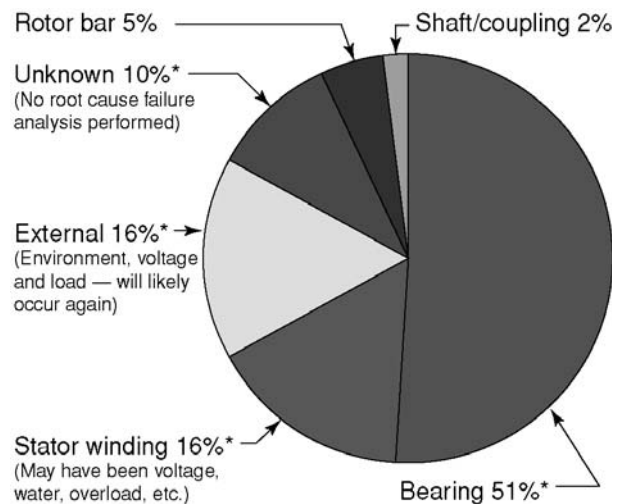
These surveys focus on the motor component that actually failed but does not address the root cause of that failure. As an example, a bearing failure is not the root cause: it is simply the component that failed. The root cause may have been contamination, vibration, lack of lubricant, etc.

To assist in this analysis, it is useful to use a technique known as Failure Mode Effects Analysis (FMEA), which is a procedure for identifying those components that may fail prematurely. The first step is to list all of the possible stresses that can cause a premature failure of a component. Table 1 through 4 groups these stresses by components. This information helps to narrow down the most likely causes of failure.

One additional protocol that may be useful is a procedure called benchmarking of critical motor performance parameters (ideally cradle to grave). Accumulated performance data may indicate changes that point to a premature failure. Useful data may include vibration values, winding insulation data, no load and full load performance data.

The purpose of this paper is to provide a methodology that will lead operations personnel to the most likely root cause of failure, thereby reducing the amount of downtime and the associated expenses caused by these failures.

## DISTRIBUTION OF FAILED COMPONENTS



\* For each component shown, appropriate measures to prevent or predict the failure could greatly reduce three-quarters of motor failures.

A Survey of Faults . . . , IEEE Petroleum and Chemical Industry Paper No. PCIC-94-01, Olav Vaag Thorsen and Magnus Dalva.

## TYPICAL MOTOR COMPONENTS

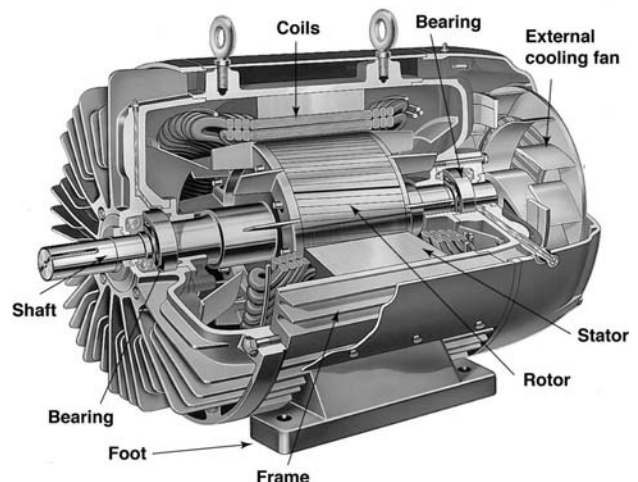


Fig. 1 Distribution of Failed Components and Typical Motor Components

## II. SUMMARY OF MOTOR STRESSES

The majority of all motor failures are caused by a combination of various stresses acting upon the winding, rotor, bearings and shaft. If these stresses are kept within the design capabilities of the system, premature failure should not occur. However, if any combination of them exceeds the design capacity, then the life may be drastically diminished and a catastrophic failure could occur.

These stresses can be broken down into the following groups or classifications shown in Table 1 through Table 4.

### STATOR STRESSES

|                                                                                                                                                                                                                                                                                                                                                                                                                                     |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    |
|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <ul style="list-style-type: none"> <li>• <b>Thermal Stresses</b> <ul style="list-style-type: none"> <li>- Thermal Aging</li> <li>- Voltage Variation</li> <li>- Cycling</li> <li>- Loading</li> <li>- Ventilation</li> <li>- Ambient</li> </ul> </li> <li>• <b>Electrical Stresses</b> <ul style="list-style-type: none"> <li>- Dielectric Aging</li> <li>- Tracking</li> <li>- Corona</li> <li>- Transients</li> </ul> </li> </ul> | <ul style="list-style-type: none"> <li>• <b>Mechanical Stresses</b> <ul style="list-style-type: none"> <li>- Coil Movement</li> <li>- Rotor Strikes</li> <li>- Defective Rotor</li> <li>- Flying Objects</li> <li>- Lugging of Leads</li> </ul> </li> <li>• <b>Environmental Stresses</b> <ul style="list-style-type: none"> <li>- Moisture</li> <li>- Chemical</li> <li>- Abrasion</li> <li>- Damaged Parts</li> <li>- Excessive Ambient</li> <li>- Restricted Ventilation</li> </ul> </li> </ul> |
|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|

Table 1

### BEARING STRESSES

|                                                                                                                                                                                                                                                                                                                                                                                                                                                                       |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <ul style="list-style-type: none"> <li>• <b>Dynamic and Static Loading</b> <ul style="list-style-type: none"> <li>- Radial</li> <li>- Axial</li> <li>- Pre-Load</li> </ul> </li> <li>• <b>Thermal</b> <ul style="list-style-type: none"> <li>- Friction</li> <li>- Lubricant</li> <li>- Ambient</li> </ul> </li> <li>• <b>Vibration and Shock</b> <ul style="list-style-type: none"> <li>- Rotor</li> <li>- Driven Equipment</li> <li>- System</li> </ul> </li> </ul> | <ul style="list-style-type: none"> <li>• <b>Electrical Currents</b> <ul style="list-style-type: none"> <li>- Air Gap Dissymmetry</li> <li>- Electrostatic Coupling</li> <li>- Static Charges</li> <li>- ASD's</li> </ul> </li> <li>• <b>Environmental</b> <ul style="list-style-type: none"> <li>- Condensation</li> <li>- Foreign Materials</li> <li>- Excessive Ambient</li> <li>- Restricted Ventilation</li> </ul> </li> <li>• <b>Mechanical</b> <ul style="list-style-type: none"> <li>- Loss of Clearances</li> <li>- Misalignment</li> <li>- Shaft/Housing Fits</li> </ul> </li> </ul> |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|

Table 2

### SHAFT STRESSES

|                                                                                                                                                                                                                                                                                                             |                                                                                                                                                                                                                                                                                                           |                                                                                                                                                                                                                                                                                                                                                            |
|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <ul style="list-style-type: none"> <li>• <b>Mechanical</b> <ul style="list-style-type: none"> <li>- Overhung Load and Bending</li> <li>- Torsional Load</li> <li>- Axial Load</li> </ul> </li> <li>• <b>Dynamic</b> <ul style="list-style-type: none"> <li>- Cyclic</li> <li>- Shock</li> </ul> </li> </ul> | <ul style="list-style-type: none"> <li>• <b>Residual</b> <ul style="list-style-type: none"> <li>- Manufacturing Processes</li> <li>- Repair Processes</li> </ul> </li> <li>• <b>Thermal</b> <ul style="list-style-type: none"> <li>- Temperature Gradients</li> <li>- Rotor Bowing</li> </ul> </li> </ul> | <ul style="list-style-type: none"> <li>• <b>Environmental</b> <ul style="list-style-type: none"> <li>- Corrosion</li> <li>- Moisture</li> <li>- Erosion</li> <li>- Wear</li> <li>- Cavitation</li> </ul> </li> <li>• <b>ElectroMagnetic</b> <ul style="list-style-type: none"> <li>- Side Loading</li> <li>- Out of Phase Reclosing</li> </ul> </li> </ul> |
|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|

Table 3

## ROTOR ASSEMBLY STRESSES

|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            |
|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <ul style="list-style-type: none"> <li>• <b>Thermal</b> <ul style="list-style-type: none"> <li>- Thermal Overload</li> <li>- Thermal Unbalance</li> <li>- Excessive Rotor Losses</li> <li>- Hot Spots</li> <li>- Sparking</li> </ul> </li> <li>• <b>Magnetic</b> <ul style="list-style-type: none"> <li>- Rotor Pullover</li> <li>- Noise</li> <li>- Vibration</li> <li>- Off Magnetic Center</li> <li>- Saturation of Lamination</li> <li>- Circulating Currents</li> </ul> </li> <li>• <b>Residual</b> <ul style="list-style-type: none"> <li>- Stress Concentrations</li> <li>- Uneven Bar Stress</li> </ul> </li> <li>• <b>Dynamic</b> <ul style="list-style-type: none"> <li>- Vibration</li> <li>- Rotor Rub</li> <li>- Overspeeding</li> <li>- Cyclic Stresses</li> <li>- Centrifugal Force</li> </ul> </li> </ul> | <ul style="list-style-type: none"> <li>• <b>Environmental</b> <ul style="list-style-type: none"> <li>- Contamination</li> <li>- Abrasion</li> <li>- Foreign Particles</li> <li>- Restricted Ventilation</li> <li>- Excessive Ambient Temperature</li> </ul> </li> <li>• <b>Mechanical</b> <ul style="list-style-type: none"> <li>- Casting Variations</li> <li>- Loose Laminations</li> <li>- Incorrect Shaft/Core Fit</li> <li>- Fatigue or Part Breakage</li> <li>- Poor Rotor to Stator Geometry</li> <li>- Material Deviations</li> </ul> </li> <li>• <b>Other</b> <ul style="list-style-type: none"> <li>- Misapplications</li> <li>- Poor Design Practices</li> <li>- Manufacturing Variation</li> <li>- Loose Bars, Core</li> <li>- Transient Torques</li> <li>- Wrong Direction of Rotation</li> </ul> </li> </ul> |
|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|

Table 4

### SUMMARY OF METHODOLOGY FOR ANALYSIS

| MOTOR COMPONENT | FAILURE MODE/CLASS                                                                                                                | FAILURE PATTERN                                                                                                                          |
|-----------------|-----------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------|
| Stator Winding  | Turn to Turn<br>Phase to Phase<br>Phase to Ground<br>Coil to Coil<br>Open Circuit                                                 | Symmetrical<br>Single Phased<br>Non-Symmetrical & Grounded<br>Non-Symmetrical & No Ground                                                |
| Rotor Assembly  | Shaft<br>Bearing<br>Lamination<br>Squirrel Cage<br>Vent. System                                                                   | Thermal<br>Magnetic<br>Residual<br>Dynamic<br>Mechanical<br>Environmental                                                                |
| Ball Bearings   | Fatigue Spalling<br>Fretting<br>Smearing<br>Skidding<br>Wear<br>Lub. Failure<br>Electric Pitting<br>Fluting<br>Cracks<br>Seizures | Thermal<br>Vib. & Noise<br>Lubricant Quality<br>Mounting/Fits<br>Contamination<br>Mechanical Damage<br>Electrical Damage<br>Load Pattern |
| Shaft           | Overload<br>Fatigue<br>Corrosion                                                                                                  | Ductile<br>Brittle<br>Beach Marks<br>Conchoidal Marks<br>Chevron Marks<br>Ratchet Marks<br>Cup/Cone<br>Shear Lips<br>Fretting            |

Table 5

### III. ROOT CAUSE METHODOLOGY

Root cause methodology is a step-by-step method for examining a failed motor and its system. It focuses on the stresses that acted upon the failed components. By better understanding these stresses, and conducting a FEMA, the service center is more likely to uncover the root cause of the failure.

The five key steps in root cause methodology are:

- **Failure mode:** The manifestation, form or arrangement of the failure (e.g., turn-to-turn, phase-to-phase, etc.), (See Table 5).
- **Failure pattern:** How the failure is configured (e.g., symmetrical or nonsymmetrical), (See Table 5).
- **Appearance:** Examination of the failed part, the entire motor and the system in which it operates. Care must be taken to inspect all motor parts for damage, contamination, moisture, cracks or other signs of stress (See Section V).
- **Application:** A close examination of the work performed by the motor and the characteristics of those types of loads (See Section V).
- **Maintenance history:** An examination of the work performed to keep the motor and system in proper operating condition (See Section V).

In an ideal world, all relevant information pertaining to the application, appearance and maintenance history would be available prior to the actual inspection of the motor or failed component. In real life, however, the methodology usually unfolds by first inspecting the failed part, then the motor and finally acquiring information about the application, appearance of the system and the system's maintenance history. This sequence is usually driven by the urgency to return the motor to service as well as the availability of applications and historical data.

Combining all of these stresses, leads to a methodology that falls into two groups. The first deals with failure modes/classes and failure patterns as shown in Table 5, which can serve as a check off sheet when conducting an inspection of the failed motor. The second group deals with the motor appearance, application and maintenance history. This will be covered in detail in the methodology checklist.

### IV. THE MOTOR SYSTEM

Although a complete system analysis is beyond the scope of this paper, when conducting a root cause failure analysis, it is important to recognize that the motor is only one components of a system. Many factors affecting the system will also affect the motor and may contribute to the motor failure and vise-versa. The following list describes the basic components in a typical motor system.

### THE POSSIBLE COMPONENTS OF A SYSTEM

- |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |
|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <ul style="list-style-type: none"><li>• <b>The Ambient</b><ul style="list-style-type: none"><li>- Moisture, chemicals</li><li>- Temperature, weather</li><li>- Air flow, ventilation, noise</li></ul></li><li>• <b>Power Supply</b><ul style="list-style-type: none"><li>- Utility or Co-Gen</li><li>- Power quality</li><li>- Interruptions, transients</li></ul></li><li>• <b>Motor Controls</b><ul style="list-style-type: none"><li>- Metering, sensors</li><li>- Power quality</li><li>- Soft start, ASD, Reduced Voltage start</li></ul></li><li>• <b>Mounting Base</b><ul style="list-style-type: none"><li>- Plate, plates</li><li>- C-face, P base</li></ul></li></ul> | <ul style="list-style-type: none"><li>• <b>Coupling Method</b><ul style="list-style-type: none"><li>- Belted or direct connected</li><li>- Clutch or gearing</li></ul></li><li>• <b>Driven Equipment</b><ul style="list-style-type: none"><li>- Pump, fan, blower, conveyors</li><li>- Compressor</li><li>- Transmission</li></ul></li><li>• <b>Process Requirements</b><ul style="list-style-type: none"><li>- Flow rate</li><li>- Cycling, duty cycle</li><li>- Constant or variable load</li></ul></li></ul> |
|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|

Table 6

### PROCESS PUMP DRIVE MOTOR IN A PETRO-CHEMICAL PLANT



Fig. 2 Process Pump Drive Motor in a Petro-Chemical Plant

# METHODOLOGY CHECKLIST

## V. APPEARANCE OF MOTOR AND SYSTEM

As the third part of the methodology, this section will serve as a check-off list to be used to gather critical information pertaining to the appearance, application and maintenance history of the motor and other related equipment. Some of these questions overlap.

When coupled with the class and pattern of failure, the general motor appearance usually gives a clue as to the possible cause of failure. The following check list will be useful in evaluating assembly conditions:

- Does the motor exhibit any foreign material?
- Are there any signs of blocked ventilation passages?
- Are there signs of overheating exhibited by insulation, lamination, bars, bearings, lubricant, painted surfaces, etc?
- Has the rotor lamination or shaft rubbed? Record all locations of rotor and stator contact.
- Are the topsticks, coils, or coil bracing loose?
- Are the rotor cooling passages free and clear of clogging debris?
- What is the physical location of the winding failure? Is it on the connection end or opposite connection end. If the motor is mounted horizontally, where is the failure with respect to the clock? Which phase or phases failed? Which group of coils failed? Was the failure in the first turn or first coil?
- Are the bearings free to rotate and operate as intended?
- Are there any sign of moisture present on the stator, rotating assembly, bearing system or any other parts?
- Are there any signs of movement between rotor and shaft or bar and lamination?
- Is the lubrication system as intended or has there been lubricant leakage or deterioration?
- Are there any signs of stalled or locked rotor?
- Was the rotor turning during the failure?
- What was the direction of rotation and does it agree with fan arrangement?
- Are any mechanical parts missing such as balance weights, bolts, rotor teeth, fan blades, etc. or has any contact occurred between rotating parts that should maintain a clearance?
- What is the condition of the coupling device, driven equipment, mounting base and other related equipment?
- What is the condition of the bearing bore, shaft journal, seals, shaft extension, keyways and bearing caps.
- Is the motor mounted, aligned and coupled correctly?
- Is the ambient usual or unusual?
- Do the stress risers show signs of weakness or cracking? (the driven end shaft keyway is a weak link)

When analyzing motor failures, it is helpful to draw a sketch of the motor and indicate the point where the failure occurred as well as the relationship of the failures to both the rotating and stationary parts such as shaft keyway, etc. Pictures are worth a thousand words.

## VI. APPLICATION CONSIDERATIONS

Usually it is difficult to reconstruct conditions at the time of failure. However, a knowledge of the general operating conditions will be helpful. The following items should be considered:

- What are the load characteristics of the driven equipment and the loading at time of failure?
- What is the operating sequence during starting?
- Does the load cycle or pulsate?
- What is the voltage during starting and operation/is there a potential for transients? Was the voltage balanced between phases?
- How long does it take for the unit to accelerate to speed?
- Have any other motors or equipment failed on this application?
- How many other units are successfully running?
- How long has the unit been in service?
- Did the unit fail on starting or while operating?
- How often is the unit starting and is this a manual or automatic operation? Part winding, wye-delta, or variable frequency drive (VFD), or across the line?
- What type of protection is provided?
- What removed or tripped unit from the line?
- Where is the unit located and what are the normal environmental conditions? What was the environment at time of failure?
- What was the ambient temperature, at time of failure, around the motor? Any recirculation of air? Is the exchange of cooling air adequate?
- Was power supplied by a variable frequency drive? What is the distance between the VFD and the motor?
- How would you describe the driven load method of coupling and mounting?

## VII. MAINTENANCE HISTORY

An understanding of the past performance of the motor can give a good indication as to the cause of the problem. Again a checklist may be helpful:

- How long has the motor been in service?
- Have any other motor failures been recorded and what was the nature of the failures?
- What failures of the driven equipment have occurred? Was any welding done?
- When was the last time any service or maintenance was performed?
- What operating levels (temperature, vibration, noise, insulation, resistance, etc.) were observed prior to the failure?
- What comments were received from the equipment operator regarding the failure or past failures?
- How long was the unit in storage or sitting idle prior to starting?
- What were the storage conditions?
- How often is the unit started? Were there shutdowns?
- Were correct lubrication procedures utilized?
- Have there been any changes made to surrounding equipment?
- What procedures were used in adjusting belt tensions?
- Are the pulleys positioned on the shaft correctly and as close to the motor bearing as possible?

The following sections contain samples of the various types of failure by motor component which can be used for comparison to unknown failures for classification.

## SECTION 1: Common Types of Stator Failures

In Figure 3, a typical turn to turn short caused by voltage spikes from an inverter.

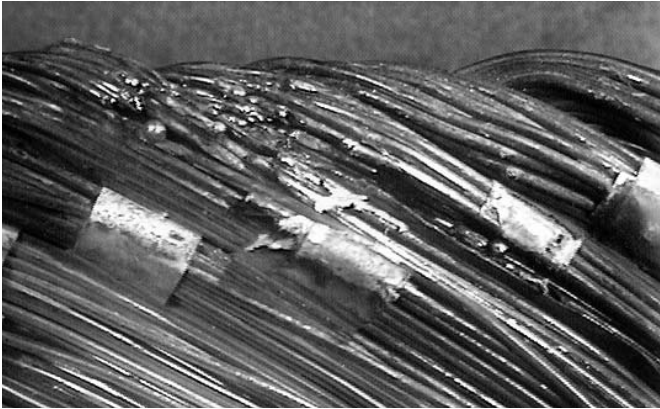


Fig. 3

In Figure 4, a typical phase to phase fault caused by a breakdown in phase insulation caused by excessive winding temperature.

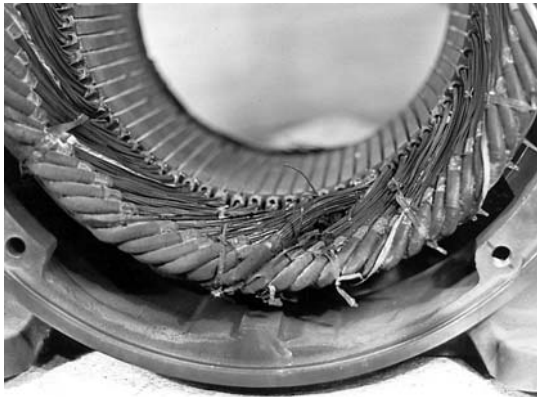


Fig. 4

In Figure 5 is a cross-section of a typical stator slot. It is not uncommon to have turn-to-turn shorts in this region.



Fig. 5

In Figure 6, a typical turn to turn short caused by defective magnet wire insulation.

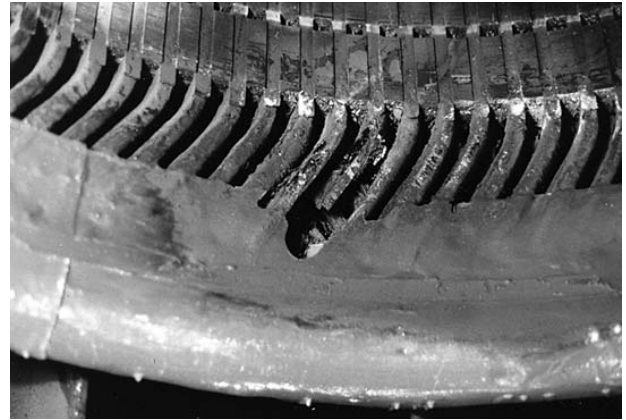


Fig. 6

In Figure 7, breakdown of ground insulation caused by corona.



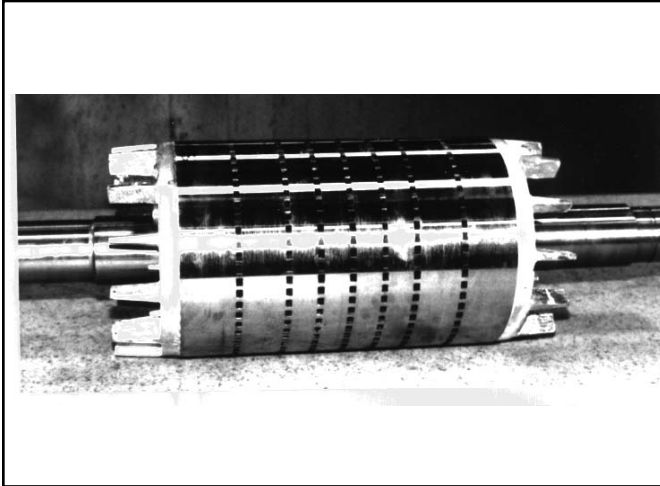
Fig. 7

Figure 8, shorting of terminal leads due to excessive operating temperature and use of class B lead wire in a class F application.



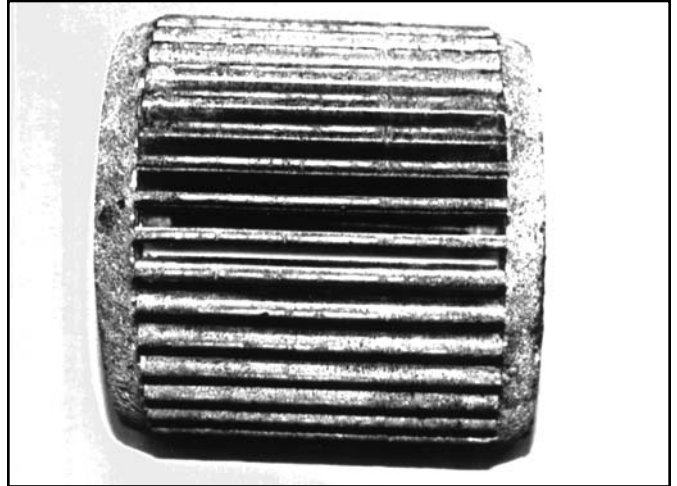
Fig. 8

## SECTION 2: Common Types of Rotor Failures



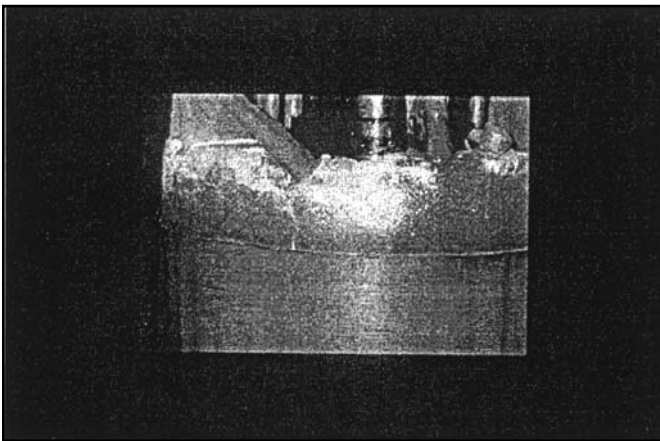
Typical cast air ducted rotor, any damage to the fans, end rings or air ducts can cause overheating and damage to the cage.

**Fig. 9**



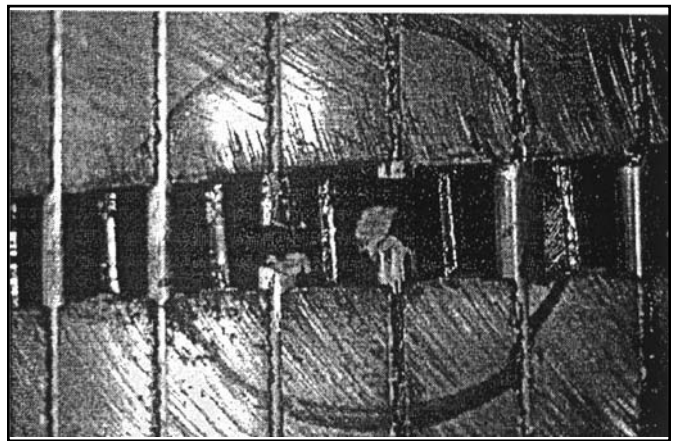
Typical aluminum squirrel cage without the lamination. Any damage to the cage will effect the motor performance.

**Fig. 12**



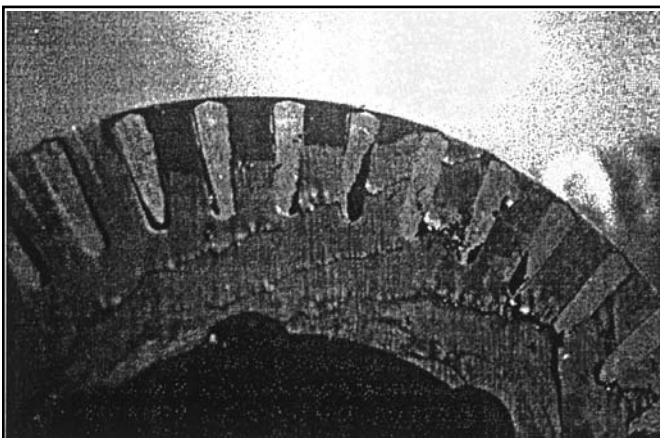
Overheated aluminum cast rotor end ring.

**Fig. 10**



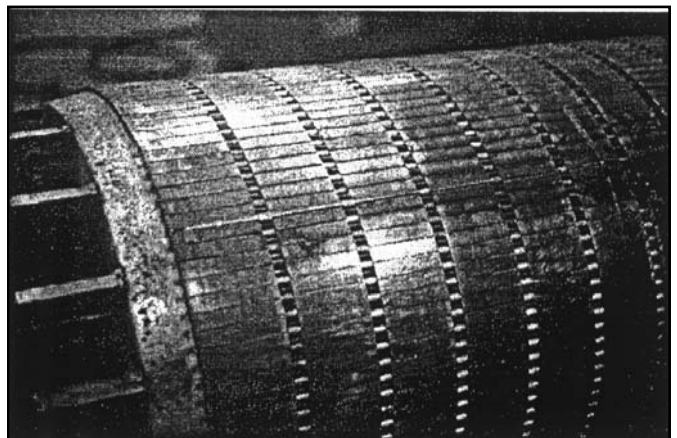
Overheated Aluminum fabricated rotor bars.

**Fig.13**



Incomplete rotor bars on aluminum cast rotor.

**Fig. 11**

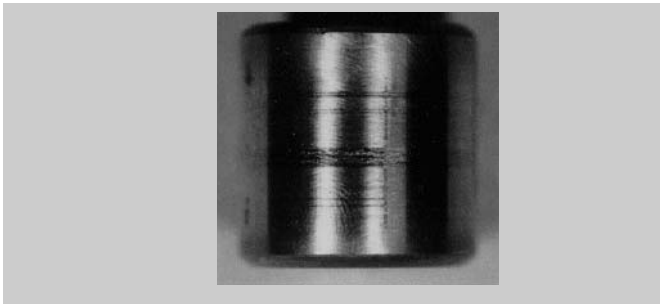


Broken and loose aluminum fabricated rotor bar.

**Fig. 14**

### SECTION 3: Common Anti-Friction of Bearing Failures

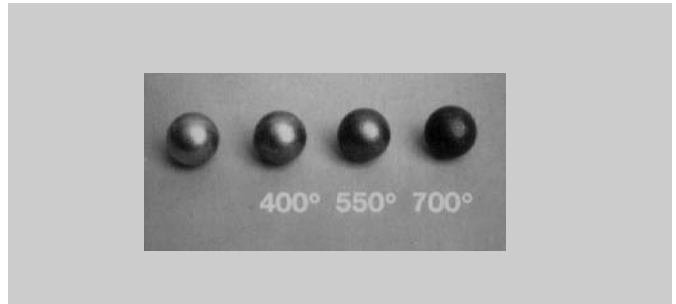
#### CONTAMINATION



Smear marks on roller caused by debris.

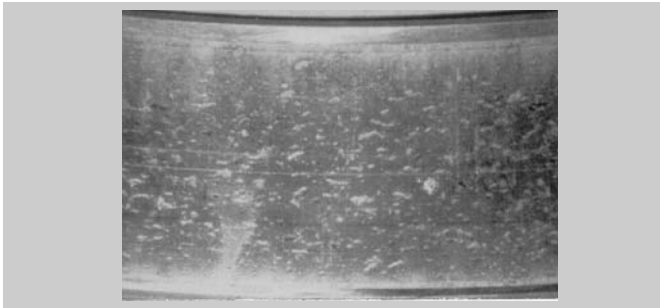
Fig. 15

#### TEMPERATURE



Color variation due to excess temperature.

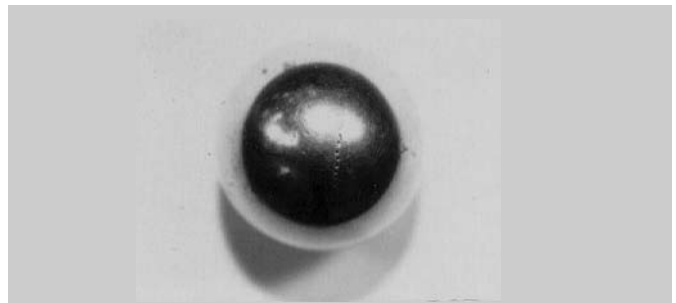
Fig. 19



Metallic contamination in raceway.

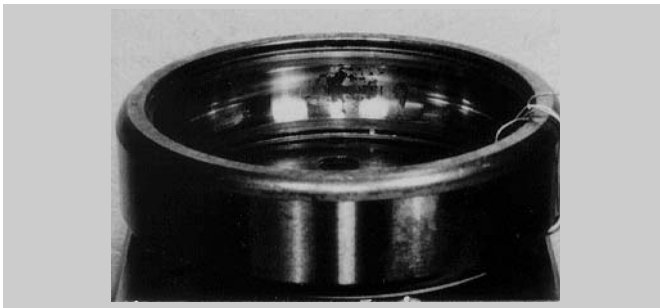
Fig. 16

#### SHAFT CURRENTS



Pitting caused by electrical currents.

Fig. 20



Damaged caused by water intrusion.

Fig. 17



Fluting caused by internally generated current.

Fig. 21

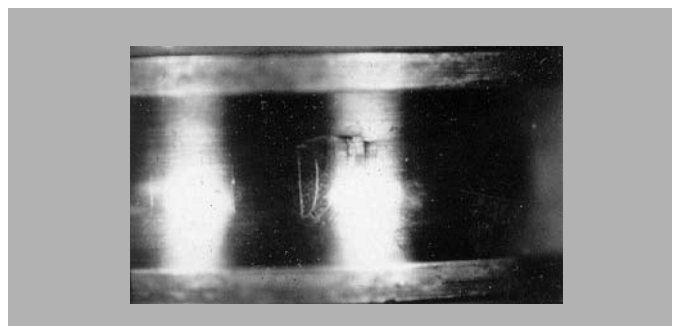
#### DEFECTIVE FITS/SEATS



Fretting Corrosion caused by loss fit & vibration

Fig.18

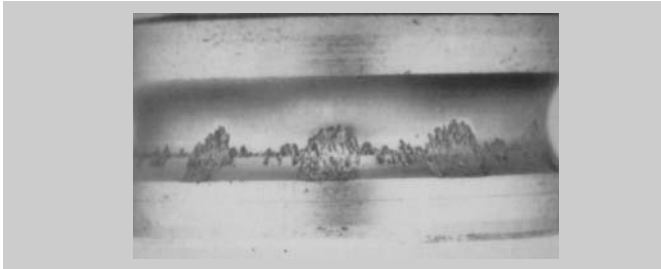
#### FATIGUE



Early stage of Spalling caused by excessive preload.

Fig. 22

## **FATIGUE (con't.)**

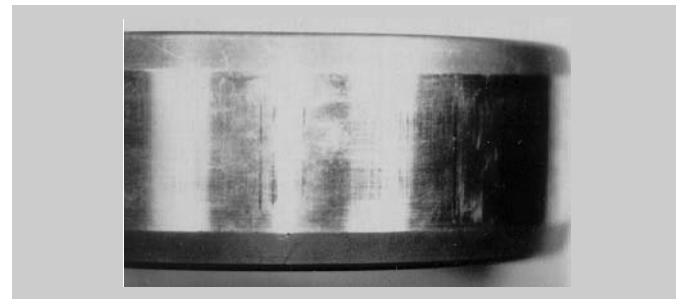
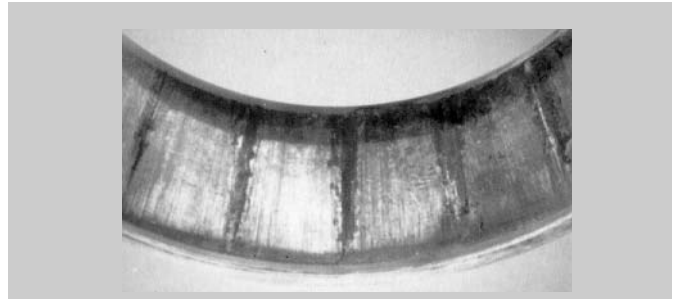


**Advanced stages of Spalling.**  
**Figs. 23 and 24**

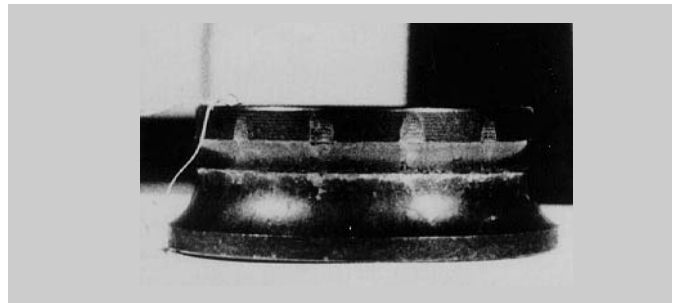


**Fatigue Fracture of outer ring caused by burrs in the housing bore.**  
**Fig. 25**

## **MECHANICAL**



**False Brinelling and Fretting caused by vibration in a non- operating condition.**  
**Figs. 26 and 27**



**Thrust on low shoulder of angular contact bearing caused by improper installation.**  
**Fig. 28**



**Excessive thrust on a Spherical Roller Bearing.**  
**Fig. 29**

## SECTION 4: Sleeve Bearing Failures

### THERMAL STRESS

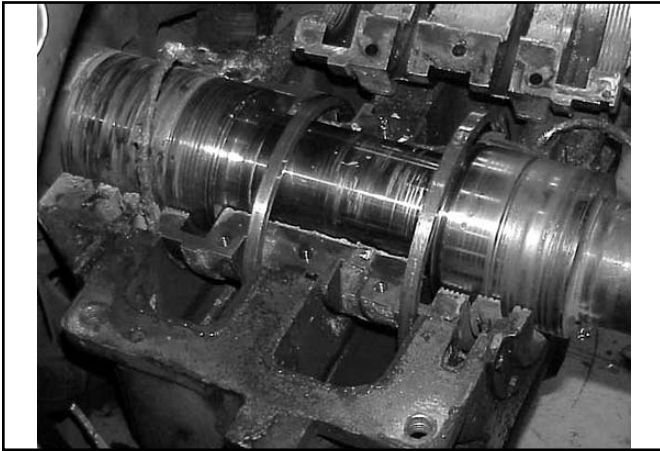


Fig. 30

### CONTAMINATION

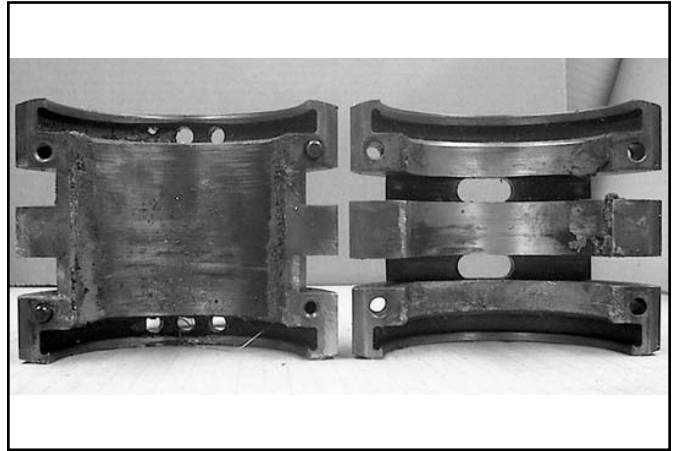


Fig. 33

### SHAFT CURRENTS

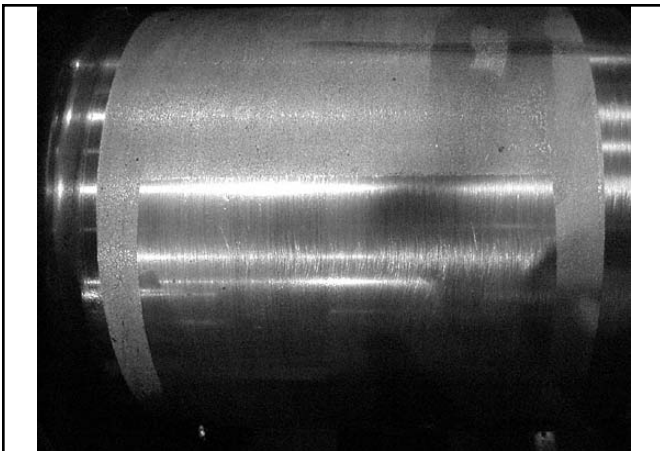


Fig. 31

### VIBRATION



Fig. 34

### LOSS OF RUNNING CLEARANCE

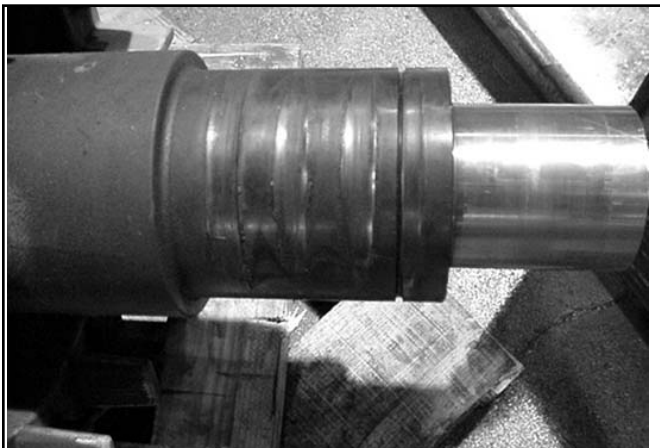


Fig. 32

### CONTACT BETWEEN SHAFT AND THRUST FACE



Fig. 35

## SECTION 5: Common Shaft Failures

Figures 36 and 37 are of a 1045 carbon steel motor shaft that failed due to rotational bending fatigue. The point of failure was at the shoulder of the customer take-off end.

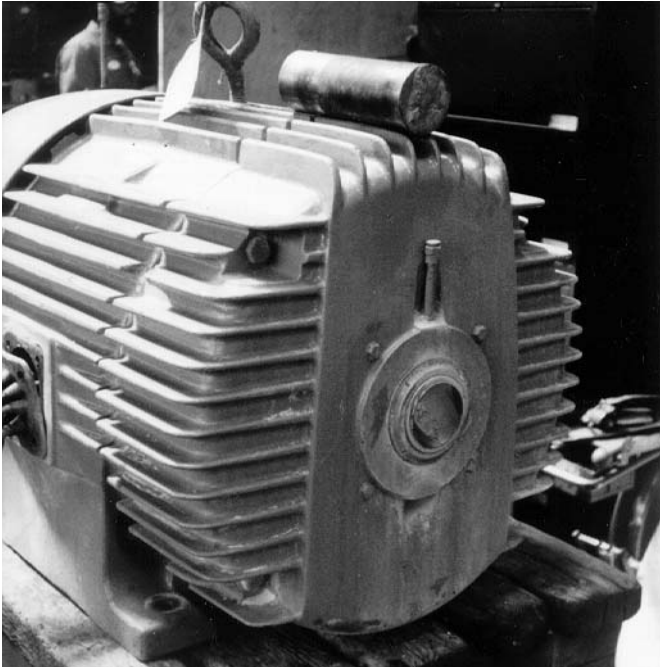


**Fig.36**

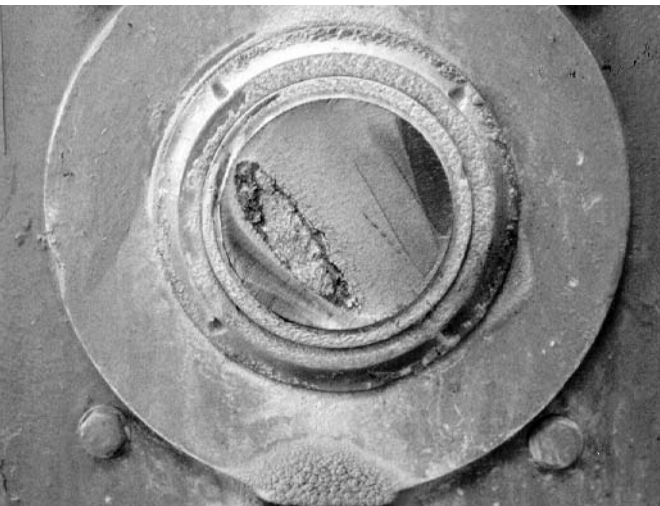


**Fig. 37**

Figures 38 and 39 are of a 1040 carbon steel motor shaft that failed due to rotational bending fatigue. The point of failure was at the bearing journal shoulder.



**Fig. 38**



**Fig. 39**

Figures 40 and 41 are shafts that failed due to high impact loading. The material is 1045 carbon steel, which has good ductility, which allowed for the severe twisting.



**Fig. 40**



**Fig. 41**

Figure 42 is a shaft material that is unknown, but possibly 4100 high tensile steel alloy. The failure is a fatigue failure due to reversed torsional loading.



**Fig. 42**

Figures 43 and 44 are of a 4140 alloy steel pump shaft that failed due to rotational bending fatigue, initiating in the root of the shaft keyway. The most likely cause was a combination of misalignment and vibration, the coupling may also have been a contributing factor. There were a number of beach marks present.



**Fig.43**



**Fig. 44**

Figure 45 is an example of extreme corrosion, wear and cracking on a pump shaft; the material is unknown.



**Fig. 45**

Figures 46, 47 and 48 are of a titanium sleeved pump shaft that failed due to rotational bending fatigue over time. The load was repetitive and cyclic. The failure originated at a fillet, there were signs of extensive fretting and beach marks were evident.

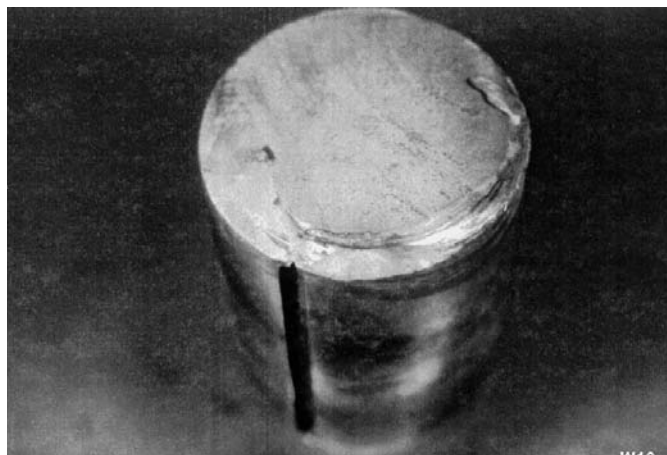


Fig. 46



Fig. 47



Fig. 48

Figures 49, 50 and 51 are of a 1051 carbon steel turbine shaft that failed due to rotational bending fatigue. There were also signs of minor torsional fatigue. Cracks initiated at the toe of a coupling weld. This material has poor weldability characteristics. There were also signs of misalignment. Note the surface pit and grinding marks, both of these conditions can weaken the shaft.

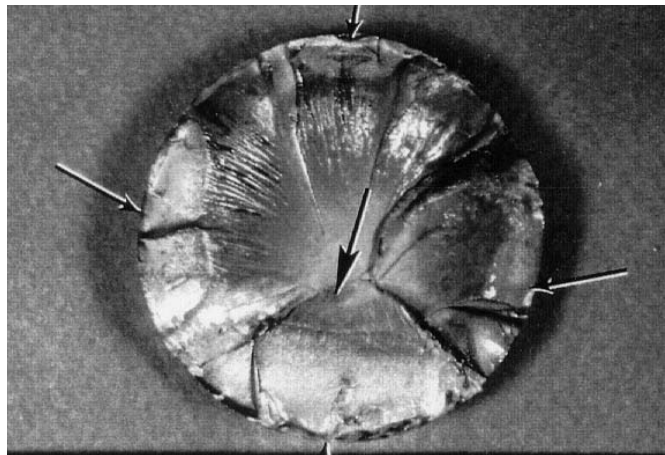


Fig. 49

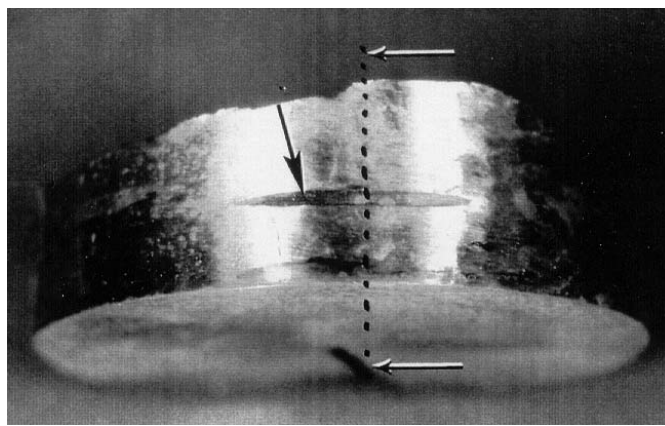


Fig. 50

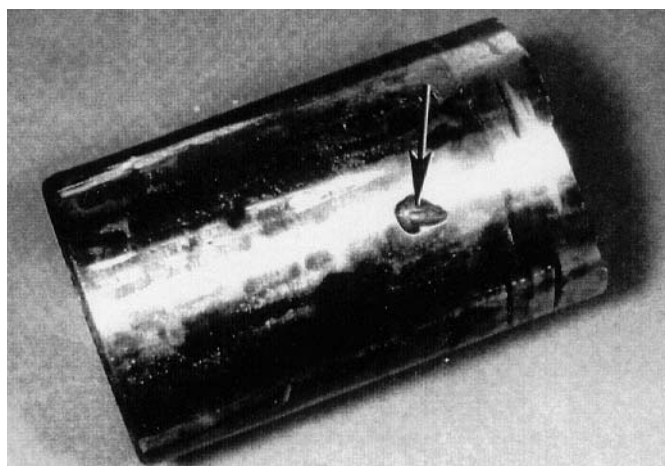


Fig. 51

## VIII. SUMMARY AND CONCLUSIONS

All too often when a motor fails, the major and sometimes only focus is the repair or replacement and get it "up and running again". Without diminishing the importance of this goal, time should be spent collecting valuable information that will assist in a root cause failure analysis. This paper, along with the previous papers will provide the reader the methodology to conduct an analysis that will properly identify failures and hopefully take the necessary steps to eliminate them.

This proposed methodology will yield the best results when the motor under analysis has been "bench marked" along with the system at the time of installation or re-start. Also information collected during a normal or abnormal operating cycle can be of great value. It may not be practical to have this kind of information on all plant systems, it might be wise to collect it going forward on critical applications or applications known have experienced difficulties in the past. Another point to consider; when a motor fails, the normal tendency is to quickly remove the motor and install a new one or get the damaged motor to the repair shop and back into operation. No thought is given to collecting information that may be helpful for an accurate analysis prior to the tear down. Investing a few extra minutes before shut down or removal, may yield critical information for the eventual analysis. It is recognized that this option is not always available, but when it is utilized, it provides valuable information.

## IX. STATOR AND ROTORS REFERENCES

For those who want a more detailed discussion on this very broad topic, the authors have provided the following list of reference materials.

- [1.] R.J. Nailen, "Stop Rotor Troubles Before They Start," Plant Engineering, Dec. 1966.
- [2.] Edgar F. Merrill and Carl R. Olson, "Sparking of A-C Motor Rotors and Its Effect on Division 2 Application," IEEE PIC, Aug. 24, 1959.
- [3.] P.G. Cummings, J.R. Dunki-Jacobs and R.H. Kerr, "Protection of Induction Motors Against Unbalanced Voltage Operation," General Electric Co., IEEE PCIC, September, 1983, PCIC-83-3.
- [4.] A.H. Bonnett, "Analysis of the Impact of PWM Waveforms on AC Induction Motors", IEEE Trans. On Industrial Applications, Vol. 32, March/April 1996
- [5.] A.H. Bonnett, "The Cause of Winding Failures in Three Phase Squirrel Cage Induction Motors," IEEE PCIC, September, 1976, PCIC-76-7.
- [6.] A.H. Bonnett, "Analysis of Winding Failures in Three Phase Squirrel Cage Induction Motors," IEEE PCIC, September, 1977, PCIC-77-4.
- [7.] A.H. Bonnett, "Prevention of Winding Failures in Three Phase Squirrel Cage Induction Motors," IEEE PCIC, September, 1978, PCIC-78-7.
- [8.] A.H. Bonnett and G.C. Soukup, "Rotor Failures in Squirrel Cage Induction Motors," IEEE PCIC, September, 1985, PCIC-85-24, and Published IAS IA Vol. 2 September/October, 1986.
- [9.] A.H. Bonnett and G.C. Soukup, "Analysis of Rotor Failures in Squirrel Cage Induction Motors," IEEE PCIC, September, 1987, PCIC-87-2.
- [10.] A.H. Bonnett and G.C. Soukup, "The Causes and Analysis of Stator and Rotor Failures in A.C. Machines", Maintenance and Reliability Conference, May 20, 1997, pg. 29.01. Published by the University of Tennessee at Knoxville.

## X. SHAFT REFERENCES

- [11.] "Metals Handbook, Volume 10, Failure Analysis and Prevention" 8th Edition. American Society for Metals, Metals Park, Ohio.
- [12.] C.R. Brooks and A. Choudhury, "Metallurgical Failure Analysis", McGraw-Hill, 1993.
- [13.] V.J. Colangelo and F.A. Heiser, "Analysis of Metallurgical Failures", John Wiley & Sons, 1974.
- [14.] A. Das, "Metallurgy of Failure Analysis", McGraw-Hill, 1996.
- [15.] N. Sachs, "Failure Analysis of Mechanical Components", Maintenance Technology, September 1993.
- [16.] C.Y.P. Qiao and C.S. Wang, "A Taxonomic Study of Fractograph Assisted Engineering Materials Failure Analysis", Maintenance and Reliability Conference, proceedings, pg. 501, May 20-22, 1997, Knoxville, TN.

## XI. BEARING REFERENCES

- [17.] O.V. Thorsen and M. Dalva, "A Survey of Faults on Induction Motors....", IEEE Transaction on Industrial Applications, Vol. 31, No. 5, September/October, 1995.
- [18.] J. Charles Berren, "Diagnosing Faults in Rolling Element Bearings, Part II, Alternative Analytical Methods," Vibrations, Vol. 4, No. 2, June, 1998.
- [19.] "Bearing Failure Analysis & Preventive Maintenance," NSK CORP. Bearing Division, Am Arbor, Michigan.
- [20.] "Bearing Failure and Their Causes," SKF Catalog, Form 310M, 10,000-11-75GP.
- [21.] A.H. Bonnett, "Cause and Analysis of Anti-Friction Bearing Failures in A.C. Induction Motors", IEEE Industrial Application Society Newsletter, September/October 1993.
- [22.] EASA: "Root Cause Failure Analysis".
- [23.] A.H. Bonnett and Chuck Yung, "Benchmarking Electric Motors Before They Fail," IEEE PCIC 2009-32.

## XII. VITAE

Austin H. Bonnett is a Life Fellow of the IEEE. His honors include the Tesla Award, the IEEE Industry Applications Society Outstanding Achievement Award, the IEEE Meritorious Award, and NEMA Kite and Key Award, the EASA 2007 Exceptional Achievement award and numerous prized paper awards. He is a Technology and Education Consultant for the Electrical Apparatus Service Association (EASA), and vice-president of Technology Emeritus at Emerson Electric. He received his Bachelor of Science Degree in Electrical Engineering from California State University at Los Angeles and his Masters Degree in Business from the University of Phoenix.

He served in the U.S. Navy from 1955 to 1958 as an electrician aboard the Icebreaker, Burton Island, stationed in both the Arctic and Antarctic. He joined U.S. Electrical Motors, Division of Emerson Electric Company, in 1963 and has since held positions in the Service, Manufacturing, Quality Control, and Engineering Departments. He holds the position of Vice President-Technology Emeritus and has retired from Emerson Electric. Previously, he held the position of Vice President of Engineering and directed all of U.S. Electrical Motors Engineering functions for 10 years. Prior to that, he held the position of Plant Manager of the Prescott Large Motor Facility for five years.