

# Root Cause Failure Analysis

**Pinpointing  
the true cause  
of electric motor  
failures**







**Reliable Solutions  
Today!**

# Root Cause Failure Analysis

This book was developed to help electric motor technicians and engineers prevent repeated failures because the root cause of failure was never determined. There are numerous reasons for not pursuing the actual cause of failure including:

- A lack of time.
- Failure to understand the total cost.
- A lack of experience.
- A lack of useful facts needed to determine the root cause.

The purpose of this book is to address the lack of experience in identifying the root cause of motor failures. By using a proven methodology combined with extensive lists of known causes of failures, one can identify the actual cause of failure without being an "industry expert." In fact,

when properly used, this material, will polish one's diagnostic skills that would qualify one as an industry expert.

The book is divided into the various components of an electric motor. In addition to a brief explanation of the function of each component and the stresses that act upon them, numerous examples of the most common causes of failure are also presented.

Since it is not always possible to pinpoint the exact cause of failure, some examples are used more than once. Due to a lack of all the necessary facts associated with the application and history of a given machine, it is only possible to assign the root cause to the most probable scenario.

A reference section is included at the back of this book for those wanting to further research root cause failure analysis.

## EDITOR'S NOTE

Many of the pictures in this book are of failures that have occurred where the actual cause was identified. However, in some cases the exact cause was never verified, nonetheless they are included along with the author's opinion of the most likely cause. In other cases, the pictures are of parts that have not failed, but the pictures are useful in illustrating how and where the part could fail.

It is difficult to segregate each type of failure into nice distinct categories and to do so would require jumping back and forth from section to section which would cause some amount of discontinuity. Hence, there is a certain amount of overlap and duplication of photos to clarify specific points.

There is no attempt to single out a particular motor manufacturer or to suggest that one product has more defects or failures than another. For this reason, we have not identified the manufacturer of the parts or motors. In some cases, the failed part is not even an original equipment part. Also, we have made no effort to identify whom may have repaired a particular motor. The intent of this book is not to place blame but to assist in a correct diagnostic procedure that will prevent repetitive failures.

The authors would like to express our appreciation to all those who have donated pictures for this edition and hope that we will continue to receive more pictures of unique types of failures to fill the gaps.

Electrical Apparatus Service Association, Inc.

1331 Baur Boulevard • St. Louis, Missouri 63132 • USA

314-993-2220 • Engineering Fax 314-993-2998 • [www.easa.com](http://www.easa.com)

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# 1

## Root Cause Methodology

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## INTRODUCTION TO FAILURE SURVEYS

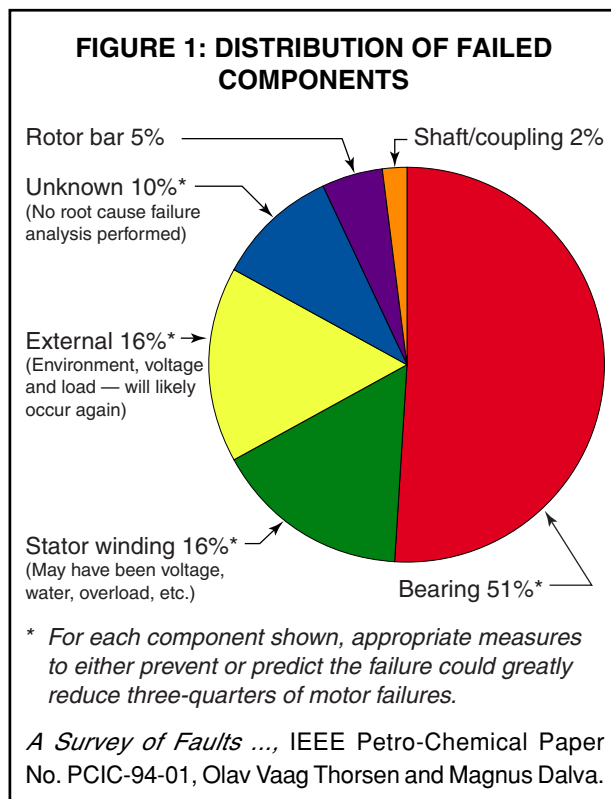
Most failure survey data for electric motors is influenced by the particular industry, the geographic location and the combination of the motors in use. Therefore, specific numbers may not always be relevant.

Most failure surveys focus on the component that actually failed but do 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 be contamination, vibration, lack of lubrication, etc.

The data provided by the Institute of Electrical and Electronics Engineers (IEEE) study shown in Figure 1 is helpful in that it points to the most likely cause of motor failure by virtue of which component has failed. It then becomes the responsibility of those analyzing the failure to search for the root cause that led to the failure of that particular component. These percentages may vary for a specific industry or location.

The real challenge lies in reducing the large category of “unknown” failures. It is these “unknown” failures that make analyzing the entire motor system so critical.

Each section of this book provides a detailed list of possible root causes of failure for a particular motor component. And in most cases, an example of that type of failure is also provided.



## 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 component. By better understanding the stresses that acted upon a failed part, 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.).
- **Failure pattern:** How the failure is configured (e.g., symmetrical or nonsymmetrical).
- **Appearance:** A visual 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.
- **Application:** A close examination of the work performed by the motor and the characteristics of those types of loads.
- **Maintenance history:** An examination of the work performed to keep the motor and system in proper operating condition.

In an ideal world, all relevant information pertaining to the application, appearance and maintenance history is available prior to the actual inspection of the motor or failed component. However, in real life, 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 application and historical data.

The good news is, in some cases, the root cause of failure is obvious. Such examples could be:

- A balancing weight comes loose and strikes the winding.
- The winding is saturated with water.
- The bearing lubricant is contaminated.

However, in a case where the root cause must be known, it is imperative that none of the steps of the methodology be skipped.

**TABLE 1: MOTOR COMPONENTS/STRESSES**

| Type of stress      | Bearings | Stator | Rotor | Shaft | Frame |
|---------------------|----------|--------|-------|-------|-------|
| Thermal             | X        | X      | X     | X     | X     |
| Electric/dielectric | X        | X      | X     |       |       |
| Mechanical          | X        | X      | X     | X     | X     |
| Dynamic             | X        | X      | X     | X     | X     |
| Shear               |          | X      | X     | X     |       |
| Vibration/shock     | X        | X      | X     | X     | X     |
| Residual            |          |        | X     | X     | X     |
| Electromagnetic     | X        | X      | X     | X     |       |
| Environmental       | X        | X      | X     | X     | X     |



**TABLE 2: DETAILED SUMMARY OF MOTOR STRESSES**

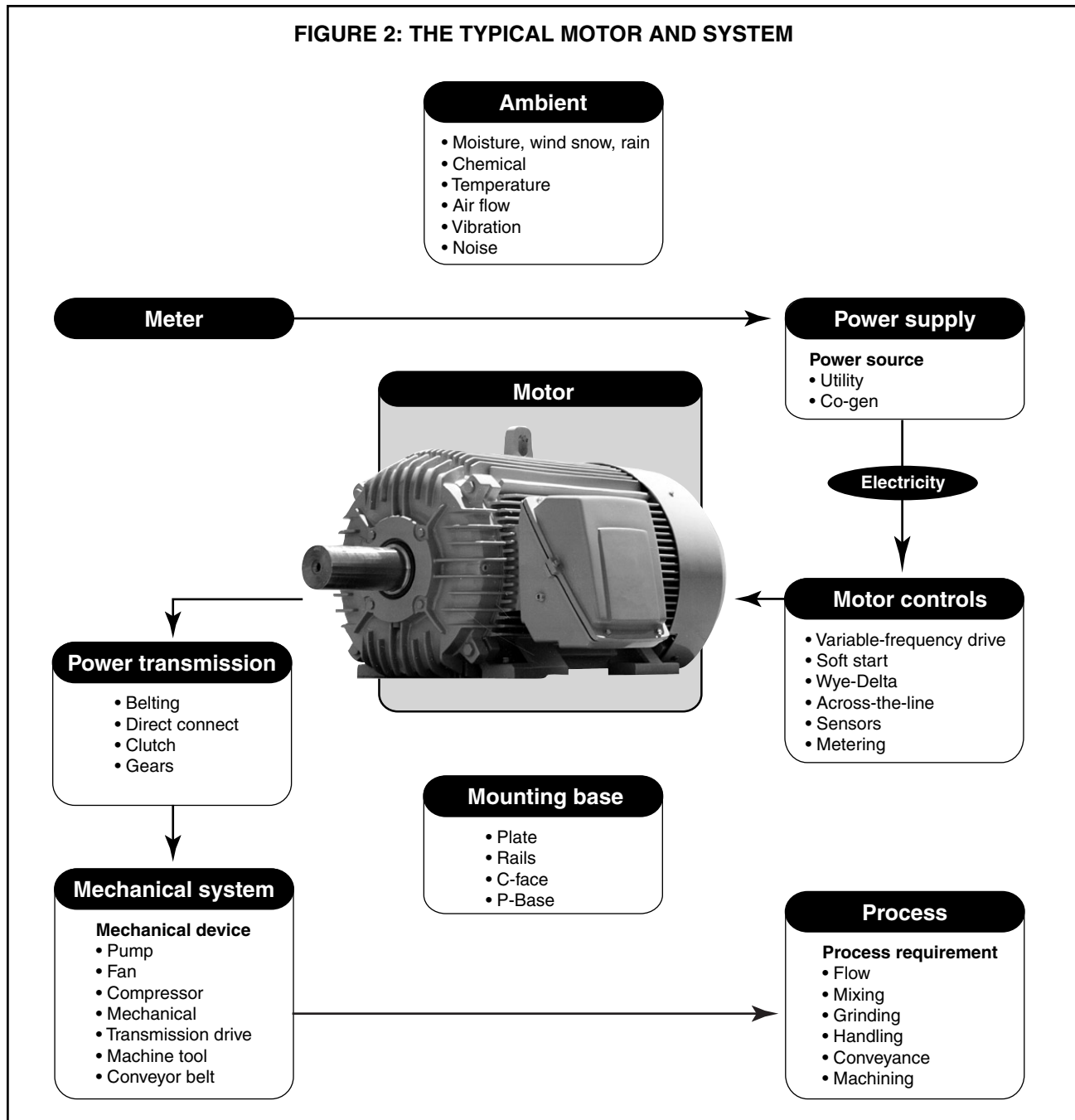
| Motor component | Stress type                | Actual stress or damage                                                                                                                                                                                                               |
|-----------------|----------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Bearings</b> | Thermal                    | Friction, lubricant, ambient                                                                                                                                                                                                          |
|                 | Dynamic and static loading | Radial, axial, preload, misapplication                                                                                                                                                                                                |
|                 | Vibration and shock        | Rotor, driven equipment, system                                                                                                                                                                                                       |
|                 | Environmental              | Condensation, foreign materials, excessive ambient, poor ventilation                                                                                                                                                                  |
|                 | Mechanical                 | Loss of clearances, misalignment, shaft and housing fits                                                                                                                                                                              |
|                 | Electrical                 | Rotor dissymmetry, electrostatic coupling, static charges, variable frequency drives                                                                                                                                                  |
| <b>Stator</b>   | Thermal                    | Thermal aging, thermal overload, voltage variation, voltage unbalance, ambient, load cycling, starting and stalling, poor ventilation                                                                                                 |
|                 | Electrical                 | Dielectric aging, transient voltages, partial discharge (corona), tracking                                                                                                                                                            |
|                 | Mechanical                 | Winding movement, damaged motor leads, improper rotor-to-stator geometry, abrasion, defective rotor, flying objects                                                                                                                   |
|                 | Environmental              | Moisture, chemical, abrasion, poor ventilation, excessive ambient                                                                                                                                                                     |
| <b>Rotor</b>    | Thermal                    | Thermal overload, thermal unbalance, excessive rotor losses, hot spots/sparking, incorrect direction of rotation, locked rotor                                                                                                        |
|                 | Dynamic                    | Vibration, loose rotor bars, rotor rub, transient torque, centrifugal force/overspeed, cyclical stress                                                                                                                                |
|                 | Mechanical                 | Casting variations/voids, loose laminations and/or bars, incorrect shaft-to-core fit, fatigue or part breakage, improper rotor-to-stator geometry, material deviations, improper mounting, improper design or manufacturing practices |
|                 | Environmental              | Contamination, abrasion, foreign materials, poor ventilation, excessive ambient temperature, unusual external forces                                                                                                                  |
|                 | Magnetic                   | Rotor pullover, uneven magnetic pull, lamination saturation, noise, circulating currents, vibration, noise, electromagnetic effect                                                                                                    |
|                 | Residual                   | Stress concentrations, uneven cage stress                                                                                                                                                                                             |
|                 | Miscellaneous              | Misapplication, effects of poor design, manufacturing variations, inadequate maintenance, improper operation, improper mounting                                                                                                       |
| <b>Shaft</b>    | Dynamic                    | Cyclic loads, overload, shock                                                                                                                                                                                                         |
|                 | Mechanical                 | Overhung load and bending, torsional load, axial load                                                                                                                                                                                 |
|                 | Environmental              | Corrosion, moisture, erosion, wear, cavitation                                                                                                                                                                                        |
|                 | Thermal                    | Temperature gradients, rotor bowing                                                                                                                                                                                                   |
|                 | Residual                   | Manufacturing processes, repair processes                                                                                                                                                                                             |
|                 | Electromagnetic            | Excessive radial load, out-of-phase reclosing                                                                                                                                                                                         |

**SUMMARY OF MOTOR STRESSES**

The majority of all motor failures are caused by a combination of various stresses acting upon the bearings, stator,

rotor and shaft. (See Table 1.) If these stresses are kept within the design capabilities of the system, premature failure should not occur. However, if any combination of the

FIGURE 2: THE TYPICAL MOTOR AND SYSTEM



stresses exceeds the design capacity, then the life of the system may be drastically reduced and catastrophic failure could occur.

These stresses can be broken down into the following groups or classifications:

- **Bearing stresses:** Thermal, dynamic and static loading, vibration and shock, environmental, mechanical, electrical.
- **Stator stresses:** Thermal, electrical, mechanical and environmental.
- **Rotor stresses:** Thermal, dynamic, mechanical, environmental, magnetic, residual, miscellaneous.

- **Shaft stresses:** Dynamic, mechanical, environmental, thermal, residual, electromagnetic.

For a more detailed summary of these stresses, see Table 2.

## ANALYSIS OF THE MOTOR AND SYSTEM

Surrounding the motor is a system that consists of the power supply, mounting, coupling and driven equipment. The environment, including the ambient, acts as an umbrella covering all of the elements of the system. Even the



end product or process can be considered part of this system. (See Figure 2.)

Many factors affecting the system will also affect the motor and may contribute to the motor failure and vice-versa. Failure to consider each of these elements of the complete motor system could lead to an incorrect diagnosis of the root cause of failure. An effective tool for a systems approach is to conduct a failure mode effect analysis (FMEA) of the complete system. The idea is to determine what the possible failure modes are for a component and then determine how that failure can impact the system where the component resides. This will offer at least some of the possible scenarios that can lead to a motor failure.

It is important to note that a number of failure mechanisms can lead to the same failed part with a common mode and pattern of failure. As examples, improper voltage, too much load, blocked ventilation, excessive cycling and excessive ambient can all produce the same type of winding failure. It is not always possible to correctly identify the problem without considering the entire system.

In many cases, arriving at the correct conclusion is a process of elimination driven by the collection of accurate data and facts associated with the system. At the risk of stating the obvious, failure to eliminate the root cause will usually assure expensive downtime and repeated motor failures. A classic example is the repeated replacement of failed bearings without ever trying to assess the root cause of failure.

## ARRIVING AT THE CORRECT CONCLUSION

When analyzing a motor failure, it is important not to assume facts that may fill in the gaps in information supplied by the customer.

The service center often does not know much about the motor application, much less the power supply and/or maintenance history. The customer dealing with the service center is probably not the person who removed the motor from service, and may not be the operator who is familiar with the motor or its application.

Incorrect, incomplete or even misleading information is the common. It may be impossible to draw the correct conclusion from the evidence provided. Never assume a piece of evidence exists just to force the “conclusion” to fit the “facts.”

When a conclusion is built around erroneous information mingled with “facts,” the root cause of failure is seldom correct. The result is additional failures or assigning blame to the wrong parties.

**Example:** A winding has failed, after a very short run time, with a turn-to-turn failure. The customer might believe that the motor's short life indicates poor workmanship, whether the motor is new or rewound.

The customer failed to advise (or the service center failed to ask) that the motor was operating on a pulse modulated width (PWM) drive with a 100' (30.5 m) cable run. This would have been a valuable piece of information for the service center and, at the same time, it would have accurately described the motor's power supply.

Without the knowledge of the PWM drive, the service center “forces” the conclusion that the motor manufacturer must have damaged the winding, even though there was no such evidence. The manufacturer “must have damaged it in some not so obvious way.”

The wrong party is assigned responsibility for, and the cost of, repairing the failed motor. More importantly, the problem is not fixed and will likely occur again.

The location of the failure is critical evidence that may explain the real reason for the winding failure. If the turn-to-turn failure is in a coil connected to a line lead, then a transient voltage could be the culprit. The location of this failure should alert the service center to find out more about the power supply.

When a motor is operating from a PWM drive, especially with a long cable run [more than 50' (15.25 m)], a turn-to-turn failure in the lead coil is classic indication of high voltage spikes produced by that PWM drive and the long cable run.

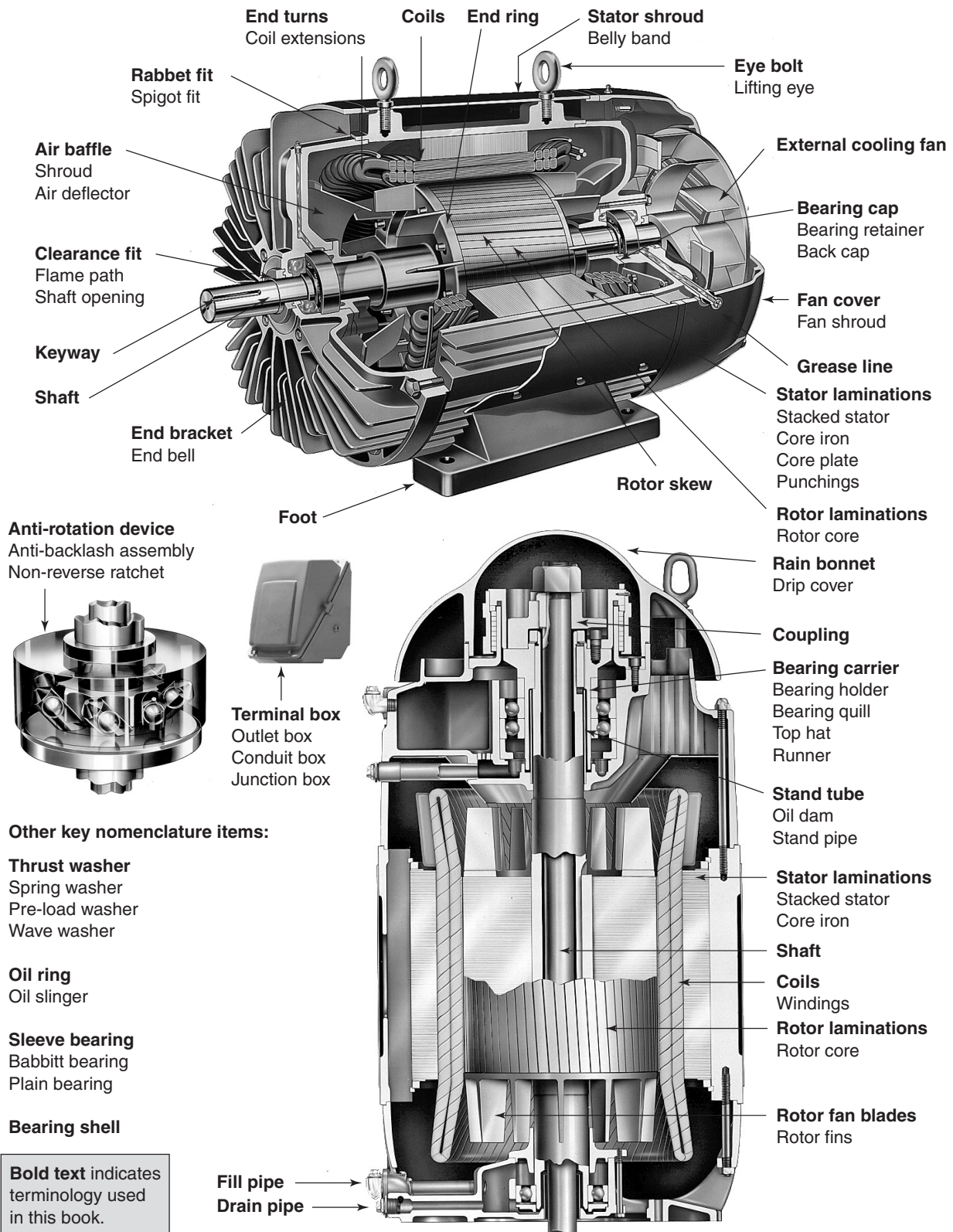
The difference in knowledge will:

- Assign the responsibility and cost of the repair to the correct party.
- Give credibility to the service center.
- And most importantly, make sure the root cause of the failure is identified and corrected.

## RESOURCE MATERIALS

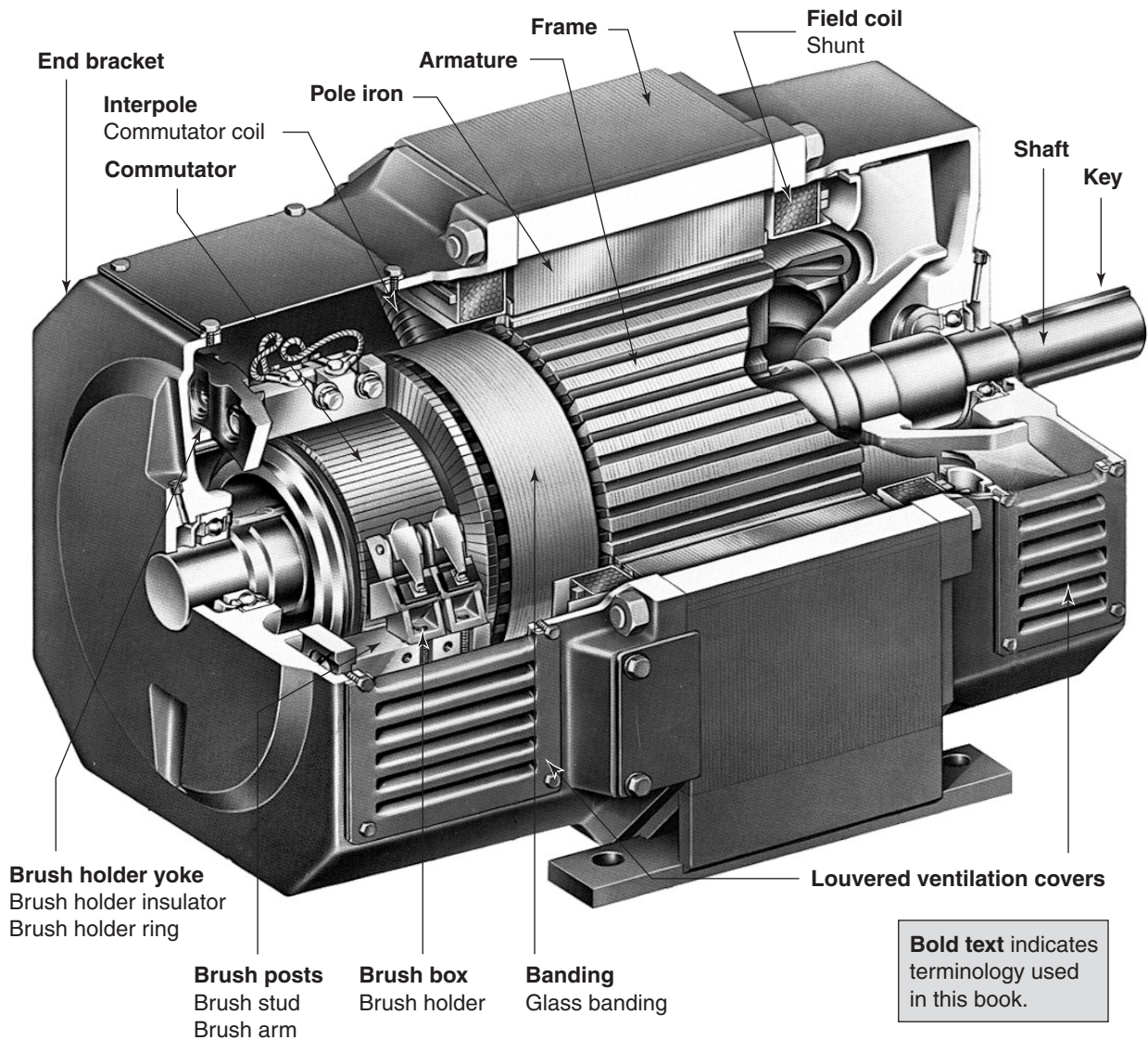
The following pages provide some useful resources to help correctly identify motor failures including basic nomenclature for horizontal and vertical motors, charts for the collection of data, and lists of questions useful in analyzing a motor failure.

## BASIC AC MOTOR NOMENCLATURE AND COMMON ALTERNATIVES





## BASIC DC MOTOR NOMENCLATURE AND COMMON ALTERNATIVES



**METHODOLOGY FORMS**  
**APPEARANCE OF MOTOR AND SYSTEM**

| ITEM                                                                                                                                                                                                                                                                                                           | REMARKS |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------|
| Are there signs of foreign material within the motor?                                                                                                                                                                                                                                                          |         |
| Are there signs of blocked ventilation passages?                                                                                                                                                                                                                                                               |         |
| Are there signs of overheating present in the insulation, laminations, bars, bearings, lubricant, painted surfaces, etc?                                                                                                                                                                                       |         |
| Have the rotor laminations or shaft rubbed? Record all locations of rotor and stator contact.                                                                                                                                                                                                                  |         |
| Are the topsticks, coils or coil bracings 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? Is the failure in the first turn or first coil? |         |
| Are the bearings free to rotate and operate as intended?                                                                                                                                                                                                                                                       |         |
| Are there signs of moisture on the stator, rotating assembly, bearing system or any other parts?                                                                                                                                                                                                               |         |
| Are there any signs of movement between rotor and shaft or bars and laminations?                                                                                                                                                                                                                               |         |
| Is the lubrication system as intended or has there been lubricant leakage or deterioration?                                                                                                                                                                                                                    |         |
| Are there any signs of a stalled or locked rotor?                                                                                                                                                                                                                                                              |         |
| Was the rotor turning during the failure?                                                                                                                                                                                                                                                                      |         |
| What was the direction of rotation and does it agree with the 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 an often overlooked weak link.)                                                                                                                                                                                       |         |



**METHODOLOGY FORMS  
APPLICATION CONSIDERATIONS**

| ITEM                                                                                                                                                                            | REMARKS |
|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------|
| What are the load characteristics of the driven equipment?<br>What was the loading at the 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 potential for transient voltages? Was the voltage balanced between phases?                                          |         |
| How long does it take for the motor to accelerate to operating speed?                                                                                                           |         |
| Have any other motors or equipment failed on this application?                                                                                                                  |         |
| How many other motors are successfully running?                                                                                                                                 |         |
| How long has the motor been in service?                                                                                                                                         |         |
| Did the motor fail on starting or while operating?                                                                                                                              |         |
| How often is the motor started? Is this a manual or automatic operation? Is it a part-winding, wye-delta, variable frequency drive (VFD) or across-the-line method of starting? |         |
| What type of protection is provided?                                                                                                                                            |         |
| What removed or tripped the motor from the line?                                                                                                                                |         |
| Where is the motor located and what are the normal environmental conditions in which it operates? What was the environment like when the motor failed?                          |         |
| What was the ambient temperature around the motor at the time of the failure? Was there any recirculation of air? Is the exchange of cooling air adequate?                      |         |
| Is the power supplied by a variable frequency drive (VFD)? What is the distance of the cable run between the VFD and the motor?                                                 |         |
| How would you describe the coupling and mounting method for the driven load?                                                                                                    |         |

**METHODOLOGY FORMS  
MAINTENANCE HISTORY**

| ITEM                                                                                                                    | REMARKS |
|-------------------------------------------------------------------------------------------------------------------------|---------|
| How long has the motor been in service?                                                                                 |         |
| Have any other motor failures been recorded? If so, what were the nature of these failures?                             |         |
| What failures of the driven equipment have occurred? Was any welding done in the area of the motor?                     |         |
| 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 motor in storage or sitting idle prior to starting?                                                    |         |
| What were the storage conditions?                                                                                       |         |
| How often is the motor started? Were there any shutdowns?                                                               |         |
| Were correct lubrication procedures used?                                                                               |         |
| Have any changes been made to surrounding equipment?<br>Has there been any recent balancing of driven equipment?        |         |
| What procedures were used in adjusting the tension of belts?                                                            |         |
| Are the pulleys positioned on the shaft correctly and as close to the motor bearing as possible?                        |         |

## MOTOR SYSTEM AND ENVIRONMENT CHECKLIST

## POWER SUPPLY INFORMATION

## SINEWAVE POWER

## Across-the-line starting

Voltage      RMS current

 $V_{ab}$        $I_A$  $V_{ac}$        $I_B$  $V_{bc}$        $I_C$ 

% unbalanced

## Controlled start

☐ Reduced voltage☐ Part-winding☐ Wye-delta☐ Soft start

## NON-SINEWAVE POWER

## Type of drive

☐ Pulse width modulated☐ Other \_\_\_\_\_

Cable run length \_\_\_\_\_

## Known transients

☐ Lightning☐ Switching☐ Other \_\_\_\_\_

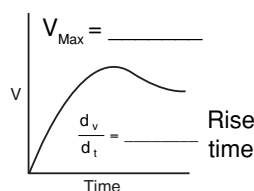
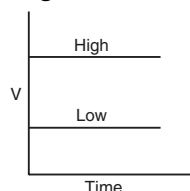
## Recorded incidents

☐ Trips☐ Failed starts☐ Known harmonics☐ Other \_\_\_\_\_

## Other

☐ Power factor correction☐ Surge capacitors☐ Lightning arrestors☐ Reactors

## Voltage variations



## ENCLOSURE AND ENVIRONMENT

## Location of motor

☐ Outdoors☐ Confined space☐ Indoors☐ Other \_\_\_\_\_☐ Above grade☐ At grade

— Ground level

☐ Below grade

## Examine ambient

☐ High temperature☐ Low temperature☐ Moisture conditions☐ Altitude, coastal or mining☐ Other \_\_\_\_\_

## Recent events

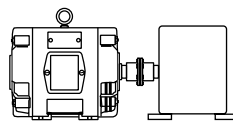
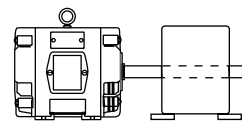
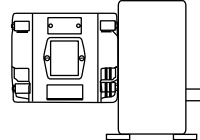
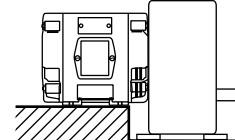
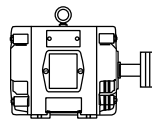
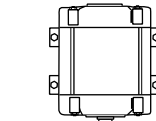
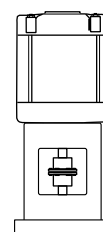
☐ Rain☐ Flood☐ Spills☐ Lightning☐ Other \_\_\_\_\_

## List possible contaminants

\_\_\_\_\_

\_\_\_\_\_

## MOUNTING AND COUPLING

☐ Direct coupled☐ Common shaft☐ Integral cantilever☐ Integral but foot mounted☐ Overhung load☐ Belts☐ Sprocket☐ Other \_\_\_\_\_☐ Wall mounted☐ Ceiling mounted☐ Other \_\_\_\_\_☐ Solid shaft, coupled lower end☐ Hollow shaft, coupled top end

## APPLICATION INFORMATION

## Equipment type

☐ Pump☐ Blower/Fan☐ Compressor☐ Material handling(Conveyor,  
crusher, etc.)

## Description

☐ Centrifugal☐ Reciprocating☐ Submersible☐ Reciprocating☐ Rotary screw type

## Starting requirements

Inertia

☐ Low☐ Medium☐ High

Torque

☐ Constant☐ Variable☐ Constant horsepower☐ Other \_\_\_\_\_

## Starting cycle

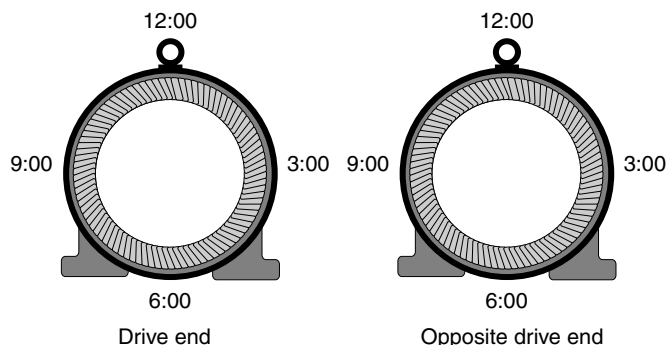
☐ Acceleration☐ Frequency/on-off time

## Loading conditions

☐ Light☐ Medium☐ High☐ Overload



### STATOR COIL LAYOUT FOR LOCATION AND IDENTIFICATION OF FAULT



The leads are ☐ F1 mounted  
☐ F2 mounted

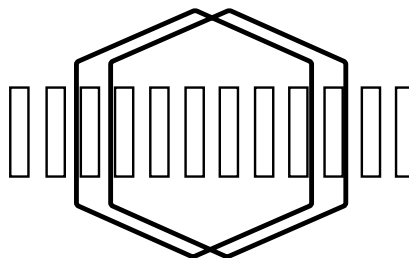
The connection is on the ☐ drive end (DE)  
☐ opposite drive end (ODE)

How many leads are there? \_\_\_\_\_

How are the leads marked? \_\_\_\_\_

Mark the location of failure(s) above. Identify on which end of the motor the failure occurred and its position on the clock.

Identify which coil in the group failed, and relationship to the lead coil.



Is there core damage?

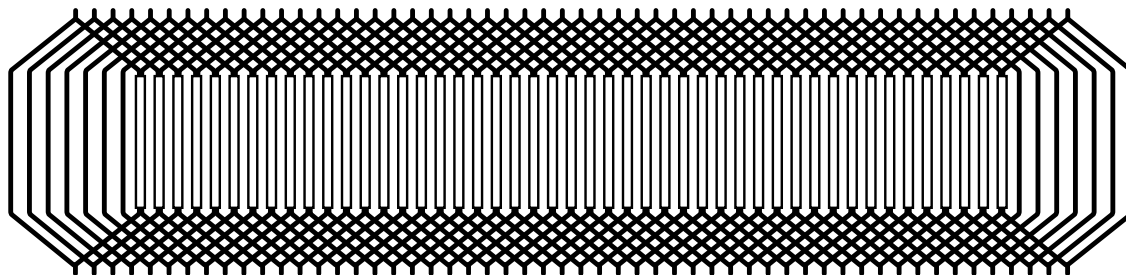
☐ Yes  
☐ No

If so, how extensive is the damage?

Is there grease, water or dirt on the windings?

How many slots are affected? \_\_\_\_\_

Length of damaged area? \_\_\_\_\_



Number of:

Poles \_\_\_\_\_

Slots \_\_\_\_\_

Coils per group \_\_\_\_\_

Circuits \_\_\_\_\_

Connection ☐ Wye ☐ Delta

CUST: \_\_\_\_\_  
P.O. #: \_\_\_\_\_  
JOB #: \_\_\_\_\_  
DATE: \_\_\_\_\_

MAJOR REPAIR ITEMS

☐ INSPECT/CLEAN

☐ REWIND

☐ RESTACK ROTOR

☐ BEARING REPLACEMENT

☐ JOURNAL SURFACE RECONDITION

☐ SHAFT STRAIGHTENED

☐ SHAFT REPLACED

☐ HOUSING LINE BORED

☐ ROTOR BALANCED

☐ PAINTED

☐ OTHER \_\_\_\_\_

COND. BEFORE REPAIR

1. BEARING

DE

ODE

GOOD CONDITION

☐

☐

CHATTER

☐

☐

FROZEN TO SHAFT

☐

☐

SCORED/WIPED

☐

☐

OTHER

\_\_\_\_\_

\_\_\_\_\_

2. LUBRICATION

INBOARD

☐ NORMAL

☐ VARNISHED

OUTBOARD

☐ NORMAL

☐ VARNISHED

3. ROTOR

☐ GOOD CONDITION

☐ ARCED/FUSED AREAS

☐ DISCOLORED/HOT SPOTS

☐ ROTOR FAN CRACKED

☐ CRACKED ROTOR BARS

☐ RUBBED TO STATOR

☐ OTHER

\_\_\_\_\_

4. SHAFT

☐ GOOD CONDITION

☐ DIAM @ SLEEVE BEARING

☐ BENT

☐ RUN OUT / TIR

☐ JOURNAL SURFACE DAMAGED

☐ OTHER

\_\_\_\_\_

5. STATOR

☐ GOOD CONDITION

☐ ARCED/FUSED AREAS

☐ DISCOLORED/HOT SPOTS

☐ BENT LAMINATIONS

☐ RUBBED/WARPED/WORN

☐ LOOSENESS

☐ OTHER

\_\_\_\_\_

6. FLAME PATH BUSHING

☐ GOOD CONDITION

I.D. \_\_\_\_\_

☐ WEAR

OUT OF ROUND/TIR \_\_\_\_\_

☐ SCORING

JOURNAL CLEARANCE \_\_\_\_\_

7. SUSPECTED CAUSE OF FAILURE, COMMENTS, SUGG.

\_\_\_\_\_

\_\_\_\_\_

\_\_\_\_\_

AS FOUND REPORT

DISASSEMBLY

OVERALL LENGTH \_\_\_\_\_

NUMBER OF LEAD WIRES \_\_\_\_\_

NORMAL THICKNESS \_\_\_\_\_

SIZE OF LEAD WIRE \_\_\_\_\_

INSIDE DIAMETER \_\_\_\_\_

SIZE OF MAGNET WIRE \_\_\_\_\_

OUTSIDE DIAMETER \_\_\_\_\_

TYPE OF MAGNET WIRE \_\_\_\_\_

WINDING FLAPS \_\_\_\_\_

NUMBER OF TURNS PER COIL \_\_\_\_\_

FRAME CLEARANCE \_\_\_\_\_

NUMBER OF COILS PER POLE \_\_\_\_\_

WINDING PITCH \_\_\_\_\_

NUMBER OF SLOTS \_\_\_\_\_

CONDITION OF CONNECTION LEADS \_\_\_\_\_

MECHANICAL REPAIR

Disassembled By: \_\_\_\_\_

Mechanical Readings: \_\_\_\_\_

Electrical Readings: \_\_\_\_\_

Reassembled By: \_\_\_\_\_

Tested By: \_\_\_\_\_

12:00

9:00

3:00

6:00

DRIVE END (DE)

OPPOSITE DRIVE END (ODE)

12:00

9:00

3:00

6:00

SHAFT

TIR INITIAL \_\_\_\_\_

TIR FINAL \_\_\_\_\_

STRAIGHTENING METHOD

☐ NOT APPLICABLE

☐ PEENING

☐ HEATING

☐ BENDING

LOCATION OF BEND \_\_\_\_\_

(DISTANCE FROM IB END)

JOURNAL RECONDITION

☐ NOT RECONDITIONED

CHROME PLATE DEPOSITION THICKNESS

DRIVE END \_\_\_\_\_

OPPOSITE DRIVE END \_\_\_\_\_

AIR GAP (AS VIEWED FROM COUPLING END)

INITIAL 12:00

3:00

6:00

9:00

FINAL 12:00

3:00

6:00

9:00

IB

OB

BEARINGS

MFG.

DRIVE END

OPP. DRIVE END

MEASUREMENTS

IB

OB

BRG. HOUSING I.D.

BRG. O.D.

CLEARANCE

BRG I.D.

JOURNAL O.D.

CLEARANCE

END FLOAT

ENTER VALUES

MAG. CTR.

MOTOR INFORMATION

MANUFACTURER \_\_\_\_\_

SERVICE FACTOR \_\_\_\_\_

SERIAL NO. \_\_\_\_\_

NEMA TYPE \_\_\_\_\_

HORSE POWER \_\_\_\_\_

RPM \_\_\_\_\_

VOLTAGE \_\_\_\_\_

BEARING TYPE \_\_\_\_\_

PHASES \_\_\_\_\_

FULL LOAD AMPS \_\_\_\_\_

☐ YES ☐ NO

 COUPLING OR PULLEY ATTACHED TO MOTOR ON ARRIVAL?

☐ DELTA COIL CONNECTION

☐ WYE COIL CONNECTION

☐ YES ☐ NO

 CONNECTION BOX ATTACHED TO MOTOR ON ARRIVAL?

TEST

NO LOAD CURRENT 1ST PHASE \_\_\_\_\_

NO LOAD SPEED (RPM) \_\_\_\_\_

2ND PHASE \_\_\_\_\_

INSULATION RESISTANCE \_\_\_\_\_

3RD PHASE \_\_\_\_\_

TEST VOLTS \_\_\_\_\_

INSULATION RESISTANCE DURING TEST (IF REQUIRED)

0 SEC \_\_\_\_\_

1 MIN 30 SEC \_\_\_\_\_

6 MIN \_\_\_\_\_

15 SEC \_\_\_\_\_

1 MIN 45 SEC \_\_\_\_\_

7 MIN \_\_\_\_\_

30 SEC \_\_\_\_\_

2 MIN 0 SEC \_\_\_\_\_

8 MIN \_\_\_\_\_

45 SEC \_\_\_\_\_

3 MIN \_\_\_\_\_

9 MIN \_\_\_\_\_

1 MIN 0 SEC \_\_\_\_\_

4 MIN \_\_\_\_\_

10 MIN \_\_\_\_\_

1 MIN 15 SEC \_\_\_\_\_

5 MIN \_\_\_\_\_

RESISTANCE (MEGAHOMS)

100

90

80

70

60

50

40

30

20

10

9

8

7

6

5

4

3

2

1

0

1

2

3

4

5

6

7

8

9

10

MINUTES INTO TEST

POLORIZATION INDEX =

RESISTANCE : VALUE @ 10 MIN:

RESISTANCE : VALUE @ 1 MIN:

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1 - 13

AS RELEASED REPORT

ASSEMBLY

OVERALL LENGTH \_\_\_\_\_  
NORMAL THICKNESS \_\_\_\_\_  
INSIDE DIAMETER \_\_\_\_\_  
OUTSIDE DIAMETER \_\_\_\_\_  
WINDING FLAPS \_\_\_\_\_  
FRAME CLEARANCE \_\_\_\_\_  
WINDING PITCH \_\_\_\_\_

NUMBER OF LEAD WIRES \_\_\_\_\_  
SIZE OF LEAD WIRE \_\_\_\_\_  
SIZE OF MAGNET WIRE \_\_\_\_\_  
TYPE OF MAGNET WIRE \_\_\_\_\_  
NUMBER OF TURNS PER COIL \_\_\_\_\_  
NUMBER OF COILS PER POLE \_\_\_\_\_  
NUMBER OF SLOTS \_\_\_\_\_  
CONDITION OF CONNECTION LEADS \_\_\_\_\_

MOTOR INFORMATION

MANUFACTURER \_\_\_\_\_  
SERIAL NO. \_\_\_\_\_  
HORSE POWER \_\_\_\_\_  
VOLTAGE \_\_\_\_\_  
PHASES \_\_\_\_\_

SERVICE FACTOR \_\_\_\_\_  
NEMA TYPE \_\_\_\_\_  
RPM \_\_\_\_\_  
BEARING TYPE \_\_\_\_\_  
FULL LOAD AMPS \_\_\_\_\_

☐ YES ☐ NO COUPLING OR PULLEY ATTACHED TO MOTOR ON ARRIVAL?  
☐ DELTA COIL CONNECTION ☐ WYE COIL CONNECTION  
☐ YES ☐ NO CONNECTION BOX ATTACHED TO MOTOR ON ARRIVAL?

COND. AFTER REPAIR

1. BEARING

DE

ODE

GOOD CONDITION ☐

CHATTER ☐

FROZEN TO SHAFT ☐

SCORED/WIPED ☐

OTHER \_\_\_\_\_

2. LUBRICATION

INBOARD ☐ NORMAL ☐ VARNISHED

OUTBOARD ☐ NORMAL ☐ VARNISHED

3. ROTOR

☐ GOOD CONDITION ☐ ARCED/FUSED AREAS

☐ DISCOLORED/HOT SPOTS ☐ ROTOR FAN CRACKED

☐ CRACKED ROTOR BARS ☐ RUBBED TO STATOR

☐ OTHER \_\_\_\_\_

4. SHAFT

☐ GOOD CONDITION ☐ DIAM @ SLEEVE BEARING

☐ BENT ☐ RUN OUT / TIR

☐ JOURNAL SURFACE DAMAGED

☐ OTHER \_\_\_\_\_

5. STATOR

☐ GOOD CONDITION ☐ ARCED/FUSED AREAS

☐ DISCOLORED/HOT SPOTS ☐ BENT LAMINATIONS

☐ RUBBED/WARPED/WORN ☐ LOOSENESS

☐ OTHER \_\_\_\_\_

6. FLAME PATH BUSHING

☐ GOOD CONDITION I.D. \_\_\_\_\_

☐ WEAR OUT OF ROUND/TIR \_\_\_\_\_

☐ SCORING JOURNAL CLEARANCE \_\_\_\_\_

7. SUSPECTED CAUSE OF FAILURE, COMMENTS, SUGG.

\_\_\_\_\_

\_\_\_\_\_

\_\_\_\_\_

MECHANICAL REPAIR

Disassembled By: \_\_\_\_\_  
Mechanical Readings: \_\_\_\_\_  
Electrical Readings: \_\_\_\_\_  
Reassembled By: \_\_\_\_\_  
Tested By: \_\_\_\_\_

12:00

9:00

3:00

6:00

12:00

9:00

3:00

6:00

OPPOSITE DRIVE END (ODE)

SHAFT

TIR INITIAL \_\_\_\_\_

TIR FINAL \_\_\_\_\_

STRAIGHTENING METHOD

☐ NOT APPLICABLE

☐ PEENING

☐ HEATING

☐ BENDING

LOCATION OF BEND \_\_\_\_\_

(DISTANCE FROM IB END)

JOURNAL RECONDITION

☐ NOT RECONDITIONED

CHROME PLATE DEPOSITION THICKNESS

DRIVE END \_\_\_\_\_

OPPOSITE DRIVE END \_\_\_\_\_

END FLOAT

ENTER VALUES

MAG. CTR.

DRIVE END (DE)

12:00

9:00

3:00

6:00

☐ SLEEVE

☐ ANTIFRICTION

BEARINGS

|                   | MFG. |    |
|-------------------|------|----|
|                   | IB   | OB |
| DRIVE END         |      |    |
| OPP. DRIVE END    |      |    |
| MEASUREMENTS      |      |    |
| BRG. HOUSING I.D. |      |    |
| BRG. O.D.         |      |    |
| CLEARANCE         |      |    |
| BRG I.D.          |      |    |
| JOURNAL O.D.      |      |    |
| CLEARANCE         |      |    |

AIR GAP (AS VIEWED FROM COUPLING END)

|               | IB | OB |
|---------------|----|----|
| INITIAL 12:00 |    |    |
| 3:00          |    |    |
| 6:00          |    |    |
| 9:00          |    |    |
| FINAL 12:00   |    |    |
| 3:00          |    |    |
| 6:00          |    |    |
| 9:00          |    |    |

TEST

NO LOAD CURRENT 1ST PHASE \_\_\_\_\_

2ND PHASE \_\_\_\_\_

3RD PHASE \_\_\_\_\_

NO LOAD SPEED (RPM) \_\_\_\_\_

INSULATION RESISTANCE \_\_\_\_\_

TEST VOLTS \_\_\_\_\_

INSULATION RESISTANCE DURING TEST (IF REQUIRED)

0 SEC \_\_\_\_\_

15 SEC \_\_\_\_\_

30 SEC \_\_\_\_\_

45 SEC \_\_\_\_\_

1 MIN 0 SEC \_\_\_\_\_

1 MIN 15 SEC \_\_\_\_\_

1 MIN 30 SEC \_\_\_\_\_

2 MIN 0 SEC \_\_\_\_\_

3 MIN \_\_\_\_\_

4 MIN \_\_\_\_\_

5 MIN \_\_\_\_\_

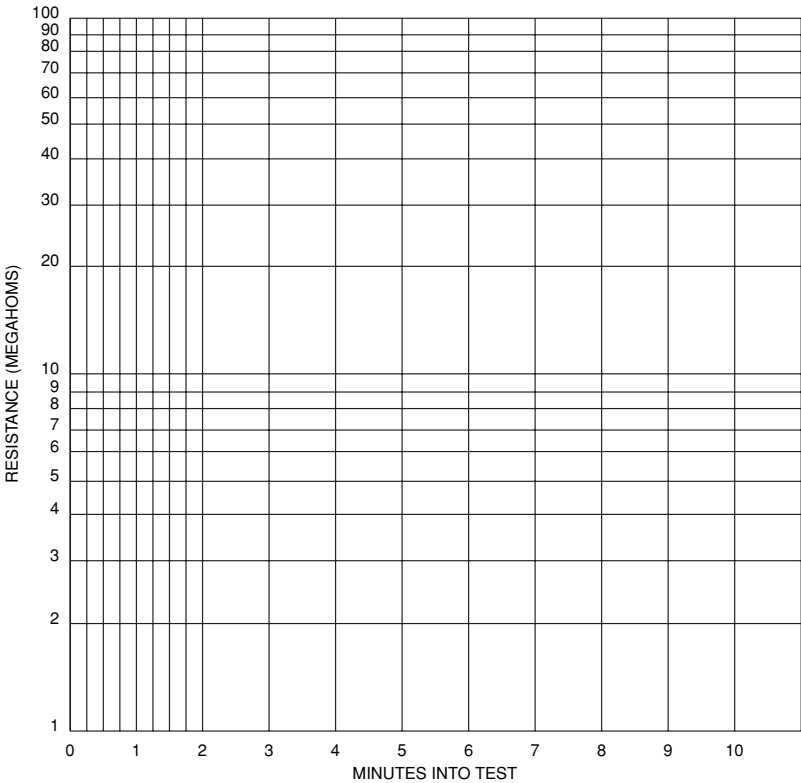
6 MIN \_\_\_\_\_

7 MIN \_\_\_\_\_

8 MIN \_\_\_\_\_

9 MIN \_\_\_\_\_

10 MIN \_\_\_\_\_



POLORIZATION INDEX =  $\frac{\text{RESISTANCE : VALUE @ 10 MIN:}}{\text{RESISTANCE : VALUE @ 1 MIN:}}$



# 2

## Bearing Failures

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## DETERMINING BEARING LIFE

Bearing life is a function of rotational speed, dynamic load, lubricant quality, impact loading and bearing size. The prediction of rating fatigue life, commonly referred to as “ $L_{10}$ ” life is based on the assumption that the ultimate cause of failure is material fatigue. Excessive heat, lack of lubricant, or excessive loads simply accelerate the fatigue process. The  $L_{10}$  life is the estimated time for 10% of a large population to fail. If  $L_{10}$  is one year, then  $L_{50}$  (the point at which half the bearings will have failed) is 5 times that or 5 years. This means that for an application with a  $L_{10}$  life of 1 year, 10% of the bearings may fail within that first year, and that one-half the bearings may fail after 5 years.

The life for ball bearings is approximately inversely proportional to the load cubed and inversely proportional to the speed. These relationships are only valid within certain constraints relating to the bearing size, design, lubrication, temperature, load and speed. Bearings are subject to speed limitations that are affected by the size and material of the bearing, as well as the lubricant. Oil lubrication increases bearing speed limits by at least 10 to 15%.

$$L_{10} = (C/P)^p$$

When rpm is constant,  $L_{10h}$  can be derived:

$$L_{10h} = 1,000,000/60n (C/P)^p$$

Where:  $L_{10}$  is basic rating life, millions of revolutions  
 $p = 3$  for ball bearings  
 $p = 10/3$  for roller bearings  
 $C$  = Bearing dynamic load rating  
 $P$  = Equivalent bearing load  
 $n$  = Rotational speed, rpm

The bearing industry has long used this formula to predict bearing life. The  $L_{10}$  bearing life gives satisfactory assurance of bearing life for the purpose of selecting the appropriate bearing for each application.

In the real world, manufacturers try to reduce costs by using the smallest bearing that will give satisfactory performance. Sometimes motors are built with smaller bearings than are prudent. End users apply motors for applications (and in environments) for which they were not intended. In addition, maintenance personnel do not always lubricate bearings on schedule. The repair industry has to contend with each of these realities.

The mode of bearing failure is fatigue, which may be greatly accelerated by the factors listed later in this section.

## THE FATIGUE PROCESS AND STRESSES THAT ACT UPON ROLLING ELEMENT BEARINGS

- Microscopic subsurface fractures of metal due to cyclic loading stress, producing thin layers of surface separation, which flake off (spalling).
- Some increase in noise and vibration will occur.
- A change in critical dimension occurs.
- Noise, vibration, friction, heat and wear accompanied by more advanced spalling. It is no longer safe or prudent to operate the machine.
- The final step is advanced spalling, usually followed by catastrophic failure. (See Figure 1.)

The above 5 steps outline the failure process; the rate at which that process occurs depends on the variables in the  $L_{10}$  formula, but can be further influenced by several external factors. The majority of bearing failures can be attributed to a variety of stresses that can be grouped as follows:

### Thermal stress

- Friction.
- Lubricant.
- Ambient.

### Dynamic and static loading stress

- Radial.
- Axial.
- Preload.

### Vibration and shock stress

- Rotor.
- Driven equipment.
- System.

### Environmental stress

- Condensation.
- Foreign material.
- Excessive ambient.
- Poor ventilation.

### Mechanical stress

- Loss of clearance.
- Misalignment.
- Shaft fit out of tolerance.
- Housing fit out of tolerance.

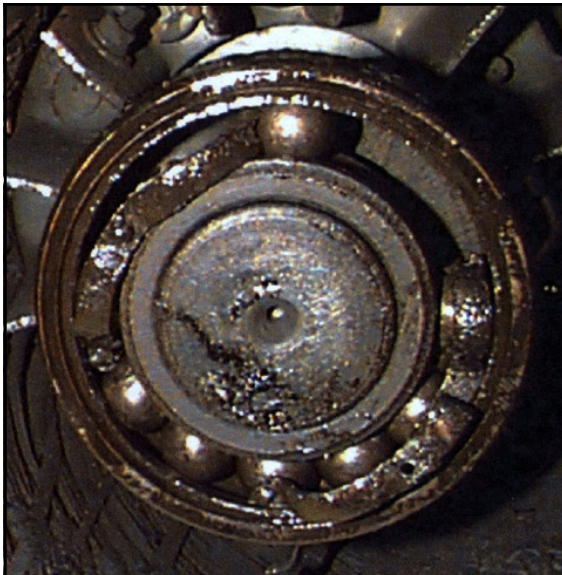
## PHOTOGRAPHS OF BEARING FAILURES

### Rolling element bearings

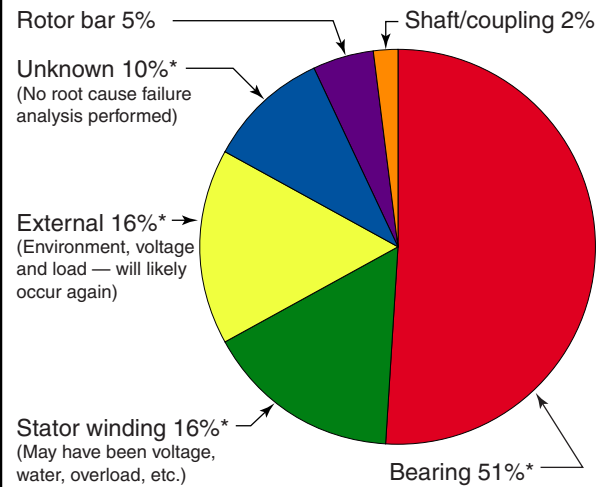
|                                         |      |
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### Sleeve bearings

|                                         |      |
|-----------------------------------------|------|
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| Environmental stress .....              | 2-38 |
| Mechanical stress .....                 | 2-40 |
| Vibration and shock stress .....        | 2-41 |
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**FIGURE 1: THE FATIGUE PROCESS**

These photographs show the progression of a fatigue failure, from microscopic fractures, through spalling, to catastrophic failure. How quickly this happens depends on speed, time, temperature, load, vibration and lubricant.

**FIGURE 2: DISTRIBUTION OF FAILED COMPONENTS**

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

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

#### Electrical currents

- Rotor dissymmetry.
- Electrostatic coupling.
- Static charges.
- Variable frequency drives.

Since more than half of electric motor failures start as bearing failures (Figure 2), it is important to correctly analyze the failure to determine the root cause to prevent future failures. Because severe thermal failures also destroy the lubricant, evaluation of the bearing independent of the system is difficult (Figure 3).

**FIGURE 3: LUBRICANT DESTROYED BY THERMAL STRESS**

## TIPS FOR INTERPRETING BEARING FAILURES

In order to correctly interpret a bearing failure, it is helpful to mark the position of each bearing as it is removed. When axial thrust is a factor, the direction of thrust may point to a coupling problem or an internal preload condition. A practical method is to use a die grinder or engraver to identify which side of each bearing is toward the rotor before the bearings are removed. Dissect the bearing using a die grinder rather than a torch, which heats and destroys evidence.

The wear pattern on the raceways offers important evidence. Axial displacement (thrusting) is indicated by a ball path that is offset to opposite sides of the inner and outer races. Misalignment is indicated by a ball path that angles from one side of the outer race to the other. A displaced (cocked) inner race is indicated by a wider path on the inner race. Internal misalignment (indicated by the angled ball path) often results from a cocked bearing bracket, or a bearing housing that has been bored and sleeved improperly.

In the case of thrust bearings, indications of internal misalignment are important because misalignment will drastically shorten bearing load capacity and life.

Some bearing failures, especially sleeve bearing failures, can only be interpreted in conjunction with the lubricant. When possible, preserve a sample of the lubricant for analysis. In the case of rolling element bearings, the appearance of the lubricant can be critically important.



Above, the side of the bearing toward the rotor has been marked prior to dissection. Below, a dissected ball bearing.



If a bearing is to be sent out for outside expertise, do not clean the bearing first! Sandwich bags are great for packaging a bearing with its lubricant before shipping.

## METHODOLOGY FOR ANALYZING ROLLING ELEMENT BEARING FAILURES

There are five key areas which should be considered and related to one another in order to accurately diagnose the root cause of rolling element bearing failures. They are:

- Failure mode.
- Failure pattern.
- Appearance.
- Application.
- Maintenance history.

### FAILURE MODES

Failure modes can be grouped into twelve categories, which are usually the result of combined stresses acting on the bearing to the point of damage or failure. This is arbitrarily referred to as the failure mode.

- Fatigue.
- Fretting.
- Smearing.
- Skidding.
- Scoring.
- Abrasive or abnormal wear.

- Corrosion.
- Lubrication failure.
- True or false brinelling.
- Electric pitting or fluting.
- Cracks.
- Seizures.

These modes do not represent the cause of the bearing problem; instead they are the result or way that the problem is manifested.

### FAILURE PATTERNS

Closely associated with the failure mode, yet different, is the failure pattern. Each bearing failure has associated with it a certain pattern which can be grouped into some combination of the following categories.

- Temperature levels (discoloration).
- Noise levels.
- Vibration levels.
- Lubrication quality.
- Condition of mounting fits.
- Internal clearances.
- Contamination.
- Mechanical or electrical damage.
- Load paths and patterns (alignment).



### APPEARANCE CONSIDERATIONS

When coupled with the mode and pattern of failure, the motor, bearing and load appearance usually give a clue as to the possible cause of failure. The following checklist will be useful in the evaluation.

- Are there signs of contamination in the area of the bearings? Any recent welding?
- Are there signs of excessive temperature anywhere in the motor or driven equipment?
- What is the quality of the bearing lubricant?
- Are there signs of moisture or rust?
- What is the condition of the coupling device used to connect the motor and the load?
- What levels of noise or vibration were present prior to failure?
- Are there any missing parts on the rotating member?
- What is the condition of the bearing bore, shaft journal, seals, shaft extension and bearing cap?
- What was the direction of rotation? Was there an overhung load or any axial thrust? Are they supported by the bearing wear patterns?
- Does the outer or inner face show signs of fretting?
- Is the motor mounted, aligned and coupled correctly?

Do not destroy the failed bearing until it has been properly inspected. It is also important to save a sample of the bearing lubricant.

### APPLICATION CONSIDERATIONS

Usually it is difficult to reconstruct the actual operating 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?
- Does the load cycle or pulsate?
- How many other units are successfully operating?
- How often is the unit started?
- What type of bearing protection is provided?
- Where is the unit located and what are the normal environmental conditions?
- Is the motor enclosure adequate for the application?
- What were the environmental conditions at time of failure?
- Is the mounting base correct for proper support to the motor?
- Is the belting or method of connection to the load correct for the application?

### 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 in the area?
- When was the last time any service or maintenance was performed?
- What operating levels (temperature, vibration, noise, etc.) were observed prior to the failure? What tripped the motor off the line?
- 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 the lubrication procedures correct?
- Have any changes been 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?

### LUBRICATION

Because lubrication is inseparable from many bearing failures, there is lubrication information distributed throughout the bearing failure section. This portion of the section focuses specifically on lubrication issues, to facilitate its use as a reference.

The role of lubricant is to reduce friction between the rolling or sliding parts, dissipate heat generated by the bearings and protect the surface finish of the bearing parts from corrosion. To a lesser extent, lubrication excludes foreign contamination by displacement.

Lubrication normally means either grease or oil, each of which can be delivered by several different methods.

### GREASE LUBRICATION

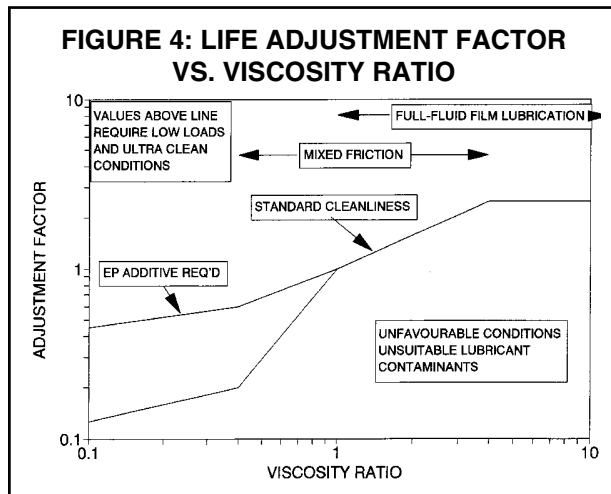
Grease is oil suspended in a base so that the oil is available to lubricate the bearing as needed. Grease lubrication is almost exclusively for ball and roller bearings.

When a bearing housing is designed for grease lubrication, a cavity is provided within the bracket to hold a quantity of grease. Some designs incorporate metering plates and similar methods to regulate the flow of grease to the bearing. An inner bearing retainer (or cap) is often provided to retain the grease and exclude contamination. In many cases, the retainer also is used to establish endplay.

Lubrication can be affected by temperature, environmental conditions, dynamic bearing load, and speed. Lubrication selection can affect vibration levels, bearing temperature and longevity.

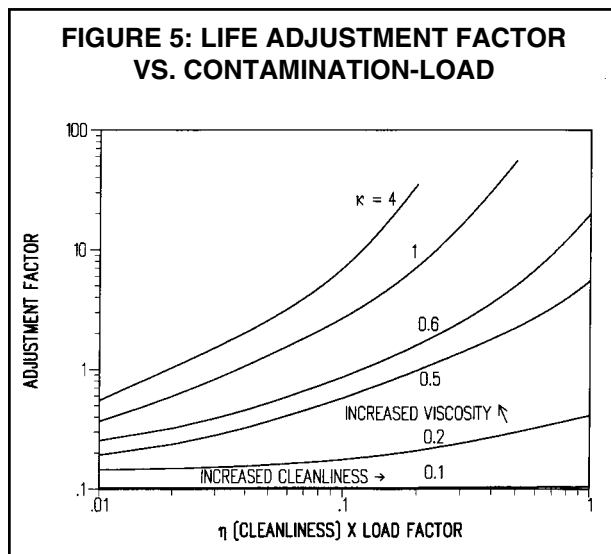
Grease selection should consider the above variables. The best grease for an open pit copper mine in the desert [130° F (54° C) ambient] is probably not the best grease to use in the arctic [-50° F (-45° C) ambient]. The same is true for dry climates (5% humidity) versus coastal regions (98% humidity). Additional concerns include contamination of the lubricant. Contamination, high temperature and friction reduce the effectiveness of lubricants.

Present research is making it possible to predict bearing life more accurately. The use of Elasto-Hydrodynamic Lubrication theory (EHL), introduced in the 1960s, for calculating film thickness and pressure profiles, has been the key to many investigations and the base for understanding failure modes. Since the early 1970s, lubrication and film thickness have been recognized as significant factors in the life equation. The ABMA Standard 9/ANSI B3.15, and ISO 281 standards were modified in 1972 and 1977 respectively, to include this effect by the addition of the  $a_2$  (material) and  $a_3$  (operating conditions) life adjustment factors.



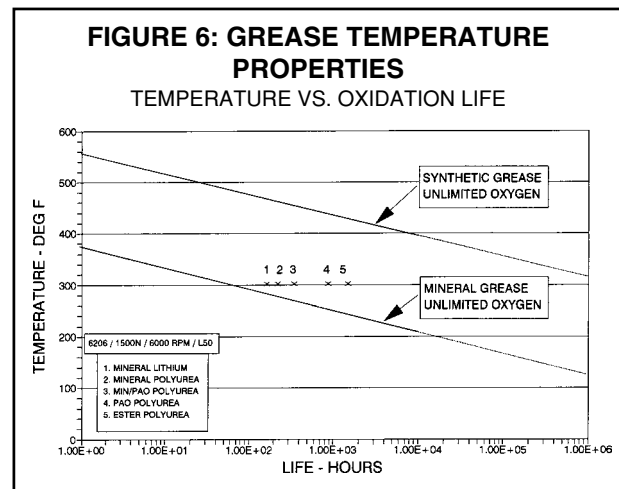
Typical factors used are shown in Figure 4. The latest efforts have been in the area of particle contamination and lubricant cleanliness. These new studies are tending to reshape the life prediction equations. According to one bearing manufacturer, the true nature of the failure mode mechanism was hidden and not understood until recently for the following reasons:

- The high loads used to accelerate testing resulted in insufficient time for wear to manifest itself.
- Surface initiated cracks, from particle indentation,



which penetrated into deeper areas of high stress and culminated in flaking, could not be distinguished from flaking caused by cracks formed below the surface.

Based on these latest studies, bearing life theory has been further refined to use a family of curves to establish an adjustment factor to the unmodified life. Of primary importance is the  $\eta$  factor used to correct for contamination. An accurate assessment of the  $\eta$  factor requires an analysis on a computer with accurate knowledge of the application. Figure 5 is typical of the curves used to determine the life adjustment factor for contamination. These refinements, along with similar actions taken by other manufacturers, can only lead to a more precise determination of bearing life. In addition to new life prediction theories, new lubricants and lubrication methods are being devised which will extend the operating life. Synthetic greases are capable of extending grease life significantly as indicated by the oxidation characteristics shown in Figure 6. Although grease life is a function of more than just oxidation life, it is a good indicator of the type of gain that can be made using synthetic grease.



Synthetic greases can be formulated with a lower sensitivity to temperature variations, and therefore, have a larger useful temperature range and the potential for lower losses.

The question frequently asked about greases, deals with the compatibility of them if mixed during the relubrication process. Table 1 is a guideline to assist in this process. If in doubt, do not mix without checking with the lubricant manufacturer.

Lubrication arrangements for grease-lubricated bearings, shown in Figure 7, vary among manufacturers and designs. Grease viscosity, motor mounting position, and bearing enclosure impact the effectiveness of the lubrication porting. For example, the grease-through design shown in Example C does not work well with a double-shielded bearing.

While some margin exists, a good rule of thumb for bearing temperature is 80-90-100, where 80° C is the operating temperature, 90° C is the alarm setting, and 100° C is the shutdown limit. For higher temperatures, synthetic lubricants (oil or grease) are available. In general,

**TABLE 1: RESULTS OF GREASE INCOMPATIBILITY STUDY**

|                    | Aluminum Complex | Barium | Calcium | Calcium 12-hydroxy | Calcium Complex | Clay | Lithium | Lithium 12-hydroxy | Lithium Complex | Polyurea |
|--------------------|------------------|--------|---------|--------------------|-----------------|------|---------|--------------------|-----------------|----------|
| Aluminum Complex   | X                | I      | I       | C                  | I               | I    | I       | I                  | C               | I        |
| Barium             | I                | X      | I       | C                  | I               | I    | I       | I                  | I               | I        |
| Calcium            | I                | I      | X       | C                  | I               | C    | C       | B                  | C               | I        |
| Calcium 12-hydroxy | C                | C      | C       | X                  | B               | C    | C       | C                  | C               | I        |
| Calcium Complex    | I                | I      | I       | B                  | X               | I    | I       | I                  | C               | C        |
| Clay               | I                | I      | C       | C                  | I               | X    | I       | I                  | I               | I        |
| Lithium            | I                | I      | C       | C                  | I               | I    | X       | C                  | C               | I        |
| Lithium 12-hydroxy | I                | I      | B       | C                  | I               | I    | C       | X                  | C               | I        |
| Lithium Complex    | C                | I      | C       | C                  | C               | I    | C       | C                  | X               | I        |
| Polyurea           | I                | I      | I       | I                  | C               | I    | I       | I                  | I               | X        |

B = Borderline Compatibility; C = Compatible; I = Incompatible.

Bonnett, A. *EASA Tech Note No. 27: The Cause and Analysis of Bearing and Shaft Failures in Electric Motors*. 1999.

the use of synthetic lubricants can increase the safe operating temperature by up to 30° C.

Grease compatibility is important, but easily overlooked. The results of mixing incompatible greases can range from a soupy liquid to a near-plastic solid, depending on the bases mixed.

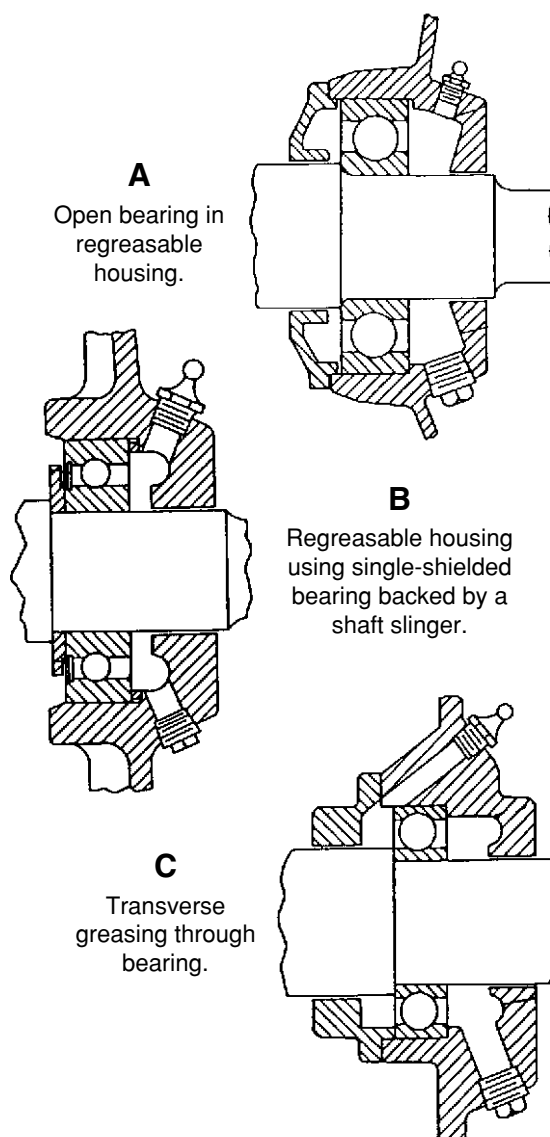
Table 2 provides some clues based on the appearance of the grease.

**TABLE 2: APPEARANCE OF GREASE**

| Appearance                              | What may have happened                                               |
|-----------------------------------------|----------------------------------------------------------------------|
| Clean grease in a badly-failed bearing. | Grease was added after bearing failed.                               |
| No grease in grease fitting or pipes.   | Grease has not been added since installation.                        |
| Excess grease in the windings, etc.     | Motor was overgreased.                                               |
| Emulsified appearance.                  | Water mixed with grease.                                             |
| Grease is hard and dry.                 | Motor was idle for long enough that the oil separated from the base. |
| Grease is dry and powdered.             | Contamination mixed with grease.                                     |

### OIL LUBRICATION

Oil lubrication is used for nearly all sleeve bearings, and some ball bearing machines. On horizontal motors, the

**FIGURE 7: HOUSING ARRANGEMENTS FOR BEARINGS AND HOUSINGS**

These are just three of the lubrication paths manufacturers have used.

normal method of delivery for sleeve bearings is a sump, with oil rings to deliver oil from the sump to the shaft where it flows through the bearing.

Oil may also be delivered using either an oil mist or forced-lubrication method.

### OIL MIST

Correctly done, an oil mist system is an effective way to continuously lubricate bearings with minimal quantities of oil. Oil is passed through an atomizer to reduce the droplet size to a vapor. Oil, in a low pressure air stream, is carried to the bearings, where oil droplets condense on the bearing. The nature of vapor also makes the oil mist useful for

preventing corrosion during long idle periods. Bearings lubricated by oil mist should have seals or bearing isolators to contain the oil. Recovery methods vary from drip cups to passing the exiting vapor through a reclassifier. A reclassifier reconsolidates the oil droplets.

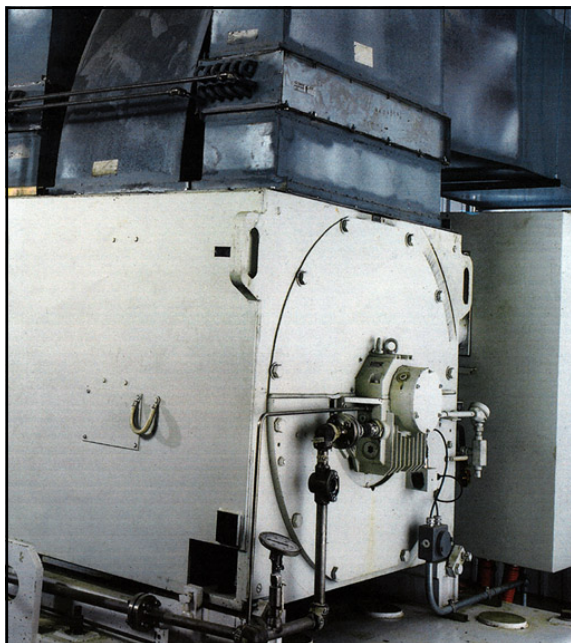
Oil mist has drawbacks, each of which is difficult to detect until the motor has been dismantled. First, oil mist is a vapor that can exit the bearing chamber and cause other problems. Environmental contamination may result when the vapor recovery system fails. Oil chemically attacks some insulation materials—especially lead wire insulation.

Oil selection is affected by the application, temperature, environment and bearing design. Aside from the obvious factors already listed, oil viscosity can affect vibration levels of sleeve bearing machines by altering the stiffness of the shaft-bearing interface. As a rule-of-thumb, the closer the ratio of bearing length to bearing diameter is to 1, the more important oil viscosity is likely to be.

### FORCED LUBRICATION

Forced lubrication systems are added to reduce bearing temperature (Figure 8). In effect, the forced lubrication system simply increases the size of the oil reservoir. The role of the oil reservoir is to ensure a steady supply of oil to lubricate the bearings, but also to cool the oil by recircula-

**FIGURE 8: SLEEVE BEARING MOTOR EQUIPPED WITH A FORCED LUBRICATION SYSTEM**



The piping is part of a forced lubrication system used to reduce bearing temperatures.

tion. When a high ambient condition exists, or when it is desirable to lower bearing temperatures, a forced lubrication system is used.

Most sleeve bearings require 2 to 3 gallons per minute (1.5 to 2 liters per minute) for adequate lubrication. To control the volume of oil through a forced lubrication system, the inlet is pressurized and oil forced through a small orifice (or metering plate). System pressure is 10 to 15 psi, and orifice sizes are typically around 0.030" (0.8 mm) to provide the desired flow rate. To test the flow rate, use a bucket to measure the oil exiting the bearing for one timed minute. One common cause of apparent oil leaks is a missing orifice. This occurs because the orifice is installed in the motor piping, and can get lost when the motor plumbing is disconnected.

Table 3 provides some clues based on the appearance of the oil.

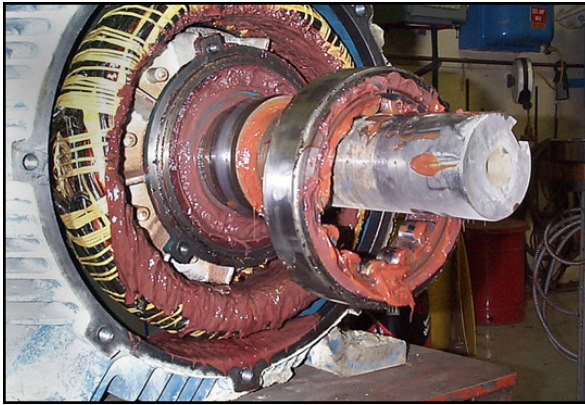
**TABLE 3: APPEARANCE OF OIL**

| Appearance                 | What may have happened                                                                                                     |
|----------------------------|----------------------------------------------------------------------------------------------------------------------------|
| Clean oil, melted babbitt. | Oil was added after bearing failed.                                                                                        |
| Milky appearance.          | Water in the oil.                                                                                                          |
| Oil appears muddy.         | Contamination in oil.                                                                                                      |
| Oil-soaked windings.       | Excessive labyrinth seal clearance, oil level too high, pressurized bearing chamber or forced-lubrication volume too high. |

### LUBRICATION PRECAUTIONS

- All motor housings, shafts, seals and relubrication paths must be kept thoroughly clean throughout the motor's life.
- Avoid any dirt, moisture, chips or foreign matter contaminating the grease.
- Identify the temperature range for the application and select a grease that will perform satisfactorily.
- Over greasing may cause elevated bearing and/or winding temperatures which can lead to premature failures. Be sure to properly purge excess grease.
- When regreasing, be sure that the new grease is compatible with the existing grease and that it has the desired performance characteristics.
- Synthetic grease may not be as suitable as petroleum greases for high-speed applications. Some applications may require an extreme pressure (EP) grease.
- Some common greases are not suitable for motor applications. If they are too soft, whipping can occur. If too stiff; noise and poor bleeding characteristics can occur.
- Do not try to lubricate sealed bearings.

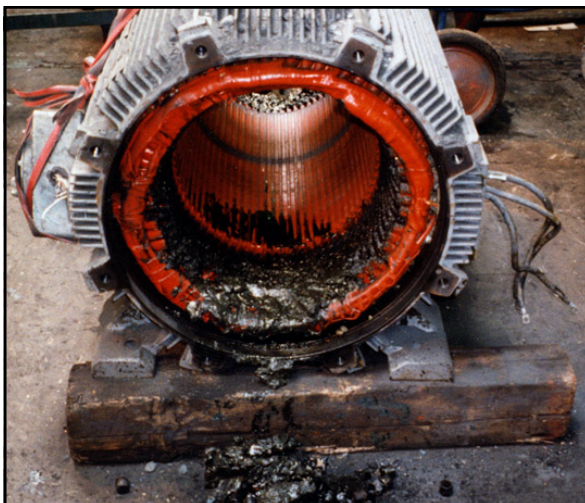


**OVERLUBRICATION**

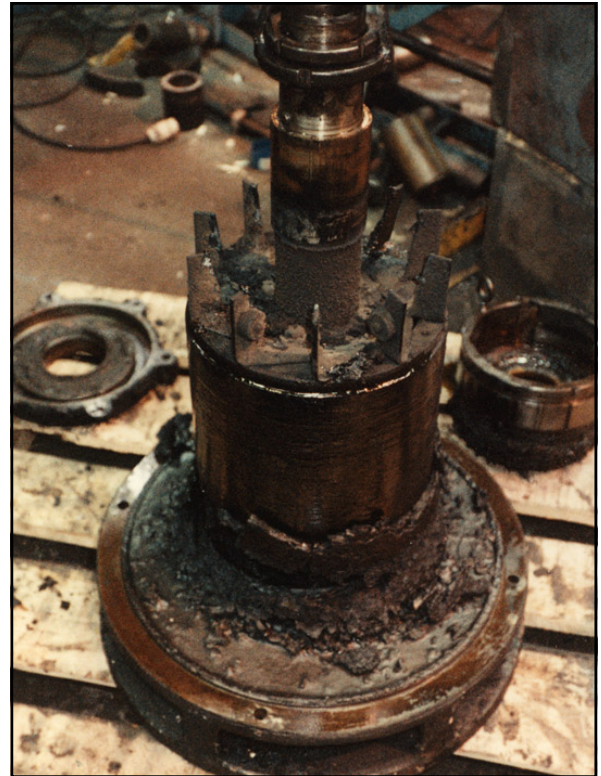
Thin grease used in this roller bearing migrated past the inner bearing cap. A lip seal would prevent this by retaining the grease.



Grease quiets a noisy bearing. This bearing was noisy for quite some time.



Overgreasing a noisy bearing treats the symptom rather than the cause. The result may cause other problems, most notably an increase in winding temperature.



The upper bearing carrier, bolted inside the end bracket, has too much clearance to the shaft. Gravity, grease and dirt are not a good combination.



THERMAL STRESS

A rolling element bearing should operate at temperatures not in excess of 100° C. The rule of thumb, “80-90-100,” refers to an operating temperature of 80° C (170° F), an alarm temperature of 90° C (190° F) and a shutdown temperature of 100° C (210° F). (Note: 30° C may be added for synthetic lubricants, however, synthetic grease is often not suitable for high-speed applications.) (See Table 4.) For sealed bearings, the rpm rating is significantly lower than for open bearings.

At temperatures above 100° C (130° C for synthetic lubricants), thermal expansion of the component parts may reduce the internal clearance, resulting in premature failure of the bearing. In addition, lubricant breakdown will result in higher bearing temperatures and bearing failure.

Bearing temperature is affected by the temperature of the surroundings (air, windings, rotor), as well as by the lubricant (type, quantity, viscosity and condition), the bearing itself (internal clearance, open/shielded/sealed,) and load

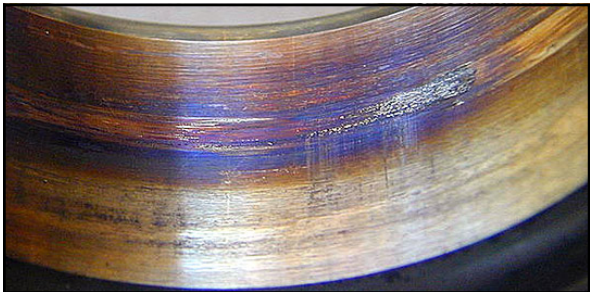
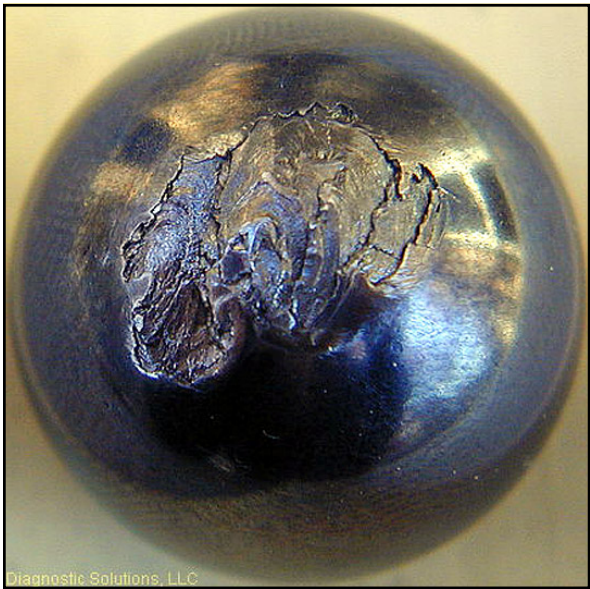
TABLE 4: BEARING MONITORING TEMPERATURES

| Monitoring condition | Temperature     |
|----------------------|-----------------|
| Normal               | 170° F (80° C)  |
| Alarm                | 190° F (90° C)  |
| Shutdown             | 210° F (100° C) |

Add 30° C when synthetic lubricants are used, however, synthetic grease is often not suitable for high-speed applications.

(dynamic load, direction of load, speed and impact cycling). The bearing should be sized appropriately for all of these conditions, but in the real world not all equipment is created equal. Understanding the root cause may lead to suggestions to modify a unit to make it more suitable, or even replace it.

THERMAL STRESS



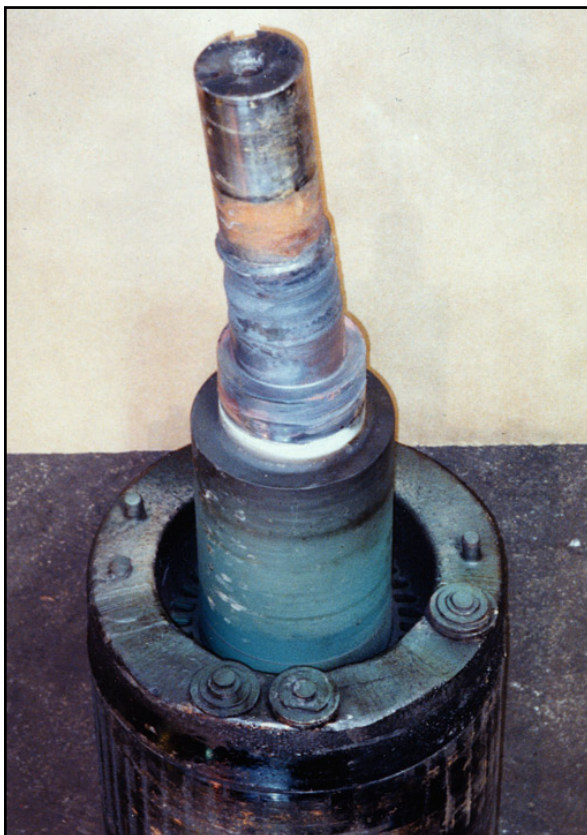
Heat discoloration indicates the inner race reached 700° F (370° C). Possible causes include loss of fit to the shaft, lubricant failure or improper installation. Localized discoloration may indicate that a torch was used to heat the inner race.



Symptoms of overheating are discoloration of the races, balls and cages from straw to blue. Temperatures in excess of 400° F (205° C) can anneal the race and ball materials. The resulting loss in hardness reduces the bearing capacity, causing early failure. Courtesy of The Barden Corporation



## THERMAL STRESS



Diligence and protection mean the difference between minor damage and this type of failure.



Lubricant failure will lead to excessive wear, overheating and subsequent bearing failure.

Courtesy of The Barden Corporation



The temperature of this bearing exceeded the “dropping point” of the grease. This is the temperature at which oil separates—or drops out—from the grease base. This bearing failure led to the bent shaft.

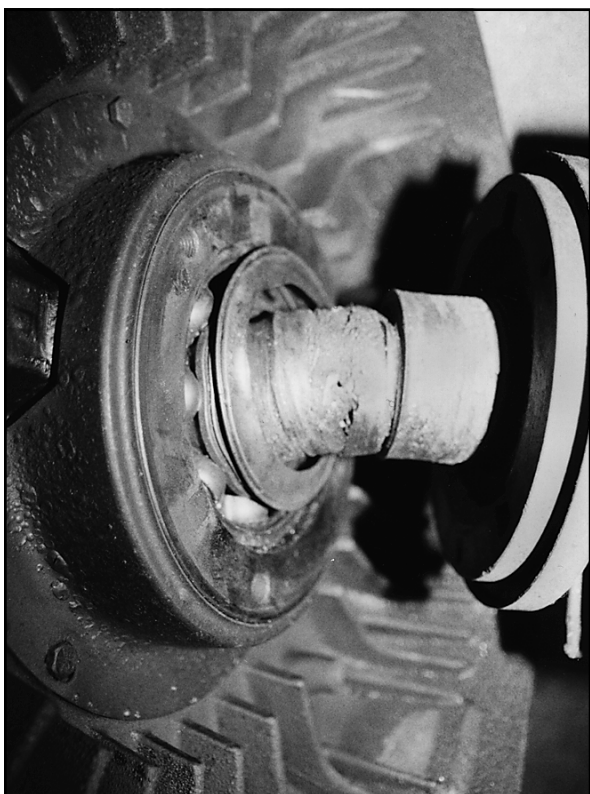


This motor failure started as a failed bearing. The burnt paint shows the extreme heat created by this failure. The bearing failure resulted in damage to the rotor as well as the stator.



**THERMAL STRESS**

In this case, the heat source was a stalled rotor. Heat migrated from the rotor through the shaft to the bearing. Different greases have different dropping points (the temperature at which oil separates from the grease base).



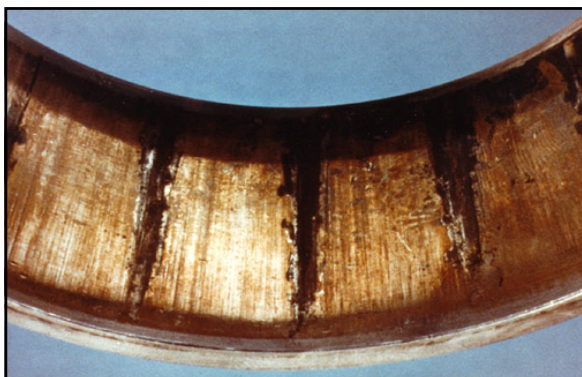
By the time this bearing failed, the shaft temperature exceeded 900° F (480° C).



This bearing shows signs of heat discoloration. It was overheated prior to installation.



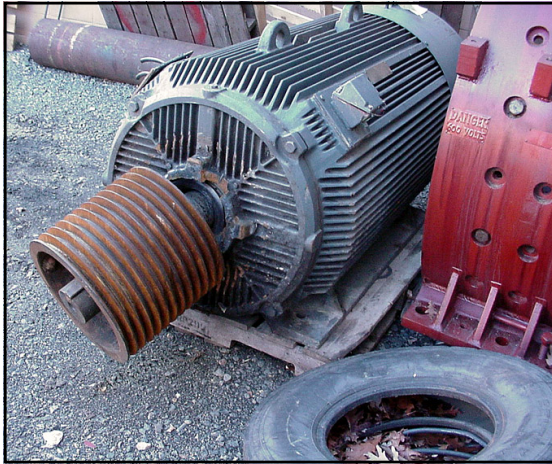
The additional air shroud on the drive end deflects air across the drive end bearing housing. If removed by an end user or previous repairer, the drive end bearing temperature will increase.



Loss of lubrication damaged this spherical roller bearing.



**FIGURE 9: RESULTS OF EXTREME OVERHUNG LOAD ON A BELTED APPLICATION**



**FIGURE 10: BELTED APPLICATION**



Pulley diameter and number of belts can affect radial loads. See alignment material in Section 6.

## DYNAMIC AND STATIC LOADING STRESS

Load characteristics of the bearing in its unique application include radial load and/or thrust load. Radial load may result from a belted application (Figures 9 and 10), misalignment or other factors not immediately apparent. Thrust loads may be external or internal in source. A vertical application supporting a pump may require a thrust bearing capable of handling substantial thrust loads. An identical motor might be designed with different bearings for high-, medium- or low-thrust applications. Thrust load may also result from internal preloading of the motor. Prior machine work such as a shaft replacement, missing gaskets or swapped bearing caps (when both bearings are the same size) can also cause this condition.

For vertically-mounted machines, axial thrust load of the non-thrust bearing may result from improper assembly. Thermal expansion of the shaft during service may move the axial load from the thrust bearing to the non-thrust bearing. This is also true of axially-loaded horizontal machines. It is worth noting that there are end users who install horizontal motors in nonstandard positions (Figure 11), reducing the effectiveness of the lubrication paths. If something about the evidence doesn't seem to fit, it may indicate an unusual mounting condition. Look for an answer that fits ALL the evidence.

Axial loading may also result from improper alignment if the coupling preloads the locating bearing; for example when a rigid coupling is used, if the installer pries the coupling halves apart (or draws them together using the coupling bolts) after the motor base is secured.

**FIGURE 11: HORIZONTAL MOTOR MOUNTED VERTICALLY**



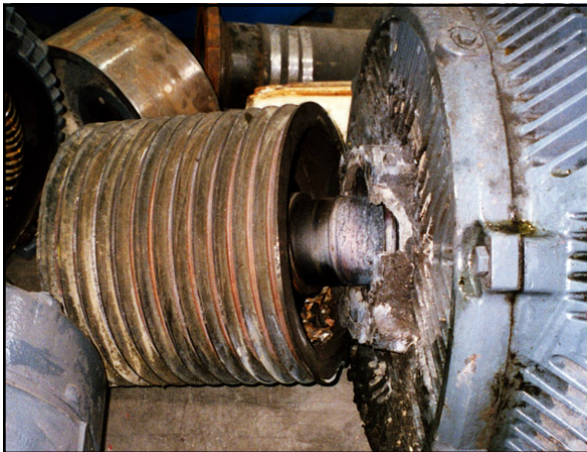
An end user may save money by purchasing a horizontal C-face motor instead of a vertical. However, this may reduce the effectiveness of lubrication paths.



## DYNAMIC AND STATIC LOADING STRESS



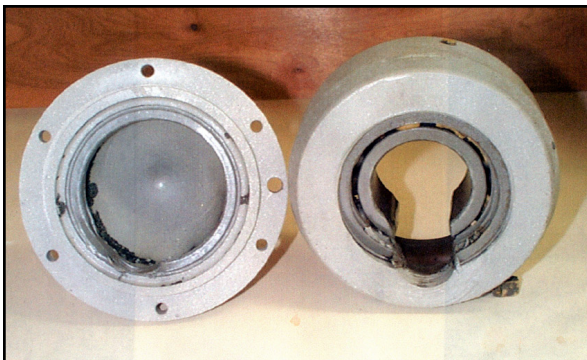
These shafts show signs of a classic case of excess radial load on a ball bearing.



This application requires a roller bearing for the drive end. The pulley should be installed as close to the bracket as possible. Worn belt grooves increase belt slip and may cause the operator to overtighten the belts and overload the bearing.



Heavy shock loads can cause unusual fractures of the outer race and/or balls.



This bearing stopped rotating, but the undersized shaft did not. A heavy radial load caused this unique failure pattern.



Severe spalling caused by excessive load. This spalling is part of the natural failure process as a bearing reaches the end of its life.

Courtesy of The Barden Corporation



## VIBRATION AND SHOCK STRESS

Vibration may result from rotor unbalance, unbalance in the driven equipment, looseness in the mounting of the motor or driven load, or even high vibration in equipment operating nearby. Road machinery, construction, rail or heavy truck traffic can all contribute. Shock may be attributed to most of the above non-system causes or to specific

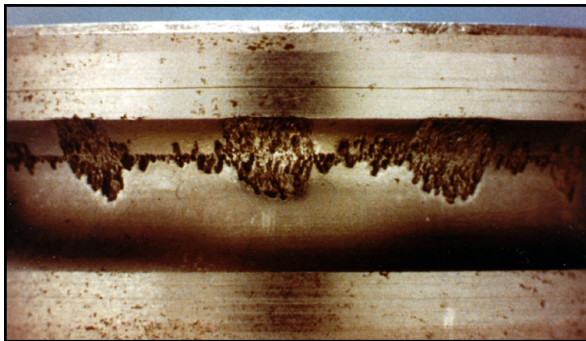
applications such as hammer mills or rock crushers.

Motors placed in storage, or otherwise idled for a long time, may have bearing damage resulting from false brinelling. Repeated vibration when the bearings are not rotated can result in damage that is uniformly spaced at the same intervals as the rolling elements.

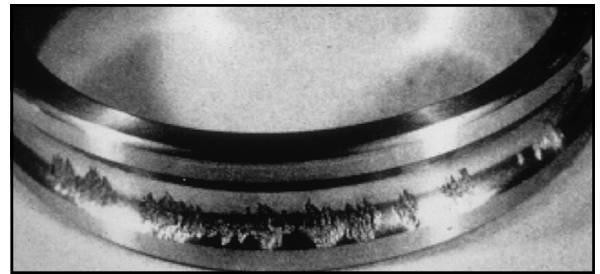
### VIBRATION AND SHOCK STRESS



When a spherical roller bearing is used, momentary upthrust conditions can cause impact damage when the thrust load is suddenly restored. Some spherical roller bearings are spring loaded to prevent this sort of damage.



The damage shown here corresponds to the spacing of the rolling elements. This damage started as non-rotating vibration. This can result from shipping (rail, rough roads) or vibration from nearby equipment.



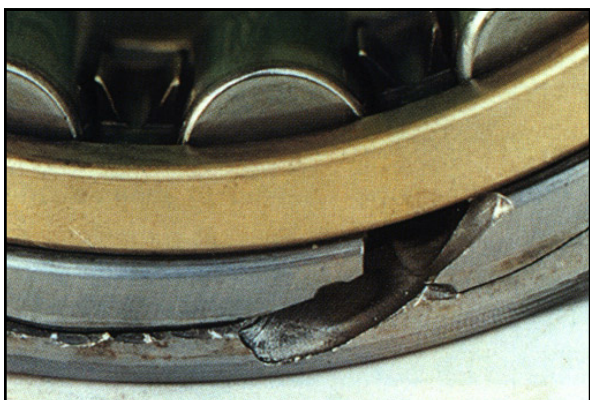
Vertical motor, upper thrust bearing damaged by shock load. This type of damage may be caused by cavitation (momentary up thrust with high impact when the thrust load is restored) or shipping damage.



## VIBRATION AND SHOCK STRESS

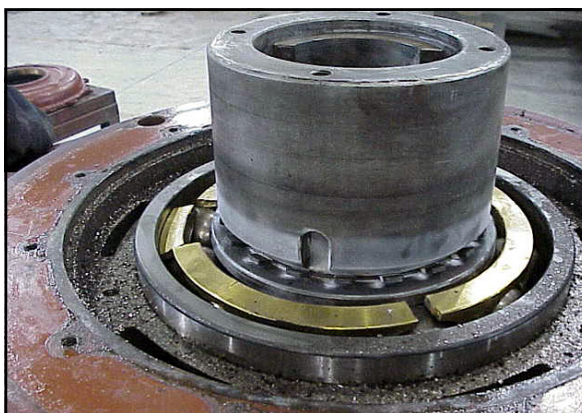


A split outer race (circumferentially) is caused by high shock impact. This unusual failure is more common in applications such as a crusher or hammer mill.



Heavy axial loading or axial impact can chip the outer race shoulder of a roller bearing.

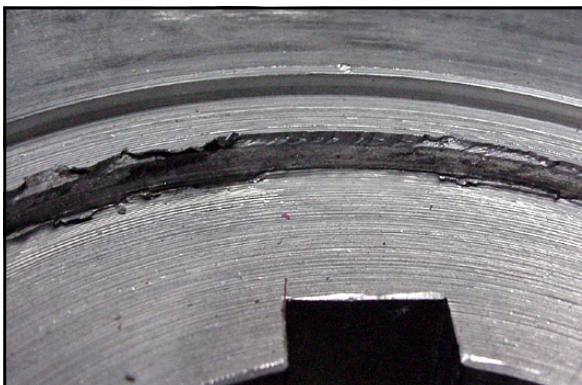
Courtesy of Koyo



Excessive load may cause bearing cage failure.



The bearing of this motor was damaged by vibration caused by a damaged cooling fan.



Rotational shock load caused this coupling to fracture. Most service centers do not receive the coupling with the motor, so evaluating a bearing failure without all the evidence can be tough. The coupling can provide valuable information.



## ENVIRONMENTAL STRESS

Lubricants are produced with varying degrees of moisture resistance. It is up to the end user to select the most appropriate lubricant for the application. Condensation may cause rust on the surface of the bearing and internal motor parts. Corrosion on the bearing raceways or rolling elements will work quickly to further damage the bearing surface.

Foreign material may include liquid or vapor that attacks the bearing surface or the lubricant. Examples include nitric or hydrochloric acid, which can flash-rust a bearing when the vapor is present, even in small quantities. Foreign material also includes grease incompatibility. See Table 1 (Page 2-7) for specifics, but the results of mixing incompatible greases vary. Some combinations result in a soupy liquid while others harden into a solid mass that resembles plastic.

Excessive ambient temperature is not restricted to the air surrounding the motor. An exposed steam line near one end of a motor may elevate temperatures on that end only. Radiant heat sources may be a considerable distance from the machine and still raise bracket temperature *without affecting air temperature*. A motor operating within a confined space (e.g., compressor) may be subject to recirculation as the temperature of the 'cooling' air is raised each time it passes through the motor. The smaller the  $\Delta T$ , the less effective the cooling medium becomes. ( $\Delta T$  is the temperature difference, in this case between the air in and air out.)

In the case of restricted ventilation, the temperature of the windings and rotor increases. The shaft functions partly as a heat sink to conduct heat away from the rotor. That, in turn, increases the bearing and lubricant temperature. Buildup of contamination (dirt, pulp, product) on the exterior of the motor insulates the bearing, trapping heat.

## ENVIRONMENTAL STRESS



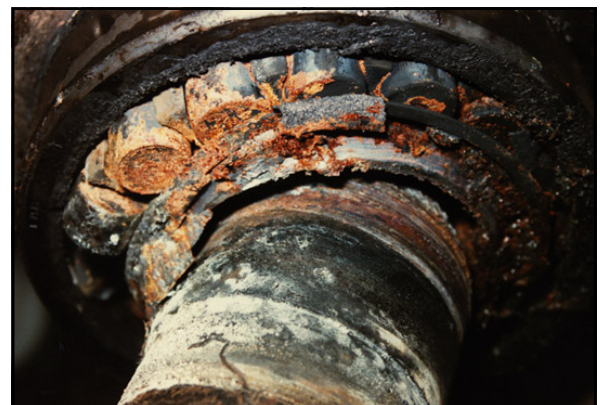
Grease was flushed from this bearing. Water, steam or solvents are often the cause of this type of damage.



The irregular striped discoloration was caused when contamination was pressed in the roller path.



The lubricant was washed out of the bearing. Rust is evident.

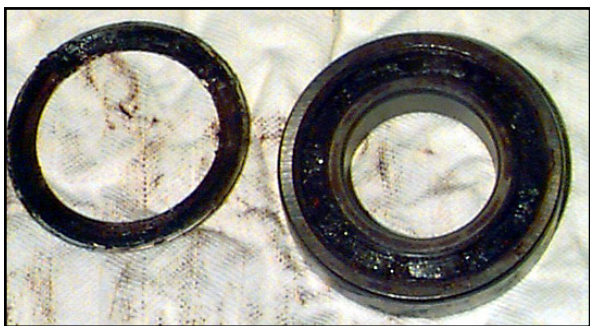


Corrosion caused the initial damage to this roller bearing.



**ENVIRONMENTAL STRESS**

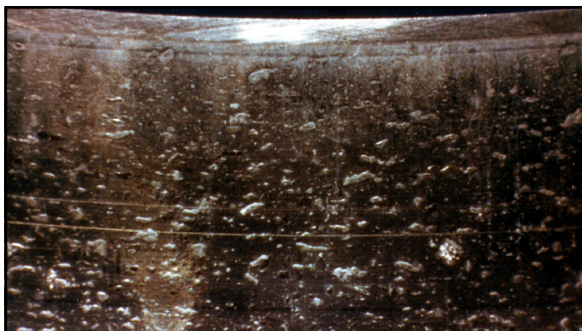
Restricted ventilation may increase winding and/or rotor temperatures. Heat transfers to the bearing housing and elevates the bearing temperature.



Dust and other fine dry contaminants absorb oil and thicken the grease base.



Grease compatibility problems may result from mixing incompatible greases, or from ingress of other contaminants. Dry powders may absorb the oil causing the grease to thicken.



Dirt in the roller path imbeds in the raceway, decreasing bearing life.



## MECHANICAL STRESS

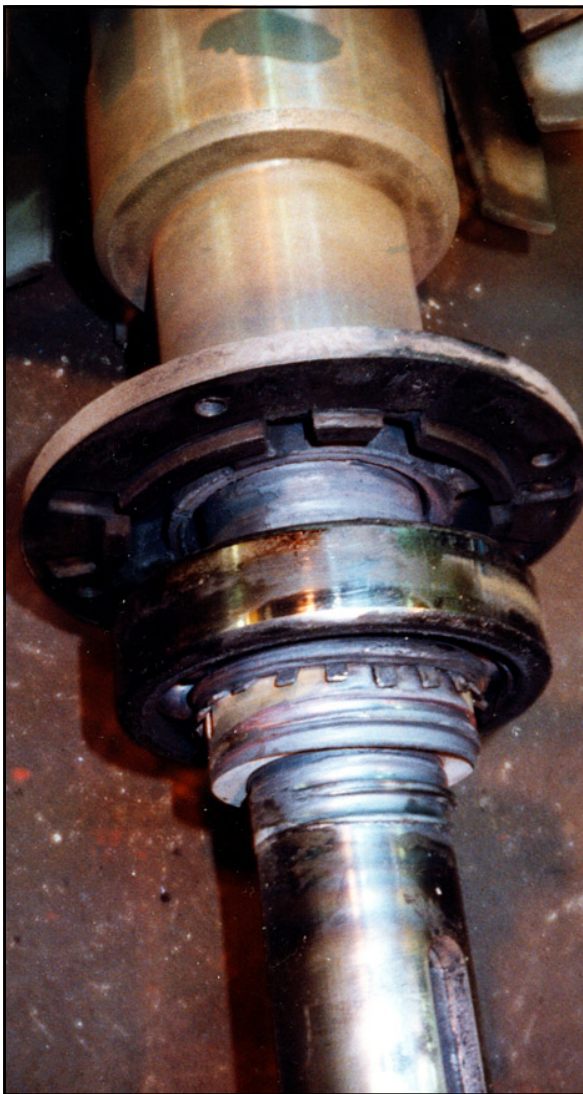
Bearing failures can also result from a variety of mechanical causes, either internal or external in origin. Contamination and/or corrosion may reduce the clearance between the shaft and end bracket resulting in heat-generating friction.

Misalignment of the motor and driven equipment increases the dynamic load on the bearing. Improper manufacturing or repair procedures may result in a loss of internal bearing clearance. A shaft fit that is too large, or a bearing housing that is too small, results in a tighter fit and reduces internal clearance of the bearing. Too loose a fit may permit the bearing to slip on the shaft (or in the housing), generating more heat.

In specific cases, use of the wrong bearing for the application can lead to the same failures. Vibrator (shaker-screen) motors are designed with loose shaft fits and tight housing fits. They require the use of C4 internal clearance bearings. Some dragline motors utilize higher interference fits between the shaft and bearing (m6 rather than k5), but may also adjust the bearing housing fit to preserve the bearings internal clearance.

Crushers are often fitted with spherical roller bearings on tapered journals. The distance the bearing is advanced onto the tapered journal controls the internal clearance of the bearing. Once the bearing is removed, it is too late to check the internal clearance.

## MECHANICAL STRESS

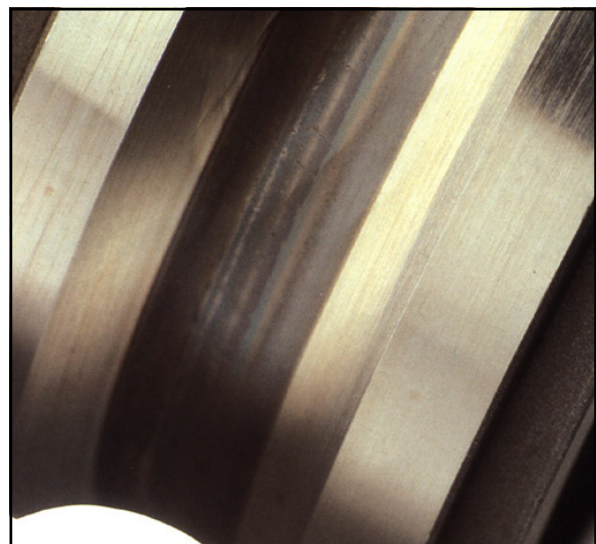


This drive end bearing was forced over the bearing lock washer after the inner race spun and got hot enough to forge. A heavy axial preload from the load caused the failure.



Discoloration and scoring is the result of the outer race slipping in the bearing housing.

Courtesy of The Barden Corporation



Heavy ball path wear indicates a tight fit.

Courtesy of The Barden Corporation



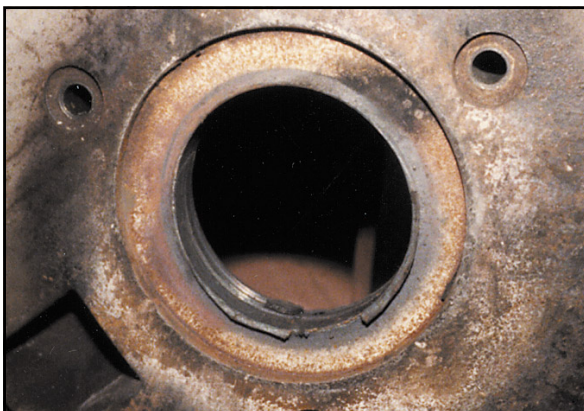
## MECHANICAL STRESS



Severe vibration literally forged the inner race of this bearing once the race temperature reached 1200° F (650° C).



Loss of fit damaged this bearing. The inner race spun on the shaft, generating heat. Thermal breakdown of the lubricant followed causing the rolling elements to seize and forge to the inner race, which expanded it further.



Loss of fit (left) may follow a bearing failure or it may result from corrosion, product contaminants or insufficient clearance. A motor in a corrosive atmosphere, operating infrequently, is susceptible to this mode of failure. The combination of an aluminum bracket and steel shaft can be vulnerable. Resulting friction could cause the shaft to seize, or friction-generated heat could weaken the shaft (right).

## ELECTRICAL STRESS

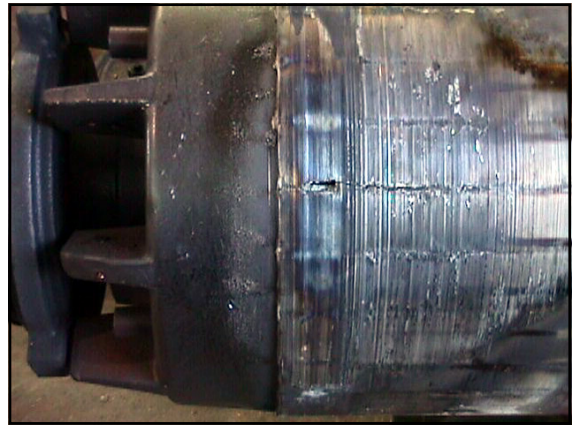
Current discharge from voltage passing through the bearings can damage them. These shaft voltages have long been associated with medium and large electric machines; however, the increased use of variable frequency drives (VFDs) has since resulted in shaft voltages in much smaller motors.

In standard machines, any break from uniformity in the rotor or stator can cause shaft voltages. Shorted laminations (Figure 12), gaps in the stator laminations (as occur with large machines built with segmented laminations), variations in air gap or spacing for fields or interpoles in a DC machine; all can result in shaft voltages in rotating equipment. Shaft voltages may also result from static electric discharge from the driven equipment or process. One example is a large continuous paper roll, where static electricity can build up and discharge through the bearings.

Indications of shaft voltages are fluting when rpm is steady, or frosting when speed varies continuously. In some cases, the appearance of the balls offers the best clue. Instead of a highly-polished finish, the rolling elements may have a dull appearance.

The “rule of thumb” for voltage limits is 100 mV for ball bearings and 200 mV for sleeve bearings. Variable frequency drives can result in shaft voltages as high as 20 to 25 volts. Because of capacitive coupling between the rotor and stator, both bearings must be electrically isolated. The standard method of insulating only one bearing will not protect bearings in a machine operated from a VFD.

**FIGURE 12: SHORTED LAMINATIONS**



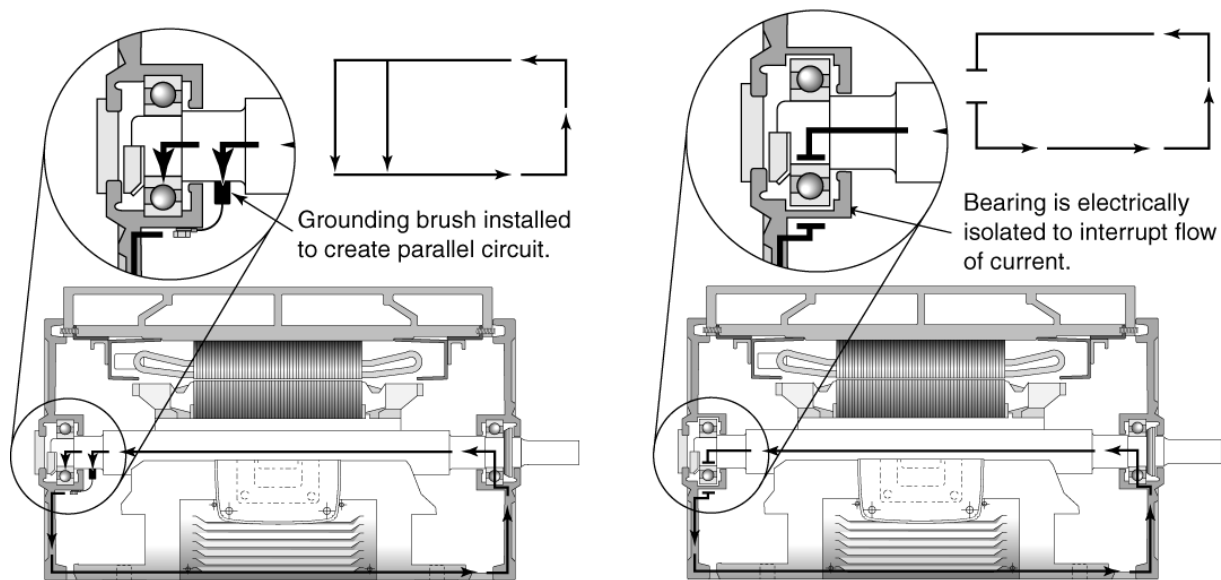
This severe damage resulted from a bearing failure that progressed.

## METHODS OF PROTECTION

Before pulse width modulated (PWM) inverters, shaft-riding brushes were used or the opposite drive end bearing was insulated. Insulating the bearing was the preferred method. This breaks the circuit and interrupts the flow of voltage. (See Figure 13.) A good analogy is a light switch: When the switch is turned off, the light goes off because the switch breaks the circuit.

The grounding brush provides a parallel path to the

**FIGURE 13: METHODS OF PROTECTING AGAINST SHAFT CURRENTS**



The addition of a grounding brush creates a parallel circuit, sharing the current flow through the bearing. The flow of current through each path of the parallel circuit depends upon the relative resistance. Current on the drive end remains unchanged.

Electrically isolating one bearing can be done by insulating the housing or the bracket at the frame, or by use of special factory-insulated bearings. When this method is used, the flow of current through both bearings is halted. No current means no damage.



bearing, diverting some of the current from the bearing to the brush. Voltage follows the path of least resistance, so if the brush is highly conductive and has good contact with the shaft, most of the voltage will flow through the brush. But as the shaft oxidizes or as dirt builds up on the shaft, the resistance through the brush/shaft connection increases. The bearing becomes the path of least resistance and more of the voltage flows through the bearing.

A partial list of better preventive measures includes:

- Install ground brushes on both ends.
- Insulate both bearing housings.
- Insulate both shaft journals.
- Use ceramic (insulated) bearings.
- Use bearings with ceramic balls.
- Install in-line filters between the motor and VFD to reduce the problem.
- Improve grounding of the motor and drive.

If a motor is critical, a short-term corrective action is to decrease the switching frequency of the drive to less than 5 kHz. That may permit the motor to operate until another option can be implemented.

Grounding brushes still have all the problems mentioned previously, but are utilized by some manufacturers. For very large machines, a copper “toothbrush style” brush is available. In most cases, the brush is constructed like a

conventional carbon brush, but with a high silver content to increase conductivity.

Grounding brushes should be located as close as practical to the bearing. The longer the supporting bracket, the higher the resistance of the bracket/brush/shaft path.

Ceramic spray can be applied to the shaft journal, and must be precision-ground to size (Figure 14). Ceramic chips easily, so handling requires care. Because the layer of ceramic is relatively thin, care should be taken when balancing a shaft with ceramic-coated journals. The rotor weight should not be placed on the journals, for balancing or inspection, because the point-loading is likely to break the ceramic loose from the shaft. The damage often does not show up until the motor is in service, at which time the ceramic fractures, leaving the bearing with a loose shaft fit.

A thermal spray aluminum oxide may be used for sleeve bearing exteriors. Aluminum oxide is the same material used for emery cloth and abrasive grinding wheels. With the aluminum oxide bearing shell, vibration can eventually cause the bearing housing to wear due to the abrasive action. The higher the vibration, the more likely this is to occur. Aluminum oxide coatings can also be compromised by moisture and corrosion.

Insulating the bearing housings requires that other parts (like bearing caps) not bypass the insulation. When a bearing exhibits evidence of shaft currents, and the housing is insulated, verify the integrity of the insulation with that end of the motor assembled. (See Figure 15.)

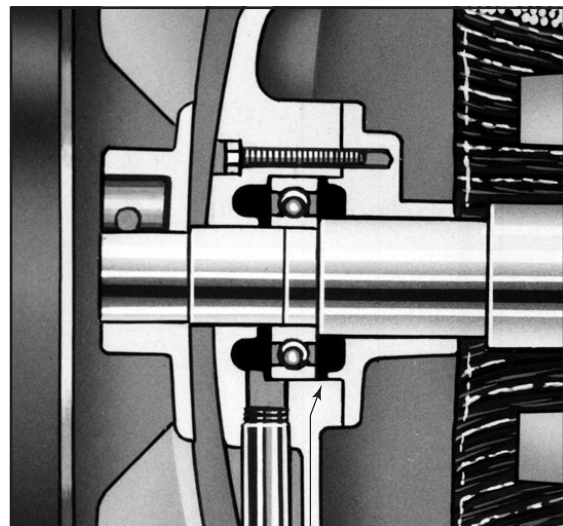
Space-age epoxy putties (Devcon, Belzona) also can be used, but caution should be exercised to avoid exceeding the load capacity of these materials.

**FIGURE 14: INSULATING WITH CERAMIC SPRAY**



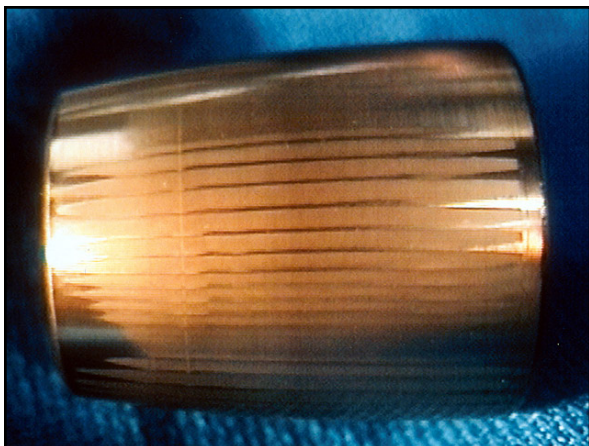
Ceramic or aluminum oxide spray is one method of insulating. Above, an opposite drive end bearing journal, and below, vertical motor bearing carriers, all of which have been insulated with ceramic spray.

**FIGURE 15: PRECAUTION WHEN INSULATING BEARING CAPS**

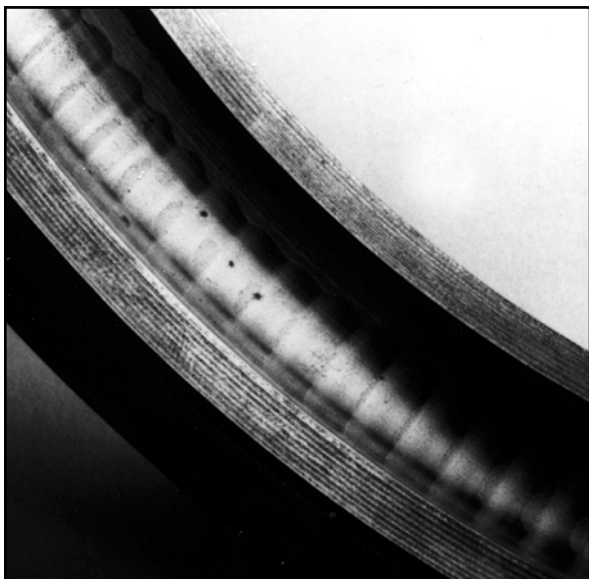


When insulating a bearing housing, the repairer must also insulate the face of the bearing cap. The bearing cap could come into contact with the face of the bearing, bypassing any insulation on the bearing housing.

## ELECTRICAL STRESS



Fluting due to shaft currents on both a roller bearing, above, and a ball bearing, below.



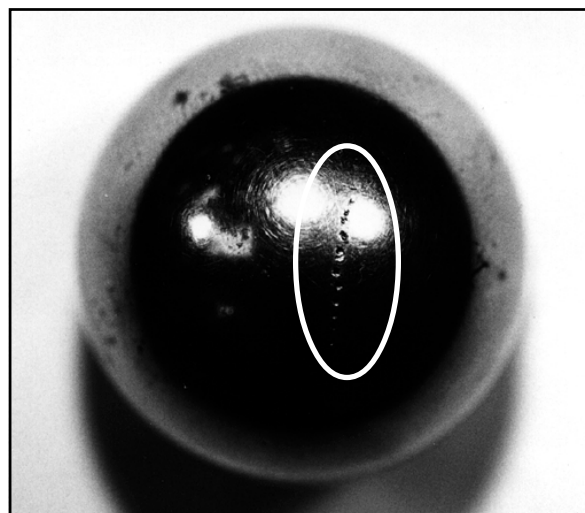
The spacing of the fluting marks depends on rpm, diameter, radial load and magnitude of the shaft voltage.



When rotational speed varies, the shaft currents may cause a dull, frosted appearance instead of fluting.



Fluting only occurred on the non-loaded roller path because the arcing occurred only at the gap between the rollers and the race. A good analogy is the points in an older automobile ignition system.



The arcing on this ball was caused by welding done near the motor.



## VERTICAL MOTOR BEARING SYSTEMS: SPECIAL CASES

There are several features unique to vertical motors. Those features are grouped together here for the convenience of those inspecting vertical machines. Because a vertical motor is often coupled to a pump, the motor may be required to support the weight and thrust load of the pump as well as the weight of the rotor. With pump designs ranging from low- to medium- to high-thrust, the upper bearing arrangement of seemingly identical vertical motors can vary tremendously according to the bearing size, quantity and direction of thrust. (See Figure 16.)

When an end user changes the pump without matching the thrust load requirement to the thrust load capacity of the motor, or when an aftermarket spare motor is purchased, there is potential for misapplication.

The service center may not be aware of all the circumstances surrounding a bearing failure. A key consideration is the length of time in service *with the same pump and thrust load* for the motor. Recent installation, pump work or other changes are cause for further investigation.

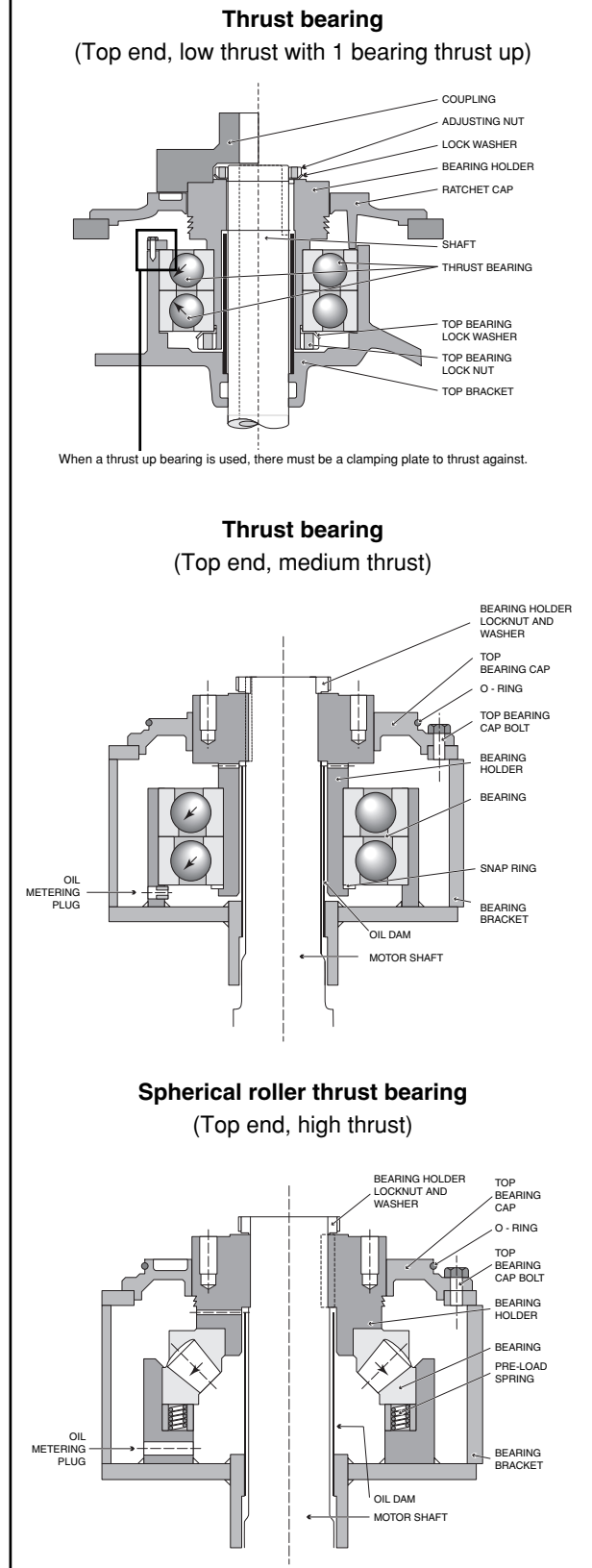
The following checklist will help focus the inspection on probable causes:

- Has the pump been recently replaced or serviced?
- Was any base or foundation work done?
- Has the motor been coupled to the same pump? Has it been moved recently?
- Has there been a change in the material being pumped?
- Are there records of vibration levels and/or current?
- Is there on-line monitoring equipment for vibration/current? Are the records available?
- Has there been any recent maintenance to the motor or pump?
- Is the pump or motor part of a redundant system? If so, are some units run continuously or is the starting sequence alternated?
- Have maintenance personnel recently checked the alignment or vibration?

Following is a list of possible misapplications for vertical machines:

- Mismatch of thrust needs.
  - High-thrust bearings coupled to a low-thrust pump.
  - Low-thrust bearings coupled to a high-thrust pump.
  - Lack of upthrust capability on a pump with occasional upthrust.
- Bearing arrangement has been changed for occasional upthrust, but no clamping ring/thrust shoulder is provided. The bearing orientations are correct, but the upthrust bearing cannot function because there is nothing to thrust against. (See the top illustration in Figure 16.)
- Bearing thrust capacity has been changed by adding or removing a bearing without changing lubrication provisions. If a thrust bearing is removed from a 2-thrust-bearing arrangement, the lower bearing should be removed, with a spacer (Figure 17) used beneath the remaining bearing. A clue is to compare the oil level

**FIGURE 16: VERTICAL SOLID SHAFT BEARING ASSEMBLIES**



**FIGURE 17: BEARING SPACER**

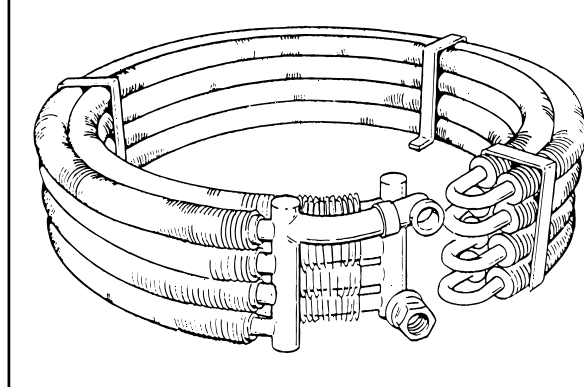
The spacer supports the thrust bearing, ensuring that the bearing is positioned correctly for the oil level.

to the position of the lower bearing. The oil level should be at or near the bottom of the lowest remaining bearing.

### DESIGN COMPARISONS

While many manufacturers have built vertical motors, the vast majority of vertical motors are built by only a few of them. Experience is a factor in motor design, so comparison of various designs can be instructive. This is especially true when dealing with lubrication, bearing temperature or bearing life problems. Oil-lubricated, anti-friction bearings (ball or roller) must be supplied enough oil to lubricate and cool the bearings. Too much oil will increase bearing temperature. Too little oil may result in increased friction. Either scenario can reduce bearing life.

Thrust bearing temperatures can be affected by regulating the volume of oil to the bearings, by adjusting the size of

**FIGURE 18: COOLING COIL**

the oil reservoir, or by auxiliary cooling (water- or air-tube cooled) of the oil reservoir. (See Figure 18.)

The most reliable method for regulating oil flow is to design the chamber to cause oil to enter under the bearing(s), pass a regulated volume through the bearing(s), and exit the top to circulate through the oil in the chamber. One role of the oil reservoir is to cool the hot oil that exits the bearing(s), but reservoir size is a variable beyond the control of the service center. If a reservoir is deemed to be too small for the load and ambient conditions, a cooling tube can be designed and installed. The most common cooling medium is water, primarily because of its availability and low cost. The greater the temperature difference between the cooling medium and the oil ( $\Delta T$ ), the more effective the heat exchanger.

### BEARING SIZE AND THRUST RATING

Bearing size and thrust rating relative to the actual thrust load also affect the bearing's operating temperature. When more than one bearing is mounted, a matched set of bearings must be used. (See Figure 19.) Heavy thrust damaged only one bearing, because they were not a

### MOUNTING COMBINATIONS FOR DUPLEX PAIRS

When thrust bearings are mounted in pairs, there are 3 possible combinations, each of which has specific advantages and drawbacks. The bearings may be mounted face-to-face, back-to-back, or both with the thrust in the same direction. In all cases, the bearings used must be specified as a matched set. Replacement bearings, when ordered, must be ordered as a matched set.

The thrust support shoulder of the outer race is referred to as the "back" of the bearing. In the "back to back" mounting, the thrust shoulders of the outer races are placed together. This mounting arrangement provides good rigidity, and is sometimes used for horizontal pumps.

For face-to-face mounting, the thrust faces

are to the outside of the pair. This method will accept some misalignment, and is used for applications where some shaft movement, relative to the housing, is normal.

The tandem mounting positions both thrust bearings with the thrust in the same direction. This method increases the thrust capacity by 60% over that of a single bearing.

When a pair of thrust bearings fails, they should be inspected to determine whether or not the bearings were a matched set. The biggest clue is when a pair of bearings are removed, and found to be from different bearing manufacturers. When two unmatched bearings (even if from the same bearing manufacturer) are paired, the load is not divided between them, and they will not function as the designer intended.



Back-to-back

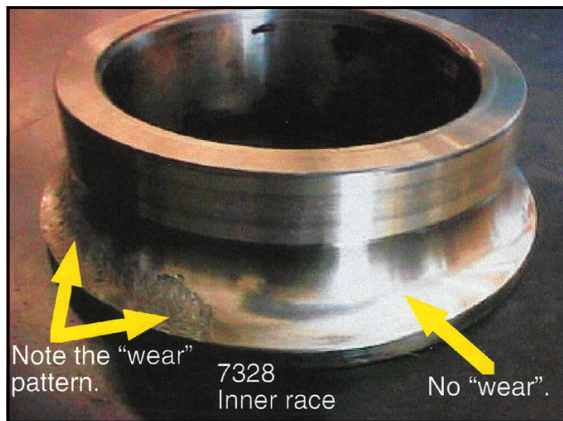


Face-to-face



Tandem



**FIGURE 19: MISMATCHED BEARING**

When two bearings are paired, it is essential that they be a matched pair of bearings. If the bearings are not a matched pair, one bearing will carry a disproportionate amount of the thrust load until it fails. The second bearing will, at some point, start to carry thrust load, but it will be hampered by the heat generated by the first bearing, which is in the process of failing.

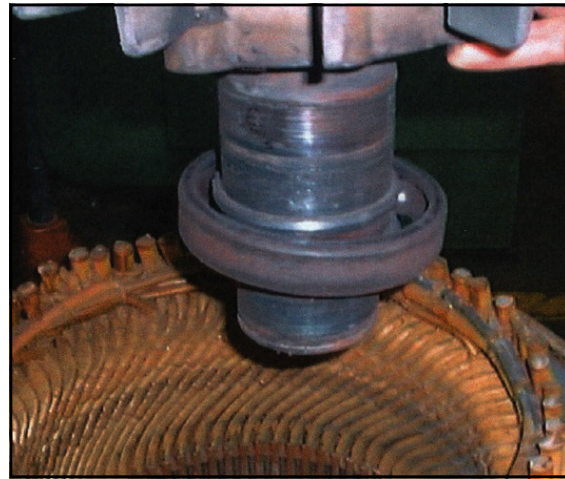
matched set. If two unmatched bearings are mounted in duplex, it is almost certain that one bearing will carry virtually all the thrust load. That bearing will fail if the load exceeds its capacity. Sometime during the bearing failure, the load will transfer to the remaining bearing which will subsequently be overloaded and fail. High bearing temperatures from the first failed bearing will often cause the second bearing to fail within minutes of the first bearing.

When a matched set of bearings is used, each additional bearing adds only 60% of its single-rated capacity to the bearing stack.

For higher thrust loads, a spherical roller thrust bearing is used. The spherical roller bearing has a higher thrust-carrying capacity, but it also generates more heat. It also is sensitive to misalignment of the raceways. Slight angular tilting greatly reduces bearing life. Because the spherical roller bearing is separable, preload springs are often used under the outer race. If the load may have momentary up thrusts, it is necessary for the outer race to be spring-loaded to keep the rollers in constant contact with the outer race. The spring set should be sized to lift the rotor weight plus approximately 20 to 30% of the normal thrust load.

If the springs are too weak, they will not lift the rotor and keep the bearing assembly together during brief, sudden episodes of upthrust. The shock impact each time the load is restored will cause impact damage to the bearing. Indicative of this problem is the presence of regularly spaced chipped areas on the outer race. The symptoms and appearance are consistent with brinelling.

If the springs are too strong, the thrust load may not keep the bearing seated in the housing. Unless the outer race is firmly seated in the housing it will tilt, causing misalignment with the rollers. Symptoms include heavy wear only part way around the roller path of the outer race. If the motor is

**FIGURE 20: DAMAGE TO LOWER GUIDE BEARING**

The failure of a bottom guide bearing warrants careful investigation. Possible causes include thrust load, “washing” of the lubricant, misalignment or a lack of lubrication. It is also possible that the bearing just reached the end of its fatigue life.

assembled when inspected, confirm that the springs are fully compressed by pressing the shaft down. Depending on the thrust load settings, it may require several tons of pressure to fully compress the springs.

If the rotor weight and thrust load cannot compress the springs, an axial upthrust load will result on the lower guide bearing (Figure 20). Close inspection of a failed lower guide bearing is necessary to prove whether the failure resulted from inadequate thrust load or from improper thrust adjustment by the assembler.

Thrust is an important consideration, because of the implications about the correctness of the assembly process. If a conventional thrust bearing is used in the upper end, and endplay is incorrectly set, then thermal expansion of the shaft can cause the bottom bearing to carry downthrust load. The bearing, having a significantly lower thrust rating than the upper thrust bearing, will fail quickly.

If the upper bearing is a spherical roller thrust bearing, and is spring loaded, then operation of the motor without a thrust load can damage the lower bearing. The preload springs place a thrust load on the lower guide bearing.

If the motor has a spherical thrust bearing, which is spring loaded, and the thrust load of the pump is less than the motor is designed to carry, the springs may still preload the lower guide bearing. In the first case (7000 series thrust bearing in top), the guide bearing will have a thrust load in the up direction. Hence, the need for documentation of the bearing mounting position.

## OIL LEAKS

Loss of lubrication, when cooling tubes are present, is a warning flag to closely inspect and pressure test the cooling

coil. Water tubes should be pressure tested at least 20% higher than the user's water pressure. Visual inspection should also be standard practice. Tubes tend to fracture at or near solder joints, bracing and supports. Corrosion inside the cooling tubes may not be visible, but will reduce the effectiveness of the heat exchanger. The local radiator shop is equipped to "boil out" the cooling tubes using standard radiator cleaning procedures.

Oil leaks can result from overfilling, excessive clearances, blocked vent passages, foaming oil, machining problems, missing parts, design flaws and other causes. The location of the oil leak can sometimes be traced back from the oil trail. Oil traces from the vent openings may indicate pressurization of the oil chamber, often caused by blocked vent passages elsewhere in the assembly. Oil coating the rotor and windings may indicate a loosened stand tube (Figure 21) or improper machining of the interior of the bearing carrier (Figure 22).

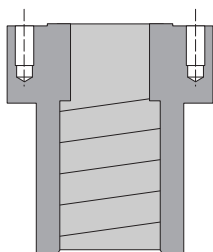
**FIGURE 21: STAND TUBE**



The stand tube serves as an oil drain. If bumped during the assembly process, the tube can be tilted or made to leak.

**FIGURE 22: IMPROPER MACHINING OF THE BEARING CARRIER**

Threading on the interior of the bearing carrier, depending upon the direction of rotation, may act like an oil pump, lifting oil over the stand tube.



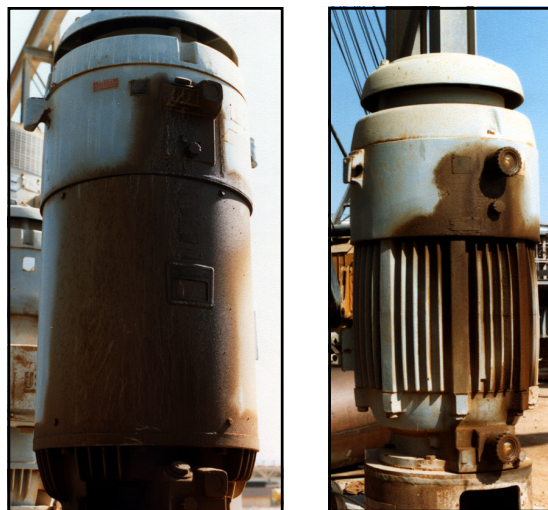
Many vertical designs position the bottom end of the bearing carrier in the oil to form an effective seal. If the inside bore of the bearing carrier has threading (even slight machining marks), that can act as an oil pump (Figure 22). Oil will be lifted along the threads, pool at the step in the bore,

**FIGURE 23: OIL POOLED IN THE BOTTOM BRACKET**



The quantity of oil in this bottom end bracket indicates an oil leak of significant duration.

**FIGURE 24: VERTICAL MOTORS SHOWING OBVIOUS OIL LEAKS**



Oil leaks may offer a clue to their cause. The pull-out oil fill (top right) can leak if not tightened, or when the cork gasket deteriorates. Sight glass gaskets or obstructed vents are also items to examine closely.

and spill across the stand tube. It will then travel down the shaft to the rotor, where centrifugal force and airflow deposit the oil on the windings.

Oil pooled on the rotor, but not coating the windings, usually results from shipping and handling after the motor was removed from service. In either case, the stand tube should be inspected for possible leaks. Oil pooled in the bottom bracket may offer clues as to the magnitude of the leak (Figure 23).

Foaming oil is sometimes caused by dents or dings that interrupt the symmetry of the bearing carrier, especially in areas where the bearing carrier is submerged in oil. An

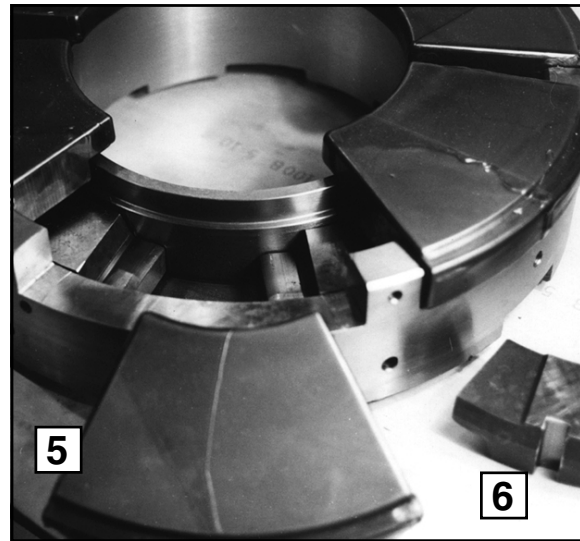


FIGURE 25: TILT PAD BEARINGS



The tilt pads have a thin layer of babbitt, precision-machined and etched (bottom right) to aid oil retention. Parts of a tilt pad bearing include:

- 1) Thrust runner.
- 2) Babbitt guide bearing.



- 3) Tilt pad and leveling assembly.
- 4) Upthrust limiting plate.
- 5) Tilt pad
- 6) Leveler/rocker.

overfilled oil chamber can raise the oil level enough to cause foaming, if it changes the dynamics of the airflow inside the oil chamber. Occasionally, oil is used that lacks important anti-foaming properties.

Some vertical designs include a splashplate above the upper bearing. There are designs where the splashplate must be placed on the bearing carrier before new bearings are installed. More than one technician (service center or end user) has forgotten the splashplate and then disposed of the evidence. Evidence of a missing splashplate include:

- Tapped holes in the bracket above the oil level that appear to serve no purpose.
- A machined step on the exterior of the major diameter of the bearing carrier.

- Oil leaks that exit around the top of the bearing carrier, or excessive splashing.

The presence of a splashplate in an identical motor may be helpful, but the absence of a splashplate is inconclusive.

### TILT PAD BEARINGS

The babbitt tilt pad bearing (Kingsbury™ bearing, plate bearing, hydrodynamic bearing) has an enviable record for longevity. The typical application for the tilt pad bearing has been hydroelectric generators, where low speed and continuous operation are the norm. One or two starts per year, and operating speeds around 100 to 400 rpm are favorable conditions for any bearing. Tilt pad bearing do not perform well when started frequently or at higher rpms. (See Figure 25.)

## INTRODUCTION TO SLEEVE BEARING FAILURES

Sleeve bearings, also known as babbitt bearings, have been used in almost all sizes of electric motors. For reasons of economics, most motor designs now use ball bearings whenever possible. Currently, fractional horsepower and large motors (where the desired life cannot be achieved with rolling-element type bearings) are the applications where sleeve bearings are normally used. The limiting factor in larger motors is the diameter of the shaft and the rotating speed of its rolling element.

The appearance of a sleeve bearing is deceptively simple. (See Figures 26, 27 and 28.) A soft metal (babbitt) coated with a film of oil supports a rotating shaft. The soft metal conforms to the shape of the shaft and the oil lubricates the surface to minimize wear. One or more rotating oil rings provide a continuously circulating flow of oil from the reservoir to the bearing surface. Because the oil is continuously circulating, it also an efficient means of cooling. The soft babbitt bearing material embeds foreign material that gets between the bearing and shaft, thus protecting the harder—and more costly—shaft.

**Note:** Do not clean the failed bearing until it has been properly inspected. It is also important to save a sample of the bearing lubricant.

For a sleeve bearing the failure mode is usually thermal, expedited by factors similar to those that affect anti-friction bearings. While babbitt melts at temperatures above 400° F (205° C), its use for bearings is limited to about 220° F (105° C). Lubrication failures, contamination, excessive load or shaft currents may each act to elevate bearing temperature. The aforementioned factors can be classified under the following stresses and grouped as follows:

### Thermal stress

- Lubricant.
- Ambient.

### Dynamic and static loading stress

- Radial.
- Axial thrusting.

### Environmental stress

- Moisture.
- Foreign material.
- Poor ventilation.

### Mechanical stress

- Misalignment.
- Housing too loose.
- Excessive shaft clearance.

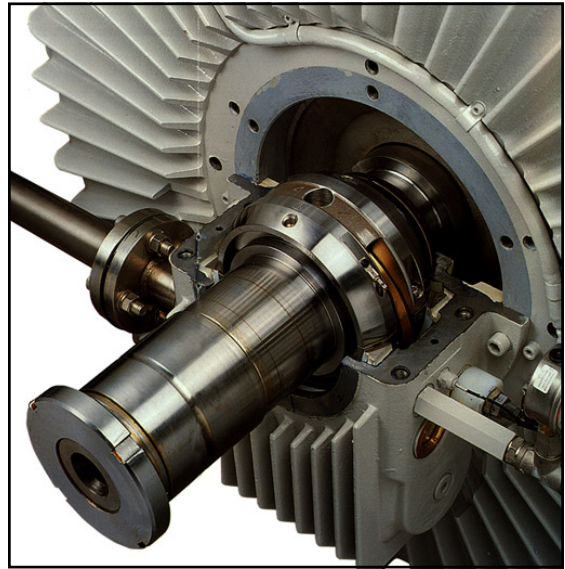
### Vibration and shock stress

- Rotor unbalance.
- Driven equipment unbalance.
- Other external sources.

### Electrical currents

- Rotor dissymmetry.
- Stator dissymmetry.
- Shorted laminations.

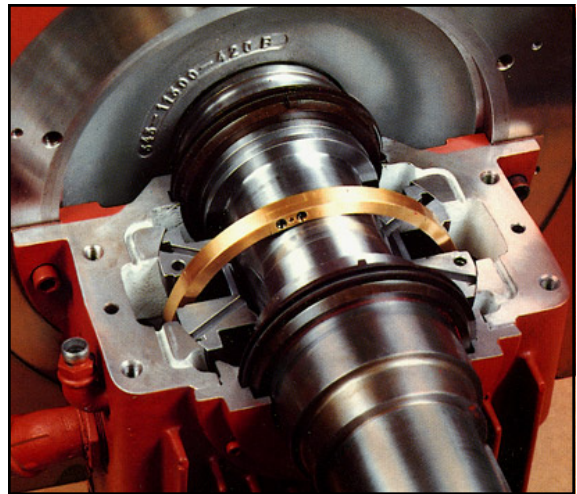
FIGURE 26: SLEEVE BEARING



Sleeve bearing with the top half of housing removed. Note the forced-oil piping, bearing temperature device and pressure gauge. The special coupling design requires that the bearing and oil ring both be separable. The bearing has a spherical outside diameter, making it self-aligning.

Courtesy of ABB

FIGURE 27: SLEEVE BEARING WITH OIL RING VISIBLE



This is a typical sleeve bearing arrangement. The top half of the housing has been removed for inspection. Note that the separable oil ring can be removed without further disassembly.

- Non-insulated through-bolts.
- Welding/other sources of electricity in the vicinity.
- Variable frequency drives (VFDs).



## METHODOLOGY FOR ANALYZING SLEEVE BEARING FAILURES

There are five key areas which should be considered and related to one another in order to accurately diagnose the root cause of sleeve bearing failures. They are:

- Failure mode.
- Failure pattern.
- Appearance.
- Application.
- Maintenance history.

### FAILURE MODES

Failure modes can be grouped into categories, which are usually the result of combined stresses acting on the bearing to the point of damage or failure. The modes of failure are:

- Corrosion.
- Lubrication failure.
- Electric pitting or fluting.
- Seizures.

These modes do not represent the cause of the bearing problem; instead they are the result or way that the problem is manifested.

### FAILURE PATTERNS

Closely associated with the failure mode, yet different, is the failure pattern. Each bearing failure has associated with it a certain pattern which can be grouped into some combination of the following categories.

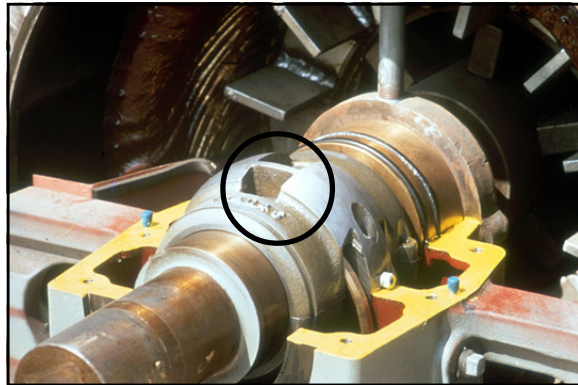
- Temperature levels (discoloration).
- Lubrication quality.
- Internal clearances.
- Contamination.
- Mechanical or electrical damage.
- Load paths and patterns (alignment).

### APPEARANCE CONSIDERATIONS

When coupled with the mode and pattern of failure, the motor, bearing and load appearance usually give a clue as to the possible cause of failure. The following checklist will be useful in the evaluation.

- Are there signs of contamination in the area of the bearings?
- Are there signs of excessive temperature anywhere in the motor or driven equipment?
- What is the quality of the bearing lubricant?
- Are there signs of moisture or rust?
- What is the condition of the coupling device used to connect the motor and the load?
- What levels of noise or vibration were present prior to failure?
- Are there any missing parts on the rotating element?
- What is the condition of the bearing bore, shaft journal, seals and shaft extension?
- Is the motor mounted, aligned and coupled correctly?

**FIGURE 28: SLEEVE BEARING**



This sleeve bearing has a narrow saddle helping to support the rotor weight. Note the two oil rings and the anti-rotation pin holes that prevent the bearing from rotating.

### APPLICATION CONSIDERATIONS

Usually it is difficult to reconstruct the actual operating 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?
- Does the load cycle or pulsate?
- How many other units are successfully operating?
- How often is the unit operated?
- What type of bearing protection is provided?
- Where is the unit located and what are the normal environmental conditions?
- Is the motor enclosure adequate for the application?
- What were the environmental conditions at time of failure?
- Is the mounting base correct for proper support of the motor?

### 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 in the area?
- Has there been any welding recently?
- When was the last time any service or maintenance was performed?
- What operating levels (temperature, vibration, noise, etc.) were observed prior to the failure? What tripped the motor off the line?
- 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? Has it tripped off line?
- Were the lubrication procedures correct?
- Have any changes been made to surrounding equipment?

## THERMAL STRESS

Bearing temperature varies according to rotor weight, rotational speed and the type of oil used. Sleeve bearing temperatures above 150° F (65° C) can usually be improved by fitting. Some motor designs are subject to inherently higher temperatures; in rare cases as high as 220° F (105° C). When monitoring bearing temperatures during no-load test runs, it is important to factor in the temperature rise of the motor. (See Table 5.)

| TABLE 5: BEARING MONITORING TEMPERATURES                          |                 |
|-------------------------------------------------------------------|-----------------|
| Monitoring condition                                              | Temperature     |
| Normal                                                            | 170° F (80° C)  |
| Alarm                                                             | 190° F (90° C)  |
| Shutdown                                                          | 210° F (100° C) |
| These values are realistic for most babbitt bearing applications. |                 |

Sleeve bearing failure analysis cannot be easily separated from lubrication analysis, so the two should be examined together whenever possible.

Lubrication for a sleeve bearing machine almost always means oil; typically 10 to 30 weight turbine oil. Viscosity can affect load carrying capacity as well as vibration levels.

The key to sleeve bearing life is adequate lubrication to maintain minimum friction. Some sleeve bearing designs incorporate guides or wipers to more effectively transfer oil from each ring to the shaft and bearing. The guide also keeps the ring tracking straight which is especially important in high speed machines. A ring that tracks erratically turns slower and moves less oil which can also lead to increased bearing temperature.

Oil rings must be round [within about 0.002" (0.5mm)] and flat to rotate at a consistent speed. An eccentric ring will "lope," or change speed as it rotates. A bent ring will track erratically, causing the oil to foam. (See Figure 29.)

The oil distribution groove (Figure 30), sometimes called a fly cut or side pocket, holds in reserve a continuous supply of oil. The oil in the distribution groove maintains a steady flow of oil between the bearing and shaft. The oil exits the drain groove at either end and is cooled by circulation with oil in the reservoir / sump. The end seal (Figure 31) helps in recovering the oil by containing the oil droplets and minimizing spray.

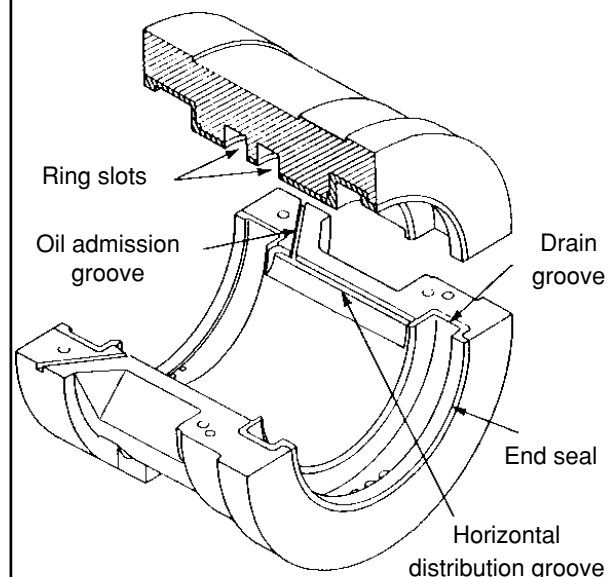
The size of the distribution groove can be critical, espe-

FIGURE 29: OIL RING SHAPE



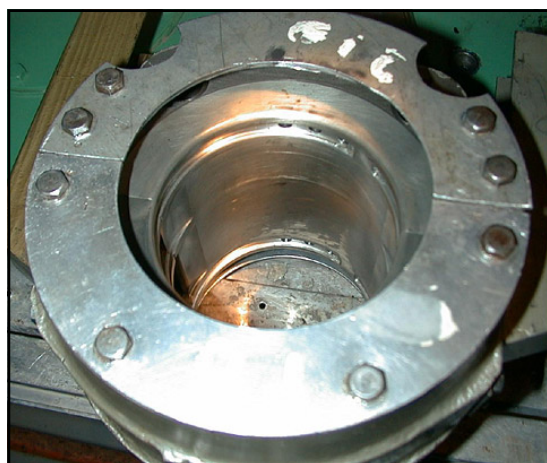
Oil rings must be round (within about 0.002") and flat to rotate at a consistent speed. Above, the oil ring on the left has an obvious elliptical shape. At left, the oil ring appears round with a simple visual inspection, but it is actually .030" out of round.

FIGURE 30: TYPICAL SLEEVE BEARING



The horizontal distribution groove is critical to bearing performance. The diagonal groove visible at the split line is a channel for forced oil systems. A forced oil system increases the volume of oil through the bearing, which acts to cool the bearing.



**FIGURE 31: END SEAL**

Various methods are employed to contain splashing oil. These split end plates supplement the labyrinth seal.

cially with 2-pole machines. Too small a distribution groove will not hold enough oil in reserve.

When bearings are replaced in a 2-pole machine, too small a distribution groove is evidenced by heat, a 'patchy' appearance to the babbitt surface, and difficulty in obtaining a good wear pattern. (See Figure 32.)

#### BABBITT GRADE

Babbitt grades are selected for specific applications based on shaft surface speed, lubrication type and dynamic load. Other considerations include embeddability of dirt (contaminants are much more prevalent in a cement mill, for example, than in a food manufacturing plant) as well as load and temperature. Babbitt grade is determined by the relative composition of tin, antimony, lead and copper (Table 6). ASTM alloy grade numbers range from 1 to 19, although babbitt grades 1, 2 and 3 are the most frequently encountered. Tin is the major component of babbitt grades 1 through 5, with lead being the main component of grades 6 through 19. Lead babbitt is lower in strength and less

**FIGURE 32: OIL DISTRIBUTION GROOVE TOO SMALL**

The patchy contact pattern is one indication that the bearing is "oil starved." A deeper, wider distribution groove is required.

resistant to corrosion than tin babbitt, but offers better embeddability of contaminants than tin.

Tin-based babbitt bearings for electric motors have load-carrying capacities in the range of 800 to 1500 psi, while the capacity of lead-based babbitt bearings range from 800 to 1200 psi. The babbitt used for a lightweight, high-rpm induction motor will differ from that used in a large, low-speed synchronous ball-mill motor. To confirm babbitt grade, send a sample to a lab for analysis or contact the OEM for the original grade.

#### SOME COMMON CAUSES OF FAILURE

Babbitt bearing failures ultimately result from heat. Some of the more common causes are:

- Contamination in the oil.
- Lack of lubrication.
- Shaft currents.
- Excess lubrication.
- Excessive ambient temperature.

**TABLE 6: BABBITT GRADE**

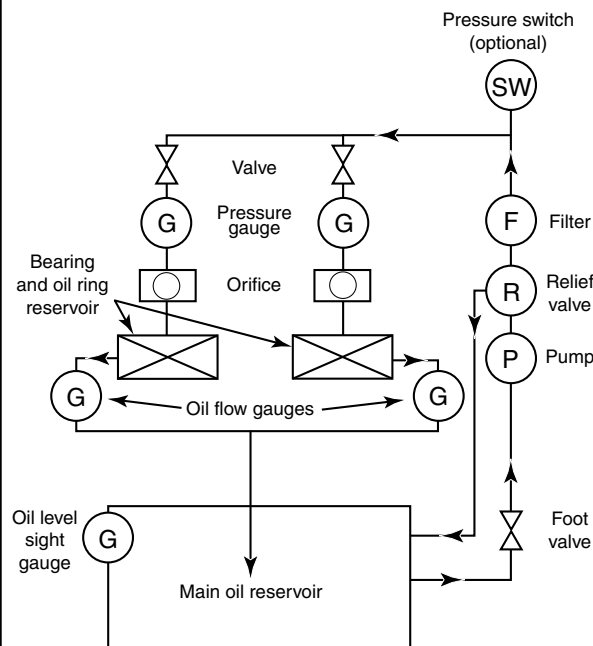
| ASTM grade number | Percent tin | Percent antimony | Percent lead | Percent copper | Melting point   | Pouring temperature |
|-------------------|-------------|------------------|--------------|----------------|-----------------|---------------------|
| 1                 | 91          | 4.5              | —            | 4.5            | 433° F (223° C) | 825° F (441° C)     |
| 2                 | 89          | 7.5              | —            | 3.5            | 466° F (241° C) | 795° F (424° C)     |
| 3                 | 83          | 8.3              | —            | 8.3            | 464° F (240° C) | 915° F (491° C)     |
| 5                 | 65          | 15               | 18           | 2              | 358° F (181° C) | 690° F (366° C)     |
| 7                 | 10          | 15               | 75           | 1.5            | 464° F (240° C) | 640° F (338° C)     |

While melting temperatures are similar, the correct casting temperatures vary considerably among babbitt grades. Pouring babbitt at too low a temperature reduces the chance for a good bond between the babbitt and the shell.

Under-lubrication may result from oil splashing (missing ring guides, for instance), excess labyrinth seal clearance (oil migrates from the chamber), or a pressure differential between the outside air and the interior of the bearing chamber. Inspect the vent openings for blockages.

Over-lubrication can be as much of a problem as under-

**FIGURE 33: FORCED LUBRICATION SYSTEM**



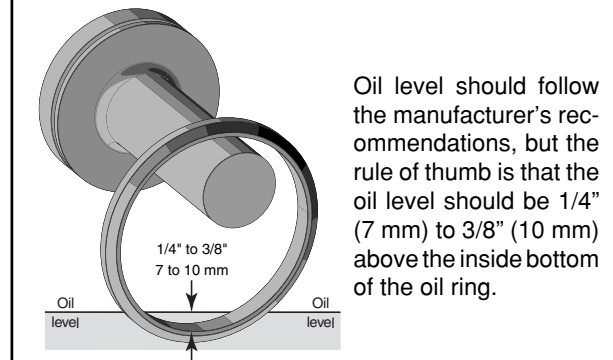
This is a schematic of a forced lubrication system. Careful attention must be paid to the orifice which may be lost during routine repairs or when the motor is removed from service. A pressure gauge should be located at each bearing.

lubrication. One common problem encountered with forced lubrication systems is the loss of the orifice used in the pressure-side of the oil supply plumbing to each bearing (Figure 33). The function of this orifice is to meter the oil volume. The correct supply of oil to each bearing depends on the system pressure and oil volume. The volume of oil delivered is controlled by the orifice size. To determine the oil volume supplied by a forced lubrication system, open the drain line and measure the quantity of oil circulated in one (timed) minute and compare that to OEM specifications. If the volume of oil is considerably more than that specified by the OEM, the orifice is missing.

The oil level should be approximately 3/8" (10 mm) above the inside of the bottom of the oil ring (Figure 34). Too low a stationary level means that the oil level is dangerously low when some of the oil is in play (in the bearing, dripping down the inside of the chamber, etc.) The rings are more likely to bounce, causing inconsistent oil delivery to the bearing. Too high an oil level means increased friction between oil and ring. The ring turns slower, supplying less oil to the bearing.

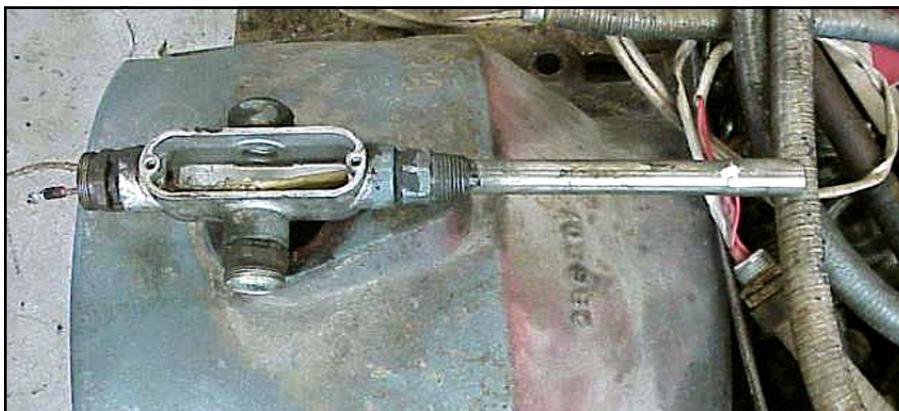
When an oil leak is suspected, use a manometer to measure the pressure differential between the inside of the bearing chamber and the motor enclosure.

**FIGURE 34: OIL RING AND PROPER OIL LEVEL**



Oil level should follow the manufacturer's recommendations, but the rule of thumb is that the oil level should be 1/4" (7 mm) to 3/8" (10 mm) above the inside bottom of the oil ring.

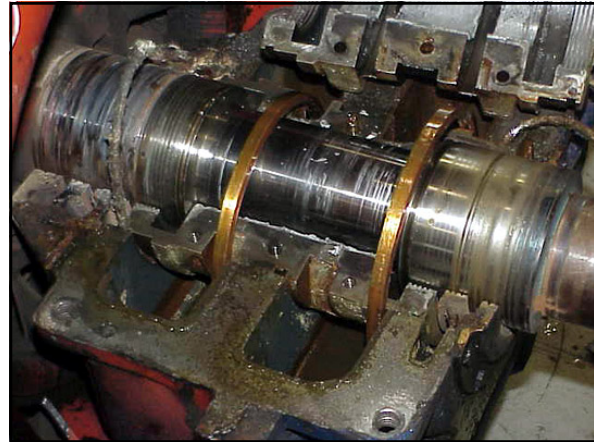
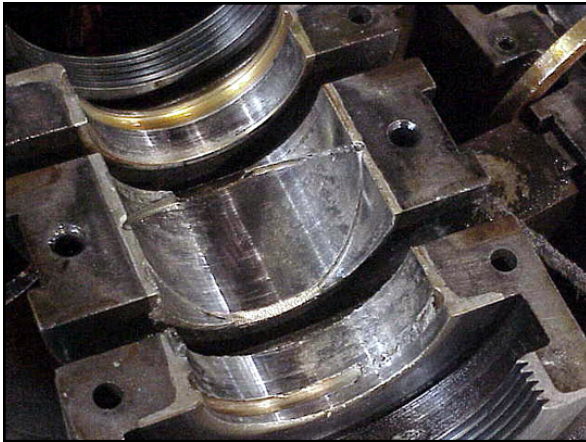
## THERMAL STRESS



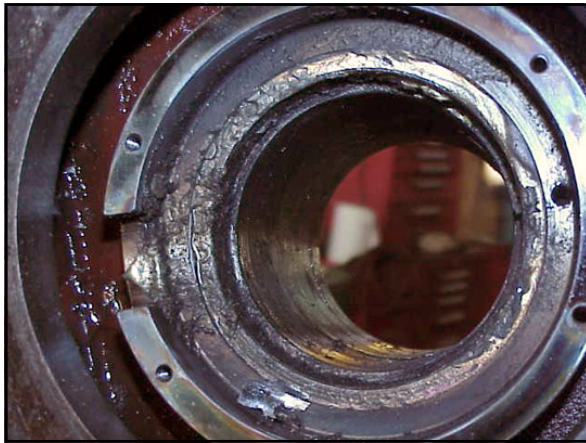
Thermal switches are often used in cold climates. Pipelines often use a thermostat and space heater combination; immersing both in the oil. A malfunctioning heater or thermostat could result in hot oil or in oil at ambient. When the ambient is -30° F (-35° C), the oil is too thick to flow. For temperatures below 50° F (10° C), special measures may be needed.



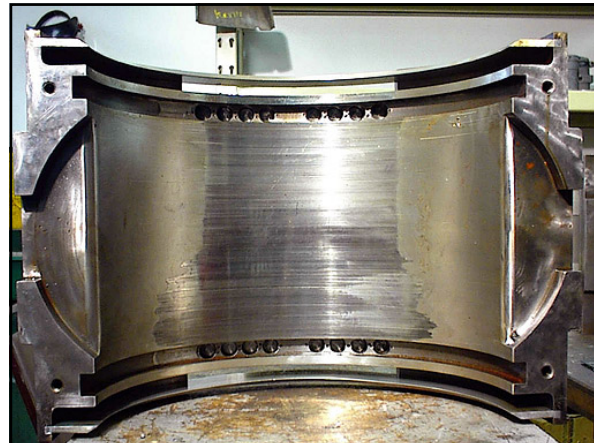
## THERMAL STRESS



Evidence of heat includes babbitt smeared across machined grooves in the babbitt surface (top half of bearing, left) and a feathered edge on the bottom half of the bearing (right).



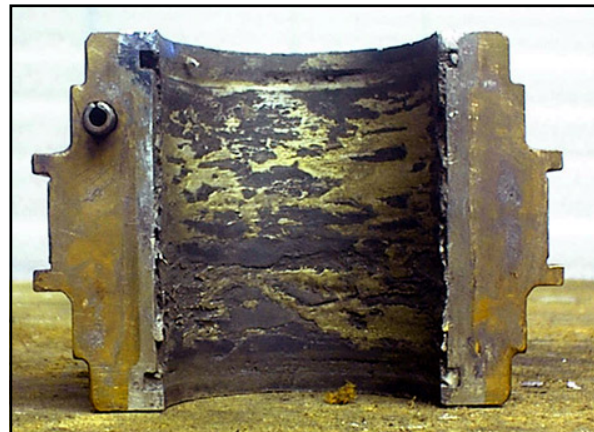
Continuous thrusting caused friction, overheating the babbitt nearest the thrust shoulder. Note the drip of melted babbitt. The end shield has been removed for visibility.



This sleeve bearing is beginning to show signs of wiping. Note the smeared babbitt.



This bearing has been puddled and machined. The mottled surface was caused by using a babbitt grade different from the parent material. Note the irregular edge of the distribution groove.



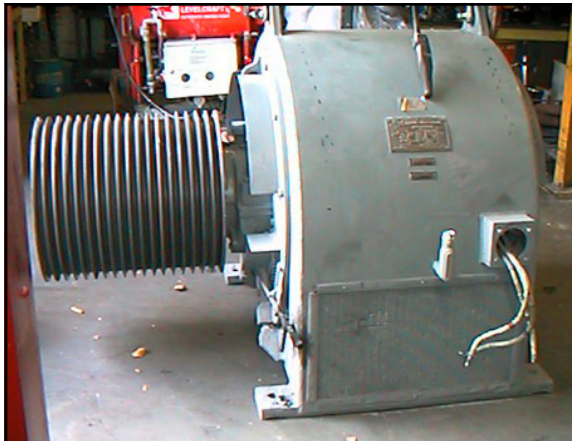
A thin layer of babbitt remains bonded only to the tinned shell.



## DYNAMIC AND STATIC LOADING STRESS

Radial loads present a problem for sleeve bearings, which perform best in direct coupled applications. Excess radial load applications do exist, so don't assume that the end user knows about the incompatibility between radial load and sleeve bearings. (See Figure 35.)

**FIGURE 35: EXAMPLE OF HIGH RADIAL LOAD**



Sleeve bearings are not well-suited for high radial loads such as this 18-belt pulley.

The 1500 psi limit for tin-based babbitt bearings (1200 psi for lead-based) should be considered an absolute limit, based on half the area of the bearing surface. Applications that result in higher radial loads should be avoided or modified to reduce the radial load on the bearing.

The thrust shoulder of a sleeve bearing is not intended to carry sustained thrust loads. Its only purpose is to limit the axial movement of the shaft during startup and coast-down. Evidence of wear on a thrust surface indicates improper alignment. The coupling end float should be limited to meet guidelines published in NEMA MG 1-1998 (Table 7).

Thrusting—heavy wear on one thrust shoulder of a bearing—can be caused by improper axial placement during installation. It may also indicate a defective coupling. Couplings require lubrication, too—but safety guards make them difficult to access. A “frozen” coupling will prevent axial movement.

Foundation settling is a less-common cause of this type of wear. With machinery subject to long coast-down times (e.g., centrifugal pump), precise level of the shafts is important. If one end of a motor is higher than the other end, the shaft will drift towards the low end.

The use of thrust-limiting couplings is strongly recommended to prevent thrust-shoulder contact. The higher the rpm (fewer poles), the less force is required to move a rotor axially from its magnetic center. That makes the aforementioned factors more critical for 2-pole machines than for low-speed machines.

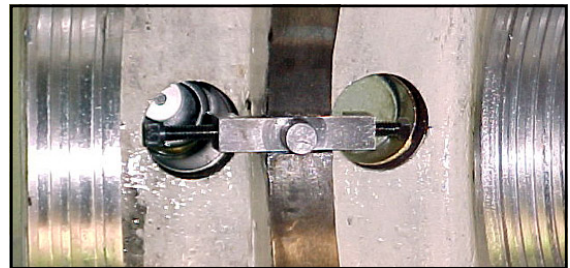
End float and magnetic center are important consider-

**TABLE 7: END PLAY AND ROTOR FLOAT FOR COUPLED SLEEVE BEARING HORIZONTAL INDUCTION MOTORS**

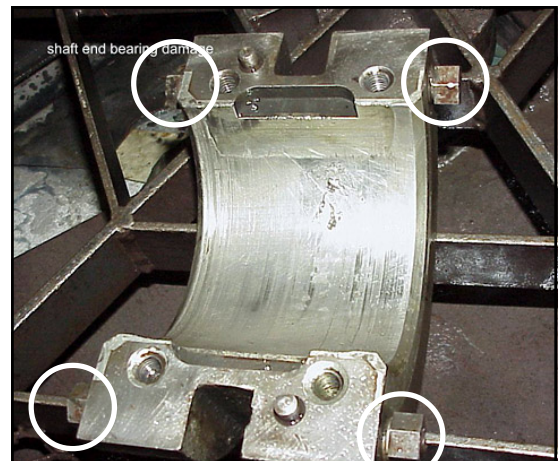
| Machine hp            | Synchronous speed  | Min. rotor end float | Max. coupling end float |
|-----------------------|--------------------|----------------------|-------------------------|
| 500 hp and below      | 1800 rpm and below | 0.25" (6.5 mm)       | 0.09" (2.3 mm)          |
| 300 to 500 hp         | 3600 and 3000 rpm  | 0.50" (13 mm)        | 0.19" (4.8 mm)          |
| 600 hp and higher     | All speeds         | 0.50" (13 mm)        | 0.19" (4.8 mm)          |
| NEMA MG 1-1998, 20.30 |                    |                      |                         |

ations when rebuilding sleeve bearing machines (Figure 36). Magnetic center should be clearly marked during the final test run. Mechanical center and the magnetic center should closely coincide. In rare cases, the magnetic center may change from no-load to full load, especially with 2-pole machines.

**FIGURE 36: LOCATING MAGNETIC CENTER**

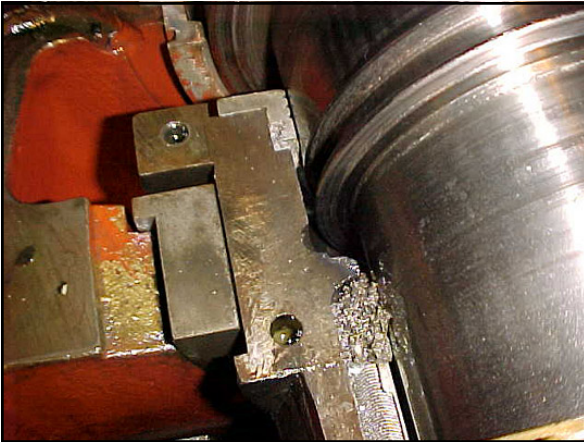


Various methods are used for adjusting the bearings to improve magnetic center. Above, an awkward method. Below, the studs must be adjusted with the top of the bearing housing removed.

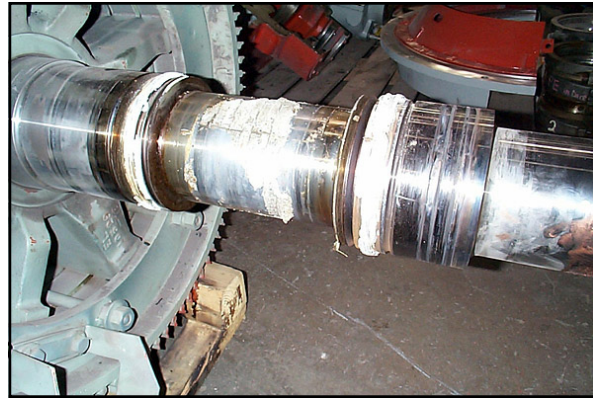
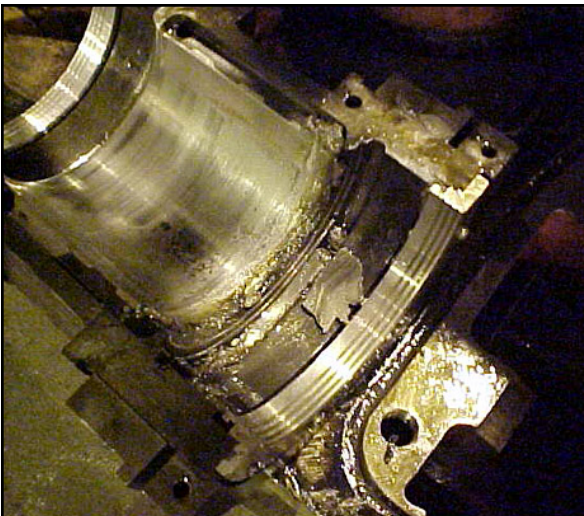
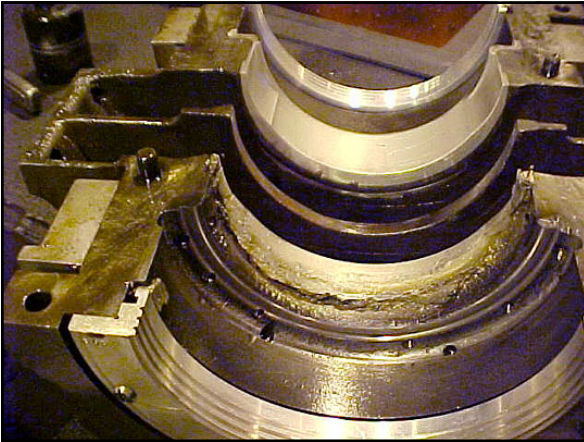




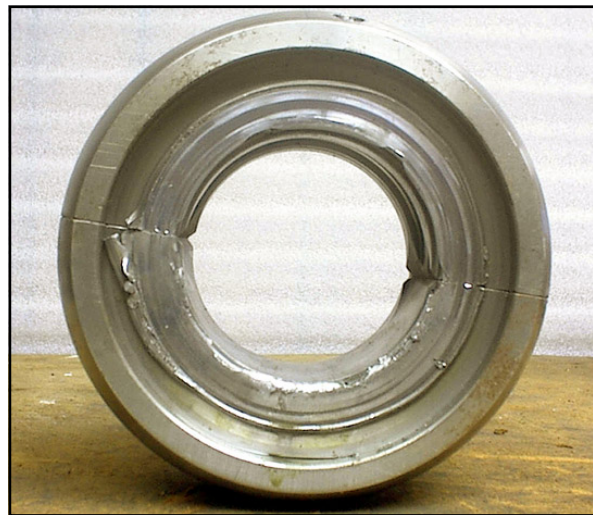
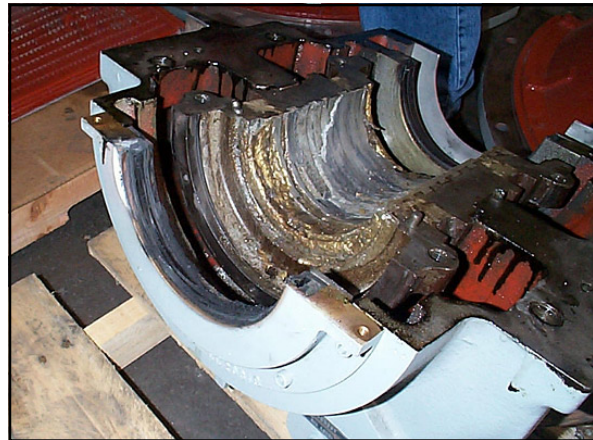
## DYNAMIC AND STATIC LOADING STRESS



A bad combination: This end of the motor was low, and the driven pump coasted for 15 to 20 minutes each time it was shut down. The top half of the bearing (middle) as well as the bottom half (bottom) show signs of damage caused by friction on the thrust shoulder.



This bearing journal (above) and sleeve bearing (below) are from a low-speed motor used in a belted application. Radial loads can damage a sleeve bearing.



This bearing was damaged during coast down. The coupling end float was not limited as prescribed by NEMA MG 1-1998, 20.30.



## ENVIRONMENTAL STRESS

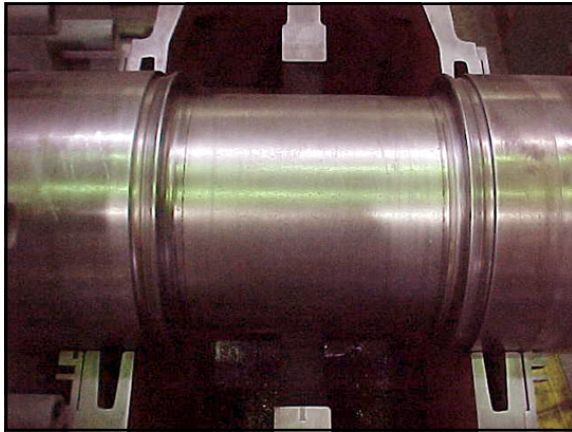
Contamination of the lubricating oil may result from a dirty environment, intermittent splashing or wash down of machinery, extended periods without regular lubrication changes, damaged or missing seals or similar problems.

### LABYRINTH SEALS

The area of contact with the labyrinth seal may give further clues about a failure. Contact anywhere other than at the bottom may indicate misalignment. Dirty, oil-soaked windings are a good indication of an ongoing oil leak caused by excessive clearance of the labyrinth seal or by a pressure differential between the oil chamber and atmosphere. The longer the leak has been present, the more dirt will be found mixed into the oil. This “mud” restricts air flow through the windings and the oil can damage insulation.

Perhaps a vent has been inadvertently blocked, or “mud-daubing” insects have nested in the vent opening (not

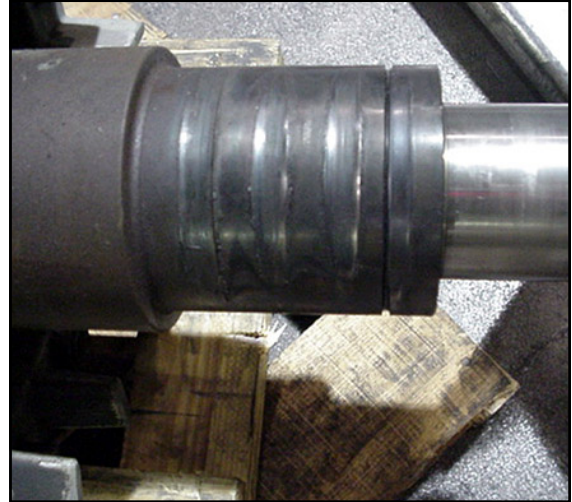
**FIGURE 37: LABYRINTH SEALS**



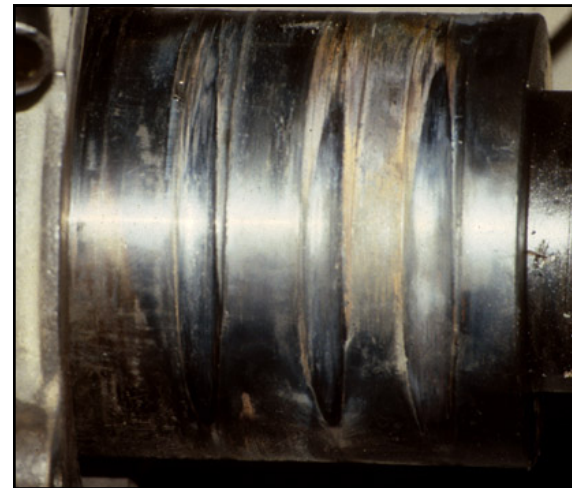
Labyrinth seals may be integral to the bracket (top), or removable by design (middle and bottom).

uncommon in the vent openings, especially in warmer climates). It is important that these areas be inspected before any parts cleaning takes place. Evidence lost may prevent correct interpretation of the failure.

**FIGURE 38: SHAFT CONTACT WITH LABYRINTH SEAL**



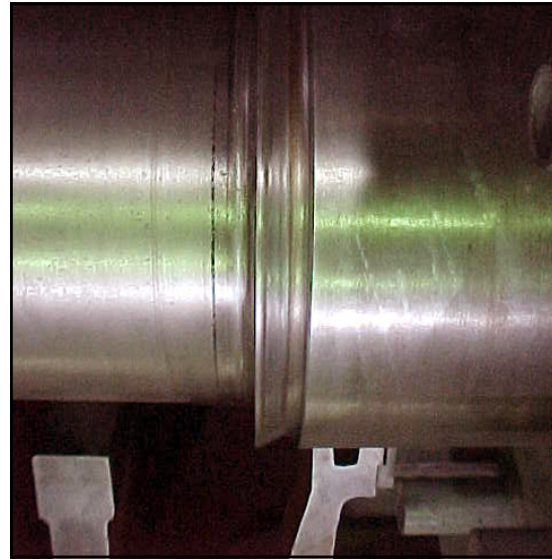
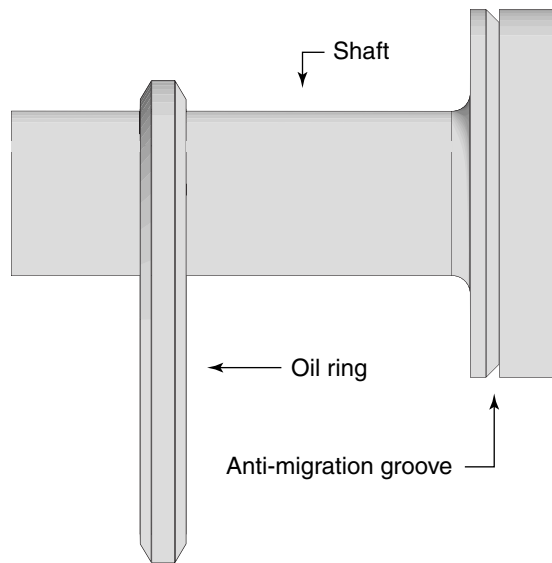
Oil contamination may cause bearing failure, with subsequent damage to the labyrinth seals. If not properly repaired, this permits contaminants to enter the bearing chamber. These shafts should be carefully checked for cracks and bending.



Excess clearance of labyrinth seals can result from a bearing failure that permits the shaft to contact the seal (Figure 38). Once contact takes place, the seal rub will generate even more heat. Typical diametrical clearance for the labyrinth seal of a sleeve bearing machine is 0.007" (0.18 mm) to 0.020" (0.51 mm) depending on speed and shaft diameter. Removable labyrinth seals should be sealed during assembly, using an approved sealant, silicone or other similar products. Non-hardening products are preferred to facilitate future disassembly.

When previous shaft repairs may have been done, one

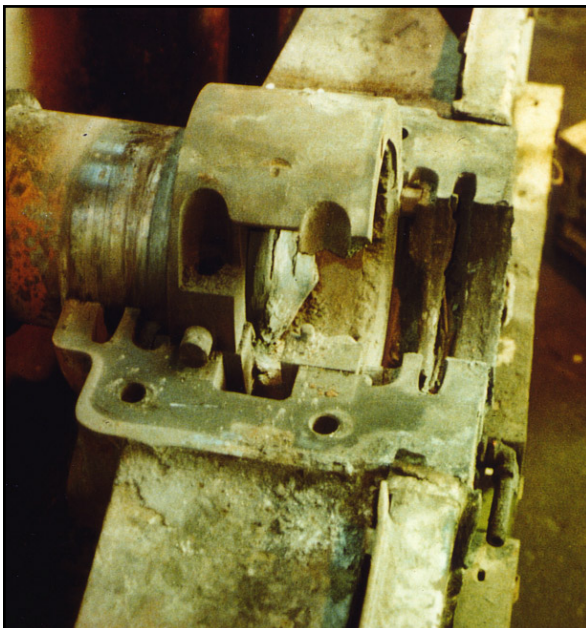


**FIGURE 39: ANTI-MIGRATION GROOVE**

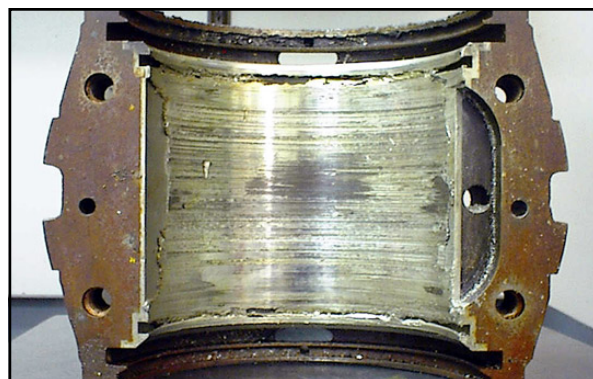
easily missed cause of oil leaks is the anti-migration groove (anti-creep groove) machined in the shaft just within the bearing chamber (Figure 39). This prevents oil from migrating past the labyrinth seal. Centrifugal force prevents the oil from passing the groove.

While blocked labyrinth vents may cause pressure differential (and oil leaks), ventilation problems resulting from foreign material buildup on the exterior of the bearing chamber or oil reservoir may raise the  $\Delta T$  between oil and bearing, diminishing the ability of the oil to cool the bearing.

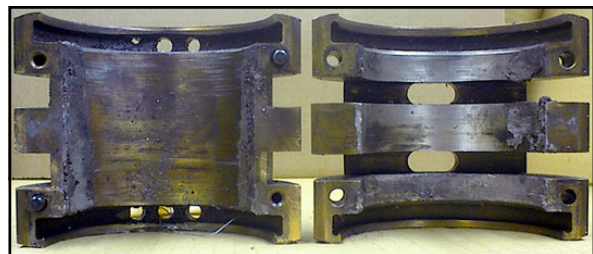
## ENVIRONMENTAL STRESS



The drive end of this shaft broke at the bearing journal. Contamination turned the oil to "mud." Without effective lubrication, the bearing seized and the shaft twisted.



Contamination in the oil deposited on the bearing, scoring both the shaft and bearing.



Chemical corrosion of the babbitt makes the bearing less effective.

## MECHANICAL STRESS

Clearance between the shaft and bearing keeps the shaft position stable. Too little clearance results in excessive heat due to friction between the shaft and bearing. Too much clearance can lead to unwanted movement (vibration or loss of concentric orbit).

One rule of thumb for bearing-to-shaft clearance is 0.001" plus 0.001" per inch of shaft diameter, although factors such as rotational speed, bearing diameter/length ratio, oil viscosity and load each play a role in determining the optimal clearance for a particular bearing.

Bearing-to-shaft clearance must be within customer tolerances; absent OEM specs, refer to the table of recommended clearances in EASA's Technical Manual, Section 9.

The different coefficients of expansion for different materials (steel shaft, brass or cast iron bearing shell, babbitt bearing surface and cast-iron housing) makes some clearance between bracket and bearing outside diameter essential. If the bearing-to-housing fit has zero clearance, the bearing shell cannot expand outwards as it heats up. Thermal expansion will cause the bearing to grow "in," reducing the bearing-to-shaft clearance. If the bearing-to-shaft clearance becomes too tight, the bearing will fail. Too much clearance between the bearing and housing increase high vibration. Most electric motor sleeve bearings perform best with housing clearances of 0.001" to 0.003".

One manufacturer designed their sleeve bearing housings with a loose fit, outfitting the top bracket with setscrews which were adjusted to obtain the desired tightness. That same manufacturer also deliberately bored babbitt bearings off-center (the bore was not concentric to the outside diameter), calling them "high-lift" bearings.

Spherical bearings (Figure 40), also called self-aligning

bearings, can be difficult to measure. Use soft lead wire or Plastigage to crush-gauge the clearance for difficult to measure bearings.

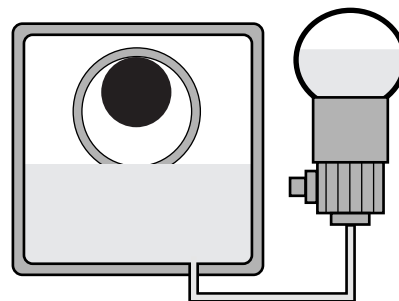
## MISALIGNMENT

Sleeve bearing machines are particularly sensitive to misalignment. Severe misalignment is obvious when the points of contact on a sleeve bearing are at diagonally opposite corners of the bearing. Rotor speed is not the only consideration when determining required alignment accuracy. At any given rpm, alignment is more critical for longer sleeve bearings.

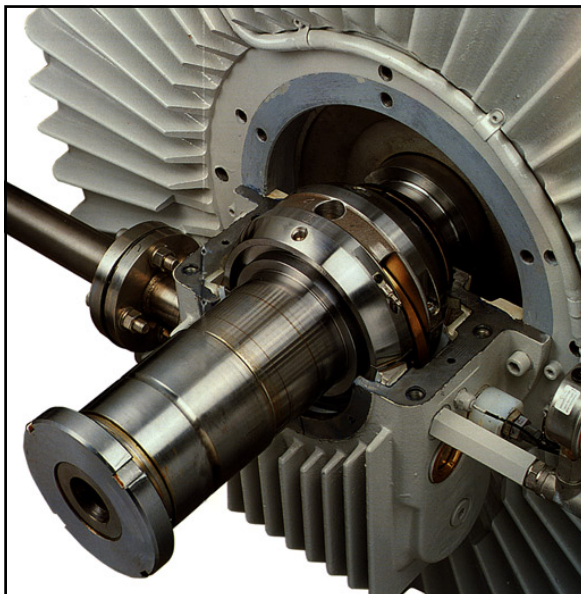
## LUBRICATION

If the oilers are adjustable, verify the oil level setting (Figure 41). Replacement oilers are sometimes installed and adjusted incorrectly. Automatic oilers are available in several styles. The relationship of oil level to piping entrance

**FIGURE 41: CONSTANT LEVEL OILER**



**FIGURE 40: SPHERICAL SLEEVE BEARINGS**



The spherical sleeve bearing, if properly installed, will align itself to the shaft.



differs considerably among these. It is not unusual to have to change the piping configuration when changing an oiler. An automatic oiler set too high will often cause an oil leak. When changing a defective oiler it is advisable to change both, so as to avoid confusion when setting or checking oil level.

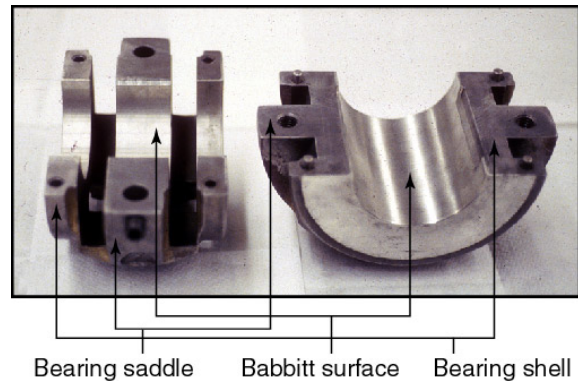
### INSPECTION

Inspection of new / rebuilt babbitt bearings should include nondestructive testing (NDT). An ultrasound inspection is the best way to evaluate the bond between bearing shell and babbitt. Navy specification minimums adopted by some end users require 80% minimum bond for the load zone, and 40% for the overall bearing. The percent bond in the bottom half of a bearing is more critical than in the top half. Likewise the percent bond for a 2 pole machine is more critical than for a very low-speed application. Common problems affecting the bond between the babbitt and the bearing shell are presence of oil in the bearing shell (or in the material used to seal openings in the shell), failure to tin the shell before rebabbiting, or pouring the babbitt at the wrong temperature. (See Table 4.)

### FITTING

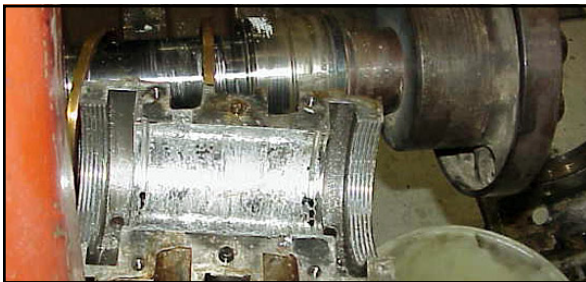
Fitting a new sleeve bearing is an important part of the assembly process to ensure successful performance. The objective is a minimum of 60% contact centered in the

**FIGURE 42: SOME BASIC COMPONENTS OF SLEEVE BEARING**

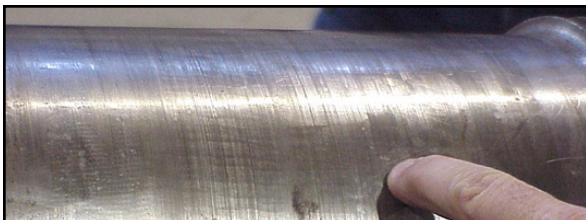


bottom half, with no contact at the corners or top. Too tight a bearing-to-housing fit may distort the bearing shell and cause bearing-to-shaft contact that was not evident during the initial fitting process. In some cases the top cap may also tilt the bearing, changing the orientation of the bearing relative to the shaft. A warped stator frame or end bracket can do the same. With a failed babbitt bearing, there may be no evidence of such a problem until the rebuilt motor is reassembled.

## MECHANICAL STRESS



Misalignment can damage a sleeve bearing in a very short time. Misalignment usually causes thermal stress; the failure often masks the mode of failure.



This shaft journal was welded and machined. Axial passes with a stick welder are more likely to bend the shaft. Varying hardness is also more likely, resulting in a bearing journal that is not perfectly round. Irregularities will increase friction and cause difficulty when fitting the bearing.



A bearing loose in the housing could permit the shaft to come into contact with the seal.



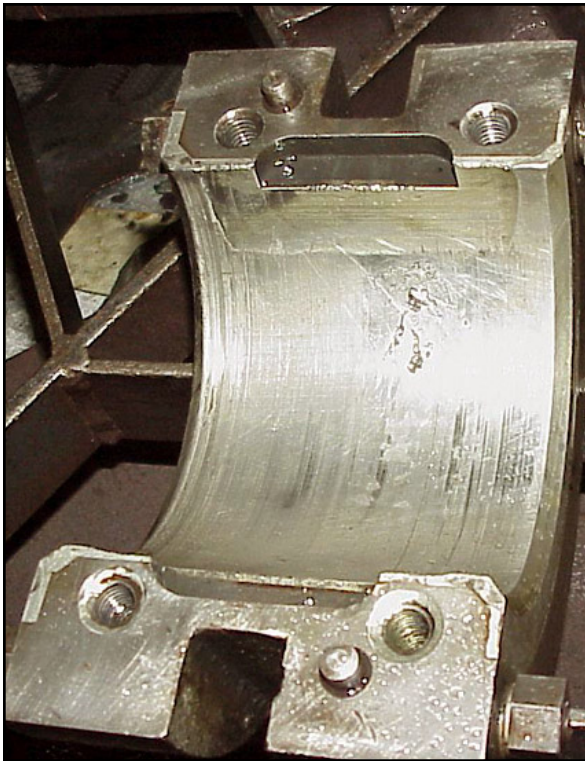
## VIBRATION AND SHOCK STRESS

Vibration may result from rotor unbalance, unbalance of the driven load, structural defects or vibration of nearby equipment. For that reason, it is all but impossible to conclusively evaluate a bearing failure independent of the system. Circumferential contact around the entire bearing is one indication of severe radial unbalance. Fractured babbit is often an indicator of severe impact from repeated shock load.

While rotor unbalance can be confirmed by the service center, an unbalanced coupling may be at fault. Not all customers send the coupling when the motor is sent for repair. If a fan / pump / other driven equipment is rebuilt while the motor is out, it will be all the more difficult to prove the source of the unbalance.

Applications such as a hammer mill, ball mill or rod mill often produce shock loads. Broken welds in the building structure, a disbanded soleplate, or similar equipment problems can cause high levels of shock stress.

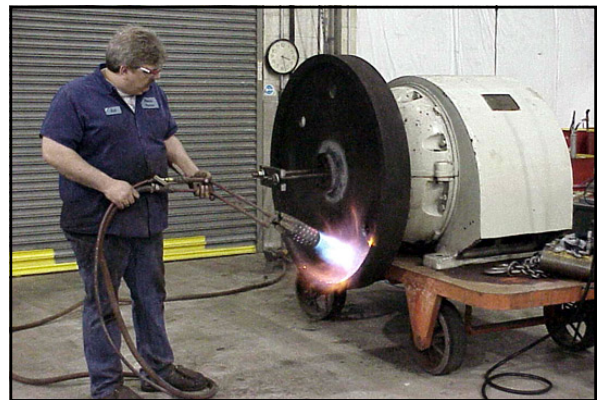
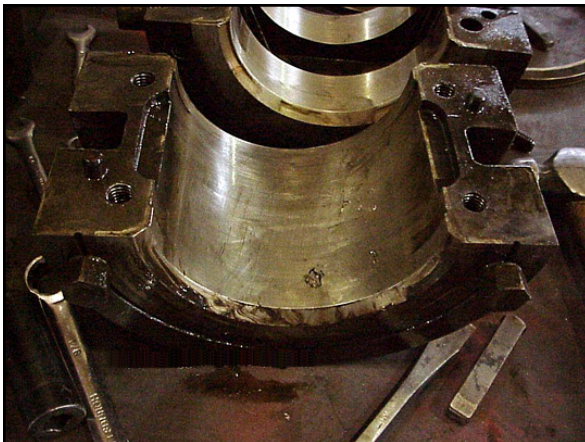
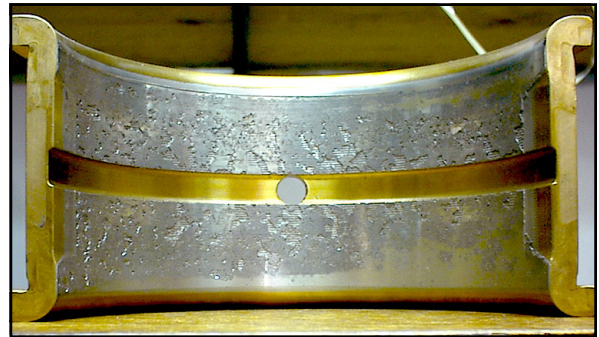
## VIBRATION AND SHOCK STRESS



With shock stress, the mode of failure is babbit that has been pounded to the point of breaking.



Examples (above and below) of babbit fractured by high vibration and/or impact damage.



The source of vibration could be the coupling or pulley.



## ELECTRICAL STRESS

Electrical stress acting upon sleeve bearings can be caused by:

- Rotor dissymmetry.
- Stator dissymmetry.
- Shorted laminations.
- Non-insulated through-bolts.
- Welding.
- Variable frequency drives.

A sleeve bearing can withstand higher shaft currents than a ball bearing, but shaft currents are still a source of trouble. The magnetic dissymmetry often responsible for these currents is more common in large machines with segmented laminations, and large machines are more likely to have sleeve bearings. The suggested threshold value for a sleeve bearing is 200 mV.

Even when a bearing is properly insulated, problems can occur. For example, conductive contaminants such as coal dust or carbon black may build up in the oil, effectively bypassing the bearing insulation. Water may cause rust, which can also bypass the insulation.

Some manufacturers use an aluminum oxide thermal spray to insulate the shell. The thin coating can be chipped by improper handling, and rust caused by exposure to water rust can compromise the insulation. A less common prob-

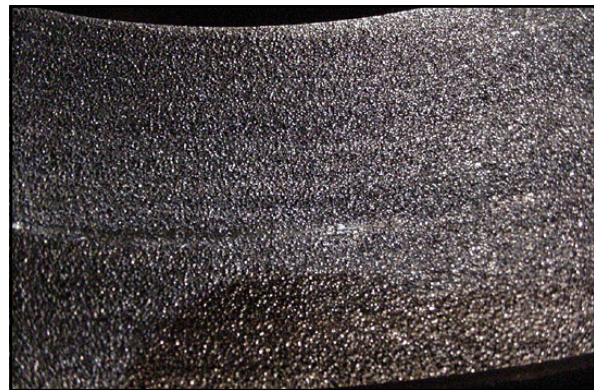
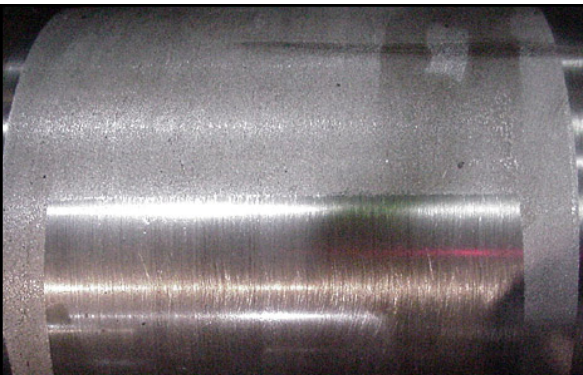
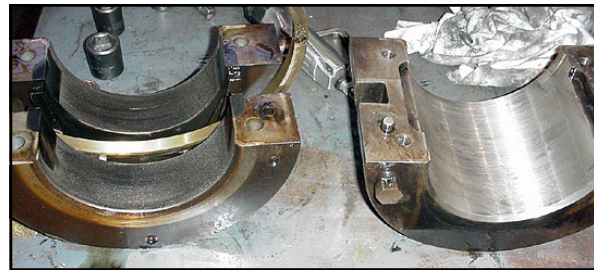
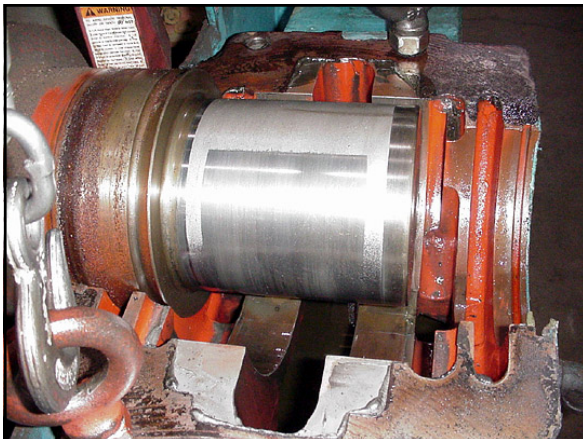
lem can occur when oil goes unchanged for very long periods: brass material worn from the oil rings may cause the oil to become conductive. For bearings insulated with an oxide-coated shell, inspect the oil ring slots for overspray. As the rings rotate, the abrasive action of the oversprayed material will quickly wear down oil rings. When an oil ring lacks symmetry, inspect the adjacent surfaces for abrasive material.

Other manufacturers apply ceramic spray to the shaft journal. The ceramic is precision-ground to obtain the desired size and surface finish, and has the added benefit of reducing friction and corrosion.

Larger machines sometimes have an insulated bearing pedestal. In those cases, the associated bolts and dowel pins must also be insulated. Additional concerns include conductive paint and grounding cables installed improperly by well-meaning plant personnel.

A less common cause of electrical damage to sleeve bearings occurs when welding is done in the vicinity of the motor. Careless grounding can result in current passing through the bearings and shaft, arcing across areas with small clearances. The photographs are uncommon, because the damage occurred while the motor was idle, and an inspection uncovered the problem before the motor was energized. Too often, the damage results in catastrophic bearing failure.

## ELECTRICAL STRESS



Welding repairs were done near this idle motor. Fortunately, it was inspected before being run. Arcing caused pitting on the bearing and shaft surfaces. Had this motor been started, the evidence might have been lost in the resulting failure.

# 3

## Winding Failures

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## INTRODUCTION TO WINDING FAILURES

The majority of all stator failures are caused by a combination of various stresses which act on the winding. These stresses can be grouped as follows:

### Thermal stress

- Thermal aging.
- Overloading.
- Voltage variation.
- Voltage unbalance.
- Ambient.
- Load cycling, starting and stalling.
- Poor ventilation.
- Circulating currents.

### Electrical stress

- Dielectric aging.
- Transient voltages.
- Partial discharge (corona) and tracking.
- Insulation inadequacies.

### Mechanical stress

- Coil movement.
- Rotor strikes.
- Defective rotor.
- Flying objects and foreign materials.
- Improper lugging of leads.
- Damaged leads.

### Environmental stress

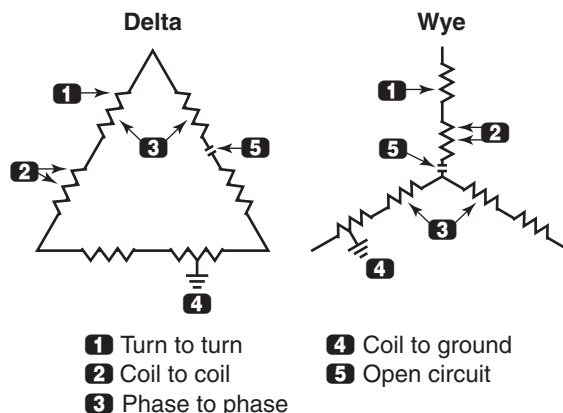
- Moisture.
- Chemical.
- Abrasion.
- Damage.

If a motor is designed, manufactured, applied, installed, operated and maintained properly, these stresses can remain under control and the motor will function as intended for many years. However, as each of these factors varies from user to user, so does the anticipated life of the motor.

## ANALYSIS OF WINDING FAILURES

This section identifies the various kinds of failure modes and patterns and relates them to the probable specific cause of the failure.

**FIGURE 1: POSSIBLE FAILURE MODES IN DELTA AND WYE STATORS**



Note: It is possible to have any combination of these failure modes.

Five key areas should be considered and related to one another to accurately diagnose the cause of a winding failure. These areas are failure mode, failure pattern, appearance, application and maintenance history.

The following is a brief discussion of each of these areas.

### FAILURE MODES

Regardless of the cause of failure, the mode of failure can be broken down into five groups, as shown in Figure 1.

In analyzing winding failures, it is difficult to determine which of the above conditions was the initial problem and which was the result of the problem. A simple example will illustrate this point.

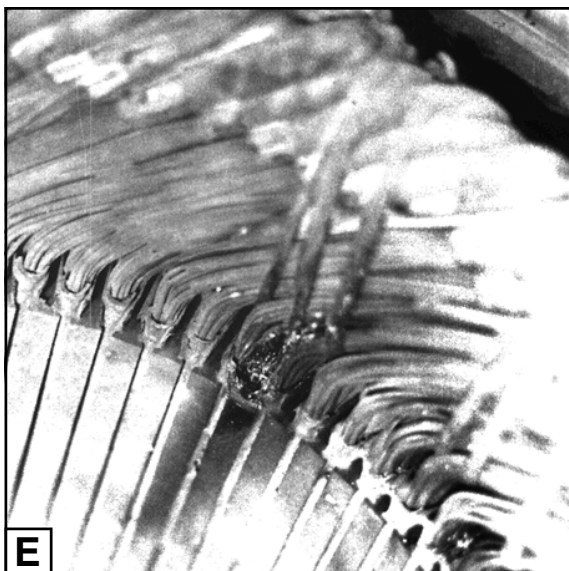
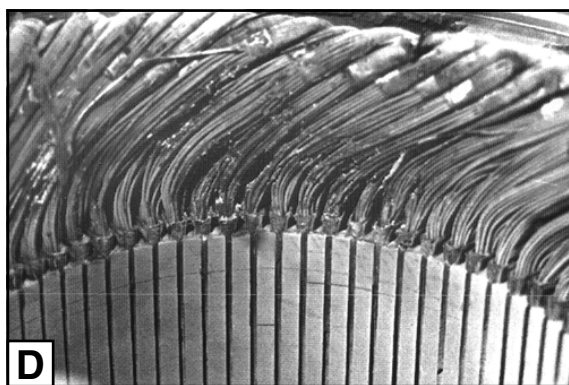
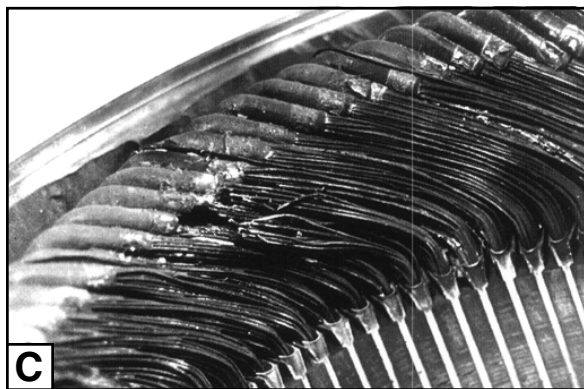
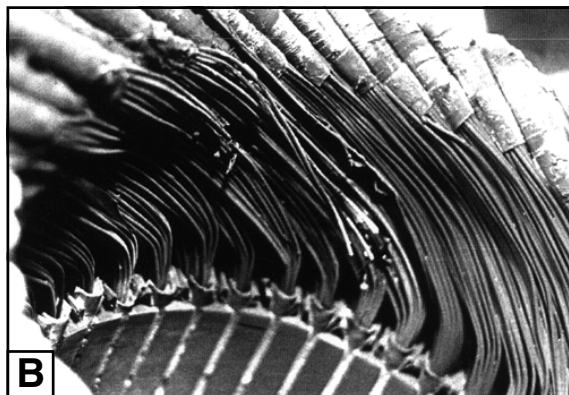
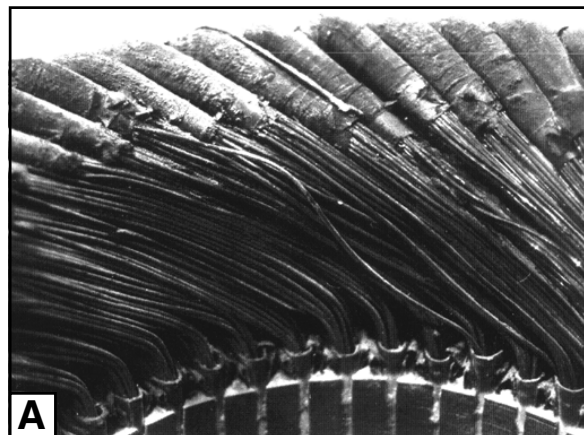
A random-wound motor is started frequently, and due to excessive coil movement sustains a minor turn-to-turn short within one coil. As this condition progresses, excessive heating is generated within the shorted coil, resulting in insulation deterioration and eventually in a partial ground through the slot liner. Depending upon the type of motor protection, the motor may continue to run. More heat would then be generated in the damaged area until the phase or ground insulation is destroyed. At this point a direct phase-to-phase fault or ground fault occurs, and the motor is

### PHOTOGRAPHS OF WINDING FAILURES

|                                         |      |                                             |      |
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| Winding movement and coil bracing ..... | 3-26 | Contaminated wire .....                     | 3-49 |
| Damaged motor leads .....               | 3-30 | Damaged wire .....                          | 3-50 |



FIGURE 2: FAILURE PATTERNS



In **Example A**, the pattern is symmetrical; each coil of each phase has been overheated. The failure mode is multiple turn-to-turn shorting. The cause of failure was excessive overheating caused by an overload condition. In **Example B**, the pattern is single-phasing; one complete phase has overheated resulting in a turn-to-turn short. The cause of failure was single-phasing. In **Example C**, the pattern is non-symmetrical without grounding; several groups of coils have been overheated. The failure mode is also multiple turn-to-turn shorting. The cause of failure was damaged wire. In **Example D**, the pattern is non-symmetrical with grounding; one coil is grounded and there is multiple turn-to-turn shorting. The cause of failure was damaged cell wall or slot insulation. In **Example E**, the ground fault can be seen. Note that the turn-to-turn short occurred 180° opposite of the grounded coil.

quickly dropped off the line.

Inspection could reveal all five modes of failure, but the turn-to-turn condition was the initial problem and the others resulted from the problem. A turn-to-turn failure is usually very difficult to recognize due to the destructive nature of the final fault conditions.

#### FAILURE PATTERNS

Closely related to the mode of failure, but to be considered separately, is the pattern of failure, which can be classified into the following four groups.

- Symmetrical with all phases overheated.
- Symmetrical with some phases overheated.

- Nonsymmetrical with winding grounded.
- Nonsymmetrical excluding grounds.

Combining the mode and pattern of failure can provide clues as to the cause of failure. The examples in Figure 2 are of units failed under controlled conditions.

In each case, the defect was deliberately inflicted. The stator was then energized, and the failure was observed and photographed.

The key point to remember is that it is absolutely necessary to tie the mode and pattern of failure together to make an accurate diagnosis. In each of the above cases, the mode of failure was turn-to-turn, but the cause of failure was different. It was the pattern of failure which better indicates the cause of failure.

### APPEARANCE CONSIDERATIONS

When coupled with the mode and pattern of failure, the general appearance of the motor usually gives a clue as to the possible cause of failure. The following checklist will be useful.

- Is the winding clean?
- What foreign materials are present?
- Are there signs of moisture?
- Has there been rotor rub or pullover?
- What is the condition of the rotor? Does it show signs of overheating? Are there any signs of stall or locking of the rotor?
- Does the rotor appear to have been turning when the failure occurred?
- Are the topsticks, coils or coil bracing loose?
- Are the bearings free to rotate? Are there signs of moisture contamination in the frame or bearing housings?
- Are any mechanical parts missing that could have hit the winding, such as nuts, washers, bolts or balancing weights? Are the rotor cooling fins or fans intact?
- Are the motor cooling passages free and clear of clogging debris?
- Is the failure 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?

When analyzing winding failures, it is helpful to draw a sketch of the winding and indicate the point where the failure occurred.

### APPLICATION CONSIDERATIONS

Usually, it is difficult to reconstruct the actual operating 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?
- Were there cycling or pulsating loads?
- Was there any chance of stall or pullout?

- What was the applied voltage? Was it balanced?
- Was the motor powered by a variable-frequency drive?
- Are there any signs of transient voltage conditions past or present?
- Have other motors failed on this application? If so, how?
- How long had the motor been running, or did it fail on startup?
- What was the acceleration time?
- Does the motor start across-the-line, at reduced voltage or on part-winding start? What was the starter timer set at?
- What was the condition of the motor controller?
- What kind of motor protection is in the system, and what tripped?
- What is the motor's environment like? Is the motor indoors or outdoors?
- Was there rain, snow or lightning just prior to the failure?
- What was the ambient temperature?

### MAINTENANCE HISTORY

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

- How long has the motor been in service? If it failed on initial startup, such things as contamination, transients, coil movement and thermal aging can usually be eliminated as a potential cause.
- During the early or initial operation of the motor, were any unusual phenomena observed? Did the load accelerate properly? Did the motor carry the load at normal speed and thermal characteristics?
- Was the winding resistance and current balanced?
- Do past maintenance records indicate any weaknesses, such as cracking or aging of the insulation system?
- Is there a past history of insulation resistance readings or previous problems with moisture and contaminants?

## SUMMARY OF WINDING FAILURES AND METHODOLOGY

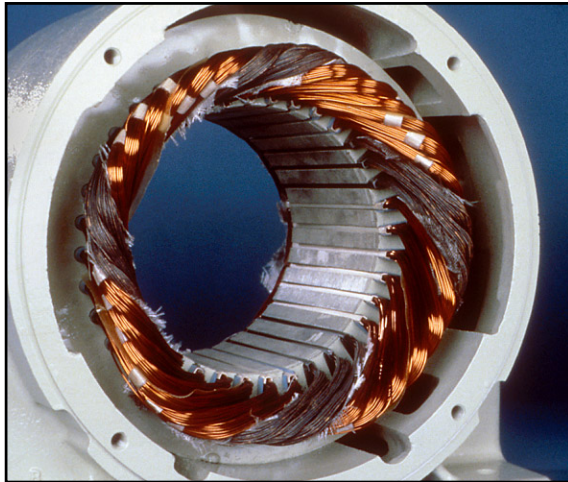
The following summary groups the various causes of winding failures in accordance with burnout patterns. These patterns are:

- Symmetrical damage pattern with all phases overheated.
- Symmetrical damage pattern with some phases overheated.
  - Single phase - 1/3 or 2/3 of winding overheated.
  - Part-winding start - 1/2 of winding overheated.
- Nonsymmetrical damage pattern (winding is grounded).
- Nonsymmetrical damage pattern (excluding grounds).

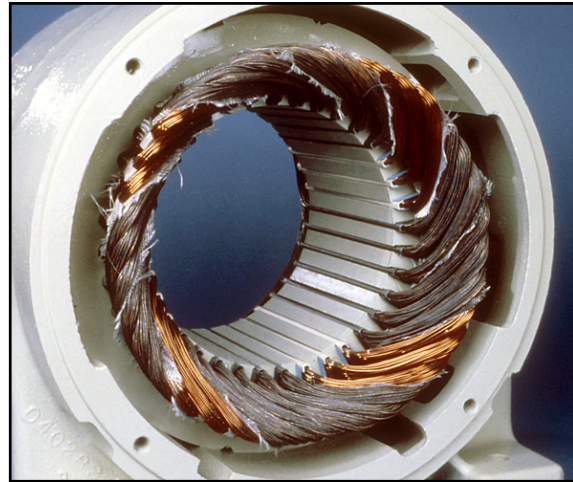
### SYMMETRICAL DAMAGE PATTERN WITH ALL PHASES OVERHEATED

In each case, an excessive amount of heat was gener-



**FIGURE 3: EXAMPLES OF SYMMETRICAL DAMAGE WITH 1/3 AND 2/3 OF WINDING OVERHEATED**

One-third of winding overheated.



Two-thirds of winding overheated.

ated symmetrically throughout the winding. The heat was either caused by too much current or the inability of the motor to dissipate the normal heat generated.

**Possible cause**

- Low or high voltage.
- Excessive loading.
- Excessive number of starts.
- Lack of proper ventilation.
- High ambient condition.
- Defective rotor or stator core.
- Complete bearing failure leading to a stall.

**Winding appearance (pattern)**

In general, each coil group will show signs of overheating evidenced by discoloration and insulation breakdown depending on the amount of heat.

**Mode of failure**

The actual failure usually occurs due to a combination of shorts and opens. The winding may also be grounded due to extreme heating in the stator slot or motor leads.

**SYMMETRICAL DAMAGE PATTERN WITH 1/3 OR 2/3 OF PHASES OVERHEATED**

These failures are usually the easiest of all to identify because of their unique patterns. Figure 3 is a typical example.

**Possible cause**

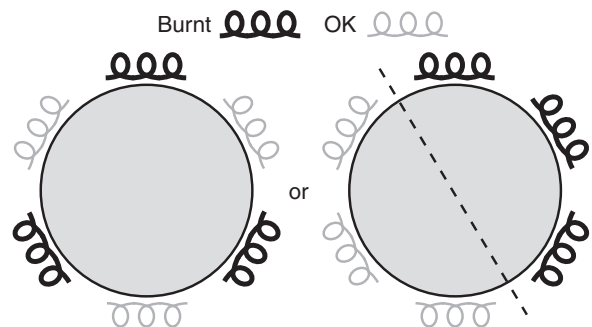
- Single-phased controls or power supply.
- Open winding lead or wire.
- Improper connection.
- Unbalanced voltage source.

**Winding appearance (pattern)**

Depending on whether wye or delta connected, either one or two phase may overheat and usually fail due to turn-to-turn shorting within the overheated phases.

**Mode of failure**

If the cause is internal to the winding, the unheated phase or phases will have an open circuit. There will usually be signs of multiple turn-to-turn shorting. Note: The motor controls and protection equipment, or some other element of the power distribution system, may also show signs of single-phasing.

**FIGURE 4: PART-WINDING START WITH EXCESSIVE START TIME**

The burnout pattern in a failed part-winding start motor varies depending on the connection scheme.

**SYMMETRICAL DAMAGE PATTERN WITH 1/2 OF PHASES OVERHEATED**

The appearance of this failure is similar to the single-phased patterns, except half the phases are overheated. With a part-winding start connection, the pattern depends on the connection method used. Some part-winding start connections divide the winding into hemispheres, others divide the winding by alternating groups (Figure 4). Still others utilize the entire winding during starting.

If one side of the winding is overheated, or if alternate groups are overheated, the motor was operated in the start mode for too long. The timer for a part-winding start starter

should switch to the run mode within 2 to 3 seconds. While various part-winding start schemes produce 50 to 70% of total current during starting, the half of the winding that is energized draws the same current it would during an across-the-line start. Since it produces about 50% of normal torque, a long acceleration period will quickly overheat half of the winding.

The double-delta or extended-delta connection method offers the advantage of energizing the entire winding during starting. The effect is similar to the starting mode of the wye-delta starter in that the windings are temporarily connected for higher-than-line voltage. This reduces the heat generated in the windings. For all part-winding start methods, the times should be limited to 2 to 3 seconds.

### **NONSYMMETRICAL DAMAGE PATTERN (WINDING IS GROUNDED)**

Depending upon the type of motor protection used, a ground failure can be the most destructive type of failure. Not only is the winding damaged, but in some cases the laminations are badly damaged due to high fault currents.

This type of failure also has the greatest potential for electrical shock and hazard to operating personnel.

#### **Possible causes**

- Internal discharges occurring in cavities of dielectric.
- Surface discharges occurring on the surface the coils.
- Point discharges occurring in a strong electric field around a sharp point or edge.
- Rotor rub against stator lamination during starting or running condition.
- Damaged insulation, slot end turns or leads.
- Transient voltage switching surges or lightning strikes.
- Contamination, moisture, chemicals or foreign materials.
- Low-voltage tracking or corona deterioration of insulation.
- Overheating in the stator slot due to excessive current or poor heat dissipation.
- Coil movement in the slot or end turns.

#### **Winding appearance (pattern)**

The winding failure is usually limited to specific spots in the stator slot and, with the exception of transient-type voltages, does not give the appearance of a general overheating condition.

#### **Mode of failure**

The primary failure mode is coil-to-ground. However, there can be signs of turn-to-turn and phase-to-phase shorting.

### **NONSYMMETRICAL DAMAGE PATTERN (EXCLUDING GROUNDS)**

Many of those items listed above, which are responsible for ground failures, can also cause a turn-to-turn failure. The determining factor is directly related to the strength or weakness of the insulation system. For example, if a stator is exposed to an extreme moisture condition, it will fail at the

weakest point in the insulation system of that particular machine. If there has been previous coil movement in the end turns resulting in some damage, the mode of failure could be turn-to-turn. If the stator slot insulation was weakened by the same coil movement, then the failure mode could be coil-to-ground. The failure mode could also be phase-to-phase or coil-to-coil. Most of these types of failures are isolated to specific areas of the winding without any definite pattern, except for those caused by transient or steep wave-fronted voltages. In these cases, the failure is usually at the beginning or the end of a phase.

#### **Possible causes**

- Rotor balancing weights come loose and strike the stator.
- Loose nuts or bolts strike the stator.
- Foreign particles enter the motor through the ventilation system and strike the stator.
- Rotor fan blades come loose and strike the stator.
- A defective rotor (usually open rotor bars) can cause the stator to overheat and fail.
- Poor lugging of connections from the motor leads to the incoming line leads causes overheating and failure.
- Broken lamination teeth or spacers break loose due to fatigue and strike the stator.
- Bearing failures, shaft deflection or rotor-to-stator misalignment cause damage to the stator.

#### **Winding appearance (mode & pattern)**

The appearance will generally be evidenced by isolated turn-to-turn shorts and opens, normally without the overall heating of the winding. However, there may be signs of excessive heating adjacent to the failed area, and frequently, a phase-to-phase fault which occurs and takes the motor off line.

## **THE NEED TO SEPARATE CAUSE AND EFFECT**

There are many cases where the damage is severe enough that it masks the original fault. Since the majority of winding failures begin as turn-to-turn failures, it is necessary to look at the entire system. Even if the damage appears extensive, the system offers clues to the root cause of the failure.

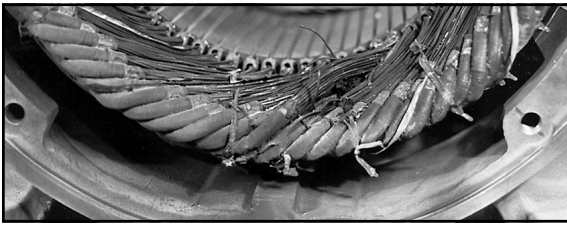
### **LINE AND GROUND FAULTS**

Often the only condition that will take a motor off line is a phase-to-phase fault. Because the fault current is so high, extreme damage is usually done to all turns and coils on both sides of the phase as illustrated in Figure 5.

This type of failure is often misdiagnosed as defective, damaged or misplaced phase paper, and indeed that is one possibility. But in many cases, it is only the result and not the cause of the failure.

If the motor protection is not sized or set properly, the motor may continue to run even after a turn-to-turn short occurs, thereby generating enough heat to destroy the phase-to-phase insulation.



**FIGURE 5: GROUND FAULTS**

Random wound



Form wound

If the turn-to-turn short occurs closer to the groundwall insulation than the phase paper, it is possible to generate enough heat to cause a turn-to-ground fault.

It can be difficult to diagnose the exact cause of failure due to the tremendous physical force and heat that is normally generated with these types of faults.

The cause of these faults is difficult to pinpoint and could be the result of any combination of the following conditions:

- Defective, damaged, inadequate or displaced phase paper.
- Coil or turn movement caused by poor varnish bond strength, inadequate coil bracing, or excessive cycling combined with elevated temperatures.
- Transient voltages.
- Excessive heating.
- Severe contamination or moisture.
- Flying objects that strike the winding.
- Abrasive materials that erode away the turn insulation.

To pinpoint these types of failures, it is normally necessary to have more information about the operating conditions of the motor. A complete inspection of the winding, particularly in those areas where damage may not have yet occurred, can reveal evidence of what might have caused the failure. Remember, the motor usually fails at its weakest link, and the “next” weakest link may be the best indication as to the root cause of failure.

This section shows a wide variety of failures that originated as turn-to-turn failures for a variety of reasons. Some were taken off line prior to a serious line fault and others ran until either a ground or phase-to-phase fault occurred.

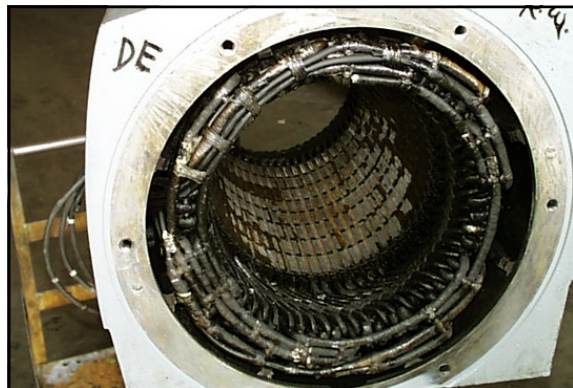
### SPECIAL THERMAL PATTERNS

Not all thermal damage to the winding insulation system fits into the traditional patterns of symmetrical overheating as shown in Figure 6.

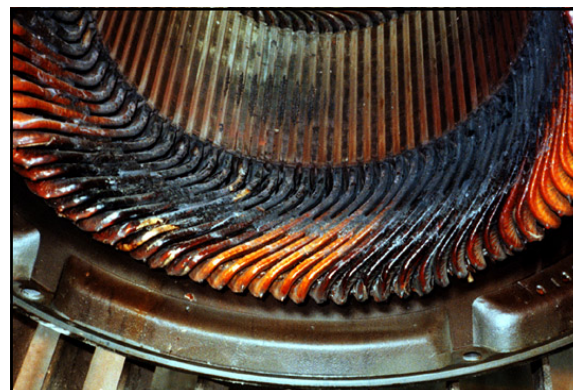
If the heating is the result of unbalanced voltage or single

**FIGURE 6: TRADITIONAL THERMAL OVERLOAD PATTERNS**

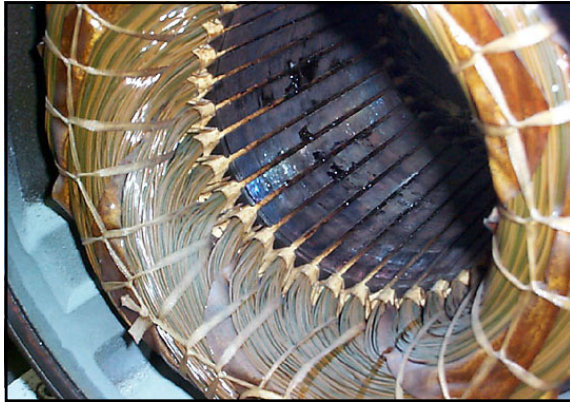
Symmetrical overheating caused by an excessive amount of equal current in each coil. The burned appearance indicates there was more heat in the core than in the winding's endturns.



Uniform overheating caused by restricted ventilation or excessive ambient temperatures.

**FIGURE 7: UNBALANCED VOLTAGE OR SINGLED PHASE PATTERN**

Damage caused by single phasing or unbalanced voltage may yield similar burnout patterns as shown above.

**FIGURE 8: THERMAL RUNAWAY IN STATOR BORE**

The extreme temperature in the stator bore broke down the varnish.

**FIGURE 9: NONSYMMETRICAL THERMAL OVERHEATING**

This type of pattern is normally caused by a defective internal connection.

phasing (the extreme unbalanced condition), the overheating pattern will appear as shown in Figure 7.

Other abnormal heating patterns can be caused by the cooling circuit of the motor not producing even cooling throughout the winding as shown in Figure 8. In these cases the damaging current could be equal in all circuits of the winding but the heating could be uneven due to the non-symmetrical cooling.

There is also the condition where the overheating, albeit usually in isolated spots of the winding, is indeed caused by turn-to-turn or turn-to-ground short as shown in Figure 9.

## THERMAL STRESS

A motor is under thermal stress whether it is running or not. However, the higher the temperature, the higher the thermal stress and the higher the likelihood of premature winding failure.

Thermal stress is made up of eight basic stresses which include:

- Thermal aging.
- Overloading.
- Voltage variation.
- Voltage unbalance.
- Ambient.
- Load cycling, starting and stalling.
- Poor ventilation.
- Circulating currents.

## THERMAL AGING PROCESS

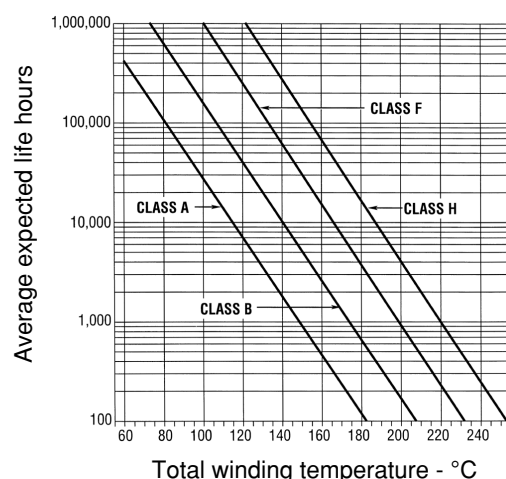
The thermal aging process is always present and ongoing, even when the motor is not running. When a motor is at rest, the rate of aging is determined by the ambient temperature to which the winding is exposed. At the other extreme, the motor is operating under service factor conditions, which is limited to 155° C (Class F) average winding temperature.

The steps in the thermal aging process are:

- Oxidation.
- Loss of volatile product.
- Molecular polymerization.
- Reaction to moisture.
- Chemical breakdown.
- Vulnerability to other stresses.

Other stresses present while the motor is running include dielectric, mechanical and environmental stresses (which may also be present when the motor is not running). At some point, thermal aging renders the winding insulation vulnerable to these stresses and the system begins to “short out” between turns or to ground, at which time the insulation system, by definition, has failed.

Figure 10 shows the temperature life curves for the standard motor winding insulation systems that are used

**FIGURE 10: TEMPERATURE VS. LIFE CURVES FOR INSULATION SYSTEMS\***

\*Per IEEE 117-1996 and 275-1992



today. These curves assume that the insulation life doubles for every 10° C decrease in total winding temperature.

### OVERLOADING

Motor manufacturers normally design a margin of safety into their motors. This is usually done by designing the motor to operate below the normal limits for a specific insulation system, or using an insulation system with a rating which is well above the operating temperature. On the latest NEMA re-rates, this was usually accomplished by using a Class F insulation system with Class B operating temperatures. Within certain limits, it can be estimated that the winding temperature rise will increase as the square of

the load ( $T \propto L^2$ ). Table 1 illustrates the impact of loading on various motor parts.

### VOLTAGE VARIATION

Voltage variation has been classified as a thermal stress because of the effect severe overvoltage, undervoltage, or unbalanced voltage have on winding temperature. These all cause increased losses in the stator and/or rotor that subsequently cause increased winding temperature and eventual failure. Table 2 shows the impact of voltage variation for typical energy-efficient motors. Remember, the thermal insulation life is cut in half for each 10° C increase in total winding temperature.

### VOLTAGE UNBALANCE

NEMA MG 1-1998, 14.36.1 offers the following explanation of the impact of voltage unbalance on motor performance and life: "When the line voltage applied in a polyphase induction motor is not equal, unbalanced currents in the stator winding will result. A small percentage voltage unbalance will result in a much larger percentage current unbalance. Consequently, the temperature rise of the motor operating at a particular load and percentage voltage unbalance will be greater than for the motor operating under the same conditions with balanced voltage."

The amount of unbalance is calculated as follows:

$$\% \text{ voltage unbalance} = 100 \times \frac{\text{Max. voltage deviation from average voltage}}{\text{Average voltage}}$$

Example: If L1, L2 and L3 = 460, 467 and 450 volts respectively, the maximum deviation from the average is 9 and the percent unbalance is:

$$100 \times \frac{9}{459} = 1.96\%$$

A 5% voltage unbalance is too high, except for very short periods of time. Frequently, the operator does not know

**TABLE 1: TEMPERATURE RISE (°C)  
VS. PERCENT LOADING**

| Size/load                                                                                                                                                         | 50% | 100% | 115% | 125% |
|-------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|------|------|------|
| <b>20 hp</b>                                                                                                                                                      |     |      |      |      |
| Avg. winding temp.                                                                                                                                                | 23  | 56   | 75   | 91   |
| Max. rotor temp.                                                                                                                                                  | 28  | 79   | 100  | 126  |
| Max. bearing housing temp.                                                                                                                                        | 15  | 37   | 49   | 62   |
| <b>50 hp</b>                                                                                                                                                      |     |      |      |      |
| Avg. winding temp.                                                                                                                                                | 28  | 75   | 102  | 128  |
| Max. rotor temp.                                                                                                                                                  | 33  | 93   | 126  | 139  |
| Max. bearing housing temp.                                                                                                                                        | 20  | 50   | 70   | 80   |
| <b>100 hp</b>                                                                                                                                                     |     |      |      |      |
| Avg. winding temp.                                                                                                                                                | 32  | 64   | 80   | 94   |
| Max. rotor temp.                                                                                                                                                  | 39  | 84   | 107  | 127  |
| Max. bearing housing temp.                                                                                                                                        | 21  | 41   | 51   | 60   |
| <b>200 hp</b>                                                                                                                                                     |     |      |      |      |
| Avg. winding temp.                                                                                                                                                | 31  | 69   | 80   | 108  |
| Max. rotor temp.                                                                                                                                                  | 39  | 98   | 130  | 160  |
| Max. bearing housing temp.                                                                                                                                        | 17  | 37   | 48   | 58   |
| IEEE 841 TEFC, 4 pole, 460V                                                                                                                                       |     |      |      |      |
| <b>Notes:</b> Bearing housing temperature is the drive end bearing. Maximum rotor temperature is in the rotor bar. These temperatures are the rise above ambient. |     |      |      |      |

**TABLE 2: IMPACT OF VOLTAGE VARIATION ON TEMPERATURE RISE,  
FULL LOAD AMPS AND EFFICIENCY FOR TEFC ENERGY-EFFICIENT, 4-POLE MOTOR**

| HP at full load | Voltage     |                |            |               |                |            |             |                |            |
|-----------------|-------------|----------------|------------|---------------|----------------|------------|-------------|----------------|------------|
|                 | -10% (414V) |                |            | Normal (460V) |                |            | +10% (506V) |                |            |
|                 | Temp (° C)  | Full load amps | Efficiency | Temp (° C)    | Full load amps | Efficiency | Temp (° C)  | Full load amps | Efficiency |
| 10              | 66          | 13.5           | 90.0       | 56            | 12.3           | 91.4       | 55          | 12.0           | 91.5       |
| 20              | 84          | 27.2           | 90.4       | 70            | 24.3           | 91.8       | 67          | 24.3           | 92.1       |
| 50              | 84          | 64.4           | 91.9       | 69            | 57.1           | 93.1       | 62          | 52.6           | 93.6       |
| 100             | 82          | 125.8          | 94.2       | 72            | 113.1          | 94.8       | 69          | 106.8          | 94.9       |
| 200             | 90          | 254            | 94.9       | 77            | 228            | 95.5       | 74          | 215.3          | 95.7       |

Saturation is the key to actual results. EPACT, U-frame and other conservative designs (low flux density) will perform better at +10% voltage compared to a highly-saturated design (IEC).

what the actual load is, nor can the operator control it. A 3% unbalance will result in at least an 18° C increase in winding temperature, reducing the thermal life of the insulation to one-quarter its original value.

#### Rule of thumb

The percent increase in temperature rise is about twice the square of the percent voltage unbalance.

The impact of increased heating in the rotor by the negative sequence voltage may also affect the bearing and lubrication life.

It is recommended that voltage unbalance be held to no more than 1%.

### Winding damage caused by single-phased condition

There are a variety of situations that can result in what is commonly called a single-phased condition — the ultimate unbalanced voltage scenario. The problem can originate in the following areas:

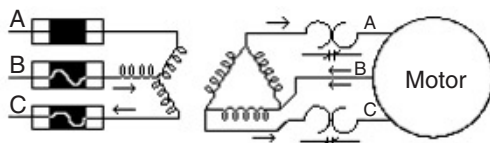
- On the primary side of the distribution transformer.
- At the transformer.
- On the secondary side of the transformer.
- In the motor controls.
- At the line to motor lead connections.
- Inside the stator winding.

To assign responsibility and to properly correct this situation, it is important to properly identify the source of the single phase. It should also be noted that there are a number of control devices that will sense this condition and take the motor off line before serious damage occurs. The rotor can also be damaged during this condition due to severe overheating caused by the non-symmetrical component that exists due to unbalanced voltage.

Depending on how the motor is connected internally, the motor may run and even start while single-phased depending on the amount of load the motor is carrying.

### Five cases where three-phase electric motors may run single phased

If a single phase conductor supplying a 3-phase running motor is opened, the motor usually continues to run as a single-phase machine. But current drawn by the operating phase is greater than design conditions for the winding. The operator may not discover single-phasing until the winding is damaged. Under some conditions, the operator may not recognize it at all. Preventing trouble is simple: Use overload protectors in all three phases.

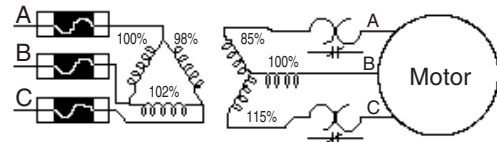


Typical single-phase condition

#### 1. Typical single-phase conditions

The motor-circuit fuse blows or circuit opens because of burned connection, worn switch contacts, etc. and the motor continues running. Two overload

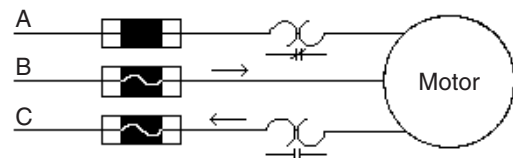
relays are sufficient to protect the motor. Suitable dual-element fuses may be used instead of relays. This trouble often occurs because relay heaters selected are too high, or have been tampered with or neglected. Check relays regularly.



Open primary phase

#### 2. Open primary phase

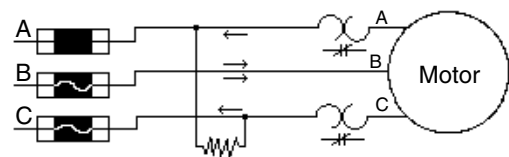
Where transformers are connected wye-delta or delta-wye and have an isolated neutral, they can cause severely unbalanced three-phase current in a motor. Current in one phase sometimes runs as much as twice that in the other phases. If the high phase lacks relays, like phase B above, the motor keeps on running until the winding is damaged. On starting attempts, damage may be done before the overload relays trip.



Unbalanced primary phase

#### 3. Unbalanced primary voltage

Delta-wye, wye-delta transformers can also be a source of trouble. A 2% voltage unbalance in one phase of primary can cause 15% overcurrent in one motor phase. If this phase is the unprotected one of a heavily-loaded motor, the winding can be damaged. Voltage unbalance isn't rare, so three relays are in order where you use this transformer connection.



Single-phase load

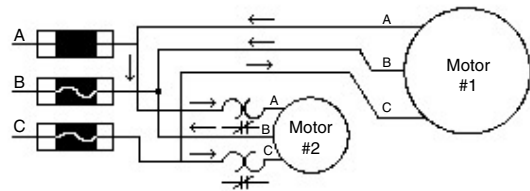
Shunted single-phase load

#### 4. Shunted single-phase load

The shunted single phase-load can produce unbalanced currents in a motor when one line is opened. Depending on the magnitude of the shunted load and the load on the motor, one phase may carry current high enough to damage the winding. This is another case where detection may not be easy, so avoid



trouble with a third relay. Most modern starters provide plenty of space for easy installation of third relay.



Paralleled three-phase motors

5. Paralleled three-phase motors

Paralleled three-phase motors that are supplied from the same power source can exchange current under some circumstances when one line is open. The larger motor (Number 1) will supply unbalanced three-phase current to the smaller motor (Number 2). The smaller motor may be able to start, but one phase will carry overload while the other two lines will carry almost normal current or lower. Again, damage may result to the unprotected phase.

AMBIENT

Most industrial motors are designed to operate in a 40° C ambient. There are several key points to consider:

- Do not assume average ambients; confirm that a 40° C limit is acceptable. One hot month with a 50° C ambient could damage the bearing lubricant even though the Class F winding would still function satisfactorily.
- Most of the time, the ambient consists of the heat generated by the heating or cooling system surrounding the motor (this would include the sun or lack thereof). However, there are times when there are other heat sources in close proximity to the motor that will have a significant influence on the surrounding ambient. The bearing and lubrication system is affected by these conditions.
- Recirculation commonly occurs when a motor operates in a confined space. Air passing through or over the motor is heated and mingles with other air inside the confined area causing the ambient temperature to rise. The already-warmed air then passes through or over the motor again creating a vicious cycle. Poor positioning of duct openings, such as on a weather-protected enclosure, can also result in recirculation.

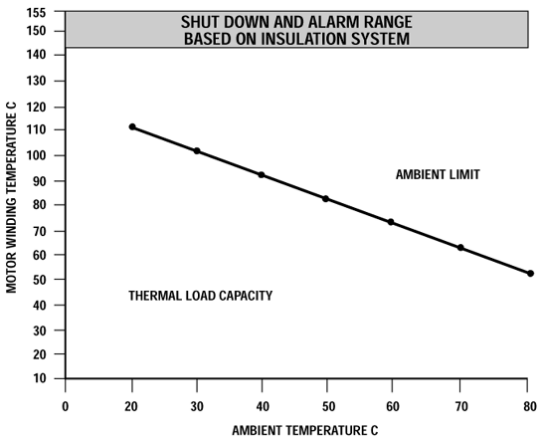
Items that could contribute to higher than normal ambient include coupling or belting losses, the driven equipment, the process, piping, or plumbing and other machines in close proximity. Typical belting systems are in the 95% efficient range which means that their losses could be as high as those of the motor.

It is best to think of the ambient temperature as the sum of all heat sources including recirculation, that are influencing the motor intake cooling air.

Figure 11 illustrates the allowed temperature rise of the stator winding and bearing systems for changes in the total ambient to which the motor is exposed. Note that both systems must be considered.

FIGURE 11: THERMAL CHANGES

Winding thermal changes vs. ambient



Bearing temperature vs. ambient

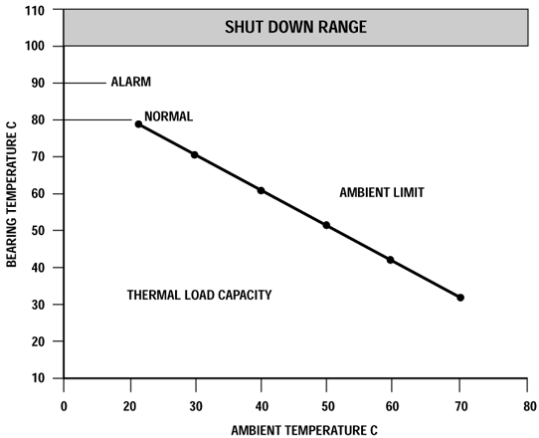


TABLE 3: EFFECT OF AMBIENT ON INSULATION LIFE

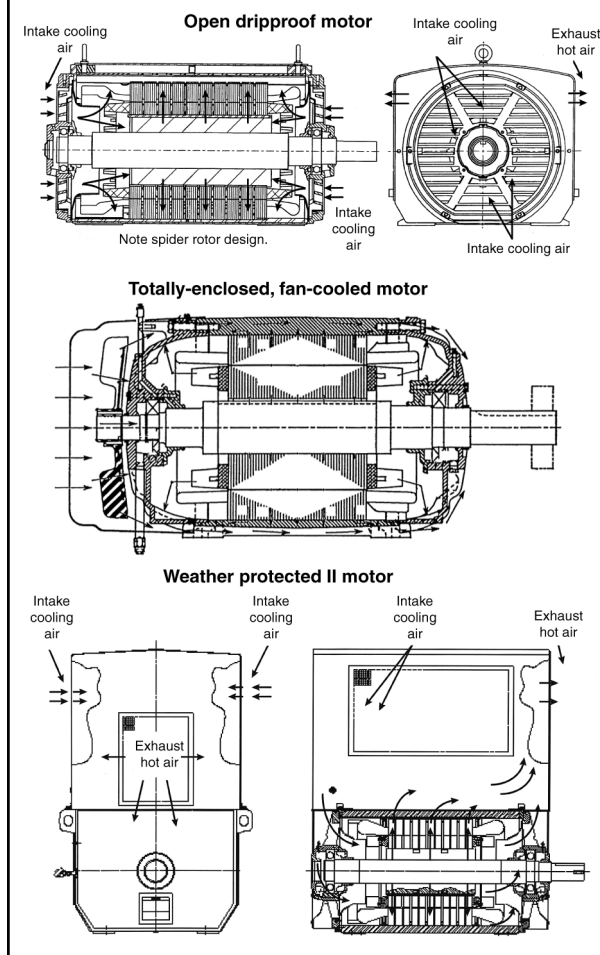
| Ambient (° C) | Insulation life (hours) |
|---------------|-------------------------|
| 30            | 250,000                 |
| 40            | 125,000                 |
| 50            | 60,000                  |
| 60            | 30,000                  |

Class F insulation with Class B rise

Table 3 illustrates the effects on the insulation life when the allowed temperature rise of the stator winding is exceeded.

LOAD CYCLING, STARTING AND STALLING

During starting, a typical motor will draw anywhere from five to eight times the normal current required to run under full-load conditions. If a motor is subjected to repeated starts within a short period of time, the winding temperature will rapidly increase due to the high starting current.

**FIGURE 12: EXAMPLES OF AIRFLOW THROUGH MOTOR ENCLOSURES**

Depending on the specific application, each motor has its own limitations. For example, two motors are identical with one driving a centrifugal water pump and the other a high-inertia flywheel. The motor used to drive the pump could be started many more times per hour than the one driving the flywheel and still remain within safe thermal limits.

If there is some question as to how many starts can be safely made, check with the motor manufacturer. To save time, be sure to supply the specifics of the load such as inertia, weight, starting load speed torque curve and starting cycle.

Another effect of thermal cycling is to cause expansion and contraction of the insulation system. Over an extended period of time, insulation materials will tend to become brittle and crack. The insulation designer must be sure the materials are flexible enough to withstand this movement without cracking, and yet not so flexible as to cause a failure due to mechanical forces.

If the motor stalls or fails to come up to speed, the heating will be greatly accelerated.

### POOR VENTILATION

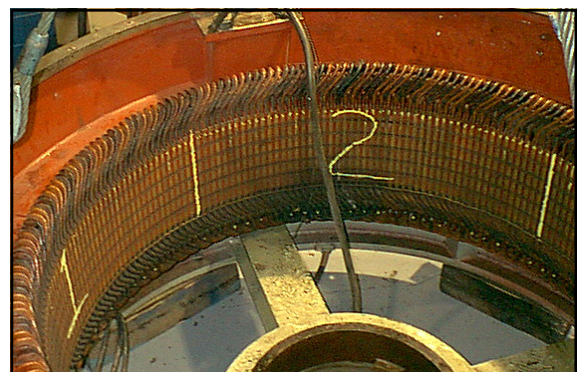
Heat generated in the rotor and stator is dissipated by

conduction, convection and radiation. Anything that obstructs the flow of air through or over the motor, or that impedes the radiation of heat from the motor, will cause an increase in winding temperature. Figure 12 illustrates the airflow for several motor enclosures. Anything that upsets this flow of air may cause the winding temperature to increase.

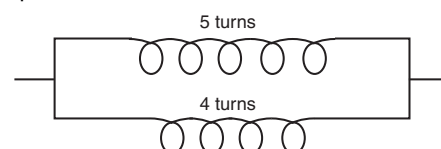
### CIRCULATING CURRENTS

Within a winding, there are cases where circulating currents contribute to the overall motor current and heating, without contributing to the torque developed to do work. These harmful currents are present when a winding is interleaved, when an incorrect sequence is selected for a motor with odd grouping or when each phase does not have the same number of total turns. A large motor with damaged coils "cut out" of the circuit will often have circulating currents.

In theory, parallel paths that do not have balanced voltage can develop circulating currents. The value of the circulating current is equal to the voltage difference divided by the circuit impedance. (Circuit impedance = stator resistance + leakage reactance of the stator slot.) This circulating current adds to the line current, producing  $I^2R$  losses equal to the current squared. The effect is to reduce efficiency and increase winding temperature. A better-known example of circulating currents is the two-speed, two-winding motor that has been connected using the incorrect jumpers (adjacent versus skip pole).

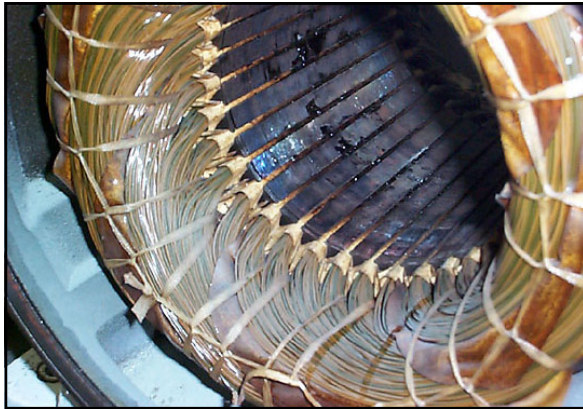
**FIGURE 13: CIRCULATING CURRENTS**

Parallel circuits must have an equal number of total turns. The motor above was connected incorrectly. With 96 groups and 32 poles, the stator had 24 groups of 3 and 72 groups of 2. It was grouped incorrectly, and connected 2Y. The result: 5 groups of 2 coils were paralleled with 3 groups of 3 coils and 3 groups of 2 coils [ $5 \times 2 \neq (3 \times 3) + (3 \times 2)$ ]. The result was high circulating currents with extreme heating of the circuit containing 5 groups of 2 coils.

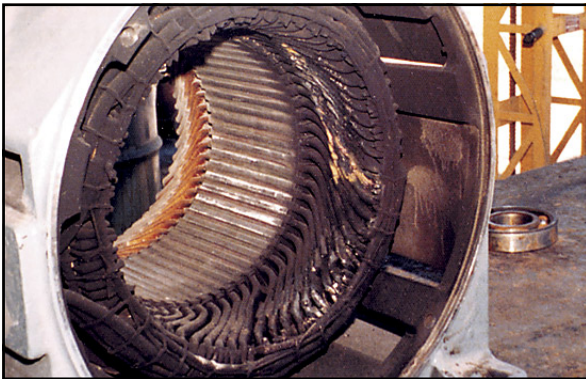




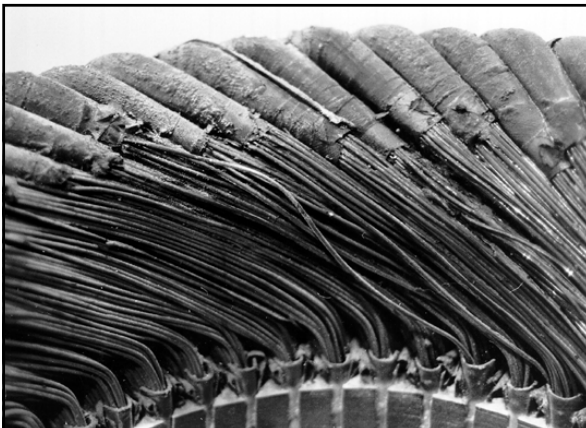
## OVERLOADING



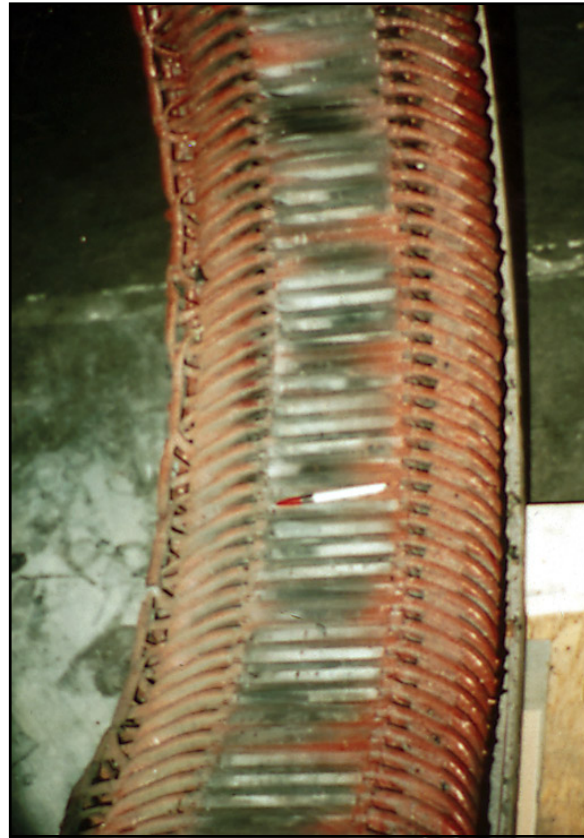
This winding appears to be fairly new, as evidenced by the condition of the coil extension. The varnish bubbled from the bore and the overall heated appearance of the stator iron, indicate the rotor was the heat source. A shorted stator core will give a similar appearance, except the wedges would also be uniformly heated. Note the melted ties, evidence that the coil extensions were hot.



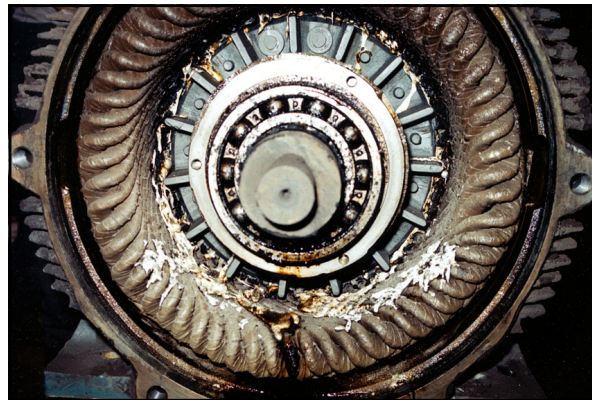
This is a typical overheating pattern for a form wound stator where all coils have experienced similar thermal damage.



Excessive current in each phase overheated the winding which shorted turn-to-turn and then phase-to-phase.

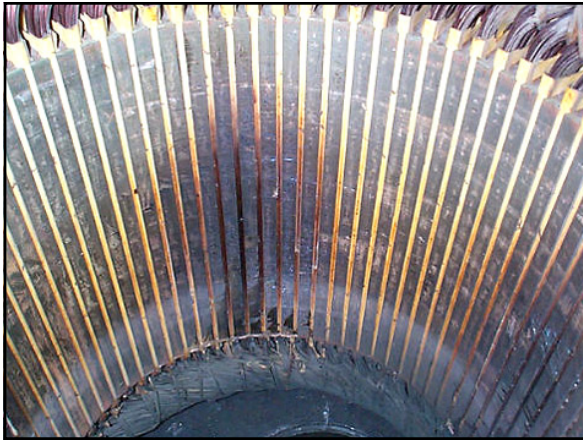


In the bore of this synchronous motor, the slots spanned by each rotor pole show evidence of heat, while the slots between poles do not. Clearly, the rotor was stationary when this occurred. An attempt to start the motor with too much load is the probable cause of this pattern. Examples would include a loaded ball mill, a common synchronous application.

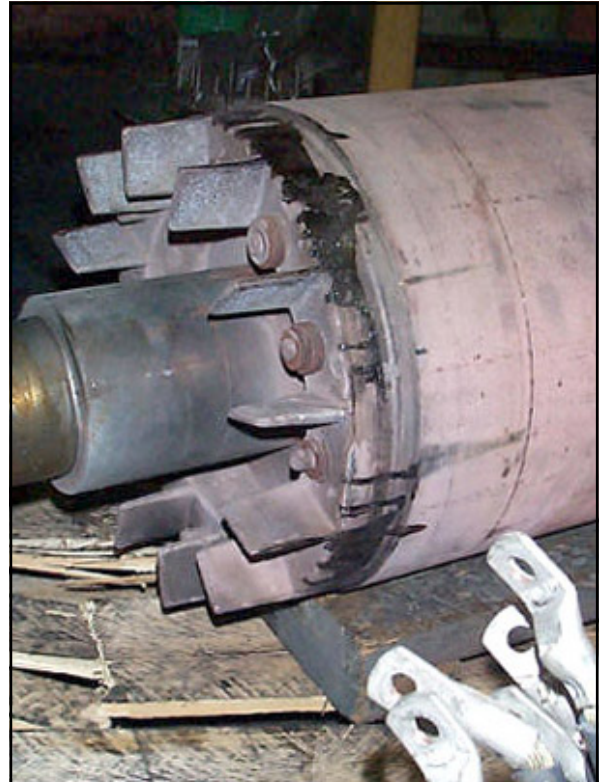


This motor failed to accelerate to full speed causing the rotor bars to overheat and eventually melt. The thermal limit of the rotor bars was less than that of the stator winding, however, the windings were still damaged.



**UNBALANCED VOLTAGE**

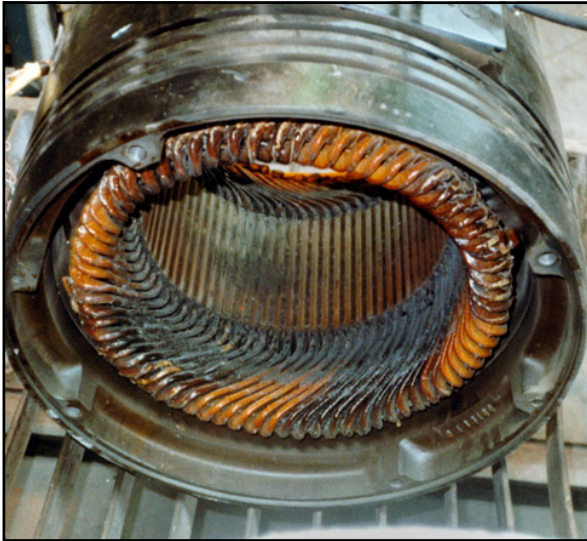
Unbalanced voltage can cause symmetrical overheating of the rotor and uneven heating in the stator. Depending on the source of the unbalanced voltage, the stator will have either one or two phases that show signs of overheating. The end turns may not show signs of overheating since they are cooler than the winding in the slot, if there is adequate airflow. In this example, the voltage unbalance was severe enough that it eventually led to a ground failure in the slot due to overheating of the rotor. The winding itself shows no damage except in the 4 poles around the stator, in the center. The center of the rotor was the hottest spot due to the unbalance.



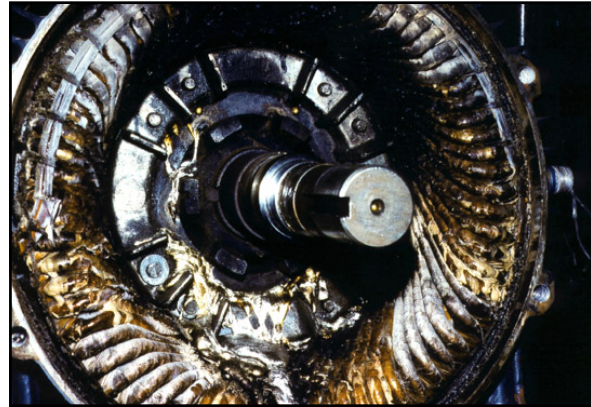


## SINGLE PHASED

In the most extreme cases of unbalanced voltage, damage may occur in seconds. Whether form coil or random wound, the resulting pattern is distinctive. Depending upon the design, the thermal “weak link” may be the rotor.



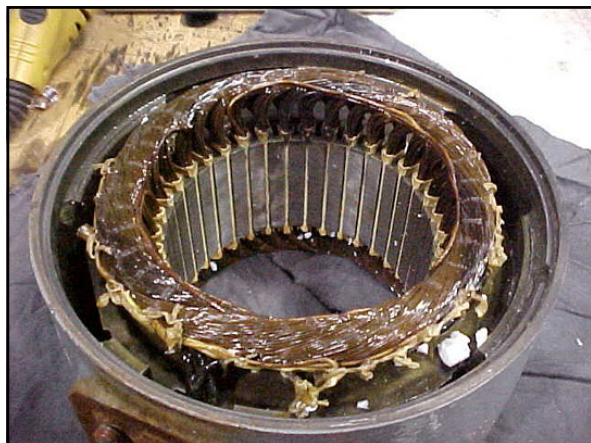
This is a multispeed winding where two-thirds of the groups are burned in the single phased condition. It is also possible that this winding was connected for a part-winding start and was left in the starting mode too long.



The windings above are wye connected and failed during starting. One-third of the groups are burned indicating the windings were subject to single phasing. The heating was so severe that the aluminum rotor melted. The evidence of “flung” aluminum indicates that the motor was running for a period of time before it failed.



This single-phased condition resulted from an internal open. A broken jumper, a wire broken at the star point or a corner of a delta connection could each result in a single-phased condition. Not all single-phased failures result from fuse or contactor problems. If a customer insists that the fuses are intact and finds no other evidence of a single-phased condition, check the connection for evidence of open circuits.



This stator appears to be single phased, but upon closer inspection it was found to be a nine lead motor that was misconnected.

## ELECTRICAL STRESS

Electrical stresses can range from low-voltage turn stresses to high-speed, high-voltage transients. Electrical stresses include:

- Dielectric aging.
- Transient voltages.
- Partial discharge (corona) and tracking.

Insulation inadequacies or defects are mechanical in nature but can also lead to electrical stresses.

It is difficult to differentiate between cause and effect when assessing the specific cause of a winding failure associated with electrical stress. Mechanical, thermal and environmental stresses can all break down an insulation system, both separately and collectively. In addition, electrical stress can cause breakdown whose appearance may resemble that of other stresses. Often, the only practical way to isolate the electrical stress is to eliminate other stresses as the cause of the failure.

Voltage variation and unbalanced voltage are not being considered as electrical stresses for this discussion. Instead, they are treated as thermal stresses based on a rule of thumb: the percent increase in temperature rise is about twice the square of the percent voltage unbalance.

### DIELECTRIC AGING

All insulation materials have a predetermined life cycle. Increased levels of electrical stress can result in an insulation system whose life expectancy is greatly reduced. This process is similar to the thermal aging process and occurs at a predictable rate unless the stress reaches extreme levels; then the failure is greatly accelerated. Improper selection of insulation materials can hasten this process as can material incompatibility.

### TRANSIENT VOLTAGES

A transient voltage is defined as an unexpected change in voltage, such as a spike, which can be destructive to a motor winding. Transient voltages may occur, reducing winding life through premature failures such as turn-to-turn or turn-to-ground.

During recent years, substantial evidence has shown that a significant number of motors are exposed to transient voltages. Transient voltages include:

- **Line-to-line, line-to-ground, multi-phase line-to-ground and 3-phase faults:** These can cause overvoltages that can reach 3-1/2 times their normal peak values with extremely short rise times.
- **Repetitive striking** where the system is ungrounded and an intermittent ground on the circuit occurs causing high voltage oscillations and multiplication.
- **Current limiting fuses:** Where current interruption occurs, stored magnetic field energy in the circuit inductance is not zero, causing voltage oscillations or resonance.
- **Rapid bus transfers:** When a motor is de-energized, the electromagnetic field in the stator may take several seconds to decay. During this time, the field synchro-

nizes to the decelerating rotor. If an attempt is made to restart the motor before the field decays, the combined voltages will be at greatly different frequencies. The result can be an RMS voltage in excess of 150% of line voltage.

- **Opening and closing of circuit breakers:** This starting surge is continually present. An impulse wave can be produced that travels in a circuit at a specific rate. When a contact closes, arcing occurs due to a potential difference at the contacts. This arc influences the voltage wave entering the motor circuit. Surges can also occur when the breaker contacts do not engage simultaneously and bounce or vibrate, causing an irregular voltage wave of a surge variety (similar to repetitive restriking). Use of high-speed motor control devices, such as vacuum contactors, can cause steep surges when "current chopping" is produced by the opening of the contacts in a vacuum with no arc to sustain the current. Some devices have been shown, as discussed above, to produce fast-rising surges when the contacts slowly close in on each other.
- **Capacitor switching:** When capacitors are used for power factor improvement, surges can develop when they are switched off and on. Extremely high voltage surges can occur during instances where a motor and capacitor are switched off together, disconnecting them from the power source. Magnitudes of the surge are dependent on the value of the capacitance. Capacitors switched with the motor are a source of excitation at the motor terminals and high voltages are induced. This problem is usually great on high inertia drives where speed reduction is a factor for continued excitation.
- **Insulation failure:** When a breakdown or puncture of the insulation occurs at points other than at the motor, impulse surges can develop. Such a breakdown, in high-voltage designs, can cause surge voltages that will exceed 3 times normal line-to-ground voltages in a system that is not solidly grounded.
- **Lightning:** Voltage surges can be caused by lightning through direct contact of a lightning strike or by induction by a nearby strike. These voltage waves propagate along the line with the magnitudes of the crest a function of the lightning current and rise times dependent upon the surge impedance of the system.
- **Variable frequency drives:** Depending on the specific design, it is possible during starting and stopping, or even during the switching of each half-cycle, to introduce voltage spikes. Estimates of the magnitude of these surges normally range from two to five times the normal line-to-neutral crest voltage with rise times ranging from 0.1 to 1 microsecond. Winding failures caused by these transients usually appear as turn-to-turn or turn-to-ground faults. Frequently the cause is confused with some other mode of failure. The motor manufacturer normally does not have sufficient application information available to determine when to include surge and lightning protection on the motor. However, they can determine the surge limits which the motor can withstand and still give satisfactory life.



**FIGURE 14: EXAMPLE OF PARTIAL DISCHARGE (CORONA)**



Adjacent coils of different phases are in close contact. Properly-spaced coils have additional insulation: the air gap between them.

#### **PARTIAL DISCHARGE (CORONA) AND TRACKING**

Air is an insulator and it can break down like any other insulator. Partial discharge occurs when the voltage is high enough that pockets of air reach their dielectric limit. As the insulation (air) breaks down, two things happen:

- Arcing takes place, which erodes or etches the adjacent coil insulation.
- The air breaks down (ionizes) and releases ozone, which chemically attacks the insulation.

It takes only about a 0.040" (1 mm) void for partial discharge to occur. Smaller voids are not large enough for destructive arcing to occur. Large gaps between coils are like thicker insulation — the corona inception voltage is significantly raised. Partial discharge is most destructive when coils are loosely fitted in the slots, since damage is directly to the insulation between the conductor and ground potential. It can also occur on the coil extensions, which is why high-voltage windings use gradient tape to provide a path back to ground to control partial discharge. Lack of gradient tape on the end turns can result in surface tracking damage to the insulation or arcing between coils that are poorly separated.

There are three basic areas where partial discharge occurs. The areas are:

- Internal discharges occur in cavities of the dielectric.
- Surface discharges occur on the surface of the coils.

#### **INSULATION INADEQUACIES OR DEFECTS**

The integrity of the stator winding is directly related to the quality of the insulating materials separating the magnet wire from the stator laminations and other mechanical parts. If any of the insulating materials are inadequate, defective or damaged, there is a risk of a winding failure which can appear as shorts between adjacent turns or ground.

Common insulation inadequacies or defects include:

- Improper cell wall or slot insulation.
- Inadequate phase insulation.
- Poor coil bracing.
- Inadequate sleeving.
- Poor winding treatment.
- Damaged lead wire.
- Damaged magnet wire.
- Loose magnet wire.
- Irregular laminations (shorts or burrs).

Insulation inadequacies are discussed in further detail beginning on Page 3-46.

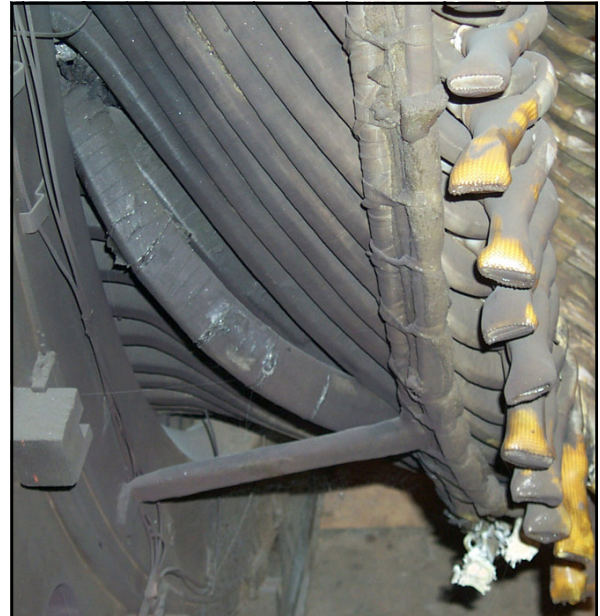
- Point discharges occur in a strong electrical field around a sharp point or edge.

Partial discharge is normally associated with insulation systems for applications of 6900 volts or higher, except in the case of high-speed insulated gate bipolar transistor (IGBT) inverters. These conditions are magnified by the presence of elevated temperatures, excessive moisture, contamination, voids and insulation flaws.

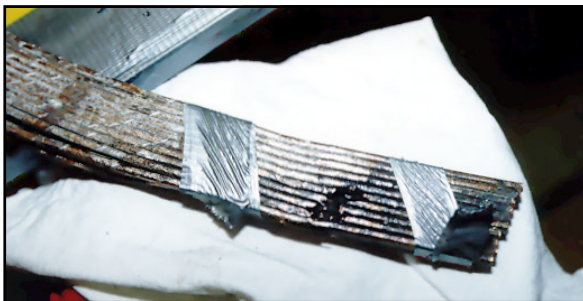
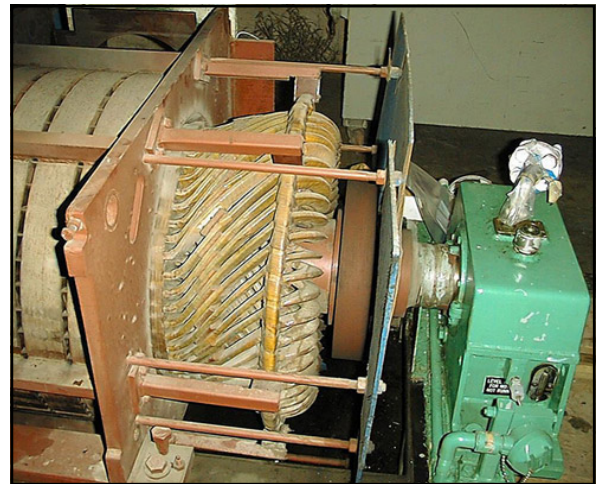
Partial discharge should be kept within the bounds which will assure adequate motor life. However, it is also important keep the motor clean and cool to minimize the effects of partial discharge.

Partial discharge tracking differs from partial discharge that occurs within voids in the insulation. When coils of different phases are too closely spaced, surface discharge can take place. A similar phenomenon, also referred to as tracking, can happen when a sealed insulation system is top-coated with material of a lower dielectric quality. Although it is unusual, capacitance between the two insulations can result in tracking between them.

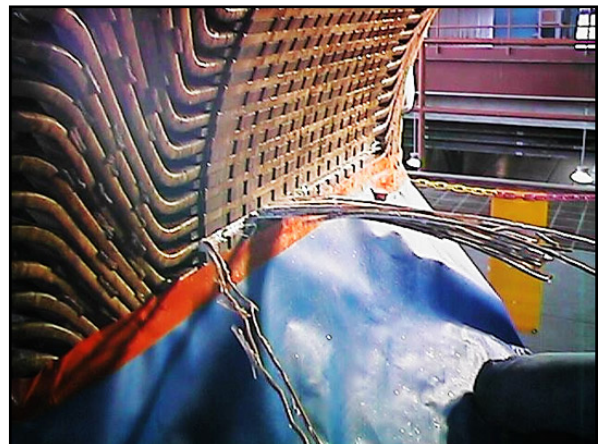
Point discharge was the justification for the use of "loop" or "horseshoe" series rather than stub series. The use of stub series is now common for voltages up to 7200 volts AC with an adequate insulation system.

**RECLOSURE/TRANSIENT VOLTAGES**

Whether caused by a rapid bus transfer, lightning, over-correction of power factor or “other,” the result of a high-voltage transient often looks like sabotage. A 200% overvoltage may result in 30 to 40 times line current, with  $(30 \text{ to } 40)^2$  increase in mechanical force acting to displace the coils. In many cases the damage is most noticeable at the lead coils. The extremely high stresses involved cause the winding to fail at the weakest point. The more sturdy the coil blocking, and the shorter the coil extensions, the more resistant a winding is to this type of failure.

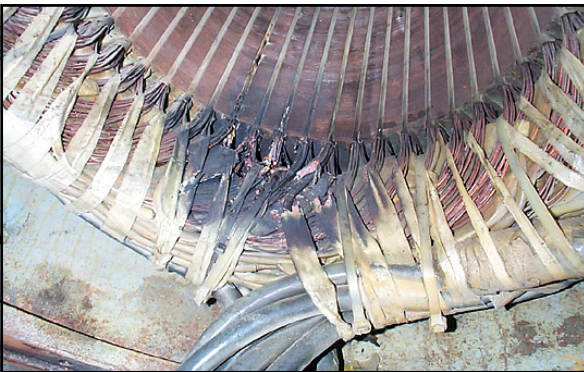
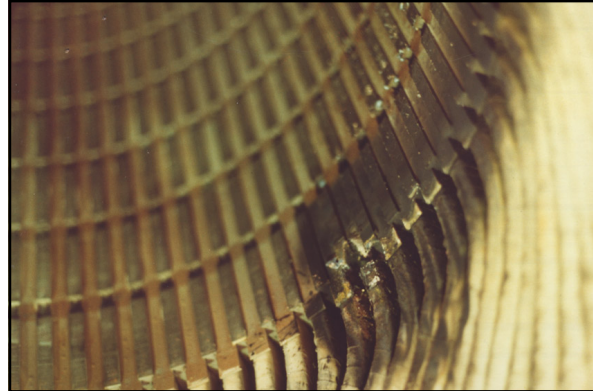


As these photographs show, sometimes the damage penetrates the coil insulation.

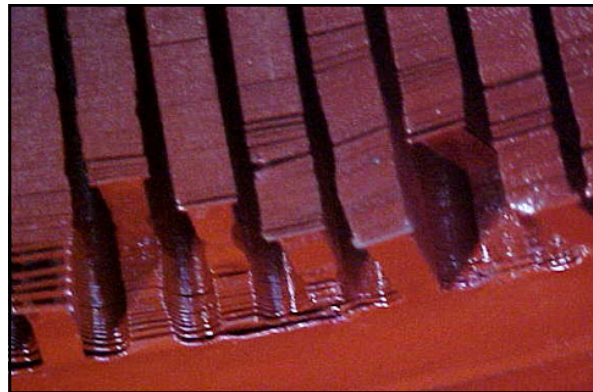
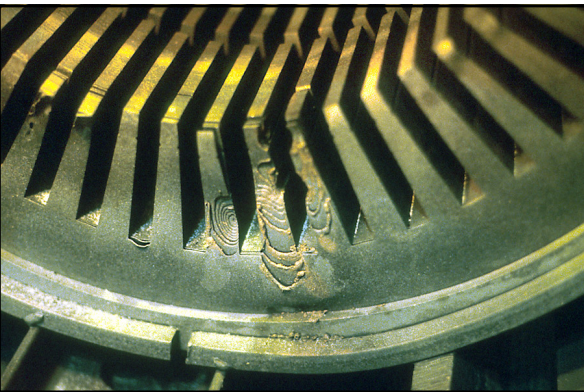




## GROUNDS AND SHORTS



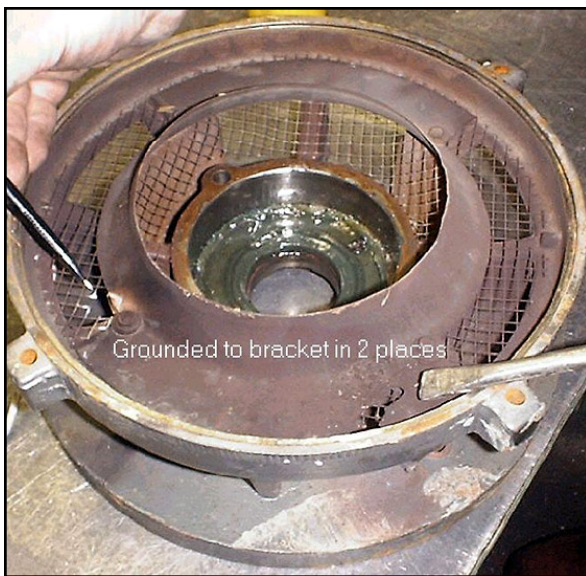
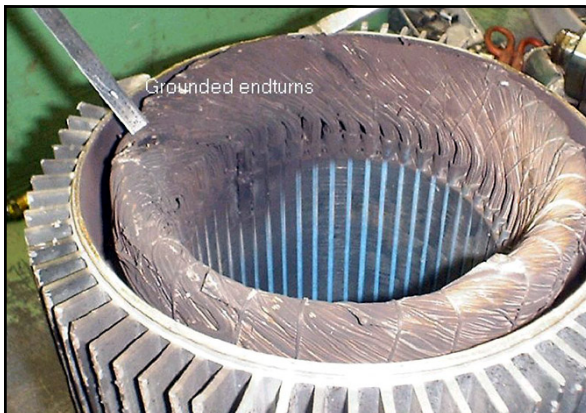
The end of each slot acts as a fulcrum where force from the flexing coil is concentrated. Not only is this a point of mechanical stress, but it is also subject to electrical stress as ground potential. The combination of electrical and mechanical stress make this the most likely place for ground failures. Eddy-current losses are one result of ground failures in the laminated core, as laminations are fused together, sometimes with copper from the failed windings. Failure to clear these shorted regions results in hot spots in the core, which shorten the insulation life of a replacement winding.



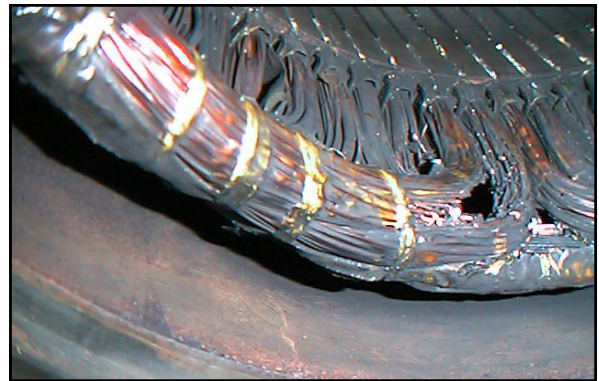
When a winding fails in the same physical area as a previous failure, there is a good possibility that lamination damage was not corrected during the previous repair. Damaged or shorted laminations should be cleared by rotary burr whenever possible. Removing large portions of teeth (right) will increase the flux density in adjacent areas and increase stray losses.



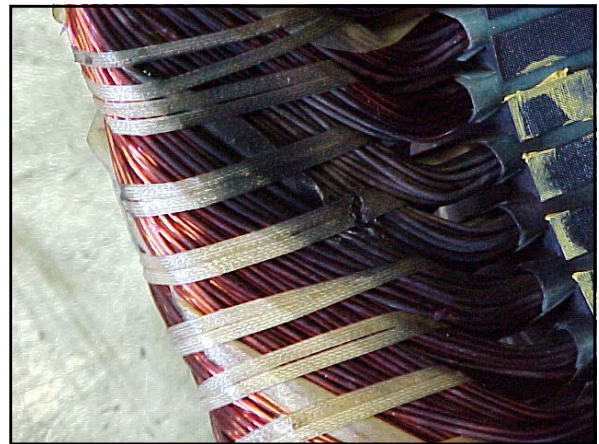
## GROUNDS AND SHORTS



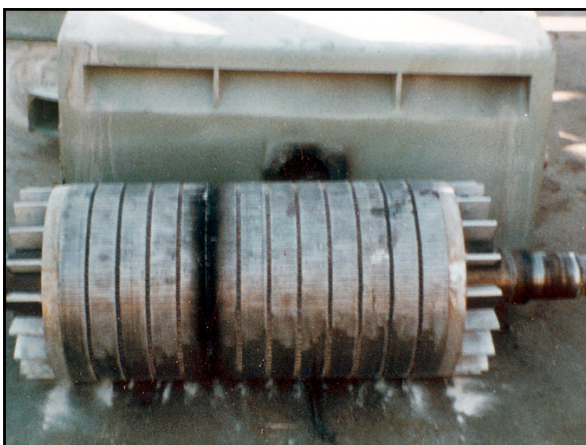
This winding failed as a result of direct contact with the air baffle.



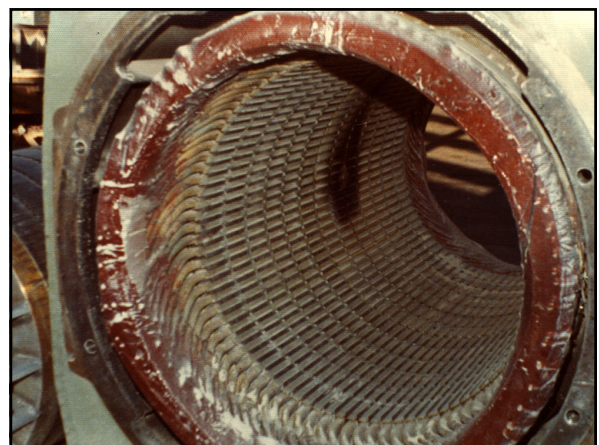
A turn-to-turn short is visible. The short expanded to a coil-to-coil failure.



This is a turn-to-turn short in the first (or last) coil in the group. This failure should be examined; if the coil is connected to a line lead, this could be a result of a voltage spike from a pulse width modulated (PWM) drive.



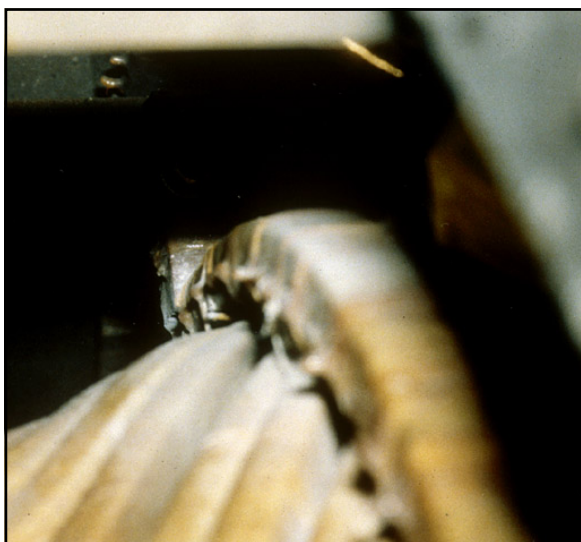
This rotor appears to have overheated, however, inspection of the stator shows that the thermal damage was the result of a ground in the stator while the rotor was rotating.



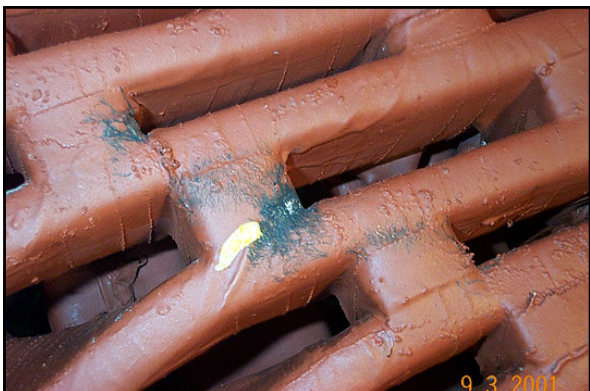
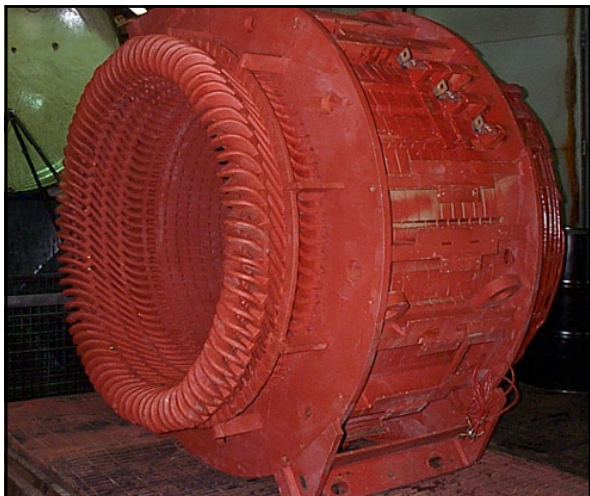


**PARTIAL DISCHARGE (CORONA)**

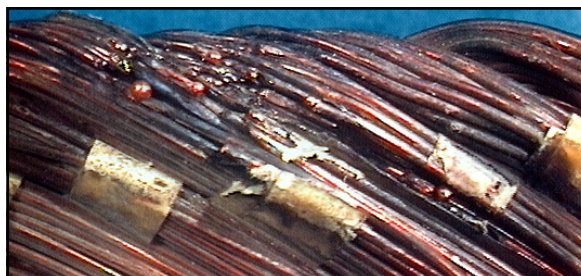
Adjacent coils of different phases are in close contact. It is common for coil manufacturers to use less insulation on the coil ends than on the slot sections where ground potential is a concern. Properly-spaced coils have additional insulation: the air gap between them. Partial discharge tracking is usually evident as a white residue from the continual electrical discharge that occurs.



At first glance, this looks like partial discharge. Closer inspection revealed poor bracing support of the coils. Felt padding or use of surge rope would eliminate this problem.



Evidence of partial discharge, referred to as "greasing" for obvious reasons.



This turn-to-turn damage was caused by a pulse width modulated inverter with a long connection between the motor and the inverter.

## MECHANICAL STRESS

Mechanical stress encompasses a broad range of forces, in addition to those generated by the winding. Any of them can exert enough stress on the insulating materials to cause damage to the winding.

Mechanical stress can include:

- Winding movement.
- Damaged motor leads.
- Improper rotor-to-stator geometry (loss of air gap).
- Abrasion from foreign materials.
- Miscellaneous stress such as damage caused by loose balancing weights, poor lugging of leads or a defective rotor.

Frequently, the reason for failures of this type are difficult to explain, since the cause and effect are hard to separate. This is because the failure point is usually an electrical fault (phase-to-phase, phase-to-ground or turn-to-turn).

## WINDING MOVEMENT AND BRACING

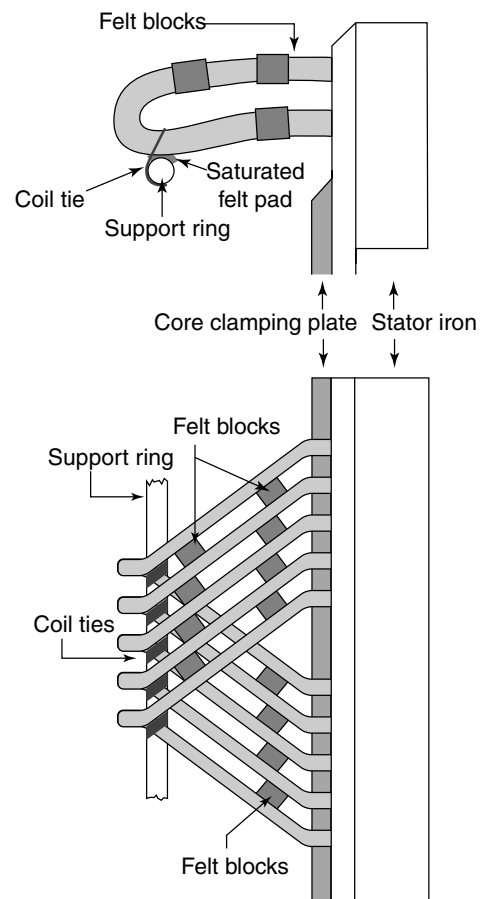
The current in the stator winding produces a force on the coils which is proportional to the square of the current ( $F \propto I^2$ ).

This force is at its maximum during starting (e.g., if the starting current is six times full-load current, the force would be 36 times as great). Vibration can lead to severe damage to the coil insulation and loosening of the topsticks, which will eventually result in a ground failure. Ground failures typically occur at the end of the slot.

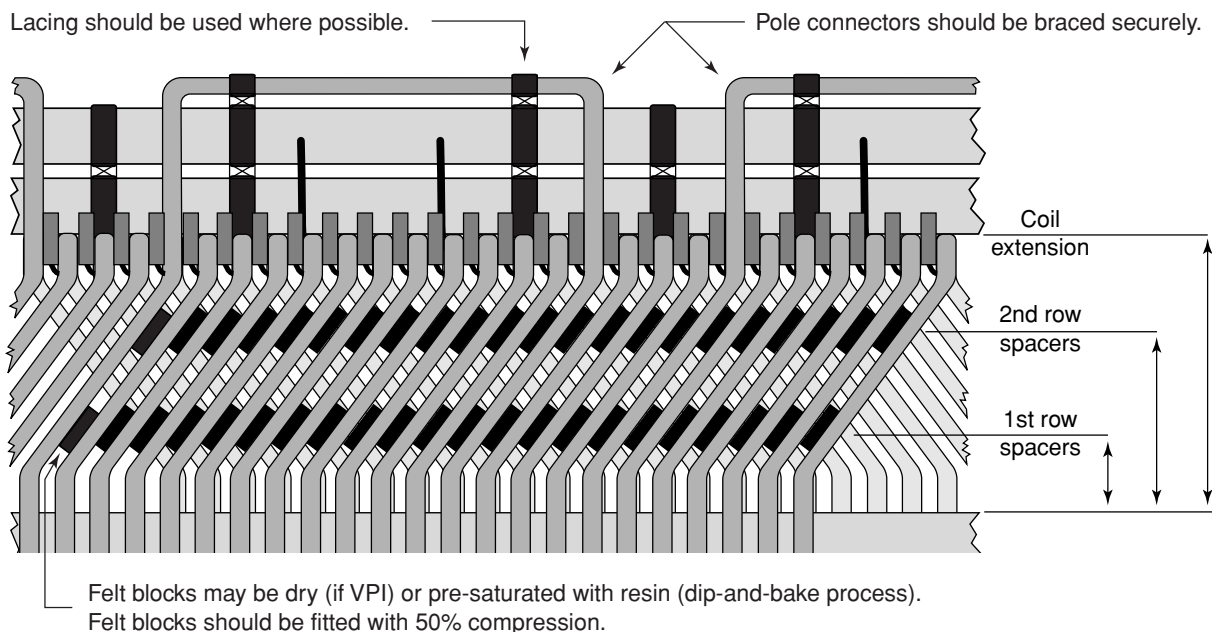
Large, high-speed machines generally suffer more from coil movement than small, low-speed machines. The longer the coil extensions, the greater the leverage exerted.

Frequency of starts and the length of acceleration time also weaken an insulation system. The greater the fre-

**FIGURE 15: BLOCKING AND TYING**



**FIGURE 16: EXAMPLE OF PROPER BLOCKING WITH MULTIPLE ROWS OF JUMPERS**





quency of starts, or the greater the acceleration time, the greater the opportunity to damage the coil insulation.

Hence, many turn-to-turn and ground failures are actually caused by winding movement over time which breaks down the insulation system. This can occur in the slot, end turns or connections.

Winding movement can be controlled or lessened by the use of coil bracing. There are a variety of methods used to brace the end turns of form- and random-wound windings.

The basic elements of coil bracing are:

- Varnish or resin treatments.
- Bracing within the slots and on the end turns.
- Properly secured connections.

The most basic form of bracing is the varnish or resin treatment used on the winding. Some systems penetrate the winding better than others, some have better retention during the cure cycle and some have better bond strength, particularly at elevated operating temperatures. A fundamental part of winding failure analysis is evaluating the quality of the winding treatment with build, penetration and movement as measurable criteria.

Next, coils can be braced in the slots and on the end turns. Windings with low slot fills will have more coil movement than higher slot fills; this is especially true of random-wound stators. Form-wound stators usually have bottom sticks and separators which act as fillers in the slot.

Evidence of coil movement can indicate severe starting conditions, or inadequate bracing in the original winding. Separation between coils and felt blocking can result from lack of varnish saturation of the felt blocking (this can be confirmed by removing and inspecting felt blocks), or from too little compression of the felt blocks during the winding process. Properly installed felt blocks should be compressed about 50% when inserted between coils. A vacuum pressure impregnation (VPI) winding is normally wound and blocked with dry felt in the expectation that proper VPI processing will fully saturate the felt blocks.

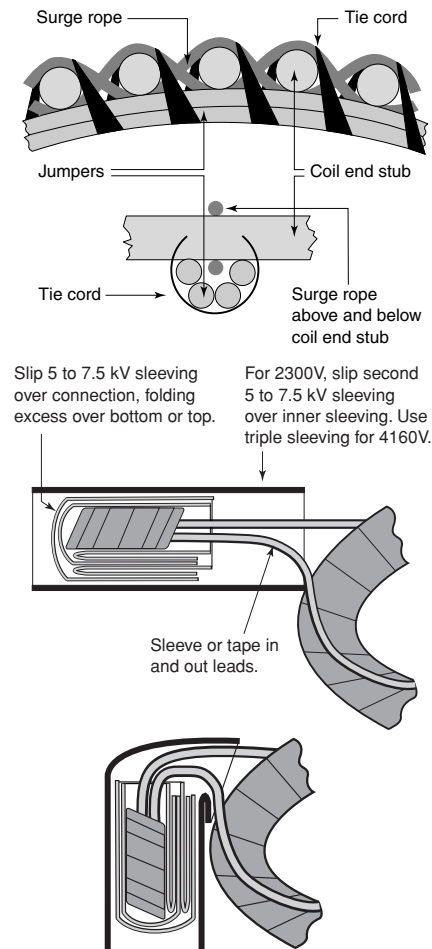
A winding that is to be dipped and baked should be blocked using pre-saturated felt blocks. The dip and bake process will not reliably saturate felt blocks. Dry felt blocks do not adhere to the coils, and may absorb and hold oil and other contaminants.

Coil movement may also result from inconsistent alignment of felt blocks. Each block, independently placed, acts as a fulcrum to the leverage exerted on each coil. Properly positioned, the felt blocks form a straight line parallel to the end of the stator bore. (See Figures 15 and 16.) The tangential force acting on each coil is equal to and opposite the direction of rotor rotation. An unbroken ring of felt blocks stiffens the winding extension and resists movement. Surge rings, whether steel or braided rope, brace the windings in the same manner.

The force exerted on a lever is a function of the length of the lever. The longer the coil extension, the greater the force on each coil at the slot end. Coil movement may indicate an insufficient number of blocking rows or surge rings, proportional to the length of the coil extension.

Movement at the coil-to-surge ring contact may indicate inadequate resin treatment or poor nesting of the coils to the

**FIGURE 17: PROPERLY SECURING STUB CONNECTIONS**

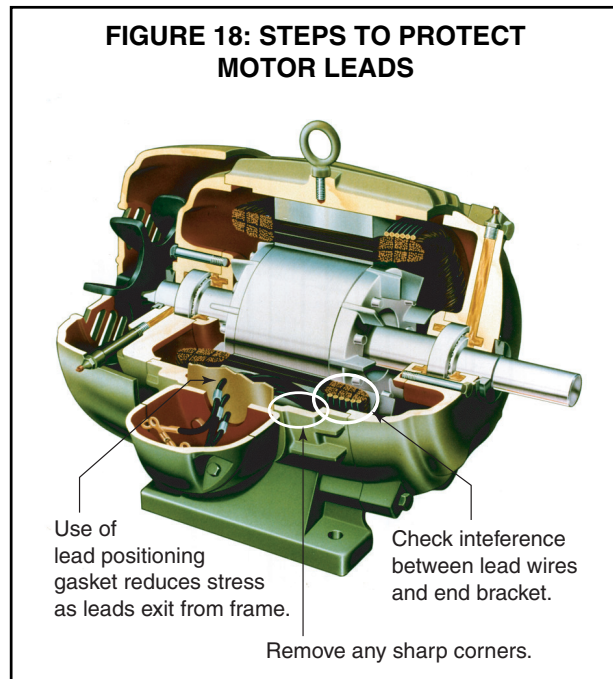


ring. Chafing of the coil may leave telltale powdered resin, which may be mistaken for partial discharge. Bedding of the coils into a felt-covered steel ring, or a surge rope, provides secure bonding when the treatment method is adequate. As with felt blocks, the selection of dry or treated surge rope should be dictated by the intended treatment process (dry for VPI, pre-saturated for dip and bake). Large machines are less likely to be VPI processed, increasing the importance of pre-saturated felts.

### DAMAGED MOTOR LEADS

If the insulation on the motor lead wire is damaged, there is the eventual danger of a fault occurring. This will usually occur to ground but may also occur between phases.

The insulating material does not always have good “cut through” or “cold flow” properties. In other words, some insulating materials have relatively poor physical properties that make them susceptible to damage when point pressure is applied (cut-through resistance) or when surface pressure over a broad area is applied (cold flow resistance).



Hence, if the leads are pressed against the edge of the laminations, or the corner of the stator frame or outlet box entry, there is the possibility of damage to the insulation over a period of time. This condition is worsened with the surge of high current such as what occurs during starting of the motor. During normal repairs of the motor, leads should be inspected for possible damage, particularly in these areas.

If damage is evident or a failure has occurred, in addition to repairing the winding, attention should be given to reducing possible pressure points where the leads may rest. It is acceptable to grind a generous radius on the edge of the lamination or on corners of the frame. In some instances, it may be necessary to add sleeving over the leads to protect them. Gasket or weather stripping can be used to make an effective grommet.

On totally-enclosed motors, there are occasions where the leads or end turns may come in contact with the end bracket. This is especially true if the end bell has internal ribs or deep register fits. Several options to protect the leads include:

- Rewind with shorter end turns.
- Improve shaping of the end turns.
- Remove some of the rib material recognizing that this may weaken the end bell strength or reduce the heat transfer. (Such actions may still be acceptable.)

If the motor has internal air deflectors or baffles, they too may be a source of interference. In these cases, reshaping of the end turns is usually the best course.

If it appears that lead damage is a possibility due to the heretofore mentioned conditions, it may also be possible to lessen the tensions or stress on the leads by using smaller lead wire and doubling the number of leads. On single-voltage windings, this may be a good option. On some occasions, it may be possible to bring half of the leads out one end of the winding while bringing the remaining leads

out of the other end. This approach can greatly reduce the amount of stress on the leads. Of course, the winding connection must be modified to compensate for this change.

### IMPROPER ROTOR-TO-STATOR GEOMETRY (LOSS OF AIR GAP)

There are a number of reasons why the rotor will strike the stator. The most common reasons are:

- Bearing failure.
- Shaft deflection.
- Rotor to stator misalignment (air gap eccentricity).

Whenever the geometry of the air gap is distorted, there is a possibility that the rotor will come in contact with the stator during starting or running conditions. The forces that contribute to this condition are a function of the voltage squared — the higher the voltage, the greater the chance of the two parts coming into contact.

The photographs on Pages 3-32 and 3-33 show the damage caused due to contact from the rotor. Eventual overheating from this condition would cause severe winding damage. The contact also can cause severe heating to occur on the rotor surface.

When contact between the stator and rotor occurs, several things can happen. If the strike only occurs during starting, the force of the rotor can eventually cause the stator laminations to puncture the coil insulation, resulting in a grounded coil. Sometimes a motor can operate for years with this condition without failing, depending on the frequency of starts and the amount of contact between the stator and the rotor. If contact is made while the motor is running at full speed, the result is usually a very premature grounding of the coil in the stator slot caused by excessive heat generated at the point of contact.

### ABRASION FROM FOREIGN MATERIALS

Foreign materials that enter a motor can cause immediate damage if they strike the winding and damage the insulation materials. In some cases, the foreign materials can clog or block the ventilation path through the motor. (This is covered in more detail on Page 3-40.)

Damage caused by abrasion is usually a slow process that wears away the insulation material. This reduces the creepage distance between the conductors and ground.

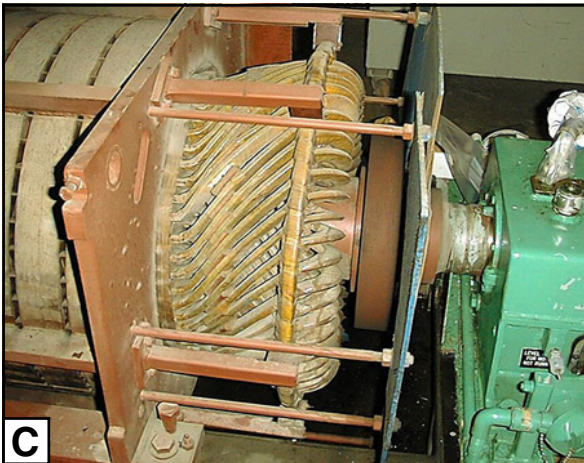
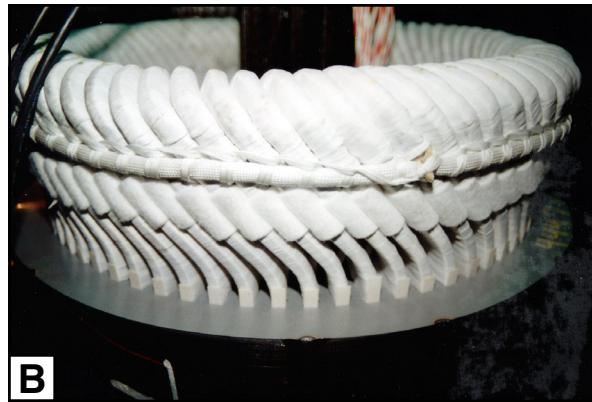
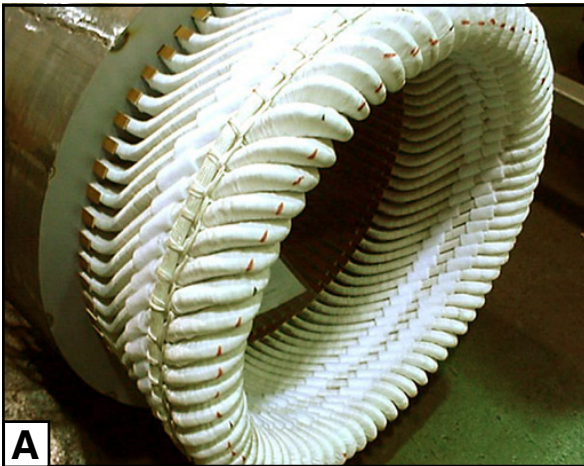
### MISCELLANEOUS MECHANICAL STRESSES

Some other common causes of winding failures that can be considered mechanical include:

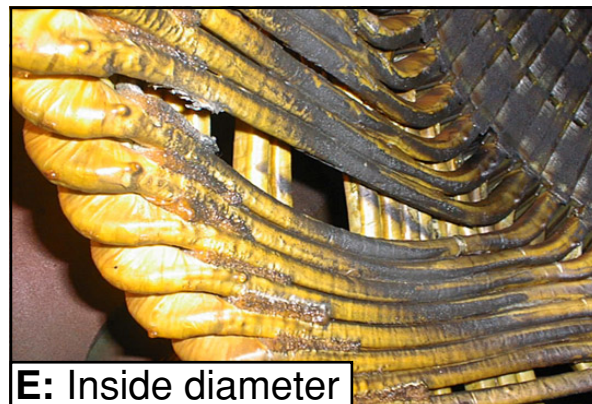
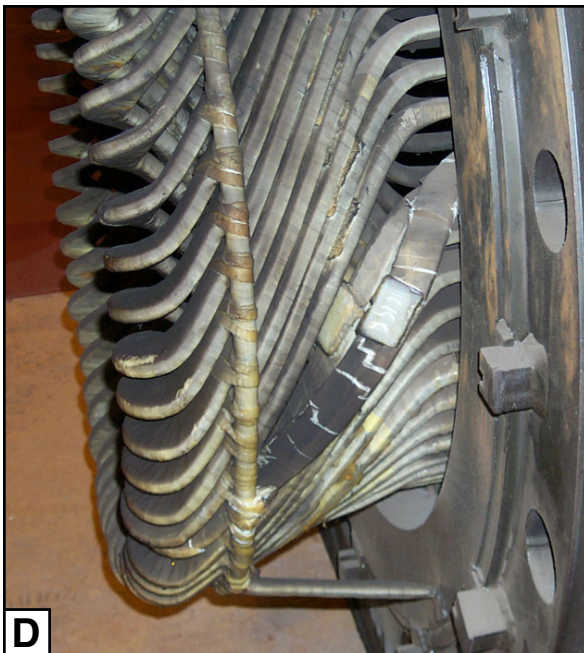
- Rotor balancing weights coming loose and striking the stator.
- Rotor fan blades coming loose and striking the stator.
- Loose nuts and bolts striking the stator.
- A defective rotor (usually open rotor bars) can cause the stator to overheat and fail.
- Poor lugging of connections from the motor leads to the incoming line leads can cause overheating and failure.
- Broken rotor or stator lamination teeth.
- Improper assembly.



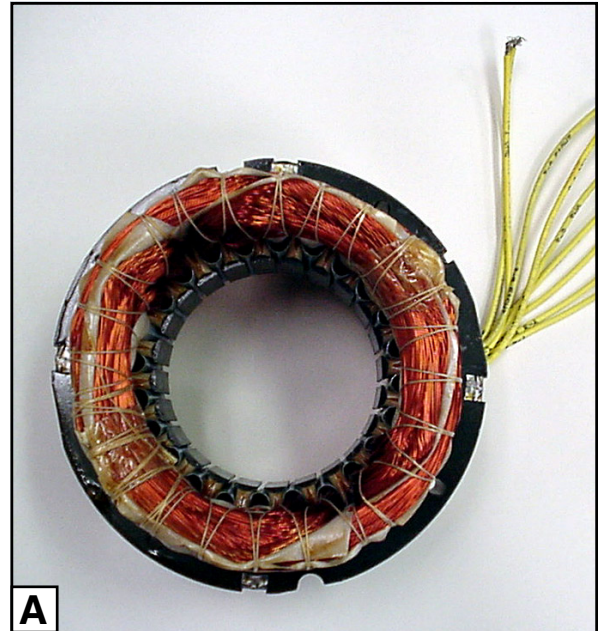
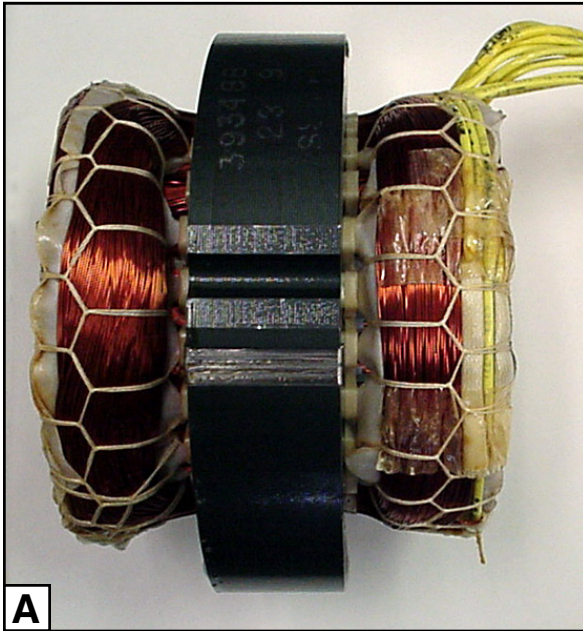
## WINDING MOVEMENT AND BRACING



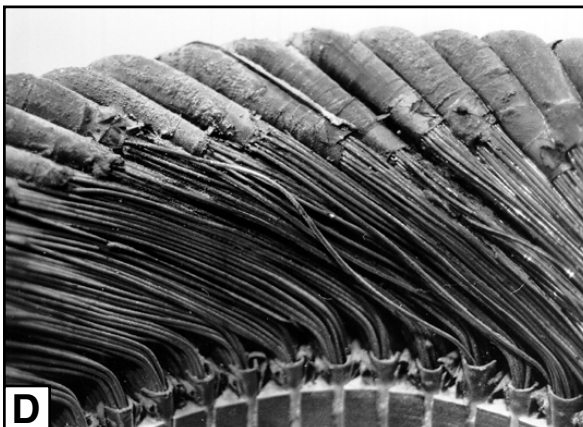
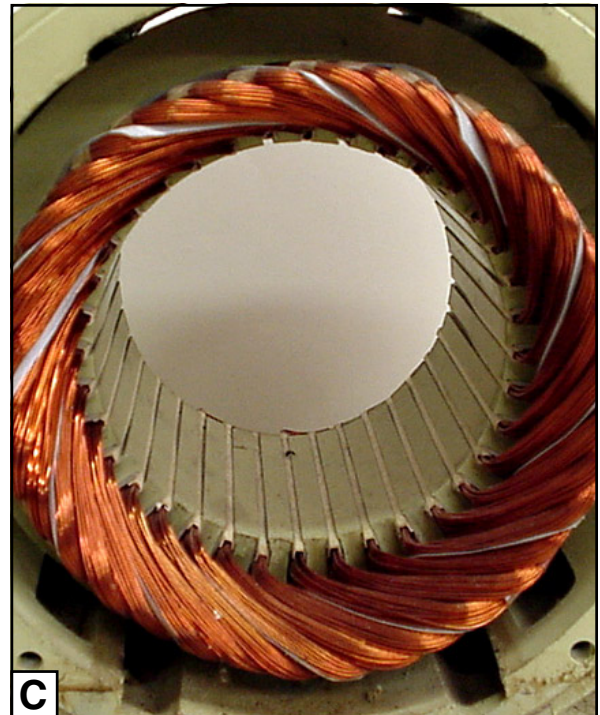
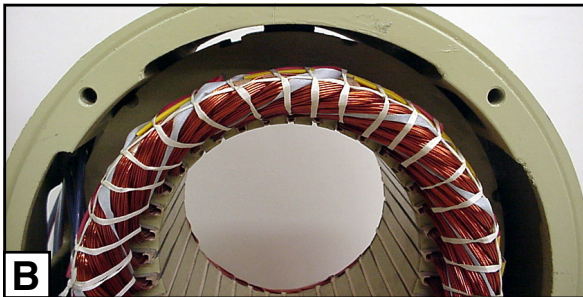
Compare the straight line of blocking in Examples A and B to the staggered line of blocks in Example C. The straight line of surge rope and felt blocks in Examples A and B will provide strength to minimize coil movement. The long end turns in Examples C, D and E should have been braced by two rows of blocks, however, only one row was used. In Example D, the felt block is also not tall enough to form the desired “dog bone” shape which further locks the block to the coil. Whether individual or a continuous strip tucked between coils, the felt block can only bond when in contact with the coils. In Example E, one felt block was used on the inside diameter, but it was placed too close to the knuckle and provided very little bracing. On the outside diameter, no felt blocks were used.



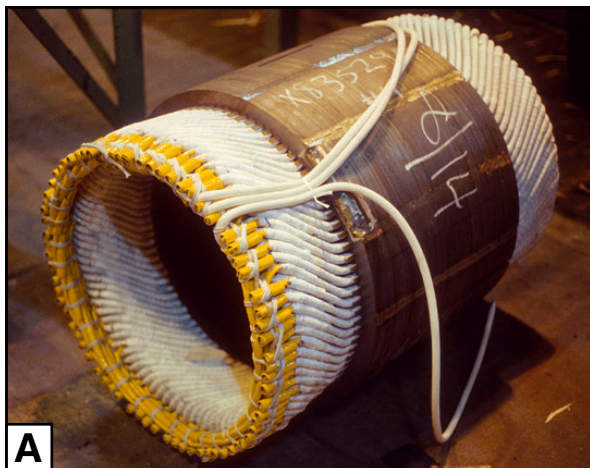


**WINDING MOVEMENT AND COIL BRACING**

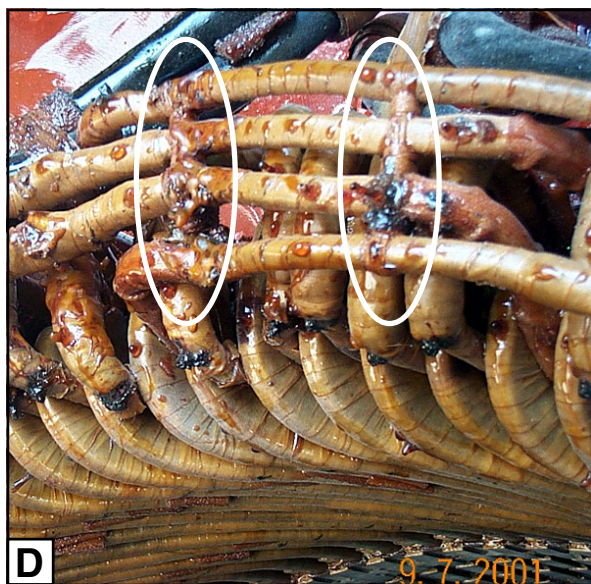
Random winding bracing is dependent on the bond strength between conductors in the end turns. The lock stitch lacing in Example A is evenly spaced and increases the bonding even before treatment of the windings. Because of the way it is tied, if one tie burns and breaks, the remaining ties will remain intact. Another alternative popular for lap windings is the continuous lacing as shown in Example B. In Example C, no ties were used and it relies purely on the physical contact of the wires and the bond strength of the varnish. This method is not recommended. In Example D, the winder relied on the taped knuckles to bond adjacent coils. Strength in that area is great, but loose conductors between the taped area and the slot are more likely to chafe.



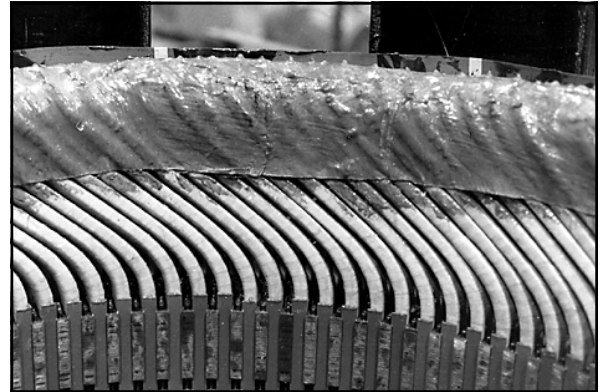
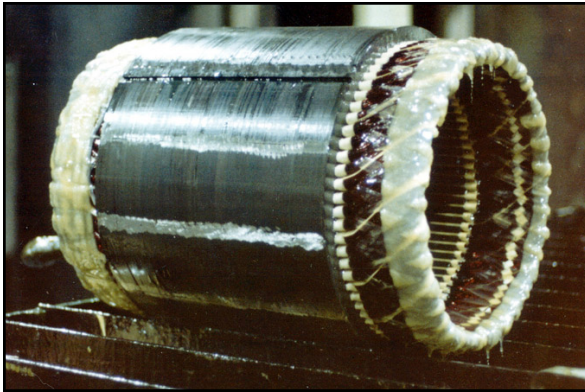


**WINDING MOVEMENT AND COIL BRACING**

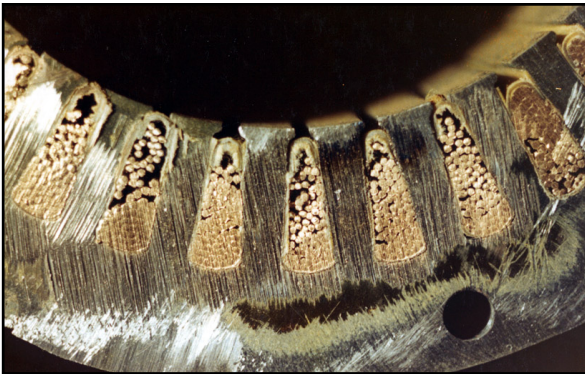
Bracing of the connection is also critical to prevent work-hardening of the copper, or chafing of the sleeving that ultimately results in phase-to-phase failure. Compare the series stubs in Examples A and B to those unbraced in Example C. If the series connections can be easily moved, failure is more likely than if they are solid. Jumpers that fail may indicate movement or inadequate spacing. Compare the “butterfly tie” lacing used in Example D to the uncontrolled contact in Example E.





**WINDING MOVEMENT AND COIL BRACING**

Two examples of alternative bracing on a random winding (left) and a form winding (right). These examples use epoxy to simulate a surge ring.



High slot fill also helps brace windings. Low slot fill (above) can lead to failures like the example at right.



The support posts secure the surge ring to the stator frame. Ring placement just behind the coil knuckles is preferred. The felt blocks in this winding are irregular, reducing their effectiveness.



## DAMAGED MOTOR LEADS

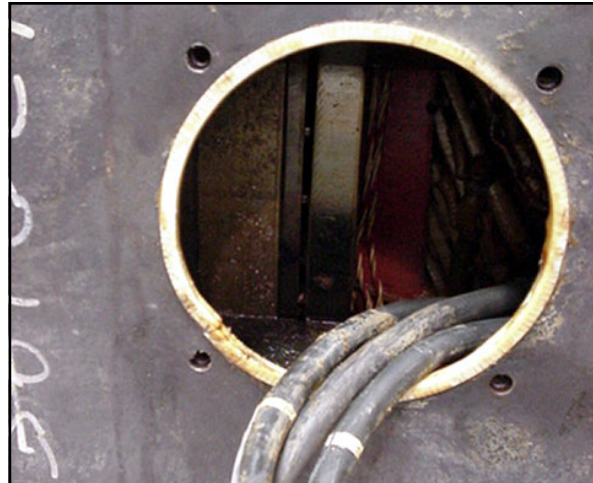


These leads failed during overload condition before the winding had a chance to fail. The leads were Class B while the winding was Class F. Upon changing to Class H leads, the winding then failed turn to turn under an overload condition. Some service centers oversize the leads to reduce the current density.

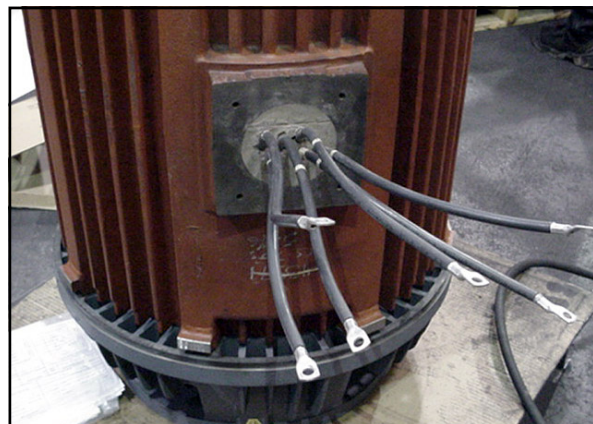


This nine-lead motor has several leads resting against the sharp corner of the frame. More leads equals more potential for grounds. Also note the metal chips left in the terminal box after conduit hole was drilled.

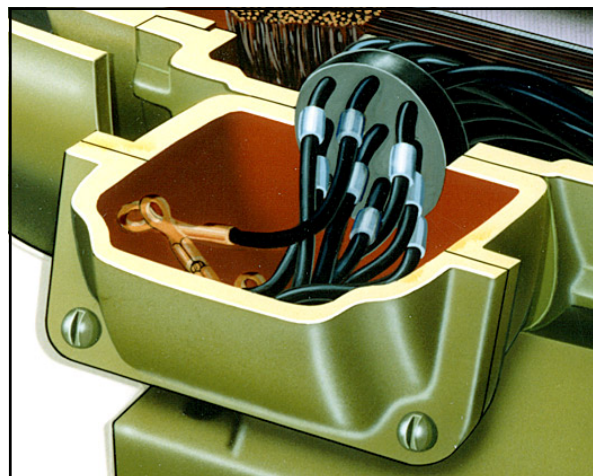
Three examples of how to improve the protection of motor leads.



Grommet protects leads from sharp edges of stator frame.



Lead potting is required for explosion-proof enclosures and also helps exclude contaminants.



Lead positioning gasket.



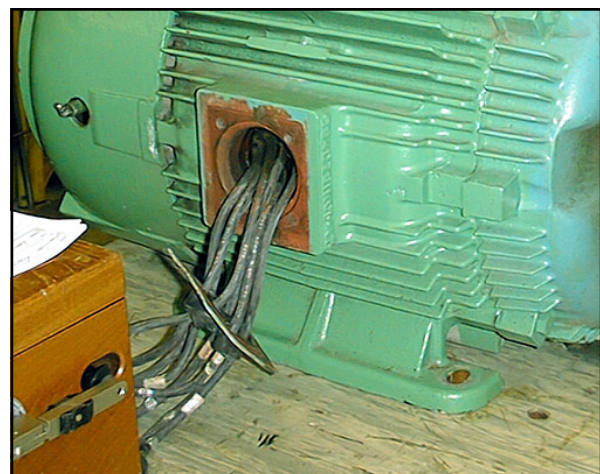
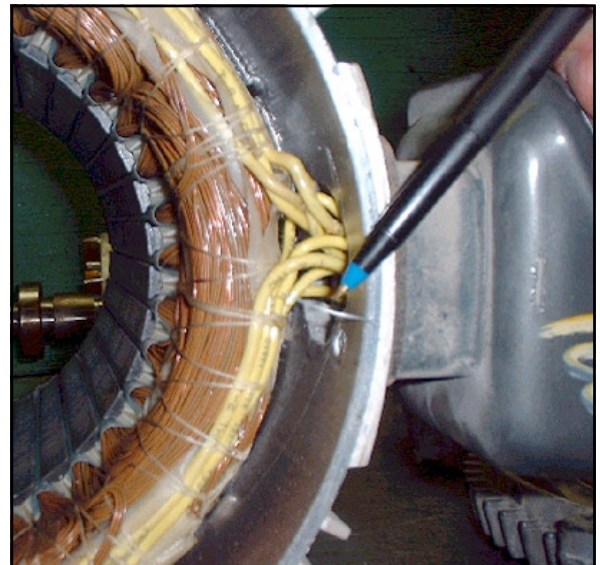
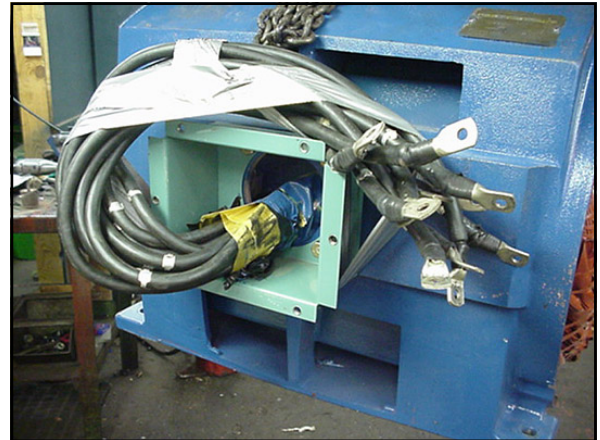
## DAMAGED MOTOR LEADS



This winding has only three leads, which reduces the stress on the leads, but they are not sufficiently protected from the edge of the stator frame.

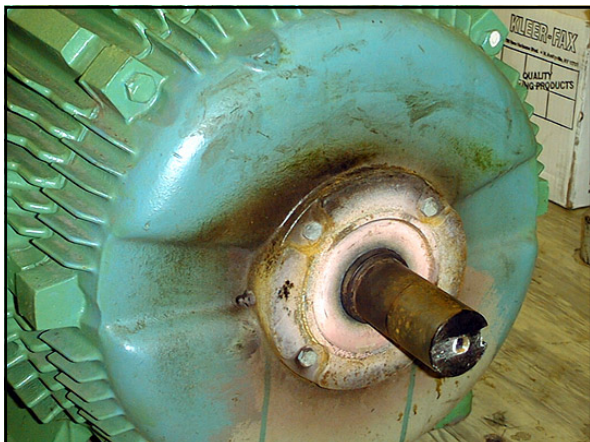


Oil chemically attacks some lead insulations, such as Hypalon, causing it to soften and swell. Cut through and cold flow properties are greatly reduced. When oil/petroleum products are present, Teflon or silicone lead insulations are preferred.

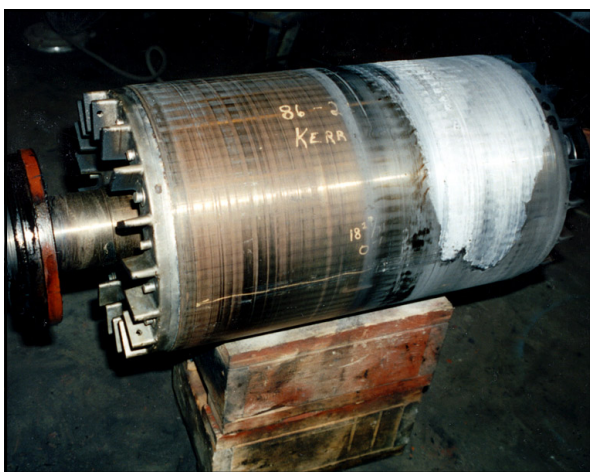
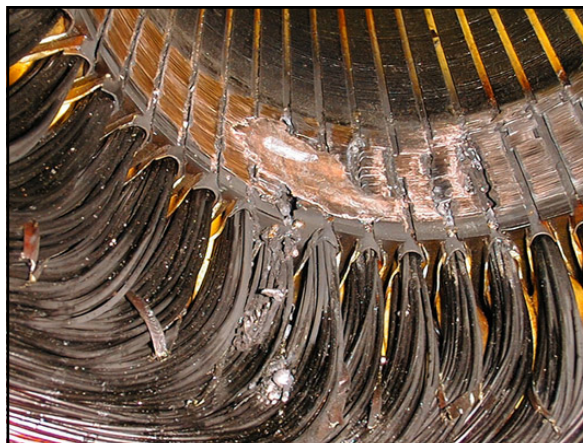
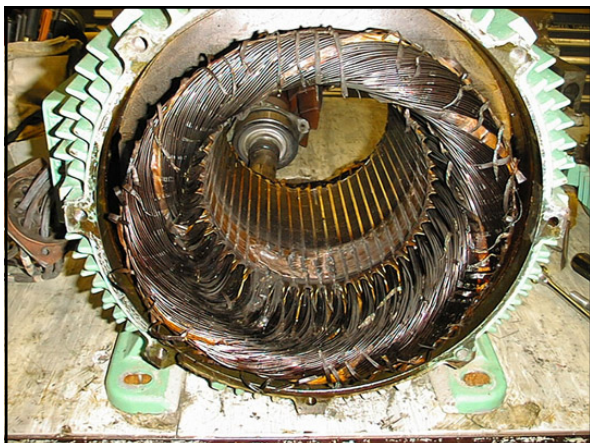


If possible, the three above motors should be reconnected to decrease the number of leads from nine to three. This would reduce the physical pressure on the leads and allow for possible oversizing of the leads.

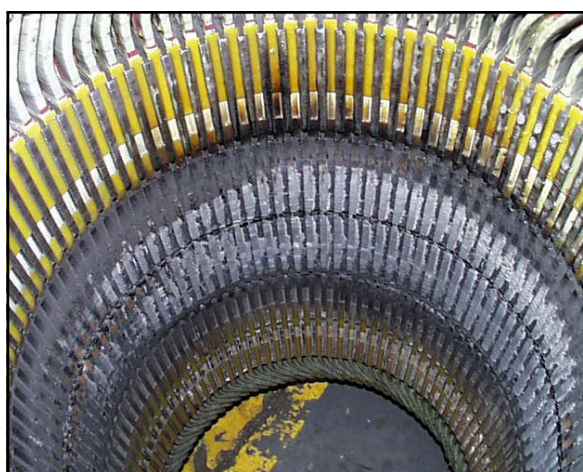


**IMPROPER ROTOR-TO-STATOR GEOMETRY (LOSS OF AIR GAP)**

In this example, the bearing failure went unnoticed until the rotor dropped and came into contact with the stator. The damage to the rotor and stator could have been avoided if bearing resistance temperature detectors (RTDs) were installed to monitor the bearings.



When only one side of a rotor comes into contact with the stator, the shaft may be bent.

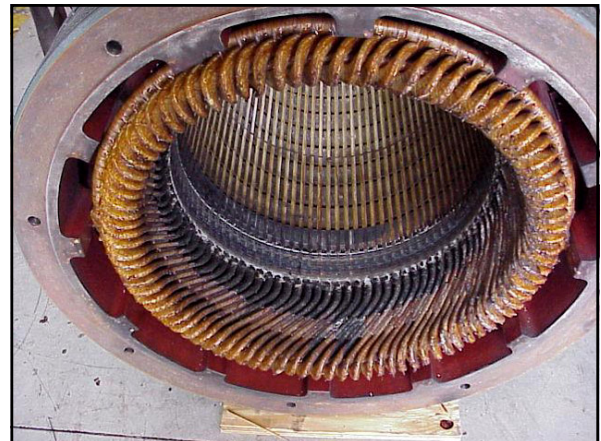
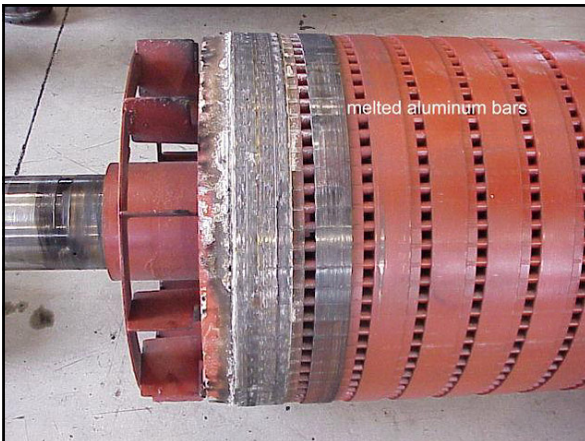


When the entire rotor surface comes into contact with one side of the stator, look for excessive radial load or an eccentric stator bore.

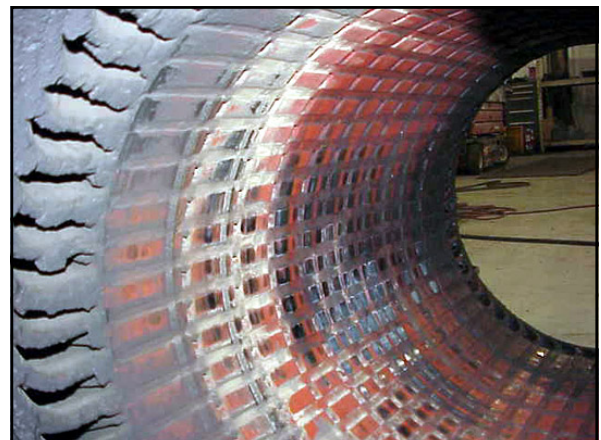
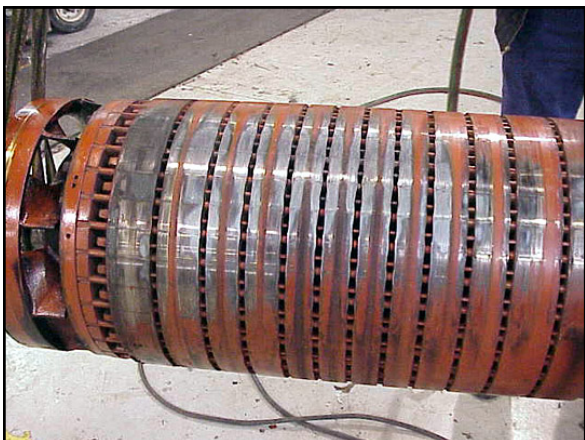


**IMPROPER ROTOR-TO-STATOR GEOMETRY (LOSS OF AIR GAP)**

Evidence of a rotor strike on only one side of the rotor often indicates a bent shaft. This may result from a bearing failure or from a manufacturing/repair defect.

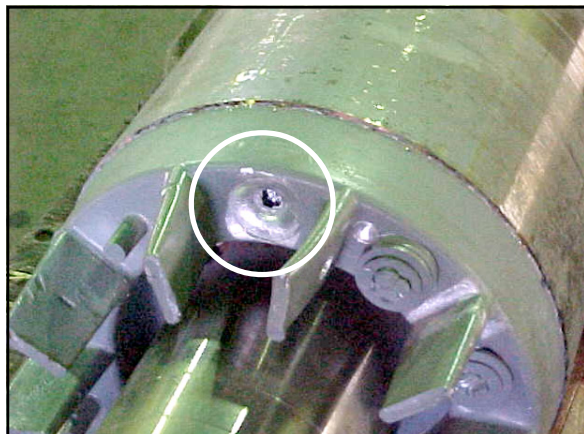


The full circumference of only one end of this rotor rubbed the stator. The cause was a bearing failure. Looseness in the failed bearing allowed the rotor to strike the stator at several areas around the stator.



The contact between this rotor and stator was triggered by a failure of the drive end sleeve bearing.



**FAILED BALANCING WEIGHTS**

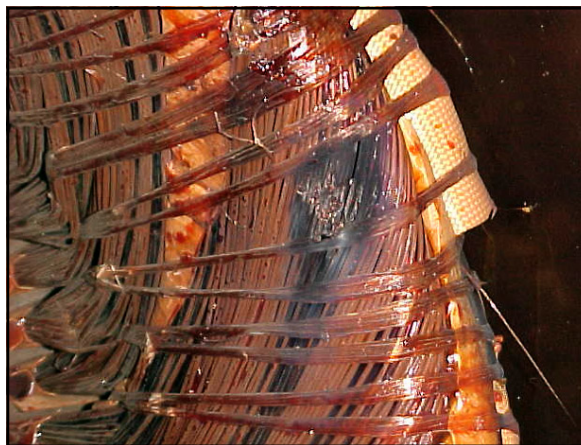
A balancing nib broke loose at the point highlighted above. An unusual concentration of balance weights is a strong indication of a porosity problem.



The porosity of this end ring weakened the balancing nib shown in the photograph at left. The nib and its weights broke away from the end ring, hit the fan blades and were thrown into the winding as shown below.



Broken balancing nib and balancing weights.



Turn-to-turn damage caused by broken balancing nib and its weights.

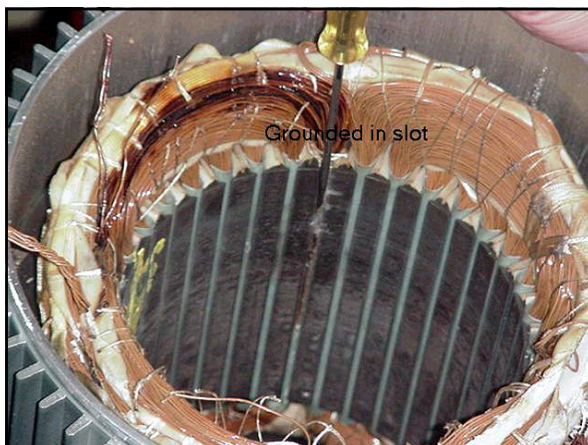


The balancing weight was not properly secured to the rotor nib and eventually was thrown into the stator winding causing a turn-to-turn short.





## POOR WORKMANSHIP



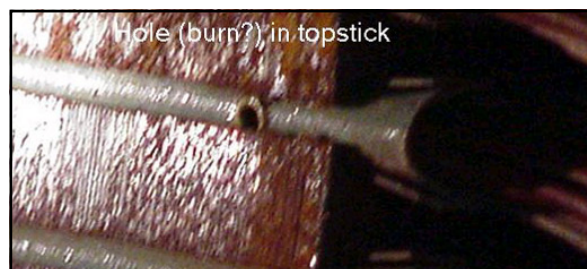
The wedge in the top photograph was damaged during insertion resulting in a ground failure. However, the root cause was poor workmanship. Driving a wedge in carelessly or using pliers may fracture the wedge. A sharp burr on the underside of the slot top may also have sliced the wedge. The bottom photograph shows a failure that progressed slightly further.



Dripped brazing material, weld splatter or copper nuggets from a previous failure can cause shorting of the winding. This drip (shown actual size) lead to a winding failure.



This photograph shows the aftermath of a crossover without proper insulation (missing sleeving). The voltage stresses are much higher than the designer intended.



A pin hole in this wedge became a path to ground once moisture entered the motor.

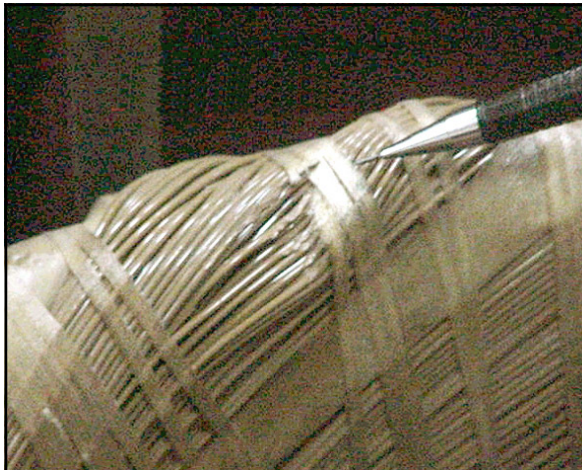
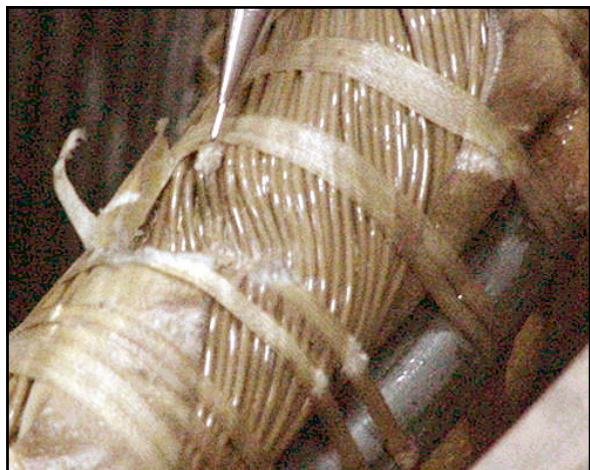
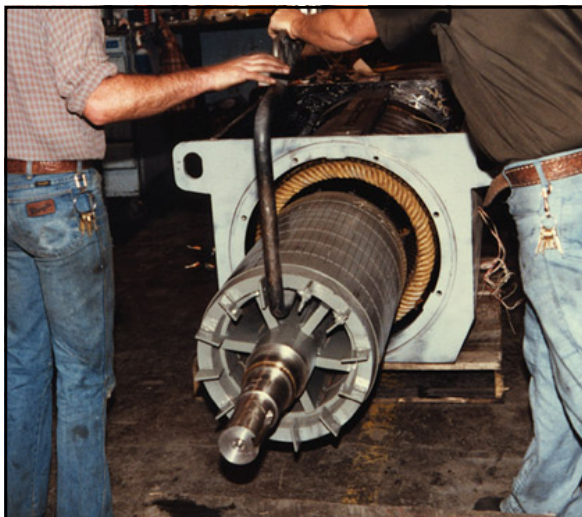


A less-obvious thermal problem is shown above. Airflow across the windings should be uniform. A buried coil cannot transfer heat as effectively. The same problem exists when a long winding extension is formed back with a mallet, resulting in a bulky coil extension. The mode of failure is this: The conductors deep within the coil extension cannot dissipate heat as effectively as those on the surface. Elevated temperatures weaken the bond strength of the resin allowing the conductors to move and chafe resulting in turn-to-turn or coil-to-coil failure. Movement may be caused by vibration over time, or a sudden event like across-the-line starting when the windings are hot.



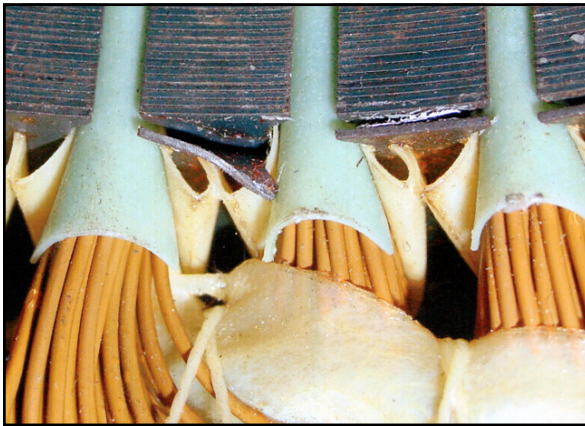
**POOR WORKMANSHIP**

A common area of mechanical damage to the end turns occurs when the rotor bumps the stator during removal or insertion. Take measures to safeguard the end turns during this step of assembly or disassembly.

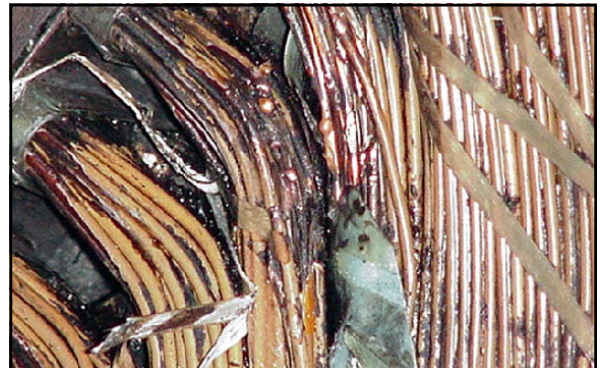
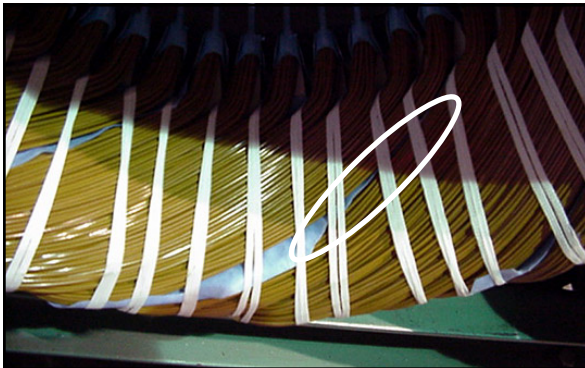


The factory welded the core (left) into the frame without protecting the windings. Weld splatter damaged the windings, resulting in a turn-to-turn failure. Above, this stator to frame weld broke allowing the stator to shift 1/8 inch.

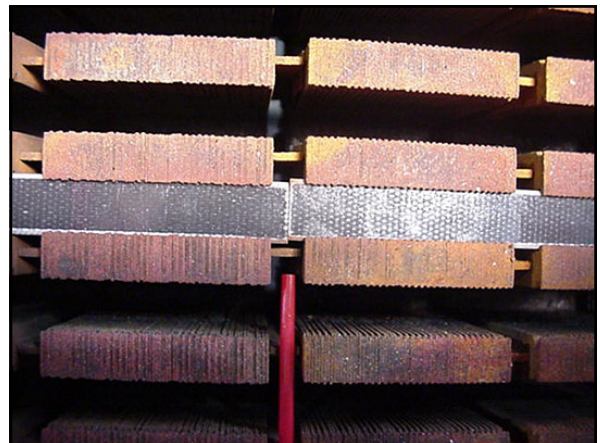
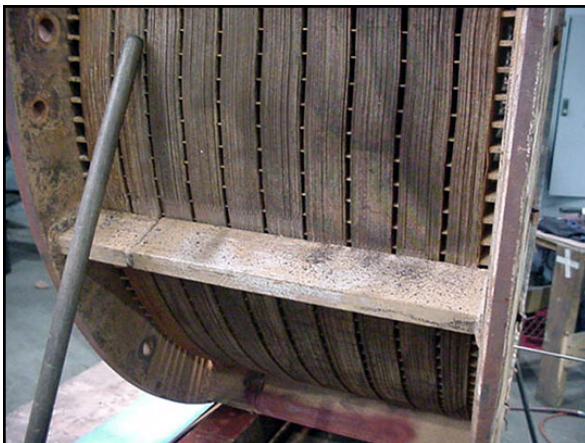


**POOR WORKMANSHIP**

A lamination displaced during lacing (left) can vibrate and cut slot insulation causing a ground failure similar to the one shown at right.



Phase insulation out of position (left) can lead to a phase-to-phase failure similar to the one shown at right.



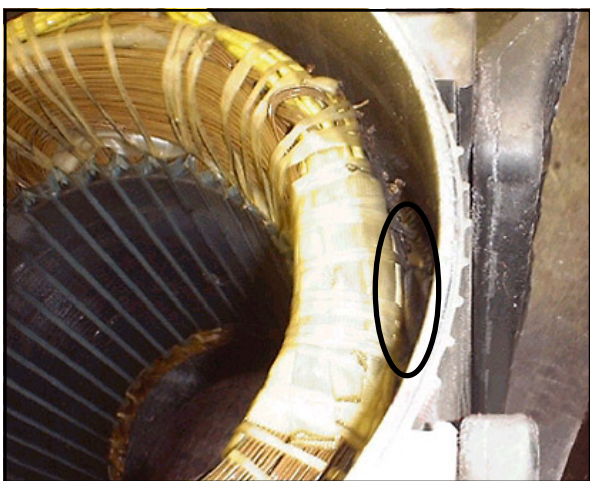
The frame rib (left) is cracked causing distortion of the stator stack (right). In addition to the distortion, this restack is very rough and likely to cut coil insulation. The sawtooth edges and the offset in the slot (compare ends of wedges) will make coil insertion difficult and may damage the coil.



## POOR WORKMANSHIP



Loose laminations, low slot fill, phase insulation out of place and improper full-slot lap winding method.



The conductor was improperly placed outside the cell wall/topstick so that it came into contact with the laminations resulting in a ground failure.



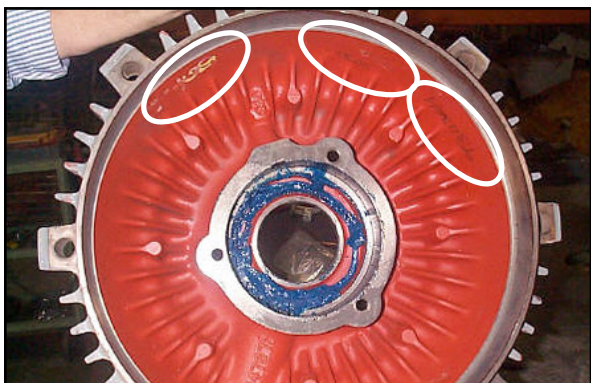
A bolt (top) or washer (middle) dropped during motor assembly, or a washer that comes loose during operation (bottom), can cause a ground failure. Be sure to account for all the bolts, nuts and other hardware.



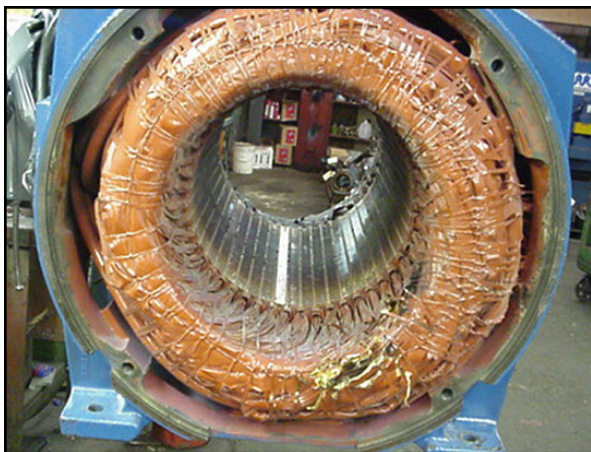
This stator shows signs of loose coils and low slot fill. Loose wires will vibrate in the slots causing chafed insulation and fatigue fractures. Note the poorly positioned separators, the extra space at the bottom square corners and the voids. Heat transfer also suffers. Filler spacers, more copper or better varnish retention would improve this winding.



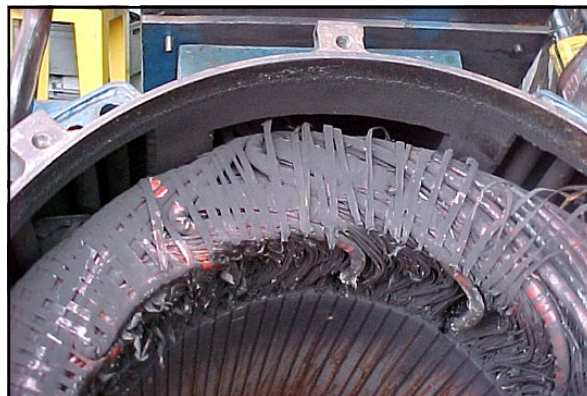
## POOR WORKMANSHIP



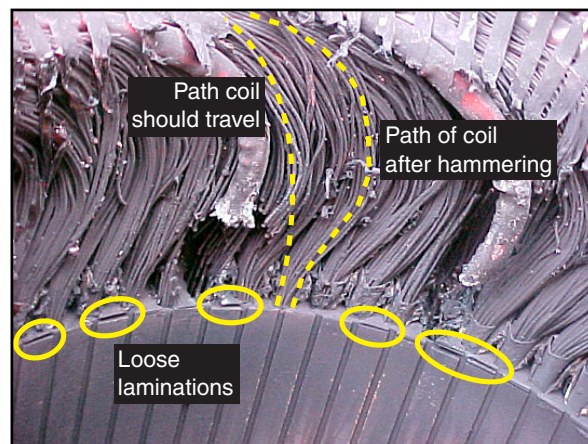
The winding extension is too long and actually was in contact with the end bracket when the motor was assembled. A ground failure is imminent.



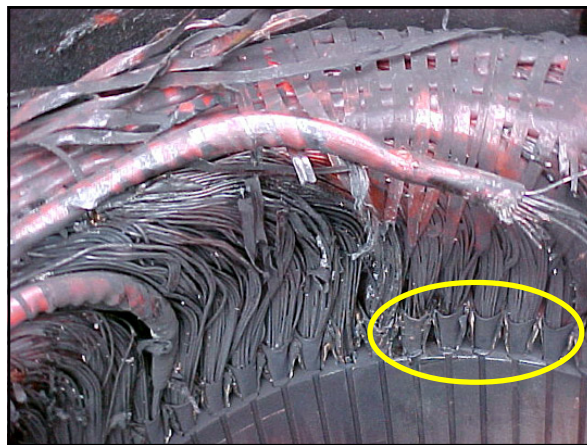
The coil extension is too long. To prevent it from coming into contact with the end bracket, the winder used a mallet to shape the extension. Doing this bulks up the winding, reducing its ability to dissipate heat. It can also displace wires, phase insulation and wedges. Slot insulation may also be strained and split.



This is a 500 kW (670 hp), 440 volt, 4 pole, 775 amp motor. Note the heavily flattened end of this stator, a clue that the winding extension was too long. Too much mallet work displaced and damaged the insulation.



Too much mallet work distorted the shape of the coils and led to the phase insulation "fading out" behind the bowed coils. Also note the loose laminations.



A mallet and board were used to create rotor clearance. This led to kinking of the wedges and straining of the slot insulation.



## ENVIRONMENTAL STRESS

Another term for environmental stress is contamination. One of the most important steps a motor user can take is to keep the motor clean and dry, both externally and internally. The impact of contamination can be one or more of the following:

- A reduction in heat dissipation. Built up contaminants acts as an insulating blanket, trapping heat in the motor. The more material is present, and the better its thermal insulating characteristics, the more serious the problem.
- An acceleration in the thermal degradation of the insulation (and lubricant).
- Abrasion of the winding insulation.
- A compromise of the insulation's dielectric strength. Conductive materials, or moisture, may drastically reduce the ability of the insulation to function.

If it is not practical to keep the motor exterior clean and dry it is essential to select an appropriate enclosure, and/or insulation system, that offers the greatest protection against the environmental stresses that are present. From the repair perspective, it is usually possible to improve mean time between failures by customizing the motor for its unique application.

Environmental stress can be broken down into four main types:

- Moisture including condensation, splashing or wash-down.
- Abrasion.
- Poor ventilation or excessive ambient.
- Chemical damage.

## MOISTURE

Moisture is a common problem, whether it results from accidental wash-down or excess humidity.

Condensation is a major cause of moisture in electric motors. Warm air within the motor enclosure cools when the motor is de-energized. As air cools, moisture drops out of suspension, resulting in condensation on the motor's interior parts. The result is rust distributed around the motor interior. Flooding, by contrast, may leave a high-water mark. Water ingress from spraying is often more evident near the path of entry. A leaking pump seal may result in water migration along the shaft, with emulsification or washing of the lubricant. Rust tracking evident on either rabbet fit indicates spraying, dripping or standing water.

Motors placed into storage, if wrapped in plastic as some customers request, may suffer more damage from condensation than they would have from the elements if not wrapped. Space heaters, properly sized, keep the air temperature above the dew point to prevent condensation. They offer protection for stored motors as well as those in service.

In the case of splashing or direct wash-down, the repairer has some options to control the potential damage. Installation of seals or bearing isolators, the use of silicon to seal rabbet fits between stator and brackets, sealing of the motor leads; all are options that help protect the motor interior.

Corrective measures include the use of space heaters or trickle heating of the windings. While installation of space heaters require motor disassembly, trickle heat can be applied from the motor control center. Heat should be applied when the motor is de-energized, especially for long periods. Sealed winding systems can also be used to improve winding life.

Drains are standard on many enclosed motors, to allow for drainage of condensation buildup from inside the motor. In hostile environments (chemical plants, corrosive chemicals, saltwater nearby) standard drains may clog due to rust buildup, mineral deposits left by evaporating water, or dirt-dobbing insects. Oversized drain holes, or "jiggle-drains," help prevent clogged drains.

## ABRASION

Damage to the motor interior can result from abrasive particles carried along by the airflow into the motor. Commonly encountered abrasive materials include fly ash (in coal-fired power plants), cement dust and sand. Coil extensions are susceptible to abrasion, although areas exposed to higher air velocity are more likely to suffer damage. Exposed sections of stator coils in the vent ducts are susceptible, especially when the rotor and stator ducts are aligned. Centrifugal force of the rotor increases the velocity of particles carried in the airflow, contributing to the sand-blasting effect on the stator coils.

Abrasion can be excluded from the motor by selecting an appropriate enclosure, but open dripproof or weather protected 1 motors can benefit by top-coating the windings with abrasion-resistant materials such as silicone or epoxy. Coils should be wedged the full length of the slots to protect the coils from abrasive material.

## POOR VENTILATION

High winding temperatures may result from blocked ventilation paths, high ambient temperature, recirculation or other similar problems. Depending on the motor enclosure, there may be corrective steps available such as:

- Filters can be added to a weather protected or open dripproof motor.
- A totally-enclosed fan-cooled motor can have a "belly band" added to prevent surface buildup of contamination.
- Airflow may be increased by use of a more effective fan.
- Cooling air may be ducted from another location.
- A radiator can be placed into the incoming airflow to chill the air prior to entering the motor.

Foreign material clogging the vent ducts restricts the airflow and adds thermal insulation to the windings. Dirt buildup on the coil extensions act as thermal insulation to trap heat in the windings. Coarse products, like paper pulp or shredded bark, can block fan shroud grills, restricting airflow across the exterior of the motor. Rocks or hard products may damage or break the external fan of a totally-enclosed fan-cooled motor, stopping airflow. Any material that builds up on the exterior of the motor also acts as a thermal insulation, trapping heat in the motor.

The affect of some materials is less obvious. Dark paints

or materials that discolor paint may not act as thermal insulation, but the dark color absorbs heat, especially in areas of intense sunshine. A black motor exterior may be 40° C hotter than the same motor painted with light or reflective colors.

Some materials are conductive, further compounding the problem. Fly ash, common in coal-fired power plants, is a fine abrasive dust that finds its way into the motor. Not only will it literally sandblast through the insulation, it is conductive and can bridge the insulation, leading to a ground failure. Carbon black, used in manufacturing tires and other rubber products, is also conductive. Moisture, especially

saltwater, compromises insulation. These and similar materials reduce the effectiveness of insulation, and can contribute to winding failure.

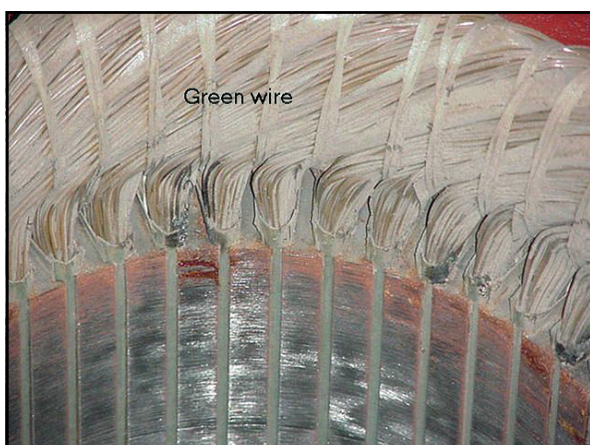
#### CHEMICAL DAMAGE

Chemical damage may include acids or chemicals that damage the insulation itself, or chemicals that damage copper windings (e.g., chlorine, hydrochloric acid). Some treatment resins (epoxy vs. polyester) may be more resistant to specific chemicals and therefore more suitable. Other chemicals attack aluminum, steel, iron, Nomex, plastics or other materials. (See Table 4.)

**TABLE 4: MATERIALS AND CHEMICAL THREATS**

| Material  | Chemical threat                               | Special notes                                                          |
|-----------|-----------------------------------------------|------------------------------------------------------------------------|
| Copper    | Saltwater, H <sub>2</sub> S                   | Difficult to flush from motor.                                         |
| Aluminum  | Caustic materials                             | Dipping the rotor helps seal it.                                       |
| Cast iron | Saltwater, moisture, nitric acid, HCl         | Zinc-based primers and epoxy paints provide some degree of protection. |
| Steel     | Saltwater, moisture, nitric acid, HCl         | Zinc-based primers and epoxy paints provide some degree of protection. |
| Plastic   | Acetone, MEK, solvents                        | Not all plastics are affected by the same solvents.                    |
| Polyester | Inert to most chemicals in limited quantities | Good moisture-resistant properties.                                    |
| Nomex     | Freon 123                                     | EPA-approved freons are compatible.                                    |
| Mylar     | Solvents                                      |                                                                        |
| Epoxies   | Inert to most chemicals                       | Very good moisture-resistant properties.                               |
| Lead wire | Oil, oil mist                                 | Hypalon/neoprene lead insulation becomes spongy and splits.            |

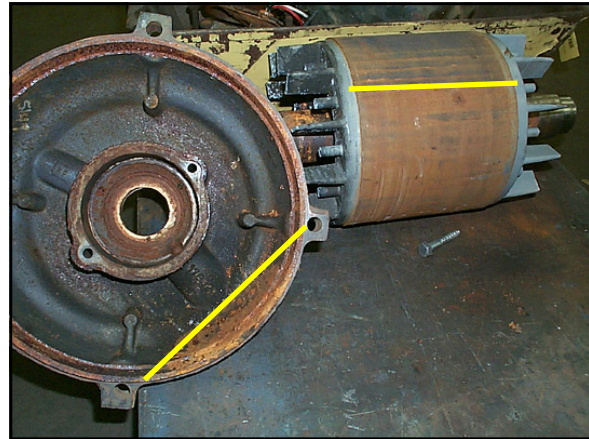
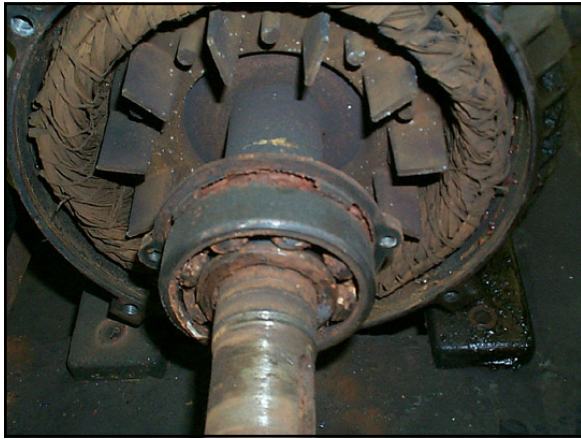
### MOISTURE, CORROSION AND CONTAMINATION



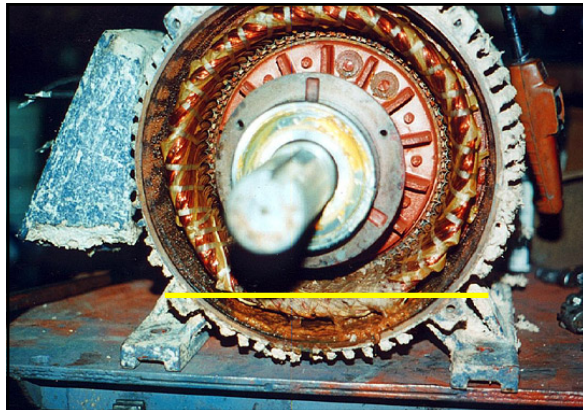
Severe moisture resulted in corrosion which attacked the insulation. Rust buildup on the laminations is strong evidence of this. Green coloration of the copper shows that the corrosion has been ongoing for some time.



## MOISTURE, CORROSION AND CONTAMINATION



The grease has washed out of this bearing. The residue on the windings is evidence that they were submerged. Note the water line in the bracket and on the rotor in the photograph at right. This was more than just condensation.



This motor has been operating in a wet environment as evidenced by the corrosion and buildup of product on the motor frame. Inside the motor, discoloration and buildup of foreign material in the lower portion of the end turns are all signs of flooding (line indicates water level). Condensation results in surface oxidation of all bare exposed steel and iron.



Contamination can come from within the motor. Overgreasing has led to contamination of the windings which in turn created thermal problems.





**MOISTURE, CORROSION AND CONTAMINATION**

Foreign material: The conduit hole was drilled and filings were left in the terminal box.



Thermal cycling of space heaters makes them susceptible to moisture and corrosion.



Cooling tube corrosion can occur inside or outside the tubes, wherever the atmosphere is most corrosive. Not only can the tubes leak, but oxidation is a thermal insulation.



Moisture combined with foreign material can pack the windings or vent passages. This open motor is filled with pulp which restricts the flow of air. As a result, the winding overheated and failed.



**ABRASION**

The coil insulation has been sandblasted through thus exposing the coil turns. Continued abrasion would remove the conductor insulation. The exposed turns are now susceptible to moisture, contamination and tracking.



Abrasion has removed varnish and some of the enamel from the magnet wire. This is most often found in areas of high air velocity, usually in line with fans, vent ducts, etc.



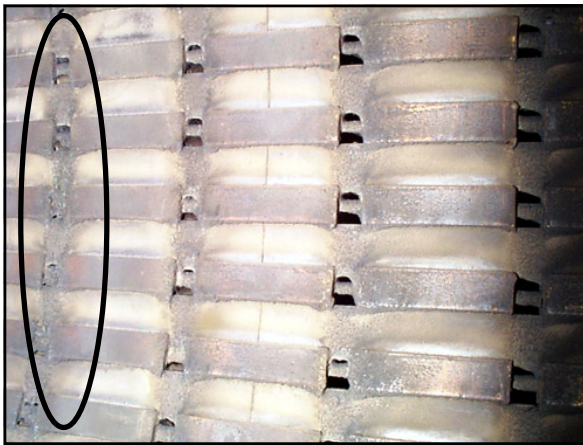
This stator has been sprayed with an abrasion-resistant silicone rubber to minimize the type of damage caused to the other windings pictured on this page.



## POOR VENTILATION



For the open dripproof motor, contaminants carried by the air stream build up on the windings, trapping heat and possibly absorbing moisture. This motor may have the wrong enclosure for the application.



These stator vent ducts are partially blocked by foreign material. High-velocity abrasive particles abrade the coils in this area, while soft, damp particles tend to clog the vent ducts and restrict the airflow. Note the one row of ducts that is almost completely blocked.



This expanded metal screen does not clog as easily as a screen with smaller openings, but contaminants can still build up, especially when moisture is present.



For the totally-enclosed, fan-cooled motor, the exterior plays an important role in cooling the motor. Cement dust, limestone, paper pulp and other product can collect and insulate the motor, drastically increasing winding temperatures.



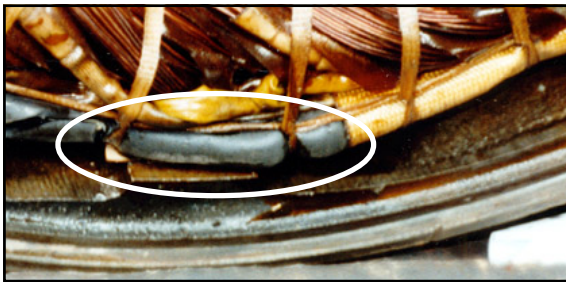
In a winding designed with a partly-encapsulated coil extension (for increased winding rigidity), ventilation among the exposed portions of coils is even more critical. The stator vent ducts in this motor, as well as the coil extensions, are blocked by contaminants.



## WINDING MATERIALS

Insulating material plays a critical role in winding life, depending on environmental and thermal factors. An insulation that performs well in a clean environment may give very poor performance when saturated with oil, for example. Lead wire, such as Hypalon, is commonly used in many applications with good success. The same Hypalon, if saturated with oil (as in an oil-mist motor, or a machine tool application) becomes spongy and literally falls apart (Figure 19). Hence, the need to know the application of a motor in order to determine the cause of failure. Without understanding why a motor fails, it is impossible to select the best methods of repair.

**FIGURE 19: SPONGY LEAD WIRE**



These leads were exposed to oil.

## PROPERTIES OF INSULATION MATERIALS

Insulation material has to be flexible enough to prevent cracking, rigid enough to prevent extrusion under compression and mechanically strong enough to resist tearing while being easily formed and cut to size. Some sheet insulation tears easily in one direction only, with the grain, while others are cross-laminated for additional strength. While rarely used in the repair industry, “cuff paper” has increased mechanical strength at the slot ends (Figure 20).

At the same time, insulation must be temperature resistant without being indestructible. After all, the motor will eventually need to be rewound, and the insulation must be cremated at a temperature well below that of the lamination insulation. It must also be absorbent enough to soak up resin when the winding is treated, yet not absorb moisture once the motor is placed into service.

Mylar has great mechanical strength, but melts at a low temperature. Nomex is highly temperature-resistant, but tears easily with the grain. Cross-ply insulations increase mechanical strength, and complimentary materials can be laminated together to benefit from the strengths of each.

## TREATMENT METHODS

The intended treatment method will also affect the selection of materials. Windings designed for vacuum pressure impregnation (VPI) will be insulated using dry absorbent tapes, while a winding designed to be dipped (or a field rewind that may only be sprayed to topcoat) should be insulated using pre-saturated tapes. The goal of winding treatment is not only to seal the windings, but also to add

**FIGURE 20: CUFF PAPER**



Cuff paper is folded double on each end, so it must be stocked in appropriate lengths.

rigidity. While VPI methods improve the chance of penetration, the stiffness of the resin used also is important.

A winding duplicated in all aspects by a repairer, but dipped instead of VPI'd, or VPI'd using a more flexible resin, will probably have less mechanical strength. Subject to frequent across-the-line starting, the windings are more likely to fail prematurely. Operating from a VFD, ramping slowly to speed, the same windings could last for decades.

Lacing materials are designed to shrink 2 to 5% when exposed to heat, which serves to further tighten the laced windings prior to resin treatment. Excess shrinkage may cut into the coils, while too little shrinkage may leave the windings loose.

## TEMPERATURE

A material that performs well at class B or F temperatures may not withstand class H temperatures. That means that a group of identical motors may not give satisfactory performance in similar—but different—applications, even at identical loads. A kiln motor may fail due to thermal stress within a relatively short time, whereas the same motor might last for years operating the same fan at a reasonable ambient temperature.

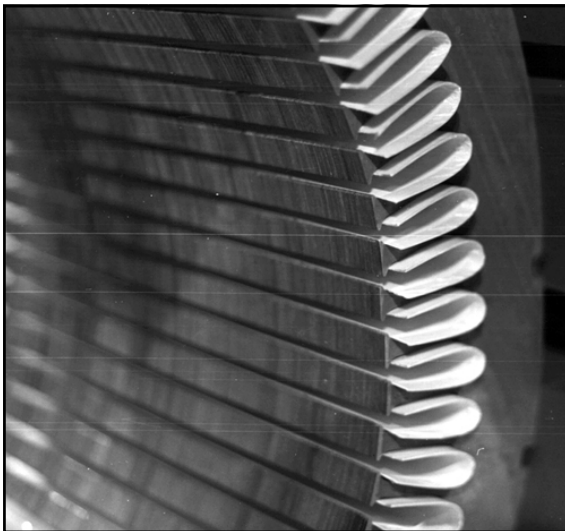
### WEDGE MATERIAL

Wedge material selected for a stationary stator is different than that intended for a rotor or armature. Standard stator wedges are suitable for retaining stator form coils, but will not withstand the centrifugal force of a winding rotating at high speeds. A resin with high bond strength, but low temperature resistance, is not suitable for use on an armature that operates near 200° C (329° F).

### APPEARANCE OFFERS CLUES

The appearance of many insulating materials offers clues as to the cause of failure. Lacing that has burned or melted indicates a sudden thermal rise, even if the windings are not discolored. Slot insulation that has broken at the slot ends may be too brittle, or may indicate a chemical reaction with something in its the environment. Insulating resin that is sticky, green corrosion on copper windings, heavy buildup of resin blocking vent ducts, or Nomex insulation that appears to be disintegrated are all indications that a change in material should be considered.

**FIGURE 21: INSULATION EXTENSION AT SLOT EDGE**



Slot insulation should protrude at least 3/8" beyond the end of the slot.

### PROPER WINDING INSULATION

Slot insulation must protrude beyond the slot end in order to prevent creepage. (See Figure 21.) Contaminants that contribute to tracking decrease the effectiveness of the slot insulation extension. Typical slot insulation should protrude 3/8" beyond the slot end, although for 2300 volt random windings, the recommendation is a full inch.

Phase insulation serves to separate the coils in different phases, and must be left long enough to prevent creeping during the process of handling, lacing the coil extensions, varnish treatment and curing, as well as movement during starting and operation of the motor. (See Figure 22.) If inspection shows that the phase insulation disappears in

**FIGURE 22: PHASE INSULATION**



Phase insulation should protrude past the phase coils.

places, and the failure mode is phase-to-phase, workmanship may be the issue.

The sleeving used at the ends of each group of a random wound motor are also phase insulation. If the sleeving does not isolate the group lead from groups the lead is laid across during the process of connecting the motor, phase-phase failure may occur. For medium-voltage machines, the sleeving used to insulate each series (and the jumpers) act as ground and/or phase insulation. Using 600 volt sleeving, double-thickness, may be adequate for the series if they are carefully separated, but the jumpers must be isolated to prevent phase-phase failures.

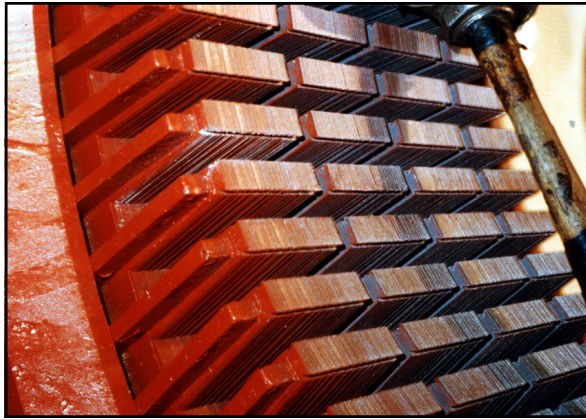
Winding treatment, whether VPI, dip and bake or trickle epoxy, must seal the windings from moisture, bond the conductors together to minimize movement, and transfer heat from the conductors to the laminated core.

Large voids in the slot regions act as thermal insulation and trap heat in the conductors. Remember the 10° rule. Loose conductors may chafe and abrade, resulting in turn-to-turn failure. In a wet environment, sealing the windings may be more important.

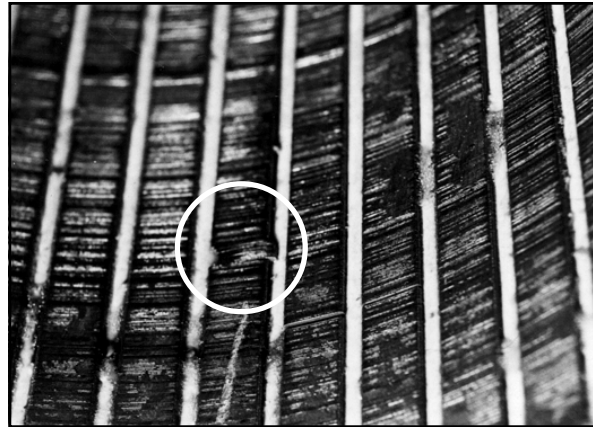
### INSPECT LAMINATIONS

Laminations are generally inspected when preparing to rewind a stator and when performing a core test, but can still be a cause of ground failures. Loose laminations often vibrate when a winding is energized, and may cut or abrade through the slot insulation leading to a ground failure. Rough laminations, especially at the slot ends, can cause ground failures. (See Figure 23.)



**FIGURE 23: CAREFULLY INSPECT LAMINATIONS**

Inspect the core for loose or displaced laminations.



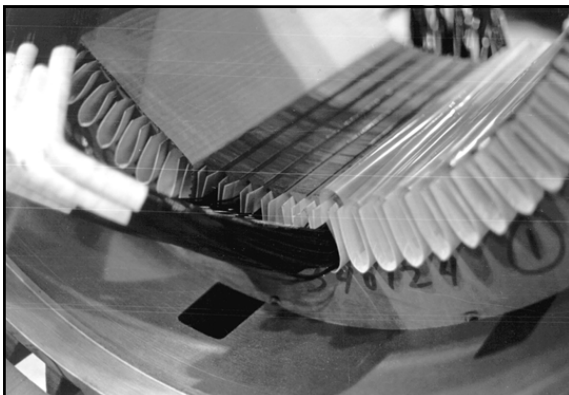
Displaced laminations increase the contact pressure on the slot insulation and may cause a ground failure.

### SCUFF PAPER

Coil insertion can be aided by the use of scuff paper (a.k.a. feeler paper, feeder paper). Scuff paper helps protect the conductors from scraping during insertion (Figure 24). The material most often used for this is Mylar, due to its mechanical strength and slick surface.

The normal practice is to place scuff paper into the slot (one piece on either side), then slide the coil between them to ease insertion and when done, move the scuff paper to the next slot to insert that coil. Scuff paper can be used until it wears out.

Separate pieces should be cut for the coil bottom sides and the top sides. The use of scuff paper expedites coil insertion as well as protecting the conductors. There is a perception among some winders that scuff paper is a lot like training wheels — that a “good” winder does not need it. The reality is that rough laminations can result in scraped wires, regardless of the winders skill.

**FIGURE 24: SCUFF PAPER**

The use of scuff paper helps protect the insulation of conductors during the installation process.

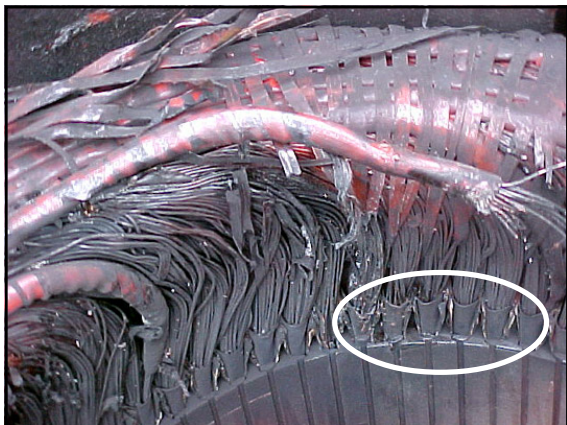
### LOCATION OF FAILURE IS AN IMPORTANT CLUE

The location of a ground failure in a new winding could be a clue as to the cause. If located at the end of a slot (Figure 25), or at a vent duct, a sharp edge or loose lamination could be the cause. If the failure is turn-to-turn within a slot, and the slot edges appear jagged, the magnet wire may have been scratched during insertion. A failure in the same location as a previous ground failure may indicate the presence of shorted laminations that were not properly cleared before the winding was inserted. Shorted laminations, whether welded or fused with copper from the earlier failure, cause localized hot spots that result in additional failures in the same area.

A failure in only one slot — when the wedge is damaged

**FIGURE 25: GROUND AT END OF SLOT**

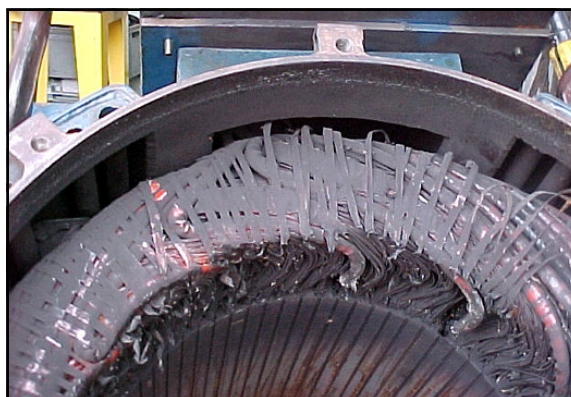
The end of each slot is the fulcrum to the leverage exerted by each flexing coil. Not only is this a point of mechanical stress, but it is also subject to electrical stress as ground potential for each line. The combination of electrical and mechanical stress make this the most likely place for ground failures.

**FIGURE 26: KINKED WEDGES**

This damage at the end of the slot was caused by a mallet and board used to create rotor clearance. This kinked the wedges and strained slot insulation.

— may be caused by rough laminations. As the wedge is slid into position the lamination acts like a saw, cutting through the wedge. Careful inspection of the protruding ends of the wedge often will confirm this: One end will bear telltale marks in line with the tooth edges.

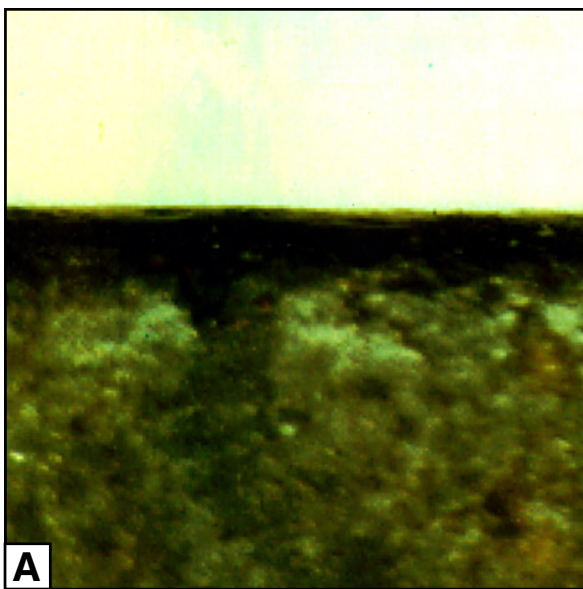
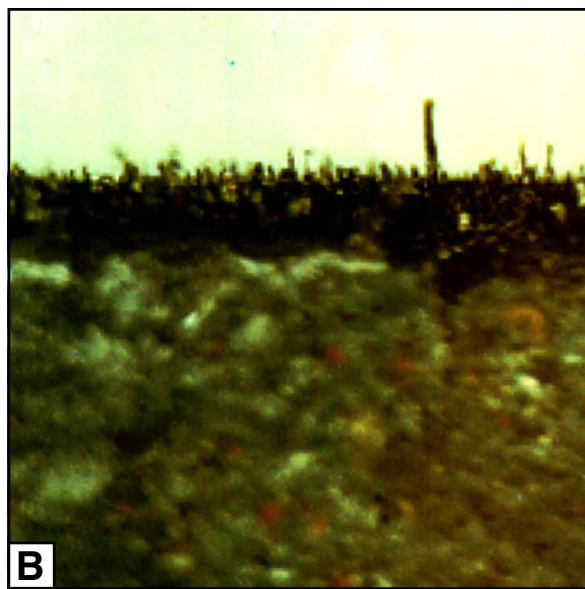
Damaged wedges that appear kinked (Figure 26) indicate difficulty in insertion, or the heavy use of a winding mallet. That may indicate an unskilled winder or a tightly packed slot. If the winding extensions are bulky and the

**FIGURE 27: FLATTENED END TURNS**

This is a 500 kW, 4-pole motor. Note the heavily flattened end of this stator, a clue that the winding extension was too long. Too much mallet work displaced and damaged the insulation.

ends are heavily flattened (Figure 27), the winder made the coil extensions too long and shaped them to clear the end bracket, air baffle or frame. The more a winding mallet is used, the greater the chance of insulation damage and ground failure; displacement of phase insulation; damage to wedges and damage to magnet wire. In addition, a bulkier winding extension has a smaller surface area-to-volume ratio for heat dissipation.

## CONTAMINATED WIRE

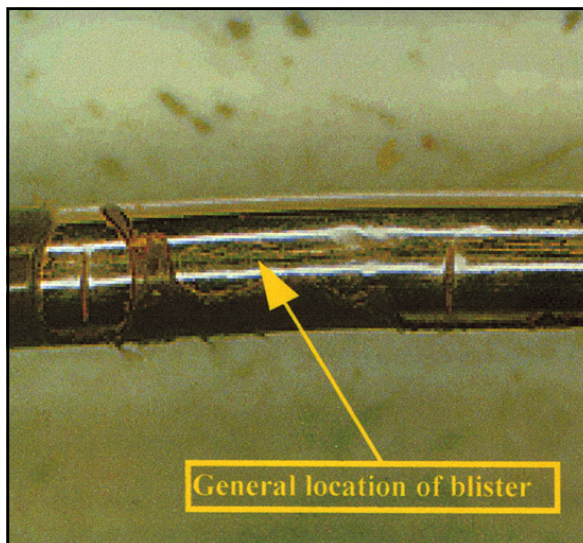
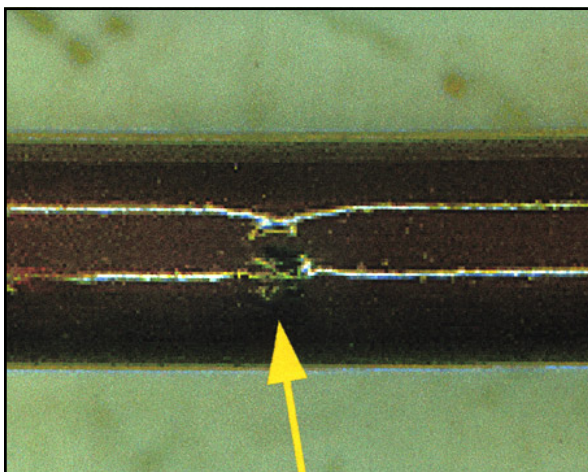
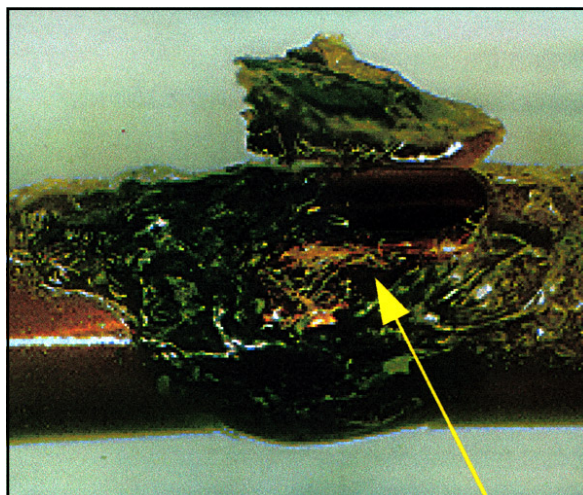
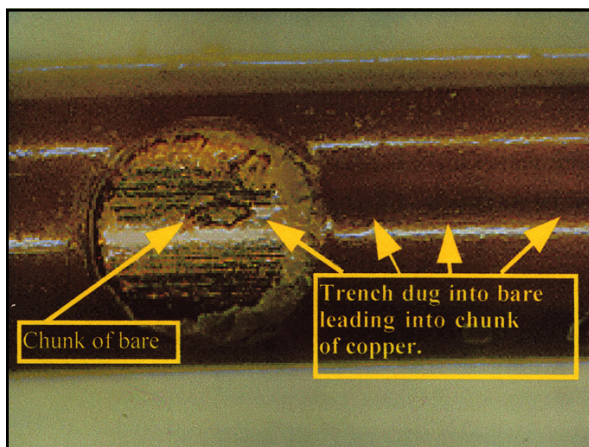
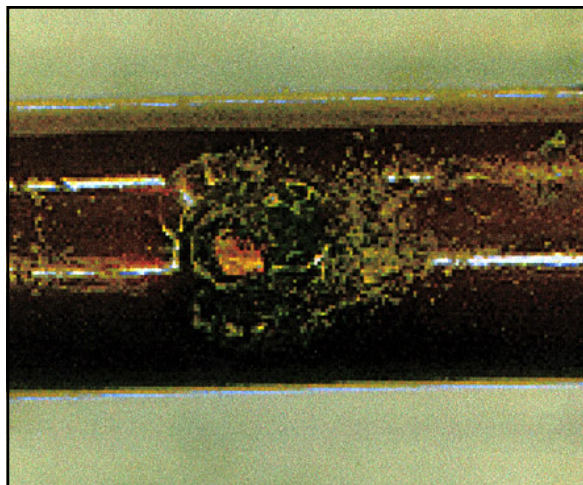
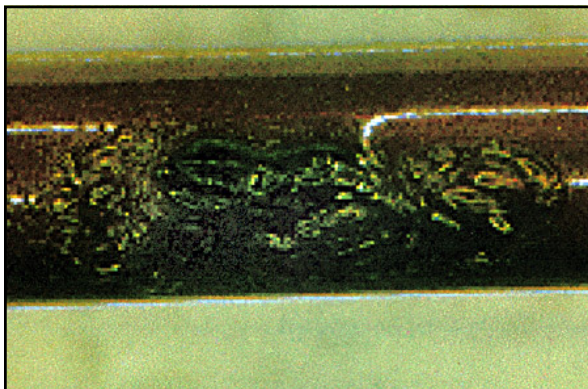
**A****B**

Because of the environment that surrounds motor manufacturing and repair facilities, it is possible to contaminate the insulation material and magnetic wire. Example A is a photograph of clean wire. Example B has been contaminated with metallic dust which can eventually lead to a turn-to-turn or ground failure.



**DAMAGED WIRE**

These are all examples of wire damaged during the manufacturing process. Not all wire damage is a result of the winding process. Microscopic examination may be the only way to prove the wire was damaged when received from the manufacturer.



This blister (left) was discovered by the customer. The bare wire (right) shows the area located under the blister.

# 4

## Shaft Failures

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INTRODUCTION TO SHAFT FAILURES

The majority of shaft failures are caused by a combination of various stresses that act upon the rotor assembly. As long as the stresses are kept within the intended design and application limits, shaft failures should not occur during the expected life of the motor. These stresses can be broken down into the following groups:

Dynamic/Mechanical

- Overloads including sudden shock loads
- Cyclic loads.
- Overhung load and bending.
- Torsional load.
- Axial load.

Environmental

- Corrosion.
- Moisture.
- Erosion.

- Wear.
- Cavitation.

Thermal

- Temperature gradients.
- Rotor bowing.

Residual

- Manufacturing processes.
- Repair processes.

Electromagnetic

- Side loading.
- Out-of-phase reclosing.

It is assumed that the reader has a fundamental knowledge of physics and mechanics and is already familiar with the basic terms, nomenclature and theory associated with motor shafting.

Figure 1 shows a variety of rotor shafts used in electric motors.

MOTOR SHAFT MATERIALS

For most motor applications, hot-rolled carbon steel is a good choice. When higher loads are present, an alloyed steel such as chromium-molybdenum (Cr-Mo) is frequently used. For applications with extreme corrosion or a hostile environment, a stainless steel material is required. Table 1 shows some of the most common steels and their characteristics.

With the stainless steel, you give up yield and tensile strength in favor of resistance to corrosion.

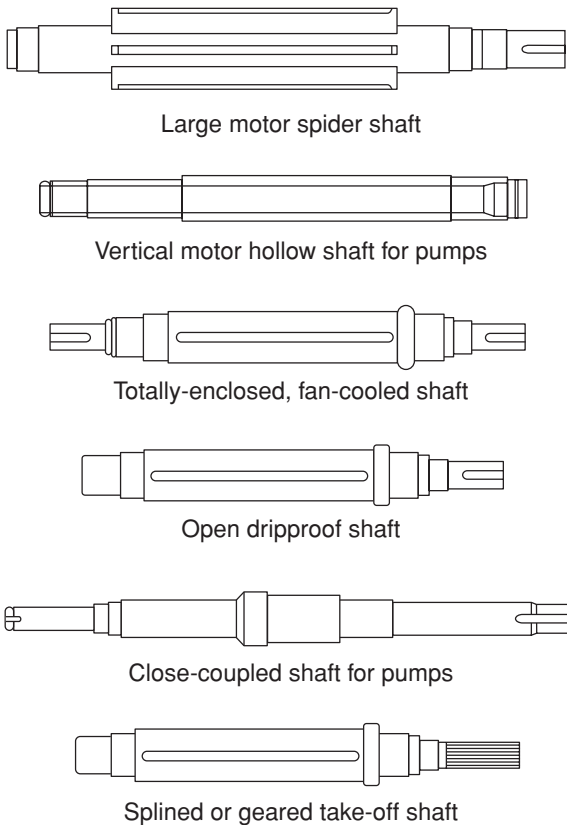
TABLE 1: COMMON SHAFT MATERIALS

| AISI | Material          | Application                  | Tensil      | Yield      |
|------|-------------------|------------------------------|-------------|------------|
| 1045 | Hot-rolled carbon | General purpose              | 82,000 psi  | 45,000 psi |
| 4142 | Cr-Mo             | High stress                  | 100,000 psi | 75,000 psi |
| 416  | Stainless         | Corrosive environment        | 70,000 psi  | 40,000 psi |
| 1144 | Cold-drawn carbon | General-purpose small motors | 108,000 psi | 90,000 psi |

STRESS SYSTEMS ACTING ON SHAFTS

Before the causes of shaft failures can accurately be determined, it is necessary to clearly understand the loading and stresses acting on the shaft. These stresses can best be illustrated by the use of simple free body diagrams. The

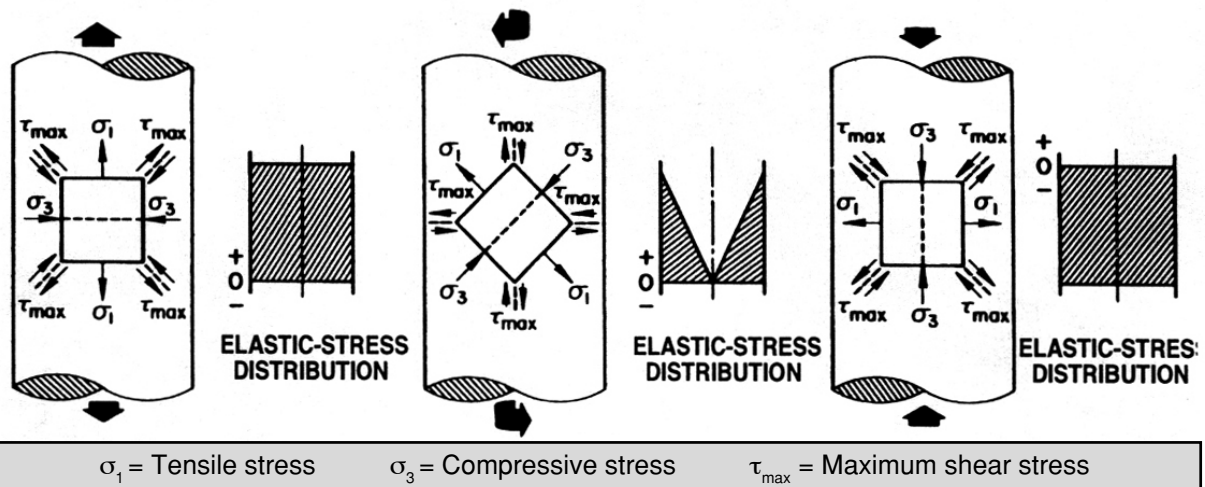
FIGURE 1: TYPICAL MOTOR SHAFT CONFIGURATIONS



PHOTOGRAPHS OF SHAFT FAILURES

|                                     |      |                              |      |
|-------------------------------------|------|------------------------------|------|
| Dynamic and mechanical stress ..... | 4-12 | Residual stress .....        | 4-20 |
| Environmental stress .....          | 4-14 | Electromagnetic stress ..... | 4-22 |
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FIGURE 2: STRESSES ACTING ON SHAFTS



These diagrams show the orientation of normal stresses and shear stresses acting on a shaft under simple tension, torsion and compressive loading.

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free body diagram is simply a sketch showing the types and directions of forces acting on a shaft under tensile, compressive and shear stress.

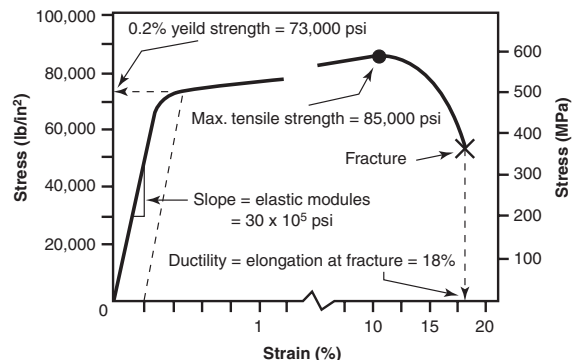
Figure 2 is reproduced from the Metals Handbook, Volume 10 and illustrates how tension, compression, and torsion act on the shaft for both ductile and brittle materials. In the case of motor shafts, the most common materials can be classified as ductile. However, in the presence of a stress riser, a normally ductile material can act as a brittle material and fail rapidly. Failures caused by bending can be treated as a combination of tension and compression where the convex side is in tension and the concave side is in compression.

## STRESS/STRAIN CURVES

To understand the failure mechanisms of a steel motor shaft, it is important to know the relationship between stress and strain for a particular shaft material along with other characteristics associated with a specific material. Figure 3 is a typical stress/strain curve for motor applications.

This stress-strain diagram for cold-rolled 0.18% carbon steel, showing how the 0.2 percent yield strength and other tensile mechanical properties are determined. When a tensile stress is added to a material, the material will begin to deform at a certain level of stress. This deformation is elastic until the stress reaches the yield strength point of steel (at 73,000 psi in Figure 3). Elastic deformation simply means that the material will return to its original shape when the force is removed. Strain is measured by the percent of deformation, and the yield strength is where the strain is at 0.2%. After the applied stress is greater than the yield strength, the deformation is plastic and the steel will not return to its original shape. At this point, the bond between the molecules of steel has been altered, or the molecules have been “torn apart” and cannot go back. The maximum tensile strength is the point at which it is just about to fracture.

FIGURE 3: TYPICAL STRESS/STRAIN CURVE FOR MOTOR SHAFTS  
(Cold-rolled 0.18% carbon steel)



Information from C.R. Brooks and A. Choudry, *“Metallurgical Failure Analysis,”* McGraw-Hill, 1993.

## THE TOOLS OF SHAFT FAILURE ANALYSIS

The ability to properly characterize the microstructure and the surface topology of a failed shaft are critical steps in analyzing failures. The most common tools available to do this can be categorized as follows:

- Visual
- Optical microscope
- Scanning electron microscope
- Transmission electron microscope
- Metallurgical analysis

It is assumed that it may be necessary to employ the services of a skilled metallurgical laboratory to obtain some



of the required information. However, a significant number of failures can be diagnosed with a fundamental knowledge of motor shaft failure causes and visual inspection. This may then lead to confirmation through a metallurgical laboratory. The material presented in this article will help lead to an accurate assessment of the root cause of failure.

## FAILURE ANALYSIS SEQUENCE

There is no absolute specific sequence for determining the cause of failure. The sequence steps may depend on the type of failure. However, the following steps may be useful to determine the cause of a shaft failure:

- Describe failure situation.
- Visual examination.
- Stress analysis.
- Chemical analysis.
- Metallurgical examination—to determine the composition of the shaft material.
- Material properties—to determine if the right material is used for the application.
- Failure simulation.

## METHODOLOGY FOR ANALYSIS

To be consistent with the previous material on stator, rotor and bearing failures and in combination with the above sequence, it is proposed that the analysis of shaft failures contain at least the following elements:

- Failure mode.
- Failure pattern.
- Appearance.
- Application.
- Maintenance history.

## FAILURE MODE

For motor shafts, 90% of all failures can be grouped into the modes shown in Table 2. If the shaft is not designed,

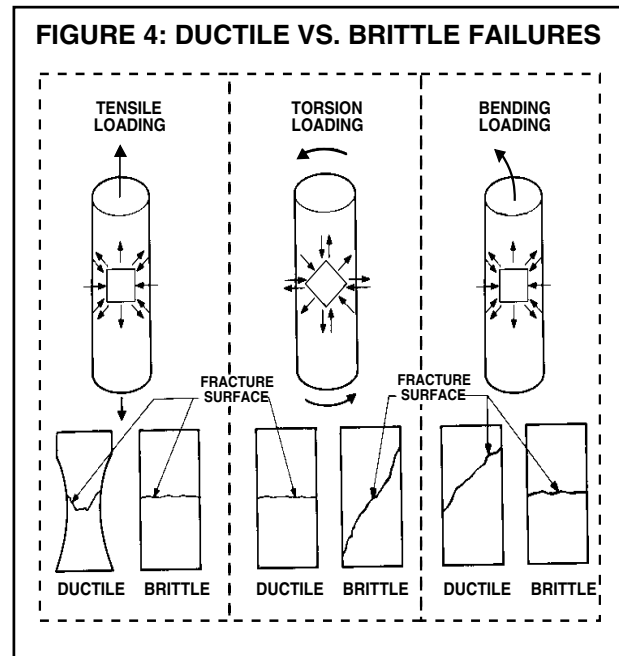
| TABLE 2: FAILURE MODES AND THEIR CAUSES |                                                                                                          |
|-----------------------------------------|----------------------------------------------------------------------------------------------------------|
| Failure mode                            | Cause                                                                                                    |
| Overload                                | High-impact loading (quick stop or jam)                                                                  |
| Fatigue (mechanical or dynamic)         | Excessive rotary bending, such as an overhung load, high torsional load or damage causing stress raisers |
| Corrosion (environmental)               | Wear pitting, fretting, and/or cavitation can result in a fatigue failure if severe enough               |
| Thermal                                 | Temperature gradients, rotor bowing or loss of running fits                                              |
| Residual                                | Surface finish, surface coating, welding, etc.                                                           |
| Electromagnetic                         | Side loading, out-of-phase reclosing                                                                     |

built, applied or used properly, a premature failure may occur in any of the failure modes.

## FAILURE PATTERN

Failure patterns can be associated with the appearance of the shaft after failure. Shaft fractures can be classified as ductile or brittle.

Plastic deformation is associated with ductile fractures since only part of the energy is absorbed as the shaft is deformed. In brittle fractures, most of the energy goes into the fracture and most of the broken pieces fit together quite well. Ductile failures have smooth surfaces and brittle failures have rough surfaces as shown in Figure 4, which is an expansion of Figure 2, where the stresses acting on shafts are shown.



## APPEARANCE CONSIDERATIONS

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 that may have contributed to the shaft failure:

- Is there evidence of foreign material in the motor?
- Are there any signs of blocked ventilation passages?
- Are there signs of overheating exhibited on the surface of the shaft, insulation, lamination, bars, bearings, lubricant, painted surfaces, etc.?
- Have the rotor laminations or the shaft rubbed? Record all locations of contact.
- Are the motor cooling passages clear of debris?
- What is the physical location of the shaft failure? Which end is it on? Did the failure occur at the keyway, bearing shoulder, or elsewhere along the shaft?
- Are the bearings free to rotate and are they operating as intended?

- Are there any signs of moisture on the stator or rotating assembly or contamination of the bearing lubricant or corrosion on the shaft?
- Are there any signs of movement between rotor and shaft or bars and laminations?
- Is the lubrication system as intended or has there been lubricant leakage or deterioration?
- Are there any signs of a stall or locked rotor?
- Was the rotor turning at the time of failure?
- What was the direction of rotation and does it agree with the fan arrangement?
- Are any mechanical parts missing such as balance weights, bolts, rotor teeth, fan blades, etc., or has any contact occurred?
- What is the condition of the coupling device, driven equipment, mounting base, and other related equipment? What is the condition of the pulley? Is it worn?
- 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 shaft loaded axially or radially?
- Do the stress risers show signs of weakness or cracking (the driven end shaft keyway is a weak link)?
- Was there a proper radius on each shoulder along the shaft?
- Was the keyway sledded or milled? Are there stress risers on the sides and back of the keyway?
- What material is the shaft made from? Is it stainless steel? If so, it is magnetic or non-magnetic?
- What is the shaft runout and geometry along all surfaces?
- Is the shaft bent or is there any twisting?

When analyzing shaft failures, it is helpful to draw a sketch of the shaft 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.

### APPLICATION CONSIDERATIONS

It is usually 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 what was the load at the 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? Does the motor use power factor correction capacitors that could cause the shaft to break if the power factor is overcorrected?
- How long does it take for the unit to accelerate to full 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 during operation?
- How often is the unit started and is it manual or automatic? Does it use part winding, wye-delta, ASD, or across-the-line starting?
- What type of protection is provided?
- What tripped the unit off-line?
- Where is the unit located and what are the normal environmental conditions? Are there potentially corrosive materials in the environment?
- What was the ambient temperature around the motor at the time of failure? Was there any recirculation?
- What were the environmental conditions at the time of failure?
- Does the mounting base properly support the motor?
- Was power supplied by a variable frequency drive? How far away is the drive from the motor?
- How would you describe the driven load method of coupling and mounting and exchange of cooling air?
- Is the load belted? If so, how many belts are there and were they too tight? Does the motor use individual or poly belts?

### MAINTENANCE HISTORY

An understanding of past performance of the motor can give a good indication as to the cause of the problem. Questions to ask include:

- How long has the motor been in service?
- Has this motor, or more specifically the shaft, failed in the past and what was the nature of the failure? If so, where was the failure, and what was the cause?
- 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, etc.) were observed prior to 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?
- Has the shaft been repaired previously? If so, what method was used to restore the original geometry; stubbing, welding, plating, metalizing, etc.? Was the shaft stress relieved at the time of repair?



## CAUSES OF FAILURE

Studies have been conducted to try to quantify the causes of shaft failures. One industry study provided the following results for rotating machinery as shown in Table 3.

**TABLE 3: CAUSES OF SHAFT FAILURES**

| Cause of shaft failure                          | Percent of total failures |
|-------------------------------------------------|---------------------------|
| Corrosion                                       | 29%                       |
| Fatigue                                         | 25%                       |
| Brittle fracture                                | 16%                       |
| Overload                                        | 11%                       |
| High-temperature corrosion                      | 7%                        |
| Stress corrosion fatigue/Hydrogen embrittlement | 6%                        |
| Creep                                           | 3%                        |
| Wear, abrasion and erosion                      | 3%                        |

Adapted from C.R. Brooks and A. Choudry, "Metallurgical Failure Analysis," McGraw-Hill, 1993.

There are other informal studies that suggest that the majority of all motor shaft failures are fatigue related, in the 80 to 90% range. For motor applications, it is at least the majority of all shaft failures. The number climbs into the 90% range when the result of corrosion and new stress risers are added. Hence, the main focus of this section will be failures associated with fatigue.

Figure 5 illustrates the typical loading on the shaft and bearings for both horizontal and vertical motors. These free-body diagrams show the distribution of forces in each direction of loading.

The examples in Figure 6 provide the types of motor shaft loading conditions that can lead to fatigue-type failures.

## DEFINING THE FATIGUE PROCESS

Fatigue fractures or damage occurs in repeated cyclic stresses, each of which can be below the yield strength of the shaft material. Usually, as the fatigue cracks progress, they create what is known as beach marks, since they look like the marks that waves leave on the beach.

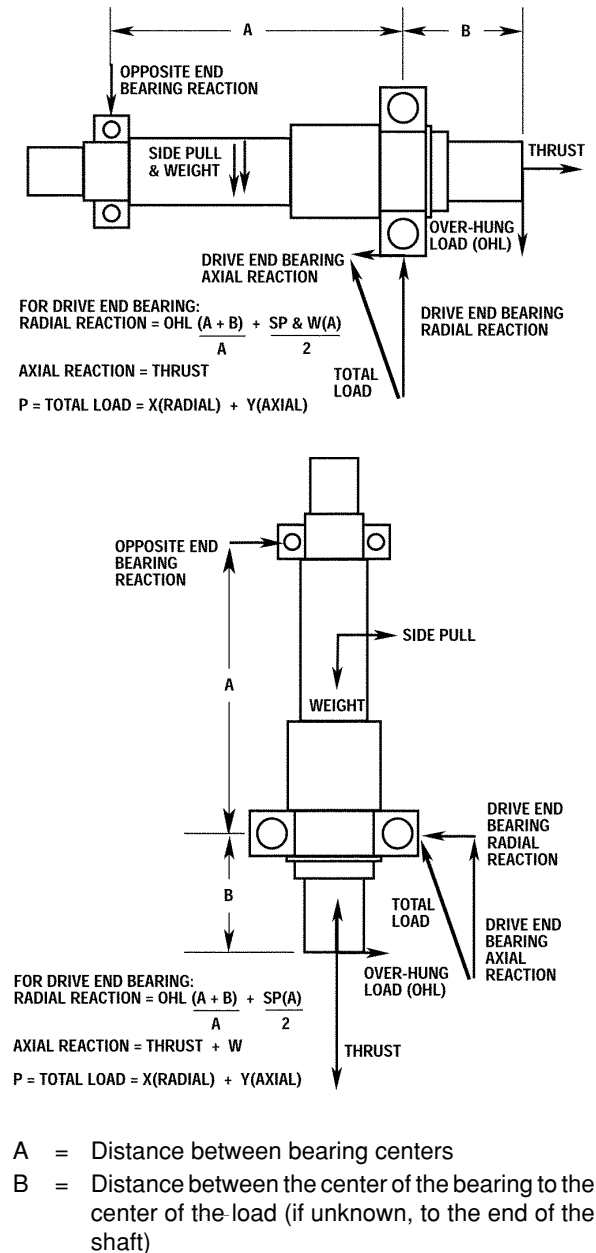
The failure process consists of the following: first, the fatigue leads to an initial crack on the surface of the part; second, the crack or cracks propagate until the remaining shaft cross-section is too weak to carry the load. Finally, a sudden fracture of the remaining area occurs.

Fatigue-type failures usually follow the weakest link theory. That is, the cracks form at the point of maximum stress or minimum strength. This is usually at a shaft discontinuity somewhere between the end of the rotor keyway and the shaft coupling.

There are many variables that affect the fatigue life of a shaft; these include temperature, environment, residual

**FIGURE 5: SHAFT LOADING CONSIDERATIONS**

It is important to understand the shaft loading and the critical stress areas in order to conduct a thorough shaft inspection. This illustration shows the various loading conditions that can exist.



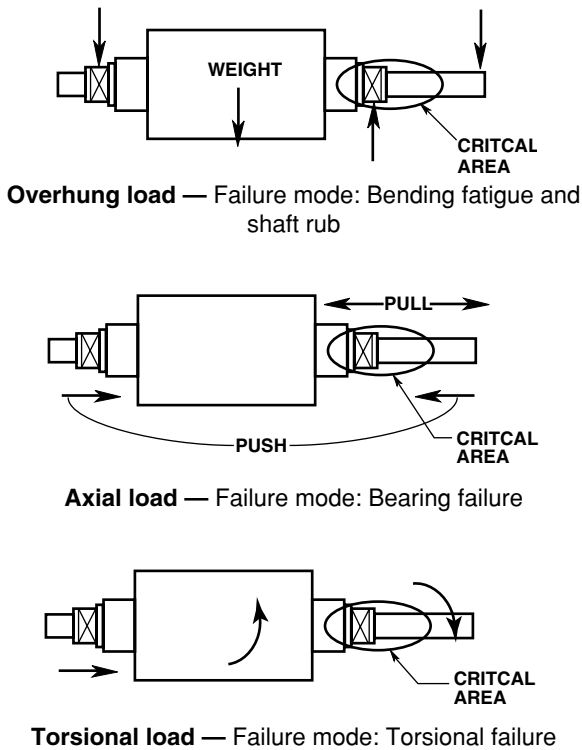
stresses, and the appearance of fretting on the surface, just to name a few.

## STRESS CYCLE (S-N) DIAGRAMS

Since most shaft failures are related to fatigue, which is failure under repeated cyclic load, it is important to understand fatigue strength and endurance limits. One way to establish

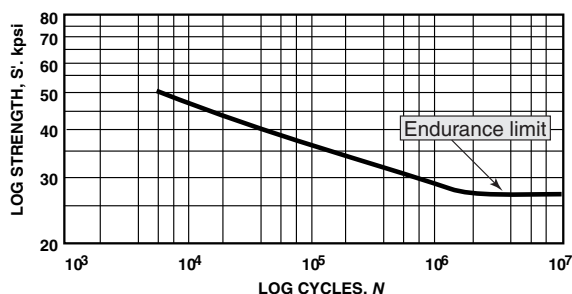
**FIGURE 6: FATIGUE FAILURES**

These three examples illustrate the most common types of motor shaft loading that can lead to fatigue failures.



the strength and limits is to develop a stress cycle or S-N diagram as shown in Figure 7 for a typical 1040 steel. The plot of the maximum stress vs. the number of cycles before failure is called the stress-cycle diagram, or commonly the S-N diagram.

To develop the curve, a steel specimen is subjected to alternating tension and compressive stress by rotating it with a bending load. The stress level is plotted against the number of cycles before the specimen fails. Subsequent tests are done with the same type of specimen at lower and lower stress levels. Each point is plotted to develop the S-N curve for the type of steel.

**FIGURE 7: S-N DIAGRAM FOR 1040 STEEL**

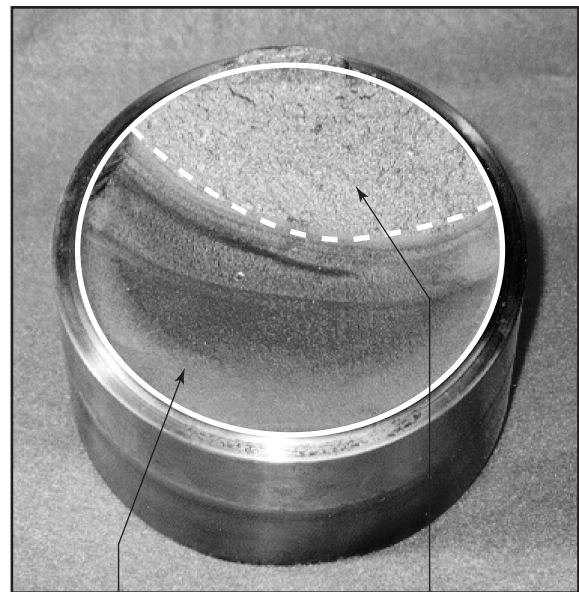
For steel, these plots become horizontal after a certain number of cycles. At a certain stress level, the piece will not fail, no matter how many cycles at which the stress is applied. This stress level, represented as the horizontal line in Figure 7 is known as the fatigue or endurance limit.

### APPEARANCE OF FATIGUE FRACTURES

The appearance of the shaft is influenced by various types of cracks, beach marks, conchoidal marks, radial marks, chevron marks, ratchet marks, cup and cone shapes, shear tip and a whole host of other topologies. (See Figure 13.) Some of the most common ones associated with motor shafts that have failed are due to rotational bending fatigue. The surface of a fatigue fracture will usually display two distinct regions as shown in Figure 8.

Region A includes the point of origin of the failure and evolves at a relative slow rate depending on the running and starting cycle, and of course, the load. Region B is the instantaneous or rapid growth area and exhibits very little plastic deformation. If the conchoidal marks were eccentric, that would indicate a cyclical load.

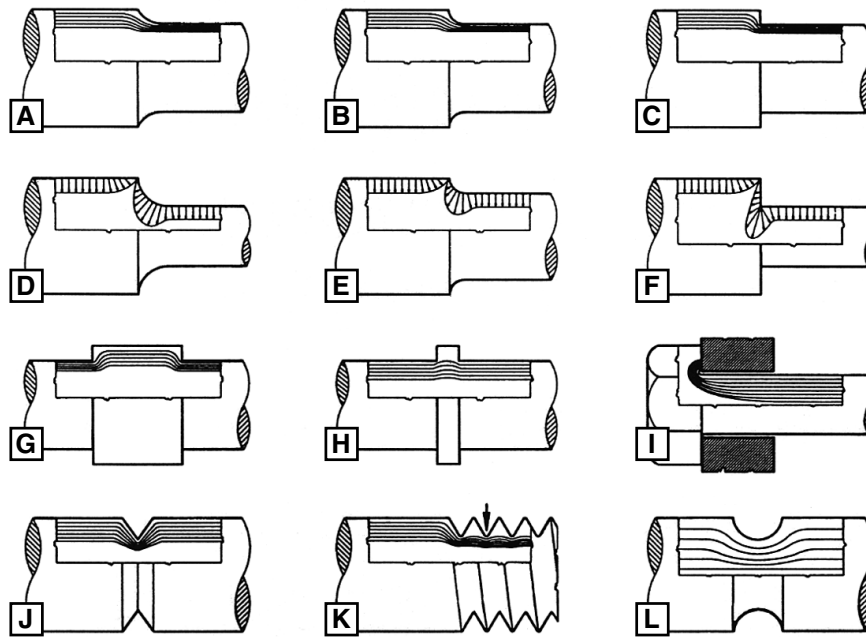
In Figure 8, both the slow growth region and instantaneous regions can be seen. This shaft fractured at the snap ring groove, which is a stress riser. Note the presence of ratchet marks on the periphery of the shaft. These point to the origin of the cracks. Ratchet marks are the boundaries of each fracture plane. The individual cracks will grow inward and eventually join together on a single plane.

**FIGURE 8: REGIONS OF A SHAFT FAILURE**

**Region A**  
Slow growth area of fracture. Note changes in color which represent change in rate of growth.

**Region B**  
Instantaneous area of fracture with little plastic deformation.



**FIGURE 9: STRESS RISERS IN SHAFTS**

Stress is represented by a series of parallel lines. The closer the lines, the higher the stress.

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## THE IMPACT OF STRESS CONCENTRATIONS ON FATIGUE STRENGTH

The origin of cracks caused by fatigue is usually the result of the presence of some surface discontinuities which are commonly referred to as stress risers. A stress riser is a physical or metallurgical discontinuity that increases the stress on a material by some factor. Examples of stress risers on motor shafts are keyways, steps, shoulders, collars, threads, splines, holes, or shaft damage or flaws. Lack of a radius on the shaft will increase the stress at that point dramatically. A larger radius better distributes the stress at the shoulder; in fact, it will be about 60% stronger than the shaft with no radius.

Figure 9 illustrates the distribution of stress as a result of various types of risers. The stress is represented by a series of parallel lines where the stress is inversely proportional to the distance between the lines: the closer the lines, the higher the stress.

It is evident in Figure 9 that the sharper the corner, the higher the level of stress at that point. Along the top row it is shown that a generous radius decreases the stress associated with a sharp inside corner on the keyway. This is one of the reasons why it may be a good idea to taper or sled the keyway because it can reduce some of the shaft failures that occur on the keyway.

Going back to the stress-strain relationships, steel is consistent for a ductile material. For a brittle material, the maximum tensile strength is the same as the yield strength.

There is no period of plastic deformation; it simply fractures brittly when it reaches the yield strength. When a ductile material has a notch, which acts as a stress riser, it tends to act like a brittle material and will fail at the yield strength point before it reaches its maximum tensile strength. So the presence of a stress riser will actually reduce the true strength of the shaft.

Whatever the type of load, the critical areas of highest stress are all in the same area for the three types of load. Most shaft fatigue failures are either behind the bearing journal or at the keyway because these are the points where the stress is the highest.

Quoting from the handbook:

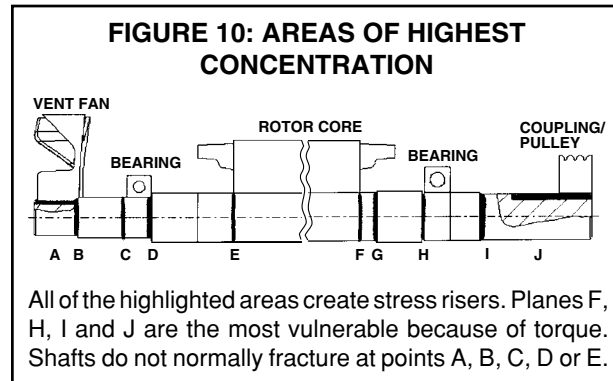
"Progressive increases in stress with decreasing fillet radii are shown in Figure 9A, 9B and 9C and the relative magnitude and distribution of stress resulting from uniform loading of these parts is indicated in Figure 9D, 9E and 9F.

Stress caused by the presence of an integral collar of considerable width is shown in Figure 9G; Figure 9H shows the decrease in stress concentration that accompanies a decrease in collar width. Stress conditions are very similar when collars or similar parts are pressed or shrunk into position. The stress flow at the junction of a bolt head and a shank is as represented in Figure 9I.

A single notch introduces a considerably greater stress concentration effect than does a continuous thread: the reason for this is clear when the stress flow is considered. The stress concentration effect of a single sharp notch is as shown in Figure 9J. The stress concentration at the

right of the arrow in Figure 9K is very similar to that in the narrow collar in Figure 9H because of the mutual relief afforded by adjacent threads. To the left of the arrow, however, the last thread is relieved from one side only and in consequence there is a considerable stress concentration, similar to that of the single notch in Figure 9J. This is why bolts so frequently fracture through the last thread.

The effects of a groove or gouge on stress concentrations is less severe than a sharp notch. A series of grooves will have an effect similar to that shown in Figure 9L."



#### AREAS OF HIGHEST CONCENTRATION

Figure 10 illustrates areas on a normal motor shaft where design stress concentrations (risers) will exist. Wherever there is a surface discontinuity such as a bearing shoulder, snap ring groove, keyway, shaft threads or a hole, a stress riser will exist. Shaft damage or corrosion can also create stress risers. Fatigue cracks and failure will usually occur in these regions. For motors, the two most common places are at the shoulder on the bearing journal (Point H) or in the coupling keyway region (Point J). Although in most cases an axial load will first result in a bearing failure, there are numerous examples where the shaft is damaged before shutdown is achieved.

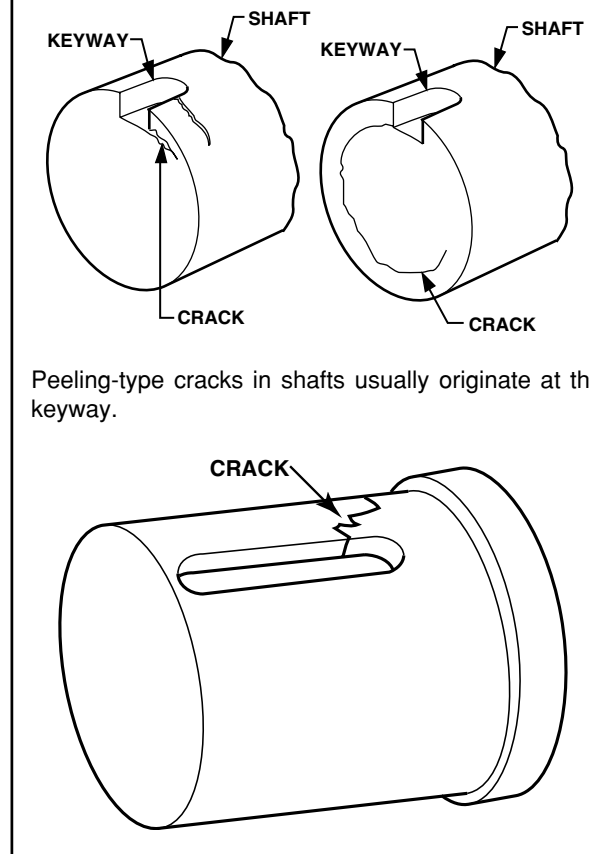
#### SHAFT KEYWAYS

Keyways are used commonly to secure fans, rotor cores and couplings to the shaft. All of these cause stress risers. However, the keyway on the take-off end or drive end of the shaft is the one of most concern because it is located in the region of highest shaft loading. When this loading has a high torsional component, fatigue cracks may start in the fillets or roots of the keyway.

Keyways that end with a sharp step have a higher level of stress concentration than those that use a "sled-runner" type of keyway. In the case of heavy shaft loading, cracks frequently emanate at this sharp step. It is important to have an adequate radius on the inside corners of the keyway. Loosely-fitted keys can cause fretting that may accelerate shaft failures. (See Figure 11.)

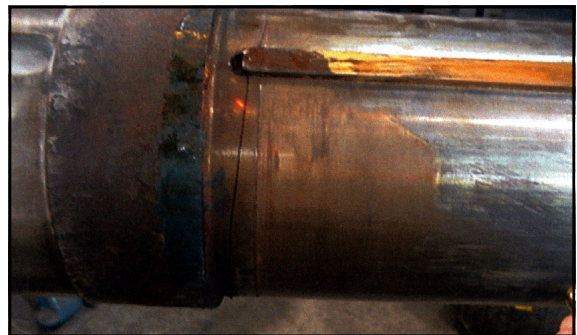
Figure 12 shows a cracked journal on the rotor core keyway that carries the rotor laminations. This particular problem was detected by vibration analysis. A visual in-

**FIGURE 11: COMMON KEYWAY FAILURES**



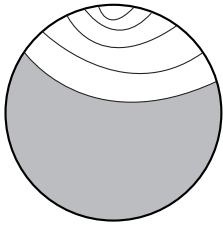
spection would only have revealed this condition if the shaft was removed from the rotor core. The crack originated in the high stress area of the keyway. If the crack had not been detected, the failure of the shaft would have been catastrophic.

**FIGURE 12: CRACKED ROTOR CORE KEYWAY**

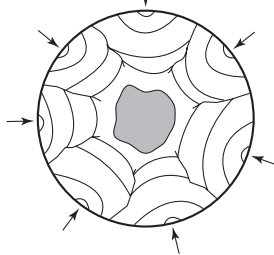


This cracked journal carries the rotor lamination and was detected through vibration analysis. A different type of keyway with a reduced stress riser may have prevented this failure from happening.

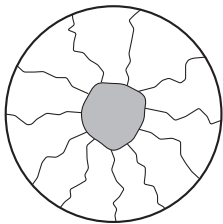


**FIGURE 13: APPEARANCE OF THE MOST COMMON SHAFT FAILURES****BEACH MARKS (CLAMSHELL, CONCHOIDAL)**

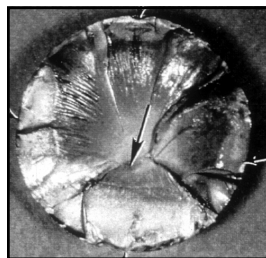
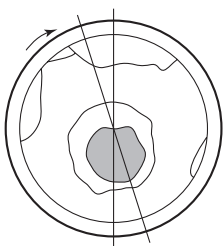
Beach marks indicate successive positions of the advancing crack front. The marks are usually smooth textured near the origin and become rougher as the crack grows.

**RATCHET MARKS (RADIAL STEPS)**

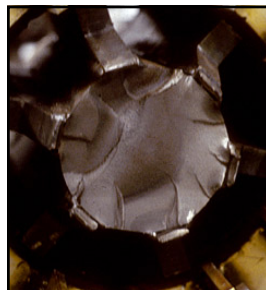
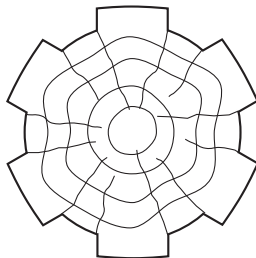
Ratchet marks are the telltale sign of several individual cracks that ultimately merge to form a single crack. Ratchet marks are present between the crack origins.

**CHEVRON MARKS**

Chevrons, or arrows, point to the origin of the crack. Some failures (like the one shown below under torsional) will have more pronounced chevrons. The more brittle the fracture, the smaller the end point of failure.

**ROTATIONAL BENDING**

Rotational bending fatigue failures occur when each part of the shaft is subject to alternating compression and tension under load. A crack can start at any point on the surface where there is a stress riser, and may grow unevenly because of the rotation. This particular shaft has several points of initiation as indicated by the ratchet marks on the perimeter.

**TORSIONAL**

Torsional failures are identified by the “twisted” appearance on the shaft. However, depending on the amount of torsional loading and whether the material is ductile or brittle, the failure may appear differently. This particular shaft shows some amount of twisting before failure. The stress risers on the shaft were at the points the spiders were welded. If the shaft material is ductile, it will show more twisting before failure; if the shaft is more brittle, or subject to extreme torsion, the fracture will have a rougher appearance.

## DYNAMIC AND MECHANICAL STRESSES

Dynamic or mechanical stresses have to do with movement. Since the shaft is one of the moving parts of the motor, it is more susceptible to damage or failure when subject to dynamic and mechanical stresses. These stresses include:

- Overloads, including sudden shock loads.
- Cyclic loads.
- Overhung loads and rotational bending.
- Torsional loads.
- Axial loads.

Dynamic and mechanical stresses are normally caused by forces that are external to the motor itself, specifically the load. Shafts can bend or break if the load causes a stress that exceeds the yield strength of the shaft material.

### OVERLOADS

All materials have a limit to the amount of load they can carry. When a shaft fails due to a single application of a load that is greater than the maximum strength of the material, it is considered an overload failure. This will usually happen almost immediately.

This type of failure can be ductile or brittle. Brittle fractures look like they could be glued back together. There are also “chevron marks” on the face of a brittle fracture that show the progression of the failure across the piece. The chevron “arrows” always point to the place where the crack started.

A severe shock load, even on ductile material, can cause it to break like a brittle material. The appearance of a failure, whether ductile or brittle, depends on a number of different factors including the shaft material, the type and magnitude of the load, and the temperature of the shaft when it failed.

### CYCLIC LOADS

Fatigue cycle life is affected by the type of load on the motor. The fatigue cycle can be described as one cycle of the load. Therefore, if it is a variable torque load, each start will represent one fatigue cycle. A reciprocal or cyclical load will fatigue cycle every time the load changes. When the shaft is subject to rotational bending, the fatigue cycle will be once every revolution.

With the presence of a stress riser, a cyclic load will only speed up the failure process when the shaft is subjected to heavy loads. In the case of a shock load, or sudden overload, the shaft may snap and appear as a brittle failure. (See Table 4.)

### OVERHUNG LOAD AND ROTATIONAL BENDING

Bending fatigue, due to overhung loads or heavy radial loads (such as a large pulley), can cause the shaft to bend

**FIGURE 14: SPALLING ON A BEARING RACEWAY**



The condition of the bearing can be a clue to the type and direction of loading on the shaft. This illustrates how excessive load can cause spalling on the bearing raceway. Spalling will normally occur as the bearing fails; however, the time to failure can be accelerated with an increase in load.

or rub. Most “bending” failures are considered rotational, since the shaft is subject to alternating tensile and compressive stress at every point around its diameter every time it makes a revolution. Each rotation is a fatigue cycle, so shaft speed will be a factor in the fatigue cycle life. If the shaft is exposed first to tension and then compression, a crack can start anywhere on the surface, and more than one crack can form. As the crack progresses across the face, it will grow unevenly.

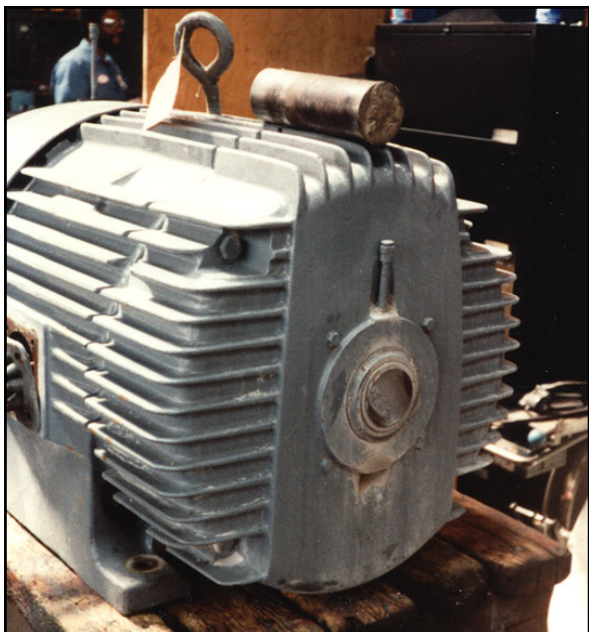
### AXIAL LOAD

Axial fatigue is commonly associated with vertical shaft mounting, but also may describe a substantial thrust load. Typically, the bearing carrying the axial load will fatigue before the shaft. This is usually evidenced by spalling of the bearing raceways (Figure 14).

### TORSIONAL LOAD

Torsional fatigue is associated with the amount of shaft torque present and transmitted load. Torsional loads describe the “twisting” load of a shaft transmitting torque. The more cyclical the load, the sooner this will lead to failure.

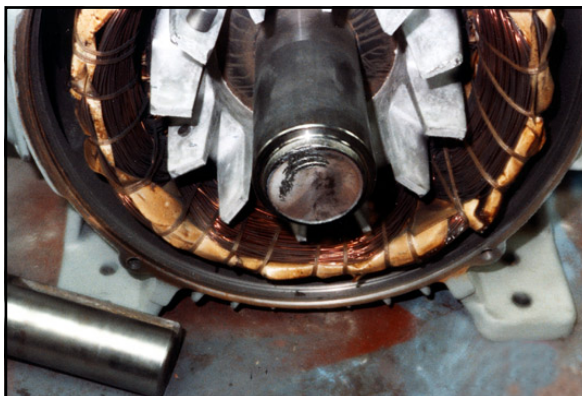


**DYNAMIC AND MECHANICAL STRESSES**

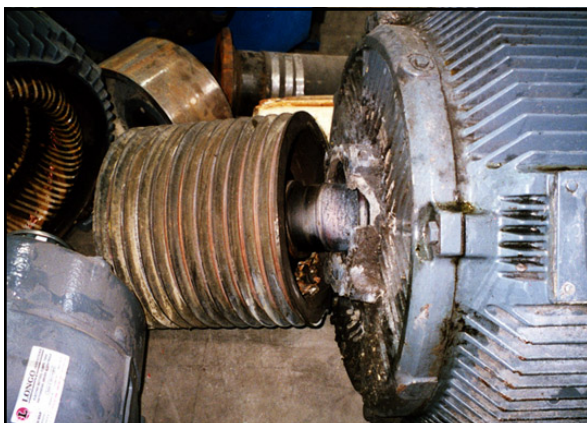
These are all examples of rotational bending. Each example clearly shows one or more points of origination, along with a region of growth before the ultimate failure of the shaft. Each failure occurred at a change in geometry of the shaft, which is a significant stress riser.



Note the ratchet marks (below) and the successive changes in shaft diameter (above).





**DYNAMIC AND MECHANICAL STRESSES**

This failure was caused by a loss of running clearance between the shaft and bracket. There are a number of possible root causes to this failure including heavy overhung load, improper lubrication practices, excessive vibration, misalignment, or excessive thermal stress.



The keyway on this shaft extends too far back, past the step. Note the torsional bending.



This shaft failed due to torsional bending. The “heads-up” service center marked the shaft as they checked for runout along each step, since there could be twisting further along the shaft.



This fatigue crack began at the high stress riser at the keyway.





## ENVIRONMENTAL STRESS

Environmental stress results from materials in the environment, whether chemical or moisture. These substances can attack the surface of the shaft to cause corrosion, abrasion and wear. Each pit or eroded area becomes a stress riser. The additional stress risers can speed up the fatigue process.

Environmental stress includes:

- Moisture.
- Erosion.
- Wear.
- Corrosion.
- Cavitation.

There are certain shaft materials that can resist the effects of chemicals, but their use requires careful consideration, since the strength of the shaft may be reduced.

The appearance of a shaft damaged by environmental factors is easy to identify. The presence of moisture might appear as rust. Abrasion, corrosion and wear will remove material from the shaft surfaces.

## CORROSION FAILURES

In corrosion failures, the stress is the environment and the reaction it has on the shaft material. Corrosion occurs when the surface of the shaft comes into contact with chemicals or moisture in the environment. It usually appears as oxidation or pitting of the shaft surface.

At the core of this problem is an electrochemical reaction that weakens the shaft. Pitting is one of the most common types of corrosion, which is usually confined to a number of small cavities on the shaft surface. Corrosion will cause a loss of material on the shaft. Even a small amount of material loss can result in perforation, with a resulting failure in a relatively short period of time without any advanced warning. On occasion, the pitting has caused stress risers that result in fatigue cracks.

When a motor is in an environment where corrosion is possible, the use of a stainless steel shaft can prevent damage. However, stainless steel has a lower yield strength and fatigue cycle life than a typical carbon steel. As a note,

if a stainless steel shaft is replaced, confirm whether the shaft is magnetic or non-magnetic stainless steel, since in rare cases the shaft material contributes to the rotor flux. If it is not properly replaced, failures can occur.

Corrosion can reduce the fatigue life of a shaft and can cause failure at lighter loads than expected. This is referred to as corrosion-induced fatigue.

## CAVITATION

In pumping applications where the flow of liquid over the shaft is turbulent, a phenomena known as cavitation can occur. Cavities, bubbles or voids are created in the fluid for short durations. As they collapse, they produce shock waves that erode the shaft surface. The shaft can be weakened and fail prematurely. A common approach to minimizing this condition is to use a stainless steel shaft, which has a much enhanced abrasion resistance and wear quality. There are also some elastomeric coatings that increase resistance to erosion.

## SHAFT FRETTING

Shaft fretting can cause serious damage to the shaft and a mating part. The cause of this condition is movement between two mating parts and the presence of oxygen in air.

Fretting occurs where two surfaces are in loose contact with each other. Typical locations are points on the shaft where a “press” or “slip” fit should exist. Keyed hubs, bearings, couplings, shaft sleeves and splines are examples.

These parts normally have an interference fit and are susceptible to very slight vibration which can cause some movement between the parts. When this happens, microscopic particles wear away from the points of contact. The particles are so small that they oxidize in air immediately. The presence of ferric oxide (rust), which is reddish-brown in color, between the mating surfaces is strong confirmation that fretting did occur. The oxide particles act as an abrasive, accelerating the rate of wear on the shaft surface.

Damage to the shaft can also occur when pulleys and couplings are not properly fitted.

## ENVIRONMENTAL STRESS



This close-coupled pump shaft shows considerable damage from corrosion. The formation of rust will reduce the fatigue life.

**ENVIRONMENTAL STRESS**

Contamination from moisture or chemicals trapped in the coupling arrangement eroded the surface of the shaft.



Severe rust has formed on the inside surfaces of this motor.



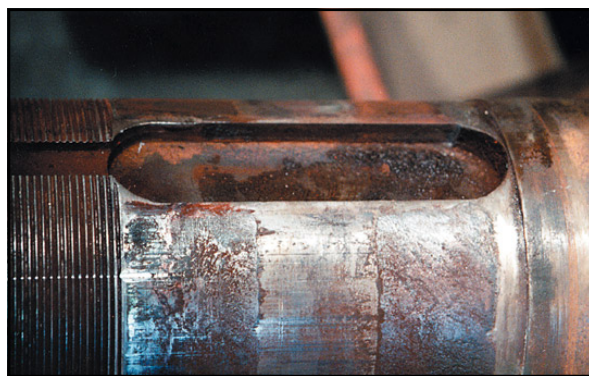
This pump shaft has been damaged by severe cavitation.



This is an example of severe corrosion on the shaft, due to seal failure. This allowed water to enter into the motor.



This is a pump shaft with considerable rust damage.



Corrosion has damaged the keyway of this shaft. The keyway is already a stress riser. If the key is at all loose, from material being worn away, the key may grind away at the surface causing more damage.



## THERMAL STRESSES

When a motor is in service, it is usually under thermal stress. Thermal stress can bend and/or discolor the shaft.

Increases in temperature cause the shaft to expand. Large variations in temperature cause the rotor and shaft to alternately grow and contract. In extreme cases of overheating, the rotor can bow causing the rotor or shaft to strike the stator winding or bore.

There may be other situations can cause the shaft temperature to heat to a point where either it bends or changes the internal structure of the steel, thus altering its strength.

Situations that can contribute to thermal stress on the shaft can include:

- Ventilation failure.
- Overload.
- Bearing failure.
- Loss of clearance.
- Stall.

In the cases listed above, the shaft may not be the weak link. However, it may be weakened or bent. If the shaft is not straightened or stress relieved, more failures could occur. If not done properly, some processes, such as welding, can thermally stress a shaft as well.

Loss of running fits between the shaft and other parts such as end brackets, shaft seals or bearing caps, can

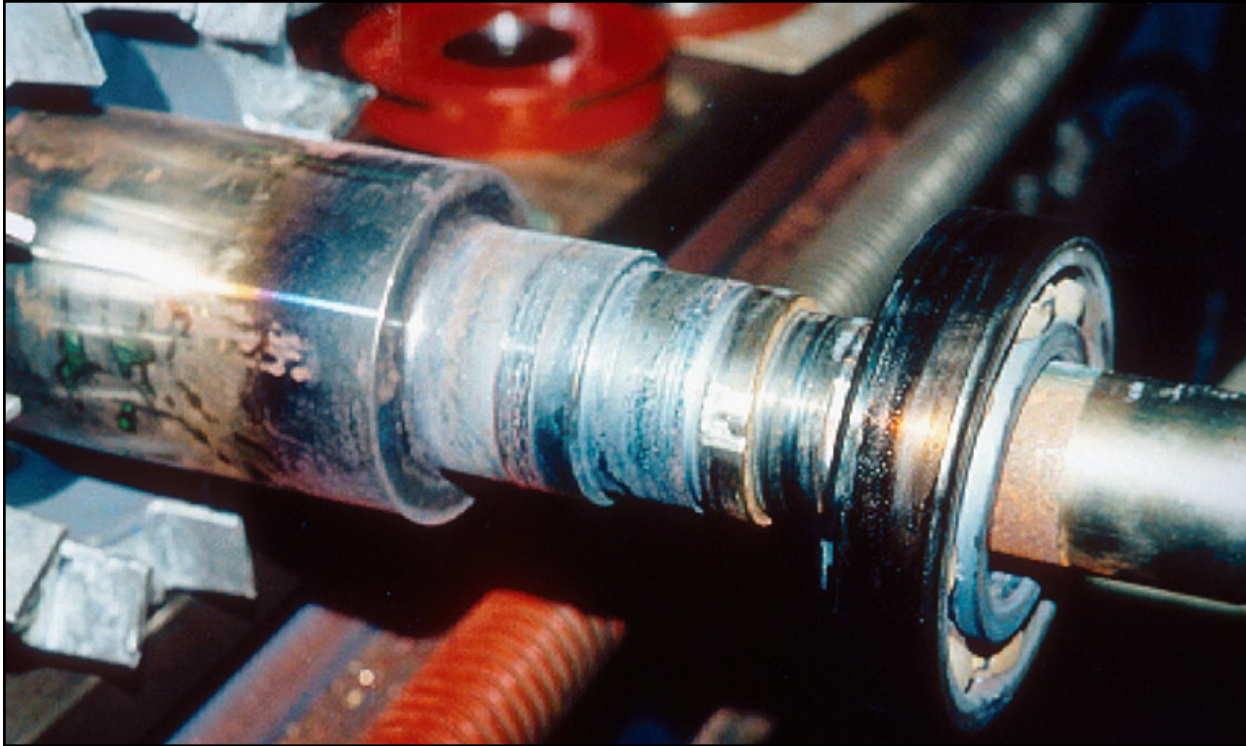
cause the temperature of the shaft to increase. This type of shaft failure is often catastrophic and can result in severe damage to the bearing, rotor and stator. The driven equipment may also be severely damaged.

If the motor continues to operate after this occurs, a tremendous amount of heat is generated at the point of contact.

Note that the motor shaft actually bends before the shaft temperature reaches the melting point.

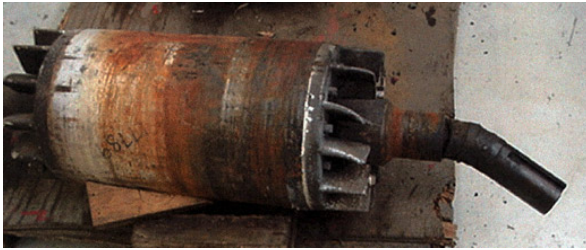
The motor over-current protection may not sense this condition. This is because the controls are usually set to trip at 125% current overload. Unfortunately, many motors operate at less than full load, but the overload protection may be sized assuming it runs fully loaded. If the bearings or shaft are heating up and failing, the current will not rise to the point where it would be taken off line, and a catastrophic failure may occur. The friction that causes the shaft to bend causes a loss of clearance. The loss of clearance will increase the load, which will in turn increase the current. If the motor is not fully loaded, then the increase in current may not trip the over-current protection. However, vibration sensors or bearing temperature detectors (if present!) will usually shut down the motor before a catastrophic failure occurs. These catastrophic failures simply illustrate the importance of a simple bearing resistance temperature detector (RTD).

### THERMAL STRESS

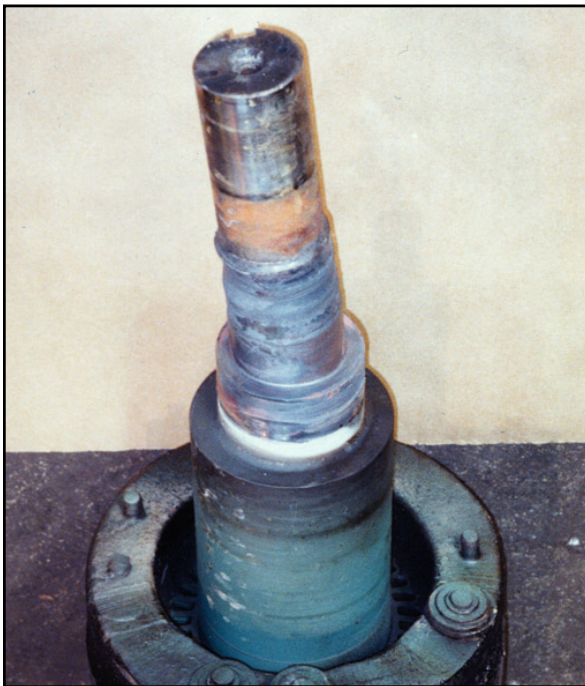


There was an enormous amount of heat generated between the bearing inner race and the shaft due to a loss of fit. The evidence that the heat originated on the shaft is that as the heat progressed inward, it was hit with cooling air from the rotor fan. The area of the shaft that was cooled by the air does not have as much damage from the heat.

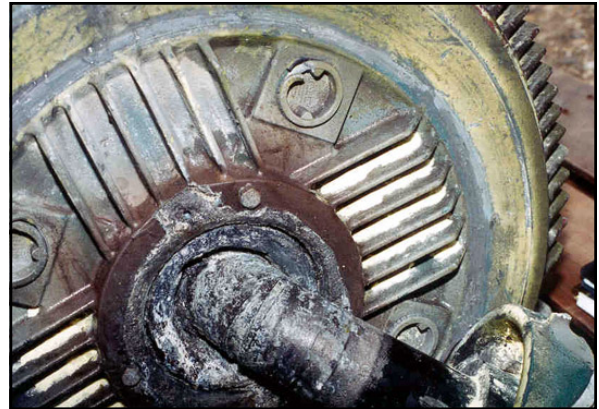


**THERMAL STRESS**

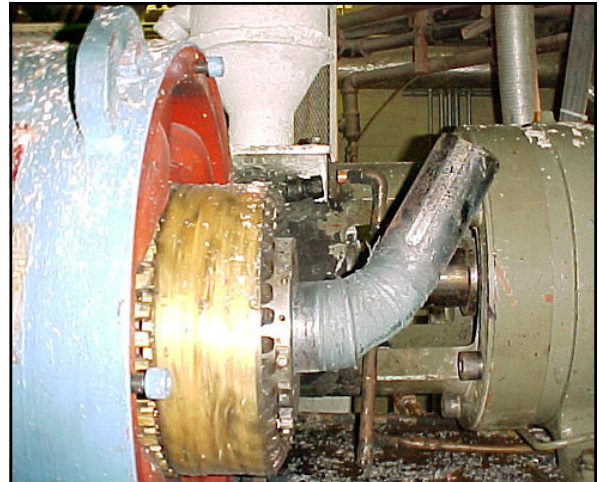
Either misalignment or vibration caused the bearing to fail which led to a loss of fit between the bearing inner race and the shaft. This generated an enormous amount of heat, bending the shaft.



Diligence and protection mean the difference between minor damage and this type of failure.



This shaft failure began when the bearing failed and led to a loss of fit on the shaft. The resulting friction caused the shaft to heat up very rapidly and bend almost 90°.

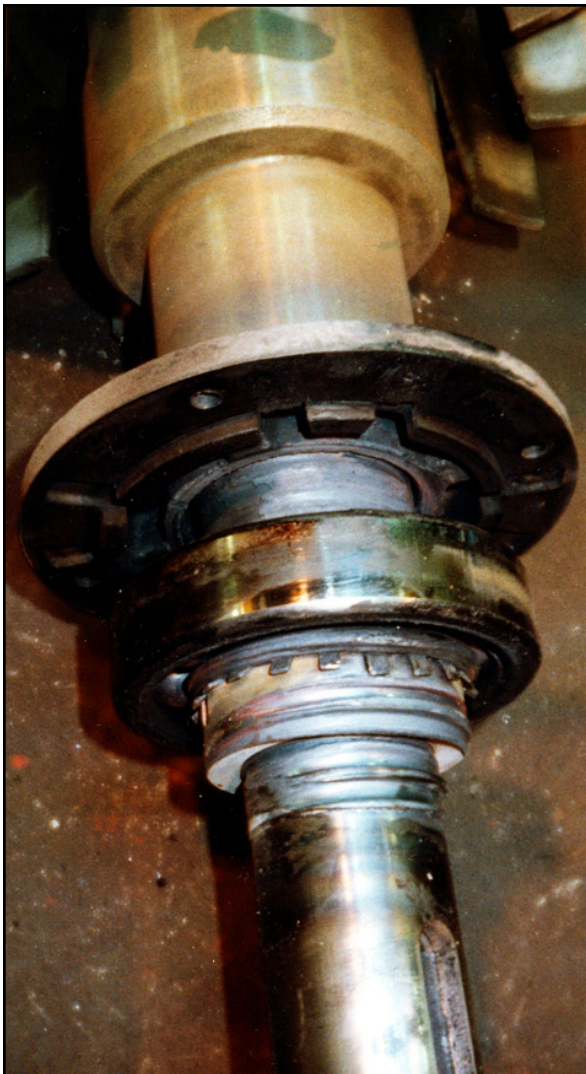
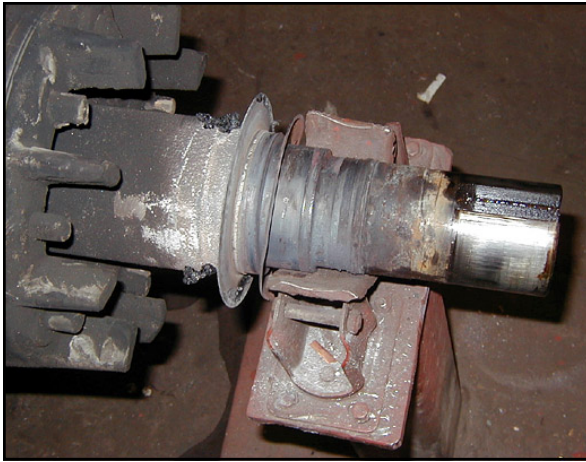


In this example, the bearing failed and disintegrated. This generated a tremendous amount of heat in the shaft, bearings, and end bracket. Due to the catastrophic nature of these types of failures, it can be difficult to determine the actual root cause of failure.



## THERMAL STRESS

In all of these examples, extreme heat was generated between the stationary and moving parts of the shaft assembly. In each case, the shaft had extreme runout.



This shaft failed due to loss of clearance. The severe gouging/scoring on the shaft generated a tremendous amount of heat from the contact between the stationary and rotating parts.

## RESIDUAL STRESS

Residual stress is independent of the external loading on the shaft. There are many manufacturing and repair procedures that can create residual stress in the shaft which may accelerate failure. These procedures can be mechanical or thermal. Mechanical procedures include:

- Drawing.
- Bending.
- Straightening.
- Machining.
- Surface rolling.
- Shot blasting or peening.
- Undercutting.
- Metallizing.

All of these operations can produce residual stresses. In addition to the above mechanical processes, thermal processes that introduce residual stress include:

- Hot rolling.
- Welding.
- Torch cutting.
- Heat treating.

Not all residual stress is detrimental to the shaft. If the stress is parallel to the load stress and in an opposite direction, it may actually be beneficial. Stress relieving will reduce the residual stresses.

## SURFACE FINISH EFFECTS

In most applications, the maximum shaft stress occurs on the surface. Hence, the surface finish can have a significant impact on fatigue life. During the manufacturing process, handling and repairs, it is important not to perform operations that would result in a rougher shaft finish. The impact of surface finish on fatigue cycle life can be seen in Table 4.

## SURFACE COATING

Shafts repaired by welding are beyond the scope of this paper. However, caution must be used in this process. The selection of the proper weld material, method of application, stress relieving, surface finish and diameter transitions are all critical to a successful repair. Not all shaft materials are good candidates for welding-type repairs as shown in Table 5.

The Metals Handbook Volume 10 provides additional information on this subject.

**TABLE 4: IMPACT OF SURFACE FINISHES**

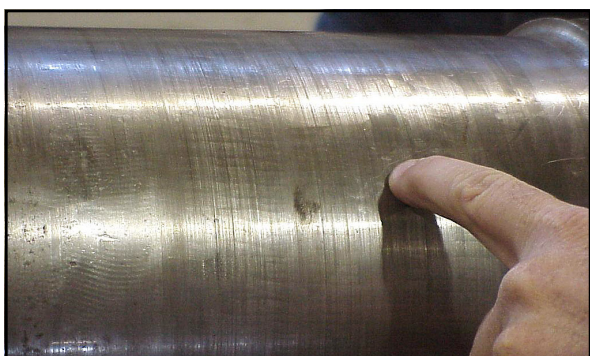
| Finishing operation                                                                                    | Surface finish<br>( $\mu$ in.) | Fatigue life<br>(cycles) |
|--------------------------------------------------------------------------------------------------------|--------------------------------|--------------------------|
| Lathe                                                                                                  | 105                            | 24,000                   |
| Partly hand polished                                                                                   | 6                              | 91,000                   |
| Hand polished                                                                                          | 5                              | 137,000                  |
| Ground                                                                                                 | 7                              | 217,000                  |
| Ground and polished                                                                                    | 2                              | 234,000                  |
| Colangelo, V.J. and Heiser, F.A. <i>"Analysis of Metallurgical Failures."</i> John Wiley & Sons, 1974. |                                |                          |

**TABLE 5: COMMON SHAFT MATERIALS**

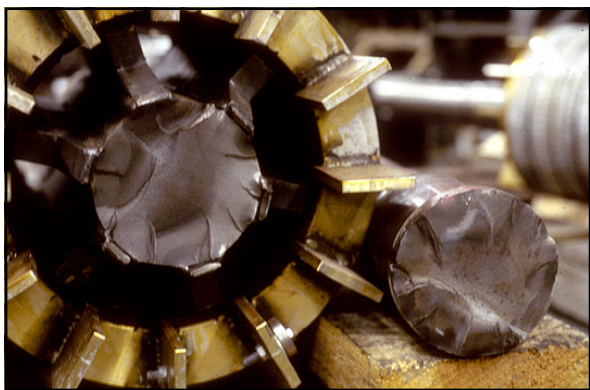
| Grade  | Material                                       | Comments                                                                                                             |
|--------|------------------------------------------------|----------------------------------------------------------------------------------------------------------------------|
| C10xx  | Plain carbon steel<br>(e.g., 1018, 1045, etc.) | Standard motors with normal torque up to 500 hp. Can be welded successfully (e.g., shafts with spiders).             |
| C41xx  | Chrome molybdenum steel (e.g., 4140, 4150)     | High strength. Used for crusher-duty applications; propeller shafts; transmission shafts. Do not weld this material. |
| C1144  | Resulfurized steel                             | Higher strength than C4150. Can be welded successfully.                                                              |
| C4340  | Nickel chrome molybdenum                       | Annealed; higher strength than C1144; heavy duty. Do not weld this material.                                         |
| 17-4PH | Magnetic stainless (e.g., 400 series)          | Use this material for explosion-proof motors that require magnetic shaft properties.                                 |



## RESIDUAL STRESS



The shaft journals above were both welded. The shaft at bottom has also been machined. Axial passes with a stick welder are more likely to bend the shaft. Varying hardness is also more likely, resulting in a bearing journal that is not perfectly round. Irregularities will increase friction and cause difficulty when fitting the bearing. Machining processes will release some of the residual stresses caused by welding. For example, milling a keyway will usually result in a bent shaft, unless the shaft is properly stress relieved after welding and before machining.



This is a fabricated rotor with a spider shaft. The points where the spider was welded to the shaft introduced stress risers in the same plane, eventually causing the rotational bending failure.



The photograph at top shows a crack that occurred at the keyway. In the photograph below, a crack repaired by welding. The welding process can introduce residual stresses into the shaft, thereby making the repair futile.



The crack on this shaft was detected with a dye penetrant.

## ELECTROMAGNETIC STRESS

Although not specifically a shaft issue, there are nonetheless electromagnetic forces that act on the shaft. When the air gap is not symmetrical, electromagnetic force acts on the rotor to pull it closer to the stator. The smaller the gap becomes, the stronger the force. Eventually, the rotor may come into contact with the stator.

The distinction should be made between rotor pullover and electromagnetic forces of an eccentric air gap, and a rotor strike or rub due to a heavy radial load (belted, chained, etc.) that causes the shaft to deflect.

Electromagnetic stress acting on the shaft will not likely cause permanent deformation, since the force of the pullover won't be greater than the yield strength of the shaft.

The shaft is typically designed with sufficient stiffness to resist bending under normal conditions. However, if a rotor strike occurs, it is often difficult to find a problem with the shaft.

Since the deformation of the shaft is not permanent, the original geometry is restored after the rub. Since rotor pullover is technically a rotor issue, it is not covered in great detail here. Rather, refer to Section 5 for additional information. Table 6 is provided as a reference to determine possible causes of a rotor strike based on the appearance of the rotor and stator laminations. Some of the causes are shaft related, while others are rotor or bearing related.

There are a few other situations that can introduce electromagnetic stresses on the shaft. These include ex-

**TABLE 6: COMMON CAUSES OF ROTOR STRIKES BASED ON POINTS OF CONTACT**

|       |           | Stator                                                                                                                                                                                               |                                                                                                                                  |                                                                                                                                                                      |      |
|-------|-----------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------|------|
|       |           | Contact area                                                                                                                                                                                         | One point                                                                                                                        | Random                                                                                                                                                               | 360° |
| Rotor | 360°      | <ul style="list-style-type: none"><li>Excessive radial load on the shaft.</li><li>Failed bearing plus radial load.</li><li>Eccentric air gap.</li><li>Bearing housing machined off center.</li></ul> |                                                                                                                                  | <ul style="list-style-type: none"><li>Failed bearing with direct-coupled load.</li><li>Broken shaft.</li><li>Severely-worn bearing fit (shaft or housing).</li></ul> |      |
|       | Random    | 2                                                                                                                                                                                                    | Strictly rotor pullover during starting. The shaft stiffness is not enough to resist magnetic forces during starting.<br>1, 3, 4 |                                                                                                                                                                      |      |
|       | One point | Eccentric rotor and the shaft rotational axis is not concentric to the stator bore.<br>2                                                                                                             | 2                                                                                                                                | <ul style="list-style-type: none"><li>Eccentric rotor.</li><li>Bent shaft.</li><li>Bearing journal is not concentric to the rotor.</li></ul>                         |      |

- 1 Although not common, inspect for a loose stator core.
- 2 If anything in the motor history indicates that the problem started suddenly, look for either high line voltage or a cracked shaft within the rotor core.
- 3 If the motor is a 2 pole, it could be operating at excessive voltage. Check for recent transformer tap changes, etc.
- 4 Prolonged operation of a motor with random stator-to-rotor contact could eventually result in an appearance of 360° contact on both parts.

Note: Severe bearing failure could result in any of the above combinations.

Vertical machines with thrust bearings: Momentary upthrust can result in random 360° contact of the rotor and stator on the thrust bearing end only.

### Detection methods

- Noise at starting (rotor slap).
- Vibration during starting, at multiple random frequencies.
- Check for flexing shaft using a vibration analyzer with a strobe light.



cessive radial loading and out-of-phase reclosing. Another situation that can cause a shaft to fail, although uncommon, would be overcorrection of power factor. Overcorrection can cause transient torques that can break shafts.

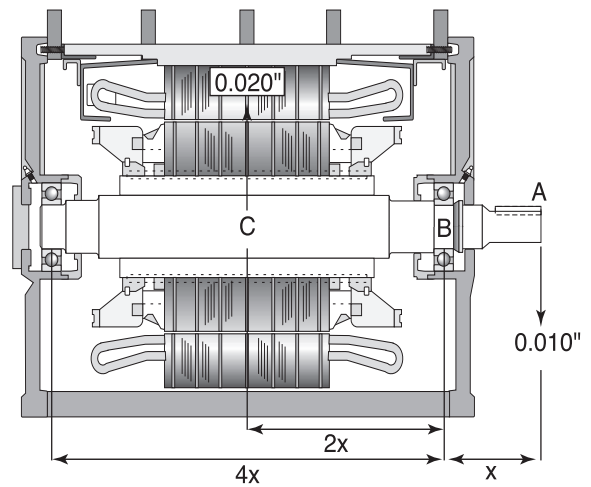
### EXCESSIVE RADIAL LOAD

If there is a very heavy radial load on a shaft, it can cause a change in the air gap geometry that can lead to a rotor rub and/or a bent shaft. This is especially true if the radial load is heavy and the shaft extension is very long. This is illustrated in Figure 15. If the length of the shaft extension is  $x$ , and the distance between bearings is  $4x$ , then if we apply a force at the end of the shaft, A, the drive end bearing at B is the fulcrum, causing maximum deflection of the shaft at C, the center point between the bearings.

### OUT-OF-PHASE RECLOSING

A reclosure is most simply stated as a high voltage transient. Although the stator winding is most likely to fail, the voltage transient can create a tremendous amount of torque on the shaft. It is important to realize that the current is related to the square of the voltage. Therefore, the higher the voltage associated with the reclosure, the higher the current, and the higher the torque that is generated. If the force is great enough, the shaft can snap due to the torsional stress.

**FIGURE 15: RADIAL LOADING**

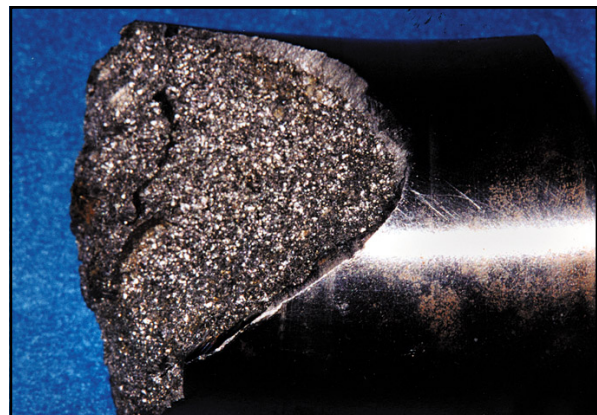


If the radial load on the shaft at Point A causes the shaft to bend by  $0.010''$ , then Point B acts as the fulcrum, and the deflection at Point C is  $0.020''$ .

## ELECTROMAGNETIC STRESS



When a motor is subjected to a transient voltage, a very high amount of torque is generated. Shaft failures such as these shown can occur in cases such as a rapid bus transfers, lightning strikes, or out-of-phase reclosures. The torsional stress on the shaft can cause it to snap. The failure will be almost immediate, and the fracture will appear very brittle.



## OTHER SHAFT PROBLEMS

There is a broad category of shaft failures or motor failures that do not result in the shaft breaking. The following is a list of the more common causes. Stress failures caught in the early stages would also fit into this category.

Most of these anomalies are the result of incorrect manufacturing or poor workmanship. These include:

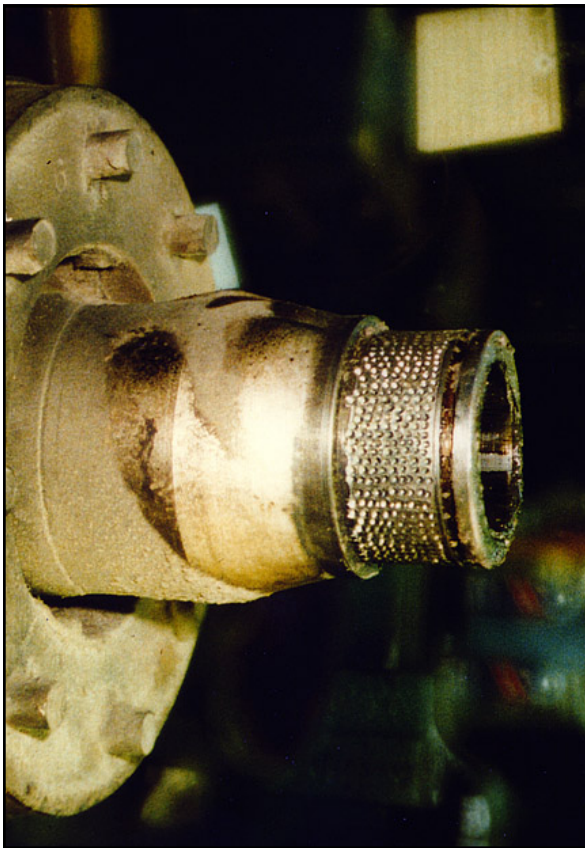
- Bending or deflection causing interference with stationary parts.
- Improper machining causing interference, runout or incorrect fits. This would also include a shaft that has too long a bearing shoulder-to-bearing shoulder distance, not allowing room for thermal growth and

preloading the bearings.

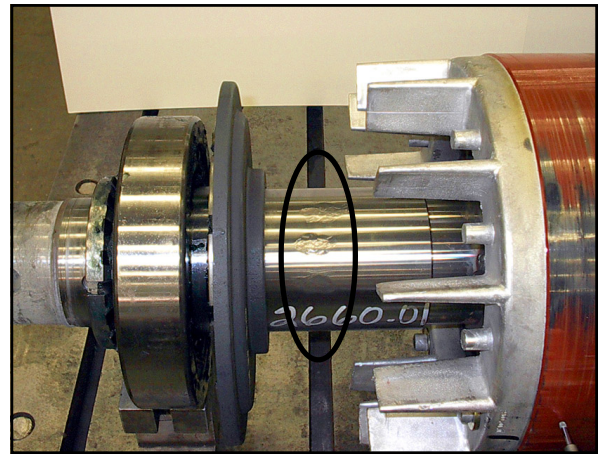
- Material problems which would include inclusions or the wrong strength of material for the application.
- Excessive vibration caused by electrical or mechanical imbalance.
- Bent shaft.
- Magnetic vs. non-magnetic shaft materials. A magnetic shaft will contribute to the flux. If the shaft is improperly replaced with non-magnetic steel, the magnetizing current will increase.

Catastrophic bearing failures may cause serious shaft damage, even if the result is not fracture.

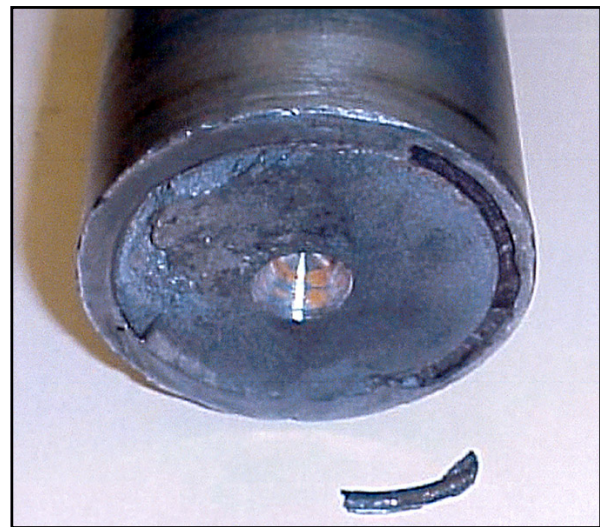
## OTHER SHAFT PROBLEMS



This was a desperate attempt to temporarily restore a bearing fit on a vertical hollow shaft pump motor by prick punching. Each point represents a stress riser; however, the real danger is that the bearing will not have full contact with the shaft journal. When it was put back into service, the bearing lost its fit resulting in high vibration and temperature.



This shaft was peened in an attempt to correct a bend. However, during operation it returned to its original shape.



The snap ring groove was cut too deep and developed an unacceptable stress riser.



## NOTES

# 5

## Rotor Failures

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## INTRODUCTION TO ROTOR FAILURES

The induction motor has often been termed the “work-horse of modern industry.” Credit for such acclaim must go to the simplicity and ruggedness of the squirrel cage rotor assembly.

The squirrel-cage rotor is so called because the electrical winding of the rotor (the bars and end rings) strongly resemble the exercise wheel often seen in the cages of pet rodents. (See Figure 1.)

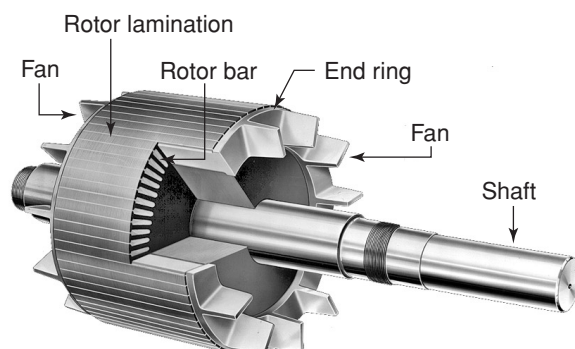
**FIGURE 1: TYPICAL SQUIRREL CAGE WITHOUT SKEW**



Since simplicity of the rotor is one of the key elements in the popularity of the induction motor, you may wonder “What’s so special about the rotor?” Primary performance variations usually come from the rotor. The stator must be designed to conform to several fairly rigid rules, but the rotor design is wide open. Such things as number of bars, amount of skew, slot shape, air gap, bar material and machining processes are variables which the designer uses to generate the performance characteristics desired.

The squirrel-cage rotor consists of laminated steel which carries the magnetic flux, transfers heat and provides structure for the cage. The squirrel cage winding carries the electric current and produces the torque. A shaft is provided to position the rotor to the load. Fans are usually mounted on the rotor to provide airflow to cool the motor. (See Figure 2.)

**FIGURE 2: TYPICAL CAST ROTOR ASSEMBLY**



The rotor may contain air ducts, in which case a “spider” will be provided on the shaft to allow air to get to the air ducts. The elements are intended to be assembled symmetrically in order to minimize balance problems and distortions to the air gap.

The majority of all rotor failures are caused by a combination of various stresses acting on the rotor. These stresses can be grouped as follows:

### Thermal stress

- Thermal overload.
- Thermal unbalance.
- Excessive rotor loss.
- Hot spots and sparking.
- Incorrect direction of rotation.
- Locked rotor.

### Dynamic stress

- Vibration.
- Loose rotor bars.
- Rotor rub.
- Transient torques.
- Centrifugal force, overspeed.
- Cyclic stress.

### Mechanical stress

- Casting variations, voids.
- Loose laminations and/or bars.
- Incorrect shaft to core fit.
- Fatigue or part breakage.
- Improper rotor-to-stator geometry (Variation in air gap).
- Material deviations.

## PHOTOGRAPHS OF ROTOR FAILURES

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**FIGURE 3: POTENTIAL ROTOR FORCES**

$F_W$  = working torque

$F_{UB}$  = unbalance dynamic force  $F_{UB} = \frac{W}{g} \times R\omega^2$

$F_X$  = torsional vibration and transient torques

$F_R$  = residual forces from casting, welding, machining and fits (radial, axial and other)

$F_{M1}$  = magnetic force caused by slot leakage, flux, vibrate at 2 x frequency of rotor current

$F_{M2}$  = magnetic force caused by air gap eccentricity

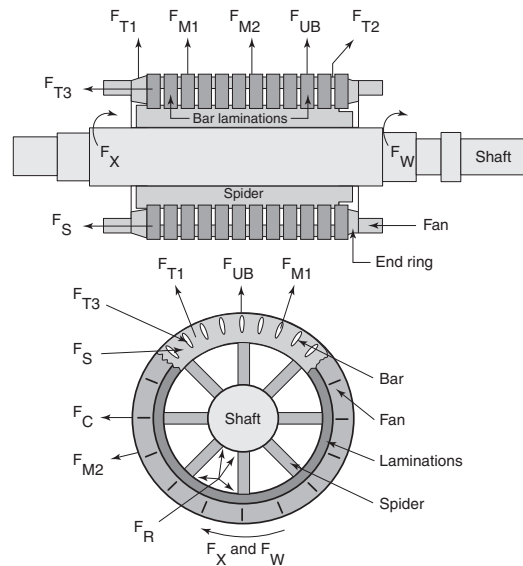
$F_C$  = centrifugal force  $F_C = \frac{W}{g} \times R\omega^2$

$F_{T1}$  = thermal stress caused by end ring heating

$F_{T2}$  = thermal stress caused by  $\Delta t$  in bar during start (skin effect)

$F_{T3}$  = thermal stress caused by axial bar growth

$F_S$  = axial forces caused by skewing the rotor bar



$\omega$  = angular velocity

$W$  = rotor weight

$r$  = rotor radius

$g$  = gradual contrast

- Improper mounting practices and/or shaft resonance.
- Improper design or manufacturing practices.

#### Environmental stress

- Contamination.
- Abrasion, foreign particles.
- Poor ventilation.
- Excessive ambient temperature.
- Unusual external forces.

#### Magnetic stress

- Rotor pullover
- Uneven magnetic pull.
- Lamination saturation.
- Circulating currents.
- Vibration, noise and electromagnetic effects.

#### Residual

- Stress concentrations.
- Uneven stress.

#### Miscellaneous

- Misapplication.
- Effects of design practices.
- Manufacturing variations.
- Inadequate maintenance.
- Improper operation.
- Improper mounting.

If a motor is designed, manufactured, applied, installed, operated and maintained properly, these stresses can

remain under control and the motor will function as intended for many years. However, as each of these factors varies from user to user, so does the anticipated life of the motor.

## METHODOLOGY FOR ANALYZING ROTOR FAILURES

There are five key areas which must be considered and related to one another in order to accurately diagnose the cause of rotor failures. These areas are:

- Failure class.
- Failure pattern.
- Appearance.
- Application.
- Maintenance history.

The following is a brief discussion of each of these areas.

### FAILURE CLASS

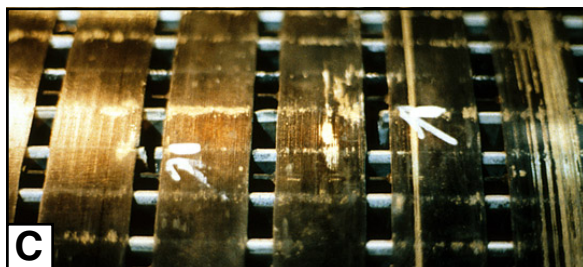
Unlike the root cause methodology for other motor components, the term "failure class" is used in place of "failure mode." Both terms are discretionary. The difference between the two terms can be defined as follows:

- **Failure mode:** Different types of damage occur on the same part (e.g., All winding damage basically includes copper wire).
- **Failure class:** Different types of damage occur on the various parts that make up the rotor assembly (shaft, laminations, squirrel cage, etc.)

FIGURE 4: FAILURE PATTERNS



A



C

Because of its simplicity, the squirrel cage rotor is often misdiagnosed and the pattern and root cause are not properly identified.

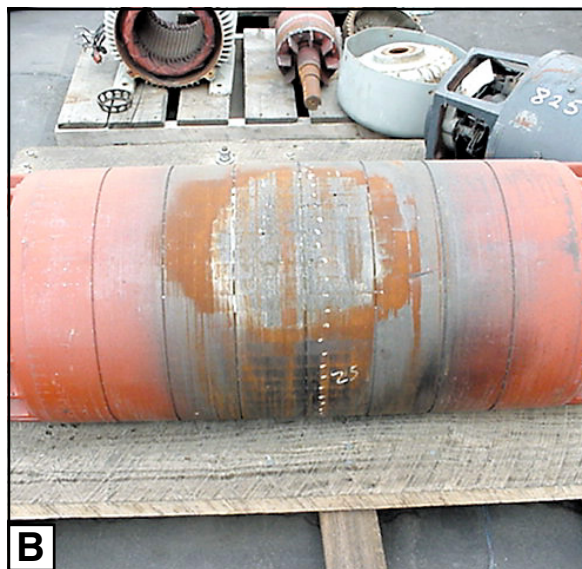
Unlike the stator winding, the squirrel cage rotor is exposed to the additional forces associated with rotation at high peripheral speeds and materials that rapidly conduct heat generated by cage losses.

The rotor is designed to operate best with a symmetrical magnetic field. Failure to do so can create unbalanced forces that result in shaft deflection, vibration, noise and loss of air gap. Unbalanced voltage can introduce a negative sequence component of current into the rotor leading to excessive losses and heating. (See Example A.)

The rotor operates best at or near a constant speed where slip varies by only a few percent. Stall, long acceleration times, rapid reversals and multiple starts can all generate extreme heating in the squirrel cage. (See Examples B and C.)

Often, the heat generated in the stator, or by failure of the cooling system, can give the appearance of a defective rotor. Also, failure of the stator to generate adequate acceleration torque can cause severe damage to the squirrel cage. (See Example D.)

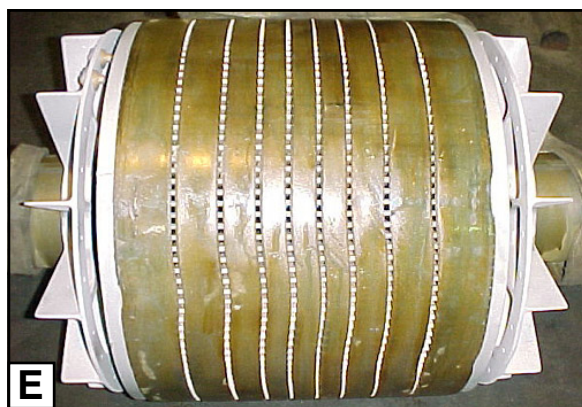
Just like the stator winding, the rotor can be improperly designed, built or applied thus introducing rapid and incipient types of failures. (See Example E.)



B



D



E

Regardless of the cause of failure, the actual class of failure can be divided into the following groups:

- Shaft.
- Bearings.
- Laminations.
- Squirrel cage.
- Ventilation system.

- Stator.
- Any combination of the above.

In analyzing rotor failures, it is difficult to determine which of the above factors was the initial problem and which resulted from the problem. A simple example will illustrate this point.

A 2-pole motor has a bent shaft causing severe vibration



that damages the bearings which results in the loss of the air gap. The rotor strikes the stator, overheating both the rotor and stator laminations along with the stator winding and rotor cage. The aluminum rotor bars melt and are slung out into the stator winding causing a line-to-line fault that shuts down the machine.

Although inspection could reveal six classes of failure, the faulty shaft was the initial problem. All other failure classes were the result the shaft problem.

Unfortunately, due to the destructive nature of this type of failure, it is often difficult to separate out the cause and effect.

### FAILURE PATTERN

Closely related to the failure class, but considered separately, is the failure pattern. Failure patterns can be grouped according to rotor stresses. They are:

- Thermal.
- Dynamic.
- Mechanical.
- Environmental.
- Magnetic.
- Residual.
- Miscellaneous (e.g., misapplication, poor design, etc.).

Determining the class and pattern of failure can provide clues to the cause of failure.

### APPEARANCE CONSIDERATIONS

The general motor appearance usually gives a clue as to the possible cause of failure. The following checklist provides questions that should be asked.

- Does the rotor show signs of foreign material?
- Are there signs of blocked ventilation passages?
- Are there signs of overheating evident in the laminations, bars, painted surfaces, etc.?
- Have the rotor laminations or shaft rubbed? Record all locations of rotor contact?
- Are there signs of a stalled or locked rotor?
- Was the rotor turning at the time of the failure?
- What was the direction of rotation and does it agree with the fan arrangement?
- Are mechanical parts missing such as balance weights, bolts, rotor teeth, fan blades, etc. Has any contact occurred?
- Does the shaft rotate freely?
- Are there signs of moisture on the rotating assembly or contamination of the bearing lubricant?
- Are there signs of movement between the rotor core and shaft, or bars and laminations?
- What is the condition of the lubrication system?
- Are there signs of cracks or fatigue on any of the rotor assembly parts?

When analyzing rotor 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.

### APPLICATION CONSIDERATIONS

Usually it is difficult to reconstruct the actual operating conditions at the time of the 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 or process changes?
- Does the load cycle or pulse?
- What is the voltage during starting and operation?
- 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 operating?
- Did the unit fail on starting or while operating?
- How often is the unit started? Is this a manual or automatic operation?
- What type of protection is provided?
- What removed or tripped the unit from the line?
- Where is the unit located and what are the normal environmental conditions?
- What was the ambient temperature at the time of failure?
- What were the environmental conditions at the time of failure?
- Is the mounting base correct for proper support of the motor?

### 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?
- When was the last time any service or maintenance been performed and what work was done?
- What operating levels (temperature, vibration, noise, etc.) were observed prior to the failure?
- What comments were received from the equipment operator regarding the failure?
- How long was the unit in storage or sitting idle prior to starting?
- What were the storage conditions? Were space heaters energized?
- Was the insulation resistance tested prior to putting the motor in service?
- Were correct lubrication procedures used?

## THERMAL STRESS

Failures due to thermal stress are generally easy to identify because of the appearance of the rotor. The ultimate cause of failure, however, can be quite difficult to pinpoint.

Thermal stress is made up of six basic stresses which include:

- Thermal overload.
- Thermal unbalance.
- Excessive rotor loss.
- Hot spots, sparking.
- Incorrect direction of rotation.
- Locked rotor.

## APPEARANCE

Rotor appearance usually shows signs of extreme heating. This can range from isolated bluing caused by hot spots, to molten aluminum either on the rotor or slung into the winding. (The normal heat treating process may cause uniform bluing of the entire rotor surface.) Many times, excessive temperature can be determined by observing the color of painted surfaces.

Telltale signs of thermal stress include:

- Thermal overload—A broad discoloration of the rotor core and painted surfaces. Discoloration of the stator varnish or lubricant may also be present.
- Thermal unbalance—A more localized discoloration on the rotor surface, particularly on non-vented rotors.
- Excessive rotor losses—Discoloration of the rotor core as well as increased rotor slip while running.
- Hot spots—Small spots of burned paint randomly spaced on the rotor surface and/or discoloration of the lamination material. This could also indicate an open rotor bar.
- Sparking—Normally accompanied by loose bars which can be checked by striking with a mallet and punch.
- Incorrect direction of rotation—Examine any smeared material and/or surface of rotor fans for direction of rotation prior to the failure.
- Locked rotor—Normally, the rotor will be hotter on the end rings or in the air ducts than on the surface of the laminations.

## FAILURE CLASS

Most failures will show an uneven pattern over the entire rotor and may be accompanied by molten aluminum from the slots or end rings. To narrow the options of possible causes, additional patterns must be noted. Locked rotors may have aluminum puddled at the bottom of the winding while thermal overloads, excessive rotor losses and incorrect rotation will have aluminum spread around the winding or rotor surfaces. On copper bar rotors, the brazed joint between the bars and end ring may melt. For air-ducted rotors, bars melted in the air passages are indicative of overheating due to stalling, failure to accelerate or excessive starting frequency. Bars melted in the lamination pockets are indicative of overheating during running or operation. Hot spots and thermal unbalance typically exhibit uneven

heating patterns on the rotor surface and can result in changes in magnitude of vibration versus time between cold starting and hot running conditions.

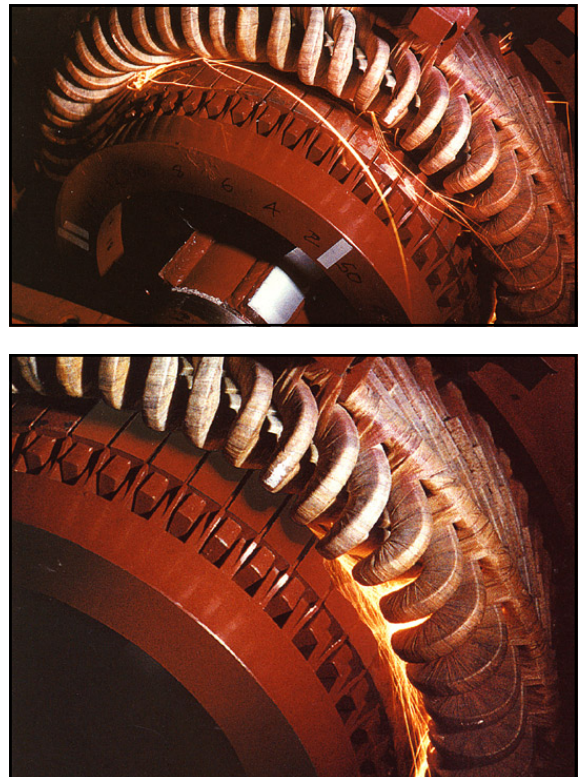
In severe cases, rotors that have bowed due to thermal instability will often exhibit a rub on the rotor surface in one area with a corresponding 360° smear on the stator or on one side of the shaft and a 360° smear of the bearing cap or oil seal.

## ROTOR SPARKING

There are several potential causes of rotor sparking on fabricated rotors. Some are of a nondestructive nature, and some can lead to rotor failure. (See Figure 5.)

Nondestructive sparking can and probably does occur during normal motor operation. Such sparking is seldom observed due to its low intensity and/or the motor enclosure prohibits its observance. Normal operation can be defined as any condition that could subject the motor to voltage dips, load fluctuation, switching disturbances, etc. Sparking usually is not observed while running at full load. The centrifugal force at full-load speed is usually greater than the electromagnetic forces acting on the bar, due to rated load current, and tends to displace and hold the bar radially in the slot. Furthermore, the frequency within the rotor circuit is very low (equal to the slip frequency). This low frequency corre-

**FIGURE 5: ROTOR SPARKING**



Note: The rotor was deliberately offset to expose the sparking for illustrative purposes. High-speed photography was used.

Courtesy of GEC Alsthom



sponds to a low impedance of the rotor cage circuit, essentially confining all rotor current to the cage itself. Therefore, while possible, sparking is not normally observed during operation at full load and speed.

During across-the-line starting, however, the current in the rotor cage can be 5 to 7 times normal. This high current combined with the higher cage impedance, due to the frequency of the rotor current initially decaying from line frequency at standstill, will cause a voltage drop along the length of the bar in excess of 6 times the normal running value. This voltage tends to send current through the laminations. In effect, during start-up, there are actually two parallel circuits—one through the rotor bar, and the other through the laminations.

The magnetic forces created by the high current flow during start-up cause the rotor bars to vibrate at a decaying frequency, starting at line frequency, which produces a force at twice line frequency. This tangential vibration within the confines of the rotor slot causes intermittent interruptions of the current flow between the bars and various portions of the laminations with resultant visible arcing.

The rotor design and manufacturing processes include measures intended to reduce sparking. However, material and manufacturing tolerances, together with the effects of differential thermal expansion and thermal cycling, preclude any motor from “sparkless” operation. Even identical or duplicate motors can and will exhibit differing levels of spark intensity, since all component parts have tolerances and are thermally cycled during operation.

The sparks observed in the air gap are actually very small particles of bar and/or core iron, heated to incandescence by current passing through the iron-bar boundary. Initial punching burrs and/or particles of bar material removed during installation can generally be expected to decrease

after several starts. However, particles generated by intermittent sparking due to bar motion will not decrease during the life of the motor.

The brief period of intensified sparking that can occur during starting is not detrimental to motor life. Motors with more than 20 years of operation have shown only slight etching of the rotor bars at areas of contact with the core iron when disassembled.

Destructive sparking can occur under several circumstances, the most common being a broken bar or a defective bar-to-end ring connection.

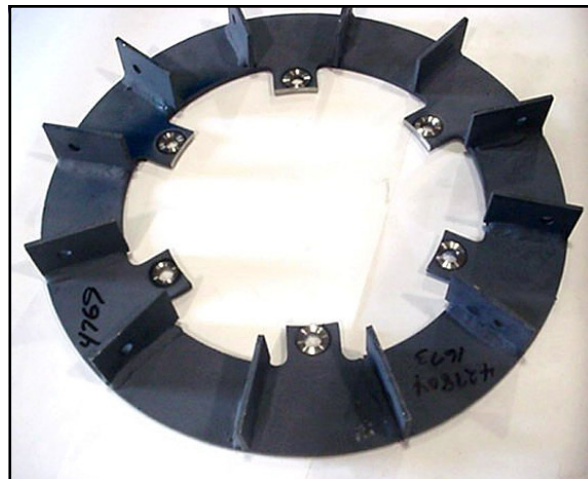
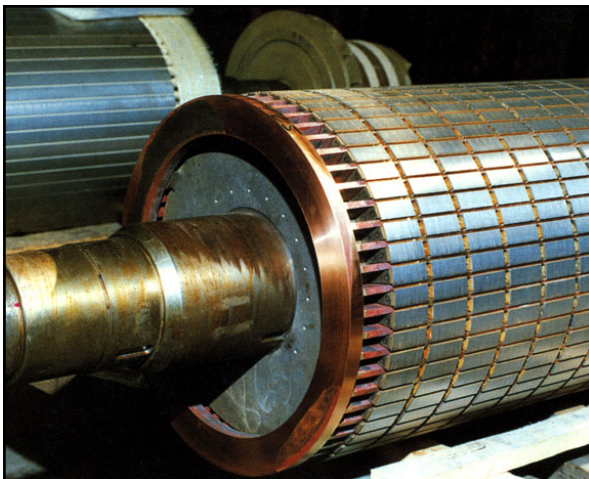
Bars usually break near where the bar connects to the end ring. Breakage is preceded by radial cracks starting either in the top or bottom of the bar. While sparking caused by fatigue failure of the rotor bar is usually greater in intensity than that previously mentioned, it is still difficult to visually detect since the majority of motor enclosures prevent “line of sight” visual observation of the air gap.

Common methods of determining whether sparking is caused by broken bars or end ring connections are:

- Visual inspection of the rotor assembly.
- Tapping the bars with a small hammer. Broken bars have a dull sound, like a cracked bell. For loose bars, tap one end of bar while feeling the opposite end for movement.
- Current pulsation when the motor is under load.
- Single-phase rotational test.
- Growler test.
- Motor current signature analysis.
- Observed noise (rattling sound) during starting cycle.
- Audible cyclical noise.

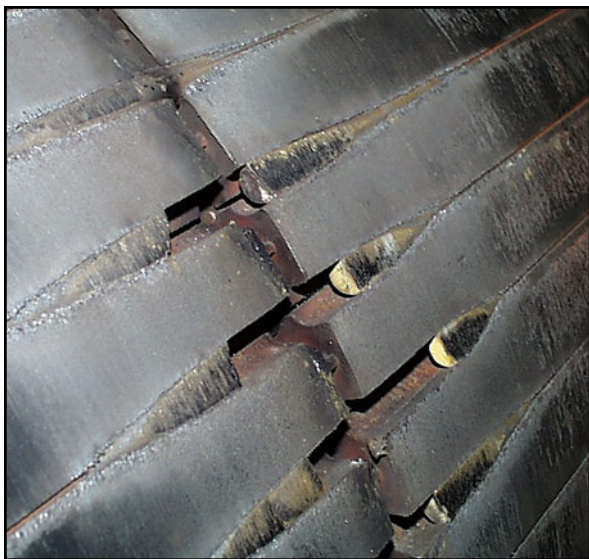
Proper design, manufacture and operation of the motor can prevent advanced levels of rotor sparking.

## THERMAL STRESS



Occasionally, it is necessary to repair the cooling fan attached to the rotor end ring or to even replace the end ring. Many rotor designs depend upon the rotor fan to help remove heat generated in the rotor cage. This is done through conduction from the rotor to fan, then by radiation from the fan to the surrounding air and then by convection. Good surface contact between the rotor end ring and fan is critical to aid this process. Failure to assure “full” contact and tightness between the end ring and fan may cause the rotor to overheat, which could cause the winding and bearings to overheat.

## THERMAL STRESS



Thermal overload led to severe bar damage at the hot spot of the rotor and, as seen here, some of the bars have actually melted. Note that this rotor has a double cage. The upper cage failed, indicating that the failure occurred during starting or excessive slip.



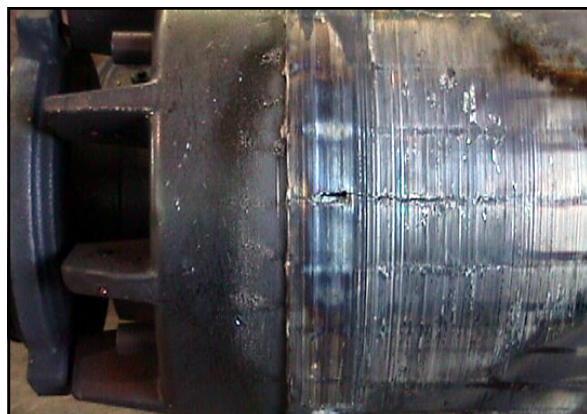
Aluminum rotor bars have begun melting in this thermally overloaded rotor. The failure occurred in the center air duct which is the hottest part of the rotor. Since the failure occurred in the vent duct, it likely took place during a stall condition.



The thermal limit of the brazing material was exceeded in the upper cage during starting. This caused the upper cage to become an open circuit.



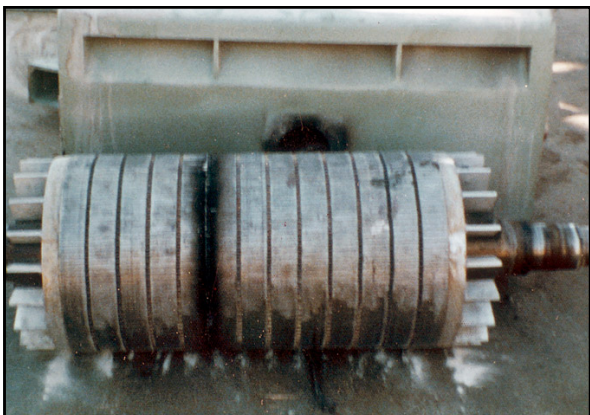
This is a classic example of overheating from excessive load.



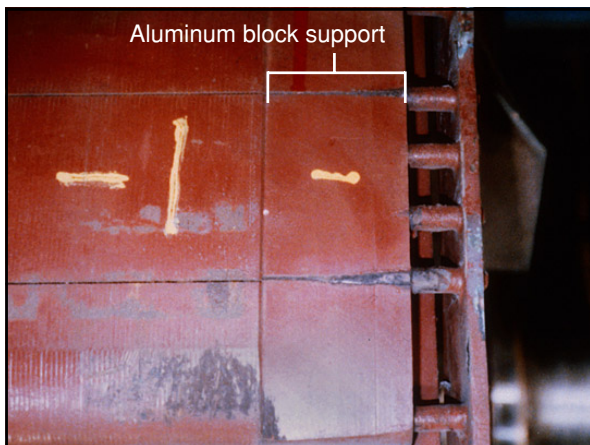
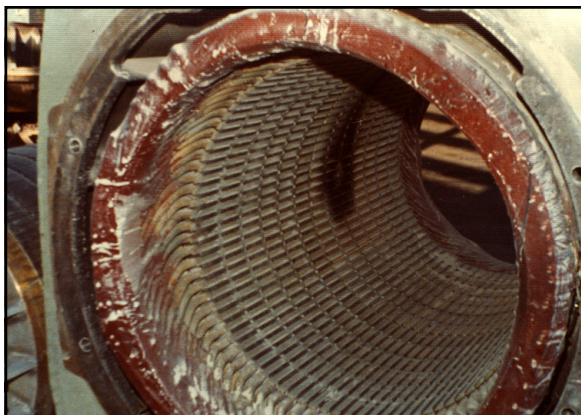
Although this rotor was subjected to extreme thermal stress, the root cause may have been loss of air gap.



## THERMAL STRESS



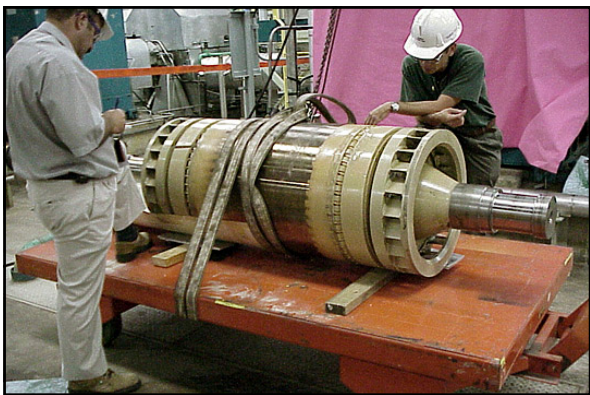
This rotor appears to have overheated; however, inspection of the stator shows that the thermal damage was the result of a ground in a single slot of the stator while the rotor was turning. Without properly inspecting both parts, the wrong diagnosis could be made.



The aluminum extension block supports the coil. In this photograph, the amortisseur bars lifted through the aluminum block.



Excessive heat in the rotor cage during starting caused the brazing material to melt causing the separation of the end rings and rotor bars.

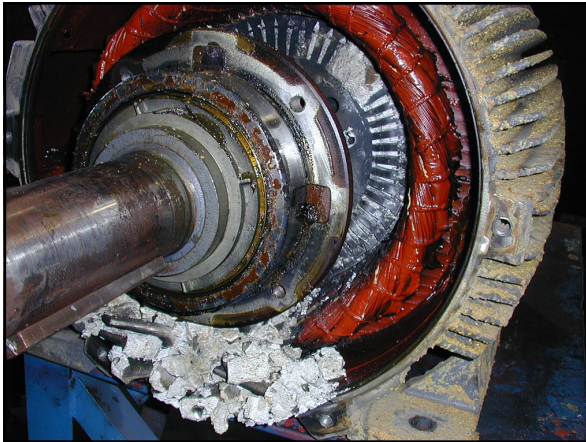


This rotor bowed at elevated temperatures and made "slight" contact with the stator. Note that the clamping plate (right) separated from the laminations.

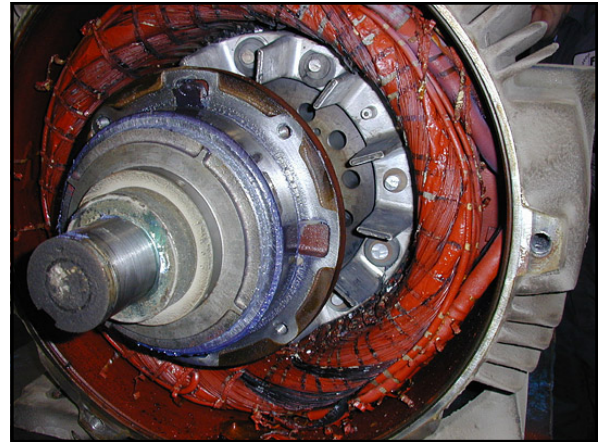




## THERMAL STRESS



**Drive end**

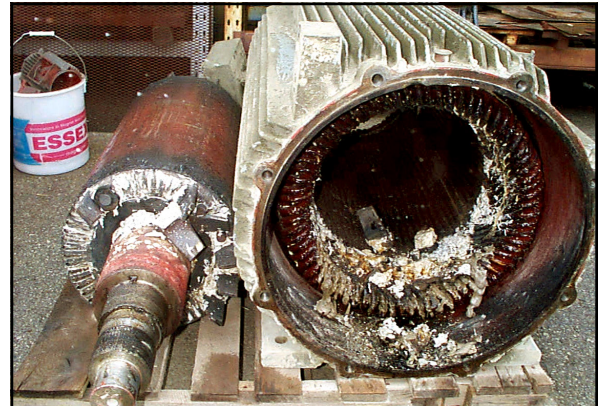


**Opposite drive end (fan end)**

This rotor was stressed beyond its thermal limit. The end ring on the opposite drive end failed because this is the hot end of a TEFC motor. The stator was also overheated but the weak link was the rotor. If the overload was caused by a stall, long acceleration cycle or repeated starts, then both end rings would have overheated equally. This overload happened while the motor was running under load or there was significant voltage unbalance.



The end ring was the weak link in this rotor and melted during severe starting conditions.



This rotor was overloaded to the point that the slip increased. The rotor and windings drew high current for a long enough time both overheated. The hottest end of the rotor failed first.



The center of the rotor is the hot spot and the hardest place to remove heat. Upon first inspection, the stator and rotor appeared in good condition. It was not until the service center removed the rotor that the damage was found.



## DYNAMIC STRESS

With a few exceptions, dynamic stress failures generally originate with forces external to the motor. Stresses of this nature must be identified and either corrected or accounted for in the design of the motor system if repeated failures are to be eliminated.

Dynamic stress is made up of six basic stresses which include:

- Vibration—originates externally or internally.
- Loose rotor bars—originates internally.
- Rotor rub—originates externally or internally.
- Transient torque—originates externally.
- Centrifugal force (overspeed)—originates externally.
- Cyclic—originates externally.

## APPEARANCE

Cyclical, vibration and torque stresses generally result in broken shafts and/or failed bearings. Overspeed evidence typically consists of broken fan blades, shifted rotor core, high vibration and damage or distortion of shaft-mounted parts such as fans and couplings.

Examination of failed parts can many times isolate the origin of the failure. As an example, a shaft torsional failure indicates a force opposite to the normal direction of rotation. This can point to an out-of-phase bus transfer or reclosure as the origin of failure.

Dynamic stress failures often result in extensive damage to the entire motor. Bearing failures may allow the rotor to contact the stator resulting in damage to the winding. Overspeeding can damage all parts of the motor.

Telltale signs of dynamic stress include:

- Vibration—Record the history including maintenance and operating information as well as isolating frequency and/or any phase angle shift.
- Loose core—A loose core may be located by physical motion on the shaft but normally is identified by rapidly increased vibration shortly after start up, many times returning to normal after a couple of hours of running, provided initial step in vibration was not too severe.
- Rotor rub—This, combined with signs of stator rub, can identify the failure class. Random spot rubs on the rotor and/or stator may be oscillations during starting. Rubs covering 360° on the rotor may be pullover. Spot rub on the rotor with 360° rub on the stator usually indicates a bowing or eccentric rotor.
- Transient torques—Look for twisted parts, sheared coupling bolts or shaft breakage which can be in- or out-of-phase to the normal rotation.
- Overspeeding—
- Cyclic stresses—Analyze the failure pattern to determine cycles (high or low) to failure.
- Centrifugal forces (overspeed)—Look for missing, bent or yielded parts such as fan blades, balance weights, etc. Even cracked paint may lead to identification of the failure's origin.

## FAILURE CLASS

It is often extremely difficult to reconstruct the exact sequence of events leading back to the origin of the failure. Many dynamic failures originate with forces external to the motor and are not available for analysis after the motor has been removed. Close inspection of component parts, couplings, etc. is mandatory. Equally important may be an analysis of the past history or operating characteristics of the unit as well as conversations with the operators on duty at the time of the failure.

## CENTRIFUGAL FORCE (OVERSPEED)

Normally, a rotor is designed to be capable of being oversped with NEMA design limits (20% for 2-pole motors and 25% for slower speeds). For more information, see NEMA MG 1-1998, 12.52. Even up to these speeds, caution is necessary if the unit is energized during this condition.

The reason for this caution is that component parts such as the rotor core-to-shaft interference fit are now required to handle both centrifugal as well as thermal stresses. Should this fit be lost, then high vibration with corresponding destructive results might occur. Examples of this condition would include inverter operation or wind generators.

Of course, centrifugal forces beyond the overspeed limits also need to be checked for causing possible problems associated with end ring or lamination stresses and/or retention of fan blades or balance weights. One example of this might be a failed or stuck check valve in a pipeline or deep well pump, where the reverse flow of liquid causes the pump to rotate backwards and overspeed the rotor.

## CYCLIC STRESS

The motor shaft can be subjected to cyclic stress that may lead to eventual fatigue failure. Cyclic stress can be caused by the application, such as misalignment, overtightened of belts or incorrect sheave size for overhung loads. Cyclic loads of this nature should be analyzed to make certain safe operating limits are maintained. Any stress riser, such as a change in shaft diameter, should be analyzed to minimize stress concentrations. Stress relieving of the shaft assembly may be necessary to assure that welding or machining stresses are within acceptable limits.

Any such failures should be referred to the manufacturer so proper analysis can be made. If possible, failed components should be returned to the manufacturer or qualified metallurgist, as high- and low-cyclic fatigue failures may each require a different fix.

## SHAFT TORQUES

The rotor shaft is designed to handle forces in excess of that normally associated with motor full load or breakdown torque. Any torque above these levels is usually of short duration and referred to as a transient torque. Transient torques commonly occur upon starting, bus transfers or out-of-phase reclosures. They can also be generated by shock loading from driven equipment or by operation on an inverter power supply.

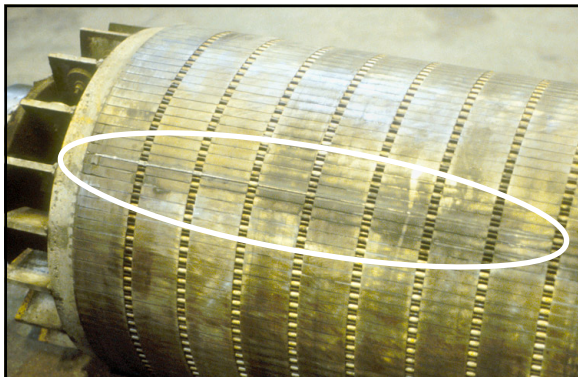
For example, it is possible to generate shaft torques that are up to 20 times the motor full load torque through an out-of-phase bus transfer. It is important that the manufacturer be consulted when any transfers will be made before the motor open circuit time constant has elapsed.

Applications involving shock loading, such as shredders, also should be identified so that adequate margin can be

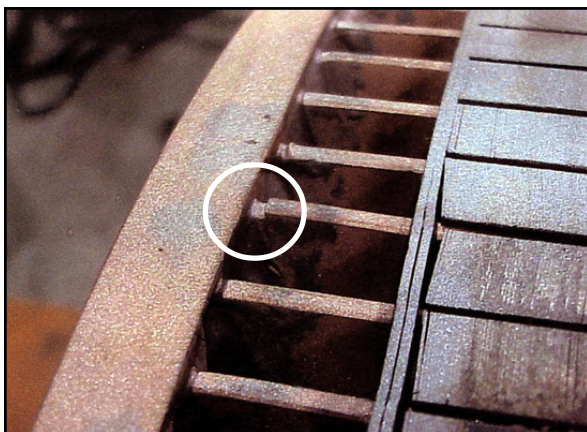
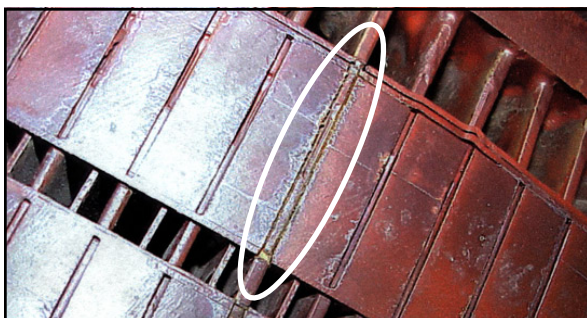
designed into the rotor.

High shaft torques can also exist under normal operating conditions if a torsional resonance occurs. This is especially true of high-speed rotors. Motors can normally accelerate quite satisfactorily through the first system critical, but will require additional analysis if operated on an inverter where sustained operation at varying speeds would be possible.

### VIBRATION AND LOOSE ROTOR BARS



Vibration led to these damaged rotor bars. Rotor bars must be tested for looseness. When tested, loose bars show evidence of vibration, whereas bars that are tight show virtually no signs of vibration.



The broken rotor bars in the photographs above have broken the clamping plates and are exiting the slot.

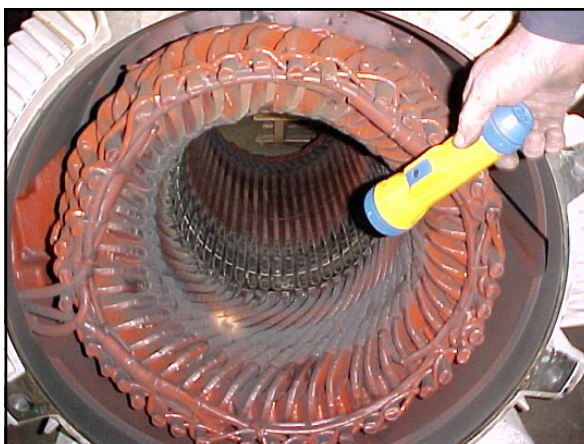


Note the cracks in the rotor bars in the region where the air duct spacers are located. These cracks were caused by nonsymmetrical thermal growth.

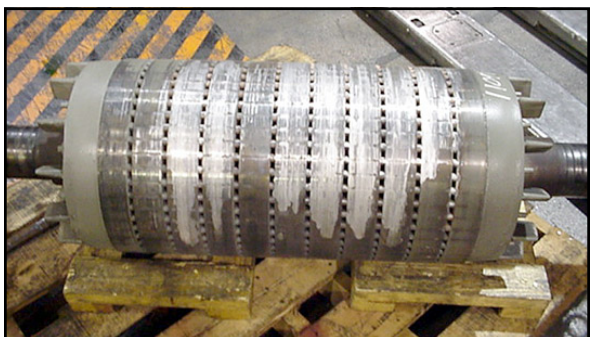
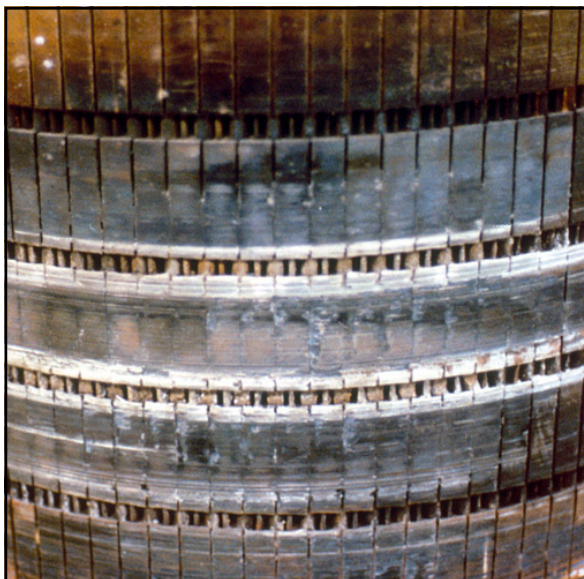
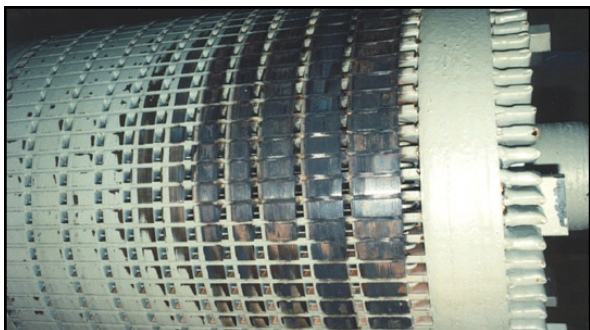
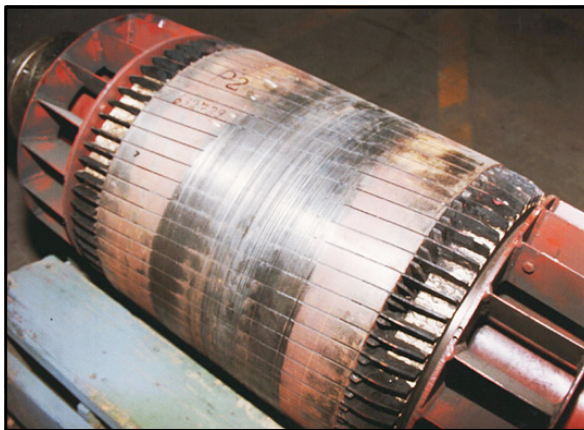


All the bars were loose in this 2-pole rotor. The complete cage moved axially until the shrink ring came into contact with the cooling fan. Note the lack of paint on the rotor bars showing how far the rotor cage has migrated.

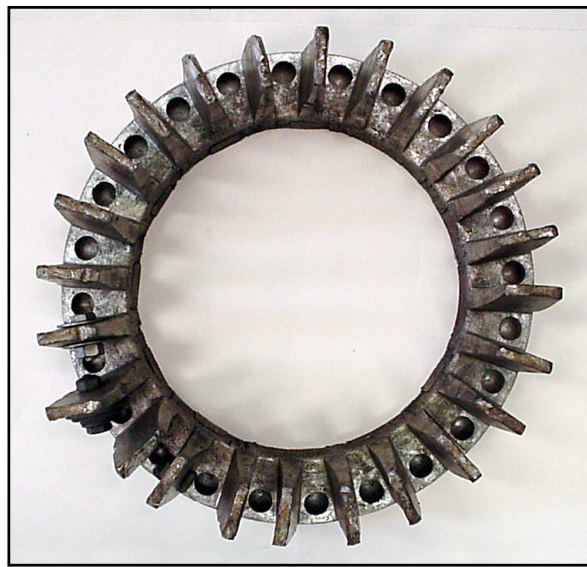


**IMPROPER ROTOR-TO-STATOR GEOMETRY (LOSS OF AIR GAP)**

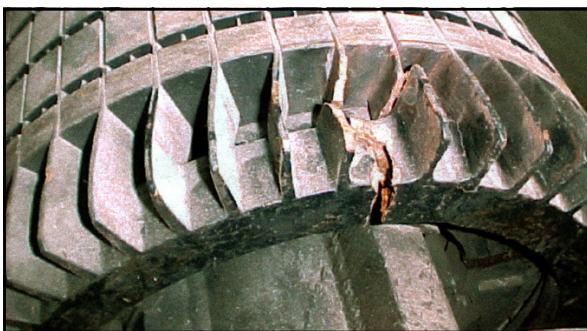
All of the photographs on this page are examples of motors “losing” the air gap while running. At more than 30 revolutions per second and a rotor weight of several hundred pounds, a tremendous amount of kinetic energy is dissipated on the surfaces of the rotor and stator. The extreme amount of heat usually causes severe damage to the rotor and/or stator. The stator at upper right shows signs of contact.



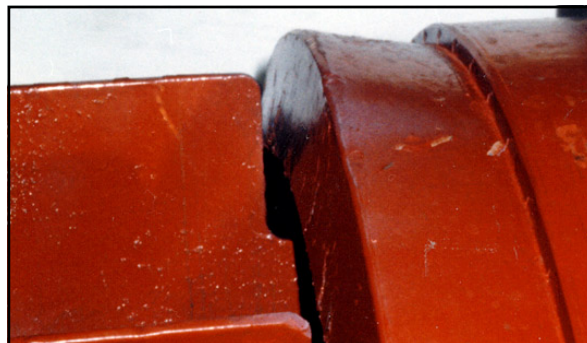


**CENTRIFUGAL FORCE (OVERSPEED)**

These end rings were removed from a 2-pole vertical pump motor that was driven overspeed (an estimated 10,000 rpm) when the check valve failed. The centrifugal force bent the fan blades over until they hit the stator end turns. The bending of the fan blades was more severe than shown since the fan blades needed to be straightened to remove the rotor from the stator bore. Note that the end ring on the left (lower end) showed more bending than the end ring at the right (upper end). More heat in the lower portion of the rotor made the aluminum in the lower end ring more susceptible to bending.



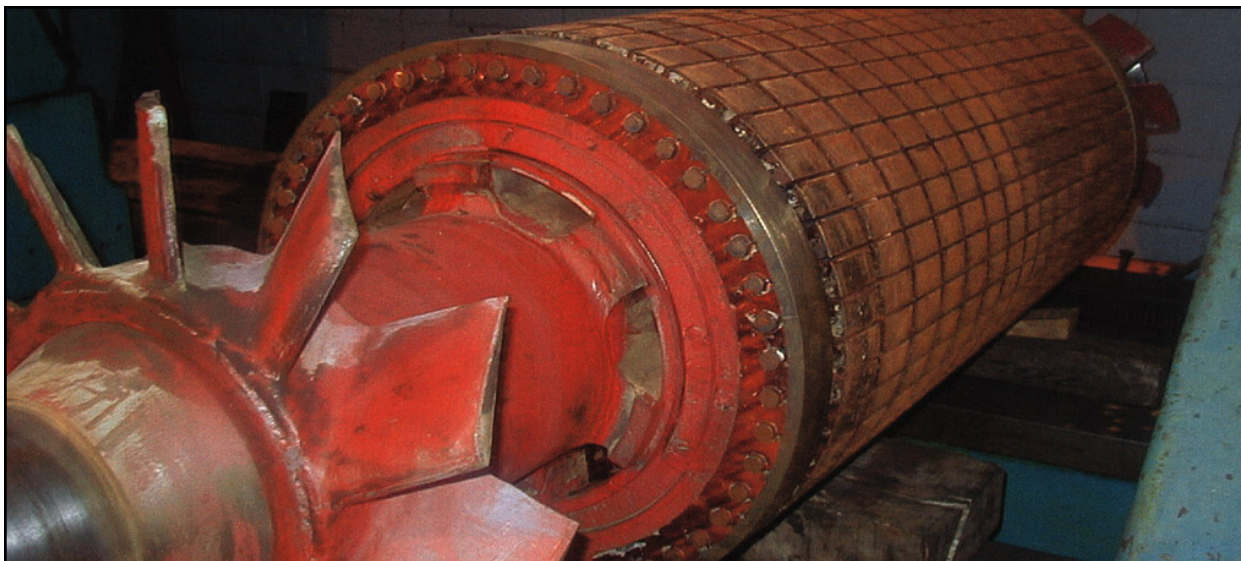
This 4-pole rotor was subjected to extreme temperatures that created bending stress in the rotor bars. This combined with centrifugal force on the end ring. The end ring eventually cracked allowing centrifugal force to displace the rotor bars and end ring.



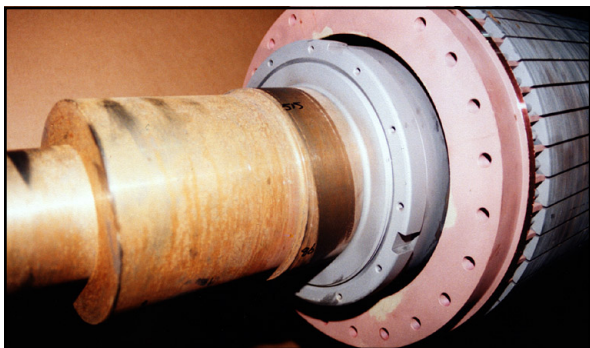
Centrifugal force due to overspeed caused the lifting of these end rings. The rotor at above was damaged by a faulty check valve or anti-rotation device. This damage can also be caused by redesigning the motor to a higher speed.



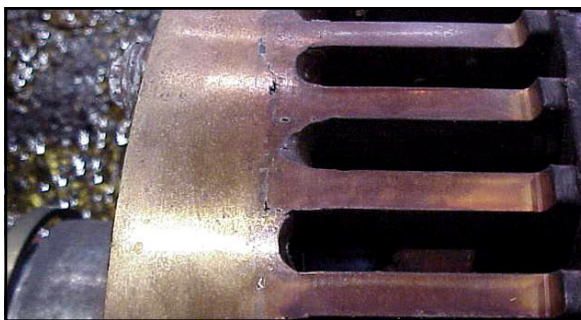


**CENTRIFUGAL FORCE (OVERSPEED)**

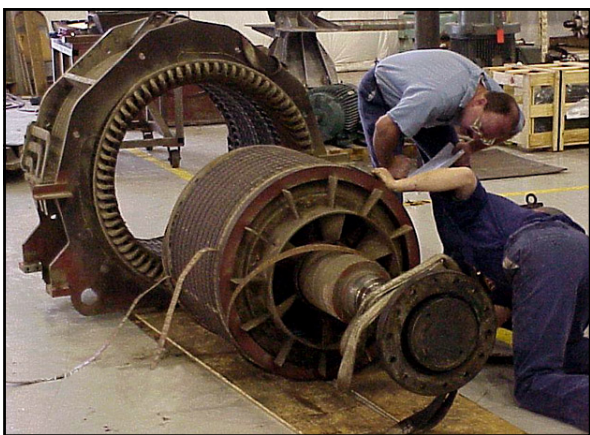
A 2-pole rotor with shrink rings installed. The shrink ring fit and high-tensile strength ring material are critical. A loss of fit can occur if the material is changed or the amount of interference fit is altered. The concentricity of the parts must yield near 100% contact between the two parts.



A 2-pole rotor ready to have the shrink ring installed.



This is an example of a rotor whose shrink ring has been removed for closer inspection of the rotor cage.



Instead of a shrink ring, inadequate banding material was used (left) which did not provide sufficient tensile strength to stay in place at operating speed. The steel shrink ring (right) will maintain an interference fit at elevated temperatures and operating speed.



## MECHANICAL STRESS

The exact cause of these types of failures is often very difficult to identify. The appearance of the failed part is very similar to failures due to other stresses. Careful analysis, however, will usually reveal physical evidence of a mechanical problem.

Mechanical stress is made up of eight basic stresses. They are:

- Casting variations.
- Loose laminations and/or bars.
- Incorrect shaft-to-core fit.
- Fatigue or part breakage.
- Improper rotor/stator geometry (variation in air gap).
- Material deviations.
- Improper mounting practice and/or shaft resonance.
- Improper design or manufacturing practices.

## APPEARANCE

The rotor can show any of the patterns mentioned previously (hot spots, smearing, fractures, movement, etc.). There is usually some form of physical damage or movement associated with this type of failure.

Telltale signs of mechanical stress include:

- Casting variations—Look for flashing or other casting variations that might prevent a part from properly seating and/or damage from a previous repair or tear down.
- Loose laminations—Look for loose or missing rotor teeth. Rotor stack pressure should prevent easy insertion of a pocket knife between laminations.
- Incorrect shaft-to-core fit—This normally requires removal for size measurement; however, look for visual signs of movement.
- Fatigue or part breakage—Look for missing parts as well as any cracking of parts. Try to identify the number of cycles that occurred prior to failure.
- Improper rotor-to-stator geometry—Look for rubs in one area of the stator bore which could be caused by an eccentric rotor. Identify dimensions between the bearing centers where the rub occurred.
- Material deviations—These are not easily identified. These may include the wrong rotor bar or end ring material, bars of varying conductivity, poor lamination surface, resistance, etc.
- Bearings — Review wear or failure patterns present to identify any external or internal forces that may have been present. Identify ball tracks, shaft currents, etc., as well as the quantity and condition of the lubricant.

## FAILURE CLASS

As with most other failures, it is extremely important to inspect all parts of the motor, not just the rotor, to determine the failure class. Rotor core or shaft rubs are common due to the rotor's axis of rotation being moved off magnetic center. Improperly located or failed motor components and/or the misalignment of overhung loads are often the cause of these failures.

Loose laminations or bars normally produce noise during starting or running. The movement of these parts can lead to fatigue failure, localized hot spots, shaft bending, rotor rubs, winding or bearing failure, etc. Fatigue failure of shafts or other components should be analyzed as to whether long- or short-term cyclic failure has occurred.

Even the appearance of external elements such as grease on belt drives may provide a clue as to the origin of failure.

## ROTOR CASTING PROBLEMS

There are a variety of problems associated with casting rotors. In many cases, these defects have little or no impact on the motor's overall performance.

The most common of these defects is casting porosity (voids) which can occur in the end rings or bars. Minor instances of porosity cause an increase in rotor resistance which creates hot spots. This in turn will increase rotor losses and slip while decreasing the motor's efficiency. If the porosity is significant enough to be characterized as voids, then the performance is significantly affected and the expected motor life is reduced. Voids in air duct spacers cause excessive heating and may eventually lead to open rotor bars. If there are no air ducts but there appears to be porosity in the top of the bars or just under the lamination bridge, the result can be burned spots on the rotor.

A large amount of balancing weights located in one spot is a sure sign of porosity and/or rotor dissymmetry. If the shaft is straight, the rotor cage may not be complete and voids or porosity may be present. Another possibility is that the lamination bridge may not be symmetrical. A close inspection of the rotor surface may confirm this.

See photographs on Pages 5-21 and 5-22.

## ALUMINUM VERSUS COPPER CONSTRUCTION

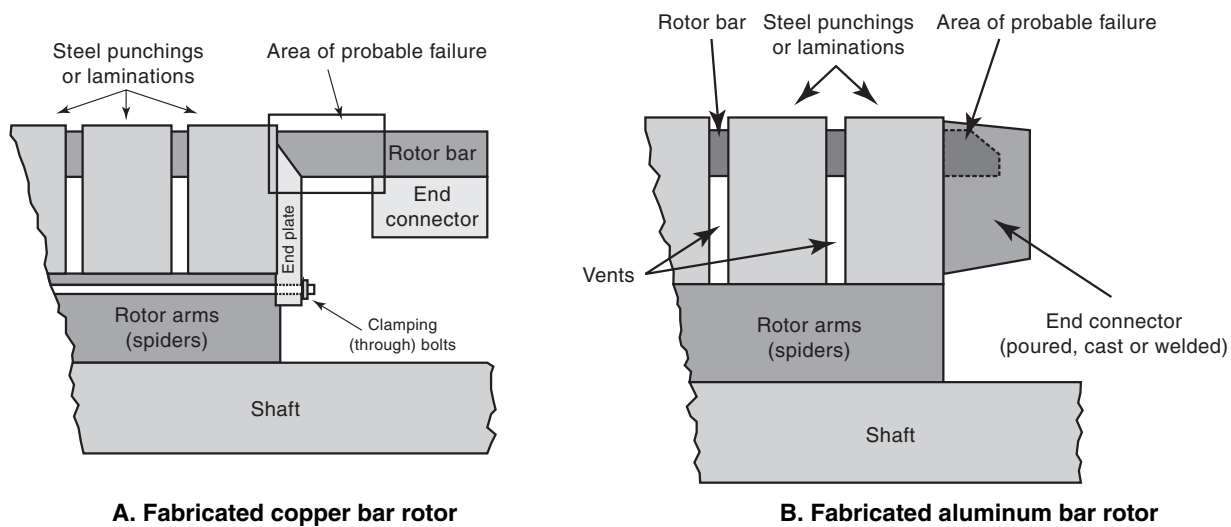
Currently, the rotors of large induction motors are constructed of either aluminum or copper and their associated alloys. It is interesting that many people exhibit a preference for one or the other of these materials in the construction of the rotor, when it is the construction itself that is important when considering rotor life. In fact, both have their advantages and are justified depending upon the specific application.

In recent years a number of manufacturers have changed from copper to aluminum fabricated rotors. Although the higher conductivity of copper usually gives it a slight reduction in losses, this can be largely overcome by the optimum shaping available in extruded aluminum bars. Extruded shapes are also available in copper but are very expensive.

Supporters of copper will argue that aluminum melts at 1250° F (677° C) as compared to copper's 1980° F (1082° C) melting point, and therefore has greater stall capacity. While true, this disregards that most copper rotors are brazed to the end rings with a brazing alloy that melts at 1100° F (593° C). The results of a stall are no less disastrous with either material once the temperature to obtain molten metal is achieved. Extensive testing has shown that rotors using either material can be designed to exhibit comparable thermal, electrical and physical characteristics, including fatigue life.



**FIGURE 6: TYPICAL END RING CONSTRUCTION FOR FABRICATED COPPER BAR AND FABRICATED ALUMINUM BAR ROTORS**



Aluminum has several advantages over copper, the most obvious of which is cost. Not only is aluminum cheaper by the pound than copper, but a given rotor would require approximately half as many pounds of aluminum as copper.

Motors with NEMA Design C and D characteristics usually use high-resistance copper alloy bar material. In a double cage design with Design C characteristics (high torque, low inrush, and low slip), the top cage is usually an alloy having 10% to 25% conductivity relative to copper. A Design D motor (high torque, high slip, and low inrush) designed for full-load slip of 8% to 13% may have rotor bars of as low as 25% conductivity.

Copper alloys are often difficult to purchase in the size and shape desired. Bars may have to be sawed and machined from bar stock. Expensive, yes, but it may be the only acceptable alternative. The alloy content can usually be determined by a conductivity check. Copper is typically 100% conductivity, aluminum is 53% to 55%, and alloys are often in the 25% to 35% range.

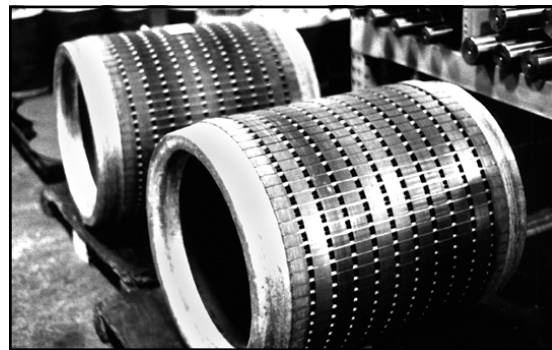
The majority of rotor cage failures are due to bar breakage, and that is more a function of the construction techniques rather than the material used. Two typical types of fabricated rotor construction are shown in Figure 6. Most fractures of the bar occur at the interface between the rotor bar and the end ring, and are due to cyclic stress of bar motion and/or thermal expansion of the end ring.

Figure 6A illustrates the type of construction normally found with copper bar rotors. The end ring provides only a shorting function, and some other type of axial core clamping is provided. The rotor in Figure 6B will not experience bar breakage because the bar is not exposed to bending stress.

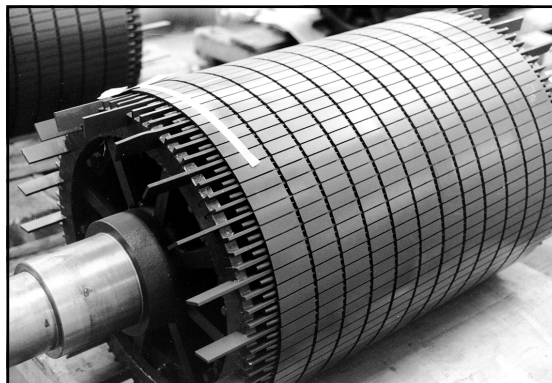
In either case, bar motion within the confines of the slot can and will lead to a fatigue failure between the ring and bar. Unrestrained bars will exhibit a life of approximately 4000 starts. This motion can be virtually eliminated by swaging or locking the rotor bars in place.

Another important difference between the two types of construction is that during starting or stall, the copper bar

**FIGURE 7: EXAMPLE OF ALUMINUM AND COPPER ROTORS**

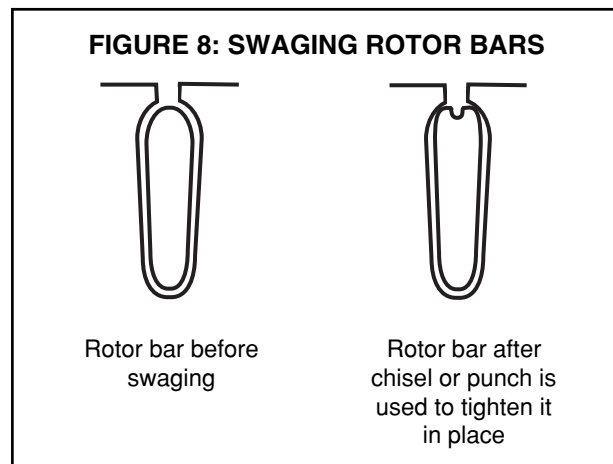


Fabricated aluminum rotors.



Fabricated copper bar rotor.

construction method shown in Figure 6A does less to restrain bar movement during differential heating, compared to the end ring attached to the bar ends as shown in Figure 6B.



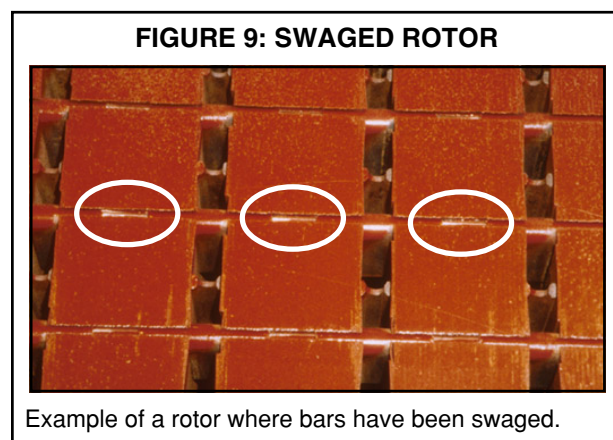
### SWAGING OF ROTOR BARS

Sometimes it is necessary to tighten rotor bars during the manufacturing process or during repair and maintenance. Swaging can be used to tighten bars that have loosened in service and minimize propagation of bar cracking.

Swaging is a relatively easy process which has been in use for years. A blunt chisel in an air hammer can be inserted into a slot and used to “spread” the top of the bar outward creating a tighter fit against the slot walls (Figure 8). Loose rotor bars should be swaged every 3” to 8” (8 cm to 20 cm) depending upon accessibility and looseness (Figure 9). Each bar should be swaged at the same locations; each row of swages should be in line around the circumference of the rotor. All swages should be of uniform depth and force.

Different manufacturers have various philosophies about rotor bar swaging. Some of those ideas have also changed with experience, so a manufacturer using a tight cage design today may have built rotors with a loose cage design in years previous. This information is provided to illustrate the complexity of the question “How tight should rotor bars be?”

One manufacturer swages only one end of each bar. Another drills and spot-welds the mid-point of several bars to locate an otherwise loose cage design. Still others use a loose cage design, but use a centering ring between the shaft and ending to prevent ending and cage distortion.



Still another actually stakes the laminated core, driving lamination edges into the bars, to prevent movement. (See failure photo on Page 6-24.)

The preferred method is to swage each bar uniformly, at even intervals, to tighten the bars in the rotor. One manufacturer reported in an IEEE paper that the expected life of a loose cage design was 4000 starts.

### FABRICATED ROTOR DISSYMMETRY

There are various problems associated with rotor dissymmetry.

If rotor bars are not of equal length, longer bars may actually break loose from the end rings when the bars expand due to thermal growth. At the very least, they may cause severe imbalance. Even if the bars are the same length, if they are not “free” to grow at the same rate, they can cause a condition known as a “bowing rotor.” This condition is thermally induced as the rotor heats up to its normal operating temperature.

Porosity in the end ring may also cause uneven heating as will high resistance connections between the bars and end rings.

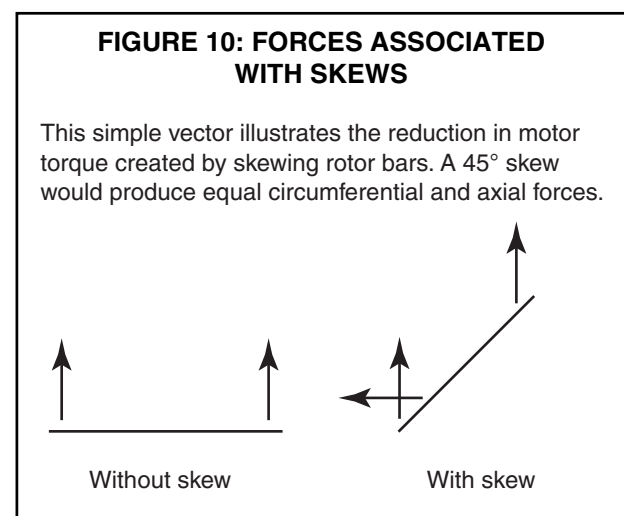
Broken or cracked rotor bars are also a form of dissymmetry and can cause an uneven flow of current or can produce connection hot spots.

### THE IMPACT OF ROTOR SKEW

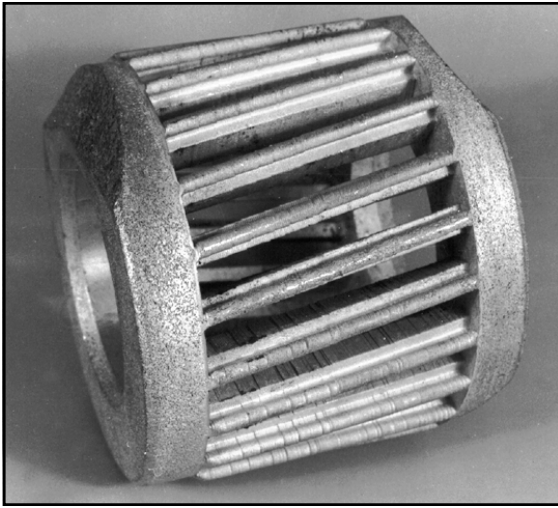
Most service centers will not normally have to change or deal with the skew of a rotor. However, there are a few cases where a motor problem or failure occurs because of the incorrect selection of or the elimination of skew. The exception to this may be in the event of restacking the laminations.

Interaction between the rotor and stator lamination teeth produces variations in the magnetic flux path in the motor. The flux path variation makes itself known by harmonics of generated current. These harmonics tend to produce stray torque effects and electrical noise.

By skewing the rotor (Figures 10, 11, 12 and 13), it is possible to reduce the flux path variations and thus reduce the magnitudes of the resulting harmonics. To be effective,





**FIGURE 11: SKEWED ROTOR CAGE**

the skew must be at least sufficient that opposite ends of a rotor bar are similarly located relative to the adjacent stator slots. Hence, the rotor is usually skewed by one slot.

The advantages of skewing are not without consequence. Skewing causes additional stray load loss, thus reducing the motor efficiency. The effect of skew is to increase the voltage between the rotor bar and laminations. If the bars are insulated and the insulation deteriorates over time, then damage can occur to the rotor bars and laminations.

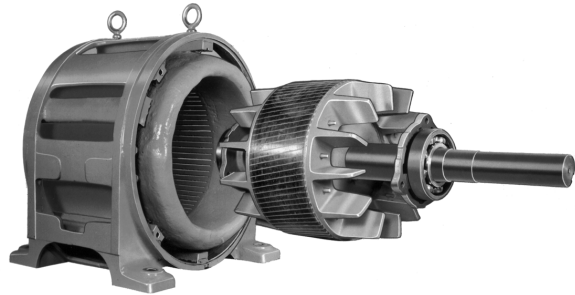
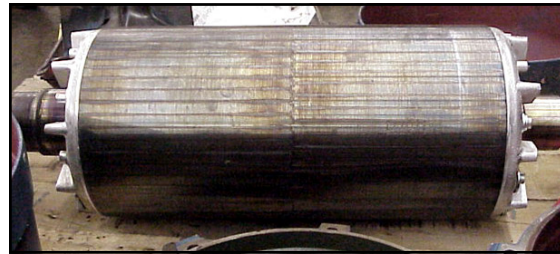
The starting characteristics are also affected. Skewing may reduce the starting torque and current, but may smooth out the accelerating torque by reducing the cogging or cusps.

For the motor designer, there is a trade off between efficiency and starting characteristics. When desirable, the rule is to only skew when necessary and only pick the optimum amount. Usually only the rotor is skewed.

The selection of the number of rotor and stator slots also influences the need for skew and the impact that it will have on motor performance. There is a wide opinion as to the optimum slot combination, but as a general rule, most manufacturers have evolved toward using less rotor than stator slots.

The results of skewing can be summed up as:

- A reduction in electromotive force in the rotor bars.
- A decrease in rotor leakage reactance.
- A nonuniform axial distribution of air gap flux.
- A reduced likelihood of noise problems.
- A current that has a circumferential component which develops a small axial force which imposes additional load on bearings.

**FIGURE 12: EXAMPLE OF ROTOR WITH SKEWED BARS****FIGURE 13: OFFSET SKEW**

This rotor has a unique construction in which the bars are straight but offset in the middle of the rotor. This is equivalent to a one-half rotor slot skew.

- A nonuniform air gap flux which increases core and stray losses.
- Improved speed/torque characteristics including elimination of locking torque at zero speed and cusps at various speeds.

**CASTING VARIATIONS AND VOIDS**

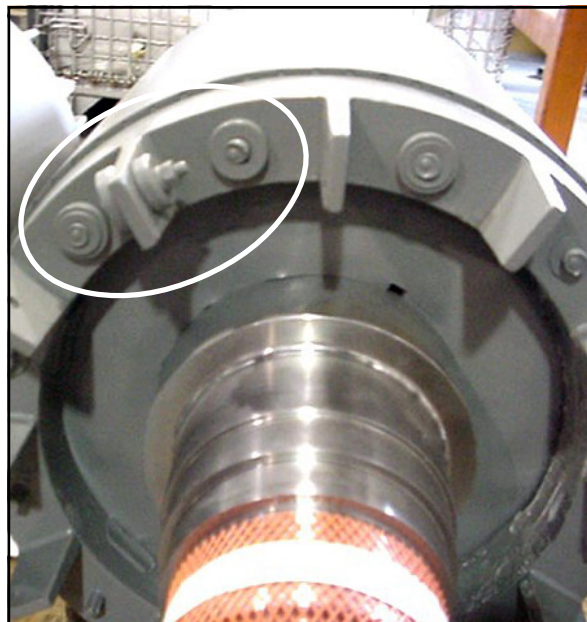
The porosity of this end ring weakened the balancing nib shown in the photograph below. The nib and its weights broke away from the end ring, hit the fan blades and were thrown into the winding.



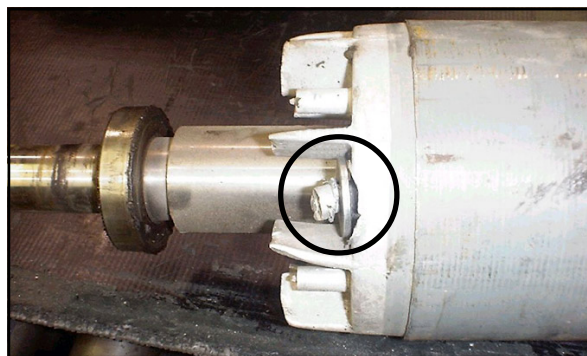
Broken balancing nib and balancing weights.



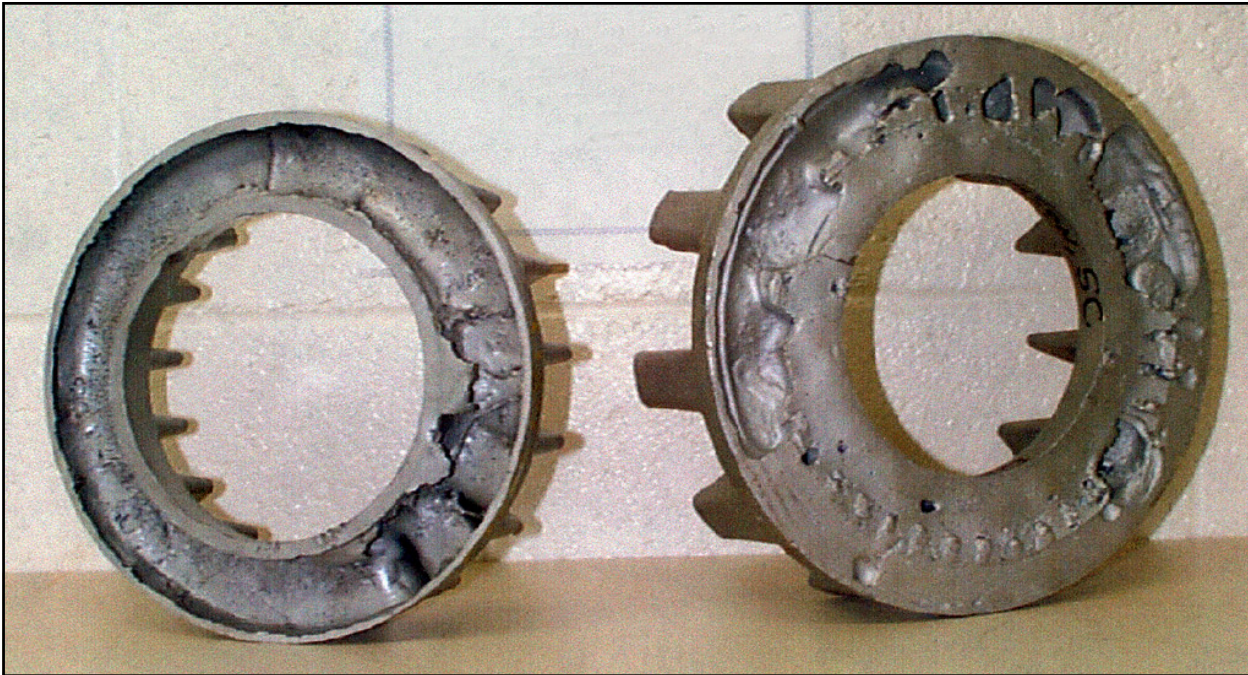
Balancing nib broke loose at the point highlighted above.



A large concentration of balancing weights in one location is a sure sign of rotor dissymmetry. If the shaft is straight, the rotor cage may not be complete and voids or porosity may be present. The other possibility is that the lamination bridge may not be symmetrical. Close inspection of the rotor surface may confirm this.





**CASTING VARIATIONS AND VOIDS**

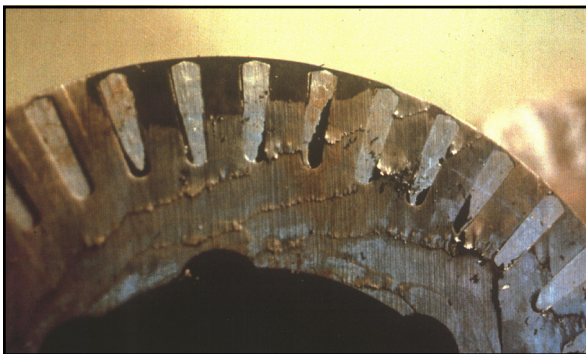
Voids and porosity can occur at any location in a cast aluminum rotor including in the end rings, on the surface and at the bottom of the slot. The end rings above show signs of extreme porosity and voids caused by problems associated with the rotor casting process.



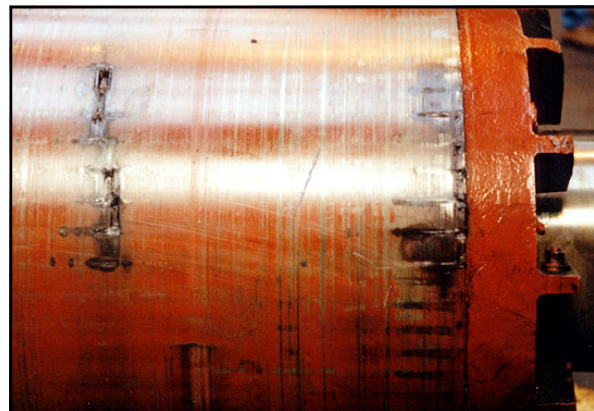
Voids located in an end ring.



Voids located near the surface of the rotor. This rotor was machined to expose the voids.

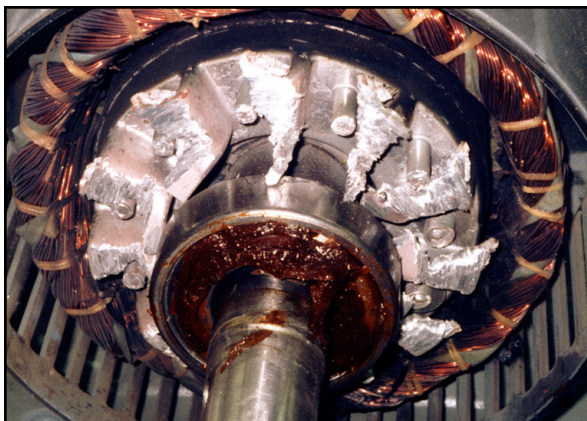


Voids located in the bottom of the slots.



Voids located on the rotor surface.



**IMPROPER DESIGN OR POOR WORKMANSHIP**

No clearance was left between the air deflector and the rotor fan blades. The rotor migrated on the shaft, causing the fan blades to hit the air deflector, destroying both.



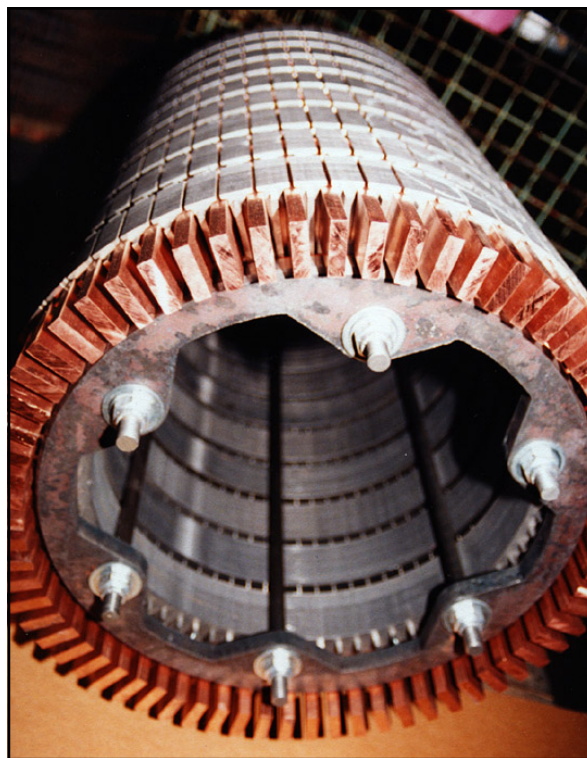
The rotor bars were not of equal length. This resulted in uneven amounts of thermal expansion, eventually breaking the brazed joints between the rotor bars and end ring. Further inspection also showed poor brazing evidenced by the appearance of the brazing material.



This design used long rotor bars to act as a cooling fan. However, the bar “overhang” was too long and the bending force caused by thermal stress fatigued the bars and caused them to fracture.



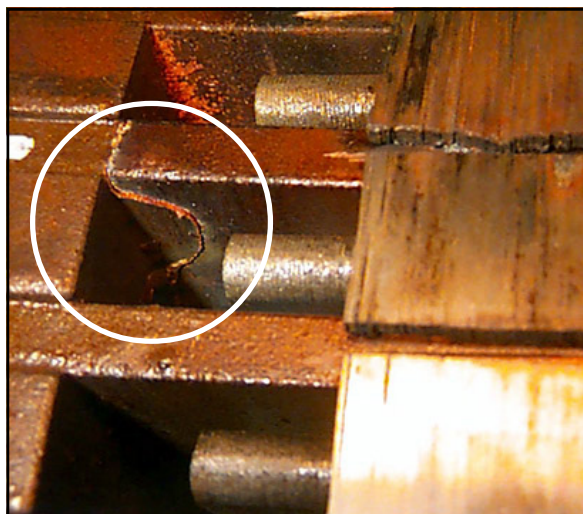
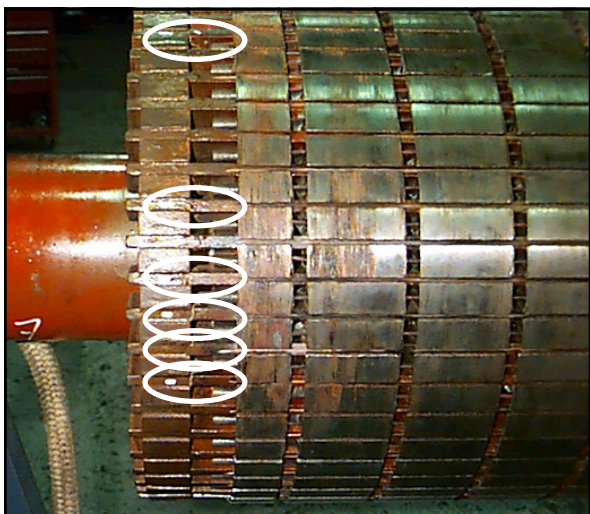
One rotor bar was too long and broke. Once broken, the rotor bar was forced over to the adjacent bar.



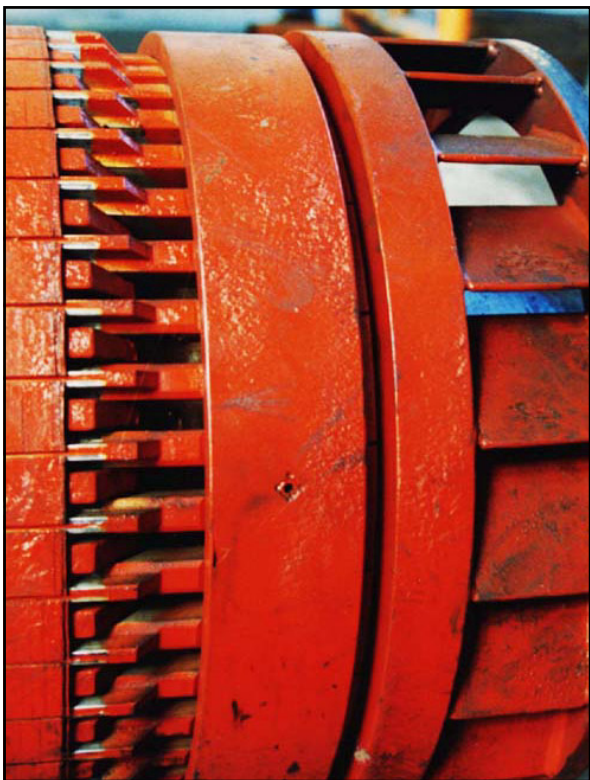
This rotor core, without the end ring installed, illustrates an ideal design. It has a moderate bar extension, all bars are of equal length and each bar is tight in the slot.



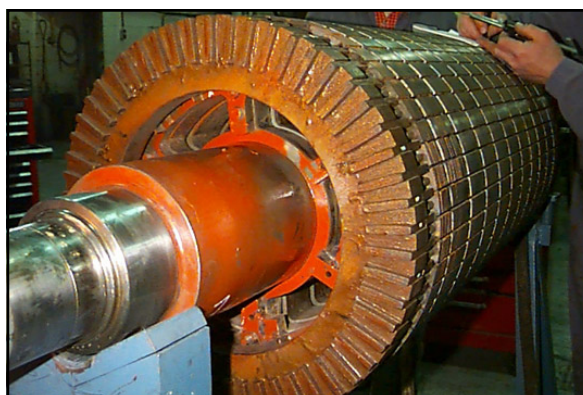
## IMPROPER DESIGN OR POOR WORKMANSHIP



Seven bars on this 6-pole motor rotor were staked through the laminations. Six of the broken bars are highlighted in the photo at left. This caused restricted thermal growth of these bars that eventually resulted in the breakage pattern shown at right. Loose rotor bars should be swaged uniformly on each bar, never on the laminations. Swaged or staked laminations increase rotor losses and may prevent movement caused by thermal expansion. The distinctive shape of the fracture is consistent with restricted movement and thermal stresses.



All the bars were loose in this 2-pole rotor. The complete cage moved axially until the shrink ring came in contact with the cooling fan. Note the lack of paint on the rotor bars showing how far the rotor cage has migrated.

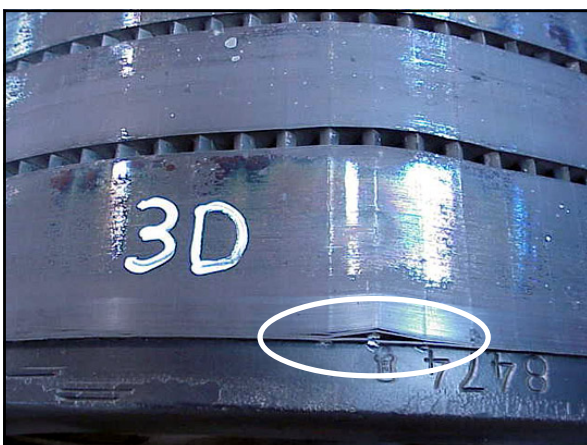
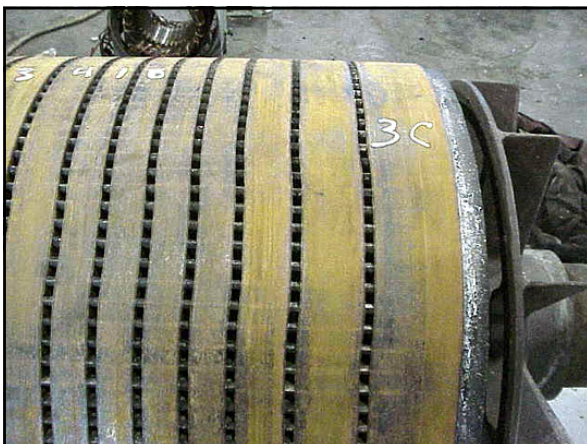
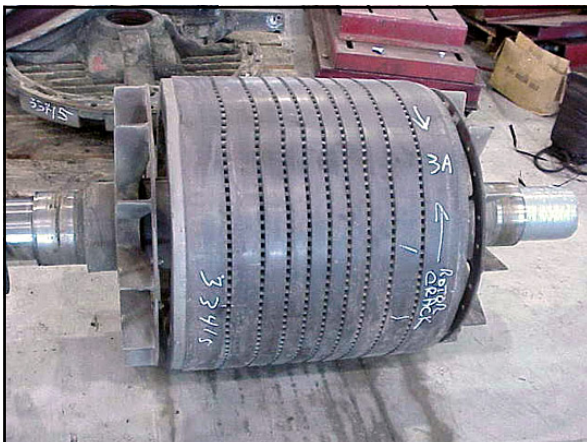


The rotor ends, above, are milled/indexed from copper plate. It is critical that the brazed joints be complete and free of voids. Note the gaps in the photograph below.





## IMPROPER DESIGN OR POOR WORKMANSHIP



A service center received five identical motors from an end user. Four of the five motors had bad rotors. The four rotors were stacked with inadequate pressure applied to the laminations. Heat transfer from the bars to the laminations to the air ducts was very poor. The poor stacking also created balancing issues and bar-to-end ring discontinuities as highlighted in the bottom photograph.



The rotor cage on this 12-pole rotor was loose enough that after one end ring was cut off, the remaining portion of the cage could be pulled from the rotor core. Note that the end ring that was cut off is sitting on top of the rotor cage.



Improper swaging of some rotor bars caused vibration and shorting current to overheat the laminations.



## ENVIRONMENTAL STRESS

Failures of this type are among the easiest to diagnose. This type of stress results from any environmental condition that may affect the life of a rotor. Examples of this include foreign materials which can cause abrasion or clog ventilation paths, or chemicals and moisture which may attack and break down the basic rotor materials.

It is especially important to observe maintenance records and operating site conditions to get the complete history surrounding the failure.

Environmental stress is made up of six basic stresses. They are:

- Contamination.
- Abrasion.
- Foreign particles.
- Restricted ventilation.
- Excessive ambient temperature.
- Unusual external forces.

## APPEARANCE

Restricted ventilation, due to deposits in air passages or ducts, or excessive ambient temperatures, will normally exhibit a heating pattern over the entire rotor as well as on other parts of the motor. Other patterns to look for include an etching on the rotor and/or aluminum surfaces, rust deposits, localized gouges in both the rotor and stator surface, "sandblasted" surfaces and foreign material lodged in the winding.

Telltale signs of environmental stress include:

- Contamination—Look for rust or etching.
- Abrasion—Look for polished or abraded parts.
- Foreign particles—Identify any foreign material (e.g.,

magnetic or nonmagnetic, conductive or nonconductive).

- Poor ventilation—Look for blockage of air paths or loose sound-absorbing material as well as missing baffles or covers which may be necessary to provide the required cooling.
- Excessive ambient temperature—Look for signs of thermal stress as well as deterioration of bearing lubricant or abnormal leakage.

## FAILURE CLASS

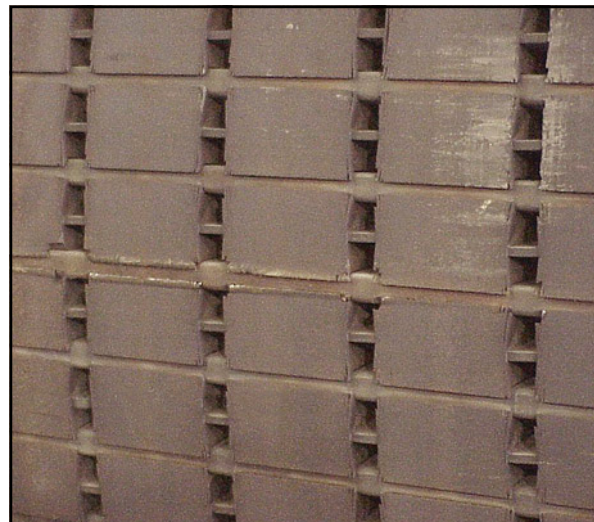
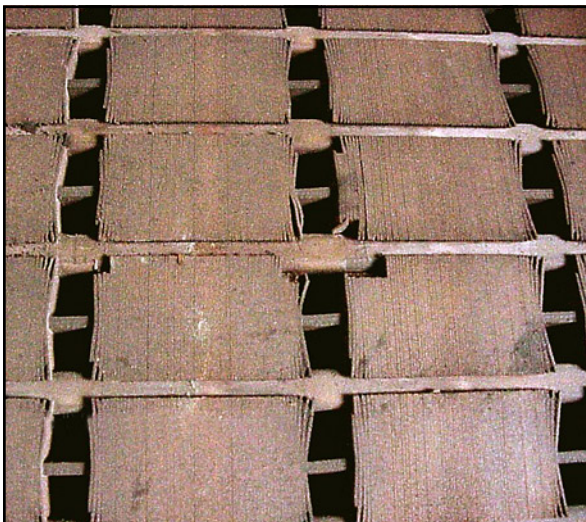
These failures are most often the result of misapplication or improper maintenance. Dust or other materials can clog filters, ventilation passages or air ducts causing general overheating. Enclosed motors can be coated with a blanket of material preventing proper heat transfer and airflow.

Chemicals or moisture can enter the motor and attack the rotor surfaces. On units with small air gaps [up to .040" (1 mm)], the rotors can become rusted to the stator inside diameter.

Foreign material can get into the rotor, breaking the fan blades or damaging the rotor surfaces. Corrosion can also cause balance weights to come loose and "sling" into the stator winding with destructive results. Where harsh environments exist, some rotors may be dipped or painted to provide additional protection.

Examination of the bearings and/or lubricant for thermal deterioration or contamination can explain certain failures. For example, the addition of even a small percentage of moisture in the lubricant significantly reduces the fatigue capability of the bearings. This can have dramatic effects on heavily-loaded applications as can the use of incompatible greases or oils which reduce the oil film strength.

## CONTAMINATION



Both of these rotors were corroded. Deterioration of the laminations caused loosening of the rotor bars. There is the potential for a stator ground failure if loose portions of the laminations were flung into the stator winding.

## MAGNETIC STRESS

Magnetic stress failures may be obvious or extremely difficult to isolate. Because of secondary damage, careful observation is necessary to accurately identify the ultimate cause of failure. Don't be misled by confusing the true cause of the failure with the affects of the failure.

Magnetic stress is made up of five basic stresses. They are:

- Rotor pullover.
- Uneven magnetic pull.
- Lamination saturation.
- Circulating currents.
- Electromagnetic noise and vibration.

## APPEARANCE

Visual evidence of magnetic stress failures is relatively limited. Rotor rubs may appear as a spot smear on the rotor outside diameter and the stator inside diameter, or a spot smear on the stator inside diameter along with a smear around the full circumference of the rotor.

Failures due to magnetic stresses where the rotor did not physically strike the stator usually display no visual pattern and can be detected only by measurements of associated parts (end brackets, frames, shafts, etc.) and the analysis of magnetic forces under actual operating conditions (operating voltage, frequency, etc.).

Audible evidence of magnetic stress is more common. Loose rotor bars usually exhibit noise or sparking during starting. They can also result in localized hot spots or bar breakage which is easily observed after disassembly. Detection of broken rotor bars without disassembly is often possible by performing a single phase test. This test consists of applying single-phase voltage of about 25% to 50% of the rated voltage to two motor leads. Slowly rotate the rotor by hand while observing line current with a clip-on ammeter. A broken bar will cause a fluctuating current every time it passes under a pole pair. Variance in current readings of 3% or greater are an indication of bar breakage.

Telltale signs of magnetic stress include:

- Rotor pullover—Look for signs of contact between the rotor outside diameter and the stator inside diameter and/or any seal or shaft rubs.
- Noise—This is not available after the failure but discussion with operators may eliminate or identify probably failure origin.
- Vibration—This is not available after the failure but be sure to review the history if it is available.
- Loose rotor bars—Check for loose bars with a mallet and punch, listening for a distinctive sound.
- Off magnetic center—Look for a wear pattern on the thrust face of sleeve bearings or the ball track on ball bearings.
- Saturation of laminations—This is not normally detectable in the rotor except for signs similar to thermal unbalance.
- Circulating currents—This is similar to hot spots except it generally covers a larger area. This condition can

lead to vibration instability. Examine the rotor teeth and through-bolts for signs of discoloration.

## FAILURE CLASS

Rotor pullover may or may not be accompanied by physical contact with the stator. If contact does occur, the first evidence may be noise, vibration or catastrophic winding failure. If contact does not occur, evidence may be limited to noise or vibration.

Prolonged excessive pullover will result in high radial bearing loading with a corresponding reduction in bearing life. Any history of short bearing life or combination of bearing failures should be examined as a potential pullover problem.

Rotor rubs due to eccentricity typically show heavy smearing in a small area of the rotor outside diameter and around the entire stator bore. Uneven magnetic pull typically exhibits a rub in a small area of the stator and around the entire outside diameter of the rotor. This is caused by the axis of rotation being different than the magnetic axis of the winding. Precise measurements would be necessary to detect this condition.

Saturation and circulating currents would result in poor performance of the motor and could be detected by the motor manufacturer. They are in the best position to isolate performance problems.

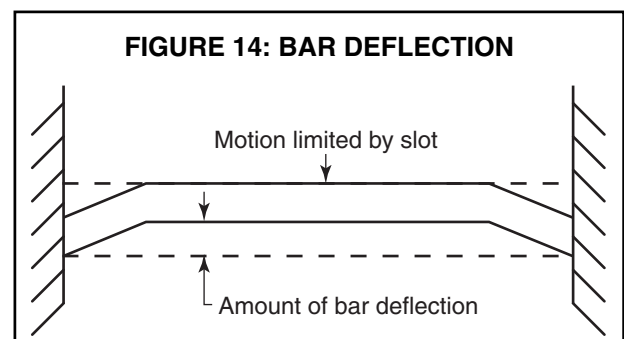
Magnetic stress failures not involving contact can manifest themselves as noise and/or vibration. Eccentric rotor cores (particularly 2-pole rotors) will generally exhibit a pulsating beat at slip frequency, while slow-speed motors normally exhibit vibration. These magnetic forces are easily isolated as they cease immediately upon removal of power.

Broken rotor bars can lead to vibration problems but, in severe cases, the bar lifts out of the slot and makes contact with the stator core or winding. A rattling sound at start up or under load may be the start of loose or broken rotor bars.

## ELECTROMAGNETIC EFFECT

The action of the slot leakage flux, created by bar current, creates electrodynamic forces. These forces are proportional to the current squared ( $I^2$ ), are unidirectional and tend to displace the bar radially between the top and bottom of the slot.

These forces vibrate the bar at twice the frequency of the rotor current. (See Figure 14.) Hence, they produce deflection (bending stress) in the bar. If the deflection is high





**FIGURE 15: DAMAGE CAUSE BY ELECTROMAGNETIC EFFECT**



This rotor shows evidence of magnetic resonance which caused the bars to loosen and vibrate.

enough, a fatigue failure in the bar will occur (Figure 15).

It can be shown that the radial force acting on the rotor bar will cause a deflection during starting that would be greater than that allowed by the normal slot confinement. [For a typical 1750 hp, 6-pole motor, the force was calculated at 78 pounds per inch of core length with a non-constrained deflection of 0.017" (0.4 mm).]

It is theorized that the bar actually flattens out in the center of the slot so that the stress at the end connector-to-bar joint is higher than that allowed by simple slot constrained bar motion.

#### UNBALANCED MAGNETIC PULL AND ROTOR RUB

As shown in Figure 17, unbalanced magnetic pull is a potential problem which can cause the rotor to bend and

**TABLE 1: COMMON CAUSES OF ROTOR STRIKES BASED ON POINTS OF CONTACT**

|       | Contact area | Stator                                                                                                                                                                                                    |                                                                                                                                  |                                                                                                                                                                          |
|-------|--------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|       |              | One point                                                                                                                                                                                                 | Random                                                                                                                           | 360°                                                                                                                                                                     |
| Rotor | 360°         | <ul style="list-style-type: none"> <li>Excessive radial load on the shaft.</li> <li>Failed bearing plus radial load.</li> <li>Eccentric air gap.</li> <li>Bearing housing machined off center.</li> </ul> |                                                                                                                                  | <ul style="list-style-type: none"> <li>Failed bearing with direct-coupled load.</li> <li>Broken shaft.</li> <li>Severely-worn bearing fit (shaft or housing).</li> </ul> |
|       | Random       | 2                                                                                                                                                                                                         | Strictly rotor pullover during starting. The shaft stiffness is not enough to resist magnetic forces during starting.<br>1, 3, 4 |                                                                                                                                                                          |
|       | One point    | Eccentric rotor and the shaft rotational axis is not concentric to the stator bore.<br>2                                                                                                                  | 2                                                                                                                                | <ul style="list-style-type: none"> <li>Eccentric rotor.</li> <li>Bent shaft.</li> <li>Bearing journal is not concentric to the rotor.</li> </ul>                         |

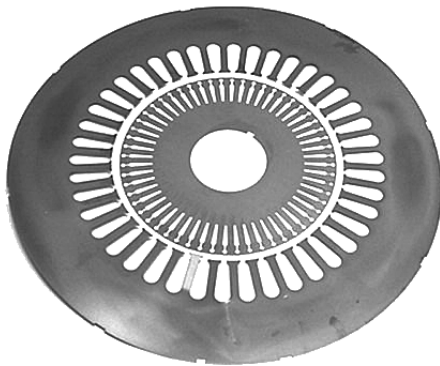
- 1 Although not common, inspect for a loose stator core.
- 2 If anything in the motor history indicates that the problem started suddenly, look for either high line voltage or a cracked shaft within the rotor core.
- 3 If the motor is a 2 pole, it could be operating at excessive voltage. Check for recent transformer tap changes, etc.
- 4 Prolonged operation of a motor with random stator-to-rotor contact could eventually result in an appearance of 360° contact on both parts.

Note: Severe bearing failure could result in any of the above combinations.

Vertical machines with thrust bearings: Momentary upthrust can result in random 360° contact of the rotor and stator on the thrust bearing end only.

#### Detection methods

- Noise at starting (rotor slap).
- Vibration during starting, at multiple random frequencies.
- Check for flexing shaft using a vibration analyzer with a strobe light.

**FIGURE 16: AIR GAP**

This photograph illustrates the air gap between the stator inside diameter and the rotor outside diameter. For illustrative purposes, the size of the air gap has been exaggerated.

strike the stator winding. The magnetic force acting to deflect the shaft are resisted only by the stiffness of the shaft. Such things as eccentricity, rotor weight, bearing wear and machine alignment all affect the air gap geometry. (See Table 1.)

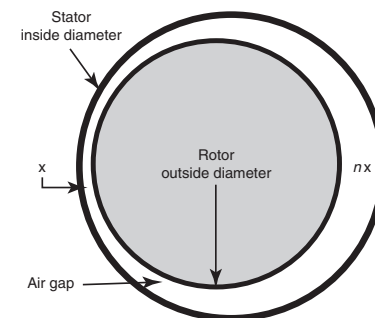
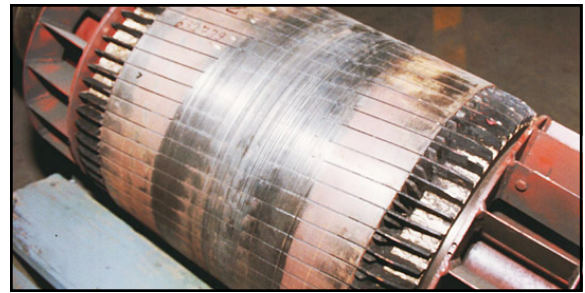
The magnetic pull varies as the square of the difference in the air gap (Figure 17). The magnetic forces acting on the rotor are resisted only by the stiffness of the shaft. The more the shaft is deflected, the greater its resistance to being bent further. In a good design, shaft stiffness is more than adequate to resist the bending forces of an imperfect air gap.

Motor designers attack this problem by setting limits on the acceptable amount of air gap eccentricity. This is usually 10% of the average air gap. The shaft size is selected, based on its ability to resist (shaft stiffness) these bending forces. The potential for rotor pullover can be described as a function of the air gap, concentricity, stack length, air gap flux density and stator winding circuitry. The chance of rotor pullover is usually greatest during the starting cycle when the ampere-turns are also greatest. If the rotor strikes the stator, it can usually be heard. Depending on the amount of contact, it may or may not result in damage to the rotor and/or stator parts. An inspection of the parts is the best way to confirm that this condition exists and how serious it is. The most common way to correct motor pullover is to improve the air gap geometry by centering the rotor within the stator bore. It has been demonstrated over the years that certain multiparallel circuits may reduce the tendency for rotor pullover. On machines where pullover is a potential problem, single-circuit connections should be avoided.

See photographs on Page 5-14.

### ELECTROMAGNETIC NOISE AND VIBRATION

In addition to pullover problems, air gap eccentricity can cause noise and/or vibration problems. The radial force produced by the stator harmonics combine with those produced by the rotor harmonics which in turn can create electromagnetic noise and/or vibration.

**FIGURE 17: MAGNETIC CENTERING FORCES AND AIR GAP**

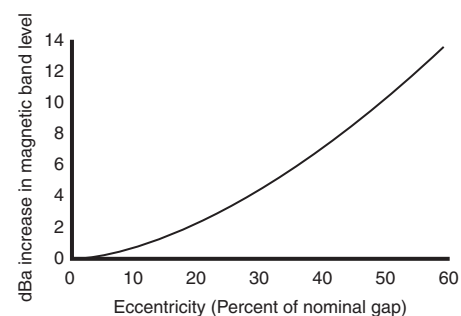
| If the ratio is: | Force at x is:    |
|------------------|-------------------|
| x and 2x         | 4 times stronger  |
| x and 3x         | 9 times stronger  |
| x and 4x         | 16 times stronger |

When started across the line, a rotor may come into contact with the stator during acceleration, even if the stator-to-rotor geometry is acceptable. Note the characteristic rub in the center of the rotor. The magnetic forces acting on the air gap vary as the square of the ratio of the air gap difference.

There are four basic types of air gap eccentricities which are:

- Rotor outer diameter is eccentric to the axis of rotation.
- Stator bore is eccentric.
- Rotor and stator are round but are not concentric.
- Rotor and shaft are round, but do not have the same axis of rotation.

These conditions may or may not cause a significant amount of electromagnetic noise or vibration. The noise at full load is usually higher than that occurring at no load.

**FIGURE 18: PERCENT ECCENTRICITY VS. INCREASE IN NOISE LEVEL (MAGNETIC FIELD)**

Courtesy of John Courtin



Vibration due to eccentricities will usually vary as a function of terminal voltage. John Courtin, in his paper *Effect on Air Gap Eccentricity on Motor Sound Level*, conducted a series of tests on NEMA-size open dripproof motors and developed the curve in Figure 18 to show the relationship between

air gap eccentricity and noise. Although the specific numbers are not totally representative of all motors, it does illustrate the magnitude of the problem. Severe air gap eccentricity (more than 25%) will typically contribute 2 to 3 dBA to the overall noise level on the machine.

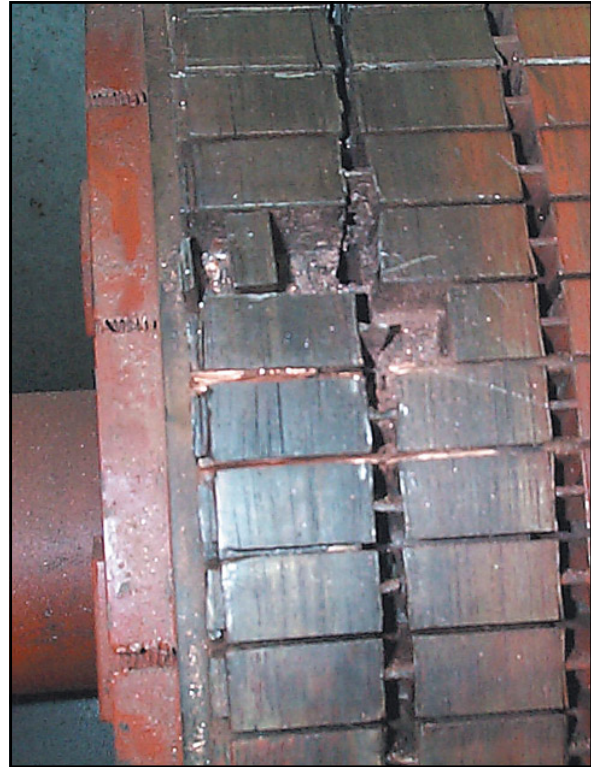
## FATIGUE OR PART BREAKAGE



The rotor teeth fractured at the root due to resonance and were slung out into the stator, causing a ground failure.



The rotor fan blades fractured above the welds due to cracks and vibration that resulted from fatigue in the aluminum.



Broken rotor bar arced and eventually eroded the rotor teeth until they fractured.



This loose bar was exposed due to severe vibration induced during a prolonged starting cycle.



## RESIDUAL STRESS

Residual stresses can be present in any plane and are normally not harmful to the rotor as long as they do not cause any significant change in the rotor geometry.

Residual stresses include:

- Stress concentrations.
- Uneven cage stresses.

## APPEARANCE

Telltale signs of residual stress include:

- Stress concentrations—Normally, there are no outward signs but parts may exhibit geometry changes from cold to hot. In those cases where there is evidence of surface abnormalities, record the location to allow analysis and obtain a vibration history.
- Uneven bar stress—Geometry changes from cold to hot due to manufacturing processes. Sometimes the

geometry may respond to either cold or hot thermal shock.

## FAILURE CLASS

Most of the more common residual stresses are the result of casting, welding, stacking and machining operations. On larger motors, it is common practice to stress relieve the rotor shaft prior to final machining. Some manufacturers have tried stress relieving to reduce the rotor cage residual stress. If any of these stresses do result in a change to the rotor geometry, they usually take place during the transition between idle and full load thermal conditions, and can cause vibration problems which might not be noticed when running at no load.

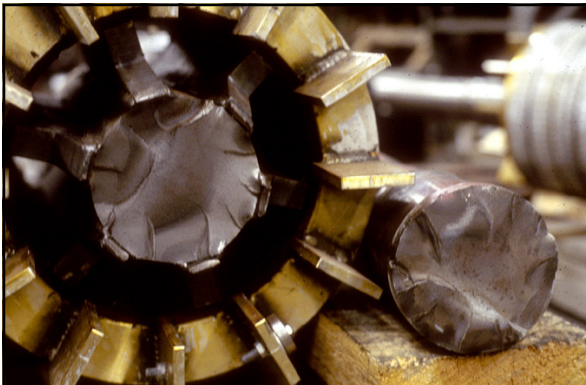
On high-speed machines, most manufacturers provide a means for refined balancing that allows for hot balancing if necessary.

As in the case of thermal stress, problems of this nature should be referred back to the motor manufacturer.

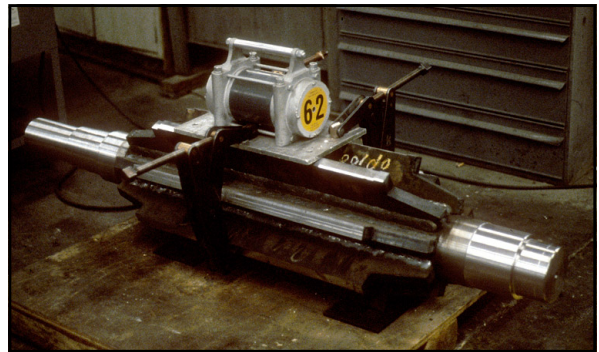
## RESIDUAL STRESS



Many large rotors have spiders that are welded to the shaft. If not done properly, a residual stress can be introduced and cause the shaft to fracture. Spiders should not be welded at the ends as shown above. This will intensify the stress risers. Shafts of this size are often stress relieved (see photograph at bottom right) in order to minimize the stress risers caused by welding the spiders to the shaft. Failure to do so may cause fractures.



This shaft was not welded on the ends of the spiders. By not doing this, the stress risers shown in the photograph at left are eliminated.



Vibratory stress relief is one method of stress relieving a shaft. Another method would be to thermally stress relieve.



## MISCELLANEOUS STRESS

Failures of this type do not readily fall into clearly-defined categories. They exhibit characteristics from each of the previously defined stresses and must be examined carefully to isolate the primary cause of failure.

Miscellaneous stress is made up of six basic stresses:

- Misapplication.
- Effects of design practice.
- Manufacturing variations.
- Inadequate maintenance.
- Improper operation.
- Improper mounting.

### APPEARANCE

All, part or none of the previously mentioned patterns may be present in this category. New patterns may also exist that could identify the failure origin.

Telltale signs of miscellaneous stress include:

- Misapplication—Look for bearings designed for high downthrust but operated lightly loaded or in upthrust, incorrect viscosity of lubricant, misalignment, incorrect mounting, etc.
- Effect of design practice—Look for signs such as providing silphos brazing alloy when sulfur fumes are present or insufficient application data.
- Manufacturing variations—Look for poor geometry of component parts such as brackets, bearing bores, etc.
- Improper maintenance, improper operation and improper mounting are not normally distinguishable by appearance.

### FAILURE CLASS

Depending on the specific cause, different classes of failure may have occurred. Inadequate, excessive or improper maintenance can lead to overheating or bearing failure. Misapplication and improper operation can result in thermal failures or broken parts. Poor system or motor

design practices can result in a range of operation from poor performance to catastrophic failure.

The motor manufacturer is normally in the best position to analyze these failures as they know the capabilities and design of their equipment.

To make an analysis, it is necessary to document the exact operating sequence in order to identify the failure origin.

This type of analysis was performed on a 2-pole motor with a failed winding, excessive rotor core and shaft rubs, failed bearings and a spun fan bore on the opposite drive end. This motor was located at an unattended remote pumping station and was removed from the line by ground fault protection. It had operated successfully for more than nine months prior to the failure. While almost all components failed, the origin of the failure was found to be a faulty check valve.

The results of the analysis support that finding.

- The shaft in the location of the damaged fan, as well as the drive end fan location, showed that all parts were in tolerance.
- Both fans' blades showed slight bowing which was duplicated by overspeeding a new fan to approximately 5000 rpm.
- The plastic nipple in the air deflector used to pressurize the opposite drive end bearing was smeared opposite to the normal direction of rotation.

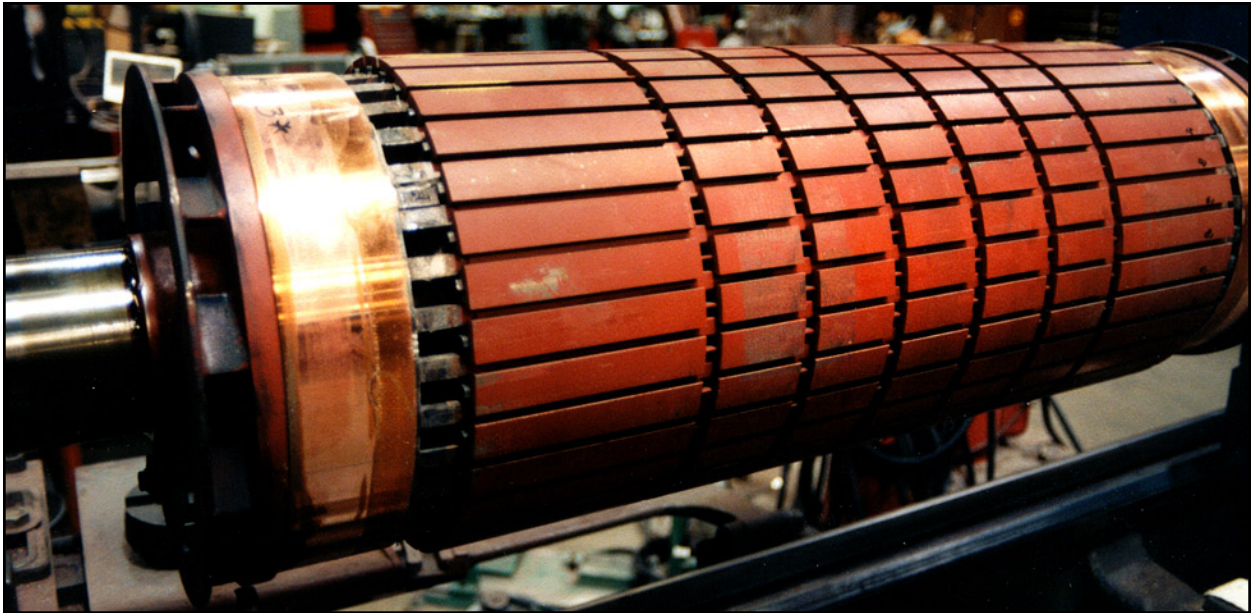
The conclusion reached was that the pumping station check valve had malfunctioned, causing the unit to overspeed in the reverse direction while unenergized. This resulted in the opposite drive end fan losing its fit and traveling down the shaft, making contact with the air deflector nipple. The next time the unit was started, the fan bore smeared in the direction of rotation causing localized heating, and ultimately a bearing failure. The dropped rotor rubbed the stator resulting in a winding failure.

To prevent recurrence, it was suggested that the check valve be repaired prior to replacement of the motor.

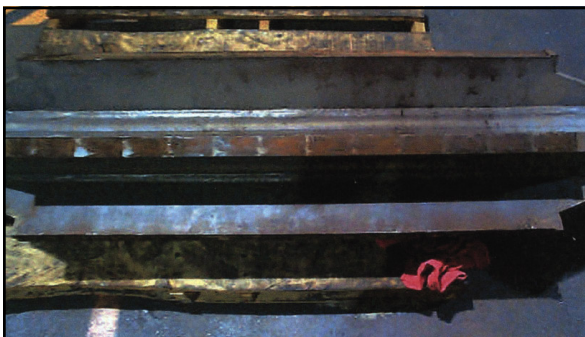
## MISCELLANEOUS STRESS



This rotor was balanced by the addition of a large balancing weight welded to the rotor clamping plate. When welding to a rotor, care should be taken to add weight where it will not cause distortion, and only to parts that are substantial enough to resist bending.

**MISCELLANEOUS STRESS**

The shrink ring moved axially due to either poor design or manufacturing process.



Loss of rotor core-to-shaft fit can occur for the following reasons including improper fits by design or tolerance, excessive thermal expansion, improper machining of the shaft, hoop stress capability of the laminations is exceeded as well as removal of the shaft resulting in a “shear off” of fit. The two photographs above are examples of spider shafts. The spiders on the shaft at left were undersized. When required to transfer torque under load, the shaft slipped within the rotor core.



## SPECIAL CASES IN INDUCTION ROTOR TESTING

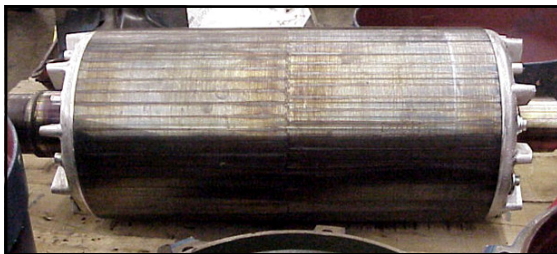
There are a couple of unusual variations to the induction motor which can alarm the tester if encountered. (See Figures 19 and 20.) These are likely to show up when a rotor is being tested using a growler (or core tester) with magnetic imaging paper, a hacksaw blade or iron filings. In each case, there is a deviation from the normal pattern of uniformly-spaced rotor bars.

Rather than skewing the rotor bars, at least one manufacturer opts to build a rotor with a step at the rotor's midpoint. The rotor bars appear to step at that point, so that while each of the two ends appear straight, they are indexed half a bar space apart. The effects on noise reduction are similar to the benefits of a skew.

The synchronous induction rotor is constructed like a conventional induction rotor except that rotor poles are created by interrupting the rotor cage. A 4-pole rotor will have four large interrupts, a 6-pole rotor will have six interrupts, etc. (See Figure 20.) The image seen when using magnetic imaging paper looks like a large smear where no bars are visible. The key is in the symmetry of the poles. In general, the synchronous induction motor will have about half to two-thirds of the horsepower capacity of a standard induction motor of the same size.

The hysteresis rotor uses no cage. Normally, this rotor is constructed of stacked hardened steel segments. This gives the appearance of a solid cylinder of steel. Flux from the rotating stator field passes through the rotor. Resistance to the rotating flux field rotates the rotor. Losses are much higher than with a comparable induction rotor. The stronger resistance to magnetic pole changes locks the rotor into synchronous speed. These are rarely seen other than in very small ratings.

**FIGURE 19: OFFSET SKEW**



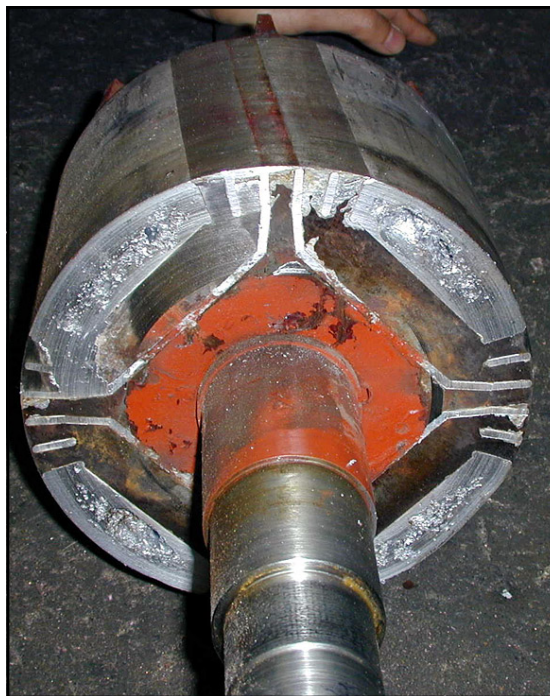
This rotor has a unique construction in which the bars are straight but offset in the middle of the rotor. This is equivalent to a one-half rotor slot skew.

## CONCLUSION

It should be noted that no mention was made of the effects of thermal or residual aging on rotor failures. This can be explained as follows:

Unless the operating temperature is extremely high, the

**FIGURE 20: EXAMPLE OF A SYNCHRONOUS INDUCTION ROTOR**



This is a 4-pole synchronous induction rotor. The image seen when using magnetic imaging paper looks like a large smear where no bars are visible

normal effect of thermal aging is to render the rotor materials vulnerable to other influencing factors and stresses that actually produce the failure. Once the rotor has lost its physical integrity, it will no longer resist the normal dynamic, magnetic, mechanical and environmental stresses. If any of the basic stresses become severe enough, a failure will occur regardless of the amount of thermal aging. This type of failure is normally identified by slow, long-term changes in vibration and many times can be brought under control by thermally shocking the rotor.

Due to the destructive nature of most failures, it is not easy and is sometimes impossible, to determine the primary cause of failure. By a process of elimination, one can usually be assured of properly identifying the most likely cause of failure.

A process of elimination is the key: Analyzing the failure pattern and class, noting the general rotor appearance, identifying the operating condition at the time of failure and studying past history of the motor and application.

If any of these steps are omitted, it would be easy to arrive at a false conclusion. Hence, the required action might not be taken and future failures of the same kind will surely occur.

# 6

## Mechanical Failures

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## INTRODUCTION TO MECHANICAL FAILURES

The previous sections of this book have focused on the various stresses and how they influence the stator, rotor, bearings and shaft.

Even though the mechanical parts are influenced by a variety of stresses, no attempt was made to separate or categorize failures by these stresses.

The categorization of mechanical parts is somewhat arbitrary. They are grouped for convenience as follows:

- Motor cooling system—Fans, air deflectors, air duct spacers, screening and baffles.
- Motor terminal boxes—Box, leads, spacers, lugs and connectors.
- Lifting devices.
- Mounting and alignment.
- Mechanical structure—Frame, feet, brackets, bearing caps and other miscellaneous mechanical items.

## THE MOTOR COOLING SYSTEM

A properly-functioning cooling system is a key element to the successful operation of an electric motor. Just like the major elements of the motor, it is susceptible to damage and must be maintained. This section will help clarify how these systems function and what can go wrong and cause damage to other parts of the motor.

Page 6-3 provides examples of motors with various cooling systems. In all of these examples, the major elements of the cooling system are the fans, baffles, deflectors, cowlings and motor surfaces that direct the flow of air through the heat path that is driven by conduction, radiation and convection.

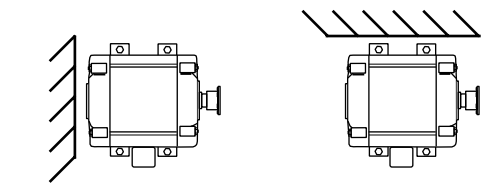
In most cases, the ambient air is the common denominator for cooling systems. If the ambient temperature, amount of air (or other cooling medium) or quality of air varies beyond the intended limits, then the increased operating temperature of the motor may cause damage or shorten its life expectancy.

If the ability of the motor to radiate the heat conducted to its surface is reduced, then the convection process associated with the ambient air will be ineffective regardless of how much air is moved through or over the motor. Contamination of the motor surfaces, including the rotor, stator, frame and end bells, can cause the motor to retain “trapped” losses in the form of heat.

When analyzing the effectiveness of the motor cooling system it is necessary to examine the area surrounding the

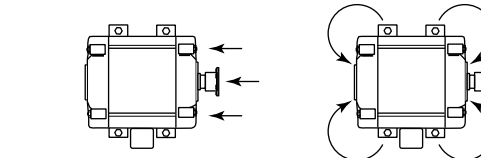
**FIGURE 1: FACTORS THAT INFLUENCE COOLING AIR**

### Open dripproof horizontal motors



Restriction of intake air due to structures being too close to the motor.

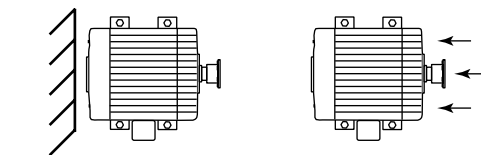
Restriction of exhaust air.



Heat from driven equipment is drawn into the air intake.

Recirculation.

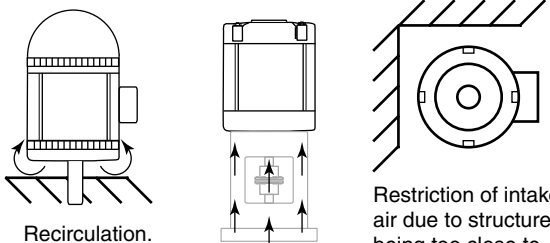
### Totally-enclosed, fan-cooled horizontal motors



Restriction of intake air due to structures being too close to the motor.

Heat from driven equipment overheats drive end bearing.

### Vertical motors



Recirculation.

Heat from driven equipment is drawn into the air intake.

Restriction of intake air due to structures being too close to the motor.

motor since it is most often the primary source of the cooling air. Anything that reduces the required volume of intake or

## PHOTOGRAPHS OF MECHANICAL FAILURES AND DAMAGE

|                                         |      |
|-----------------------------------------|------|
| Thermal overload .....                  | 6-8  |
| Vibration and loose rotor bars .....    | 6-12 |
| Improper rotor-to-stator geometry ..... | 6-13 |
| Centrifugal force (overspeed) .....     | 6-14 |
| Casting variations and voids .....      | 6-20 |

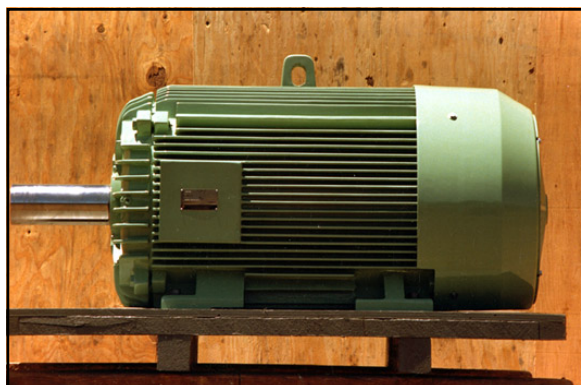
|                                           |      |
|-------------------------------------------|------|
| Improper design or poor workmanship ..... | 6-22 |
| Contamination .....                       | 6-25 |
| Fatigue or part breakage .....            | 6-29 |
| Residual stress .....                     | 6-30 |
| Miscellaneous stress .....                | 6-31 |



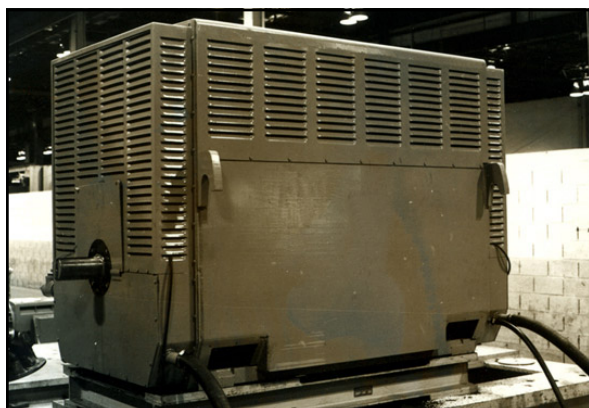
# EXAMPLES OF MOTOR ENCLOSURES AND COOLING SYSTEMS



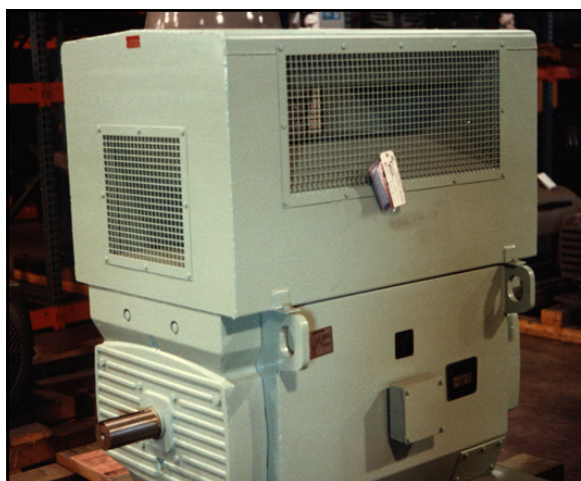
Open dripproof (ODP)



Totally-enclosed, fan-cooled motor (TEFC)



Modified open dripproof (MOD)



Weather protected I (WPI)



Weather protected II (WPII)

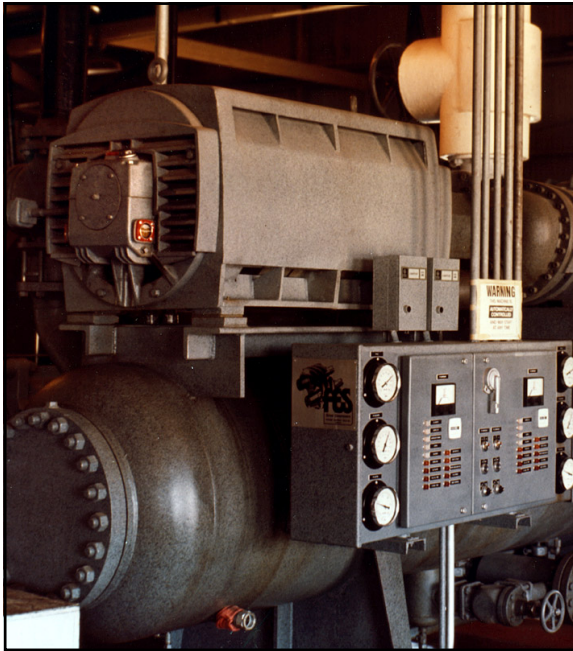


Open dripproof (ODP)



Weather protected I (WPI)

**FIGURE 2: INFLUENCE OF DRIVEN EQUIPMENT ON MOTOR TEMPERATURE**



This motor is mounted so close to the compressor system that the ambient air temperature below the motor, and immediately surrounding the motor, is much higher than ambient air in other parts of the facility. This heated air is drawn into the motor's air intakes raising its operating temperature.

exhaust air of the motor will usually cause the motor to overheat and may cause severe damage. Recirculation can also be a problem. This happens when there is not enough room for the motor to properly expel the exhaust air and it is drawn back into the motor before the air has had a chance to cool down to ambient temperature (Figure 2).

Figure 1 shows examples of conditions that can adversely affect the quality and quantity of the cooling air.

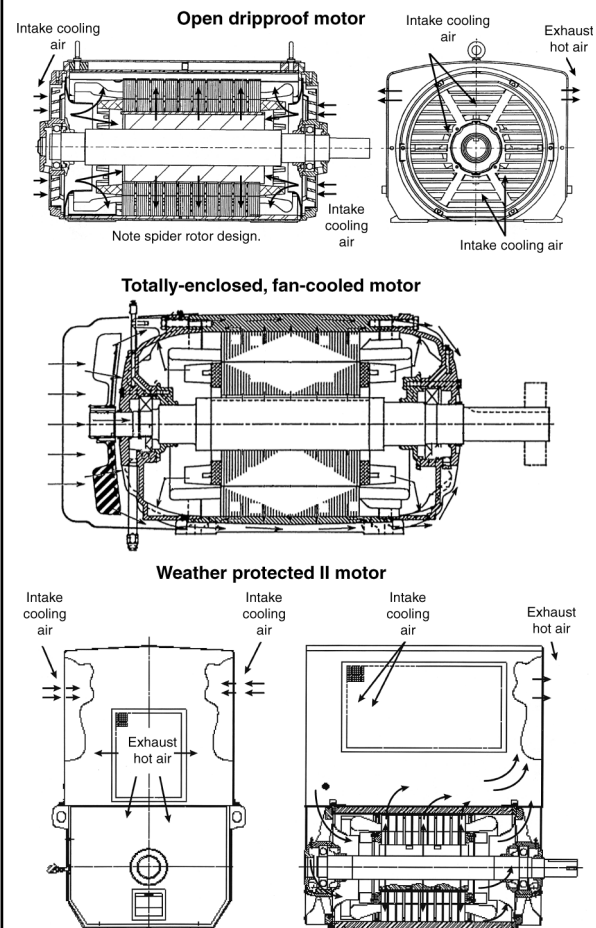
When the primary source of cooling is supplied by a forced air or water system, it too can be problematic if the volume is reduced, the temperature is too high or the coolant is contaminated.

Thermal damage to the motor caused by inadequate cooling is not always obvious. The stator, rotor and bearing systems can all be damaged from this condition. However, excessive current can also cause similar damage to these same components. In some cases, improper lubrication practices can cause similar overheating patterns in the bearing system. The key point is to not overlook this possibility when conducting a root cause failure analysis. Be sure to confirm the altitude at which the motor operates.

### AIR DUCTS

The rotor and stator core vent system provides the cooling path for motors that exchange external ambient air with internal hot air dissipated in the motor (Figure 3). Restrictions in this system, also known as air ducts, can

**FIGURE 3: EXAMPLES OF AIRFLOW THROUGH MOTOR ENCLOSURES**



hinder the effectiveness of the cooling system and cause heating of the motor. If the fans, fingers, spacers, teeth, baffles or clamping plates used to direct the air break, they can also cause serious damage to windings and bearings.

Occasionally, a severe ground, especially one caused by large transients, can cause damage to the laminations where the vents are fastened.

Excessive vibration may cause some of these parts to fatigue and break. This can happen to the lamination teeth, which in turn can cause blockage or damage. Motors with duty cycles requiring frequent starts or prolonged accelerating time are particularly susceptible to this type of damage. The cooling vents may also become blocked by repeated varnish treatment cycles or the application of material with excessively-high viscosity.

Air ducts may also become clogged by a fine dust, such as cement or pulp, drawn into the cooling passages by the motor's cooling fans. This fine dust builds up over time reducing airflow through the motor (Figure 4).

Lubricant may also be drawn from bearing cavities into the air ducts creating restricted airflow.

This clogging of air ducts causes the motor operating



**FIGURE 4: CLOGGED STATOR END TURNS AND VENT DUCTS**

In a winding designed with a partially-encapsulated coil extension (for increased winding rigidity), ventilation among the exposed portions of coils is even more critical. The stator vent ducts in this motor, as well as the coil extensions, are blocked by contaminants.

temperature to increase drastically and the thermal life of the insulation to be significantly reduced. (See Figure 5.) The operating temperature of the bearing system may also be affected.

For more information, refer to the material on environmental stress located in Section 3 of this book.

#### UNUSUAL COOLING SYSTEMS

There are a number of cooling systems that do not rely on

the motor fan to draw ambient air directly from the motor's immediate environment. Instead, a cooling medium such as air, a gas or a fluid can be used. It can be located near the motor or at a remote location.

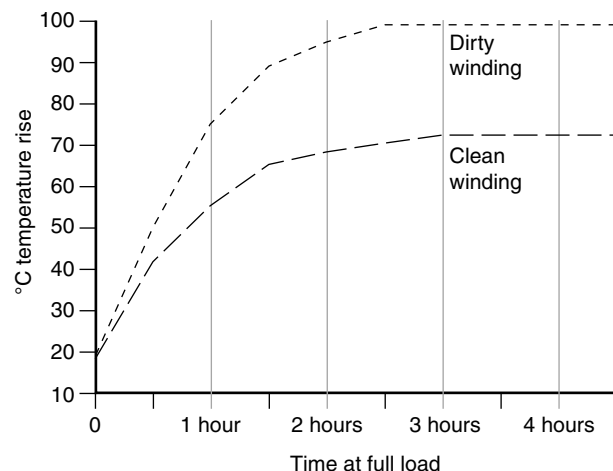
Regardless of the type of coolant or its location, the quality and quantity of this coolant should be checked whenever it is suspected that the cooling system may be contributing to a thermal or contamination problem.

The following is a partial list of such systems that are associated with definite-purpose motors.

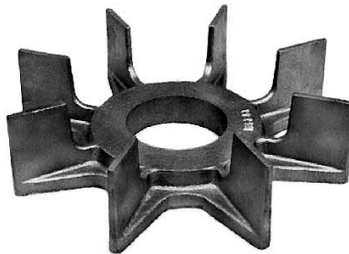
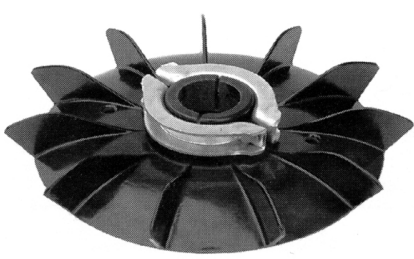
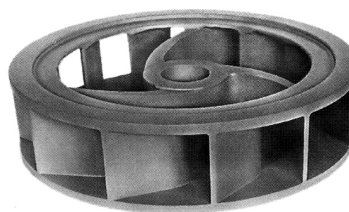
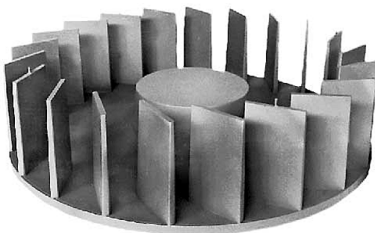
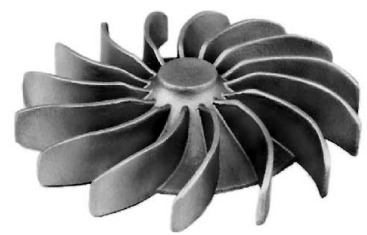
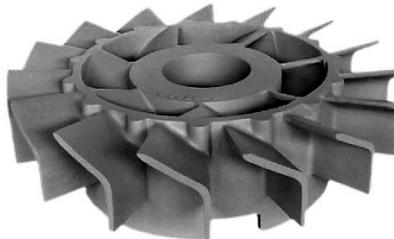
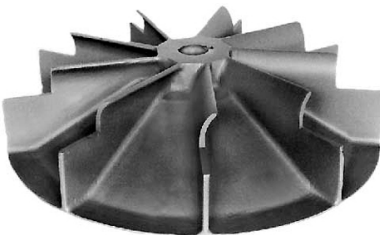
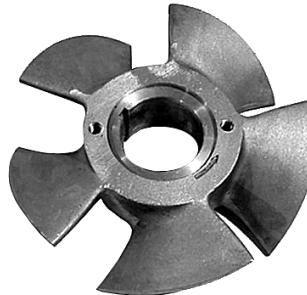
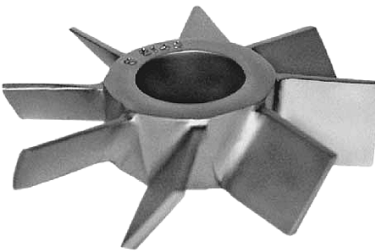
- **Air over:** The motor relies on ambient air drawn over the frame by an external fan or other source of air.
- **Pipe vent:** External cooling air is delivered to the motor through a pipe/vent system.
- **Forced air:** The motor is cooled by a small fan motor attached to the motor which directs cooling air over and into the motor.
- **Air cooled:** The motor uses an air-to-air heat exchanger attached to the motor to remove heat.
- **Water cooled:** The motor uses an air-to-water heat exchanger attached to the motor to remove heat. Other cooling fluids may be used in place of water.
- **Submersible/cryogenic/hermetic:** The stator and/or rotor are cooled by a fluid, usually the same fluid that passes through the pump or compressor.
- **Purged gas:** Instead of ambient air, the internal air of these sealed motors is an inert gas.

#### COOLING FANS

A variety of cooling fans are used to dissipate heat from the motor. These fans force cooling air through the windings of enclosed or open dripproof motors. For machines with

**FIGURE 5: EFFECTS OF CLOGGED AIR DUCTS ON MOTOR OPERATING TEMPERATURE**

Restrictions that impede the flow of cooling air through the motor are quite common in applications where significant amounts of foreign materials (dirt, fibers, process materials, lint, dust) are present. The stator above is from a 4 pole, open dripproof motor from a paper mill application. The pulp packed in the stator caused the motor to operate almost 30° C hotter than normal. This would cause a reduction in the insulation thermal life from 20,000 hours to 2,500 hours.

**EXAMPLES OF MOTOR COOLING FANS****BIDIRECTIONAL FANS****UNIDIRECTIONAL FANS**

Courtesy of Jenkins Electric Company and U.S. Electrical Motors



ducted stators and rotors, the fan and baffles divert airflow over the bearings and through the stator and rotor. Page 6-6 shows some of the many varieties of fans in use.

Cooling fans are of two basic types: those that mount to the rotor end ring and those that are shaft mounted.

Cooling fans that mount to the rotor end ring are mainly used on small- or medium-sized 2-pole motors and most 4-pole and slower motors. These can be cast as part of the end ring, welded to the end ring or bolted onto the end ring.

Some of their more common problems include:

- Casting porosity.
- Excessive balancing weights.
- Poor welding.
- Inadequate contact area between the end ring and fan.
- Damage from foreign material.
- Cracks.

Large 2-pole machines, totally-enclosed fan-cooled machines and one-way vent open dripproof machines typically use shaft-mounted fans, either internal or external to the motor. Typical problems associated with these fans include:

- Excessive balancing weight.
- Improper clamping to the shaft.
- Loss of fit to shaft.
- Improper location of fan on shaft.
- Damage from foreign material.
- Improper balancing.
- Fatigue or cracks in the blades or hub.

One of the most common problems associated with cooling fans is upsetting the balance of the rotor if the fans are removed during repair or if a part of the fan is damaged during operation.

It is important to inspect fans carefully to assure that they are not starting to crack, work loose or are damaged in some way. Some may even be severely weakened due to corrosion and are in danger of coming apart during operation. Of course, missing fan pieces may be the source of damage to other parts of the motor including the winding and bearings. The balancing weights that may be attached to the fan should also receive careful inspection for damage or looseness.

There are a few situations where rotor balancing is achieved by the removal of weight instead of adding it. Removal of weight should be done so as not to weaken the fan hub or blades. Care must be taken not to reduce the fan's effectiveness to move air. Too much weight can also cause the fan blades to break loose due to the shear force caused by the weight on the cross-section of the blade.

Fans may also lose their fit to the shaft during the repair process. In addition, press- or shrink-fit fans may be keyed and held in place with set screws. Some of these set screws have special means by which they are secured so they will not come loose during operation.

### IMPORTANCE OF POSITIONING AND DIRECTION OF ROTATION

There are times when the stator and rotor are overheated for no apparent reason. One possible, but not so obvious

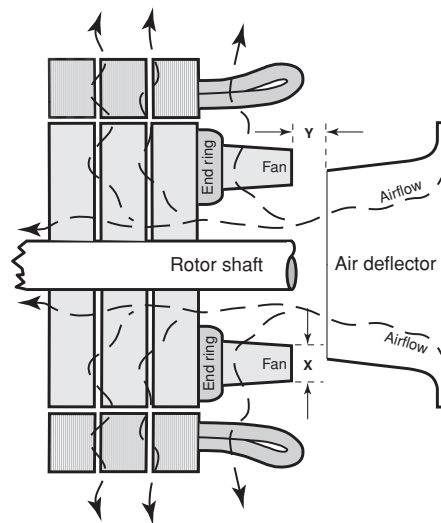
reason, is that the fans are positioned incorrectly or installed backwards.

The location of the fan must also be checked. A fan can lose its fit on the shaft allowing it to migrate to an ineffective position on the shaft.

For most applications, the direction of rotation is critical. In some applications, the motor must be capable of rotating in either direction. Hence, most general purpose motors are designed to operate satisfactorily in either direction. This requires the use of a bidirectional fan. However, larger motors and those that operate at higher speeds may often be unidirectional. The fan's direction of rotation is critical on these machines. If these motors are operated in the wrong direction, or if the fan is rotating in the wrong direction, there is a significant chance that the motor may be severely damaged due to overheating.

If it becomes necessary to confirm the correct direction of rotation after the motor is taken out of service, it may be possible to do so by inspecting the collection of dust or other foreign material on the fan blades. Fans will collect much more material on the leading edge of the blades than on the trailing edge.

**FIGURE 6: PROPER POSITIONING OF AIR DEFLECTOR FOR RADIAL FANS**



This drawing shows the proper positioning of the air deflector in relation to a radial fan. The tips of the fan blades are usually located (X and Y) so that the air deflector is in the middle third of the air fan blade.

### AIR DEFLECTORS

Air deflectors can be an integral part of the motor cooling system. The cooling fan forces air through the windings and air ducts of a motor, and the air deflector diverts and directs airflow over the bearings and through the stator and rotor.

Positioning of the fans in relationship to any air deflectors is critical if the proper airflow is to be maintained. If repairs are made in this area, when restoring the air deflector or radial fan blades, the tip of the fans are usually positioned

so that the air deflector is in the middle third of the fan blade. (See Figure 6.) Clearance between the two parts is normally between 1/4" and 1/2". Any more or any less clearance can disrupt the normal airflow. If there is too little clearance, the rotor fan blades could possibly contact the air deflector and cause major damage.

There are some enclosed motors which also use air deflectors. If they are removed, it could increase the average winding temperature 5° to 10° C. On some other enclosed motors, the air deflectors may be even more critical.

Air deflectors can be made from a variety of materials, but are normally made of sheet metal, plastic or fiberglass. Fiberglass is noncorrosive and tends to be quieter than metal. Air deflectors can be one piece; or two or more pieces welded or bolted. Sleeve bearing designs often use a two piece split air deflector.

Although the materials may be different, the most important construction feature of the air deflector is that it is made of solid material. If a motor comes into the service shop with the air deflector made of a material like a mesh screen, the deflector was obviously altered. The purpose of the deflector is to direct airflow, and a screen will only redirect the air away from the core. Overheating will likely occur.

Motors with external cooling fans may also use a variety of air deflectors or baffles on either or both ends of the motor. Some of the most common problems associated with air deflectors include:

- Contact with the stator winding.
- Contact with the rotor fan.
- Broken welds or loose bolts.
- Magnetic vibration or other noise.
- Fatigue of parts.
- Damage from foreign material.
- Contamination that weakens the deflector.
- Restriction of airflow by foreign material.
- Removal or improper location of the deflector.

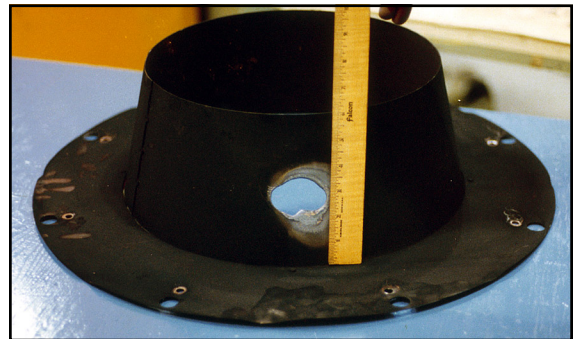
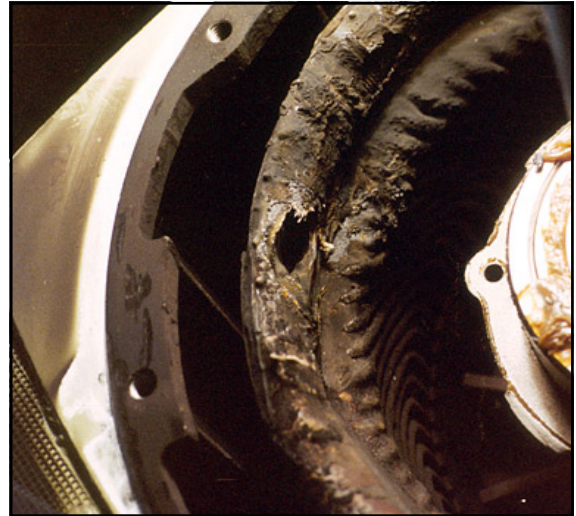
#### WINDING SHORTING TO AIR DEFLECTOR

When winding a stator, care must be taken to assure that enough clearance is provided so the air deflector does not contact the winding during starting or running, and that there is enough dielectric insulation, usually achieved by adequate air space. Figure 7 is an example of a medium voltage motor that did not have sufficient clearance between the two parts and a fault to ground was caused by vibration of the air deflector against the winding.

#### INTERNAL AIR DEFLECTORS

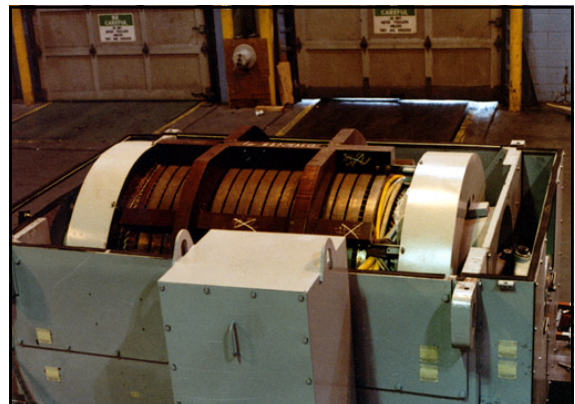
Large motors similar to those shown in Figure 8 use internal baffles to correctly channel cooling air for maximum effectiveness. If left off or installed incorrectly, the airflow may be altered enough to severely overheat the motor. Failure to secure these parts correctly can cause noise, especially during starting. Fasteners may come loose and cause damage to the motor. On rare occasions, air deflectors may become clogged by foreign materials and block airflow.

**FIGURE 7: WINDING SHORTING TO AIR DEFLECTOR**



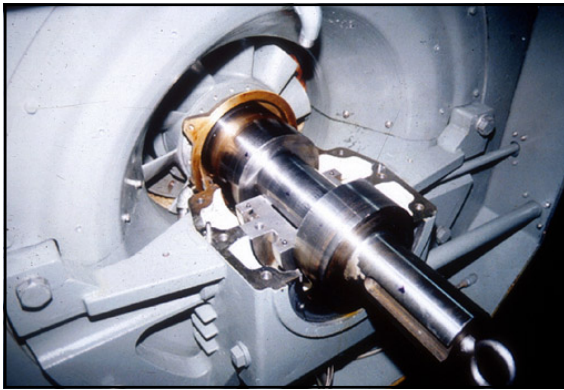
This medium-voltage motor that did not have sufficient clearance between the winding and air deflector. A fault to ground was caused by vibration of the air deflector against the winding.

**FIGURE 8: INTERNAL AIR DEFLECTORS**

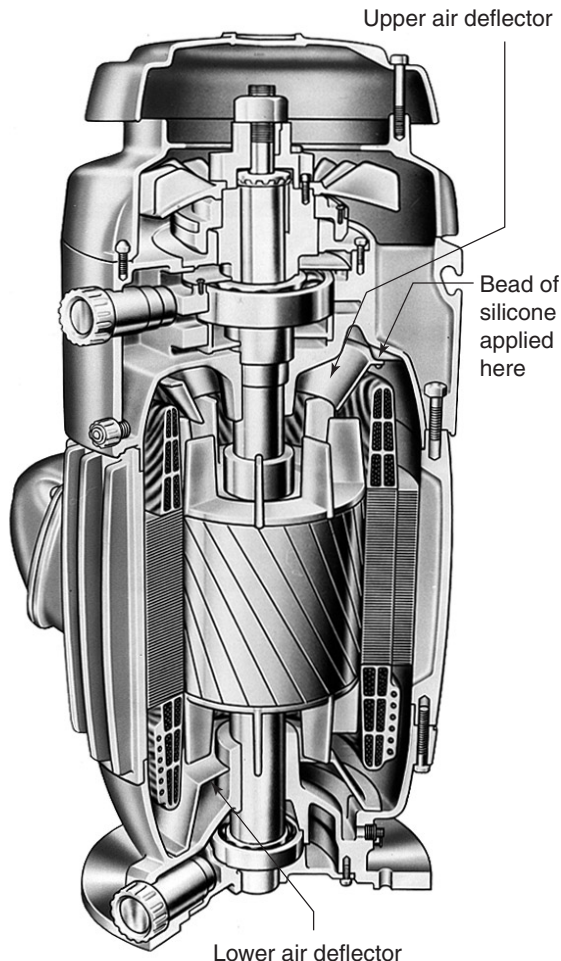


Large motors use internal air deflectors to correctly channel cooling air for maximum effectiveness.



**FIGURE 9: TWO-PIECE AIR DEFLECTOR****FIGURE 10: AIR DEFLECTORS ON VERTICAL MOTORS**

Care should be taken to properly secure the upper air deflector. If this air deflector or its bolts come loose, they may fall into the fan causing rotor or winding damage. A bead of silicone should be used as further insurance.



### TWO-PIECE DEFLECTORS

Some larger machines use two-piece air deflectors that are fastened together with bolts or other fasteners (Figure 9). If these parts come loose, they may be drawn into the winding, and can cause the winding to fail between turns or coils.

### LOOSE OR NOISY AIR DEFLECTORS

Air deflectors can pose a problem if they come loose and drop onto the rotor. Bolts can come loose as well. This can cause severe rotor or winding damage, so care must be taken to properly secure the air deflector and bolts. A bead of silicone between the air deflector and the end bracket gives a little insurance, as well as reducing the rattling noise often associated with air deflectors (Figure 10).

### DAMAGED AIR DEFLECTORS

Damaged air deflectors should always be repaired or replaced. A hole in the deflector may not seem important, but will almost always lead to thermal problems in the winding or bearings.

Fabricated steel deflectors can crack at the weld points and require careful inspection (Figure 11). These air deflectors are located in a strong magnetic field which increases by several magnitudes during starting. Defective welds will usually break under severe stress over time.

**FIGURE 11: FAILURE OF AIR DEFLECTORS**

The cone of the 2 pole air deflector fatigued due to severe vibration induced by magnetics during starting. Fabricated steel air deflectors sometimes crack at the welds.

### SPECIAL CONSIDERATIONS

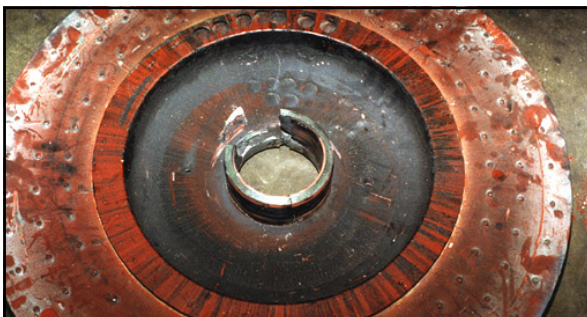
Occasionally, a motor will be retrofitted by adding special screens to prevent the entrance of small animals or insects into the motor. Care must be taken to ensure that an adequate supply of air is still allowed to pass through the motor without causing overheating. There is also a danger that these screening devices may more easily clog. It may be necessary to clean the motor more frequently.



## COOLING FAN FAILURES



A locking plate (or tab) is necessary to secure the balancing weights on this 2 pole motor. If it were missing, the fastener would be able to “work” loose and could eventually cause severe damage to the rotor or stator. The photographs at right show the damage caused to an identical motor by a balancing weight not secured by a locking plate. The outer ring and almost all of the blades were sheared off the fan. While manufacturers like locking plates, which are “dog-eared” over the flat surface of the screw head, they are prone to become weakened during subsequent repairs.



The shaft key was too shallow allowing this fan to climb over the key. This failure occurred on a large motor driving a crusher in a quarry.



Generator/alternator fans are sometimes abused by personnel while aligning the equipment.



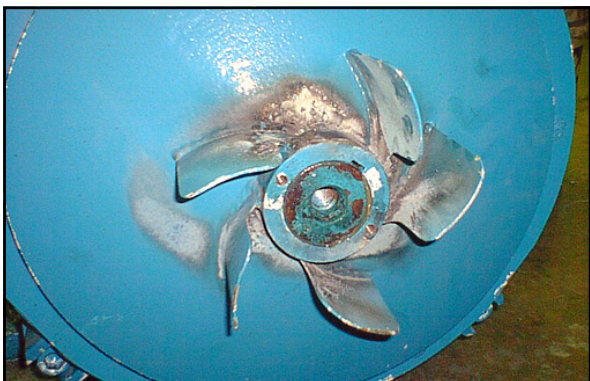
A fatigue failure just above the weld caused several aluminum fan blades to break.



## COOLING FAN FAILURES



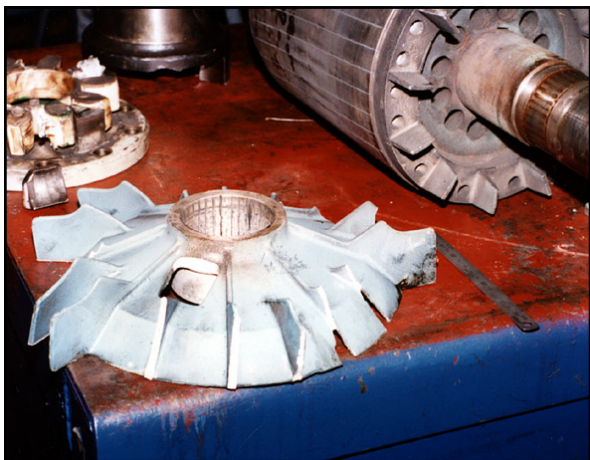
The bolts that held these fan blades in place on the end ring “worked” loose.



The tips of the blades of this rotary vacuum blower were all broken off when a metallic object was drawn into the blower by suction. This failure could have been avoided if a screen had been placed in the suction line.



A foreign object entered the cooling air intake and damaged the blades of this fan.



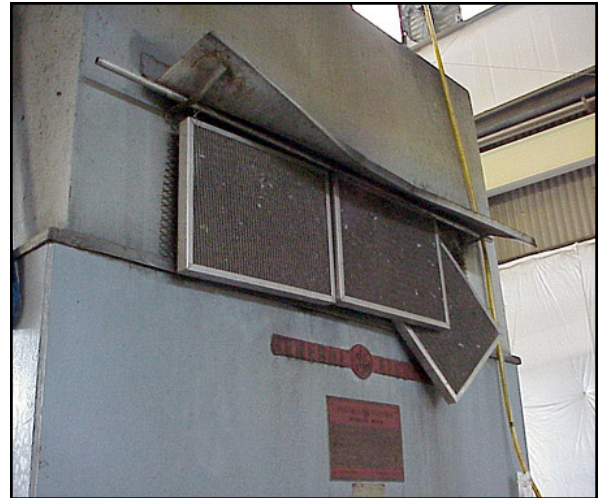
Foreign objects damaged this fan on a TEFC motor.



The blades on this unidirectional fan are being worn down by abrasion/corrosion.



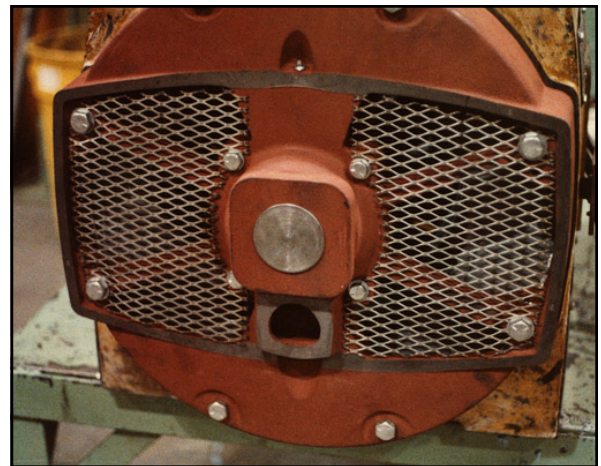
## SCREENS



These filters were added incorrectly. A filter reduces the cross-sectional area of airflow. The rain defectors further block airflow.



These types of screens are very susceptible to clogging.





## MOTOR TERMINAL BOXES

The ultimate motor terminal box failure is one that explodes. There are numerous examples of terminal box explosions due to faults in the motor or terminal box.

The terminal box is often the weakest link of the motor structure. A rapid, almost instantaneous, rise in pressure generated by the intense energy (heat) of an arc can cause an explosion in the terminal box if an adequate pressure relief is not provided. The possibility for explosion is greatest on enclosed motors where there is a chance for a buildup in pressure.

During the repair of a motor, care must be taken not to seal a terminal box that was intentionally vented by design in order to minimize the buildup of pressure. An explosion-proof terminal box must not be replaced with one that is not explosion proof if the motor operates in a hazardous environment. The most likely cause of an explosion, regardless of the motor enclosure, is a line-to-line or a line-to-ground fault which builds up excessive heat and pressure that cannot be relieved quickly.

The following is a broad and generalized list of various problems associated with motor terminal boxes (main and auxiliary).

- Failure to replace a gasket that will not seal properly (except explosion-proof terminal box which must not have gaskets).
- Failure to properly ground the motor terminal box to the motor frame.
- Improperly securing a line connector in the motor terminal box.
- The terminal box is too small for the number of leads. Sometimes an oversized terminal box is necessary.
- Incorrect lug size on the motor line leads.
- Motor and line lugs are secured with improper torque.
- Improper removal of insulation from the motor and/or line leads.

- Improper crimping of lugs to the motor and/or line leads.
- Inadequate insulation at the motor-to-line connection.
- Damage of the motor or line leads by sharp edges on the motor frame or terminal box.
- Accumulation of moisture in the terminal box.
- Inadequate drains to purge moisture or relieve excessive pressure.
- Improper mounting or spacing of accessories in the terminal box.
- Omission of lead positioning gasket.
- Failure to properly brace large terminal boxes to the motor frame.

Problems which evolve into a fault have the potential to cause severe damage or injury and possibly lead to an explosion. If the original terminal box design is altered without understanding the intent or purpose of a particular feature, serious problems can result.

### CAUTION

For motors rated above 600 volts, it is not permissible to locate accessory leads in the same terminal box as line leads. Low-voltage accessories are to be located in separate outlet boxes to prevent the possibility of inducing high voltage into low-voltage devices thus creating safety risks. If devices are commingled in the same terminal box, it is possible that high potential can damage low-voltage devices.

## MOTOR TERMINAL BOX EXPLOSIONS

Because of the safety issues associated with this subject, excerpts from a well-known and accepted IEEE paper by E.I. DuPont engineers; K. S. Crawford, D. G. Clark and R. L. Doughty, has been included. The complete text can be obtained from IEEE by referencing *Motor Terminal Box Explosions Due to Faults PCIC-91-07*.

The motor terminal box is the connection point that ties the motor to the power system. Terminal boxes can explode due to the pressure generated by a high-energy electric arc. Explosion of electrical equipment by ignition of flammable mixtures is well documented but will not be covered.

It might seem surprising that an electric arc can cause a motor terminal box to explode. Yet, on a typical 480 volt industrial distribution system, a high-energy arcing fault can concentrate up to 15 megawatts of power inside a terminal box. Since the terminal box is usually the weakest structure in the motor assembly, the rapid pressure rise generated by the intense heat of the arc may result in the box exploding. When a box does explode, the force is often strong enough to send pieces flying more than 30 feet (10 m).

A fault inside a motor with an open dripproof, weather protected type 1, or weather protected type 2 enclosure is unlikely to build up enough pressure to cause an explosion. These motors have a natural relief vent because they allow the free interchange of air between

**FIGURE 12: HAZARDOUS TERMINAL BOX**



This chaotic mixture of high- and low-voltage leads can lead to the deterioration of the insulation when moisture is present. This is a terminal box accident waiting to happen.

the windings and the outside air. A totally-enclosed motor, on the other hand, is specifically designed not to allow any exchange of air between the windings and the outside. Therefore, a fault inside a totally-enclosed motor will allow the pressure to build up. If the opening between the motor and the terminal box is not sealed, the pressure will rise in the terminal box also. Since the terminal box is typically not as sturdy as the motor housing, it may rupture and relieve the pressure.

A fault inside a terminal box can result in an explosion, no matter what type of motor it is connected to. If the opening between the terminal box and the motor is sealed or partially restricted, the pressure will rise in the box. If the opening is unobstructed, then the fault products will pass into the volume of the motor and will cool. A terminal box explosion may occur depending upon the fault energy and location, the terminal box design, the area of the opening between the motor housing and the terminal box and the type and size of the motor.

#### EXAMPLE OF A TERMINAL BOX EXPLOSION

Near New Orleans, Louisiana, in May 1990, on a solidly-grounded 480 volt system, a 200 hp TEFC pump motor in a Class 1, Division 2, Group D area had a winding failure that caused a Class L current limiting fuse in the 480 volt switchgear to blow. The fuse was replaced without locating the fault and an attempt was made to restart the motor. When the start button was pressed the motor terminal box exploded. The 18" x 18" sheet metal cover for the box, which was held in place by 12 screws, was propelled about 30 feet (10 m).

The heat generated by the winding fault resulted in a rapid pressure rise in both the motor and the terminal box. The terminal box exploded because it was not as sturdy as the motor.

Motor terminal boxes don't explode every time a totally-enclosed motor or terminal box has a fault because not all faults are high-energy arcing faults. The fault that causes the most current to flow, the bolted fault, involves no arcing and dissipates fault energy throughout the distribution system resistive elements. However, an arcing fault releases large amounts of energy at the point of the fault.

Figure 13 shows the maximum available arc power in the terminal box as a function of motor feeder length for a 200 hp, 460 volt motor. Since arc energy is proportional to the duration of the arc, protection systems which offer high-speed fault clearing are most effective in reducing arcing fault energy in terminal boxes. The arcing fault energy developed during ground faults can be significantly reduced by using resistance grounded systems. As soon as the fault escalates to more than one phase, however, the resistor is no longer effective in reducing fault energy.

#### INTERNAL PRESSURE RISE DUE TO FAULTS

An arc which is confined to a closed terminal box or motor housing generates a pressure rise due to the

heating of the air surrounding the arc, and the heating and vaporizing of conductors and other metal components.

The following general observations may be made in regard to pressure rise due to faults:

- Pressure rise increases as the motor terminal box volume decreases.
- Pressure rise increases as arc duration increases. The use of current limiting fuses to interrupt current in 1/4 cycle is beneficial in reducing the released fault energy in the terminal box and the resulting pressure rise.
- For extended fault duration, it is difficult to construct a terminal box with sufficient mechanical strength to contain the pressure generated by a fault.

#### TERMINAL BOX BURSTING PRESSURE

A structural analysis was completed on typical motor terminal box designs to determine the bursting pressure. Motor terminal boxes are generally of two designs.

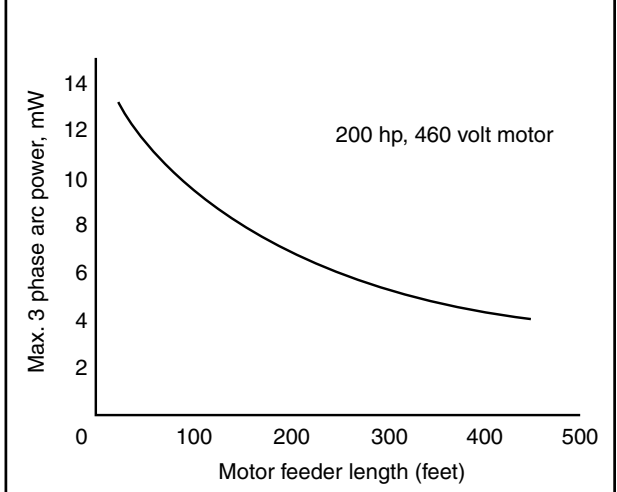
- Rectangular enclosures with bolt-on covers that are fabricated from aluminum or steel plate.
- Cast iron enclosures, typically with a diagonally split cover. This type enclosure is commonly supplied by manufacturers of TEFC motors in NEMA-frame sizes.

On NEMA frame TEFC motors, 100 hp and larger, it is common practice in some companies to replace the terminal boxes supplied by the manufacturer. The replacement is a field fabricated rectangular type, and is significantly larger to facilitate termination of cables. The additional space allows increased cable bending radius and phase-to-ground clearances.

Possible modes of failure for the rectangular enclosure are:

- Shear failure of the female screw threads in the

**FIGURE 13: MAXIMUM 3 PHASE ARC POWER AS A FUNCTION OF MOTOR FEEDER LENGTH**





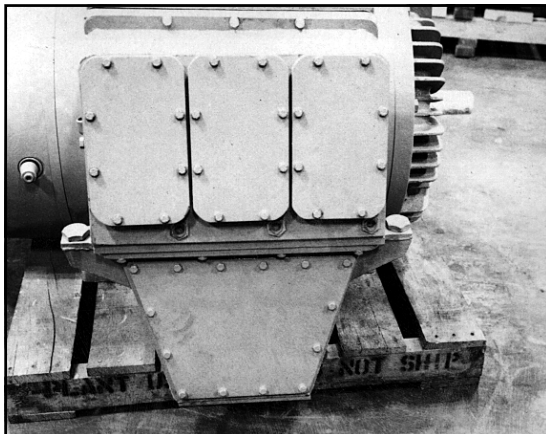
enclosure wall which engage the enclosure cover screws.

- Shear failure of the enclosure cover screw male threads.
- Tensile failure of the enclosure cover screws.
- Tensile rupture of the enclosure sides.

The most commonly observed failure mode for rectangular terminal boxes is shear failure of the female screw threads in the enclosure wall. Analysis of terminal boxes bursting strength for the above modes of failure also verified that shear failure of the female screw threads is the weakest link.

Since many explosions have occurred during motor starting, this is not a safe location for the pushbutton. The alternative is to locate the button near the end of the motor at right angles to the plane of the terminal box front cover, and away from the motor ventilation openings (if applicable). Another possibility is to start the motor from a remote location with an operator observing from a safe vantage point.

**FIGURE 14: PHASE-SEGREGATED OUTLET BOXES**



This motor uses a phase-segregated outlet box to minimize the possibility of faults between phases. In repairing this type of motor, care must be taken not to “upset” or remove the separations without proper approval.

#### MOTOR TERMINAL BOX INSULATED CONNECTIONS

Insulating all connections inside the terminal box reduces the chance of contamination causing a phase-to-ground fault. It also helps to prevent a single-phase fault from escalating to a multiphase fault. During the late 1950s, a British engineer took the idea of insulated connections to an extreme. He developed a terminal box that provided separate compartments insulated from each other, in which to terminate each phase (Figure 14). This virtually eliminates the possibility of a single-phase fault escalating to phase-to-phase fault. However, the initial cost of an isolated phase terminal box is high, and the extra cost would be hard to justify except in critical applications. In addition, tests have

shown that taped connections will not support an arc. Therefore, a minor fault is unlikely to develop into a major one if all connections are insulated.

#### LARGE TERMINAL BOXES

The use of a large motor terminal box facilitates proper termination of motor feeder cables. A very common complaint of industry is that standard size terminal boxes are too small. When a terminal box is too small, the cable bends are too sharp, and the electrician has difficulty making a quality termination. Often the box cover will not easily fit over the connected cable. The electrician then presses the box cover up against the cable with considerable pressure until he can force the cable into the box. The resulting cable damage has caused numerous faults.

#### CABLE SUPPORTS

Cable and connection supports inside the terminal box to reduce cable movement caused by starting currents and vibration. Some faults are caused by the cable insulation wearing away as it rubs up against the walls of the box. In areas subject to severe vibration, a common technique is to line the inside of the box with fluoropolymer or rubber.

#### PROPER SEALING AND DRAINAGE

Seal the terminal box to prevent moisture and chemical intrusion. In some cases, terminal boxes have exploded because of water entering through the conduit, from condensation inside the motor, or from water leaking through the cover. A small drain hole drilled in the bottom of the terminal box will prevent water buildup.

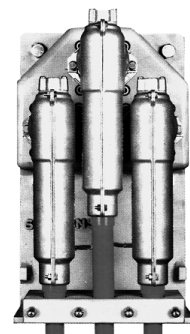
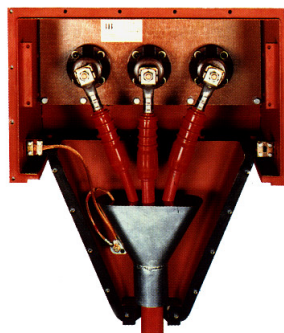
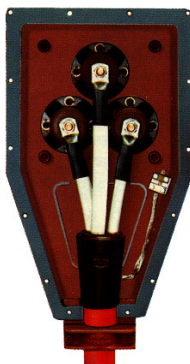
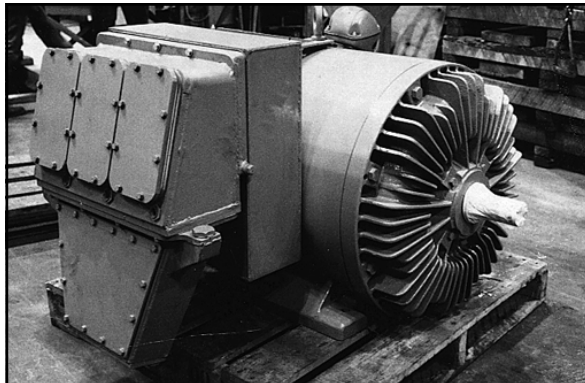
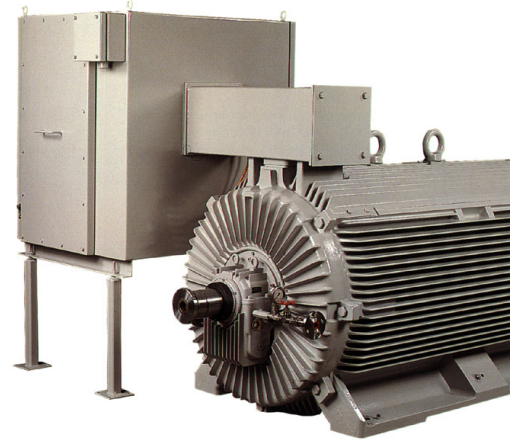
#### RECOMMENDATIONS

The design of a motor terminal box and the connections it protects are critical to the safe and reliable operation of a plant. Motor terminal boxes connected to high-energy sources will continue to explode and endanger personnel unless some modifications are made in their design and installation methods:

- Motor stop-start pushbuttons should be mounted near the end of the motor at right angles to the plane of the terminal box front cover, and away from motor ventilation openings. This avoids unnecessary exposure of operating personnel to explosions and fault arc by-products.
- All connections inside the terminal box should be insulated. Industry experience shows that insulated buses and connections reduce the number of faults, and lower the probability of ground faults escalating to multiphase faults.
- Current limiting fuses should be used in motor starters when possible to reduce the amount of energy released in a terminal box during a fault. RK1 fuses are preferred in low voltage starters since the clearing I<sup>2</sup>t is significantly lower than for a RK5 fuse.

- Sensitive ground fault protection should be provided to limit the duration of ground faults, and to prevent escalation to multiphase faults. Differential motor protection, when applied on large motors, also effectively limits the duration of motor faults
- (electrical).
- End users should have the option of installing a pressure relief device on motor terminal boxes connected to a source of high energy.

### EXAMPLES OF MOTOR TERMINAL BOXES



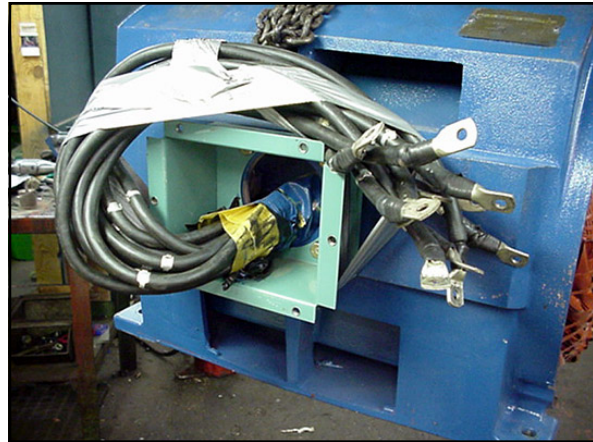


**MOTOR TERMINAL BOX FAILURES**

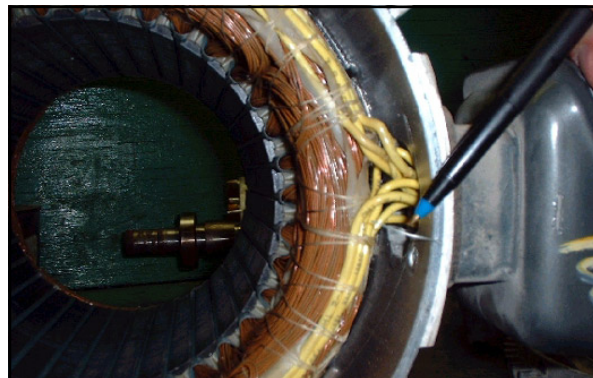
The damage to this terminal box shows the results of improper grounding. Arcing between the box and motor frame eventually caused a fire.



These leads failed during an overload condition that did not result in a winding failure. The leads were Class B while the winding was Class F.



This motor was modified to have a 9-lead connection. This will not fit in the standard terminal box and still provide adequate volume.



If possible, this motor should be reconnected to decrease the number of leads from nine to three. That would reduce the physical pressure on the leads and allow for possible oversizing of the leads.



Failure to correctly tighten this bolt on a line connection generated heat that destroyed the insulation leading to a ground fault.



FIGURE 15: LIFTING DEVICES



Courtesy of Baldor Motors

## LIFTING DEVICES

It is not common for eyebolts or other lifting means to fail on a motor, however, the consequences of one failing is so great that this part of the motor should not be neglected or overlooked during the inspection and repair process. The handling of the motor at this time should only be done after consideration is given to the condition of the lifting devices associated with the motor.

Figure 15 shows a variety of lifting methods used for horizontal motors. Note that in some cases the lifting devices are cast into the frame; and while some are offset, others are in line. Further, some eyebolts are shouldered, while others are not; and some are cast eyebolts, whereas others are forged.

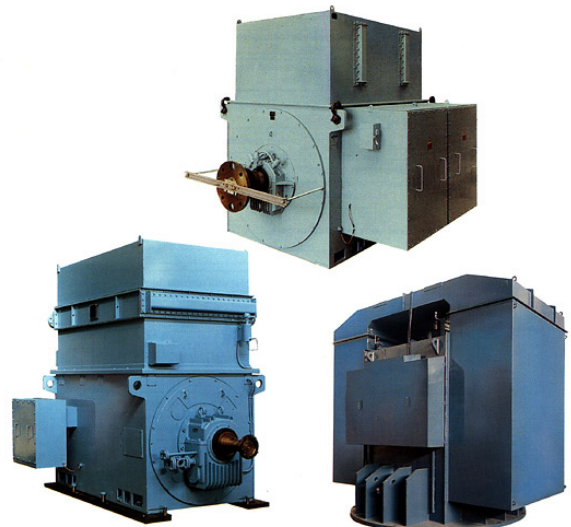
Large horizontal and vertical motors may have several sets of lifting devices, and some are only for lifting the cooling systems of the machine. Note the difference in size of the lifting devices for the motor main bodies compared to the cooling systems illustrated in Figure 16. Also take note of the similarities between the lifting devices of the vertical motor and those of the two horizontal machines in Figure 16.

Three common problems associated with lifting are:

- Not shouldering the eye bolt.
- Lifting at too great an angle (failure to use spreader bars).
- Lifting more than the motor lifting devices were designed for (e.g., base, pump, compressor).

The eyebolt illustrated in Figure 17 was broken as a result of the lifting angle being too great (it was installed in the horizontal direction for a vertical lift) and the eyebolt was not shouldered. The stator that fell as a result of the breakage

FIGURE 16: LIFTING DEVICES ON LARGE MOTORS



nearly severed one of the technician's fingers.

NEMA MG 2-1977, 2.03 and 3.16 give the following description of the motor design lifting capability:

Motors may include provisions for lifting the motor or generator by means of eyebolts, lifting rings, integrally cast bosses, etc. When lifting means are provided, they shall be designed to lift the motor at any angle from the designed lifting direction between 0 and 30 degrees for

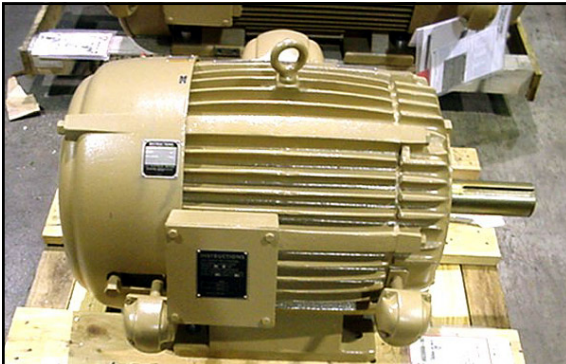


FIGURE 17: BROKEN EYEBOLT



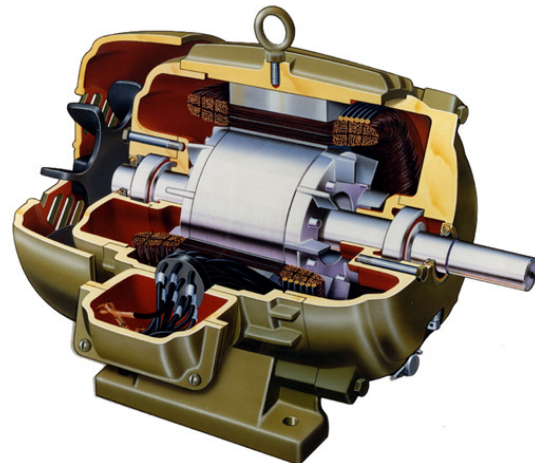
Shouldered eyebolts are not effective unless they are turned down tight against the frame. This broken eyebolt caused a stator to be dropped, almost severing a technician's finger.

FIGURE 18: SHOULDERED EYEBOLTS



In some cases, the eyebolt may bottom out before it tightens against the frame. If the eyebolt is then over-tightened, it may contact the stator core, "pushing" it through the air gap and into the rotor. Placing a spacer between the frame and eyebolt is usually an effective way to deal with this situation. If a lifting hook is used, it should go through the eye of the eyebolt without binding. If the hook is too large for the eyebolt, it will not go through fully, and will apply an added strain that could result in failure of the eyebolt.

FIGURE 19: POSITIONING OF EYEBOLTS



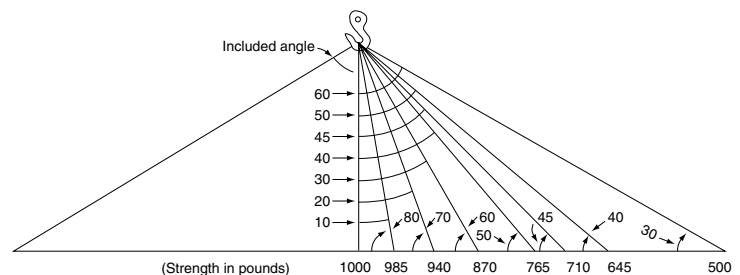
The typical eyebolt location is in line with the stator core laminations.

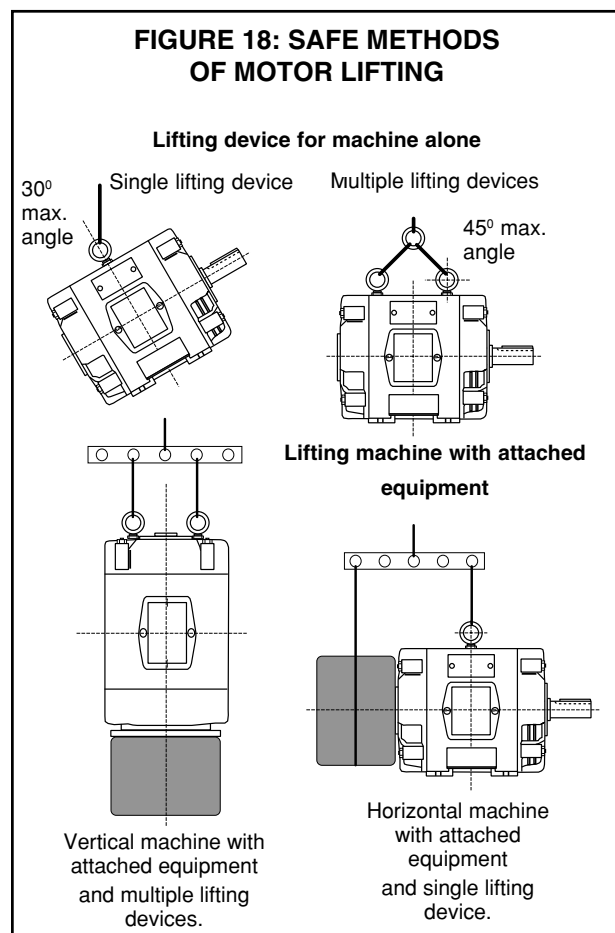
machines with single lifting points or 0 degrees and 45 degrees for machines with multiple lifting points (Figure 20) with a safety factor of at least 5 (based on the ultimate strength and the use of all intended lifting points). This is to allow for overloads due to acceleration, deceleration or shock forces encountered in handling ... the lifting means shall be designed so that when the motor is lifted in the intended manner the suspended mass is stable (i.e., normal handling forces will not cause a permanent shift or rotation of the load) ... precautions should be taken to prevent hazardous overloads due to acceleration, deceleration or shock forces. Additional care should also be used when lifting or handling at temperatures below 0° C because the ductility of the lifting means is reduced. In the case of assemblies on a common base, any lifting means provided on the motor should not be used to lift the assembly and base, but rather, the assembly should be lifted by a sling around the base or by other a lifting means provided on the base. It is recommended that a spreader bar be used when lifting assemblies on a common base.

Unless specifically allowed by the manufacturer's instruction manual and/or drawings, the lifting means

FIGURE 20: LIFTING CAPACITY

The lifting capacity of wire ropes, chains, and slings decreases as the included angle increases. For quick figuring, a 60° included angle decreases lifting capacity by 15 percent; a 90° angle causes a 30 percent loss; and a 120° angle lowers capacity by 50 percent. For precise figuring, use the chart above. **Example:** If two 1,000 lb (450 kg) capacity slings are used at a 120° included angle, each sling will have a load rating of only 500 lbs (225 kg).





provided for lifting a motor should not be used to lift the motor plus additional equipment such as gears, pumps, compressors or other driven equipment.

This standard offers the following exception as a guideline for motors with stator diameters of approximately 34 inches (.9 m) and smaller.

If care is taken to minimize shock loading, and a spreader bar and/or supporting sling (securely anchored) is used to assure a lifting force parallel with the designed lifting direction (lifting angle of 0°) and equally distributed over multiple lifting points. Connected loads not exceeding 100 percent of the motor weight can normally be safely handled with the motor lifting device (Figure 21).

**TABLE 1: EYEBOLT STRENGTH**

|                                                                                                | Shank dia. | Straight lift safe load | 45° lift safe load | 90° lift safe load |
|------------------------------------------------------------------------------------------------|------------|-------------------------|--------------------|--------------------|
| Unshouldered  | 1/2"       | 2600 lbs                | 520 lbs            | 390 lbs            |
|                                                                                                | 1"         | 8000 lbs                | 1600 lbs           | 1200 lbs           |
| Shouldered    | 1/2"       | 2600 lbs                | 650 lbs            | 520 lbs            |
|                                                                                                | 1"         | 8000 lbs                | 2000 lbs           | 1600 lbs           |

### LIFTING ACCESSORIES

Eyebolts or other lifting means such as hoist rings must be sized and used properly and only as intended. It should be understood that the strength of an eyebolt is affected by the direction of the force applied to it. If the direction of the pull is not in line with the shank of the eyebolt, the lifting capability is greatly reduced.

It should also be understood that there is a significant difference between a shouldered and unshouldered eyebolt's capability to lift with angular forces applied. Table 1 illustrates these differences for typical forged eyebolts used for normal lifting conditions.

### LIFTING STANDARDS

The following is a partial list of standards pertaining to the lifting of heavy equipment. It is recommended that those who are responsible for lifting be familiar with these standards:

1. ANSI/ASME B30.
2. OSHA Standard 20 CFR 1910 & 1926.
3. NEMA MG 2-2001.

### OPERATING PERSONNEL

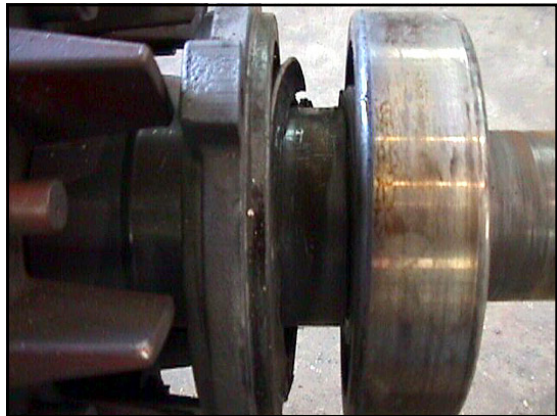
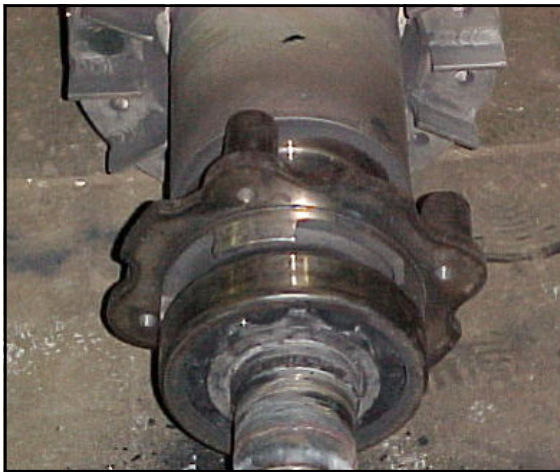
Even with all the appropriate lifting equipment and warning labels, there is no guarantee of safety without the proper use of this equipment. Too much trust is placed in the lifting equipment. Perhaps all personnel involved should assume no lift is completely safe and position themselves and act accordingly.



## MOUNTING AND ALIGNMENT

Alignment is often a contributing cause of bearing and shaft failures. Significant misalignment causes noticeable vibration, structural weakening (metal fatigue), and accelerated mechanical wear of bearings and shafts. Damage usually manifests itself at the weakest point, which is often the ODE (opposite drive end) bearing, as depicted in Figure 19. When the machine has ball bearings, this is usually the smallest bearing. ODE bearing failure frequently indicates misalignment. In addition to reduced bearing life, coupling wear, bent shafting, and bearing housing/journal wear are all common results of poor alignment. Figure 19 illustrates a failure probably due to parallel misalignment.

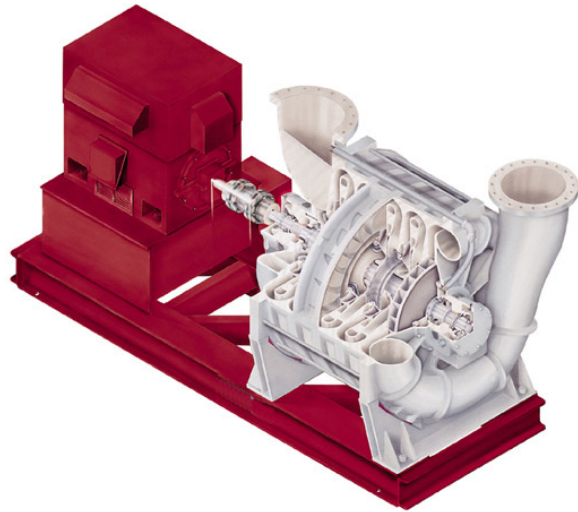
**FIGURE 19: DAMAGE TO OPPOSITE DRIVE END BEARING**



Loading on bearings, seals, couplings, and shafting can all decrease with improved alignment. Further, noise and vibration are increased by misalignment. There is ample evidence that a .005" (.125 mm) shaft offset misalignment can reduce the expected bearing life by as much as 50%. The forces from misalignment often manifest themselves as vibration in the axial (end-to-end) direction at a frequency that is twice the rotating speed.

When two (or more) pieces of rotating machinery are coupled, as in a motor and pump, the centers-of-axes of all

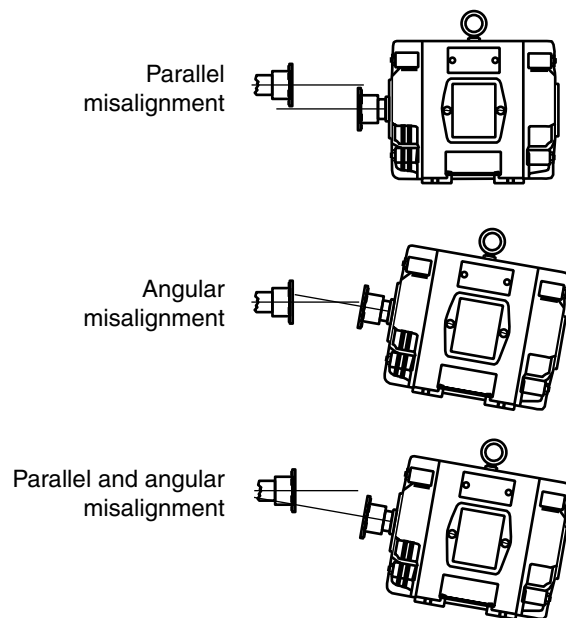
**FIGURE 20: ALIGNING THE MOTOR AND DRIVEN EQUIPMENT**



the machines must coincide (Figure 21). Proper alignment of electric motors and driven equipment is critical to the life of motor components, especially bearings. Where this is not the case, the machines are said to be misaligned. Misaligned centers-of-axes place a strain on the equipment. Misalignment can occur within a machine, and exterior to it. One form of misalignment is of internal components such as ODE bearing to DE (drive end) bearing. The other form of misalignment, exterior, applies to shaft alignment of driving and driven machines.

The goal of aligning direct coupled machines is to have

**FIGURE 22: TYPES OF MISALIGNMENT**



the shaft centerlines of the motor and driven equipment coincide when the machines are at operating temperature. Though it is sometimes misstated as coupling alignment, it is the shafts that must be aligned. Shaft alignment is equally important in other types of drives such as belts and sheaves, and sprockets and chains. For those applications, the shaft centerlines must be parallel, though they will not coincide.

There are two ways to describe misalignment: parallel and angular. These are illustrated in Figure 22. Parallel misalignment is the condition when shaft centerlines are parallel, but offset. It is measured in terms of total indicated runout (TIR). Angular misalignment describes the condition when shaft centerlines are not parallel to one another. It is measured in terms of mils per inch (mm per m) of distance between coupling faces. Misalignment almost always results in a combination of both parallel and angular misalignment.

The negative effect of misalignment on rolling bearings can be better understood by studying the formula for bearing life.

$$\text{Hours of life} = \left( \frac{16,700}{\text{rpm}} \right) \left( \frac{\text{dynamic capacity} \times \text{load rating}}{\text{force}} \right)^3$$

What is of significance is that the formula indicates that bearing life is reduced by the cube of the amount of misalignment. For example, if misalignment is doubled, bearing life will be reduced by the cube of two ( $2 \times 2 \times 2$ ), or a factor of 8. Thus, if the bearing life with acceptable misalignment were 8 years, the bearing life with twice that misalignment would be reduced to 1 year ( $1/8 \times 8$ ).

Although there is no equivalent formula for sleeve bearings, they are particularly sensitive to misalignment. Severe misalignment is obvious when the points of contact on a sleeve bearing are at diagonally opposite corners of the bearing. Rotor speed is not the only consideration when determining required alignment accuracy. At any given rotational speed, alignment is more critical for longer sleeve bearings.

Alignment can be accomplished with varying degrees of accuracy using a straightedge or dial indicators (rim-and-face, reverse-indicator or laser methods).

The straightedge method was used in years past with some success, but it did not produce very close alignment. Users were generally unaware of its shortcomings, however, because they rarely tracked equipment failures. Older motors also tended to be sturdier with larger bearings than modern motors, so they held up a little longer in unfavorable conditions.

Rim-and-face alignment also has significant limitations, since it does not account for possible coupling runout. If one shaft is bent or the coupling is bored off-center, the rim-and-face method aligns only the couplings, not the shaft centerlines. As a result, the equipment may appear to be aligned properly, but the vibration level and equipment wear due to misalignment may not have been reduced.

The reverse-indicator alignment is superior to the rim-

and-face method for several reasons. Because the indicator rotates with the shaft, coupling runout is negated. By using two indicators (one on each shaft), geometry can be used to determine the exact relationship between the shafts. This simplifies the alignment procedure to just a few moves.

To be valid, alignment performed with dial indicators must factor in "indicator sag." To determine the sag for a particular instrument, place the dial indicator on a shaft and set it up as if for alignment. Then zero the indicator, rotate the shaft  $180^\circ$  and read the dial. The difference between readings is due to indicator sag. If the sag is 0.010", then every alignment done with that indicator arrangement is actually off about 0.005".

The farther apart the couplings are, the greater the sag. Laser alignment incorporates the benefits of the reverse-indicator method while removing two potential problems. First, the computer "does the math." Second, the laser beam eliminates "indicator sag."

When possible, alignment should be performed in accordance with the manufacturer's instructions and tolerances. This includes both the manufacturer of the driven machine as well as the motor manufacturer. A good practice is to align to the stricter tolerance if the manufacturers' tolerances vary. If manufacturers' tolerances are not available for alignment, Figure 23 is suggested as an alternative.

Note that as machine speed increases, the alignment

### FIGURE 23: SUGGESTED ALIGNMENT TOLERANCES

These suggested alignment tolerances are the desired values, whether such values are zero or a targeted offset. They should be used only if machinery manufacturer alignment tolerances are not available.

|                                       | RPM  | INSTALLATION | IN SERVICE |
|---------------------------------------|------|--------------|------------|
| Soft Foot (mils) *                    | All  | $\pm 1.0$    | $\pm 1.5$  |
| Short Couplings                       |      |              |            |
| • Parallel Offset (mils)              | 1200 | $\pm 1.25$   | $\pm 2.0$  |
|                                       | 1800 | $\pm 1.0$    | $\pm 1.5$  |
|                                       | 3600 | $\pm 0.5$    | $\pm 0.75$ |
| • Angular Misalignment ** (mils/inch) | 1200 | 0.5          | 0.8        |
|                                       | 1800 | 0.3          | 0.5        |
|                                       | 3600 | 0.2          | 0.3        |
| Couplings With Spacers                |      |              |            |
| Parallel Offset                       |      |              |            |
| Per Inch of Spacer Length (mils/inch) | 1200 | 0.9          | 1.5        |
|                                       | 1800 | 0.6          | 1.0        |
|                                       | 3600 | 0.3          | 0.5        |

\* "Soft foot" describes the condition where the four mounting feet are not all in the same plane. Measured in mils (1 mil. = .001 inches).

\*\* To find angular misalignment in mils/inch of coupling diameter, measure widest opening in mils, then subtract narrowest opening in mils, and divide by diameter of coupling in inches.

Note: Up and down motion of driving and driven shafts with temperature may be in either direction.

*Mechanical Reference Handbook, EASA, 1999.*

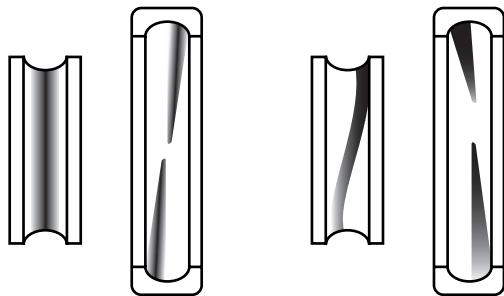


tolerance decreases. When a modern unit replaces an older more robust machine, the modern machine will probably be considerably smaller in size. Likewise, internal components such as shaft and bearings will be smaller, and hence not able to handle as much of the stress forces of misalignment. Therefore, a new replacement unit may need to be aligned to a much closer tolerance than the original machine.

In addition to the basic alignment considerations, the possibility of a “soft foot” must also be addressed. Further, alignment should be rechecked after the machinery has reached operating temperature. Few, if any, machines will thermally grow at the same rate. Therefore, machines that are in perfect alignment “cold,” (i.e., prior to startup) should not be expected to remain so after placed in service. Table 2, Page 6-29, provides a tabular guide to motor alignment.

Shaft alignment problems are usually manifested in the ball track wear patterns of ball bearing raceways. Hence, when inspecting a failed bearing, inspect the raceways to assure that the balls are riding in the correct path. Misalignment may also cause excessive vibration or heating. (See Figure 24.)

**FIGURE 24: BEARING WEAR PATTERNS**



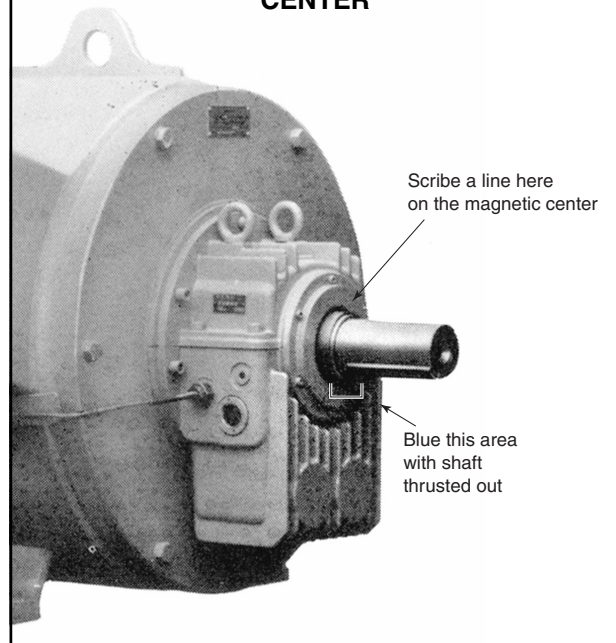
The load zone of the bearing on the left, shown as a shadowed path, indicates that the outer ring is misaligned to the shaft. The load zone of the bearing on the right indicates the inner ring is misaligned relative to the housing.

#### PROBLEMS ASSOCIATED WITH MAGNETIC CENTERING.

Failure to use the correct coupling arrangement or misalignment between the motor and driven equipment can cause damage to the bearings, shaft, or parts of the driven equipment. It can also result in misalignment between the rotor and stator, and their air ducts. This may affect motor performance characteristics, heating, or noise level. Limited endfloat couplings will keep the motor on its magnetic center assuming the shaft was scribed properly. Shaft scribing is illustrated in Figure 25. However, in some cases where “hunting” may occur, the shaft may strike the bearing thrust shoulder hard enough to cause damage.

Sleeve bearing machines should have a limited endfloat coupling. The benefit of this type of coupling is that when properly installed, it prevents the sleeve bearing shaft shoulders from coming in contact with the bearing thrust faces. Although sleeve bearings typically have thrust faces,

**FIGURE 25: MARKING THE MAGNETIC CENTER**

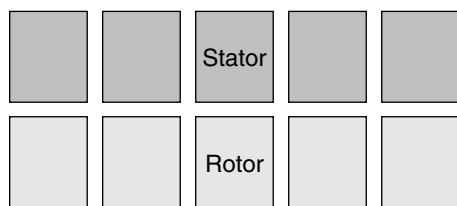


these are intended for accidental or short-term (as when run testing uncoupled) thrust only. If a sleeve bearing has a damaged thrust face, check for a missing or incorrectly sized endfloat limiting spacer. Or if the coupling is not of the limiting endfloat type, then recommend that it be replaced with an endfloat limiting coupling. Some larger motors use a rolling element bearing installed in the drive end, to act as a thrust bearing. If there is thrust face damage to a sleeve bearing in this style of motor, the rolling element bearing was probably not installed.

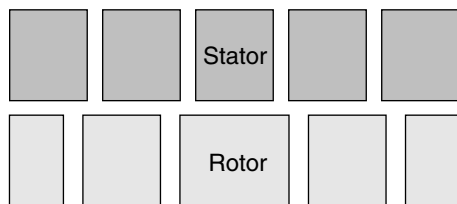
Included in this section are cases where modifications to the rotor are necessary to eliminate this type of damage. The following material from the EASA Technical Manual Section 11 and the Mechanical Repair Fundamentals book Section 13 provides options for dealing with this type of problem.

#### MAGNETIC CENTERING EFFECTS ON SLEEVE BEARING INDUCTION MOTORS

Some definition of terms is required to insure a concise understanding of magnetic centering force. First, end play is the total distance a rotor assembly can be moved axially between the limits set by the sleeve bearing thrust faces and associated shaft collars. This is typically .5" (13 mm) on large motors. Secondly, mechanical center is the position of the rotor assembly midway between the total end play. Magnetic center is the position the rotor assembly will take when energized. Magnetic centering force is that which results when the rotor is forced away from its desired magnetic center position by external means. At running uncoupled magnetic center position, the sum of the axial magnetic center force components measures zero. It is only when the rotor assembly is moved off its desired magnetic center position by external means that a restoring magnetic center force appears. Normally, magnetic and mechanical

**FIGURE 26: ALIGNMENT OF VENT DUCTS AND MAGNETIC CENTERING**

Medium-horsepower design  
Vents are aligned



Higher-horsepower design  
Vents are unaligned for noise suppression.

center do not coincide due to manufacturing variations.

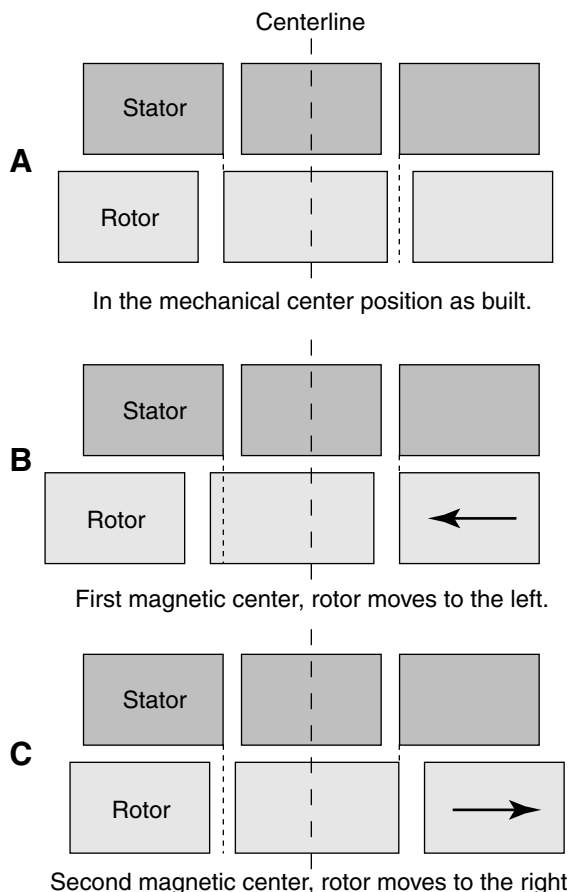
Among the factors associated with magnetic centering problems are the number of poles, the load on the motor, and a tapered stator bore or rotor OD. The following is a description of these factors.

#### Dual magnetic centers

While machines built as shown in Figure 26 can have two magnetic centers, this effect is more prevalent on motors designed with radial vents not aligned. The occurrence of two centers depends on such factors as design vent spacing and manufacturing dimensional variances. When this condition occurs due to the design and manufacturing precision of the machine, it can be quickly verified. If a motor is again run uncoupled at no load, it will appear to take a fixed position. Machines exhibiting this characteristic will generally have a somewhat weaker center than one indicating one magnetic center only.

An assembly that will develop this two center effect is shown in Figure 27. For purposes of discussion, it may be assumed it was manufactured this way rather than designed as such. Figure 27A shows the assembly in its mechanical center position. For a particular set of dimensional values, this machine, when energized, could take a magnetic center position corresponding to 27B or 27C. In either position, the sum of the magnetic forces acting toward the right or left due to the core ends and the individual stator-rotor ducts will be zero, indicating a magnetic running neutral has been found.

Another effect sometimes noted on two pole motors is that their magnetic center seems to float or oscillate around the shaft scribe mark. This is not due to a change in absolute magnetic centering force but occurs due to airflow forces on either end of the rotor that are not perfectly balanced.

**FIGURE 27: ARRANGEMENT WITH TWO MAGNETIC CENTERS**

#### Load effect on magnetic center

At no load operation, the two components of magnetic centering force that are encountered are: (1) that due to the lamination ends and (2) that caused by the stator-rotor vent ends (when these are present). If the rotor is skewed, this factor has little effect at no load due to the extremely small rotor cage currents at this condition. With load, both the skew component (for skewed slots) and the end ring component arise. The magnitude of the axial force due to skew is directly proportional to the torque and skew angle and inversely to the rotor core diameter. Its direction is dependent on the direction of skew and the rotor rotation.

When these latter two components arise and their magnitude sufficient and direction proper, they can force a change in the magnetic center position of the rotor from no load operation. Normally, this change in position is less than 1/8" (3 mm). If the no load magnetic center is very close to the mechanical center position, and the total end play is .5" (13 mm), this shift would not result in a bearing surface rubbing on an associated shaft collar.

It should be noted that the magnetic center mark scribed on the shaft extension is done while the motor is running at no load.



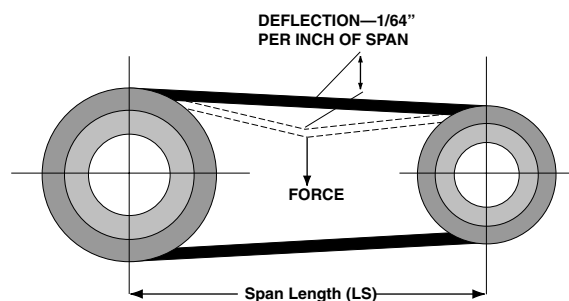
**TABLE 3: BELT TENSIONING, DEFLECTION FORCE AND ELONGATION RATIO**

**Step 1.** Calculate the deflection amount (DA).

$$DA = \frac{LS}{64}$$

Where: DA = deflection amount (inches.)  
LS = span length (inches.)

**Step 2.** At midspan, deflect the belt to the required deflection amount (DA) and record the force required.



**Step 3.** Check force required for above deflection. Refer to table on Page 57 and if force is too high, reduce to the recommended level.

$$DA \text{ (inches)} = \frac{LS \text{ (inches)}}{64}$$

*Mechanical Reference Handbook, EASA, 1999.*

| V-BELT TYPE                                        | V-BELT CROSS SECTION | SMALL SHEAVE DIAMETER RANGE (in) | RECOMMENDED DEFLECTION FORCE (lbs) |          |           |
|----------------------------------------------------|----------------------|----------------------------------|------------------------------------|----------|-----------|
|                                                    |                      |                                  | MINIMUM                            | NEW BELT | RETENSION |
| CONVENTIONAL V-BELT AND CONVENTIONAL BANDED V-BELT | A                    | 3.1 ~ 3.0                        | 2.4                                | 3.6      | 3.1       |
|                                                    |                      | 3.1 ~ 4.0                        | 2.8                                | 4.2      | 3.6       |
|                                                    |                      | 4.1 ~ 5.0                        | 3.5                                | 5.2      | 4.6       |
|                                                    |                      | 5.1 ~                            | 4.1                                | 6.1      | 5.3       |
|                                                    | B                    | 4.7 ~ 4.6                        | 4.9                                | 7.3      | 6.4       |
|                                                    |                      | 5.7 ~ 5.6                        | 5.8                                | 8.7      | 7.5       |
|                                                    |                      | 5.7 ~ 7.0                        | 6.2                                | 9.3      | 8.1       |
|                                                    |                      | 7.1 ~                            | 6.8                                | 10.0     | 8.8       |
|                                                    | C                    | 7.1 ~ 7.0                        | 8.2                                | 12.5     | 10.7      |
|                                                    |                      | 7.1 ~ 9.0                        | 10.0                               | 15.0     | 13.0      |
|                                                    |                      | 9.1 ~ 12.0                       | 12.5                               | 18.0     | 16.3      |
|                                                    |                      | 12.1 ~                           | 13.0                               | 19.5     | 16.9      |
|                                                    | D                    | 12.0 ~ 13.0                      | 17.0                               | 25.5*    | 22.1      |
|                                                    |                      | 13.1 ~ 15.5                      | 20.0                               | 30.0*    | 26.0*     |
|                                                    |                      | 15.6 ~                           | 21.5                               | 32.0*    | 28.0*     |
|                                                    |                      | 15.6 ~ 22.0                      |                                    |          |           |
| RAWEDGE COGGED BELT                                | AX                   | 3.1 ~ 3.0                        | 3.4                                | 5.1      | 4.4       |
|                                                    |                      | 3.1 ~ 4.0                        | 3.7                                | 5.5      | 4.8       |
|                                                    |                      | 4.1 ~ 5.0                        | 4.0                                | 6.0      | 5.2       |
|                                                    |                      | 5.1 ~                            | 4.5                                | 6.7      | 5.9       |
|                                                    | BX                   | 4.7 ~ 4.6                        | 6.7                                | 10.0     | 8.7       |
|                                                    |                      | 5.7 ~ 5.6                        | 7.3                                | 11.0     | 9.5       |
|                                                    |                      | 5.7 ~ 7.0                        | 7.6                                | 11.5     | 9.9       |
|                                                    |                      | 7.1 ~                            | 7.8                                | 12.0     | 10.1      |
|                                                    | CX                   | 7.1 ~ 7.0                        | 12.0                               | 18.0     | 15.6      |
|                                                    |                      | 7.1 ~ 9.0                        | 13.0                               | 19.5     | 16.9      |
|                                                    |                      | 9.1 ~ 12.0                       | 13.5                               | 20.0     | 17.6      |
|                                                    |                      | 12.1 ~                           | 14.0                               | 21.0     | 18.2      |
| WEDGE V-BELT                                       | 3V                   | 2.65 ~ 3.35                      | 3.1                                | 4.6      | 4.0       |
|                                                    |                      | 3.65 ~ 4.50                      | 3.7                                | 5.5      | 4.8       |
|                                                    |                      | 4.75 ~ 6.0                       | 4.3                                | 6.4      | 5.6       |
|                                                    |                      | 6.5 ~ 10.6                       | 4.9                                | 7.3      | 6.4       |
|                                                    | 5V                   | 7.1 ~ 10.3                       | 11.0                               | 16.5     | 14.3      |
|                                                    |                      | 10.9 ~ 11.8                      | 13.0                               | 19.5     | 16.9      |
|                                                    |                      | 12.5 ~                           | 14.0                               | 21.0     | 18.2      |
|                                                    |                      | 12.5 ~ 16.0                      |                                    |          |           |
|                                                    | 8V                   | 12.5 ~ 16.0                      | 26.0*                              | 39.0*    | 33.8*     |
|                                                    |                      | 17.0 ~ 20.0                      | 30.0*                              | 45.0*    | 39.0*     |
|                                                    |                      | 21.2 ~                           | 34.0*                              | 51.0*    | 44.2*     |
|                                                    |                      | 21.2 ~ 22.4                      |                                    |          |           |
| RAWEDGE COGGED BELT                                | 3VX                  | 2.2 ~ 2.5                        | 3.2                                | 4.8      | 4.2       |
|                                                    |                      | 2.65 ~ 4.75                      | 3.8                                | 5.7      | 4.9       |
|                                                    |                      | 5.0 ~ 6.5                        | 4.8                                | 7.2      | 6.2       |
|                                                    |                      | 6.9 ~                            | 5.8                                | 8.7      | 7.5       |
|                                                    | 5VX                  | 5.9 ~ 5.5                        | 10.0                               | 15.0     | 13.0      |
|                                                    |                      | 5.9 ~ 8.0                        | 13.0                               | 19.0     | 16.9      |
|                                                    |                      | 8.5 ~ 10.9                       | 14.0                               | 21.0     | 18.2      |
|                                                    |                      | 11.8 ~                           | 15.0                               | 22.0     | 19.5      |
|                                                    |                      | 11.8 ~                           |                                    |          |           |
|                                                    |                      |                                  |                                    |          |           |
|                                                    |                      |                                  |                                    |          |           |

\*1/2 of this deflection force can be used, but substitute deflection amount as follows:

$$DA \text{ (inches)} = \frac{LS \text{ (inches)}}{128}$$

### Tapered bore or rotor

When the air gap varies from one end to the other, either the rotor or stator bore is tapered. Axial forces will try to move the rotor toward the smaller clearance. With a sleeve bearing machine, the result may be two magnetic centers: one at no-load conditions and another when loaded. The greater the difference in air gap, the greater the force acting on the rotor.

Another cause of the dual magnetic center problem occurs when the stator or rotor are restacked incorrectly. The stator and rotor must be symmetrical on both ends. If a stator restack results in one end of the motor having more iron than the other, the axial force will vary in proportion to the stator flux.

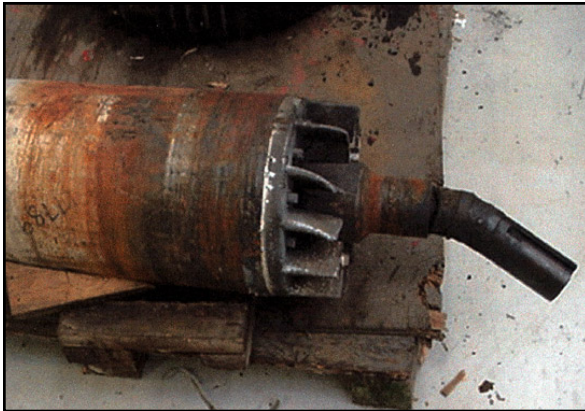
### OVERHUNG LOAD PROBLEMS

A number of bearing and shaft failures are related to incorrect belt alignment, tension and positioning. Even the selection of the number and types of belts is critical. Careful inspection of the belting as outlined in Table 3 will minimize the loading placed on the shafting. The same principles

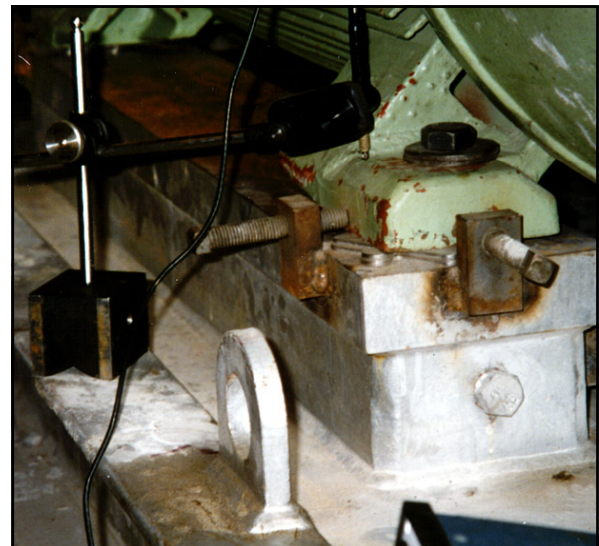
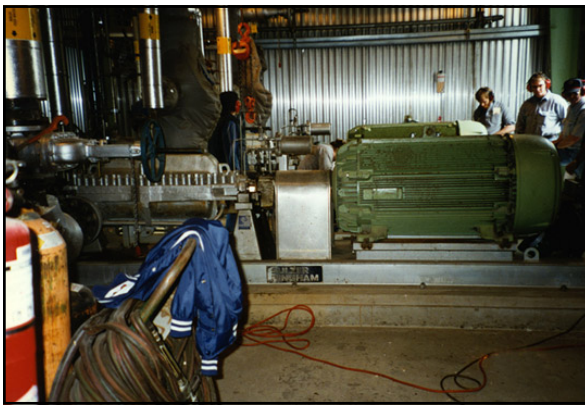
apply to other coupling methods.

The potentially destructive effect of overtensioning can be seen in Figure 26. The motor shaft has a severe bend, and the drive end housing has been virtually destroyed. The extent of the damage in this case didn't warrant dismantling the motor. It was a forgone conclusion that it should be replaced.

**FIGURE 26: OVERTENSIONING OF BELTS**

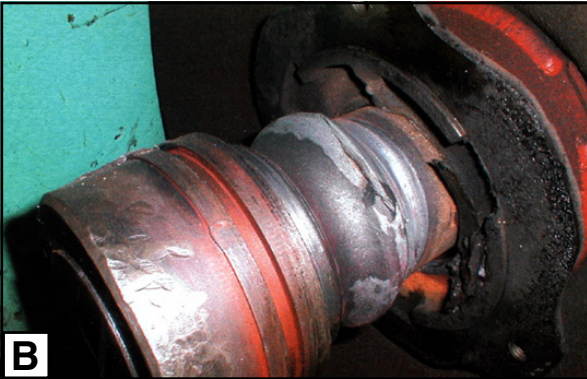
**MISALIGNMENT FAILURES**

The rotor output shaft in these photographs was bent nearly 30° from its original centerline. This could have been caused by misalignment. Note that the shaft material has weakened due to the strain and heating, resulting in tearing and twisting of the steel at the drive end bearing shaft shoulder. This type of bending is usually associated with belted applications, where there is always a high radial (side pull), or overhung load, but can also occur on direct-coupled applications with severe misalignment or vibration.

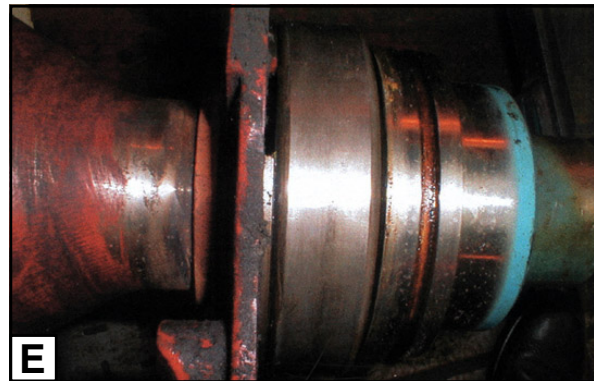
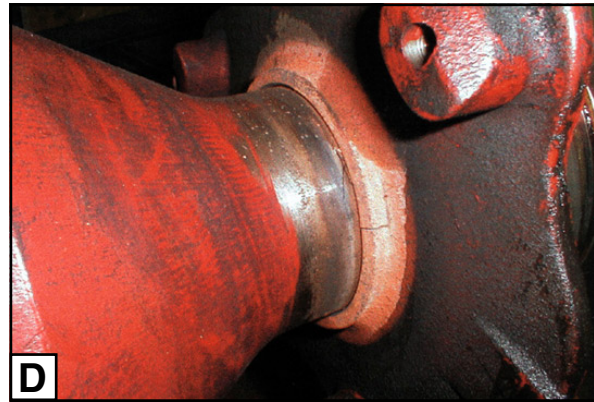


Boiler feed pumps operate at temperatures much higher than most rotating machines, therefore thermal growth has a significant effect on alignment. The initial cold alignment offset should always be obtained from the pump manufacturer and used during alignment. In the case shown here, it wasn't a thermal offset, but a soft foot that led to a bearing failure. As shown, a dial indicator can be used to check for vertical movement as each foot is progressively loosened and retightened. The cylindrical roller bearing on the drive end of the motor failed because it's housing seat had an angular distortion caused by the strain of pulling down on a soft foot. It is worth noting that cylindrical bearings are not usually well suited to direct coupled installations because, without appreciable radial load, the rollers tend to skid (i.e., stop rotating) while sliding around the bearing races.



**MISALIGNMENT FAILURES**

These photographs illustrate that misalignment often affects the opposite drive end (ODE) bearing more so than the drive end (DE). The ODE bearing and bearing cap (A and B) have been wiped out, so much so that the bearing inner race has lost its hardness and mushroomed out. The rotor core (C) has rubbed the stator core, causing lamination damage. On the DE, the inboard bearing cap (D and E) has rubbed the shaft due to the ODE bearing failure causing the rotor to drop down in the frame. This is a classic example of what may be found when misalignment results in a bearing failure.



Severe damage to a ball bearing shaft journal can be seen here. The inner race of the bearing spun on the shaft and friction-machined its way into the shaft. Note that the inboard labyrinth (left side of photo) rubbed, and a labyrinth sleeve on the outboard side came loose. The sleeve is visible on the right side of the photo. The probable cause of this failure was excess radial load due to parallel misalignment.

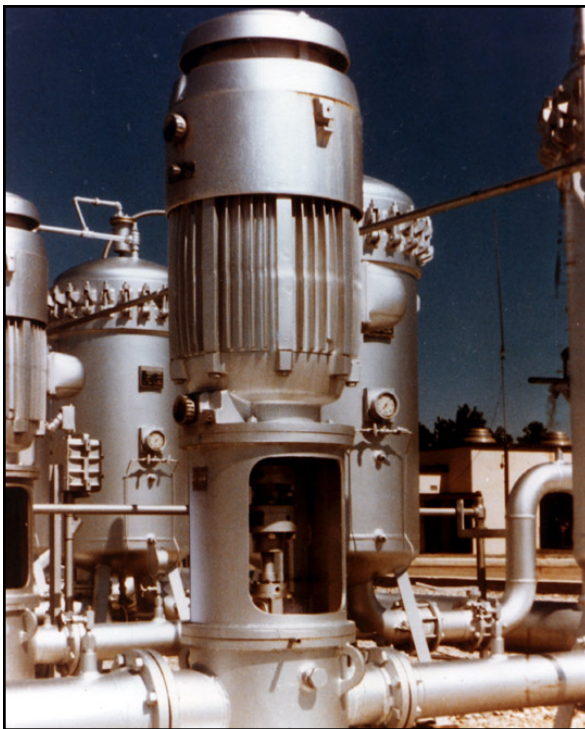




## FACTORS THAT CAN AFFECT ALIGNMENT



The shaft alignment of this motor and pump has the potential to be complicated not by just thermal growth, but by contraction as the pump is handling cold potable water. Being a pump installation, pipe strain is also a possible factor that should be checked. Note that the support base for the motor is not substantial. That could lead to vibration, particularly if the vertical elements are not cross braced.



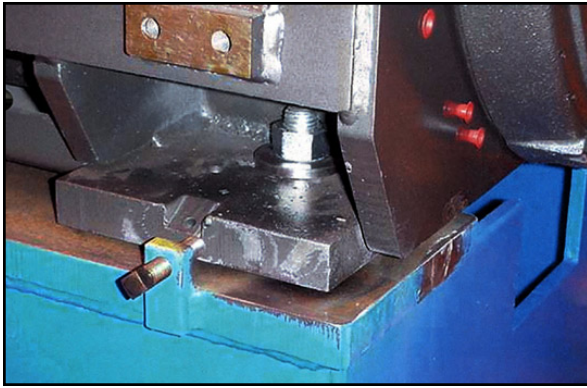
Alignment of this outdoor motor and pump installation can be affected by sunlight, which will heat one side of the motor more than the other. That will have a tendency to bow the unit in the vertical direction, with a consequential angular misalignment. Note the cutouts in the column between the motor and pump for access to the coupling. If the column is not properly designed, resonant vibration can occur.



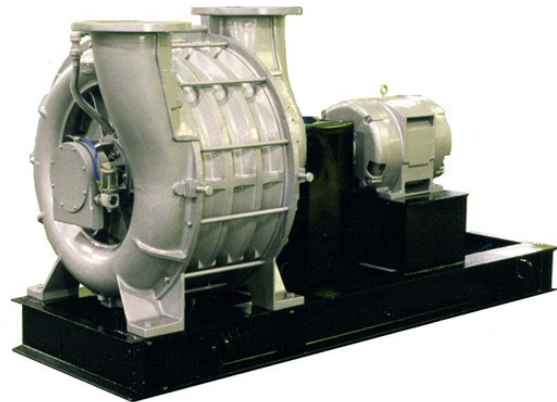
Note the tall slender body of the motor and companion column adapting it to the pump. If the stiffness of the motor and column are not adequate, a “reed frequency” resonant vibration could cause the motor to sway, thus continuously going in and out of alignment. The coupling for this unit has a jackscrew device built into it to raise or lower the pump shaft. By inserting a rod into the holes in the center of the coupling, the pump shaft can be adjusted to set the impeller clearance to the bowls (volute). A word of caution: Some motors are coupled to pumps designed for higher capacity, with a future increase in capacity in mind. While the motor might be a 200 hp, the driven pump could require 300 hp. The pump cost may be about the same as for the smaller rated unit, while the larger motor cost is proportionately higher. Installing the smaller motor allows the user to simply change out the motor to increase capacity at a later date. To compensate, while the smaller motor is coupled to the pump, the impeller shaft is lifted more than the standard 0.125” (3 mm) clearance, thus reducing the pump efficiency so that it only requires the 200 hp motor. The danger comes when no one remembers that this smaller motor is driving a 300 hp pump, and normal alignment procedures are used. The motor tries to deliver the capacity of the pump, and fails prematurely, if it operates at all.



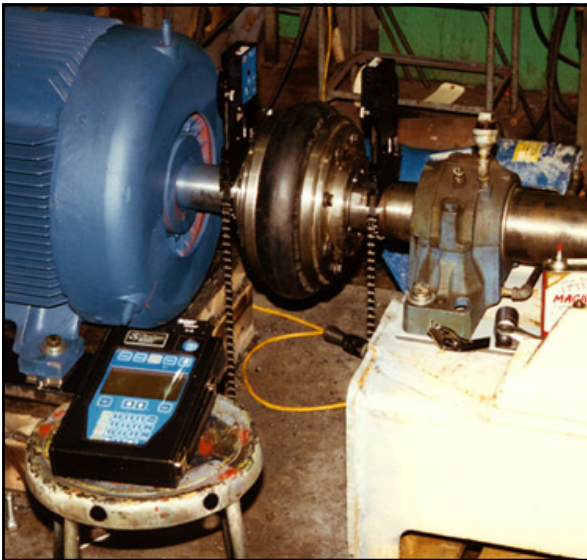
## FACTORS THAT CAN AFFECT ALIGNMENT



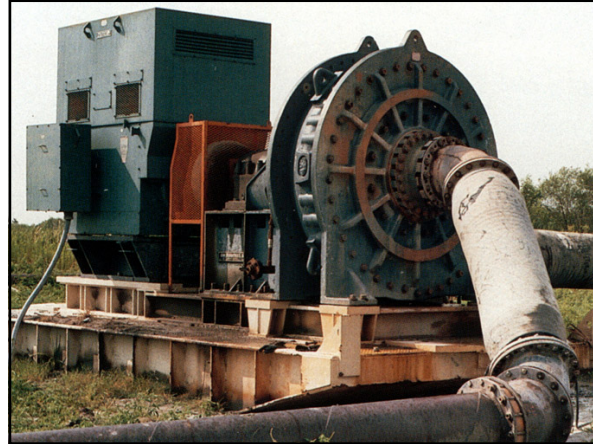
This illustrates how critical the foot location is with respect to the mounting plate. In this case, the foot is mislocated. A similar mounting issue, not caused by the motor, but by the base, is when the motor sits too high. That is, when the motor shaft centerline is above the driven machine shaft centerline, with no shims under the motor feet. In those cases, the most frequent alternatives are to machine material off of the feet of the motor or shim the driven equipment and then perform the alignment. Some driven equipment may be impractical to shim. An example would be a pump, because of the potential for pipe strain if the pump body is raised.



Thermal growth must be taken into account when aligning. The exhaust side of the blower in this photograph will grow more than the inlet side. The thermal growth of this type of blower will be greater than the motor, in most cases. Because of the temperature differences in the blower body, it will not only grow upward, but also at an angle from the cold end to the hot end. The motor is usually set intentionally higher than the blower for cold alignment (i.e., prior to startup). After the unit is at operating temperature, it should be shut down and the alignment checked hot, and realigned hot if necessary.



Different types of couplings require adjustments in alignment techniques. The relatively large diameter of the “rubber tire” coupling necessitates having alignment equipment that has enough height to clear the center “doughnut.” The many components of this coupling can also introduce a mechanical unbalance that results in vibration. If that is suspected, disconnect the coupling and rotate one side of it 180° and reconnect. If the vibration level changes, the coupling has some unbalance.



Machinery installed in areas subject to the earth settling (e.g. wetlands) may go out of alignment as the foundation support becomes unequal. This large motor and pump are mounted on what appears to be a massive base. Despite its substantial construction, the base can twist or bend as the earth beneath it gives way or settles. Another consideration is that the motor and driven equipment on a base need to be realigned whenever the base is disturbed or moved. A common example of moving is when the new equipment is shipped from the manufacturer. The manufacturer may rough-align the unit, but the motor and driven equipment always needs to be realigned after they are installed.

| GUIDE TO MOTOR ALIGNMENT                  |                         |                          |        |           |           |           |                                           |         |                                            |            |
|-------------------------------------------|-------------------------|--------------------------|--------|-----------|-----------|-----------|-------------------------------------------|---------|--------------------------------------------|------------|
|                                           |                         |                          |        |           |           |           |                                           |         |                                            |            |
| <div>Vertical</div> <div>Horizontal</div> |                         |                          |        |           |           |           |                                           |         |                                            |            |
| Case                                      | Dial indicator readings | Relative shaft positions |        | C equals  | X equals  | Y equals  | Vertical alignment<br>add or remove shims |         | Horizontal alignment<br>move left or right |            |
|                                           |                         | Compr.                   | Driver |           |           |           | X thick                                   | Y thick | X distance                                 | Y distance |
| 1                                         | +A = +B                 |                          |        | Not req'd | A/2       | A/2       | remove                                    | remove  | left                                       | left       |
| 2                                         | -A = -B                 |                          |        | Not req'd | A/2       | A/2       | add                                       | add     | right                                      | right      |
| 3                                         | +A, -B                  |                          |        | BD/A+B    | B(C+D)/2C | B(C+G)/2C | add                                       | add     | right                                      | right      |
| 4                                         | -A, +B                  |                          |        | BD/A+B    | B(C+F)/2C | B(C+G)/2C | remove                                    | remove  | left                                       | left       |
| 5                                         | -A < -B                 |                          |        | BD/B-A    | B(C+F)/2C | B(C+G)/2C | add                                       | add     | right                                      | right      |
| 6                                         | +A < +B                 |                          |        | BD/B-A    | B(C+F)/2C | B(C+G)/2C | remove                                    | remove  | left                                       | left       |
| 7a                                        | +A > +B                 |                          | BD/A-B |           | B(F-C)/2C | B(G-C)/2C | add                                       | add     | right                                      | right      |
| 7b                                        |                         |                          |        |           | B(C-F)/2C | B(G-C)/2C | remove                                    | add     | left                                       | right      |
| 7c                                        |                         |                          |        |           | B(C-F)/2C | B(C-G)/2C | remove                                    | remove  | left                                       | left       |
| 8a                                        | -A > -B                 |                          | BD/A-B |           | B(F-C)/2C | B(G-C)/2C | remove                                    | remove  | left                                       | left       |
| 8b                                        |                         |                          |        |           | B(C-F)/2C | B(G-C)/2C | add                                       | remove  | right                                      | left       |
| 8c                                        |                         |                          |        |           | B(C-F)/2C | B(C-G)/2C | add                                       | add     | right                                      | right      |
| 9                                         | A = 0, -B               |                          |        | D         | B(C+F)/2C | B(C+G)/2C | add                                       | add     | right                                      | right      |
| 10                                        | A = 0, +B               |                          |        | D         | B(C+F)/2C | B(C+G)/2C | remove                                    | remove  | left                                       | left       |
| 11                                        | +A, B = 0               |                          |        | Not req'd | FA/2D     | GA/2D     | add                                       | add     | right                                      | right      |
| 12                                        | -A, B = 0               |                          |        | Not req'd | FA/2D     | GA/2D     | remove                                    | remove  | left                                       | left       |



## MISCELLANEOUS MECHANICAL FAILURES

When analyzing a motor failure and determining what repairs are necessary, it is important not to overlook the “passive” parts of the motor. Examination for cracks, deformation, wear, looseness and corrosion are critical steps that should not be omitted. Items to examine include:

- Stator frames, end brackets and bearing caps.
  - Porosity of castings.
  - Register fits (eccentric, out-of-round, over- or under-sized, damaged).
  - Broken welds, cracks or flaws.
  - Stripped threads or improper holes.
  - Damaged lifting devices.
  - Loose, misplaced or missing baffles.
  - Improper stator core-to-frame fit.
  - Lack of foot flatness.
  - End bracket oil tube leakage or improper seal/fit.
  - Poor bearing bore fits between bearing brackets or bearing caps.
  - Clogged drain holes.
  - Clogged grease fills and drains.
  - Rust, corrosion and abrasion.
- Plumbing systems for lubrication and cooling
  - Loose fits/connections.
  - Damaged threads.
  - Improper locations, levels or angles.
  - Missing orifices or metering plates.
  - Clogged or leaking parts.
- Other
  - Damaged bearing mounts.
  - Loss of clearance between rotating and stationary parts.
  - Out-of-balance parts.

## UNIQUE PROBLEMS

### HEAT SOURCE CONSIDERATIONS

(IEEE P1349-2002)

Manufacturers sometimes use nonmetallic components as part of the enclosure to minimize circulating currents. Use of nonmetallic material lowers the stray losses and circulating currents in enclosure housings. Current may be induced in steel bolts used to hold other components to nonmetallic parts where they are located within the magnetic field of the stator winding. This is particularly true during motor starting. If the bolts are made of a magnetic material, they may become hot. Use of nonmagnetic bolts, such as 300 series stainless steel, minimizes circulating currents and hot components. Grounding of any floating hardware is recommended, as there are recorded instances of intense sparking between floating hardware and adjacent ground plates.

### JOINTS

(IEEE P1349-2002)

Motor characteristics that would minimize sparking across the joints are below:

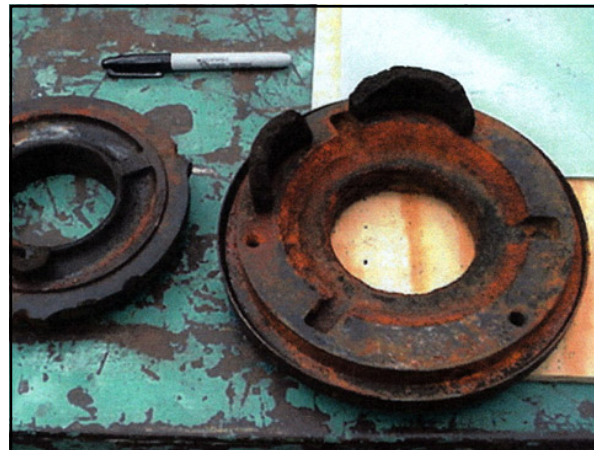
- a) One piece cast or welded fabricated frames, so there is no risk of sparking across frame joints.
- b) An adequate number of bolts to secure bearing brackets and end-covers to the frame. An adequate number of bolts should provide a path for current flow during starting.
- c) Machined surfaces between bearing bracket and frame mating surfaces insure good contact between frame and bracket.
- d) Adequate clearances between motor windings and structural parts.

Where needed, equipotential bonding conductors should be installed to prevent sparking between sections in multi-section motors. Bonds should be applied as specified by the manufacturer.

## MISCELLANEOUS MECHANICAL FAILURES AND DAMAGE



Note the contrast between a proper fitting bearing cap that is in good condition (left) and those that are no longer functional (right).



**MISCELLANEOUS MECHANICAL FAILURES AND DAMAGE**

The foot weld did not penetrate into the stator frame properly.



A severe soft foot condition caused this frame to crack.



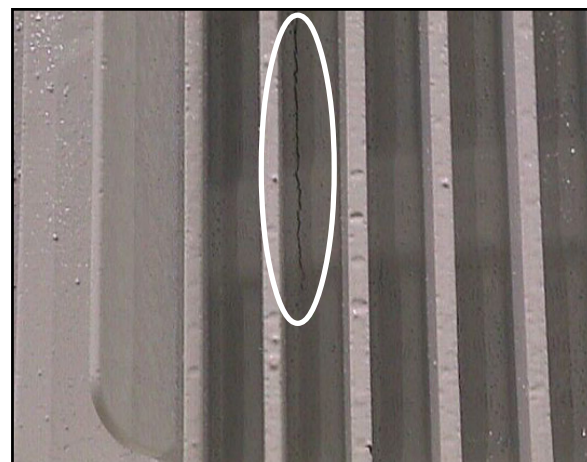
An unacceptable method was used to enlarge a frame foot hole.



The axial ribs of the fabricated frame that retains the laminations were previously cut to disassemble the core for restacking. After restacking, the frame was held together in a press and welded. The welding of the ribs resulted in uneven pressure retaining the laminations. The result was that some the lamination packets became loose and rotated, causing ground faults in the winding. The repair of this motor will require another restacking, as well as rewind.



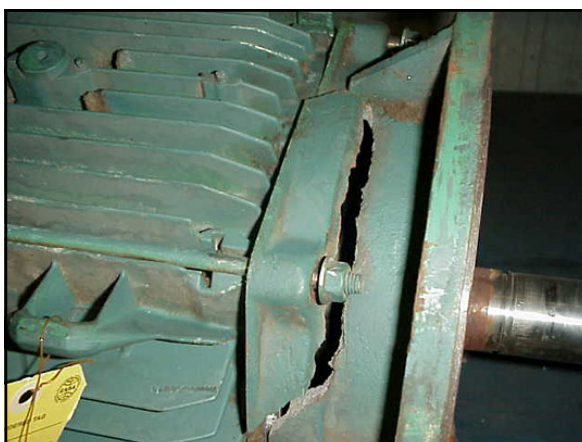
The crack in this frame was caused by an interference fit between the stator and frame that was too tight. This resulted in excessive hoop stress. When the stator expanded during operation, the frame split.



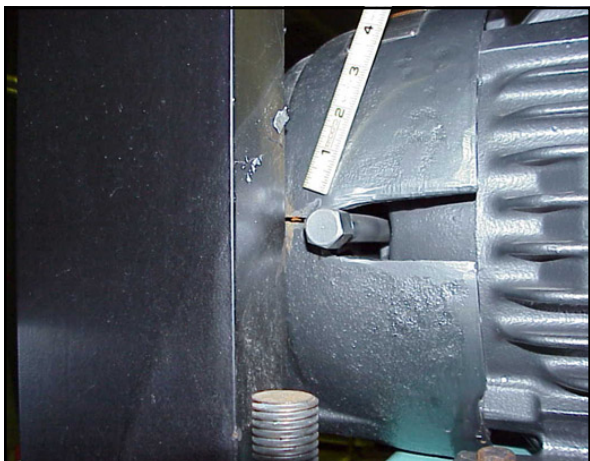


**MISCELLANEOUS MECHANICAL FAILURES AND DAMAGE**

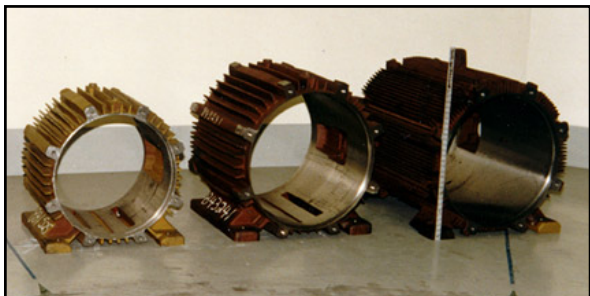
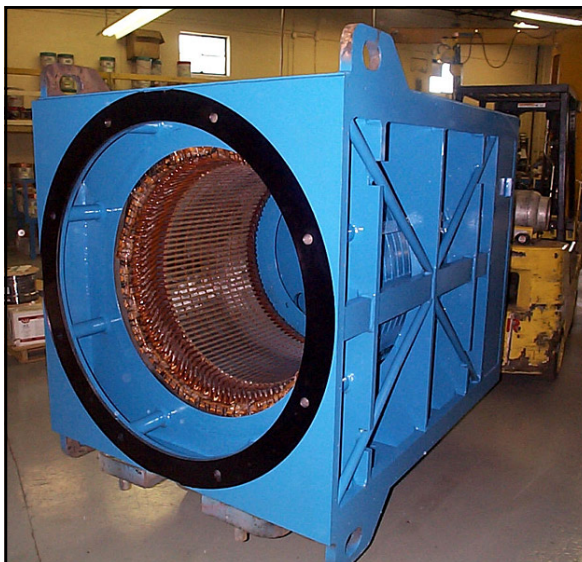
Due to excessive force, the ear cracked at the bolt circle.



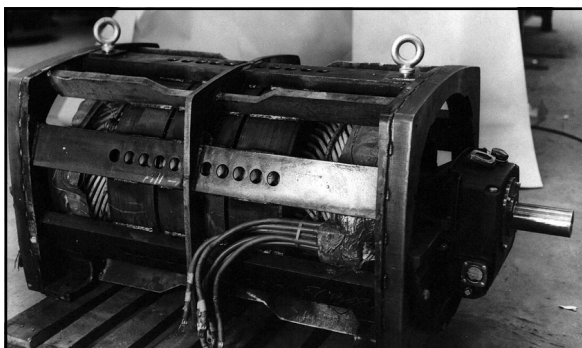
This through-bolt was overtightened which exerted more force than the square shape of the cast aluminum end bracket could resist.



This fan cover guard was cracked during installation.

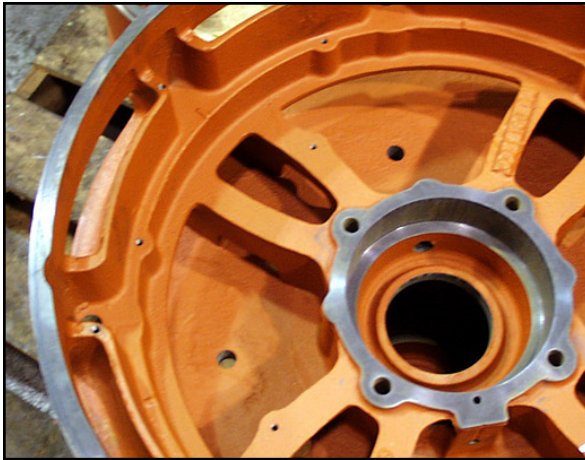


These are typical TEFC frames. It is critical that the register fits are concentric and sized properly. On TEFC frames, it is very important to get the proper fit between the stator and the frame to ensure good conduction of heat.



Many larger motors use welded or fabricated stator frames. Note that the laminations are welded directly to the frame structure. Failure to do so properly can result in excessive noise and vibration.



**MISCELLANEOUS MECHANICAL FAILURES AND DAMAGE**

All of the end bracket fits must be round, be sized properly and have the proper flatness.



Severe corrosion in the lower end bracket due to a clogged drain hole.



This end bracket lost the running clearance with the shaft.



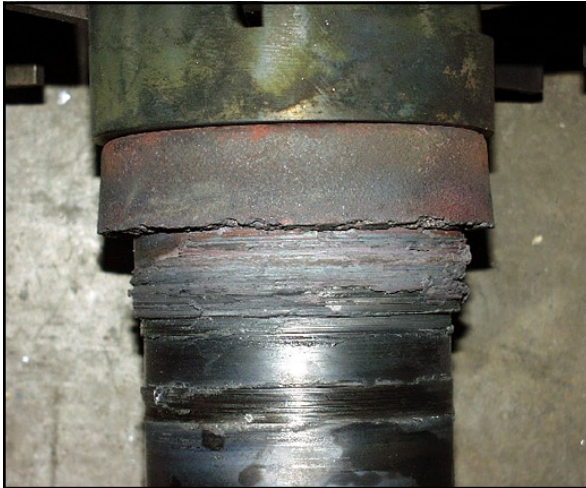
This motor's shaft, end bracket (above) and the finger fan/heat sink housed within the end bracket were damaged when a universal joint (below) failed due to a transient voltage.



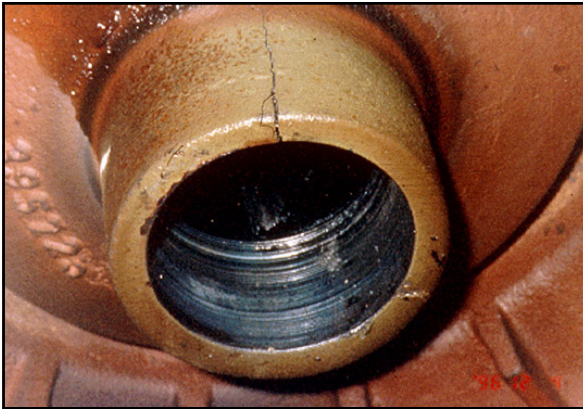


**MISCELLANEOUS MECHANICAL FAILURES AND DAMAGE**

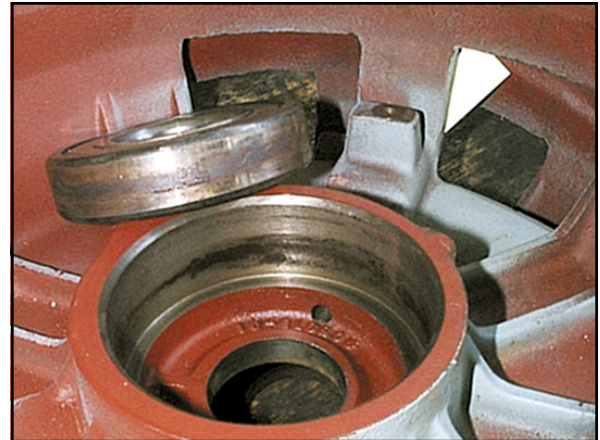
These photographs illustrate how the simple mechanical failure of a part can lead to a catastrophic motor failure. In this vertical motor, a simple bearing resistance temperature detector (RTD) or vibration detector could have protected this motor. Instead, the shaft, end bracket and winding were damaged.



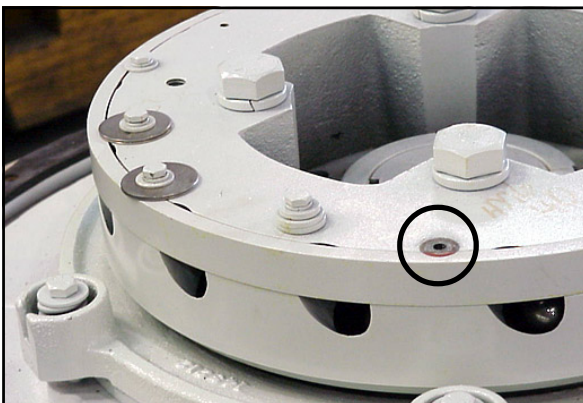


**MISCELLANEOUS MECHANICAL FAILURES AND DAMAGE**

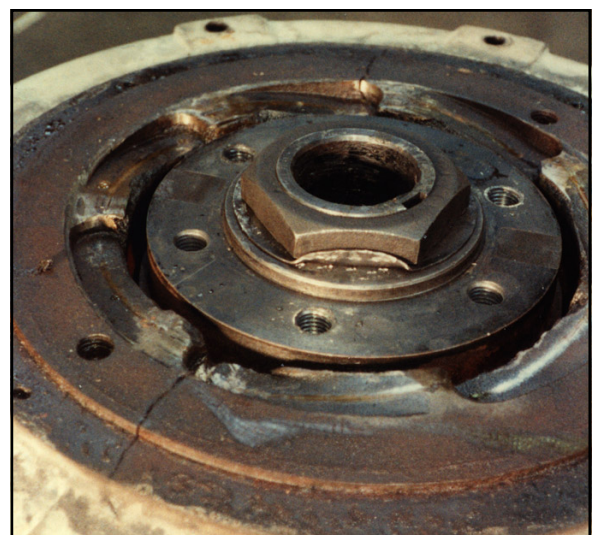
The crack in this lower end bracket was caused by loss of running clearance between the end bracket and shaft. The end bracket is now out of round and galled.



These bearing housings are oversized and out-of-round due to a loose fit which caused fretting.

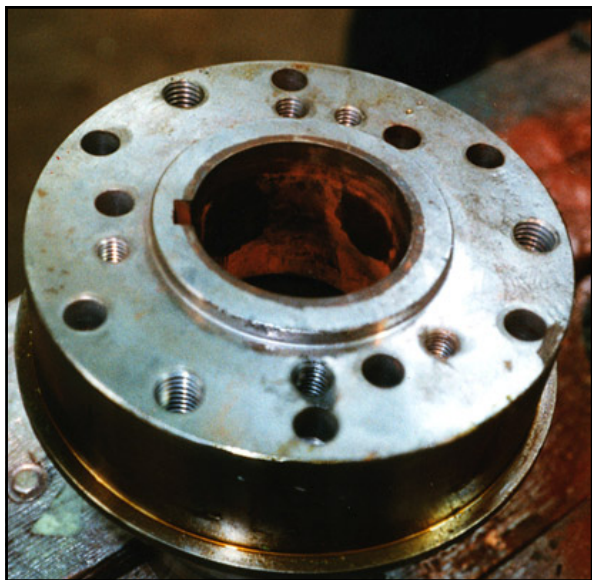


It is critical that all rotating parts fit together properly and are balanced. Note that a bolt is missing from this anti-rotation device.

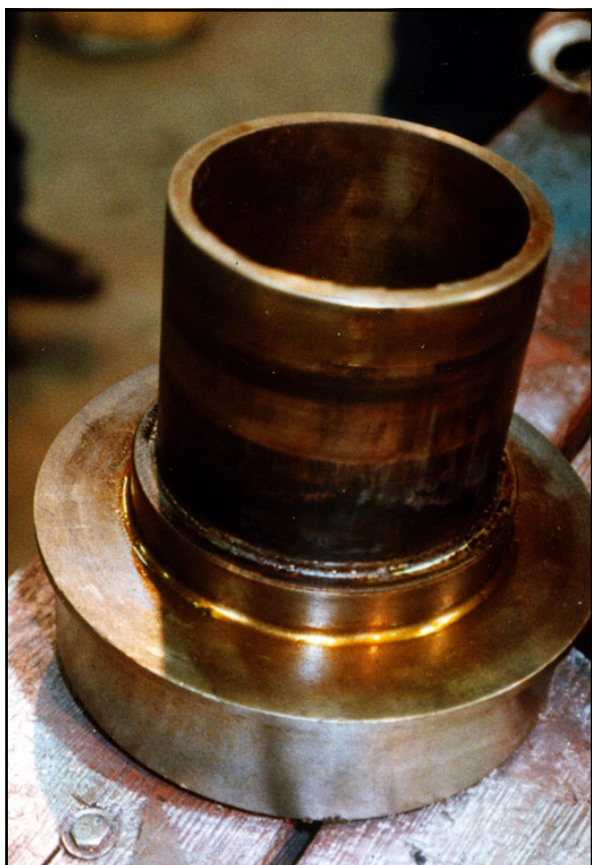


The failure of this anti-rotation device cracked the upper end bracket.

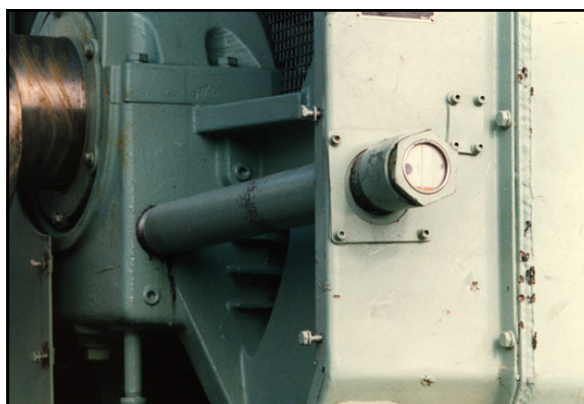
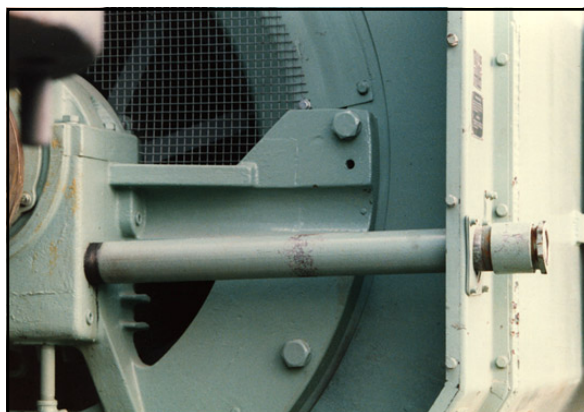


**MISCELLANEOUS MECHANICAL FAILURES AND DAMAGE**

This bearing resistance temperature detector (RTD) was damaged during shipping.



This bearing carrier lost its fit to the bearing due to fretting.



The plumbing for this sight glass was installed at an angle which raised the oil level and increased drag on the sleeve bearings. The cause for the angle was incorrect drilling and tapping of the threaded hole in the bracket.

# 7

## DC Motor Failures

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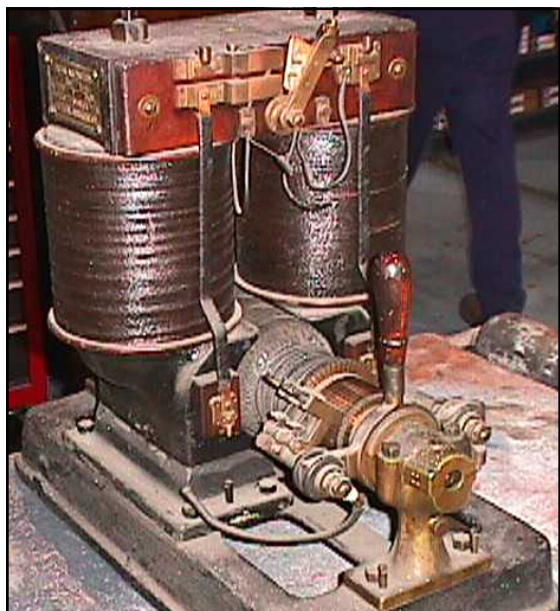


## INTRODUCTION TO DC MOTORS

While many of the components of a DC machine are common to AC machines (shaft, bearings, frame), there are parts that are unique to DC machines. This section will address those components, describe test methods and failure modes, and failure analysis. The same methodology used throughout the book is continued here, with adaptations.

It is assumed, for the purpose of this discussion, that the reader already understands how a DC motor works.

**FIGURE 1: EARLY DC MOTOR**



This 1889 Edison Electric DC motor is a 1.5 kW (2 hp) bipolar design. With no interpoles, the brush neutral had to be shifted for every load change.

The DC motor has been around since the 1880s. (See Figure 1.) Although some have been sounding its death knell since as far back as the 1950s, there seems to be no shortage of DC repair work. The windings of a DC machine differ from those of AC motors, so the evaluation process differs from that described earlier in this book.

Many problems associated with DC machines are related to their ability to dissipate heat. Thermal stress is therefore emphasized. Conductor size (circular mils/amp), volume of airflow, commutator diameter, ambient temperature and load are factors that affect temperature rise.

The section is divided into the major parts of the DC machine, with discussion following the sequence established earlier in this book. Ventilation is addressed in detail under the thermal heading.

The stresses, as they pertain to DC machinery, can be grouped as follows:

### Armature

- Thermal stress
  - Overload
  - Stalled condition
  - Hot spots
  - Poor ventilation
- Electrical stress
- Mechanical stress
  - Loose lamination to shaft fit
- Dynamic stress
  - Vibration
  - Transient torque
  - Centrifugal force
- Environmental stress
  - Contamination (carbon)
  - Abrasion
  - Obstructed ventilation

### Field coils, interpoles, series fields and compensating windings

- Thermal stress
  - Overload
  - Blower/ventilation
  - Heat transfer inhibited
- Mechanical stress
  - Loose coils, fasteners
  - Material deviation
  - Improper design or manufacturing process
- Dynamic stress
  - Vibration
- Environmental stress
  - Contamination (carbon)
  - Abrasion

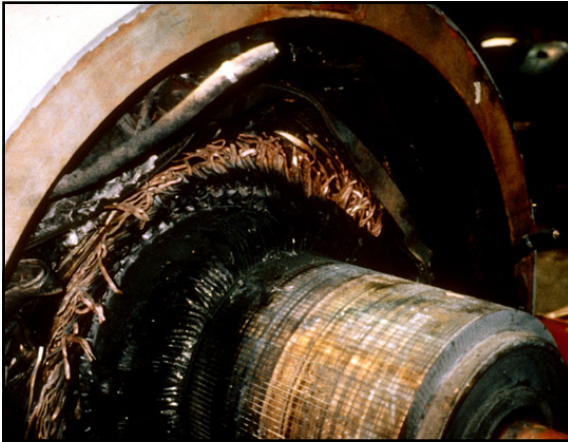
## ARMATURES

The armature is the heart of the DC machine, subject to the stresses associated with AC windings in Section 3 and the stresses associated with the AC rotor in Section 5. (See Figure 2.) The armature is comprised of coils inserted in slots, connected to individual commutator bars. The coils are retained in the slots by wedges, and the coil extensions

## ILLUSTRATIONS OF DC MOTOR COMPONENTS

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| Armature .....                 | 7-4  |
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**FIGURE 2: A DC ARMATURE**

This armature failed when the banding material deteriorated. Humid salt air weakens fiberglass banding. A high resin-content banding works best in humid conditions.

secured by banding with resin-rich fiberglass banding tape or steel wire. Both wedges and banding material must be capable of withstanding the centrifugal forces of rotation.

Voltage reaches the armature through carbon brushes riding against the commutator, so the commutator must be round and smooth. Eccentricity or high bars can cause the brushes to bounce, losing contact with the commutator and causing arcing. The armature windings are retained by banding, and must withstand elevated temperatures, voltage stresses and resist centrifugal forces.

### THERMAL STRESS

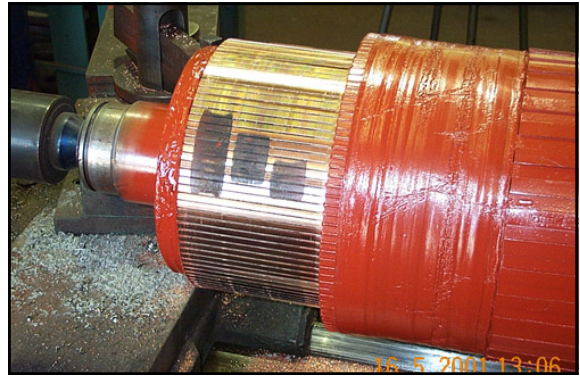
Thermal stress on the armature winding may be caused by load (current), elevated temperature or from the laminated core.

A comparison of the thermal appearance may be helpful; if the evidence of heat is greater at the wedges and coils within the slot, the laminations may be shorted. If the coil extensions appear to have been hotter, the thermal stress is more likely to be related to load or ventilation.

Thermal overload may leave the armature discolored, accelerate the end of insulation life, and soften the varnish thereby reducing bond strength. Causes include excess current, restricted ventilation, shorted laminations, commutator below minimum diameter, or high ambient temperature.

Stall conditions for a DC armature are distinctive in appearance. Current passes through the brushes to the bars they are in contact with, leaving a telltale pattern spaced at regular intervals coinciding with the brush spacing. A single episode will result in the footprint of the full complement of brushes. If there are multiple patterns, that indicates multiple stalls and may indicate a machinery problem, an untrained operator or a chronic overload situation.

One problem with a stall condition is that most commutator bars are an alloy of copper and silver. As with most

**FIGURE 3: COMMUTATOR**

This commutator has been machined, emphasizing the depth of the flat spots caused by a stall condition.

alloys, they can become heat treated. Temperatures above 550° F can temper or anneal the bars. A stall condition may soften the affected bars, changing their rate of wear and resulting in the development of flat spots. (See Figure 3.) Even after machining to restore the roundness of the commutator, the bars may continue to wear at a faster rate, causing flat spots to return. Use a spring-loaded centerpunch as a hardness tester: Press the centerpunch against the affected bar and then against a “good” bar. Compare the indentation size to assess the relative hardness of the bars.

While DC machinery operates on DC voltage, and eddy-current losses are associated with frequency, the armature of a DC machine actually is exposed to AC as the polarity in each coil reverses each time it passes a field pole. Armature frequency can be calculated as:

$$\text{Armature frequency} = \frac{\text{Poles}}{(7200/\text{rpm})} \times 60 \text{ Hz}$$

Since eddy-current losses are proportional to the square of the frequency, the higher the frequency, the more critical shorted laminations become. It has long been common practice to heat armatures with a torch in order to remove the windings. Shorted laminations in armatures resulting from this method are a very real problem. The preferred method is cold stripping as shown in Figure 4.

When the thermal damage is not caused by shorted armature laminations, the load should be evaluated, and the entire ventilation system inspected.

### ELECTRICAL STRESS

Armature insulation is subject to similar stresses as those described in the AC stator section, with the addition of centrifugal forces from rotational speeds. Carbon and moisture penetration are problematic because of the inherent exposure of the back of the risers. Winding treatment, if properly done, seals the windings from the knuckles to the risers. Commutator design requires that the commutator not be immersed in varnish, which would interfere with the function of the V-rings. That leaves portions of bare bars exposed to conductive contaminants. The underside and back of the bars are sheltered by the windings, restricting



ventilation and making cleaning difficult.

Centrifugal force traps carbon beneath the banding and beneath coils. Some armature designs are further complicated by vent ducts.

### MECHANICAL STRESS

Shaft fit to the laminated armature core, like that of the AC rotor, is necessary to transmit torque to the shaft and prevent movement that could cause vibration. In addition, the commutator fit to the shaft must be considered. Both armature core and commutator are often keyed to the shaft. Mechanical stresses to the windings are concentrated at the slot ends, support rings and banding. Not only are the coils retained by wedges and banding, but centrifugal force exerts pressure in the opposite direction to the force exerted when the wedges and banding are installed.

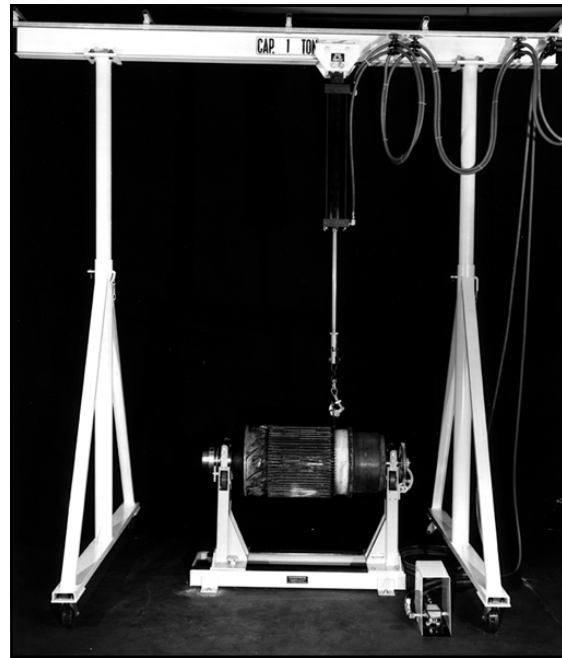
### DYNAMIC STRESS

Vibration can cause brushes to briefly lose contact with the commutator, resulting in arcing under the brushes. This generates heat, may intermittently increase current in individual bars and coils, and increases armature temperature. Severe vibration can cause coils to flex, increasing the stress on each coil where it exits the slot. While commutator designs vary, high vibration levels accelerate loosening of bars, making it more important to tighten commutator bolts at regular intervals.

Transient torques may be caused by rapid acceleration/deceleration of the armature. The tangential movement of coil extensions increase, although the armature designs most susceptible to this stress are those with heavy coils and tall free-standing risers.

Centrifugal force is proportional to  $Wr\omega^2$ ; where  $W$  is extension weight,  $r$  is the radius to the coil and  $\omega$  is rpm. That means that centrifugal force is more likely to affect longer armature coil extensions, those with a relatively wide coil pitch (e.g.; 2 pole armatures), large diameters or heavy

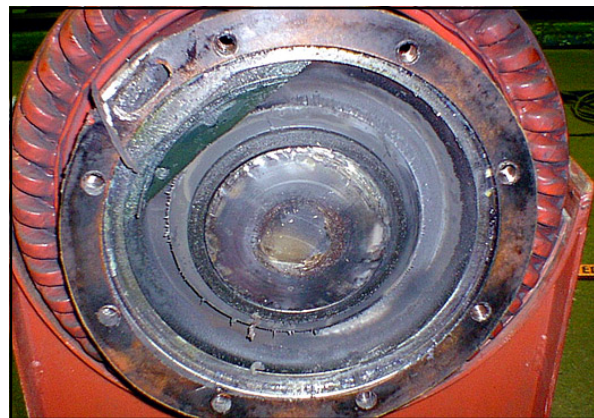
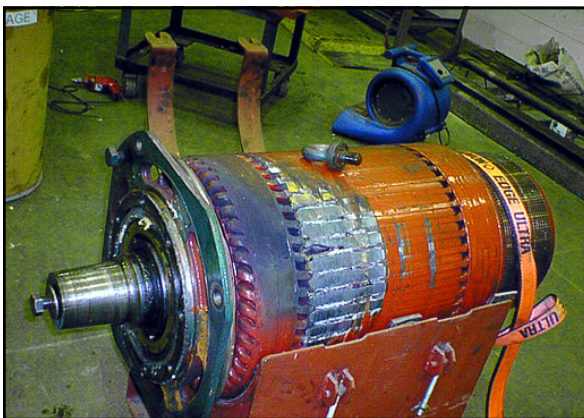
**FIGURE 4: STRIPPING AN ARMATURE**



Cold stripping an armature is popular with service centers that do traction motor repair.

coils. The higher the rpm, the greater the centrifugal force. (Note that centrifugal force is proportional to the square of the speed. If the speed doubles, the centrifugal force is multiplied four times.) Evidence of coil movement includes cracked insulation at the banding or where the coil exits the slot. Bowed or distorted coils indicate dangerous movement. If an overspeed occurs, the windings and/or commutator bars may separate from the armature with dramatic results.

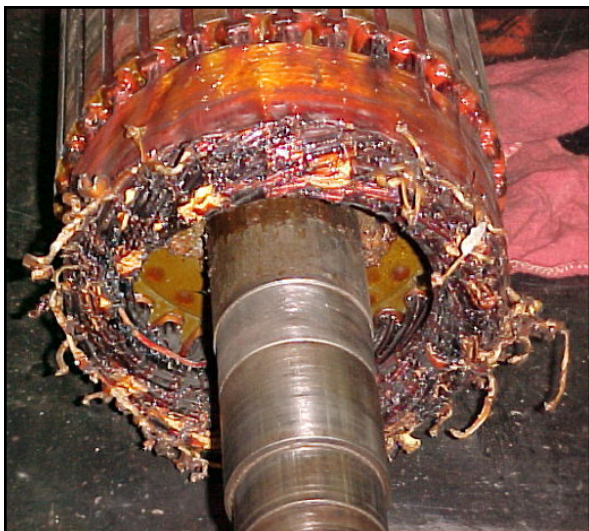
## ARMATURES



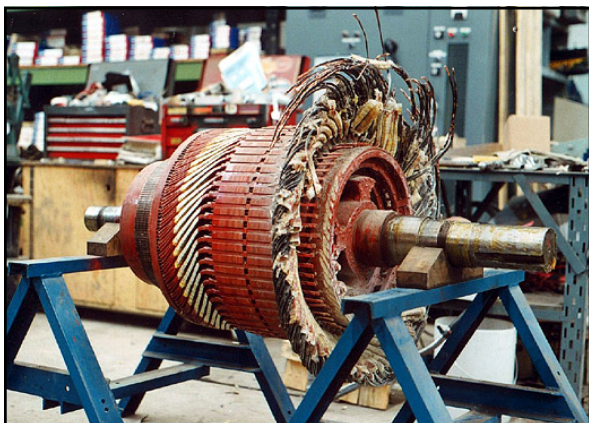
This armature rub could have resulted from a bent shaft, a loose pole dropping down onto the armature, or a broken shaft within the armature core. In this case, the shaft broke behind the bearing shoulder. The ratchet marks offer evidence of why the shaft broke. (See Section 4.)



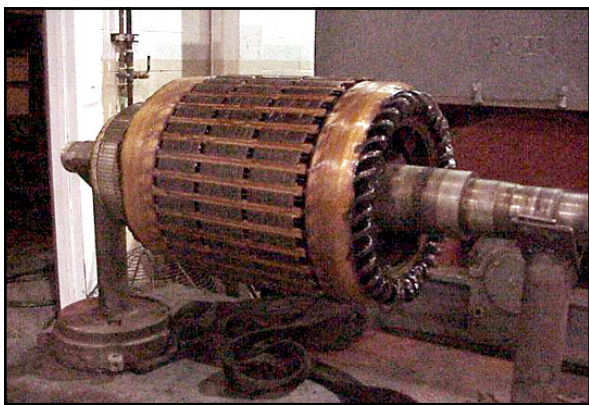
## ARMATURES



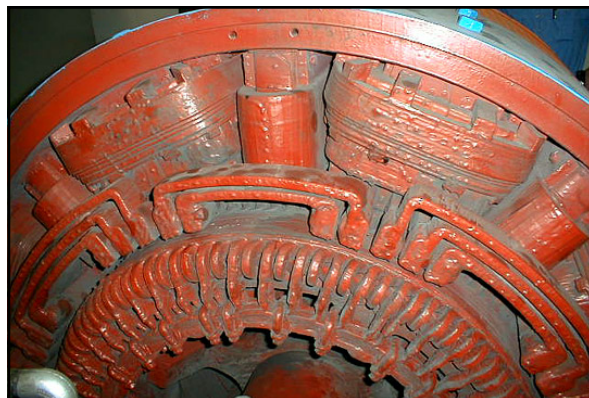
This coil extension has evidence of rapid thermal stress.



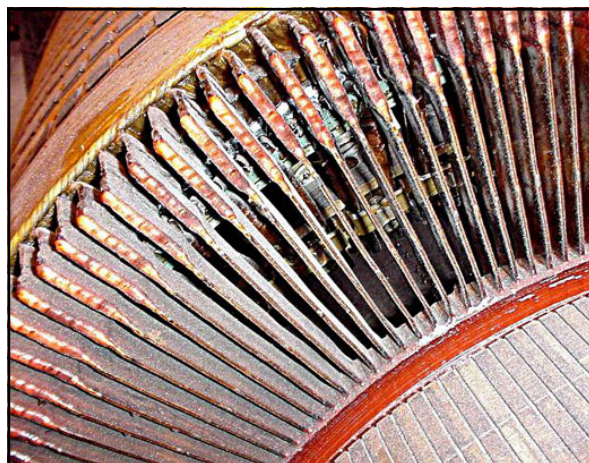
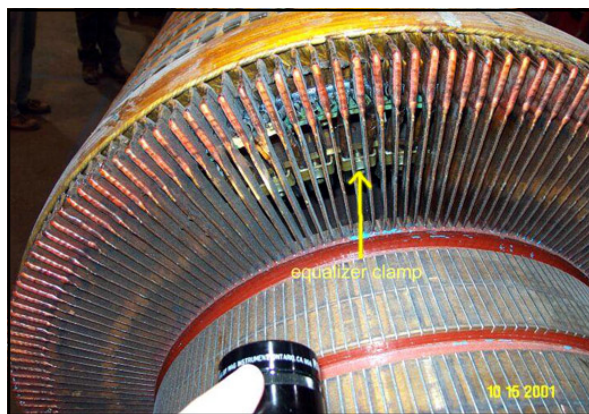
This armature was oversped when the field circuit opened.



Resin-rich fiberglass banding material retains the coil extensions. The slot wedges are high-strength epoxy "locomotive wedges."



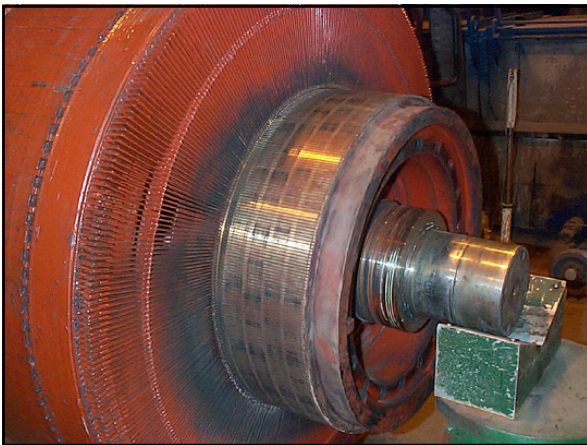
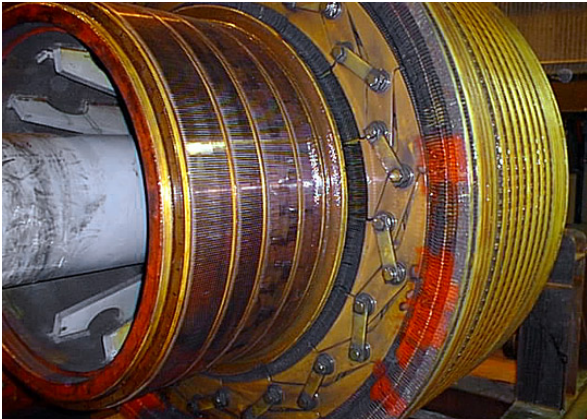
On larger machines, some manufacturers install equalizers on the opposite commutator end to facilitate replacement. When equalizers are installed behind the commutator, the armature has to be rewound if equalizer damage occurs. Common equalizer problems include carbon shorting, vibration and movement.



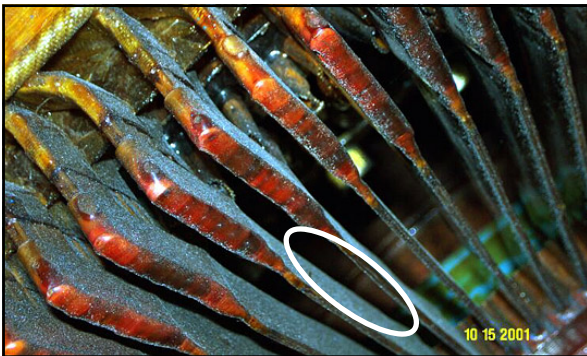
These free-standing risers are not braced. They are prone to flex and move during rapid acceleration or deceleration. A row of rigid lacing at mid-height would reduce flexing.



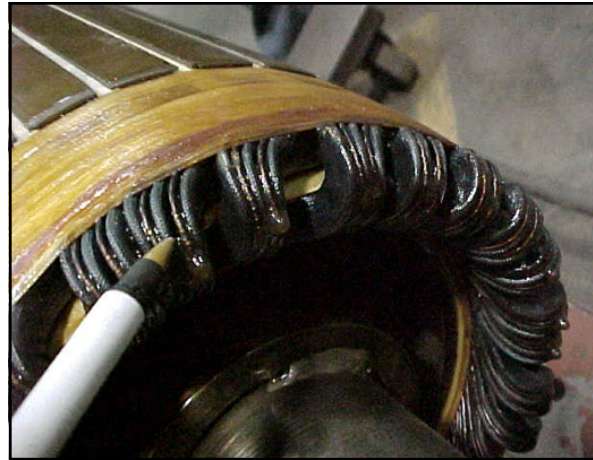
## ARMATURES



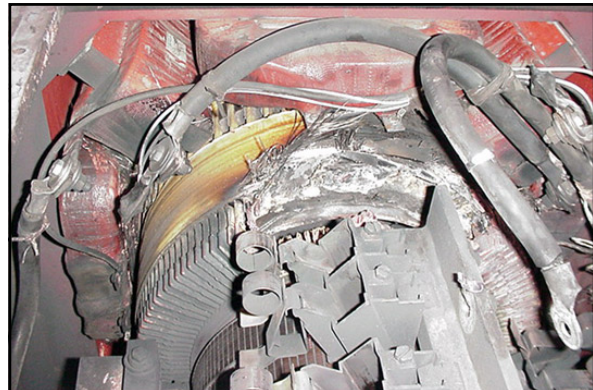
These are two methods of bracing tall free-standing risers. The elaborate method, shown at top, requires that the risers be spread to clear the bolts. This design blocks airflow through the risers. Surge rope (bottom) is sometimes used as lacing in order to brace the risers and increase rigidity.



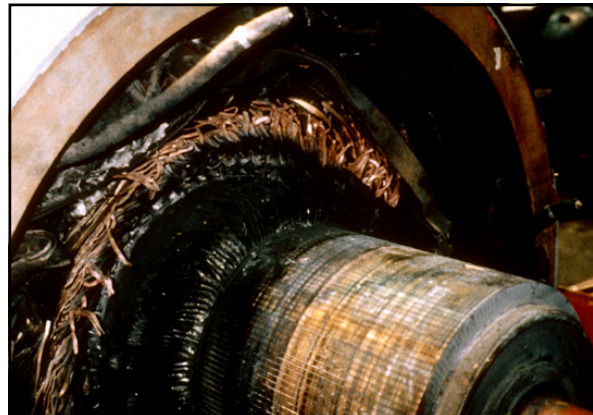
The free-standing risers are better ventilated, but are also more prone to movement. When they flex, the break occurs at or near the point at which they are more rigidly mounted. Blocking should be installed in the area of maximum movement (highlighted), not near the place where the breaks are occurring.



If spaced uniformly, these coils would have better exposure to airflow.



Flashover damaged the armature banding. Sudden reversal, caused by incorrect drive settings, was the root cause.

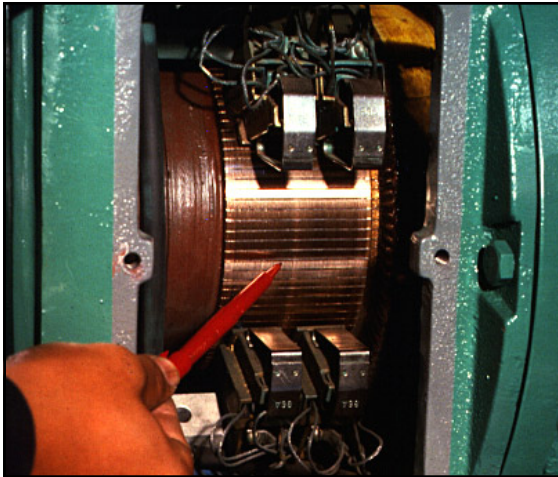


Possible causes of this damage include overspeed, failure of the banding material, inadequate banding or banding that was not fully cured.

## COMMUTATORS

Commutator condition offers useful clues about motor performance, as well as the load, air supply and condition of the windings. Because the desirable film on a commutator is only 2 tenths of a millionth of an inch thick, it is easily disrupted when something goes wrong. (See Figure 5.)

**FIGURE 5: COMMUTATOR FILM**



This is a good example of the uniform film necessary for proper commutation.

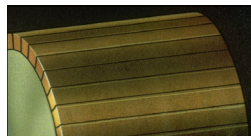
The film requires humidity and current to form, and is formed in the following manner: The positive brush of a motor deposits particles on the commutator, the negative brush picks up particles. Minute particles of copper are vaporized during this process, leaving a copper oxide film. If the rate of deposition and the rate of retrieval are balanced, the film is maintained at equilibrium.

When the balance between deposition and retrieval is disturbed, the film becomes too heavy or is stripped away. If the rate of retrieval exceeds the rate of deposit, copper material is removed from the commutator surface, causing threading in the brush path. As the threading becomes more pronounced, it affects the wear rate of the brushes riding on the threaded surface.

**Light film**



**Dark film**

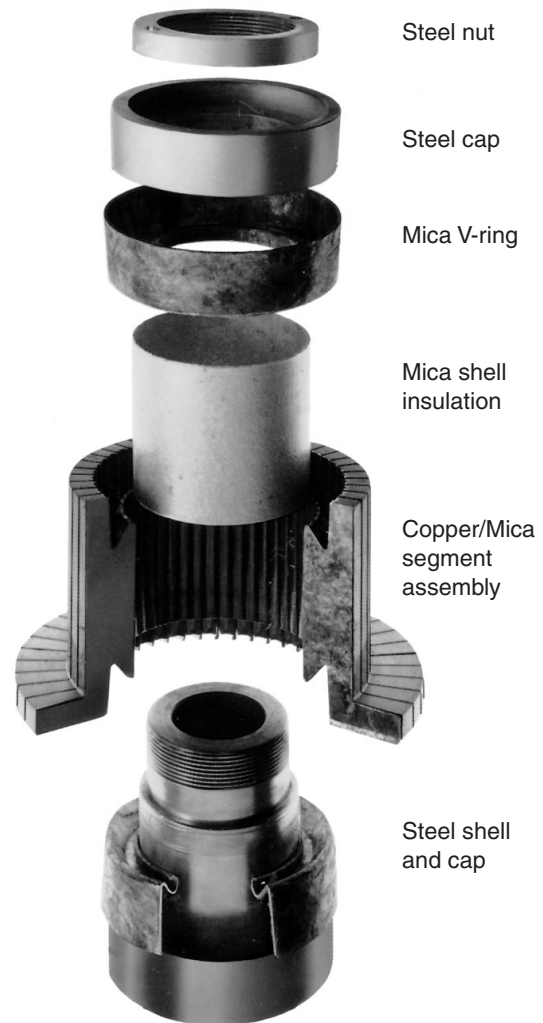


These are two of many normal conditions often seen on a well-functioning machine. This appearance should uniformly cover the brush paths.

### SLOT BAR MARKING: CAUSES AND CURES

Slot bar marking does not necessarily indicate a problem with the performance of a DC machine. In severe cases, there are remedial steps that can help to reduce the marking. (See Figure 7.)

**FIGURE 6: COMMUTATOR ASSEMBLY**



This is a typical V-bound commutator.

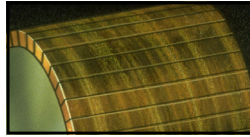
The first step in understanding the cause is to review the distribution of flux lines through the field poles. If the poles are evenly spaced, as they should be, and the commutator bars are evenly spaced, then each coil lead will pass into (and out of) the neutral plane at the same exact point. Unless the coils are placed one per slot, the symmetry is interrupted because of the manner in which the coils are inserted into the armature slots. The armature coils are bundled into slots separated by teeth. For example, an armature with 38 slots and 152 bars has 4 coils per slot. Since the coils are bundled, they do not pass into the neutral plane at exactly the same point. The iron teeth are symmetrical, which provides uniform torque.

With four coils in a slot, the end coils have armature teeth as a "neighbor" on one side. The two middle coils each have only coils as "neighbors." It is this difference that causes a magnetic disturbance, which in turn has an adverse effect on commutation.

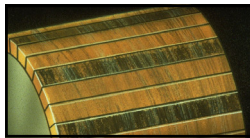


**FIGURE 7: APPEARANCE OF COMMUTATOR PROBLEMS****Streaking**

If a motor has been in service for years and streaking has not progressed, it is not considered harmful. If a newly-installed motor shows streaking, it should be monitored carefully. Streaking may progress to threading.

**Slot bar marking**

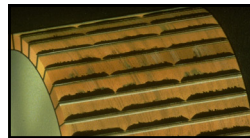
A darker film appears on bars in a definite pattern related to the number of armature conductors per slot.

**Possible causes**

- Electrical adjustment (neutral, interpole strength)
- Electrical overload
- Lubricant or chemical contamination

**Bar edge burning**

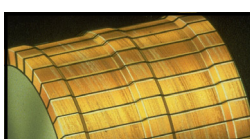
This is an abnormal buildup of commutator material, forming most often at the trailing edge of the bars. This condition can cause flashover if not checked.

**Possible causes**

- Electrical adjustment (neutral, interpole strength)
- Light brush pressure
- Vibration
- Abrasive brush or wrong brush grade
- Armature winding fault
- High mica
- Oversized brushholder
- Lubricant, chemical or abrasive dust contamination

**Grooving**

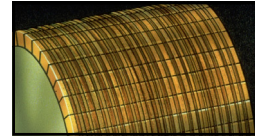
This is a mechanical condition caused by abrasive material in the brush or atmosphere.

**Possible causes**

- Abrasive brush
- Abrasive dust contamination

**Threading**

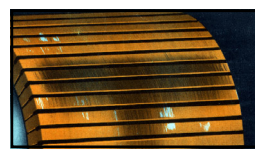
Fine lines result when excessive metal transfer occurs. Usually leads to resurfacing of commutator and rapid brush wear.

**Possible causes**

- Light electrical load
- Light brush pressure
- Porous brush
- Lubricant or chemical contamination

**Pitch bar marking**

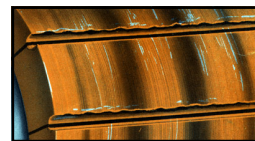
This produces low or burned spots on the commutator surface that equal half or all the number of poles on the motor.

**Possible causes**

- Armature connection
- Unbalanced shunt field
- Light brush pressure
- Vibration
- Abrasive brush

**Copper drag**

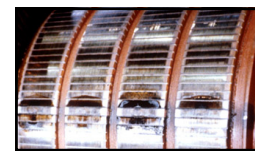
An abnormal amount of excessive commutator material at the trailing edge of the bars. Flashover could occur if not corrected.

**Possible causes**

- Vibration
- Light brush pressure
- Chemical contamination
- Abrasive brush

**Stall condition**

Footprint of each brush at regular intervals that coincide with brush spacing.

**Possible causes**

- Mechanical jam
- Operator inexperience
- Severely overloaded motor

Various innovations have been used to eliminate the problem. One coil design stacks the conductors flat through the slot section, and roll 90° after exiting the slot to enter the riser upright.

Another solution is to stagger the brushes on each post, so as to effectively widen the brush coverage to include small shifts in the neutral position.

There are a few things that can exacerbate the appearance of slot bar marking. One is electrical overload. That can mean the motor is too heavily loaded, or that the

brushes are carrying a higher current density than designed for.

Electrical adjustment often means interpoles that are not the correct strength. This is likely to be the result of improper shimming, missing shims, or nonmagnetic shims in the wrong order. A brush pencil neutral test can confirm this.

In rare cases, gas contamination can worsen the appearance of slot bar marking. Chlorine, hydrochloric acid, silicone and other gasses that affect copper can be a source of trouble.

## COMMUTATORS



This banded commutator has an uncommon failure. Carbon or moisture trapped under the band has completed the circuit to ground of the affected bar.

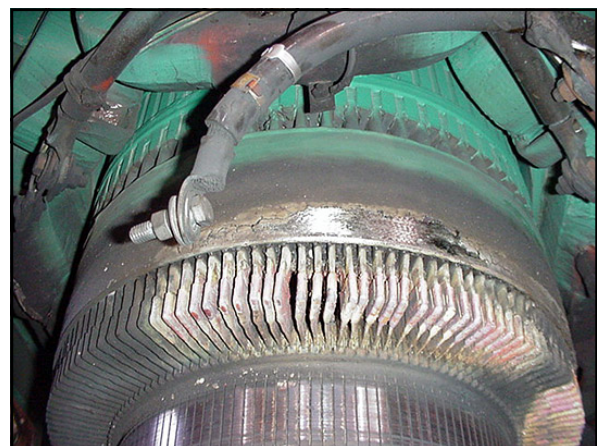


Shorted bars where copper melted.



Grooving is caused by abrasive wear by either dust in the atmosphere or too abrasive a brush grade. The two major problems associated with grooving are:

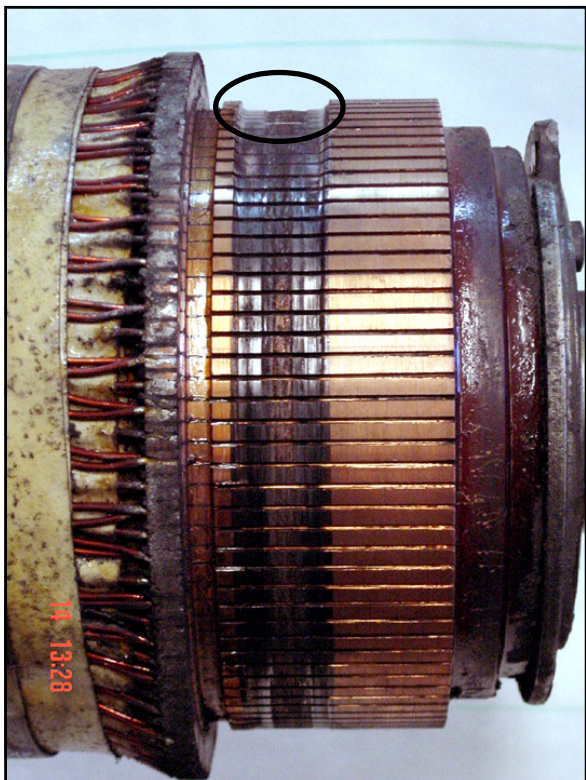
- It diverts pressure from the relatively flat bottom to the radiused sides of each groove. Reduced brush pressure increases the brush temperature.
- Rapid wear reduces the commutator to its minimum diameter more quickly. Commutator life may be reduced by years.



Carbon is a common cause of flashovers in DC machines. Carbon is carried in the airstream through the armature windings, and is often trapped under the banding or at the back of the risers.

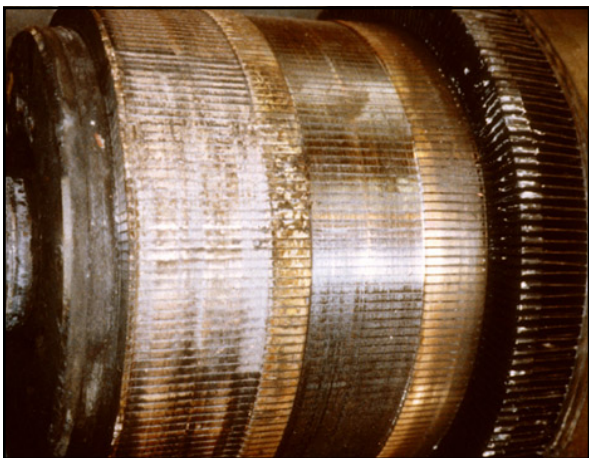


## COMMUTATORS

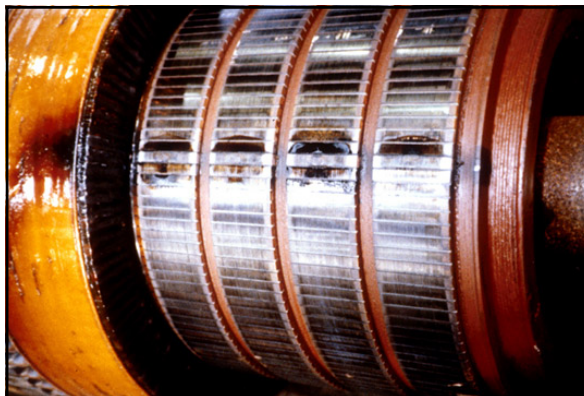


This grooving pattern is unusual, in that there is heavy wear on one side of the commutator. Note the radius at the sides of the deep groove (circled). Possible causes of asymmetrical wear (one side only) are:

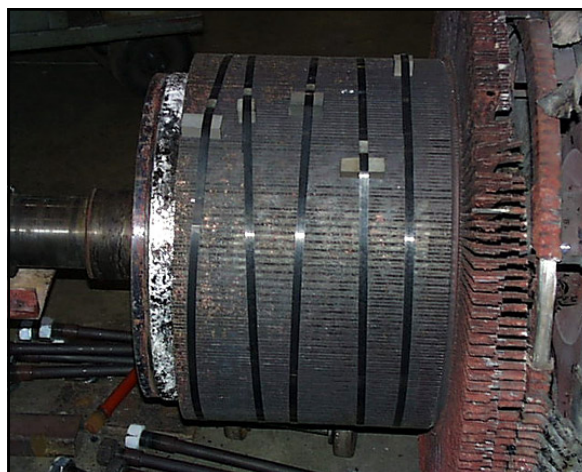
- High vibration in synch with the armature rotational speed.
- Stall condition, if the DC machine has only two brush posts 90° apart. In this case, the wear would start as two flat spots 90° apart, and gradually connect.



Lubricant from the bearing coated the outboard portion of this commutator, interfering with the film.



Classic evidence of a stall.



This commutator was cycled through the burnout oven with the armature. This should only be done when the commutator will be refilled.

## BRUSHES AND BRUSHHOLDERS

Carbon brushes may also provide helpful clues in determining root cause failure in DC motors. Carbon brush current carrying capacity is rated in amps-per-square inch. The rate of wear is affected by current density, environmental factors and spring tension. A set of brushes installed in the same machine, at the same time, with the same operating hours under the same conditions, yet displaying different wear may be a clue. Significant difference in wear rate can be caused by large differences in current density or brush pressure, or an electrical unbalance. Unless an interpole has shorted turns, electrical unbalance is often related to parallel circuits that are not carrying equal amounts of current.

Brushholders should always have equalizer jumpers connecting brush rows of the same polarity. If they do not, those parallel circuits (the brush rows themselves) will not carry equal current. Carbon brushes, otherwise identical, do not wear at the same rate when they are not carrying the same current. The lower the current density (amps per square inch), the faster the rate of brush wear.

When a DC machine is inspected, differences in brush length should be noted with respect to the brushholder positions. The positive and negative brush posts should also be identified whenever possible.

### CARBON BRUSHES: CAUSES OF UNUSUAL WEAR RATES

Unusual or non-symmetrical brush wear can be an indication of motor performance problems. The specifics of unusual brush wear offers clues as to the cause. Rapid wear indicates too light a load condition—not necessarily a lightly loaded motor in terms of horsepower, but a lightly loaded brush in terms of amps/square inch.

Manufacturers ship DC machines with brushes suitable for a wide variety of applications at or near rated load. Variables that may require a change in brush grade include lighter load, humidity, altitude, chemical environment and vibration. Variations in one or more of these variables may necessitate a change in brush grade to maximize brush performance. Failure to adjust the brush grade to actual conditions can result in rapid brush wear, with carbon contamination likely to result in low insulation to ground which increases the probability of insulation failure.

Brush grade can be varied to match the load, so that current density yields long brush life. Abrasive grades can be used to continuously clean a commutator when copper-damaging chemicals are present, and special brush tops can be used when vibration causes problems. But in each instance, these changes can only be made if someone identifies a performance problem. The appearance of the commutator film is one of the best ways to assess brush performance.

### BRUSH PRESSURE AND SPRING TENSION

Brush pressure – the actual pressure between the brush and the commutator – plays an important role in motor performance. Brush pressure depends on several other things: spring tension, brush cross-sectional area, and

**TABLE 1: BRUSH SPRING PRESSURE**

| Brush type    | Brush pressure |
|---------------|----------------|
| Industrial DC | 4 to 6 psi     |
| Traction DC   | 5 to 8 psi     |
| Soft graphite | 2.5 to 3.5 psi |
| Slip rings    | 3.5 to 4.5 psi |

brush weight. Spring tension is easily measured using a spring scale (a fish scale from the local sporting goods store works fine for this). Spring tension must be divided by the brush cross-sectional area to determine the brush pressure.

$$\frac{\text{Spring tension}}{\text{Brush cross - sectional area}} = \text{Brush pressure}$$

If spring tension is measured at 10 pounds, and the brush is 1" x 2", then brush pressure is 5 psi. (1 x 2 = 2 square inches; 10/2 = 5). For the same spring tension with a smaller brush of 0.5" x 1.25" brush pressure would be 16 psi.

Now consider a larger brush, with the same spring. If the brush is 1" x 2.5", the cross-sectional area of the brush is 2.5 square inches, so brush pressure drops to 4 psi. If the brush weighs 1 pound, the top brushes weight adds to the spring tension, while the bottom brushes (being upside down) subtract from it. So the brush pressure at 12:00 is 5 psi while at 6:00 it is only 3 psi. The weight of the brush (in our example) is enough to reduce the brush pressure for the bottom row of brushes below the recommended range. Reduced brush pressure leads to threading, increased arcing (especially when vibration is present), and other problems.

Spring tension should be measured at each spring. "Identical" springs may not have the same stiffness, especially if damaged. The constant-tension spring, where the flat leaf is curled neatly, may appear to be partly uncurled. That is evidence that current has passed through the spring. Perhaps the bolt connecting the shunt to the brushbox loosened, the spring rode against the side of the brush box, or the brush shunt tamping came loose. Current weakens a spring, and the constant-tension spring is easily identified when this occurs. Weak springs should be replaced, and constant-tension springs that are partly uncurled should never be used.

Constant tension springs may also crack near the rivet, especially if they have been sandblasted. Abrasive blasting creates stress risers on the surface of the spring, which result in premature failure.

Brushholder condition is routinely checked by visual inspection, but the brush fit in each box is often overlooked. A carbon brush should be between 0.002" to 0.004" (0.05 mm to 0.1 mm) loose in the holder. Too tight a fit, and the brush may stick. That leads to arcing as the spring is unable to firmly press the brush against the commutator. Too loose a fit, and the brush may shift in the brushholder. Chipping is likely, and the poorly supported brush may break. If the motor is reversed, the brush position can change so much



that only one edge of the brush contacts the commutator.

Brushes are replaced by most service centers, but an easy mistake is to only check the brush grade of one brush. Most customers routinely change brushes in the field. Depending on the brushes available from their stockroom, and the access to the different brush rows, not every the brushes are replaced with the correct brush.

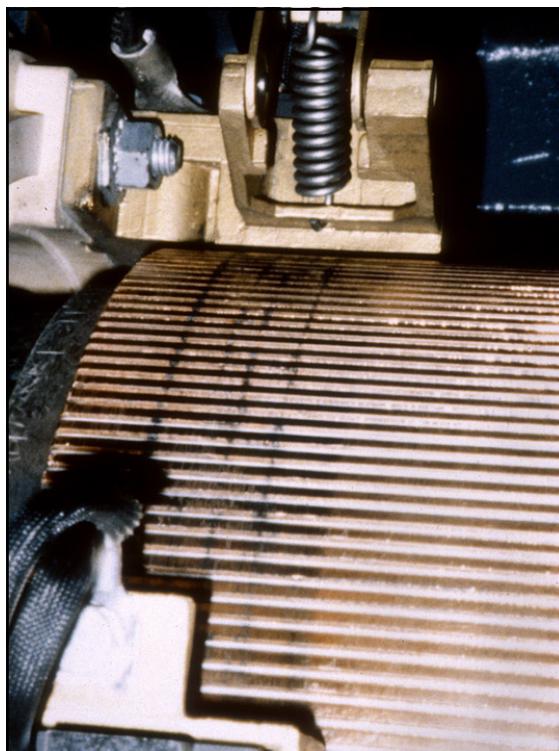
To illustrate the need for verifying the correct grade of all brush in each machine, consider this example: A plant technician takes a set of brushes from the warehouse, walks one half mile to a production line, climbs a ladder, removes the covers and old brushes only to realize that the bag of replacement brushes are not the same grade. If they are the same physical size, the odds are good that the technician will install them. Now the motor has the wrong brush grade, and performance may suffer. If the service center simply replaces the brushes without considering the appearance of the commutator film, the performance problem will continue.

Now imagine that same plant technician, perched on the ladder at the DC motor. The motor has four rows of brushes, of which only three rows are readily accessible. The bottom row cannot be reached, because the bottom cover is only an inch off the foundation. There is a very good chance that the brushes in the three accessible rows will be replaced. If the brushes were not the same grade, now the motor has two different brush grades.

The service center technician needs to verify that all the brushes in a DC machine are the same grade. If not, a phone call to the end user is essential. When the motor is dismantled and inspected, the brushes may appear to have worn at radically different rates. In this case, the differential wear rate is not the result of electrical performance issues, but faulty maintenance (i.e., changing a partial set of brushes.)

Most large end-users have enlisted the services of brush suppliers to perform a brush survey of their plant, to determine the optimum brush grade to use for each motor. Factors such as percent and variation in load, humidity, altitude and temperature, as well as chemical contamination (especially chlorine, hydrochloric acid, silicone or acetates) that might be present in the air may affect the

**FIGURE 8: COILED SPRING**



The coiled spring is less common for brushholders. The spring cannot be adjusted for the desired brush pressure.

choice of brush for identical motors operating under different conditions.

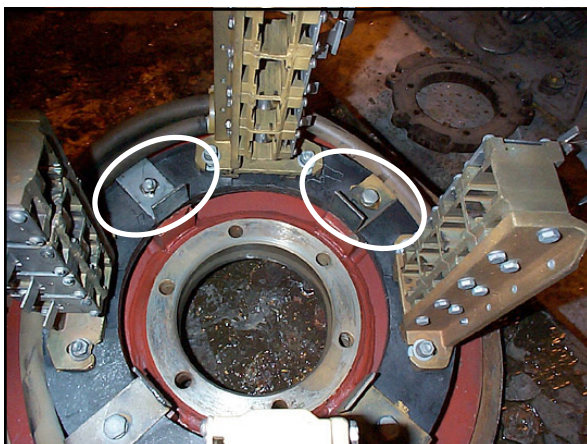
Table 2 is intended to simplify the process of identifying the causes of unusual brush wear.

To understand why these unusual rates of wear occur, it helps to review the electrical circuits involved. Draw the appropriate equivalent circuit diagram for insight into possible causes of failures.

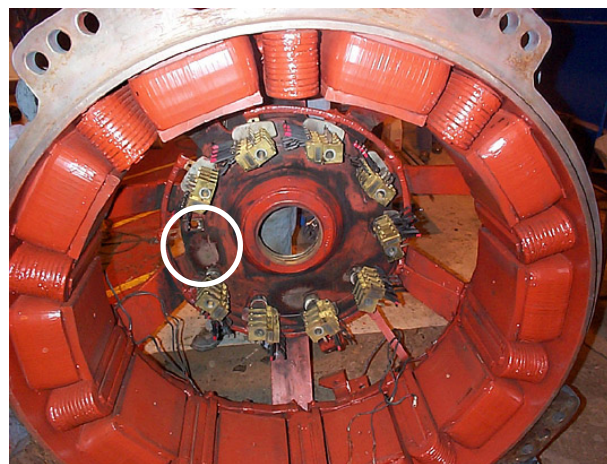
**TABLE 2: IDENTIFYING UNUSUAL BRUSH WEAR**

| Symptom                                                 | Likely cause                                                                                                             |
|---------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------|
| Rapid wear of all brushes.                              | Low brush current density.                                                                                               |
| Positive brush wearing faster.                          | Weak interpoles.                                                                                                         |
| Negative brush wearing faster.                          | Weak spring tension.                                                                                                     |
| Brushes closest to riser wearing faster.                | Excessive vibration.                                                                                                     |
| Brushes furthest from riser wearing faster.             | Lubrication contamination on the commutator.                                                                             |
| Random variation in rate of brush wear.                 | Unequal spring tension; variation in resistance between brush boxes and brush posts (corrosion, insulating paint).       |
| One positive and one negative brush row wearing faster. | Missing equalizer jumpers at the brush holders. The brush holders of like polarity should always have equalizer jumpers. |

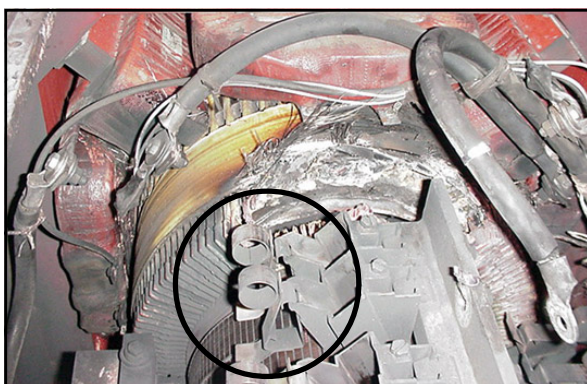
## BRUSHES AND BRUSHHOLDERS



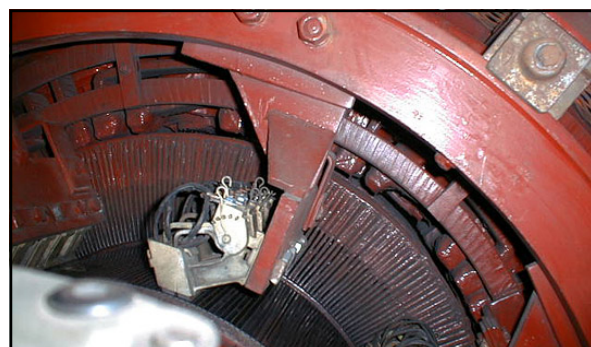
Flashover protection may be tabs (shown) or a ring. This sacrificial part protects the commutator and brushholders. Note the equalizer jumpers that ensure brush current is shared equally.



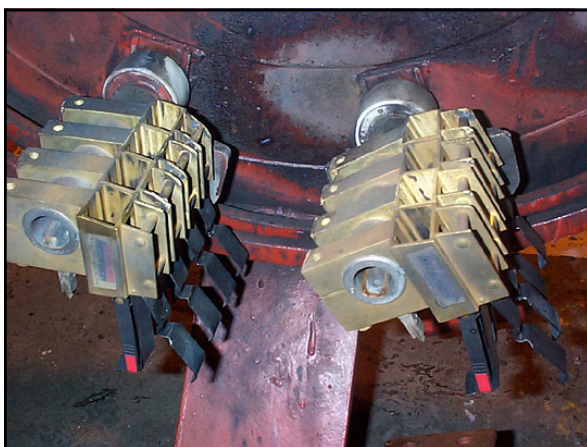
There are normally as many brush posts as field poles. Spacing of each is equally important. (Note: One brush post has been removed for inspection.)



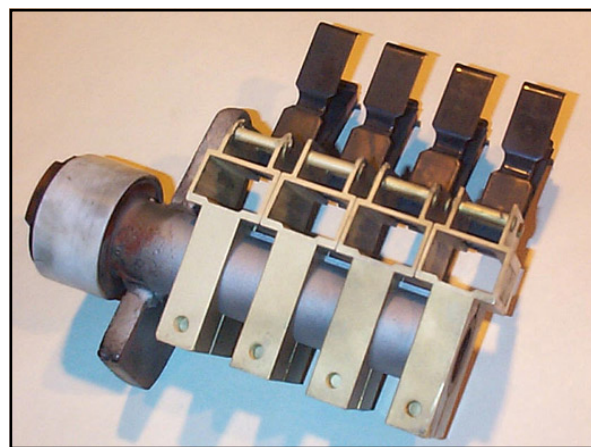
Constant-tension springs will uncurl if current weakens them.



Regardless of machine size, brush spacing around the commutator must be consistent. The rule of thumb on larger machines is spacing should be equal within 3/64".



The stud insulators should be clean, slick and free of cracks that might trap carbon. These boxes pivot on a round post, so uneven spacing above the commutator will also result in uneven spacing around the commutator circumference. Note the constant-pressure springs.





## FIELD COILS (SHUNT FIELDS)

Field coil failures are often thermally degraded in appearance, and can result from several external causes. Not all of these causes are readily apparent, so they are discussed in detail under the ventilation heading.

### THERMAL STRESS

Possible causes of thermal overload include:

- Overvoltage.
- Ventilation/blower problems.
- Restricted heat transfer.

Excessive voltage applied to the DC field coils can result from several causes, the most likely being:

- Dual-voltage fields connected for low voltage, operated on high voltage.
- Drive parameters set incorrectly and wrong voltage or current supplied.
- Field leads markings misunderstood, not all the fields were energized.
- Field economizer circuit not working. The field economizer applies reduced voltage to the fields when the motor is not running.

Ventilation/ blower issues are described in detail under ventilation; highlights include:

- Blower interlocked with armature circuit, fields left energized.
- Wrong blower direction of rotation, reduced airflow.
- Missing covers compromise airflow.
- Blocked openings, restricted airflow.

Heat transfer can also be inhibited by poor construction or design problems:

- Circular mils per amp too low.
- Poor heat transfer to the pole.
- Excessive insulation on coil exterior.

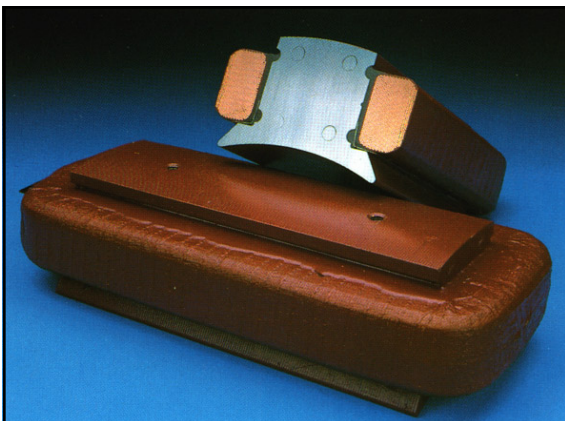
Heat generated in the windings must be dissipated by

airflow across the windings, and/or transferred to the frame where it can be dissipated to the surrounding air. Good practice dictates that field coils be designed with at least 500 circular mils per amp, although some manufacturers design with fewer cm/amp. Above 500 cm/amp, a field coil is able to dissipate heat effectively by convection to the surrounding air. Below about 500 cm/amp, the field surface is often not adequate to dissipate the heat generated.

When a field coil has less than 500 cm/amp, the contact between the wound coil and pole iron becomes critical. The field coil must be potted to the pole iron, with thermally conductive potting material (Figure 9), or the coil temperature will continue to increase. One manufacturer uses an aluminum-filled epoxy; others use conventional thermally-conductive potting compounds. At least one manufacturer winds field coils on a steel bobbin which is slipped onto the field pole. They are able to use this method because the circular mils per amp are sufficient to control field temperature.

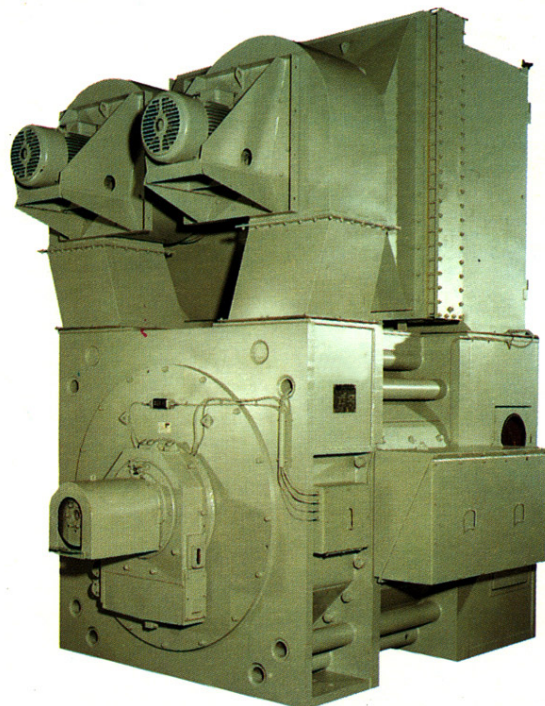
Field coil failures are often caused by an inability of the motor to dissipate the heat generated in the field coils. Because the fields must be energized before the armature circuit is energized, it is not uncommon for fields to fail simply because the operator left the fields energized for several hours without airflow. Air is supplied by one or more fan(s) mounted on the armature shaft, or by an auxiliary blower (Figure 10). Auxiliary blowers are normally interlocked with the armature circuit controller so that the armature cannot be operated independent of the air supply required

**FIGURE 9: POTTING FIELD COIL TO THE FIELD IRON**



Potting the field coil to the laminated pole iron improves heat transfer.

**FIGURE 10: AUXILIARY BLOWERS**



This large DC motor is fitted with dual auxiliary blowers.

to cool it. One expert referred to this as “weekend syndrome”—a reference to the fact that an operator might shut down the machine at the end of shift Friday, but leave the fields energized without ventilating air until returning to work Monday.

Prudent designers include an economizer relay to reduce the field voltage when the armature circuit is idled for more than an hour or so. The setting for this economizer should be related to the nature of the operation involved. In other words, 15 minutes idle is adequate for some operations, whereas an hour might be more appropriate for other applications.

### MECHANICAL STRESS

Mechanical stress, as it applies to field coils, can be broken down as:

- Loose bolts/bolts overtightened.
- Wrong bolt grade used.
- Coil movement due to looseness or vibration.

Laminated poles are bolted into the frame, requiring that holes be tapped into the edges of the laminations of each pole. This construction requires that lower bolt torque values be used to prevent stripping of the bolt holes. Field coil fasteners should be grade 5 or better to prevent stretching of bolts.

Coil movement could arguably be classified as mechanical or dynamic stress. Vibration from internal or external causes, shock impact (e.g., dragline operation) or poor fitting of the coil to the pole can result in coil movement. Chafing, cracked insulation, or loss of fit to the pole iron can result, as well as shock load that could lead to bolt breakage; all are possible modes of failure that may result from coil movement/ vibration.

Environmental damage to fields can result from foreign material, whether liquid, chemical or dry abrasive material. Aside from product contamination inherent to the application, a common contaminant in DC motors is carbon from routine brush wear.

To exclude carbon, field coils are often taped. Unfortunately, the tape can mask evidence of thermal damage and can act as a blanket, trapping heat in the coil. To visually inspect coils for evidence of thermal degradation, slit the insulation and inspect the coil for dark/brittle insulation. Any of the above ventilation issues can affect field temperature,

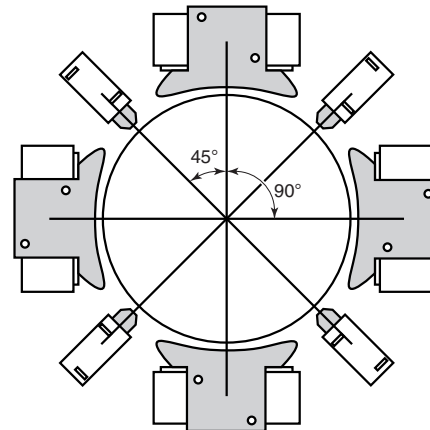
but thermal degradation of the field coil insulation often is caused by an inability to dissipate heat.

### IMPORTANCE OF SYMMETRY

An important aspect of DC machine construction is symmetry. (See Figure 11.) The spacing of the poles is as important as brushholder spacing; that, and the strength of the flux in each pole, affect the performance of a DC machine. Spacing and flux are equally important, because of the relationship between lines of flux in the fields and armature circuit.

Evidence of selective arcing at some brushholders causes most skilled technicians to check brushholder spacing around the circumference of the commutator. Arcing at one row of brushes is related to the relative position or strength of the brush, *or of the field or interpole associated with that brush*. Another cause of irregular arcing is poor workmanship when the poles were installed in the frame. This can be the result of a frame that shifted during the crucial step of drilling the pole-mounting holes in the frame, oversized clearance holes or it may be evidence that a previous repairer had to re-drill the holes in the pole itself. Careful edge-to-edge measurement between poles should confirm this.

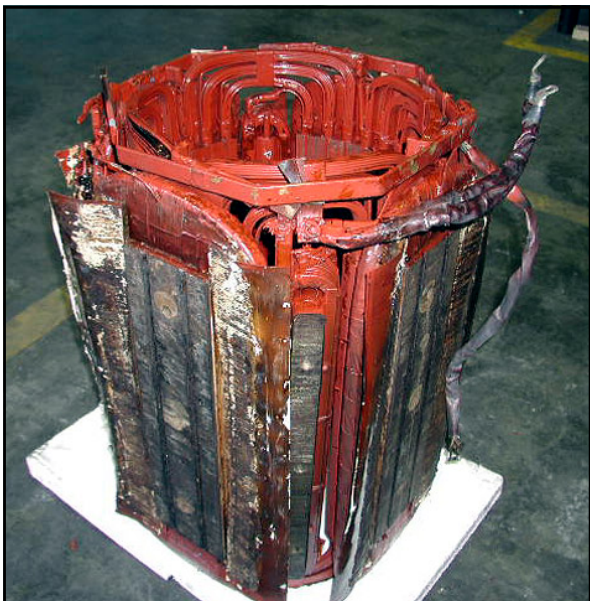
**FIGURE 11: SYMMETRY OF THE DC MOTOR**



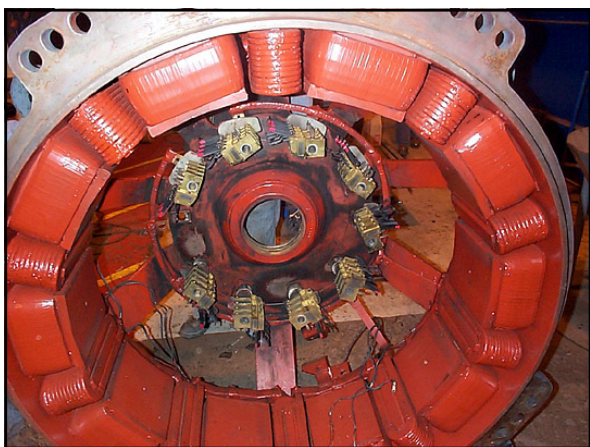
Field poles are precisely spaced ( $360^\circ/\text{poles} = \text{angle between poles}$ ). Interpole spacing is equally precise, as is brushholder spacing.



## FIELD COILS



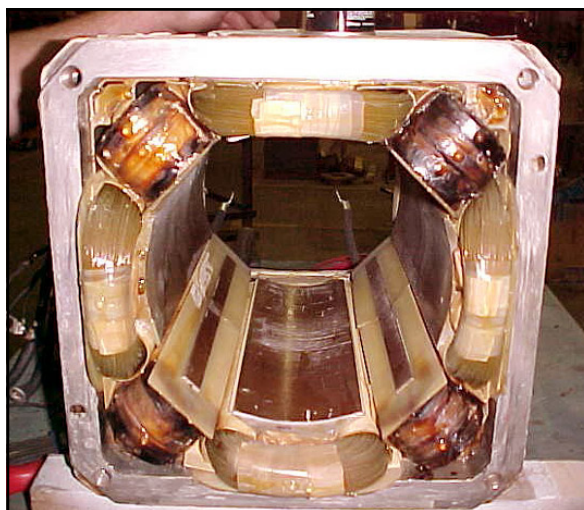
Removing these compensating windings would require several days of labor. To avoid that, the service center dropped the windings en masse. Now the shorted field coils can be removed from behind, saving time.



These field coils are taped to seal out contamination. The tape also traps heat, making visual inspection difficult. When one or more field of a set is shorted, the other fields should be visually inspected for evidence of thermal stress. Slit the tape and look for discolored wire.



Coil insulation sometimes masks thermal damage. Inspection may require careful removal of coil insulation. The tape can trap heat.



This laminated frame design is manufactured with the field pole iron integral to the frame itself. Fields are wound on a bobbin and inserted in the frame. Insulation can become brittle and crack, and the coils are exposed to contamination. Advantages include better cooling because the conductors are directly exposed to the airflow.

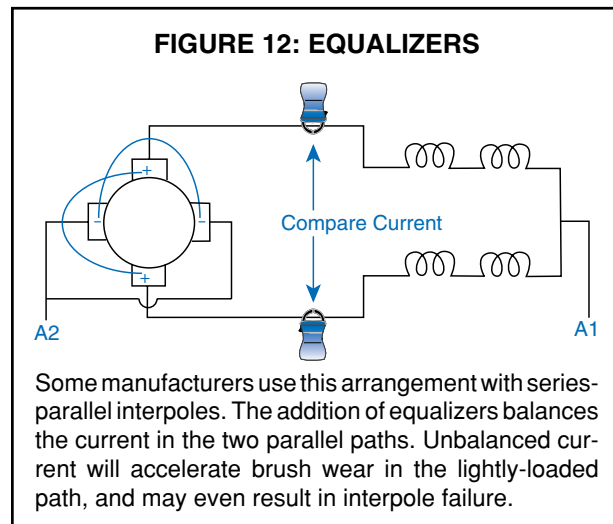
## INTERPOLES AND SERIES FIELDS

Interpoles are added to counteract the armature flux tendency to distort the field flux. The interpole flux polarity must be correct, in order to counteract the armature cross-flux. If the interpole polarity (relative to the armature) is incorrect, the field flux, rather than being maintained, will be even more distorted. Arcing will occur, in proportion to the applied load. Some designs may operate fine under no-load conditions, although most machines with the interpoles reversed will arc even at no load.

Interpoles and series fields generally require a minimum of 500 cm/amp (700-800 cm/amp is more typical) to effectively dissipate heat. This knowledge is useful when trying to determine whether or not a previous repairer used the wrong number of circuits. While a straight series connection is preferable, some manufacturers do use series-parallel or even 4-parallel connections. This has other implications, beyond determining the appropriate number of circuits.

When coils are connected in series and energized, they will always have the same current passing through each coil. Each coil has the same number of turns, and since coil strength is determined by ampere-turns, that is important. When coils are connected in any number of parallel circuits, the current is not always equally shared among those circuits. (See Table 3.)

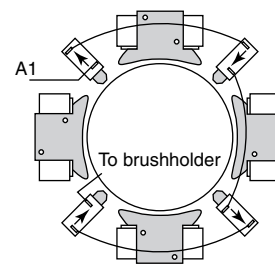
Coils that carry more current have a stronger magnetic flux than those carrying less current. With interpole resistance extremely low (often less than 0.01 Ohms), a small difference in lead length connecting the interpoles can change the current balance between parallel circuits.



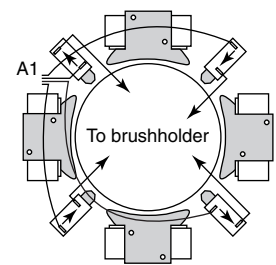
The strength of the armature circuit—armature, interpoles, brushes and series fields—varies in proportion to the load. As the load increases, armature circuit current increases. That, in turn, increases the flux of the related circuits. When parallel circuits are used, it is important to evaluate the actual balance among the circuits. During operation under

**TABLE 3: POSSIBLE CIRCUITS  
FOR A 4 POLE DC MOTOR**

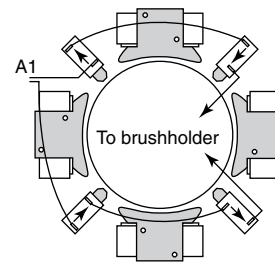
| Number of circuits | Description                          | Current (I) per coil, theoretical | Current (I), actual |
|--------------------|--------------------------------------|-----------------------------------|---------------------|
| Series             | All four coils in series             | I                                 | I                   |
| Series-parallel    | 2 parallel sets of 2 coils in series | I/2                               | $I(r_1)+I(r_2)$     |
| Parallel           | 4 coils in parallel                  | I/4                               | $I(r_1)+...+I(r_4)$ |



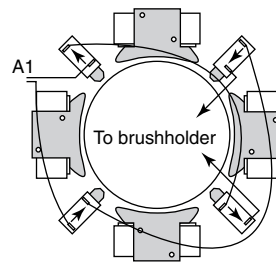
**Interpoles connected series**  
The same current passes through each interpole. Since interpole strength depends on ampere-turns, each interpole is of the same strength.



**Interpoles connected 4-parallel**  
With multiple circuits, the current may vary from 1 circuit to the next. Ampere turns therefore may also vary.



**Interpoles connected series-parallel**  
Variation 1

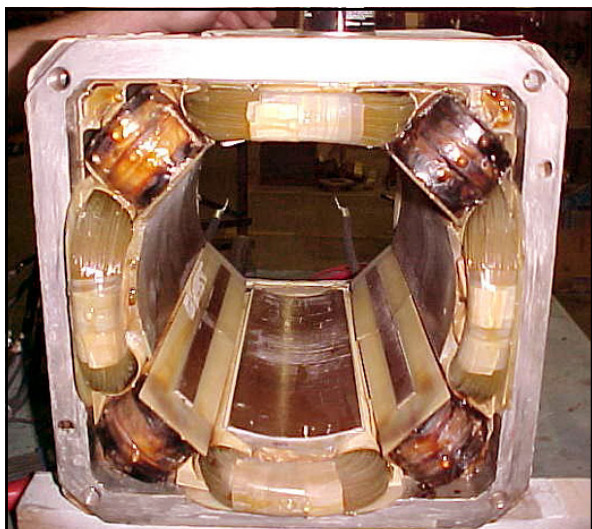


**Interpoles connected series-parallel**  
Variation 2

loaded conditions, the current in each path can be measured and compared. If the machine has been removed from service, the paths may still offer evidence of unbalanced current. First, heat discoloration can be compared to the circuit layout. If the coils evidencing thermal overload are in the same circuit, that is a strong indication of current unbalance.



## INTERPOLES AND SERIES FIELDS



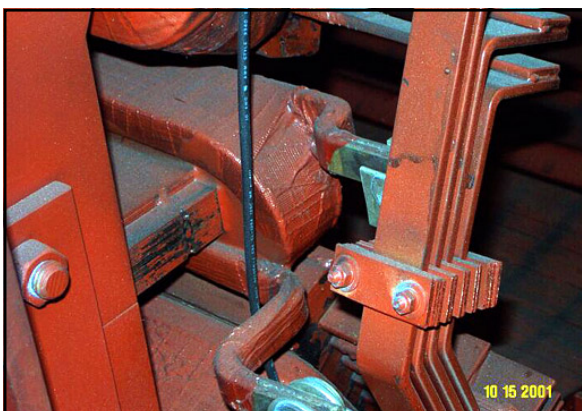
When interpoles show a marked difference in thermal stress, parallel circuits might not be balanced. The cause may be missing equalizer jumpers.



This series field is potted to the pole iron to reduce mechanical/shock stress during operation. The series coil (right) has been reinsulated and is ready to be taped and installed on the pole iron.



These interpoles are augmented by the addition of compensating windings.



This interpole is potted to the pole iron and is positioned away from the frame to increase airflow.



## INTERPOLES AND SERIES FIELDS



These interpoles exhibit obvious thermal stress. The epoxy insulation has charred due to heat, probably caused by excessive current through the interpoles. This could result from overload, incorrect connection (wrong number of parallel circuits), restricted ventilation, or related problems.



Note the offset in the lead. Interpole placement has to allow room for connecting leads/bus bars. This style is often connected using bus bar; separation and bracing are critical.





## COMPENSATING WINDINGS

With many large machine designs, and even in some small machines, the conventional interpole arrangement is no longer adequate to prevent distortion of the field flux. Manufacturers add a compensating winding, usually in the face of the field poles, to improve commutation. The compensating windings, although inserted in the field poles, are simply an extension of the interpoles. By tracing out the interpole and compensating winding which surrounds it, this becomes obvious.

While most compensating windings are symmetrical, there are designs which are not. Non-symmetrical compensating windings are sometimes unidirectional.

Often for the repairer, the difficulty with the pole face bars of compensating windings is low resistance-to-ground values. This can best be understood by considering the path from each bar to ground as a group of parallel circuits. When resistances are paralleled, the total resistance can be calculated as:

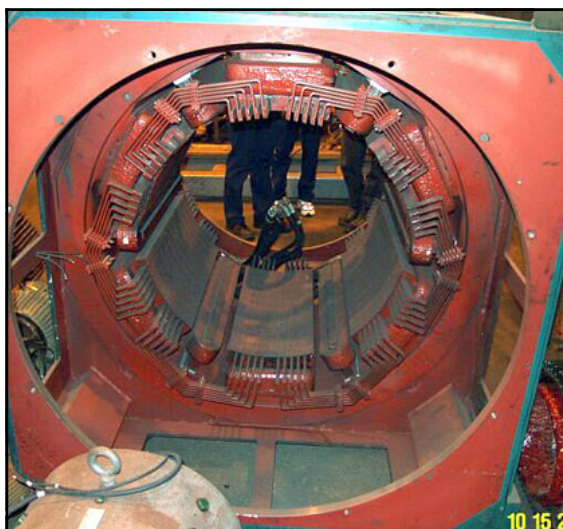
$$R = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} \dots + \frac{1}{R_n}}$$

Where:

R = Total resistance

The more resistors in the circuit, the lower the total resistance. Each bar passed through a pole is a single resistor, so the number of bars per pole times the number of poles equals the number of resistors in parallel. For this reason, large machines with compensating windings often have low resistance to ground.

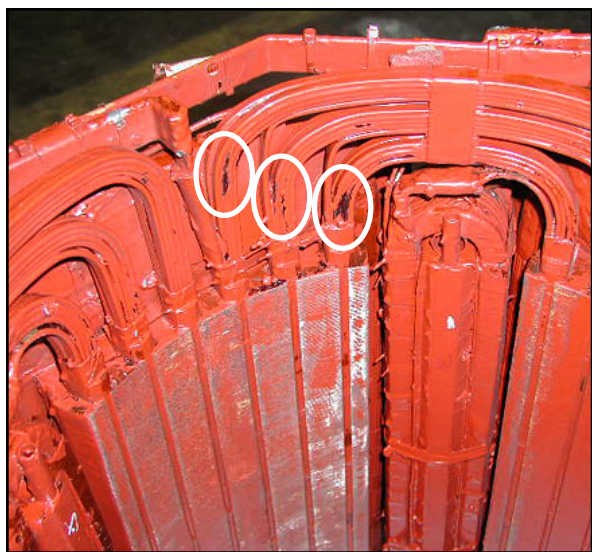
**FIGURE 13: COMPENSATING WINDINGS**



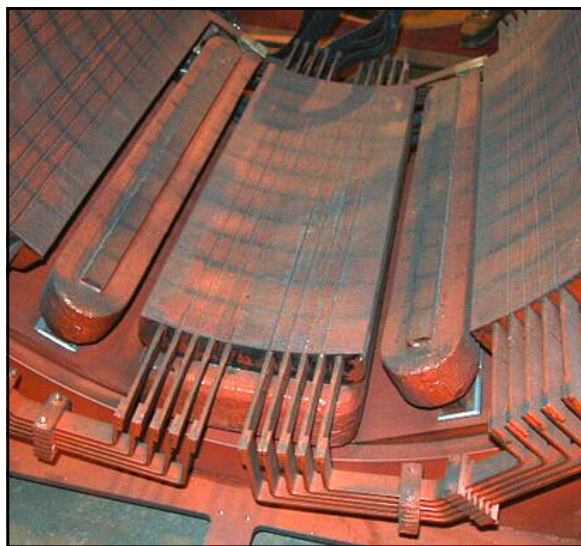
The compensating winding (pole face bars) are grouped as extensions of the interpoles.

In Figure 13, a compensating winding with 6 poles and 10 bars per pole is, in effect, 60 parallel resistors. Assuming that each bar had 500 megohms resistance to ground, the connected resistance to ground would drop to only 8.3 megohms. While a resistance to ground of 500 megohms is excellent, the 8.3 megohm value is low by many end users' standards. That results in problems when cleaning or repairing DC machines. Carbon penetration of the groundwall insulation makes matters worse by lowering the resistance-to-ground of affected bars.

## COMPENSATING WINDINGS



This type of compensating winding has multiple turns, so turn-to-turn shorts are possible.



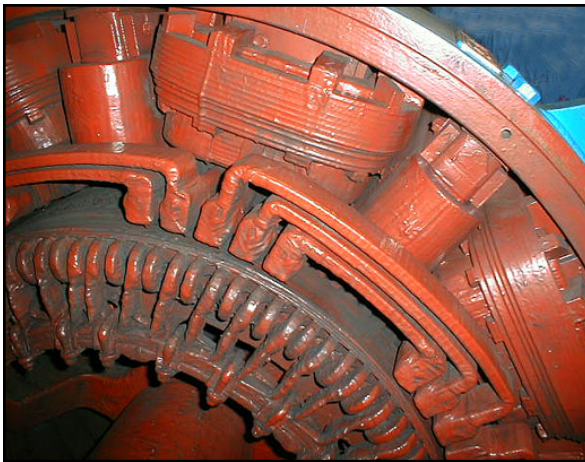
Bracing separates the individual turns of the compensating winding. Contact between turns can result in dramatic failures due to the high current involved.



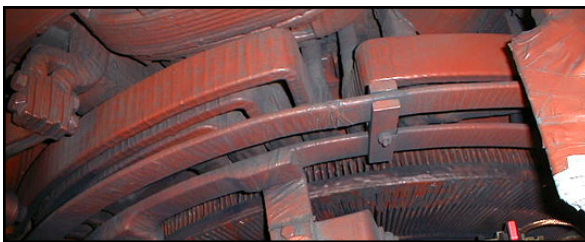
## COMPENSATING WINDINGS



These compensating windings show signs of thermal stress and deterioration of the insulation.



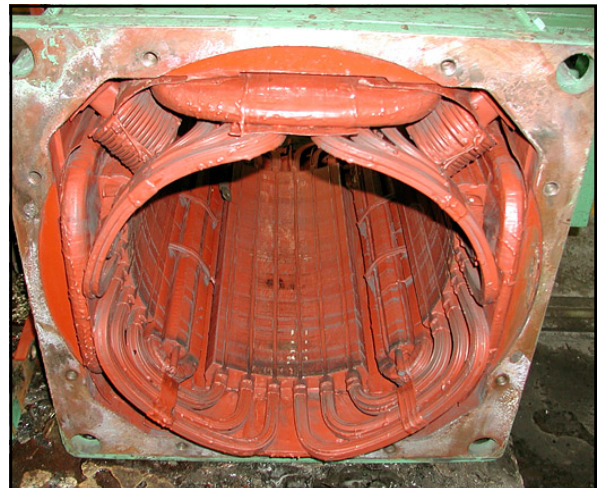
These compensating windings, and the welded connections, have been fully taped in an effort to exclude carbon. The ground circuit is basically a group of paralleled resistances to ground. Collective resistance to ground will be much lower than that of the individual bars.



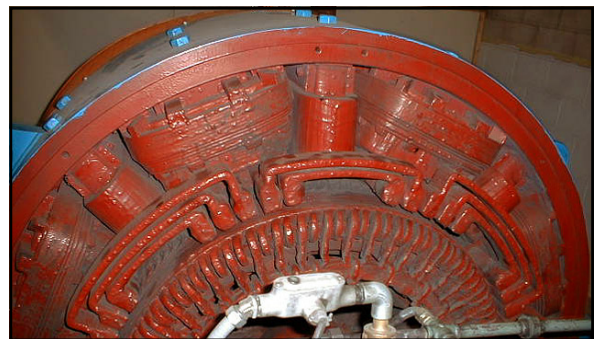
These compensating winding jumpers are fully taped, but are not physically braced to prevent contact. While this design looks very rigid, blocking between the compensating winding ends is recommended. Because of the high current carried by the compensating winding (equal to the armature current), a short between them results in dramatic faults with extensive damage.



The connections may be bolted or welded (as shown).



These compensating windings have multiple turns. The chance of shorted turns is higher with multiple turns, and extensive labor is involved in their replacement.



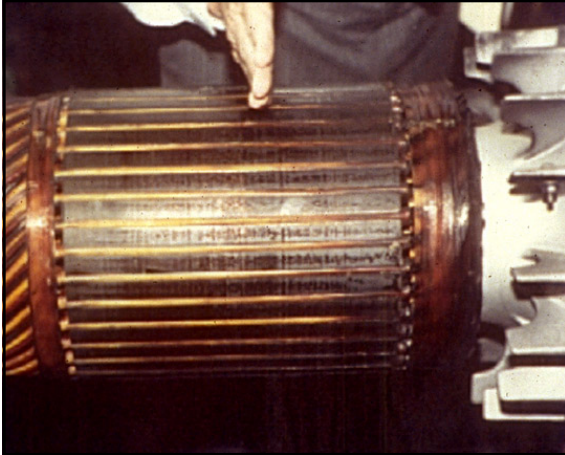
This machine could be unidirectional. Note the unequal number of pole-face bars per pole. When the compensating winding is symmetrical (an equal number of bars on each half of each pole) the machine is bidirectional. When non-symmetrical, there are cases where rotation in only one direction is possible.



## DC MOTOR VENTILATION

Figure 14 shows obvious indications of excessive heat, but a close inspection yields evidence that, if properly interpreted, can aid in pinpointing the root cause.

**FIGURE 14: EVIDENCE OF HEAT**



The thermal pattern displays clear evidence that the fan end has been much hotter than the commutator end.

The first clue is the variation in thermal aging along the length of the armature. Only the opposite commutator end is darkened. The implication is that there was adequate airflow on the commutator end, but not the fan end.

The key is to identify possible reasons for this and, by process of elimination, to determine the actual cause for this failure.

Most DC motors are fitted with a forced air blower or a fan (internal or external). Covers mounted on both ends of the motor direct airflow through the motor to dissipate heat from the armature, fields and interpoles. Ventilation will be di-

**FIGURE 15: AUXILIARY SQUIRREL CAGE BLOWER**

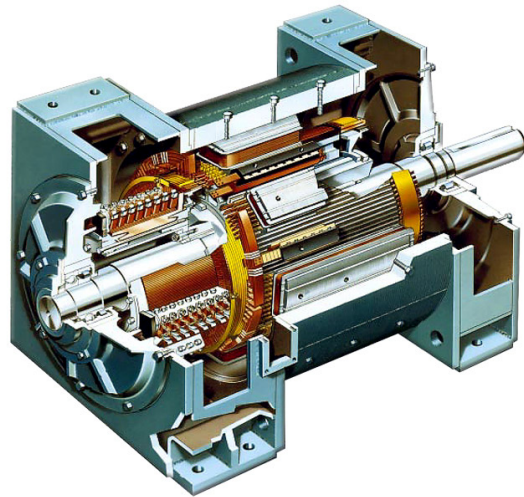


rectly affected if any of these peripheral parts is missing, damaged or malfunctioning.

The auxiliary blower has several potential problems. It is usually a squirrel cage blower mounted on a small 3-phase motor. (See Figure 15.) A 3-phase motor can be reversed by interchanging any 2 leads. Operating backwards, a reversed squirrel cage blower still moves air in the correct direction. The shape of the blower housing establishes the direction of airflow. While the direction of airflow will be unchanged, a squirrel cage blower will move approximately one-third the volume of air, at a reduced static pressure. When a DC machine has been recently installed, and the armature appears to be overheated, a reversed blower is often the cause.

When a motor is installed, the last step is usually to install the blower. In a typical scenario, production personnel are anxious to start operations and a cursory glance at the blower confirms that air is moving in the correct direction. The operator assumes that the direction of rotation is correct, *based on the direction of airflow*. Since most industrial blowers utilize three phase motors, there is only a 50% chance that the direction of rotation is correct.

**FIGURE 16: MOUNTING OF AUXILIARY BLOWERS**



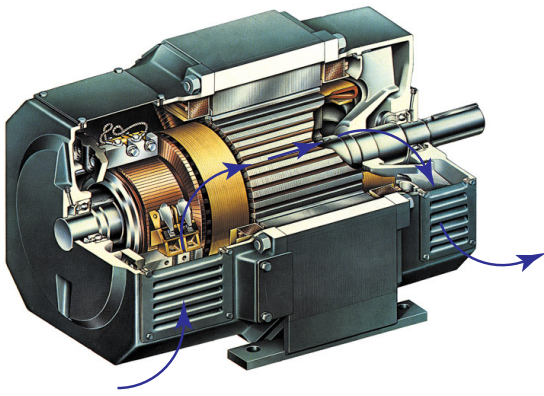
This motor design allows an auxiliary blower to be mounted on the commutator end or the drive end.

The blower is usually mounted on the commutator end, but in some cases may be installed on the drive end of the motor. (See Figure 16.) The application may dictate which end the blower can be mounted on. A source of heat in close proximity to either end of the motor may make it impractical to draw air into the motor from that area. An advantage of forcing air through from the opposite commutator end is that carbon dust will not be forced through the windings. Since the temperature of the commutator is usually higher than the rest of the motor, most designs blow cooling air directly onto the commutator.

The next item to inspect is the covers themselves. Lou-

pered/ventilated covers may be blocked by product, or louvers may be displaced—which restricts airflow. On the commutator end, a missing cover will permit air from the blower to flow straight through that end of the machine. The commutator end will have adequate airflow, the opposite end will have virtually none. This is especially likely if the

**FIGURE 17: DC MOTOR AIRFLOW**



Typical path of airflow through a DC motor.

motor has been in service for some time, but the brushes have recently been replaced. The bottom cover is often the least accessible, so it is the most likely to be left off or loosely installed.

If the armature was recently rewound, or if the shaft required machine work, inspect the shaft for evidence of a missing internal fan. If the shaft appears to be keyed for no apparent reason, or if there are marks indicating a fan was once mounted, the fan may have been removed and misplaced.

Sometimes, an end user adds a forced-air blower to a motor already equipped with an internal fan. If the blower opposes the airflow of the fan, the result will be a marked decrease in airflow.

Covers, and their placement, are also important when a DC machine has any sort of cooling airflow. In most cases, DC machines have an auxiliary blower to force a steady supply of air through the motor. Since DC machines are often operated at varying speeds, a shaft-mounted fan would not move a constant volume of air through the windings.

Other causes of overheating are: missing covers, shipping covers that should have been removed, damaged fans, an internal fan that tries to move air opposite the blower, a fan that is loose on the shaft, extraneous items such as missing insulation on a steam line, blocked ventilation, buildup of material on the motor, or drive faults that permit AC through to the armature circuit.

When an armature appears to have been overheated on the commutator end only, look for missing covers on that end. If the blower is mounted on top of the motor above the commutator, and the bottom cover on that end is missing, airflow will pass directly across the commutator, but very

little will flow through the motor. The result? The commutator end will appear normal while the opposite end will show marked thermal degradation.

If the motor is new, and newly installed, remember that many motors are sold to an OEM, installed on their equipment, and shipped to the end user. If the manufacturer sold the motor without a blower, a shipping cover was installed to protect the interior of the motor. That shipping cover may have a label warning that the shipping cover must be removed, or it may only be mentioned in the owners manual. If the OEM fails to pass along the manual, or paints the motor to match their equipment (and paints over the warning label), or if the end user assumes that the OEM would have installed a blower if the motor needed one, the motor will fail prematurely without the blower.

Louvered covers (Figures 17 and 18) are made in a variety of styles, including some that are stamped. If the motor is bumped, or the cover is removed and accidentally flattened by a passing forklift, the louvered cover is no longer louvered. It will restrict airflow, and the motor will overheat. A heavy coat of paint may even bubble over some of the louvered openings, especially those protected by rodent screens. If a motor is installed in a nonstandard mounting, the louvers may act as funnels to channel debris or moisture into the motor.

Some DC machines are fitted with internal fans that are not keyed to the shaft. The fan may loosen on the shaft, spinning freely while hot. By the time the motor reaches the service center, the fan and shaft are at the same temperature and the fan appears to be tight. No changes are made, so the fan slips when the motor is reinstalled. If no key is visible, it is worth the effort to remove the fan and inspect the bore for evidence of movement. If the fan is not keyed to the shaft, it should be either keyed, or drilled and tapped to accept a setscrew.

If the DC machine was recently repaired, or recently removed from stores, the internal fan could be missing. Machinists sometimes remove the fan for better access when shaft journal repairs are needed; winders remove the fan before rewinding the armature; and the fan is often removed prior to varnish treatment of the armature. There are lots of opportunities for the internal fan to be misplaced.

**FIGURE 18: LOUVERED COVERS**



Note the orientation of the louvers. Their orientation varies depending on the mounting position of the motor and specific environmental threats.



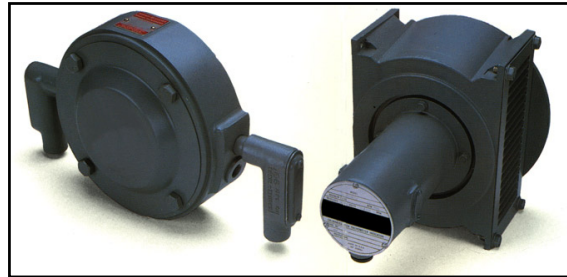
## SHAFT CURRENTS AND TACHOMETERS

Tachometers are often installed on the opposite drive end of the motor. Most end users remove the tachometer before sending a motor out for repairs. The tachometer shaft runout is important, but can be easily overlooked.

A more critical problem is when the ODE bearing is insulated to prevent shaft currents from damaging the motor bearings. The tachometer coupling must also be electrically isolated, or shaft currents will pass through the circuit created through the tachometer bearings.

Shaft currents that damage a 6212 ODE bearing in a few months may destroy 6203 tachometer bearings in a matter of hours.

**FIGURE 19: DC MOTOR TACHOMETERS**



The tachometer at left uses a pulse wheel, while the one on the right requires carbon brushes and more maintenance.

8

Accessory Failures

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| Thermal protection .....                       | 8-2  |
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## INTRODUCTION

This section addresses issues related to motor accessories. For the purpose of this discussion, accessories are the “extra” components added to the motor to enhance its performance or reliability. Even though they are extra components, they may be vitally important to protect the motor from a catastrophic failure. These include devices to monitor temperature or vibration, protect the windings from transients and other surges, or devices which may couple the motor to its driven equipment.

**FIGURE 1: SURGE PROTECTION**



The surge protection shown here is typically used for medium voltage (2300v - 4160v) motors.

## SURGE CAPACITORS AND LIGHTNING ARRESTORS

Surge protection for medium-voltage machines usually looks like the equipment shown in Figure 1. The surge capacitor is a sealed rectangular box, filled with insulating oil, supporting three insulated terminal posts. Line-to-motor leads are attached to the posts, which are electrically isolated until high voltage is applied. Under no circumstances should the surge protection device be baked. The dielectric oil will expand, deforming the case.

One error that occurs with lightning arrestors is when an operator attempts to hipot the terminals to ground. As the applied voltage approaches the design withstand voltage, the micro-amp leakage increases dramatically. To the uninitiated, it may appear that the winding is in imminent danger of failure, when in fact the lightning arrestors are functioning as intended. Table 1 lists the maximum withstand voltage and response time for various surge suppressor/lightning arrestors.

The lightning arrestors megohmmeter test should be acceptable; if not, there may be surface tracking involved. It often helps to wipe down the exterior using denatured alcohol, to remove any moisture or other contaminants.

**TABLE 1: GUIDE FOR SELECTING SURGE CAPACITORS AND LIGHTNING ARRESTORS**

| Max. motor rated voltage | Max. withstand voltage in kV | Max. rate of rise in kV/μ sec |
|--------------------------|------------------------------|-------------------------------|
| 600                      | 2.3                          | .6                            |
| 2400                     | 10                           | 1.0                           |
| 4160                     | 16                           | 1.6                           |
| 4800                     | 19                           | 1.9                           |
| 6600                     | 25                           | 2.5                           |
| 6900                     | 26                           | 2.6                           |

## THERMAL PROTECTION

Resistance temperature detectors (RTDs), thermistors or thermocouples are used to monitor winding and/or bearing temperatures. They only work when connected, and even then only when the operator heeds the warning. Thermal damage to a protected part often indicates that the protection was not utilized.

Thermal protection should be checked for a circuit and the resistance should be documented (Table 2).

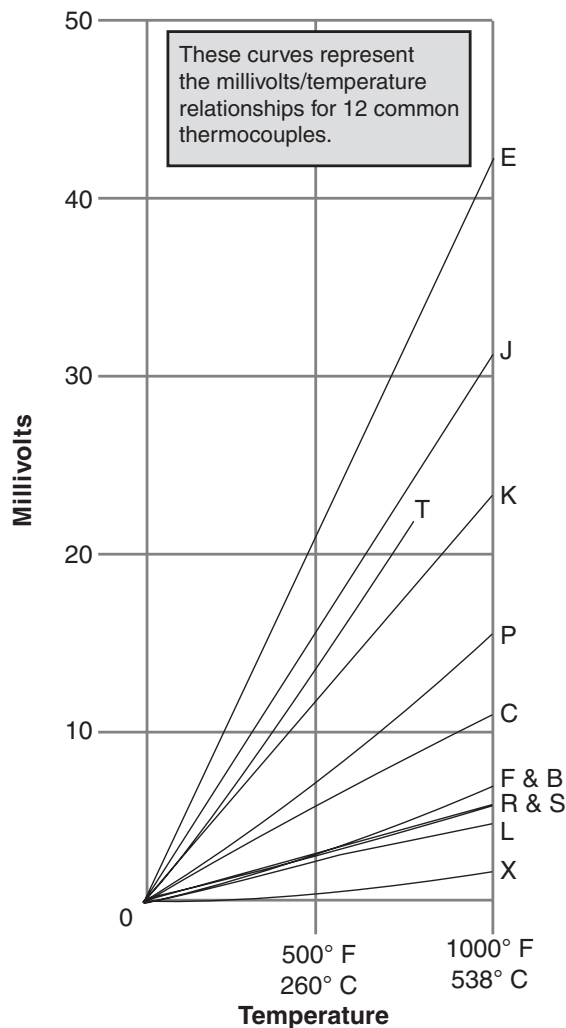
**TABLE 2: COMMON RTD MATERIALS AND THEIR RESISTANCES**

| Material | Temperature      |
|----------|------------------|
| Copper   | 10 Ohms at 25° C |
| Platinum | 100 Ohms at 0° C |
| Nickel   | 120 Ohms at 0° C |

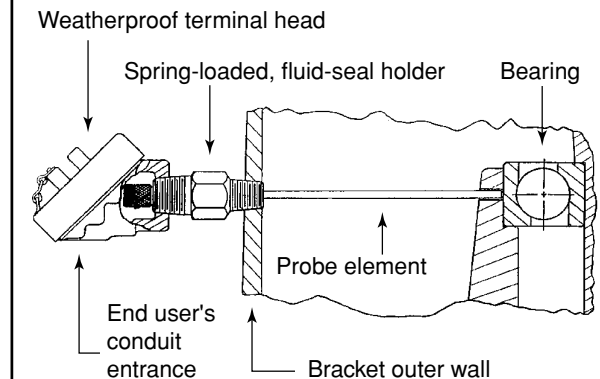
Winding temperature protection should be installed in the hottest area of the windings to be most effective. RTDs should be imbedded in the slot area, preferably between coils. RTDs, if equally spaced, will be positioned two per phase. When thermal protection is installed in the end turns, it should be installed on the hottest end. Underwriters Laboratories (UL) specifies that thermal protection should be installed “on the end opposite the fan.” While RTDs can be identified by their resistance, thermistors and thermocouples should be identified through the original equipment manufacturer (OEM). (See Figure 2.)

Bearing RTDs are tip-sensitive sensors installed in a stainless steel tubing. The mounting assembly includes a spring-loaded, bayonet-stud locking device. Correctly installed, the spring holds the probe tip against the bearing (Figure 3).

To check this, pull out on the probe and feel the tension. When released, the probe should be pulled firmly against the bearing. If incorrectly installed, the probe will only sense the air temperature surrounding the probe. Response time will be curtailed, because the heat transfer from the bearing through the surrounding air to the probe takes longer than if the probe is pressed against the bearing. If a failed bearing has an RTD, check the probe to make sure it was properly installed.

**FIGURE 2: TEMPERATURE/MILLIVOLT GRAPH FOR THERMOCOUPLES**

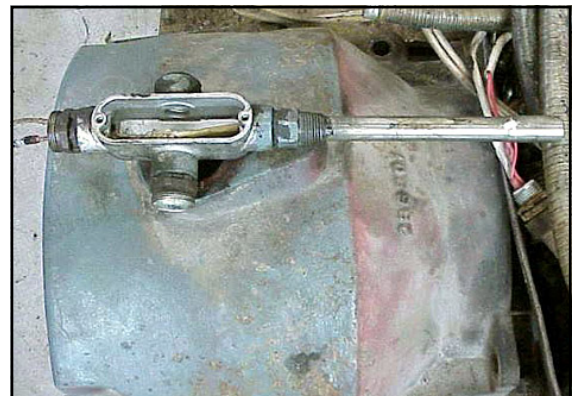
- B** ..... Tungsten/Tungsten, 26% Rhenium
- C** ..... Tungsten 5% Rhenium/Tungsten 26% Rhenium
- E** ..... Chromel/Constantan
- F** ..... Iridium/Tungsten
- J** ..... Iron/Constantan
- K** ..... Chromel/Alumel
- L** ..... Iridium/Iridium 60% Rhodium 40%
- P** ..... Geminol P/N
- R** ..... Geminol P/N
- S** ..... Platinum/Platinum 13% Rhodium
- S** ..... Platinum/Platinum 10% Rhodium
- T** ..... Copper/Constantan
- X** ..... Platinum 6% Rhodium/Platinum 30% Rhodium

**FIGURE 3: BEARING TEMPERATURE DETECTOR****BEARING CHAMBER HEATERS**

In cold climates, the oil chamber of a sleeve bearing motor may be fitted with a cartridge heater and thermostat switch to control oil temperature. The heater keeps the oil temperature from dropping below a safe level (to keep the viscosity low so the oil will flow) and the thermostat prevents the heater from raising the oil temperature too high (where the oil might no longer transfer heat from the bearing). If a bearing failure appears to result from lack of lubrication, but the oil level was correct, and the ambient was  $-30^{\circ}\text{F}$ , check the thermostat and the heater. In most cases, the thermostat switch (Figure 4) is adjustable. Immerse the switch in water and raise the temperature until the switch operates to confirm the set-point.

**COUPLINGS**

Couplings are often removed before the motor is sent into the service center. Nonetheless, the coupling may contribute to the cause of failure when there are indications of misalignment or thrusting. Geared or splined couplings require lubrication, and are often neglected. The condition

**FIGURE 4: BEARING THERMOSTAT**

A thermostat is used in series with a cartridge heater for oil chambers in cold climates. This should be considered for temperatures below  $50^{\circ}\text{F}$  ( $10^{\circ}\text{C}$ ).



of the teeth/spline offers a clue as to alignment and maintenance. If there is damage, it will normally be to the driven side of the teeth. The damage is not always symmetrical, especially if misalignment or other external causes are involved. The hard-surfacing of coupling teeth or a spline only penetrates about 0.015" (0.3 mm) deep. Any noticeable wear will accelerate quickly. Couplings with visible wear to the teeth or spline should not be placed back into service. (See Pages 8-5 through 8-7.)

## PULLEYS

Sheave wear reduces the effectiveness of the contact between belt and pulley groove. Because the belts slip, the usual response by mechanics is to increase belt tension. That often results in more radial load than the bearings can handle, so the bearings fail.

## AUXILIARY FANS/BLOWERS

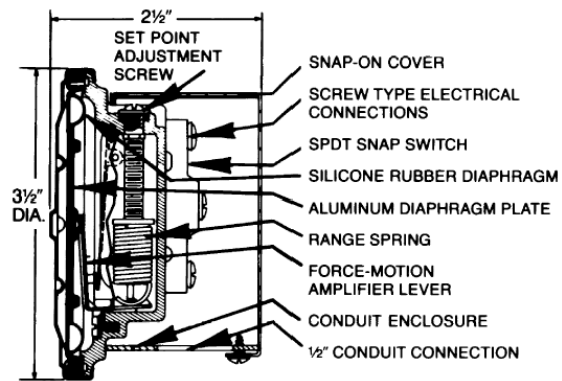
Variable speed motors are often fitted with a blower to provide a constant volume of air for cooling. Squirrel-cage designs are unidirectional, and will move less than half of their rated flow if operating backwards. However, the direction of airflow will still be correct—that is determined by the shape of the blower housing.

Differential pressure switches are sometimes used when a motor requires an external blower to dissipate heat from the windings. (See Figure 5.) Normally, the switch sensors are installed across filters to detect the decreased airflow that accompanies restricted airflow (Figure 6), or inside a terminal box to provide protection if the enclosure is opened with the motor operating. An alternative is a micro-switch to indicate when a door is opened or a critical cover removed.

## VIBRATION SENSORS

Accelerometers can be used to monitor vibration levels to provide warning of a change in vibration levels. These vary from accelerometers mounted on the frame, to non-contact probes that monitor electrical runout of the rotating shaft. Accelerometers may be single-axis or multi-axis, although most are single-axis only. Non-contact probes must be set, and the electrical runout calibrated to establish a baseline each time a change is made to the equipment. If the mechanical shaft runout differs considerably from the electrical runout, possible causes include invasive repairs to the monitored area of the shaft. Metalizing or welding can cause this phenomenon. The non-contact probe may detect the

**FIGURE 5: CUTAWAY OF A DIFFERENTIAL PRESSURE SWITCH**



**FIGURE 6: CLOGGED SCREENS**

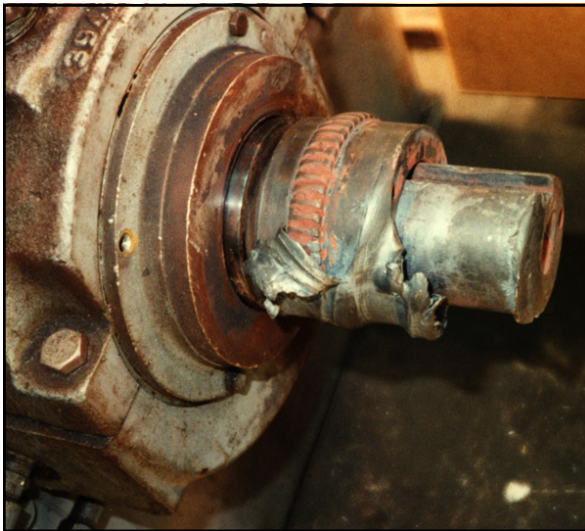


This expanded metal screen does not clog as easily as a screen with small openings, but contaminants can still build up. Sensors can be used to detect decreased airflow.

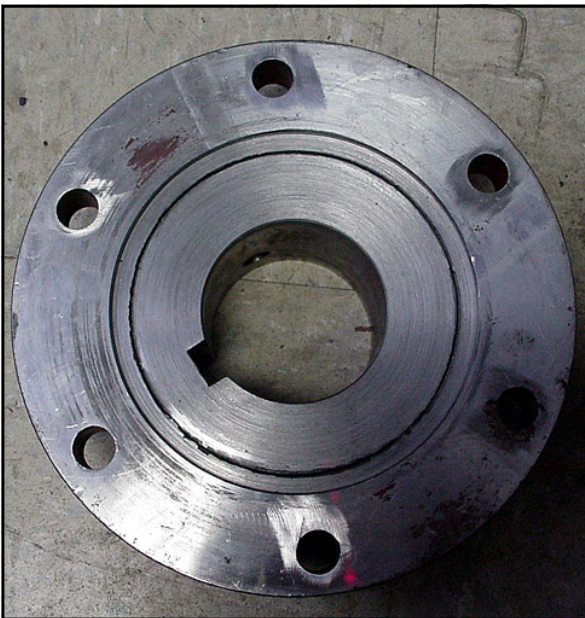
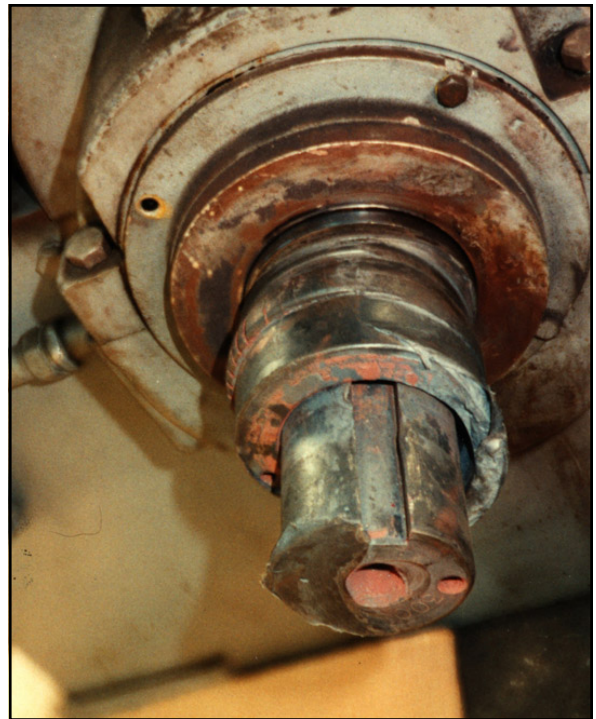
electrical runout of the substrate, rather than the shaft surface.

Depending on the accelerometer type, electrical interference can cause erroneous readings. To determine whether or not electrical interference is present, the accelerometer can be temporarily shielded with a ferrous metal can. Accelerometers should be checked using the manufacturers recommended procedures.

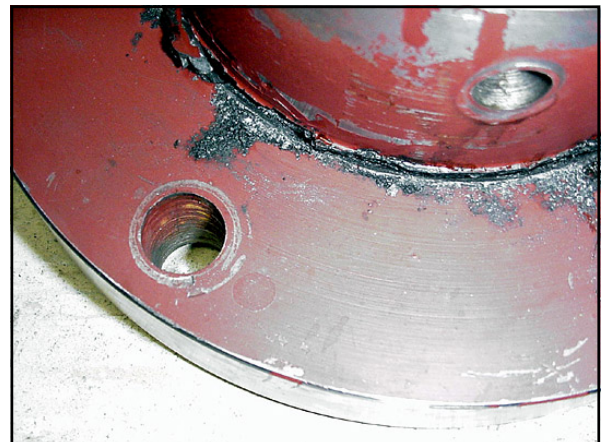
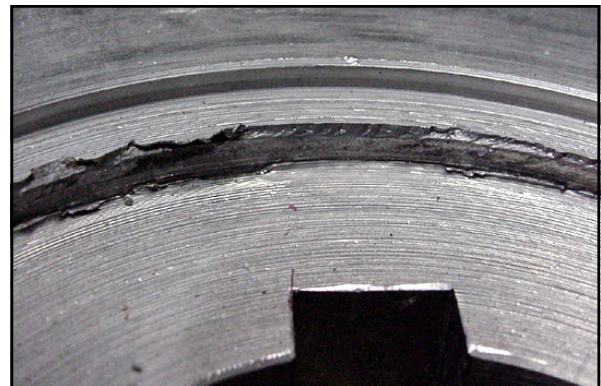
## COUPLING FAILURES



The two-piece coupling design (hub and sleeve) requires lubrication. Lack of lubrication caused friction, wearing through the hard-surfaced teeth. Vibration monitors would have detected this long before the damage progressed to this stage.

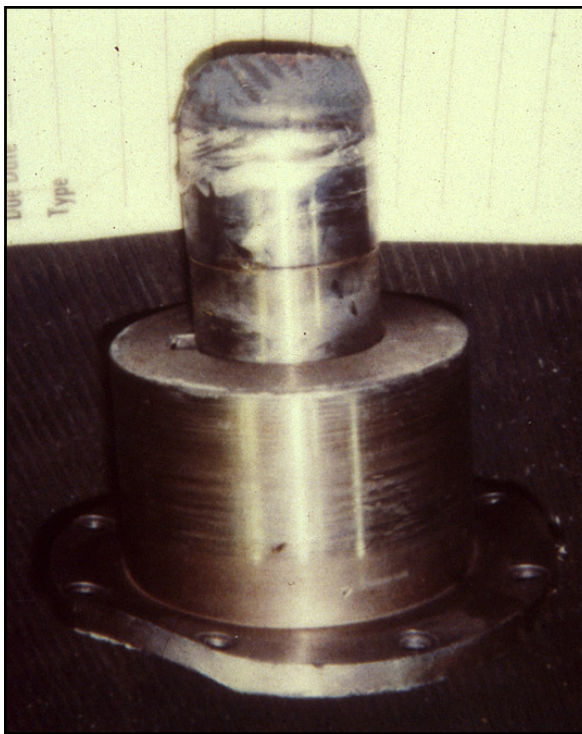
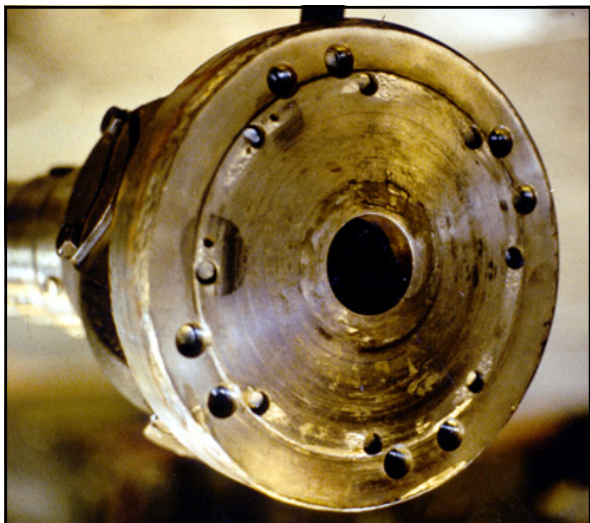


This coupling was fabricated by welding steel plate to a hub. The torsional load exceeded the capacity of the weld. Note the distortion of the keyway, possibly the result of a poor key fit.





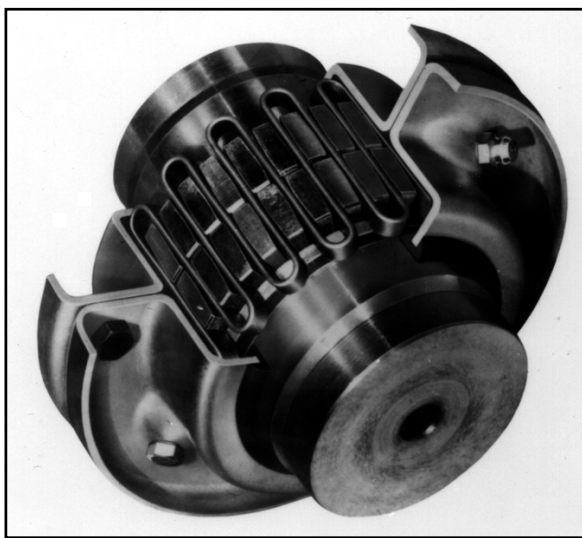
## COUPLING FAILURES



This failed universal joint (top left) illustrates the importance of a coupling guard (bottom left). The actual root cause was a transient voltage spike that increased torque to several times normal, shearing the coupling bolts. The motor continued running, flailing the large universal joint, which radially overloaded the shaft to the point of breaking. The motor's end bracket was also damaged.



This coupling/bearing carrier for a vertical hollow shaft motor shows a lot of rust and corrosion. Vertical motors need adequate an rain bonnet/drip cover.



This grid-type coupling is designed to absorb torque during starting. Excessive torque can cause the grid to fracture. This coupling must be lubricated.



## COUPLING FAILURES

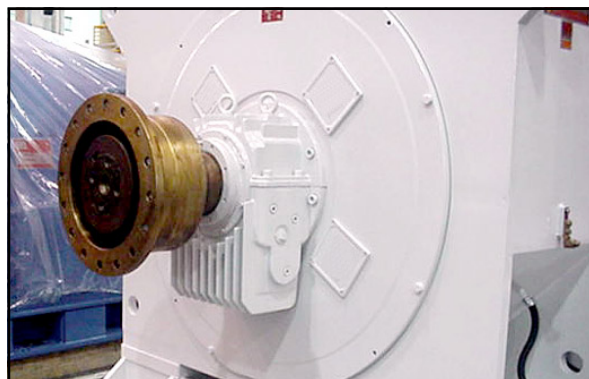
In the cases where the coupling is available, careful inspection is required to ensure that the coupling was installed or reinstalled correctly. The shaft fit can be too tight or too loose. The method of securing the coupling to the shaft can be inadequate. The key or keyway can be the wrong size. For a coupling with teeth, inspect for wear. Cracks, fretting, runout and corrosion can all render a coupling unacceptable for further use.



The teeth on this coupling show evidence of fretting (see closeup at right). Couplings are only surface hardened; once visible wear develops, the rate of wear accelerates.



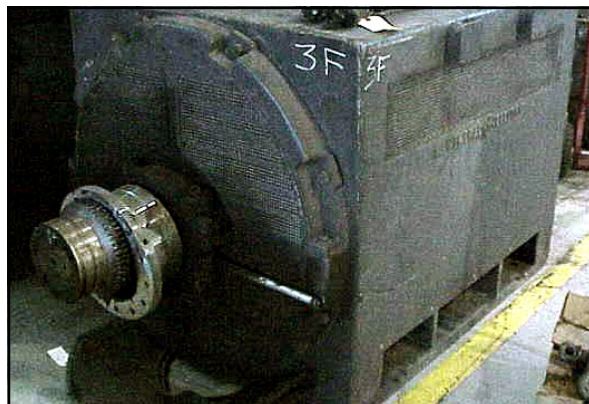
Generator coupling. Note the fretting on the guide.



The hub of this motor can be installed backwards. Check the teeth for a wear pattern.



Vertical couplings are often retained by a "nut" or drop keys to prevent the load from pull the coupling down the shaft.



This coupling style seals where the shroud and hub mate. The style above uses an O-ring (usually square).





9

Case Studies

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| Misapplication of a motor .....  | 9-5  |



## CASE STUDY #1

### Winding connection failure

450 hp • 2 pole • 6.6 kV • WPI • Drain pump motor at a power plant

This motor was approximately 30 years old. Maintenance records were not available for this analysis, however, it was operated in a power plant in a clean, dry environment. The motor powered a drain pump and was subjected to frequent starts. Just prior to the failure, it was sprayed with water from a faulty valve. When the motor failed, the resulting phase-to-phase short expelled the power supply cables 20 feet out of the cable tray. The motor's sheet metal housing was bowed outward from the force of the failure. (See Motor Terminal Box Explosions in Section 6 for details about pressure generated by high-energy electric arcs.)

Inspection of the motor revealed the following:

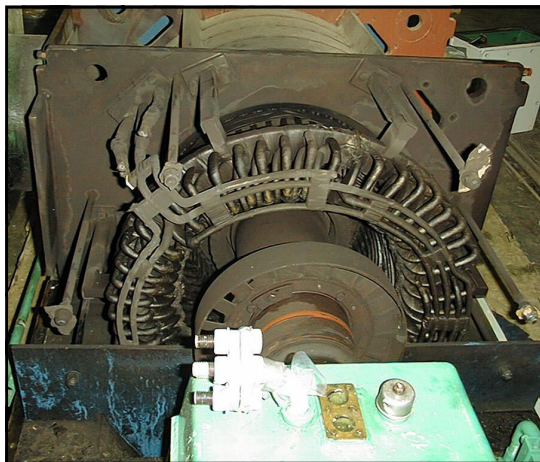
- The **pattern** of the failure was nonsymmetrical and isolated to the connection end of the winding where the line leads enter the winding.
- The **mode** of failure was an “open” fault in the winding where the line leads connect to the end turns. (See #1.)
- Stress analysis revealed the following:
  - **Thermal stress** had not caused any significant damage except in the area where the open fault occurred.
  - **Environmental stress** was evidenced by the presence of a significant amount of oil on the winding, but

this did not contribute to the actual failure. There was no evidence of water intrusion from the faulty water line.

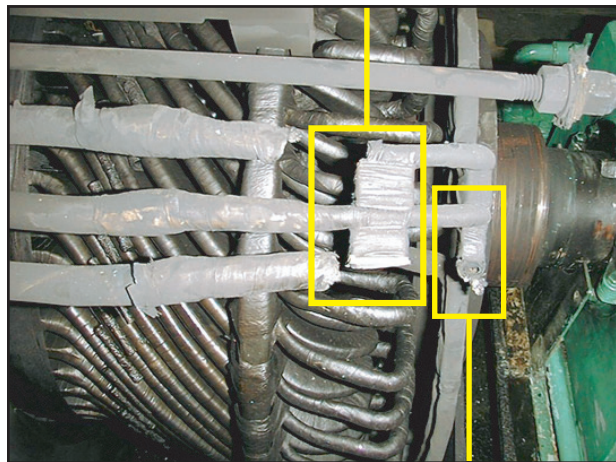
- **Electrical stress** had not caused any shorting or grounding to the main body of the winding other than what is shown in #2. The failure mode indicates that there may have been voltage transients present at the time of the failure.
- **Mechanical stresses** exceeded the withstand capability of this winding as shown in #5. In general, the winding is poorly braced for a 6.6 kV and/or 2 pole machine.
- The **appearance** of the winding indicates that it had marginal coil supports, bracing and varnish treatment (non-VPI) which made it susceptible to excessive coil movement during starting, running and when transient voltages were present.

In conclusion, the connections failed due to excessive movement that work hardened the copper lead-to-winding connections. Since the actual failure occurred in two phases at the same time, there is a high probability that a voltage transient actually caused the failure. Several repeated starts could also have triggered the failure.

**1** A and C phase motor leads had blown open at the separator block where the motor leads make the transition from the motor lead wire to the magnet wire used to connect the windings. This joint appears to be a solid crimped joint. However, this is a hand-taped area of insulation and can be a weak area for sealing out moisture. Note the dark color of the end turns and the motor lead wire. This is only present on the drive end of the motor. Also note the shiny appearance of the blackened end turns. There was an oily film on the drive end of the stator. The opposite drive end was essentially oil free.



This is an insulator block separating A, B and C phases. It is needed to help support the transition between the motor lead wire and the magnet wire of the winding.

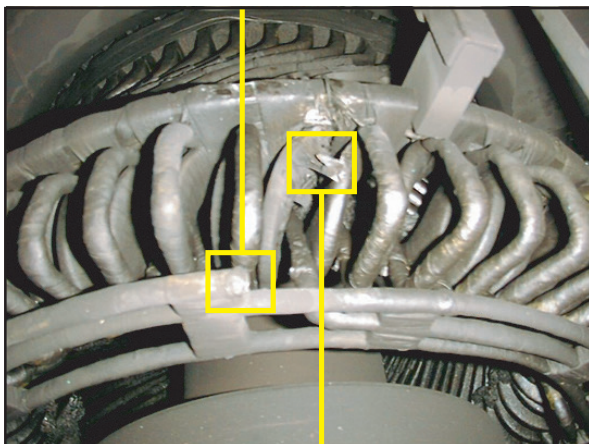


This is the insulated magnet wire. The larger diameter wire to the left is the motor lead wire.

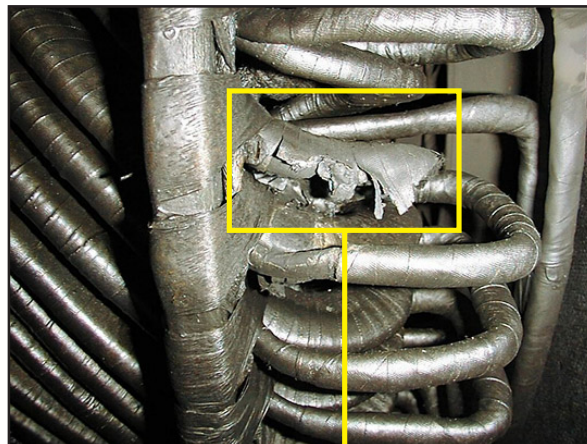
**CASE STUDY #1**

**2** Two pieces of the phase coil connection were found in the bottom of the stator housing. These are parts of the connection shown in the photograph at right.

This is the A phase jumper for the stator lead wire to the first phase coil. There is supposed to be a connection between here and the second highlighted area.



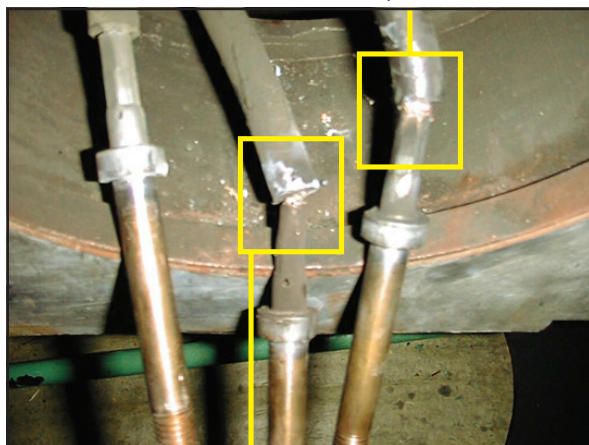
This is the first phase coil of the A phase. The magnet wire connection was blown open and partially vaporized by the fault.



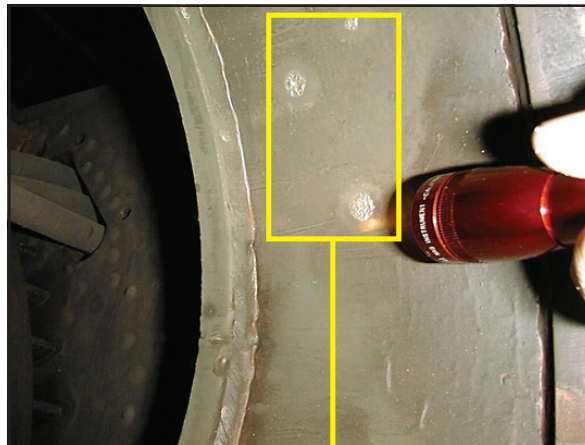
This is the first phase coil of C phase. The magnet wire connection was blown open and partially vaporized by the fault. This area is approximately 120° from the A phase coil damage.

**3** Terminal studs in the junction box were examined. Note the broken stator lead wire strands on B phase (this was the only phase that had no blown out areas) and the arcing damage on C phase. The fault generated enough fault current to arc to the side of the stator housing where the leads pass through even though the leads are separated and held away from ground by insulators in the junction box. Small beads of melted copper were found from the damaged C phase. In addition, there are three arc marks on the side of the opening where the C phase arced. Phase A had no damage in this area.

C phase

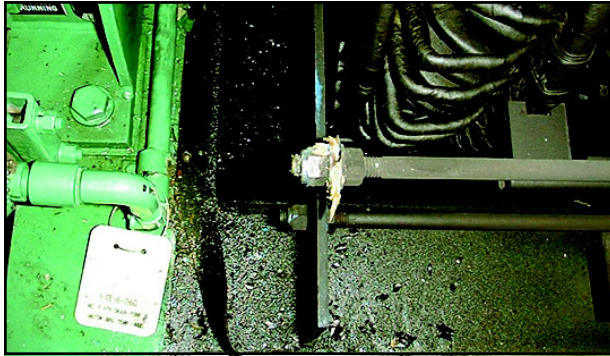


Broken strands on B phase



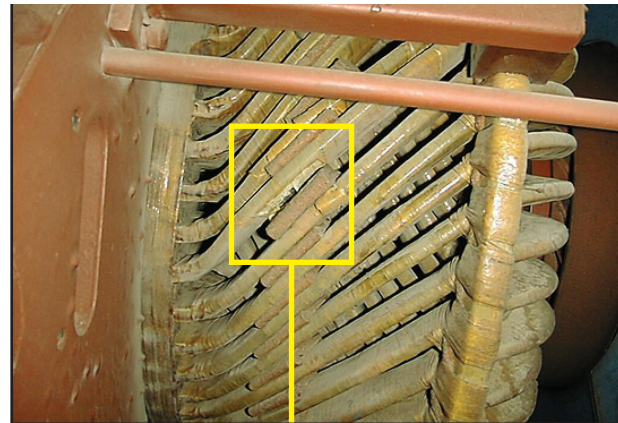
Arc marks on the area adjacent to the motor lead connections from C phase.



**CASE STUDY #1**

**4** There was a significant oil film on the drive end of the winding as well as in the stator housing below the winding.

**5** The fault created coil movement in the first phase coils of A and C phase that carried through to the opposite drive end. Note the separation of the blocking in the photograph at right.



This is coil movement of the opposite drive end of the first phase coil of A phase. With a single row of blocking and only 1 surge ring on such a long coil extension, movement is inevitable.

## CASE STUDY #2

### Misapplication of a motor

250 hp • 10 pole • 4160 v • Open dripproof • Cement plant crusher motor

This case study is a classic example of a motor being misapplied, failing, then being repaired and failing again. The application is motor connected to a cement plant crusher through 18 V-belts.

In the process of failure analysis and repair, inadequate attention was given to the application. The motor entered the service center with a wiped drive end sleeve bearing and a bent shaft. It was erroneously assumed that the motor failed catastrophically due to a worn bearing.

A new shaft was manufactured, a new drive end sleeve bearing was installed, the stator was cleaned and a thin layer of epoxy was applied to the topsticks. In addition, two days were spent with feeler gauges adjusting for the correct air gap at both ends of the rotor.

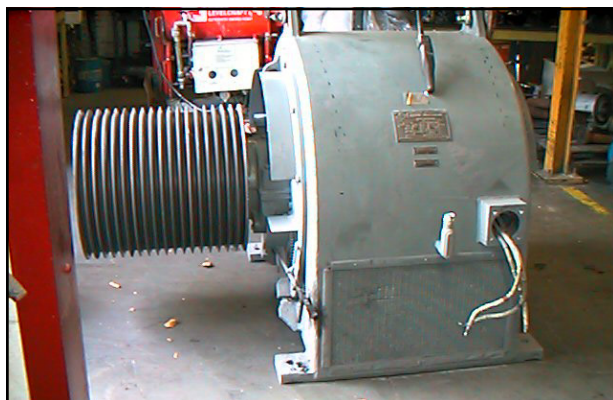
Following the repair, the motor was tested and ran satis-

factorily for two hours in the service center. It was assumed the problem associated with the root cause (a bad drive end bearing) had been corrected.

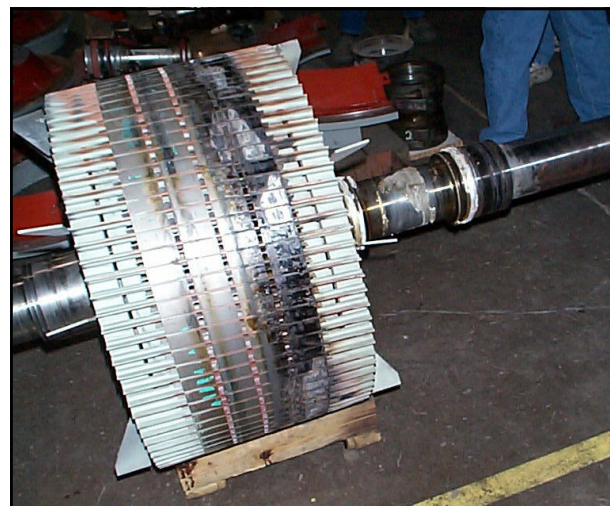
The motor was returned to the customer and installed on the crusher. The customer ran the motor for 34 minutes and said “it sounded good.” However, within the next 2 minutes, the motor “self destructed.” The failure wiped both bearings, damaged the winding and bent the shaft.

A bad bearing was not the root cause of the first failure. The actual cause of failure was an excessive overhung load. The force exerted by the large number of belts was far too severe for a sleeve bearing motor.

The key point in an effective root cause failure analysis is to include an appraisal of the entire motor system—the motor, the driven application and the motor's environment.



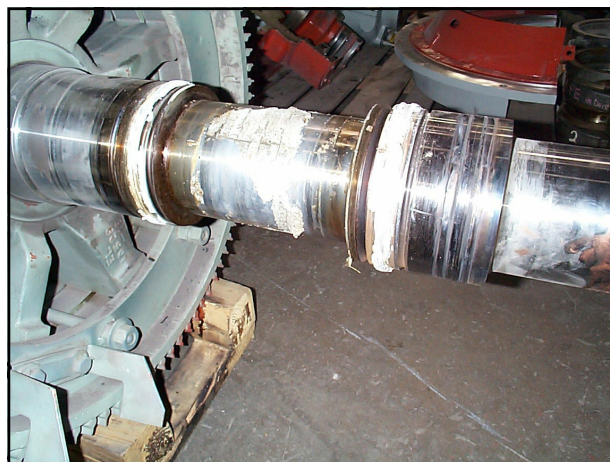
This open dripproof motor, equipped with sleeve bearings, was unable to handle the extreme overhung load.



Evidence of the rotor rubbing on the stator laminations.



The failed drive end sleeve bearing.



The bent shaft and damaged bearing journal.



While it did not contribute to this failure, another problem is the use of an open enclosure in a very dusty environment. Had the bearing not failed from the excessive overhung load, the cement dust would have eventually blocked stator and rotor vent ducts and could also have contaminated the oil.

The pictures of this case study show the damage done to the motor and illustrate how easy it would be to misdiagnose this failure without considering the application and past history of the machine. If the history of this motor had been reviewed, it would have been learned that this was a used motor that had never successfully operated on this application and that it actually failed on initial start up. If the application had been adequately reviewed, the service center would have learned that there was extreme overhung load on the motor and that the bearing was not capable of carrying such a load.

The conclusion reached after the motor failed the first time pointed to a defective bearing, when in actuality it was a misapplied bearing, and therefore a misapplied motor.

# 10

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## NOTES

# Supplement

## BURNISHING THE COMMUTATOR OF A DC MOTOR

Burnishing of the commutator, to initiate the development of the film, is especially important in areas of low humidity and/or high altitude. The commutator film requires humidity and current to form. Industries with a long history of DC work have found tricks for starting the film that is so critical to good commutation. Here are several tricks that the service center can use.

- Burnishing stone: Available from manufacturers of brush seating stones and commutator stones, this dull-red colored mild abrasive, when held firmly against the rotating commutator, will burnish the commutator surface.
- Maple: A maple block can be used in the same manner as the burnishing stone, above.
- Damp canvas: In the past, damp canvas has been placed against the commutator surface. This is a serious electrocution hazard! It is much better to place damp canvas (or a small pan of water) in the commutator end bracket, to temporarily raise the humidity.
- Hydrogen peroxide: Wipe hydrogen peroxide onto the commutator surface. This helps start a slight film.

## DC MOTOR VENTILATION

When blank covers are installed, gaskets are important to ensure that the opening is sealed. Not only can a non-gasketed cover leak air out (reducing the effectiveness of the cooling air) but it can also let water – or other contaminants – into the motor.

## OIL SIGHT GLASSES

Oil sight glasses (bullseye) are not all created equal. There are some designs with one oil level line, some with

**FIGURE 1: SIGHT GLASS WITH SINGLE LINE**



This design uses no oil level marks. The operator assumes the correct level to be the midpoint. No distinction is made between running and standstill oil levels. This press-in design is also prone to leaks.

**FIGURE 2: SIGHT GLASS WITH TWO LINES**



The oil level is identified as “MAX” and “MIN” rather than “running” and “standstill.” When the standstill oil level is at the upper line, the running level surges even higher and oil leaks are likely.

**FIGURE 3: STAINED SIGHT GLASS**



When an oil level is maintained for years the site glass may become stained, indicating oil when none is present. The boat plug style fill works well and is very convenient for operators, but it may leak if not tightened.

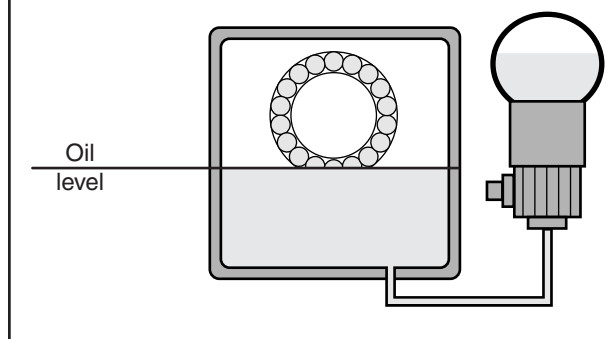
two lines, and others with no lines.

With only one line, the oil level is obvious. With no lines, the assumption is that the oil level is the center of the glass height. (See Figure 1.) But with two lines, there are problems in interpreting the correct oil level. (See Figure 2.)

Even though the manufacturer clearly identifies the function of both lines (upper line is “running” oil level, lower line



**FIGURE 4: PROPER OIL LEVEL IN A HORIZONTAL MOTOR**



is the “standstill” oil level), many users equate the dual lines to the marks on the dipstick of an automobile engine (the upper line is “full,” the lower line is “add”). If the user notes the oil level while the motor is running, there is no problem. When the same end user notices the oil level while the motor is at standstill, the impression is that the oil level is low. The end user — just like the engine dipstick — adds oil to bring the level to the top line. When the motor is next started, the oil level is well above the upper line, and oil may spill over the standtube, vent openings or other locations.

## OIL LEVEL

The oil level for ball bearings in horizontal motors is typically through the centerline of the lowermost bearing ball, when it is at bottom dead center. (See Figure 4.) Ball bearings in vertical motors will usually have the oil level with the centerline of the bearing balls. When there are multiple (i.e., stacked bearings), the oil level will normally pass through the centerline of the topmost bearing’s balls. (See Figure 5A.) The oil level for spherical roller bearings is usually in line with the point at which the vertically-oriented

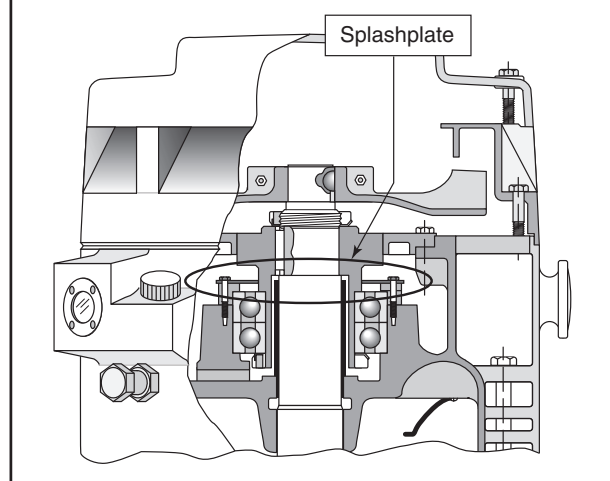
bearing roller centerline meets the upper surface of the roller. (See Figure 5B.)

## SPLASHPLATE MOUNTING

Splashplate mounting and position are another area where oil leaks can be caused. Because the splashplate for many designs fit above the thrust bearing and below the upper part of the bearing carrier, they are sometimes lost or misplaced. This might be traced back to a prior repair or an on-site bearing change.

Clues that a motor should have a splashplate include drilled and tapped holes in the upper bracket, and extra machined lip on the upper bracket, or an additional step on the bearing carrier. If part of the configuration of the bracket or bearing carrier seem to be non-functional, look for missing parts. The manufacturer can often supply a parts breakdown of the motor for confirmation.

**FIGURE 6: SPLASHPLATE ON A VERTICAL MOTOR**



**FIGURE 5: PROPER OIL LEVEL IN A VERTICAL MOTOR**

