

Reliability and Maintenance of Bolted Busbar Connections

2018 TECHNICAL REPORT

Reliability and Maintenance of Bolted Busbar Connections

3002011484

Final Report, May 2018

EPRI Project Manager
J. Sharkey

All or a portion of the requirements of the EPRI Nuclear Quality Assurance Program apply to this product.

YES NO

DISCLAIMER OF WARRANTIES AND LIMITATION OF LIABILITIES

THIS DOCUMENT WAS PREPARED BY THE ORGANIZATION(S) NAMED BELOW AS AN ACCOUNT OF WORK SPONSORED OR COSPONSORED BY THE ELECTRIC POWER RESEARCH INSTITUTE, INC. (EPRI). NEITHER EPRI, ANY MEMBER OF EPRI, ANY COSPONSOR, THE ORGANIZATION(S) BELOW, NOR ANY PERSON ACTING ON BEHALF OF ANY OF THEM:

(A) MAKES ANY WARRANTY OR REPRESENTATION WHATSOEVER, EXPRESS OR IMPLIED, (I) WITH RESPECT TO THE USE OF ANY INFORMATION, APPARATUS, METHOD, PROCESS, OR SIMILAR ITEM DISCLOSED IN THIS DOCUMENT, INCLUDING MERCHANTABILITY AND FITNESS FOR A PARTICULAR PURPOSE, OR (II) THAT SUCH USE DOES NOT INFRINGE ON OR INTERFERE WITH PRIVATELY OWNED RIGHTS, INCLUDING ANY PARTY'S INTELLECTUAL PROPERTY, OR (III) THAT THIS DOCUMENT IS SUITABLE TO ANY PARTICULAR USER'S CIRCUMSTANCE; OR

(B) ASSUMES RESPONSIBILITY FOR ANY DAMAGES OR OTHER LIABILITY WHATSOEVER (INCLUDING ANY CONSEQUENTIAL DAMAGES, EVEN IF EPRI OR ANY EPRI REPRESENTATIVE HAS BEEN ADVISED OF THE POSSIBILITY OF SUCH DAMAGES) RESULTING FROM YOUR SELECTION OR USE OF THIS DOCUMENT OR ANY INFORMATION, APPARATUS, METHOD, PROCESS, OR SIMILAR ITEM DISCLOSED IN THIS DOCUMENT.

REFERENCE HEREIN TO ANY SPECIFIC COMMERCIAL PRODUCT, PROCESS, OR SERVICE BY ITS TRADE NAME, TRADEMARK, MANUFACTURER, OR OTHERWISE, DOES NOT NECESSARILY CONSTITUTE OR IMPLY ITS ENDORSEMENT, RECOMMENDATION, OR FAVORING BY EPRI.

THE FOLLOWING ORGANIZATION, UNDER CONTRACT TO EPRI, PREPARED THIS REPORT:

Paul G. Slade, Consultant

THE TECHNICAL CONTENTS OF THIS PRODUCT WERE **NOT** PREPARED IN ACCORDANCE WITH THE EPRI QUALITY PROGRAM MANUAL THAT FULFILLS THE REQUIREMENTS OF 10 CFR 50, APPENDIX B. THIS PRODUCT IS **NOT** SUBJECT TO THE REQUIREMENTS OF 10 CFR PART 21.

NOTE

For further information about EPRI, call the EPRI Customer Assistance Center at 800.313.3774 or e-mail askepri@epri.com.

Electric Power Research Institute, EPRI, and TOGETHER...SHAPING THE FUTURE OF ELECTRICITY are registered service marks of the Electric Power Research Institute, Inc.

Copyright © 2018 Electric Power Research Institute, Inc. All rights reserved.

ACKNOWLEDGMENTS

The following organization, under contract to the Electric Power Research Institute (EPRI), prepared this report:

Paul G. Slade, Consultant
176 Oakwood Lane
Ithaca, NY 14850

Principal Investigator
P. G. Slade

This report describes research sponsored by EPRI.

EPRI acknowledges the contribution of Chris Kowal (Remote Solutions) to this report.

This publication is a corporate document that should be cited in the literature in the following manner:

Reliability and Maintenance of Bolted Busbar Connections. EPRI, Palo Alto, CA: 2018. 3002011484.

ABSTRACT

This report provides a technical basis for bolted electrical connection maintenance used in the electrical industry. This report provides information on performance testing, failure mechanisms, and the maintenance of electrical bolted connections. Applicable bolted electrical connections typically include nonsegregated phase bus work, switchgear bus work, and isolated phase bus work. The information is intended to be used by plant component engineers, system engineers, maintenance personnel, and their supervisors to develop effective maintenance programs for bolted electrical connections.

Keywords

Bolted joint
Electrical bus
Electrical connection
Maintenance
Switchgear

PRODUCT DESCRIPTION

This report provides a technical basis for bolted electrical connection maintenance used in the electrical industry. The report provides information on testing, failure mechanisms, and the maintenance of electrical bolted connections. Applicable bolted electrical connections typically include nonsegregated phase bus work, switchgear bus work, and isolated phase bus work. The information is intended to be used by plant component engineers, system engineers, maintenance personnel, and their supervisors to develop effective maintenance programs for bolted electrical connections.

Background

Industry guidance for maintenance of bolted electrical connections typically includes periodic visual inspections, bolted electrical connection resistance measurements, electrical connection bolt torque checks, and monitoring with infrared thermography. Existing industry guidance follows conventional wisdom and common practices, but the technical basis for common maintenance practices has not been well-understood or easily identified. In addition, existing industry guidance contains conflicting information on the practice of retorquing bolted electrical connections.

The EPRI-sponsored industry Circuit Breaker Users Group has conducted discussions and surveys on the topic of maintenance of bolted electrical connections. Based on working group discussions, maintenance practices among plants vary considerably. EPRI surveys show that typical maintenance frequencies are between 3 and 12 years, with the average being about 7 years for electrical buses. This means that some maintenance schedules are more frequent or less frequent.

Research is needed to provide the technical basis for the maintenance of bolted electrical connections such that catastrophic failures and extended plant downtime might be avoided. Avoiding catastrophic failures would also lower the risk of personnel injury as a result of any failures.

Objectives

The objective of this report is to document the technical basis for maintenance of bolted electrical connections such that maintenance personnel may easily develop effective maintenance programs to ensure the long-term reliability of these connections. The technical basis will include failure modes and effects as well as maintenance strategies to mitigate the failure modes identified.

Approach

This report was developed by an EPRI project team that included an expert in the field of electrical contacts. Data were reviewed from electrical connection research conducted by various organizations and researchers. This report was reviewed by industry peers and utility personnel for technical accuracy.

Results

This report identifies the possible causes of bolted electrical joint failures so that better maintenance and monitoring techniques can be employed to prevent failure of the connection. The results show that when a bolted electrical connection nears the end of its service life, its internal resistance increases—along with temperature—as the microscopic contact spots are decreased by gas corrosion or a reduction in connection force at the joint. Techniques for remaking bus connection joints are presented that include the use of Belleville washers to help control thermal expansion, ratcheting, and creep. Methods for measuring resistance at the connection are reviewed that include subtracting the resistance of the bus material when making these measurements to improve accuracy and not mask a high-resistance connection.

Applications, Value, and Use

This report was developed to establish a technical basis for maintenance of electrical bolted connections. The goal of this report is to help utilities prevent failures of electrical bolted connections, which can lead to extensive downtimes and repair costs.

Deliverable Number: 3002011484

Product Type: Technical Report

Product Title: Reliability and Maintenance of Bolted Busbar Connections

PRIMARY AUDIENCE: Generating station maintenance and engineering staff

SECONDARY AUDIENCE: Generating station management, maintenance planners, and training staff

KEY RESEARCH QUESTION

The reliability of bolted electrical connections is critical to both safety and non-safety systems within a nuclear power plant. Industry guidance for maintenance of these connections typically recommends periodic visual inspections, low-resistance measurements, checking bolt torques, and infrared thermography (IRT). This guidance simply follows conventional wisdom and common practices.

A catastrophic failure of a nonsegregated bus at a U.S. nuclear generating station in August 2009 led EPRI to begin additional research into maintaining the reliability of bolted busbar connections. In December 2013, the industry experienced another catastrophic failure at a U.S. nuclear plant, which was partially caused by inadequate maintenance practices.

Research was needed to provide the technical basis for more meaningful maintenance decisions so that catastrophic failures might be avoided. A specific research question posed: “When does a bolted bus connection show the initial sign of failure?”

RESEARCH OVERVIEW

The research team collected information from a literature search on electrical connections. The principal investigator—a prominent author and subject matter expert—was requested to condense the information identified into a report. The project team reviewed the drafts and sent draft reports out to industry personnel for review and comment.

KEY FINDINGS

- The most reliable way to determine the condition of a bolted busbar connection is by determining the joint contact resistance.
- When the joint contact resistance of the bolted bus joint is ≥ 1.5 times its initial value, the joint is in the initial stage of failure.
- Once a bolted joint exhibits signs of accelerated aging, failure can occur in a relatively short time.
- External temperature measurement via IRT is often used but is less reliable in determining the condition of a bolted connection. IRT may not catch every possible failure. For example, IRT is unreliable when the joint is shiny (that is, highly reflective). In addition, IRT cannot be used if the joint is booted or taped. If IRT does show an increase in temperature, the joint is in the initial stages of failure.

- The actual area of contact is a function of the contact load (bolt torque) and the material's hardness. It does not depend on the total area of the contact face. In other words, the actual area of contact is a function of the bolt torque and the hardness of the connection materials.
- The report discusses a method of measuring the joint contact resistance for bolted bus joints, which can also be used when the connections are covered with insulating covers (or "boots") or they are taped or wrapped with insulating materials.

WHY THIS MATTERS

Catastrophic failures of electrical buses can cause plant shutdowns and significant damage and challenge plant safety systems. Proper maintenance techniques will help ensure the reliability of electrical buses and prevent costly plant shutdowns.

HOW TO APPLY RESULTS

Information presented in this report can be used by power station personnel to develop more effective maintenance programs and procedures for bolted electrical connections. The most effective technique for measuring contact resistance is discussed. Bolted electrical connections can be found throughout the plant, but the focus is mainly on nonsegregated bus, isolated phase bus, and switchgear.

LEARNING AND ENGAGEMENT OPPORTUNITIES

- To learn more about EPRI activities regarding circuit breakers and switchgear and electrical buses, go to EPRI's Circuit Breaker Users Group Website, <https://msites.epri.com/ms/research/117997/circuit-breakers-users-group-%28cbug%29->
In addition, EPRI has published report 1015057, Isolated Phase Bus Maintenance Guide.

EPRI CONTACT: Jim Sharkey, Principal Technical Leader, jsharkey@epri.com

PROGRAMS: Nuclear Power, P41; Plant Engineering, P41.05.02

IMPLEMENTATION CATEGORY: Category 2, Plant Optimization

Together...Shaping the Future of Electricity®

Electric Power Research Institute

3420 Hillview Avenue, Palo Alto, California 94304-1338 • PO Box 10412, Palo Alto, California 94303-0813 USA

800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com

© 2018 Electric Power Research Institute (EPRI), Inc. All rights reserved. Electric Power Research Institute, EPRI, and TOGETHER...SHAPING THE FUTURE OF ELECTRICITY are registered service marks of the Electric Power Research Institute, Inc.

CONTENTS

ABSTRACT	V
PRODUCT DESCRIPTION	VII
EXECUTIVE SUMMARY	IX
1 INTRODUCTION	1-1
Background	1-1
Objectives	1-2
Approach.....	1-2
Report Highlights.....	1-2
Key Points	1-3
2 AGING BEHAVIOR, FAILURE MODES, AND PERFORMANCE	2-1
Typical Aging Behavior.....	2-1
Parameters Affecting Performance.....	2-2
Failure Modes and Effects.....	2-3
Measuring Performance: Contact Resistance Measurement	2-5
Measuring Performance: External Temperature Measurement.....	2-5
3 CONTACT RESISTANCES AND TEMPERATURES	3-1
Resistance of a Conductor	3-1
Contact Resistance	3-2
The Real Area of Contact for a Small Disk of Radius a	3-4
Contact Resistance and Contact Temperature	3-6
Calculating Contact Temperature	3-6
The Melting and Softening Temperature of Metals	3-9

4 THE BOLTED BUS CONNECTION.....	4-1
Typical Bus Materials	4-1
The Bolted Connection	4-2
Aluminum Connections.....	4-4
Joint Compounds	4-5
Thermal Expansion of Different Materials	4-6
Optimum Bus Overlap	4-9
5 MEASURING CONTACT RESISTANCE	5-1
Concept of the Contact Resistance for a Bolted Bus Joint with Multiple Bolts.....	5-1
6 CAUSES OF INCREASED JOINT CONTACT RESISTANCE	6-1
Intermetallic Compounds.....	6-1
Ingress of a Corrosive/Oxidizing Gas into the Individual Contact Spots.....	6-1
Fretting at the Bolted Joint Connection.....	6-2
Corrosion.....	6-5
7 POWER CONNECTION FAILURES	7-1
Laboratory Experiment with an Example of a Bolted Bus Failure.....	7-1
Long-Term Experiments Showing Bolted Bus Failures	7-2
Failure of Cu Bus Mated to Al Bus and Al Bus Mated to Al Bus	7-2
Failure of Al Bus Mated to Al Bus as a Function of Current.....	7-3
Failure of Al Bus Mated to Al Bus as a Function of Ambient Temperature	7-4
Failure of Al Bus Mated to Al Bus, Al Alloy Bus Mated to Al Alloy Bus, and Cu Bus Mated to Cu Bus.....	7-5
8 JOINT INSPECTION AND CORRECTIVE MEASURES	8-1
9 CONCLUSIONS	9-1
10 REFERENCES	10-1
A KEY POINTS.....	A-1

LIST OF FIGURES

Figure 2-1 The aging behavior of an electrical connection	2-1
Figure 2-2 Bolted joint performance factors.....	2-3
Figure 2-3 The IRT method does not easily detect the initial stages of connector failure.....	2-6
Figure 3-1 Contact resistance	3-2
Figure 3-2 The contact surface and the real area of contact.....	3-3
Figure 3-3 The real area of contact, A_c , for silver as a function of the contact load.....	3-4
Figure 3-4 Contact resistance and the area of contact	3-4
Figure 3-5 Contact resistance as a function of contact force	3-5
Figure 3-6 The contact spot temperature as a function of the voltage drop across the contacts calculated from Equation 3-13	3-7
Figure 4-1 The Zincate process for plating Al bus	4-2
Figure 4-2 The Alstan process for plating Al bus	4-2
Figure 4-3 Bolted connection	4-2
Figure 4-4 The bolted connection with flat washers illustrating the regions of contact force	4-3
Figure 4-5 A roughened surface breaking through a thin oxide layer.....	4-4
Figure 4-6 Bolted connection for aluminum and copper buses with Belleville washers.....	4-8
Figure 4-7 Bolted connection for aluminum-to-copper bus with Belleville washers	4-8
Figure 4-8 The bolted connection with Belleville washers together with flat washers illustrating the regions of contact force	4-9
Figure 4-9 Optimum overlap for current flow in a bolted bus joint.....	4-9
Figure 4-10 Pressure and probable current path in the region of the bolted connections	4-10
Figure 4-11 An illustration of the current flow between bolted buses	4-10
Figure 5-1 The ideal way to measure contact resistance.....	5-1
Figure 5-2 A bus connection using four bolts	5-1
Figure 5-3 Measuring the joint contact resistance, R_C , for a bus connection	5-2
Figure 6-1 An example of a Cu-Al transition washer between a copper bus and an aluminum bus.....	6-1
Figure 6-2 Runaway increases in contact resistance caused by ingress of corrosive or oxidizing gases as a function of time and ambient gas temperature	6-2
Figure 6-3 An illustration of fretting.....	6-3
Figure 6-4 The parameters that affect fretting	6-3
Figure 6-5 Fretting for aluminum (Al) against copper (Cu) and aluminum (Al) against tin (Sn) showing change in R_C as a function of fretting cycles	6-4

Figure 6-6 Possible sequences for creep and thermal-elastic ratcheting	6-4
Figure 7-1 An example of a connection failure	7-1
Figure 7-2 Failure of connected aluminum bus.....	7-2
Figure 7-3 The aging behavior of a busbar joint for Cu-to-Al and Al-to-Al bus materials.....	7-3
Figure 7-4 The aging behavior of an aluminum-to-aluminum bus as a function of current.....	7-4
Figure 7-5 The aging behavior of aluminum-to-aluminum bus as a function of ambient temperature.....	7-5
Figure 7-6 The aging behavior for different busbar joints	7-6
Figure 8-1 The inspection sequence and maintenance of bolted bus during a generating station shutdown	8-2

LIST OF TABLES

Table 2-1 Failure modes and effects analysis for bolted busbars.....	2-4
Table 3-1 Example of contact resistance values to give a 10 mV contact voltage as a function of bus current.....	3-8
Table 3-2 The melting and softening voltages for common contact materials	3-9
Table 4-1 Typical material properties of copper and aluminum	4-1
Table 4-2 The effect of different preparations of a bolted aluminum bus connection	4-5
Table 4-3 The effectiveness of commonly used joint compounds	4-6
Table 4-4 Expansion coefficients	4-7

1

INTRODUCTION

This report provides a technical basis for bolted electrical connection maintenance used in the electrical industry (see Sections 3, 4, and 5). The report provides information on performance testing (Sections 2 and 5), failure mechanisms (Sections 2, 6, and 7) and the maintenance of electrical bolted connections (Section 8). Applicable bolted electrical connections typically include nonsegregated phase bus work, switchgear bus work, and isolated phase bus work. The information is intended to be used by plant component engineers, system engineers, maintenance personnel, and their supervisors to develop effective maintenance programs for bolted electrical connections.

Background

The industry event that precipitated additional electrical bus efforts at EPRI is the failure of a nonsegregated bus at a nuclear generating station in August 2009 [1–4]. In 2013, the industry experienced a similar catastrophic failure at another U.S. nuclear plant as a result of improper installation of flexible links on buses, design inadequacies on bus connections, and inadequate preventive maintenance (PM) content on bus inspections.

Industry guidance for maintenance of bolted electrical connections typically includes periodic visual inspections, bolted electrical connection resistance measurements, electrical connection bolt torque checks, and monitoring with infrared thermography. Existing industry guidance follows conventional wisdom and common practices, but the technical basis for common maintenance practices is not usually well-understood or easily identified.

Existing industry guidance also contains conflicting information on the practice of retorquing bolted electrical connections. The U.S. Nuclear Regulatory Commission (NRC) NUREG 1801, Generic Aging Lessons Learned (GALL), Revision 2, December 2010, provides some industry guidance on testing of electrical bus work. The GALL report emphasizes thermography and low-resistance measurements, but it does not mention retorquing.

The EPRI-sponsored industry Circuit Breaker Users Group has conducted discussions and surveys on the topic of maintenance of bolted electrical connections. Based on working group discussions, maintenance practices among plants vary considerably. EPRI surveys show that typical maintenance frequencies are 7 years for electrical buses; some are more frequent or less frequent.

Research is needed to provide the technical basis for the maintenance of bolted electrical connections so that catastrophic failures and extended plant downtime might be avoided. Avoiding catastrophic failures would also lower the risk of personnel injury as a result of any failures.

Objectives

The objective of this report is to document the technical basis for maintenance of bolted electrical connections so that maintenance personnel may easily develop effective maintenance programs to ensure the long-term reliability of these connections. The technical basis will include failure modes and effects as well as maintenance strategies to mitigate failure modes identified.

Approach

This report was developed by an EPRI project team that included an expert in the field of electrical contacts. Data were reviewed from electrical connection research conducted by various organizations and researchers.

The report was reviewed by industry peers and utility personnel for technical accuracy. This report was developed to establish a technical basis for maintenance of electrical bolted connections. The goal of this document is to help utilities prevent failures of electrical bolted connections, which can lead to extensive downtimes and repair costs.

Report Highlights

This section discusses the content of each section in this report.

Section 1:

- Report objectives.
- Approach taken by the project team.
- The identification of Key Points in the report.

Section 2:

- The typical life of a bolted joint.
- A failure modes and effects analysis (FMEA).
- Electrical connections, mechanical and ambient factors that affect connection performance, and contact resistance as the best method to monitor connection performance.
- Why infrared thermography is less reliable in determining the condition of the connection.
- Why once a bolted joint exhibits signs of accelerated aging, failure can occur in a relatively short time.

Section 3:

- Contact resistance and why the actual area of contact is a function of the contact load (bolt torque) and the material's hardness. The actual area of contact does not depend on the total area of the contact face.
- How to estimate the temperature of the interface contact area by calculating the voltage drop across the contact surfaces.
- Recommended voltage drop across a well-made bolted bus joint.

Section 4:

- Typical materials used for bus in power plant electrical distribution systems.
- Bolted joint configurations and good bolting practices.
- Optimum bus overlap to maximize current flow from one bus member to the next.
- Joint preparation considerations, including compression forces, abrading process for aluminum, joint compounds, expansion coefficients, and Belleville washers.

Section 5:

- An ideal way to measure the contact resistance.
- The concept of the bus joint contact resistance for a multi-bolted bus joint.
- The ideal way to measure the joint contact resistance for a bolted bus joint.

Section 6:

- Potential causes for increases in contact resistance due to formation of intermetallic compounds, ingress of corrosive or oxidizing gas, fretting, and corrosion.

Section 7:

- Connection failures and examples of data on connections that have failed.
- Data that show that when connections begin to fail, they can fail in a relatively short time.
- Data that show that a small increase in the joint contact resistance can be significant and should be considered the beginning of a connection failure.
- The differences in life expectancy for connections with different material combinations.

Section 8:

- Joint inspection and corrective measures.

Section 9:

- Conclusions.

Section 10:

- References.

Key Points

Throughout this guide, key information is summarized in “Key Points.” Key Points are sidebars that succinctly restate information covered in detail in the adjacent text, making the key point easier to locate.

The primary intent of a Key Point is to emphasize information that will allow individuals to take action for the benefit of their plant. The information included in these Key Points was selected by EPRI personnel and the consultants and utility personnel who prepared and reviewed this guide.

The Key Points appear in one category, Technical, with an identifying icon to draw attention to it when quickly reviewing the guide.



Key Technical Point

Targets information that will lead to improved equipment reliability.

Appendix A contains a listing of the Key Points. The listing restates each key point and provides reference to its location in the body of the report. By reviewing this listing, users of this guide can determine if they have taken advantage of key information that the writers of the guide believe would benefit their plants.

2

AGING BEHAVIOR, FAILURE MODES, AND PERFORMANCE

The bolted electrical connection provides a reliable electrical joint between two conductors to carry current for a required period without overheating. Its operating performance is usually determined by measuring the total bus joint resistance (that is, the total resistance across the bolted joint; see Section 5). A more reliable and more accurate way of assessing the connection's performance is to measure the bus joint contact resistance (see also Section 5). Both the total bus joint resistance and the bus joint contact resistance can be affected by the ambient conditions, its physical properties, and degradation mechanisms (for example, corrosion, oxidation, and motion (see Section 6).

Typical Aging Behavior

Typical aging behavior of an electrical connection is shown in Figure 2-1.

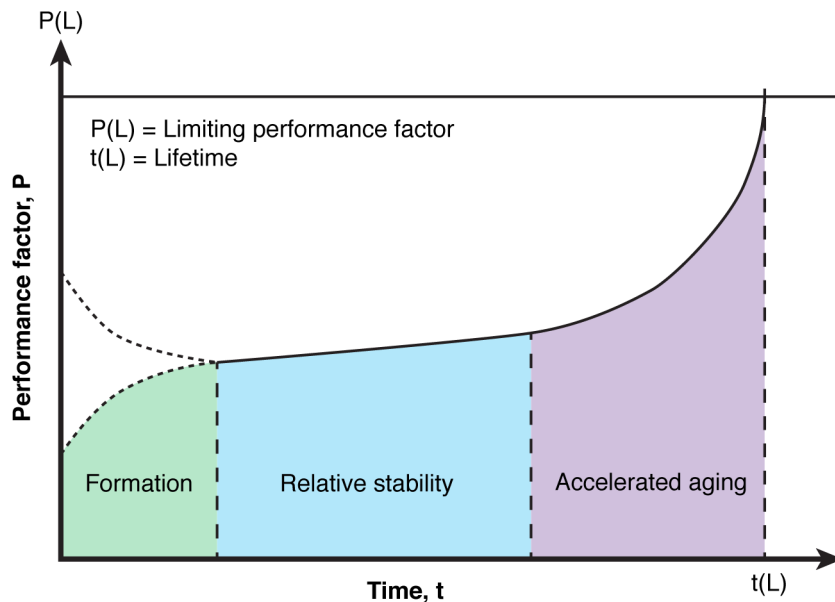


Figure 2-1
The aging behavior of an electrical connection

Once an electrical bolted joint is made, there is a brief “break-in” period during which the performance factor (for example, the bus joint resistance and the bus joint contact resistance) can either increase or decrease to some extent. Then there is a period of stability that, for a properly made bolted bus connection, may be many years [5]. In fact, an experienced utility maintenance engineer may not experience a well-made, bolted, bus joint failure for the entire life of a generating station. However, it takes only one bus joint failure to seriously affect the ability of the station (plant) to generate electricity. As the connection ages, there is a period in which the

performance factor begins to show signs of accelerated aging (or degradation) that needs to be recognized and corrective actions scheduled. This period can eventually result in a “runaway” failure. For example, the bus joint resistance can increase, which is a sign that the joint is under stress and will eventually fail. The runaway failure can occur in a relatively short time, as discussed in Section 7.



Key Technical Point

Once a bolted joint exhibits signs of accelerated aging, failure can occur in a relatively short time.

Parameters Affecting Performance

The parameters affecting the performance of the electrical bolted connection (that is, the bus joint resistance) are shown in Figure 2-2. Here, two main factors control the long-term performance: 1) mechanical factors located at the joint itself and 2) the ambient factors in which the joint finds itself. At the joint, one mechanical factor is the material of the conductors and the material of the bolt that joins them. Another mechanical factor is the mechanical loading at the joint and the circuit current, voltage, and motion—which can affect the joint’s long-term stability. The motion can be caused by vibration and/or changes in the temperature environment. Motion can result in fretting corrosion (micro-motion that increases resistance [6]; see Section 6). The result of these mechanical effects will be a reduction in the true area of contact. The ambient effects are governed by corrosive gases, dust, the formation of intermetallics (chemical compound formations caused by joining dissimilar metals), material creep (physical deformation of material due to mechanical stress), the temperature of the environment, and the current flowing in the bus. Possible causes of bus joint degradation are discussed in Section 6. To control the joint’s long-term reliability, each of these effects needs to be understood. Failure of a connection can result in a catastrophic event [7].

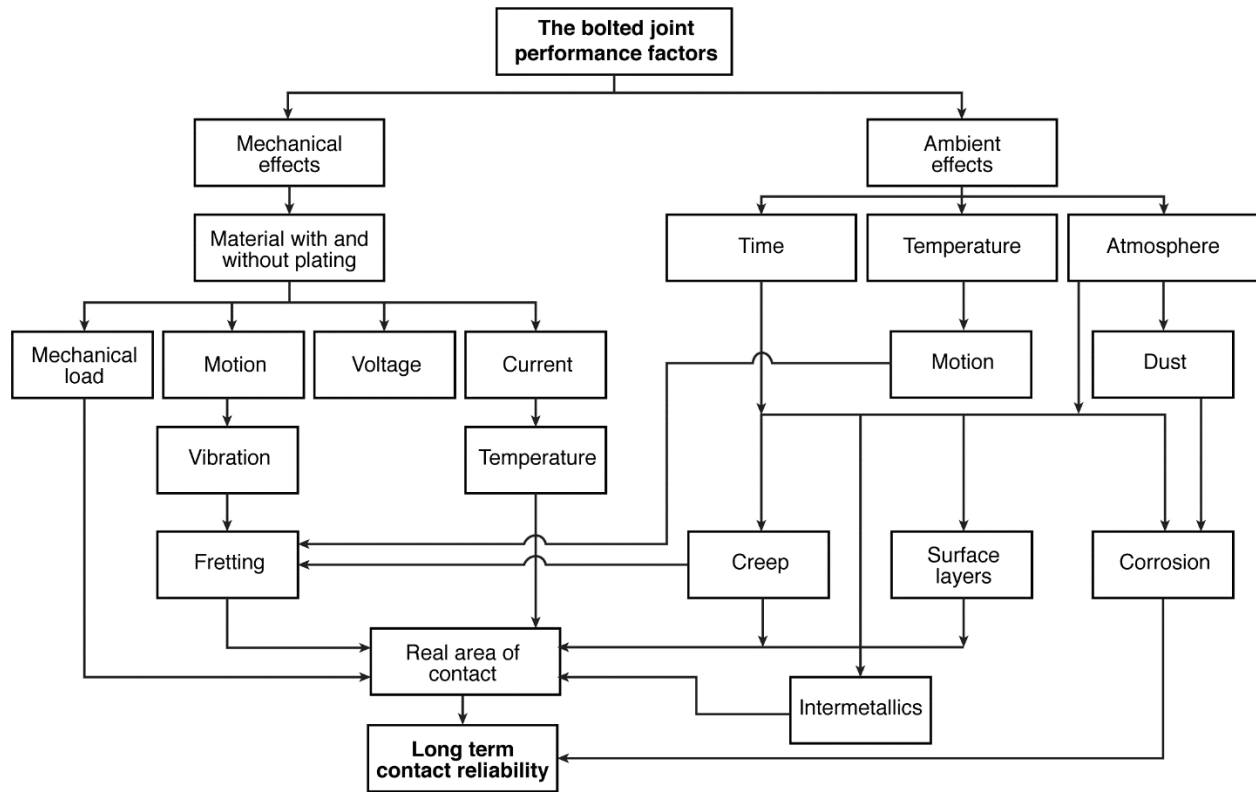


Figure 2-2
Bolted joint performance factors

Failure Modes and Effects

A failure modes and effects analysis (FMEA) was performed; the results are included in Table 2-1.

Table 2-1
Failure modes and effects analysis for bolted busbars

Failure Location	Degradation Mechanism	Degradation Influence	Discovery Methods
Bolted bus joint	Loose bolts	<ol style="list-style-type: none"> 1. Differences in thermal expansion in the presence of a varying temperature environment 2. Bus joints with steel bolts and no Belleville washers 3. Vibration 	<ol style="list-style-type: none"> 1. Measure the bus joint contact resistance (best measurement to detect early onset of failure)* 2. Measure the joint temperature using infrared thermography (will detect only an imminent failure)**
	Intermetallic formation at the joint	With different metals in contact (for example, CuAl), intermetallic formation at the contact spot forms high-resistance spots	<ol style="list-style-type: none"> 1. Measure the bus joint contact resistance (best measurement to detect early onset of failure) 2. Measure the joint temperature using infrared thermography (will detect only an imminent failure)
	Fretting at the joint	Small motion of the contact spots gives rise to higher resistance joints	<ol style="list-style-type: none"> 1. Measure the bus joint contact resistance (best measurement to detect early onset of failure) 2. Measure the joint temperature using infrared thermography (will detect only an imminent failure)
	Reduction of the individual contact spots	Ingress of corrosive or oxidizing gas reduces the effective contact area	<ol style="list-style-type: none"> 1. Measure the bus joint contact resistance (best measurement to detect early onset of failure) 2. Measure the joint temperature using infrared thermography (will detect only an imminent failure)
	Corrosion of the joint	Influence of a corrosive environment	<ol style="list-style-type: none"> 1. Visible inspection 2. Measure the bus joint contact resistance (best measurement to detect early onset of failure) 3. Measure the joint temperature using infrared thermography (will detect only an imminent failure)
	The electric arc	Evidence of arcing at or near the joint	1. Visible inspection (the joint has already failed)
	Damaged insulation	<ol style="list-style-type: none"> 1. Mechanical damage 2. Observation of overheating 	<ol style="list-style-type: none"> 1. Visible inspection 2. The joint has already failed

* Measuring the joint contact resistance is discussed in Section 5.

** The problems with measuring the joint performance using infrared thermography are discussed next in “Measuring Performance: External Temperature Measurement.”

Measuring Performance: Contact Resistance Measurement

The most reliable performance measurement is contact resistance (joint contact resistance for a bolted busbar connection), R_C , and calculating the contact voltage, U_C [8]. This measurement determines most accurately the condition of the connection. Therefore, it is the most reliable way to monitor whether the connection is under stress. The measurement of the total joint resistance (that is, the resistance measured across the total joint) is usually performed when no current is flowing in the bus (when the utility plant is on shutdown). It is possible to measure the joint contact voltage with full load current passing, but this is almost never done. The measurement of the joint contact resistance, R_C , and the calculation of the contact voltage are discussed in Section 5, the cause of increase in R_C in Section 6, and power connection failure in Section 7. One major advantage of this measurement is that it can be used on booted and taped joints.



Key Technical Point

The most reliable performance factor measurement is joint contact resistance, R_C , and calculating the contact voltage, U_C . This measurement determines most accurately the state of the actual connection interface on all bolted connections—even those that are booted or taped. An external temperature measurement is often used but is less reliable in determining the state of the connection's interface.

Measuring Performance: External Temperature Measurement

An external temperature measurement such as infrared thermography (IRT) is often used, but it cannot determine the state of the connection's interface [9]. IRT may show a connection that is not under duress even though the actual contact spot has begun the process toward failure [8, 10]. This is illustrated in Figure 2-3. In Region 1, the bulk of the bus compared to the size of the contact spot area in the connection will maintain the bus temperature at a value close to the ambient temperature even though the actual contact spot may be showing the beginnings of failure. In Region 2, the IRT may show a slight increase in the overall joint temperature, which can be easily overlooked even though the joint has started on its process to failure. When Region 3 is reached, the IRT will show a marked increase in the joint temperature, and joint failure is imminent. This measurement must be performed with the full rated current flow in the bus. The main advantage of IRT is that it gives rapid and easy measurements. It is also used when current is passing in the bus joint. Its disadvantages are low sensitivity, effects of the ambient such as temperature and weather, calibration accuracy especially for temperatures slightly above the ambient, the effects of line load, and the fact that its accuracy is affected greatly if the surface being measured is shiny (highly reflective). It also cannot be used on covered joints, such as booted or taped joints, or if direct access to the bus connection is unavailable. The major advantages of the resistance measurement are its high sensitivity and high accuracy. Its main disadvantages over the thermography measurement are that it takes longer to perform and the power to the bus needs to be disconnected.

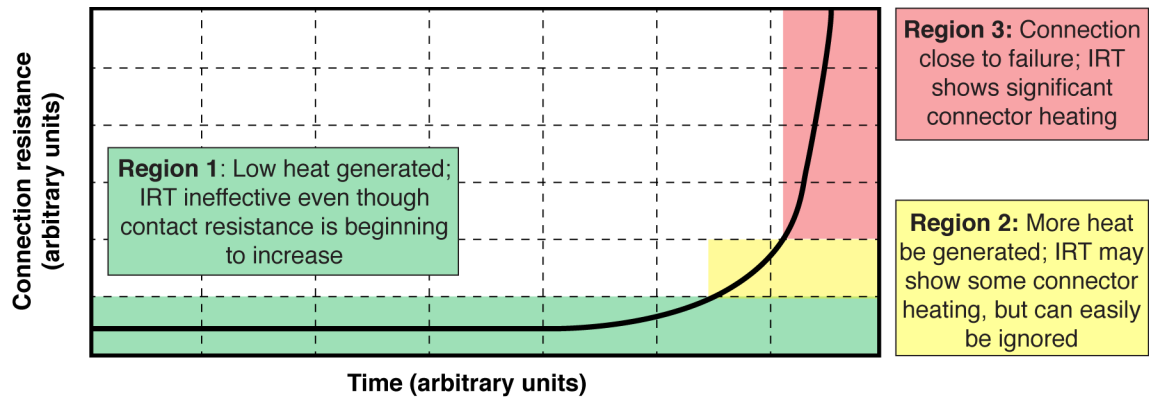


Figure 2-3
The IRT method does not easily detect the initial stages of connector failure



Key Technical Point

Infrared thermography may not catch every possible failure. If it does show an increase in temperature, the joint is in its initial stage of failure.

3

CONTACT RESISTANCES AND TEMPERATURES

This section discusses conductor and contact resistances, contact temperatures, and the melting and softening temperatures of metals.

The following main points are made in this section:

- The actual area of contact is a function of the contact load (bolt torque) and the material's hardness. It does not depend on the total area of the contact face. In other words, the actual area of contact is a function of the bolt torque and the hardness of the connection materials.
- It is possible to estimate the temperature of a contact area by measuring or calculating (using the joint contact resistance \times the bus current) the voltage dropped across the contact surfaces. A very small voltage drop across contact surfaces represents a very high temperature at the contact spots.
- It is important to understand the significance of the metal melting and softening voltage when determining bolted joint connection resistance.

Resistance of a Conductor

When the resistance of the conductor shown in Figure 3-1 is measured, its value is:

$$R_1 = \rho \frac{L}{A} \qquad \text{Eq. 3-1}$$

Conductor resistance = (Material's resistivity) \times (Distance a-b) / Conductor area

Where ρ is the material's resistivity, L is the distance between measured points a and b , and A is the conductor's area.

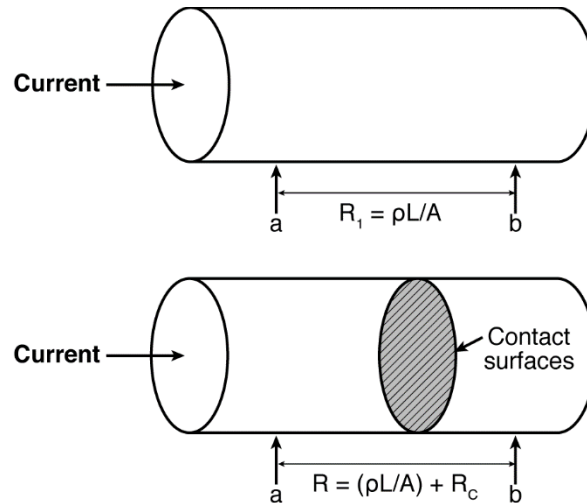


Figure 3-1
Contact resistance

Contact Resistance

If the conductor is cut in two and reassembled, and the resistance is again measured between a and b , the total value is now:

$$R = R_1 + R_C \quad \text{Eq. 3-2}$$

Resistance = Conductor Resistance + contact resistance

Where R_C is the contact resistance that results when two metals make contact. The reason for the added resistance is that no matter how carefully the cylinders' faces are prepared, they will never be perfectly flat. Indeed, they will make contact only at certain discrete points on these flat surfaces, introducing an additional R_C component [11–13]. A high-magnification picture taken of a smooth metal surface reveals several microscopic peaks and valleys at the cut. Therefore, when two such surfaces are brought together, they initially touch at the two highest micro-peaks. This is shown conceptually in Figure 3-2.

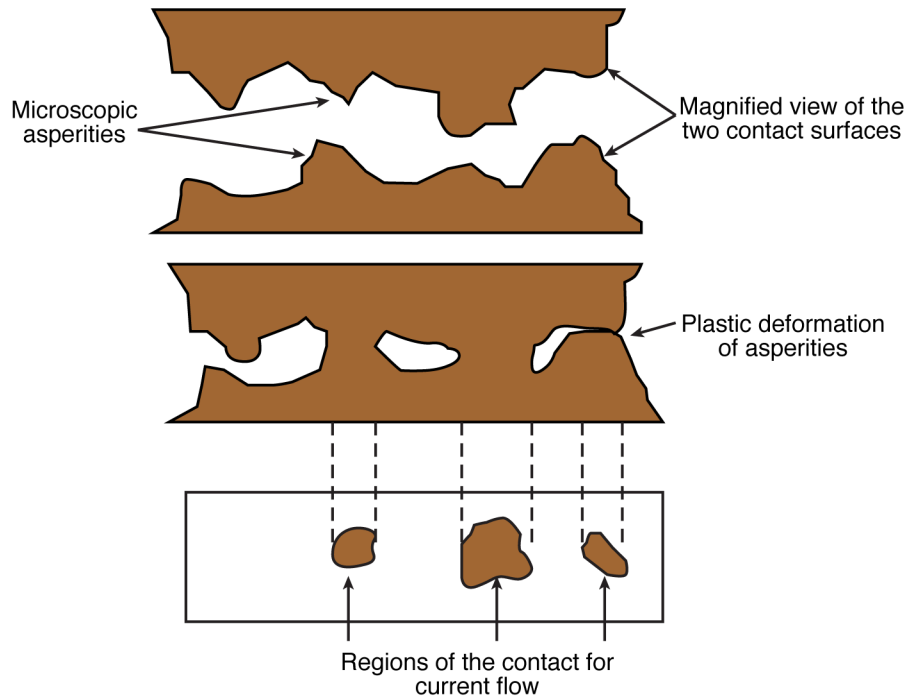


Figure 3-2
The contact surface and the real area of contact

Even under light loads, the pressures at these peaks will be very high [11, 12], so the peaks will deform plastically. As the first two micro-peaks deform, more micro-peaks will come into contact and in turn will deform plastically. This process will continue until the force on the contact surfaces is fully supported by a small number of microscopic contact spots.

The process can be represented by Equation 3-3:

$$\text{Contact load} \approx [\text{contact material's hardness}] \times [\text{The sum of the microscopic areas of contact}]$$

or

$$F = \xi x H x \Sigma A_n \quad \text{Eq. 3-3}$$

Where ξ is a constant (it is ≈ 1 for plastic deformation) and n is the n^{th} microscopic contact spot. It can be seen that Equation 3-3 implies that the actual area of contact, ΣA_n , depends only on the surface contact force F and the contact material's hardness H ; it does not depend on the total area of the contact face. This is true for contact surfaces carrying very low currents (for example, in electronic circuits) as well as for contact surfaces carrying the range of currents found in power systems (for example, 50 A to 80 kA). When analyzing how to interpret ΣA_i , it has been shown that it can be represented by a disk of radius a called the *Holm radius* [11–13]. Therefore:

$$\Sigma A_n = A_c = \pi a^2 \quad \text{Eq. 3-4}$$

$$A_c = F / H \quad \text{Eq. 3-5}$$

and

$$a = (F / \pi H)^{1/2} \quad \text{Eq. 3-6}$$

Figure 3-3 illustrates this for a 10^4 change in surface contact force. As the force on the same area of contact increases, the microscopic contact area increases as the metal is plastically deformed.

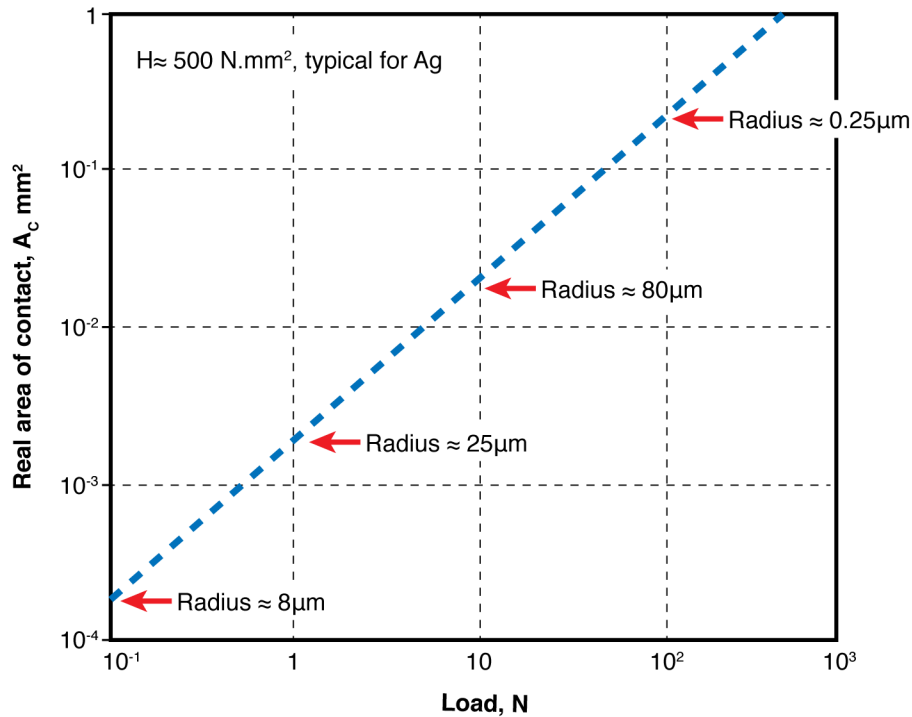


Figure 3-3
The real area of contact, A_c , for silver as a function of the contact load



Key Technical Point

The actual area of contact is a function of the contact load (bolt torque) and the material's hardness. It does not depend on the total area of the contact face. In other words, the actual area of contact is a function of the bolt torque and the hardness of the connection materials.

The Real Area of Contact for a Small Disk of Radius a

Consider Figure 3-4, where a disk-shaped area A_c of radius a is achieved after the contact surfaces have been forced together.

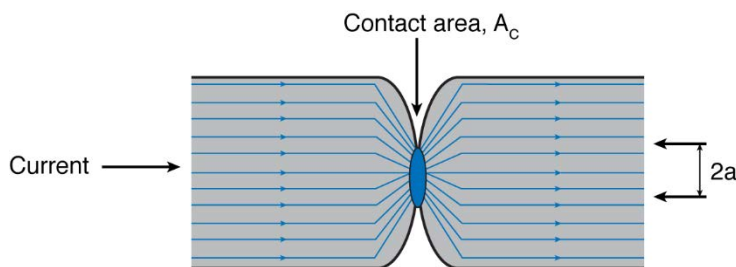


Figure 3-4
Contact resistance and the area of contact

The flow of current from one contact surface to the other would then be constrained to flow through this area, A_c . The constriction resistance, R_K , is given by Equation 3-7 [11–13]:

$$R_K = \frac{\rho}{2a} \tag{Eq. 3-7}$$

Constriction Resistance = (Material Resistivity) / (2 × the radius of the contact area)

Where ρ is the resistivity of the contact material. Substituting from Equation 3-5 and noting that the contact area $A_c = \pi a^2$, the actual constriction resistance accounting for the material hardness and force keeping the contact surfaces under load is

$$R_K = \frac{\rho}{2} \sqrt{\frac{\pi H}{F}} \tag{Eq. 3-8}$$

Constriction Resistance = The Material’s Resistivity/2 × Square root ($\pi \times$ Material Hardness/ Force)

While Equations 3-7 and 3-8 are for two surfaces connected, they do not take into account any film layer or oxide layer that may be on the surfaces being connected. The total resistance would have to add in this film resistance, R_F . If R_F is the resistance of any film (for example, an oxide layer), the total contact resistance R_C is given by ($R_C = R_K + R_F$). In practical applications, this film resistance is usually not significant in a well-made joint; if R_F is zero, then:

$$R_C = R_K \tag{Eq. 3-9}$$

Contact Resistance = Constriction Resistance

Figure 3-5 shows an example of how experimental data match Equation 3-8 [14].

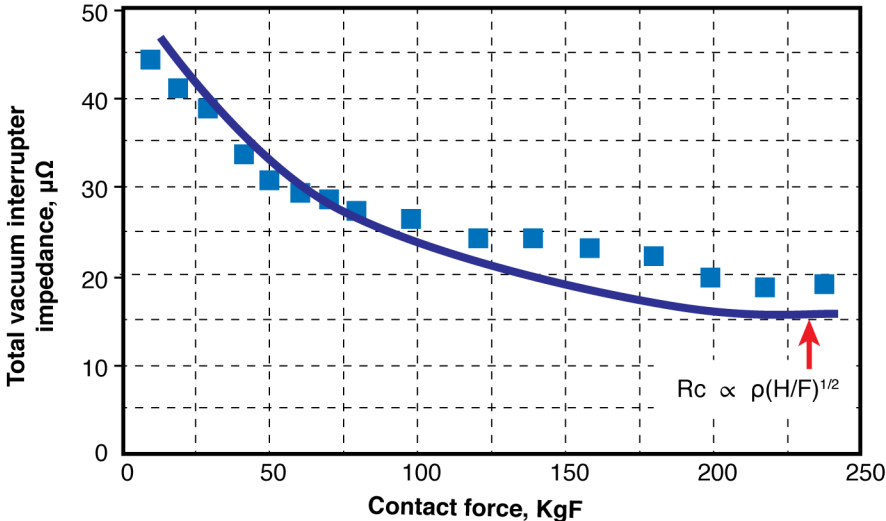


Figure 3-5
Contact resistance as a function of contact force

The actual contact spot is usually not just one spot as shown in Figure 3-4. In most practical contact systems, the region of actual surface contact is made up of several microscopic contact spots distributed within an overall contact region. Fortunately, calculations on randomly arrayed contact spots with a practical distribution of diameters [11–13] show that the microscopic effect of these spots gives a similar relationship to those given in Equations 3-5 through 3-8 with an average microscopic radius of contact like the one shown in Figure 3-4. For practicing engineers, Equations 3-7 and 3-8 give values of contact resistance, which are close enough to the real value (within 20%). These two equations satisfy most practical situations because the constriction of the current as it travels to the region of contact does not recognize that there are individual microscopic contact spots until the current flow is extremely close to each contact's surface. While the individual micro-contact spots do determine the final current path, most of the current constriction effect—and therefore the effect on the contact resistance—has already occurred. It is also fortunate that the average contact radius shown in Figures 3-3 and 3-4 gives an equivalent area of plastic deformation of the contact surface roughly equivalent to the sum of areas of all the individual contact spots.

Contact Resistance and Contact Temperature

As the total contact resistance (R_C) increases, so does the power input at the contact junction. The increase in total resistance results in a temperature increase at the contact junction. The increase in temperature can result in a temperature that can be high enough for the microscopic contact interface areas—the contact spots—to melt. It is therefore useful to estimate the temperature of the contact junction without having to actually measure the resistance.

Calculating Contact Temperature

It is a straightforward procedure to measure the contact voltage drop or to calculate it (using the joint contact resistance \times the bus current) across a contact joint. If we take any conductor and assume that the lines of equi-potential are the same as the lines of equi-temperature and that there is no heat loss by radiation and convection, it can be shown that [15, 16]:

$$\left(\frac{U_c}{2}\right)^2 = 2 \int_{T_b}^{T_p} \lambda(T) \rho(T) dT \quad \text{Eq. 3-10}$$

Where U_C is the voltage drop across the conductor, T the absolute temperature in degrees Kelvin, T_b the ambient temperature, T_p the maximum temperature the conductor reaches, ρ the resistivity, and λ the thermal conductivity. Using the Wiedemann-Franz law:

$$\rho(T)\lambda(T) = LT \quad \text{Eq. 3-11}$$

Where L is the Lorenz constant given by [16]:

$$L = \frac{\pi^2}{3} \left[\frac{k}{e} \right]^2 \quad \text{Eq. 3-12}$$

Where k is Boltzmann's constant, e is the electronic charge, $L = 2.45 \times 10^{-8} \text{ W } \Omega / (\text{degrees Kelvin})^2$. Integrating Equation 3-10 gives:

$$U_c = [4L \{T_p^2 - T_b^2\}]^{1/2} \quad \text{Eq. 3-13}$$

The contact voltage = square root of {4 times the Lorenz constant × ([temperature at the contact region (in degrees Kelvin)] squared minus [the ambient temperature (in degrees Kelvin)] squared}

If $T_p \gg T_b$ (Kelvin), this can be reduced to:

$$T_p = U_c / [2 \sqrt{L}] \tag{Eq. 3-14}$$

Maximum conductor temperature (in degrees Kelvin) = contact voltage / 2 × square root of the Lorenz constant

Figure 3-6 presents the expected temperature of the contact spot as a function of the measured voltage across a contact surface and for two values of ambient temperature, T_b . It is therefore possible to obtain a good estimate of the temperature of the actual contact junction by simply measuring the voltage across the contact surfaces. The power loss at a practical joint is not entirely drawn off by conduction. It is possible for the power losses to be dissipated by convection and radiation. Therefore, the temperature calculated using Equation 3-13 can be somewhat smaller than the actual temperature in the contact region. It is interesting to note that a fraction of a voltage drop across the contact surfaces can represent a high temperature at the region of contact (for example, if the voltage across a copper contact surface is only 0.43 V, the microscopic contact spots will be molten [see Table 3-2]).



Key Technical Point

It is possible to estimate the temperature of a contact area by measuring the voltage drop across the contact surfaces by calculating it (using the joint contact resistance × the bus current). A very small voltage drop across contact surfaces represents a very high temperature at the contact spots.

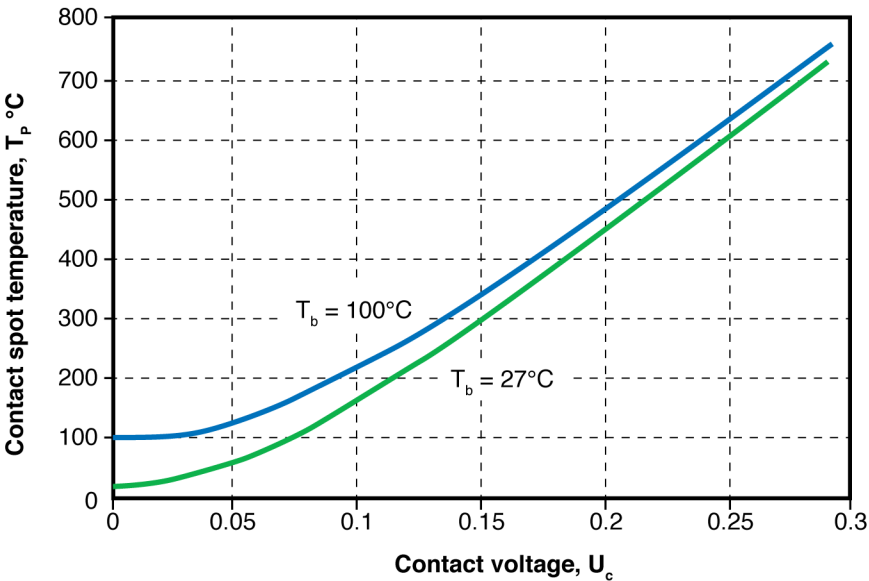


Figure 3-6
The contact spot temperature as a function of the voltage drop across the contacts calculated from Equation 3-13

The contact voltage U_C is given by:

$$U_C = R_C \times i \quad \text{Eq. 3-15}$$

Where i is the current flowing in the joint and R_C is the contact resistance. If you apply a safety factor for measurement errors and instrumentation tolerance (see, for example, Section 5), then for a well-made bolted connection, the voltage drop across the connection should be about 10 mV or less. Putting $U_C = 10$ mV in Equation 3-13 and for $T_b = 300$ K gives:

$$T_p - T_b = 1.2^\circ\text{C} \quad \text{Eq. 3-16}$$

The maximum temperature at the contact spot minus the bulk temperature of the bus = 1.2°C .

This a precautionary measure, but it is understandable because all degradation mechanisms such as oxidation, lubricant or inhibitor loss, interdiffusion of metals, and the formation of intermetallics, creep, and stress relaxation (see Section 6) are an exponential function of temperature [17]. Therefore, if you have a bus system that will carry 2000 A (rms) (that is, a peak current of 2828 A):

$$10 \text{ mV} = 2000 \times \sqrt{2} \text{ A} \times R_C \Omega \quad \text{Eq. 3-17}$$

Because $10 \text{ mV} = 2828 \text{ amperes} \times$ the contact resistance, a 10 mV drop at the joint carrying 2000 A (rms) will result in:

$$R_C = 3.5 \times 10^{-6} \Omega \text{ or } 3.5 \mu\Omega \quad \text{Eq. 3-18}$$

Therefore, in general, the contact resistance for power connections should be in the $\mu\Omega$ range; see, for example, Table 3-1.

Table 3-1
Example of contact resistance values to give a 10 mV contact voltage as a function of bus current

Recommended contact voltage for a new bus joint 10 mV				
Bus current	500 (rms)	1000 (rms)	2000 (rms)	3000 (rms)
A	707 (peak)	1414 (peak)	2828 (peak)	4243 (peak)
Contact resistance	14	7	3.5	2.3
$\mu\Omega$				

Note: If the bus joint is subjected to overload currents or has to withstand fault or short-circuit currents, the R_C values required will be much smaller. It is important to consider the effect of these higher currents because the time constant of the temperature rise at the contact spot is a few milliseconds, that is, less than one half cycle of the ac current. Therefore, during the passage of a short-circuit current, it is possible for the contact spots to soften or melt.

The Melting and Softening Temperature of Metals

Important considerations when determining bolted joint connection resistance are the melting and softening voltages of metals and their associated melting and softening temperatures. Using Equation 3-13, the melting voltage of a metal is given by:

$$U_m = [4 L \{T_m^2 - T_b^2\}]^{1/2} \quad \text{Eq. 3-19}$$

Where T_m is the metal's melting temperature in degrees Kelvin.

Melting voltage = square root of {4 times the Lorenz constant \times ([the material's melting temperature (in degrees Kelvin)] squared minus [the ambient temperature (in degrees Kelvin)] squared)}

The softening temperature is usually 25% to 45% of the material's melting temperature. The softening temperature is the point at which the metal softens and can deform plastically very easily. Equation 3-13 allows us to define a softening voltage U_s as:

$$U_s = [4 L \{(S T_m)^2 - T_b^2\}]^{1/2} \quad \text{Eq. 3-20}$$

Where S is a constant between 0.25 and 0.45, T_m is the melting temperature (in degrees Kelvin), and T_b is the ambient temperature (in degrees Kelvin).

Softening voltage = square root of {4 times the Lorenz constant \times ([a constant S {between 0.25 and 0.45}] times [the material's melting temperature (in degrees Kelvin)] squared minus [the ambient temperature (in degrees Kelvin)] squared)}

Table 3-2 shows experimentally determined melting and softening voltages for common contact materials. An extensive list can be found in Reference [18], Section 24. Table 3-2 also shows the value of the contact resistance to reach the melting voltage for currents 1–3 kA.

As Table 3-2 shows, the melting and softening voltages for all of these common contact metals are much greater than the initial 10 mV value recommended in Table 3-1. If a joint reaches these values, it will be far advanced in the failure mode.

Table 3-2
The melting and softening voltages for common contact materials

Metal	Melting Temp. T_m C	Melting Voltage U_m V	Contact Resistance R_c $\mu\Omega$ at the Melting Voltage for Usual Bus Currents			Softening Temp. T_s C	Softening Voltage U_s V	Contact Resistance R_c $\mu\Omega$ at the Softening Voltage for Usual Bus Currents		
			1 $\sqrt{2}$ kA	2 $\sqrt{2}$ kA	3 $\sqrt{2}$ kA			1 $\sqrt{2}$ kA	2 $\sqrt{2}$ kA	3 $\sqrt{2}$ kA
Cu	1083	0.43	304	152	101	190	0.13	91	46	30
Al	660	0.3	212	106	70	150	0.1	70	35	24
Ag	961	0.37	262	131	87	180	0.1	70	35	24
Sn	222	0.13	92	50	31	100	0.07	49	25	16
Ni	1453	0.54	382	191	127		0.16	113	57	38



Key Technical Point

It is important to understand the significance of the metal melting and softening voltage when determining the bolt joint contact resistance, especially if there is a possibility that the bolted connection will be subjected to the passage of a fault or short-circuit current.

The softening and/or melting temperatures in the contact region, if they occur, would most likely occur during the passage of a fault or short-circuit current. At the softening temperature, the hardness H in Equation 3-8 will decrease, which will result in a decrease in the contact resistance R_C . While this might appear to be a positive effect, the high temperature involved will stress the joint mechanically and will affect any corrosion process that can occur at the joint. If there is any evidence that either the softening or melting temperature at the contact spot has been reached, the joint should be taken apart and remade.

4

THE BOLTED BUS CONNECTION

Typical Bus Materials

The two major materials used for the electrical bus are copper (Cu) and aluminum (Al). Copper buses have been used since the beginning of electrical distribution. Aluminum has been used since the early 1900s. After about 1946, the aluminum used for bus applications was a relatively soft alloy (1350); since that time, harder alloys (for example, 6351, Al-Mg-Si) have been successfully introduced in the electric industry. Some typical properties of copper and aluminum are given in Table 4-1.

Table 4-1
Typical material properties of copper and aluminum

Property	Copper	Pure Aluminum	6351 Aluminum
Density, g.cm ⁻³	8.94	2.70	~2.70
Resistivity, μΩ.cm	1.68	2.82	3.8
Thermal expansion, 10 ⁻⁶ K ⁻¹	17	28.2	24
Tensile strength, MPa	380	200	310

The copper and aluminum densities have a ratio of 3:1. Therefore, copper is three times heavier than an equal volume of aluminum. The resistivity of aluminum is higher than that of copper, which means that the cross-sectional area of aluminum must be greater than that of copper for a given current. Aluminum is a better conductor than copper per kilogram of material by a factor of 2. Aluminum also has a significantly lower cost—six times lower—than copper per ampere. It should be noted that the 6351 aluminum alloy has a tensile strength closer to that of copper than pure aluminum and even 1350 aluminum alloy (which is closer to that of pure aluminum). Aluminum is frequently plated, commonly with silver (Ag). However, silver cannot be plated directly onto aluminum—it must be plated over another material. Two plating processes for plating aluminum are shown in Figures 4-1 and 4-2. These figures also show that the same processes can be used to plate tin (Sn) to aluminum.

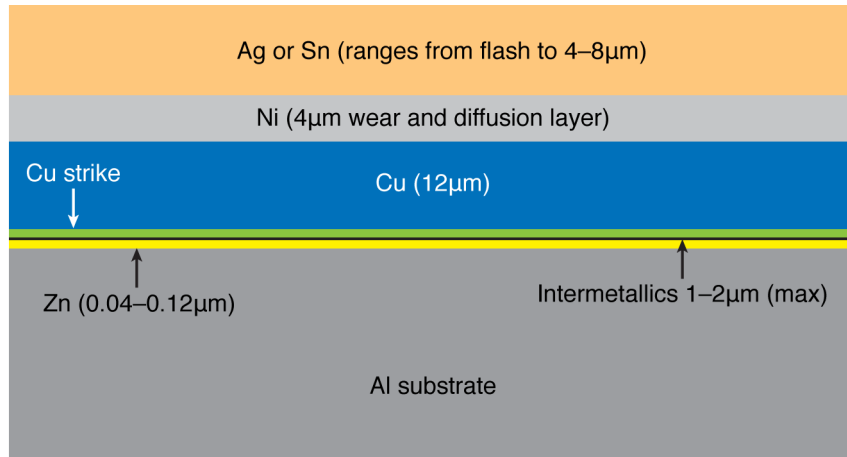


Figure 4-1
The Zincate process for plating Al bus

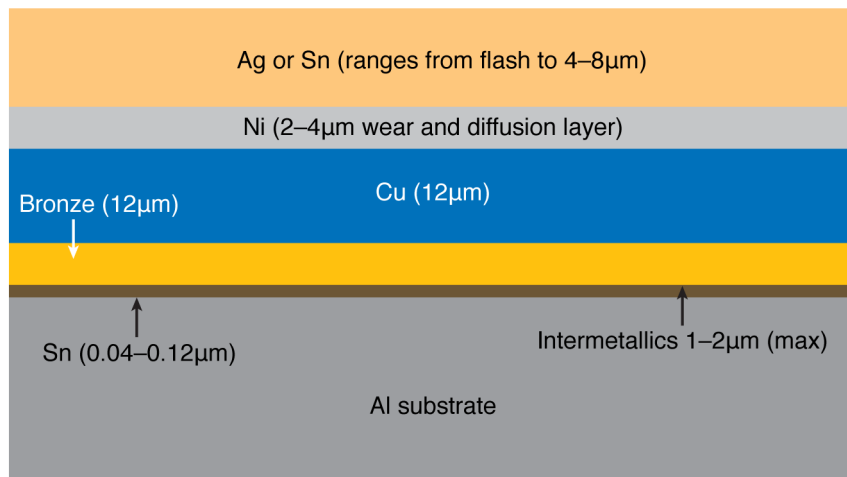


Figure 4-2
The Alstan process for plating Al bus

The Bolted Connection

A bolted connection is illustrated in Figure 4-3.

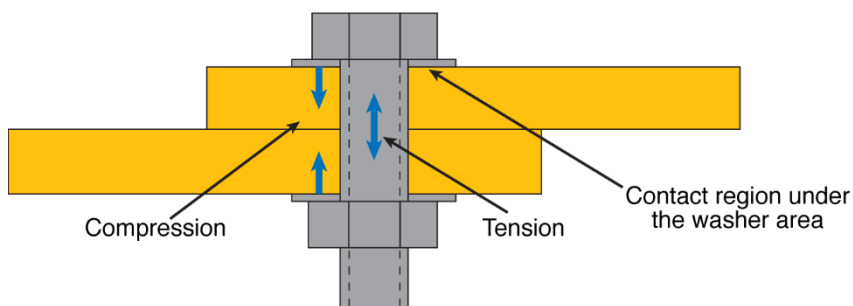


Figure 4-3
Bolted connection

Note that actual contact is made under the washer area [19]. This is illustrated in Figure 4-4.

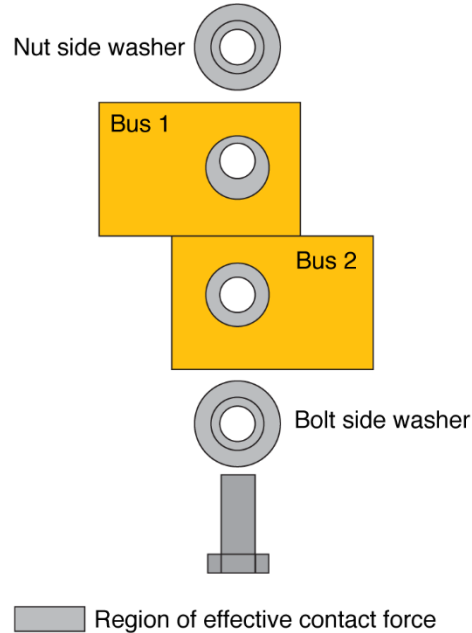


Figure 4-4
The bolted connection with flat washers illustrating the regions of contact force

As the bolt is tightened, it is placed in tension and minutely stretched. The bolt acts like a spring and applies a compression force that clamps the two busbars together. The bolt should be loaded to a clamping force in the elastic range of the bolt, based on its type, rating, and material. By keeping the bolting in the elastic range of the fastener, changes in temperature will maintain the clamping load because the bolt will be able to expand and contract like a spring. If the bolt is overtightened, either to the upper end or outside of its elastic zone, it could reach its yield strength when in service. When a bolt reaches its yield strength, it will stretch, permanently deform, and will not be able to maintain compression on the joint. The contact force on the busbars can be calculated if the torque, \bar{T} , on the bolt is known:

$$\bar{T} = KDF \quad \text{Eq. 4-1}$$

Torque = nut factor \times bolt diameter \times force

Where \bar{T} is in inch pounds (in.lb), D is the bolt diameter in inches, K is the nut factor (= 0.2 for dry bolts and 0.16 for lubricated bolts), and F is in pounds. Again, care must be taken not to exceed the yield strength of the bolt.

Aluminum Connections

Aluminum oxidizes rapidly when exposed to air. The oxide layer is very thin and forms a protective insulating layer. When making aluminum connections, this oxide layer must be overcome; following is a common method:

1. Remove any dirt and grease from the Al surfaces with a solvent.
2. Apply a protective lubricant or joint compound to surfaces.
3. Abrade the Al surface under the protective lubricant or joint compound with a fine-wire steel brush.
4. Apply a layer of joint compound.
5. Bolt the joint immediately, making sure that the joint compound is visible at each edge of the joint.

The abrading process breaks up some of the surface oxide, and the covering fluid prevents the re-formation of the aluminum oxide. It also roughens the aluminum surface, which can also break through some of the remaining oxide and therefore help make a low-resistance connection (see Figure 4-5).

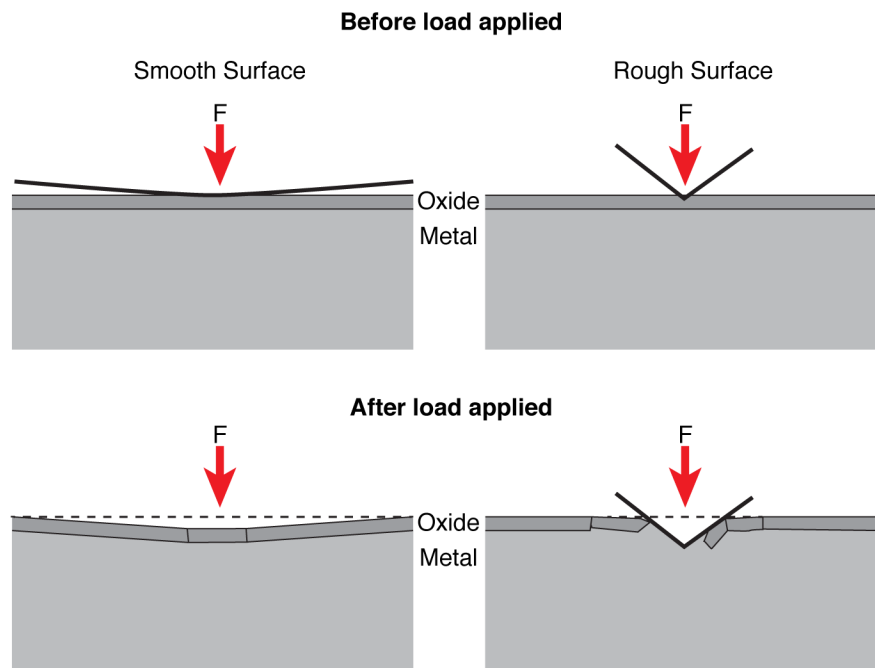


Figure 4-5
A roughened surface breaking through a thin oxide layer



Key Technical Point

Aluminum oxidizes rapidly when exposed to air. When making connections with aluminum conductors, the effects of this thin insulating aluminum oxide layer must be overcome through the use of an abrading process under joint compounds to prevent aluminum oxides re-forming.

Table 4-2 shows the effect of abrading, lubricating, and oxide formation on the resistance of a bolted aluminum joint [20].

Table 4-2
The effect of different preparations of a bolted aluminum bus connection

Aluminum Bus Preparation	Total Joint Resistance, $\mu\Omega$
Uncleaned contact surfaces making contact	15
Contacts cleaned and lubricated and immediate contact made	6
Contacts cleaned and exposed to air 60 hours before making contact	15
Contacts cleaned, lubricated, and exposed to air before making contact	9
Straight piece of bus the same length of the measured joints	5

As can be seen from this example, the effect of bolting two Al surfaces with no preparation gives a high value of the total joint resistance. It also illustrates how quickly the oxide layer forms on a freshly cleaned Al surface. When the contacting surfaces are cleaned and immediately bolted with a lubricant, the joint resistance is appreciably lower. The calculation of the joint's contact resistance, R_C , using these data is discussed in Section 5.

Joint Compounds

Many joint compounds are available for Al-to-Al contact structures. A study of joint compounds that have been used for aluminum-to-aluminum and for aluminum-to-copper joints shows that some are more effective than others [21]; see Table 4-3. Here the author determined an arbitrary "Index" of performance of these materials: the lower the number, the better the compound's performance.

Table 4-3
The effectiveness of commonly used joint compounds

Al to Al	Index	Al to Cu	Index
Contact aid compound		Contact aid compound	
Penetrox A – 13	0.7	Nikkel S – 200	0.7
Silicone vacuum grease	07	Koprshield Cp – 8	1.0
Penetrox – A	0.8	Penetrox A – 13	1.0
Aluma Shield	1.2	Pefco	1.0
Fargolene GF – 138	1.2	No-Oxide – A	1.3
Fargolene GF – 158	1.2	Fargolene GF – 158	1.4
Contactal HPG	1.3	Silicone vacuum grease	1.5
Petroleum jelly	1.3	Nonlubricated	1.6
ZLN 100	1.5	Contactal HPG	1.8
Alcan inhibitor	2.5	Petroleum jelly	1.9
Kearnalex	2.5		
Nonlubricated	2.6		

Copper bus and silver-plated bus when cleaned of oxide (sulfide) take much longer for the oxide to re-form, so when preparing a copper-to-copper or a silver-to-silver connection, there is no need to perform this process under a protective lubricant. A joint compound is also frequently used with these bus connections. The joint compound in this case is primarily used to prevent the ingress of oxidizing or corrosive gases between the two mating busbars. If the joint is aluminum bus to copper bus, the aluminum should be prepared—under a protective compound—using the common method shown in the “Aluminum Connections” subsection.

Thermal Expansion of Different Materials

Figures 4-6 and 4-7 show bolted connections. The bolt material most commonly used is either steel or stainless steel. When using steel or stainless steel material with aluminum and copper materials, the effects of their different coefficients of expansion must be considered. Table 4-4 shows the values for aluminum, copper, brass, steel, and stainless steel.

Table 4-4
Expansion coefficients

Material	Coefficient of Linear Expansion $\times 10^{-6} \text{ K}^{-1}$	Coefficient of Volumetric Expansion $\times 10^{-6} \text{ K}^{-1}$
Al	24	69
Cu	17	51
Brass	19	57
Steel	~ 12	~ 36
Stainless Steel	~ 14	52

From Table 4-4, there is a considerable difference between the expansion coefficients of aluminum (Al) and steel [22]. As the temperature increases, aluminum will expand more than the steel. The difference between the expansion rates will tend to produce a very large force on the aluminum joint, which can cause the metal to creep. When aluminum bus is used, it is important to consider the stress relaxation of the bus material. Because the expansion coefficient for copper (Cu) is closer to that of steel, the effect on a copper-to-copper joint using a steel bolt—though still present—will not be as severe. The difference in thermal expansion must also be considered when mating aluminum bus to copper bus [5]. To alleviate problems that can result from the different expansion coefficients among different materials, it is important to use a conical spring washer such as a Belleville washer when bolting the electrical bus as illustrated in Figures 4-6 through 4-8 [23–26]. If a copper-to-copper joint reaches a temperature greater than 105°C —whether through the passage of high current or from the ambient—Belleville washers will permit maintenance of the original applied contact force [27].



Key Technical Point

The difference in thermal expansion rates must be considered when mating different materials together. To alleviate problems from the different expansion coefficients among materials, it is important to use a Belleville washer.

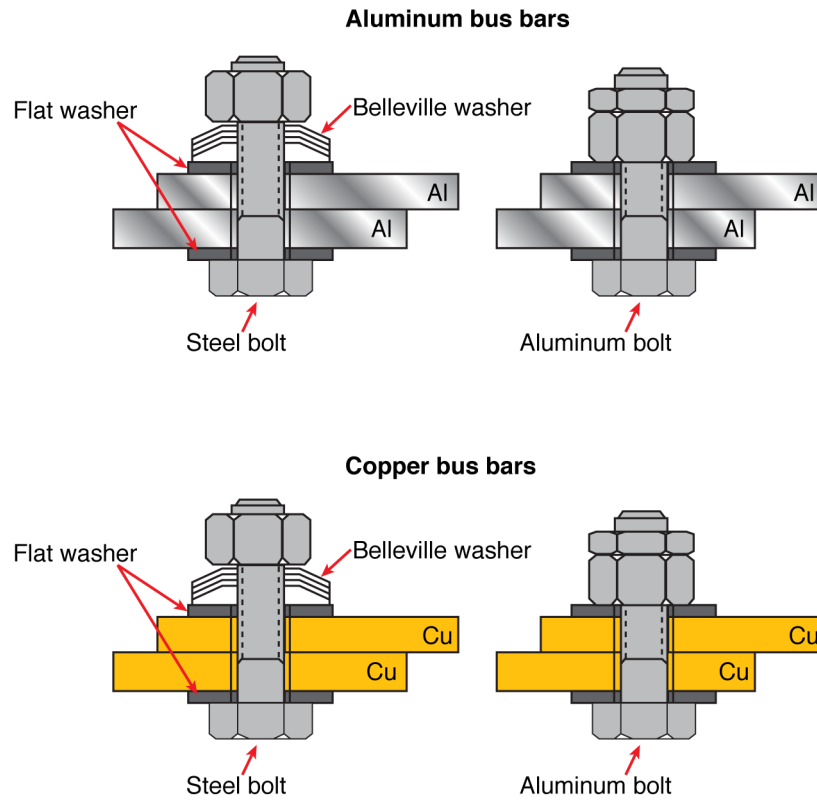


Figure 4-6
Bolted connection for aluminum and copper buses with Belleville washers

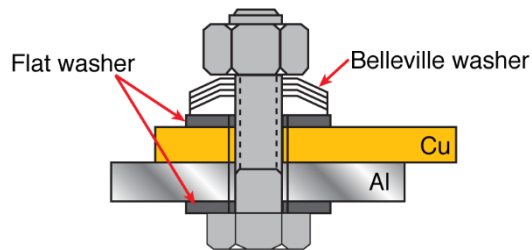


Figure 4-7
Bolted connection for aluminum-to-copper bus with Belleville washers

Another advantage of using a Belleville washer is that the contact force at the bus joint is spread over a larger area. This is illustrated in Figure 4-8.

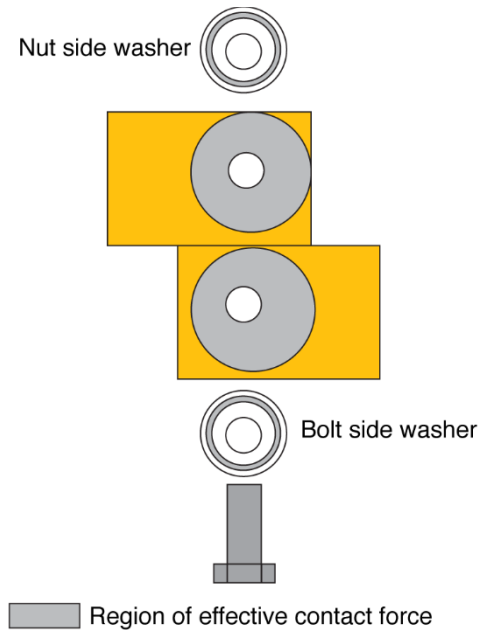


Figure 4-8
The bolted connection with Belleville washers together with flat washers illustrating the regions of contact force

For a joint using a Belleville washer to be successful, the correct size for the bolt and the required torque should be chosen. The flat washer should also have a larger diameter than the Belleville washer to prevent the edges of the washer from cutting into the bus metal.

Optimum Bus Overlap

There is an optimum bus overlap to maximize current flow from one bus member to the next (see Figure 4-9) [28]. This optimum calculation is for the ideal case in which contact is made across the entire face of the two connecting buses. The usual practice, however, is to overlap the bus with a length equal to the bus width. When a wide bus is bolted with four bolts (for higher current applications), the joint usually gives satisfactorily low contact resistance. There will be an optimum number of bolts for a given bus dimension. While the bolts can give a lower contact resistance, their bolt holes can reduce the current-conducting area of the bus itself.

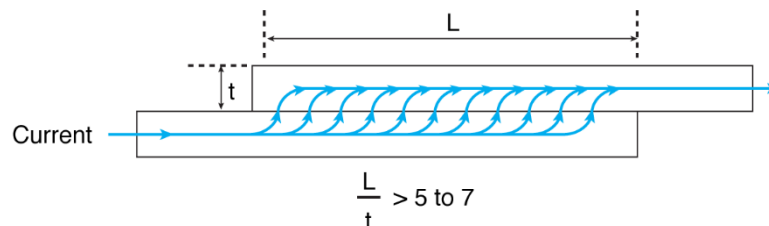


Figure 4-9
Optimum overlap for current flow in a bolted bus joint

When busbars form a bolted joint, the actual contact areas are in the region of the bolts and washers as shown in Figures 4-4 and 4-8. Figure 4-10 illustrates this for a two-bolt connection.

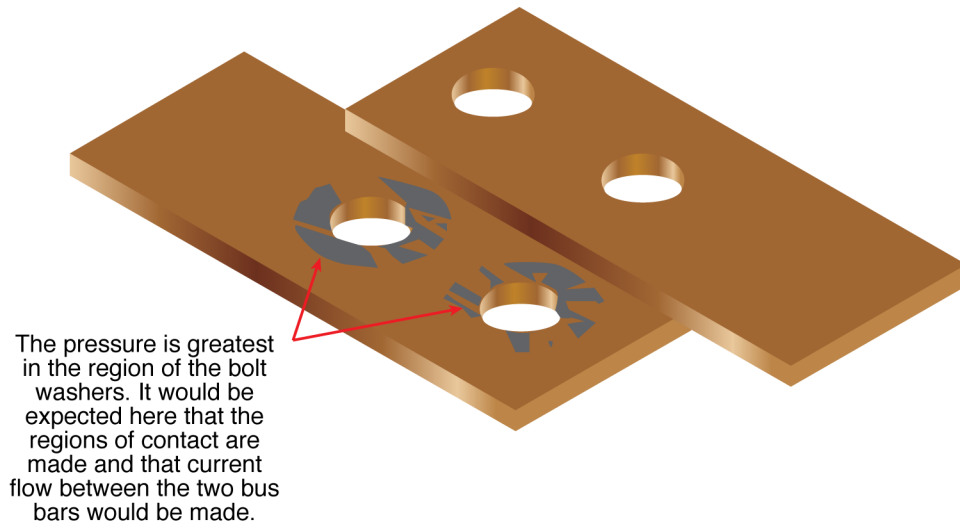


Figure 4-10
Pressure and probable current path in the region of the bolted connections

Because the current passage between the connecting bus would be mostly concentrated in the regions below the bolt washers, it is expected that the current would not be the ideal passage shown in Figure 4-9. Figure 4-11 illustrates the expected current path.

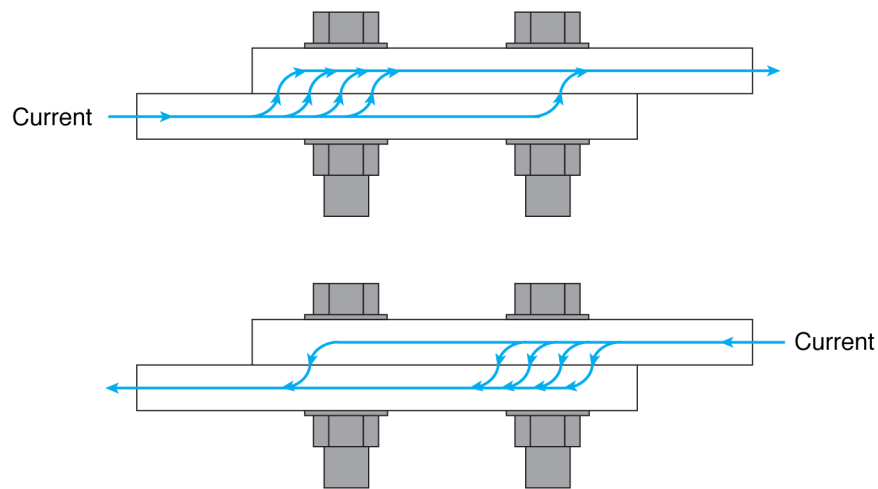


Figure 4-11
An illustration of the current flow between bolted buses

Under ac current, the current flow changes direction each half-cycle. In the top of Figure 4-11, when the current flows from the left, the first bolted region on the left will have the greatest current passage and produce the greatest stress at the contact regions there. In the bottom of Figure 4-11, when the current flows from the right, the bolted region on the right will have the greatest current passage—stressing the contact regions there.

5

MEASURING CONTACT RESISTANCE

Figure 5-1 shows the ideal way to measure contact resistance. In this example, there is a separation of the current path from the voltage measurement—so only the actual voltage at the contact spot is measured. The resistance of the current leads should not be added to the spot resistance [29].

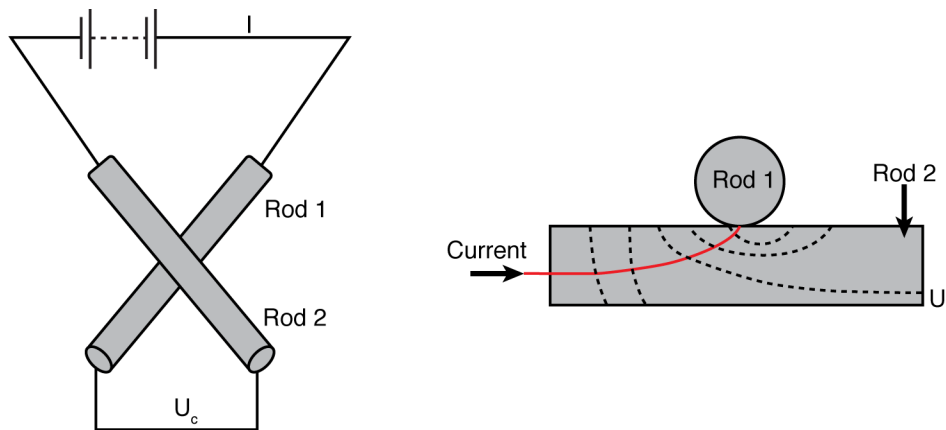


Figure 5-1
The ideal way to measure contact resistance

Contact researchers have long determined contact resistance by using the crossed-rod contact structure shown in Figure 5-1. Here the contact spot voltage U_C is measured directly because the voltage drop across the current conductors is not included. The current i path is independent from the contact voltage measurement. If the contact resistance is R_C , then:

$$R_C = U_C / i$$

Eq. 5-1

Concept of the Contact Resistance for a Bolted Bus Joint with Multiple Bolts

Utility bus joints are usually made with more than one bolt. Figure 5-2 illustrates an overlapping bus joint with four bolts.

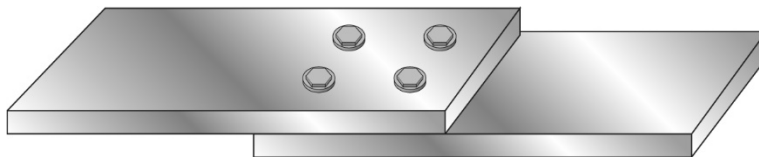


Figure 5-2
A bus connection using four bolts

The current flowing through this connection will experience a combined resistance from the individual contact resistances produced by each of the bolted regions. In addition, the resistance of the bus sections themselves will be reduced by the bolt holes reducing the average area of each bus. The measurement of resistance across this joint will produce an average joint resistance (or total joint resistance). Determining the joint contact resistance for bolted bus joint is not as straightforward as shown in Figure 5-1.

Figure 5-3 shows the direct way to obtain a reasonable estimate of the joint contact resistance, R_C , for a bus connection. Because it is not always possible to measure the contact resistance at the joint itself, the joint contact resistance can be calculated by measuring the total joint resistance R_1 across the bus joint some distance from it and also across an equal length of open bus, R_2 ; then the joint contact resistance, R_C , is approximately:

$$R_C = R_1 - R_2 \quad \text{Eq. 5-2}$$

Therefore, a good approximation of a bus joint contact resistance is:

The joint contact resistance = the total measured resistance across the joint – the resistance of an equal length of the bus that makes up the joint

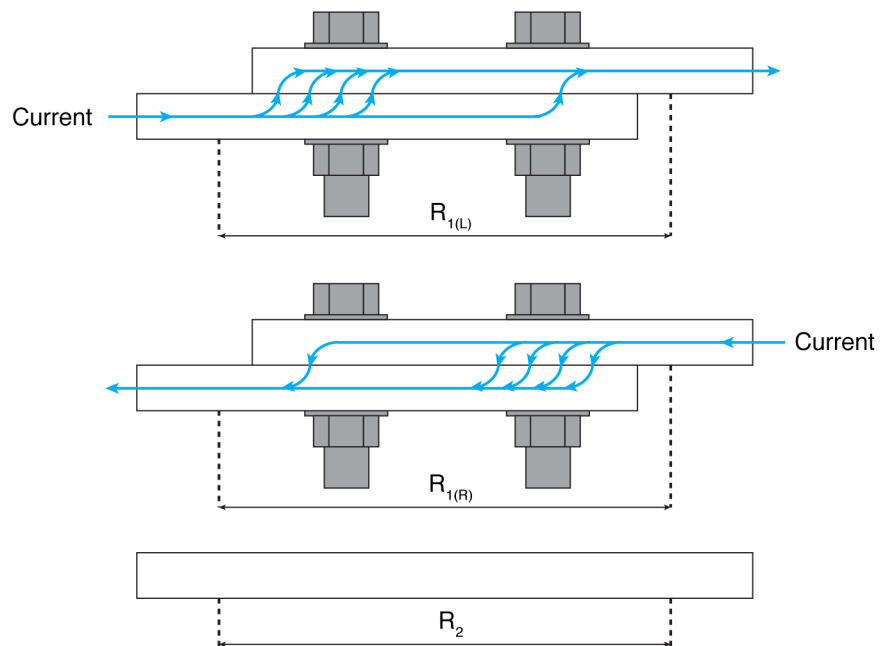


Figure 5-3
Measuring the joint contact resistance, R_C , for a bus connection

A digital low resistance ohmmeter (DLRO) using a battery current of 10 A [30] is used by most utilities to measure contact resistance (there is now a 100 A version); the voltage and current leads are contained inside of the probes of the instrument. The manufacturer of the DLRO gives the accuracy of the resistance measurement to between 2% and 5%. If the resistance measurement is performed with a DLRO that uses a dc current, two measurements should be made: the first with the positive probe upstream and the second with the positive probe downstream. This will then capture any effect of the current flow through the bolted regions shown in Figures 4-11 and 5-3. In most cases, these two measurements would be approximately equal, and the average value should be recorded. Therefore, the average joint resistance R_I should be calculated from the two measurements $R_{I(L)}$ and $R_{I(R)}$:

$$R_{I(Average)} = (R_{I(L)} + R_{I(R)}) / 2 \quad \text{Eq. 5-3}$$

A good approximation of R_C for a bus joint is given in Equation 5-4:

$$R_C = R_{I(Average)} - R_2 \quad \text{Eq. 5-4}$$

The calculated R_C is therefore the resistances measured using a DLRO [30] across the bus connection and then subtracting the resistance of an equivalent length of bus as shown in Figure 5-3 and Equation 5-4. This calculation will give a good approximation of R_C for the bus joint.

Table 4-2 [20] shows an example where $R_I = 6 \mu\Omega$ for a well-made connection and $R_2 = 5 \mu\Omega$ so $R_C = 1 \mu\Omega$. This is a method of measuring contact resistance when the connections are covered with insulating covers (or “boots”) or they are taped or wrapped with insulating materials.



Key Technical Point

This report discusses a method of measuring the joint contact resistance when the connections are covered with insulating covers (or “boots”) or they are taped or wrapped with insulating materials.

6

CAUSES OF INCREASED JOINT CONTACT RESISTANCE

Intermetallic Compounds

When two different metals are put in contact with one another, it is possible for them to form intermetallic compounds over time. In the case of copper and aluminum busbars, when they are joined, it is possible for the contact region to form intermetallic compounds of the two metals—for example, CuAl , CuAl_2 , Cu_4Al_3 , or Cu_2Al . The formation of these compounds is a function of time and the temperature of the contact spot [31]. At the spot temperature recommended in Section 3 (1.2°C), these compounds would take too long to form to be of any significance. If the copper aluminum intermetallics do form, they have resistivities approximately $8\text{--}14\ \mu\Omega\cdot\text{cm}$, which are much higher than either aluminum ($2.7\ \mu\Omega\cdot\text{cm}$) or copper ($1.7\ \mu\Omega\cdot\text{cm}$). If these compounds begin to form at the contact spots, the temperature of the spots will increase, allowing these compounds to form more readily—a potential runaway effect can follow. The effect of intermetallic formation in copper-to-aluminum connections can be alleviated by using a transition bimetal washer between the copper and the aluminum. This is illustrated in Figure 6-1.

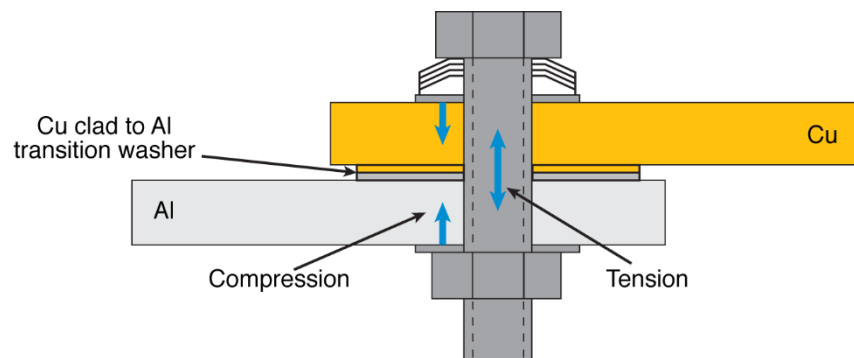


Figure 6-1
An example of a Cu-Al transition washer between a copper bus and an aluminum bus

Ingress of a Corrosive/Oxidizing Gas into the Individual Contact Spots

Figure 6-2 illustrates the ingress of corrosive or oxidizing gas into contact spots [32]. As the gas infiltrates the smaller individual contact spots that make up the contact area, the spots are removed initially by the corrosion or oxidation of the material. The removal of the smaller contact spots does not affect the constriction of the current through the contact region. However, when too many of the individual contact spots are removed by corrosion or oxidation, the overall contact resistance, R_C , will begin to increase. As the contact resistance R_C increases, the temperature of the contact region will also increase. The increase of the temperature will speed up the corrosion and/or oxidation process on the remaining contact spots. Eventually, a runaway

increase of resistance R_C will occur, and the contact spot temperature will continue to increase. It can be seen that the speed of deterioration also depends on the ambient temperature at the joint [7]. If the force from the bolts joining the bus decreases, this process will be enhanced.

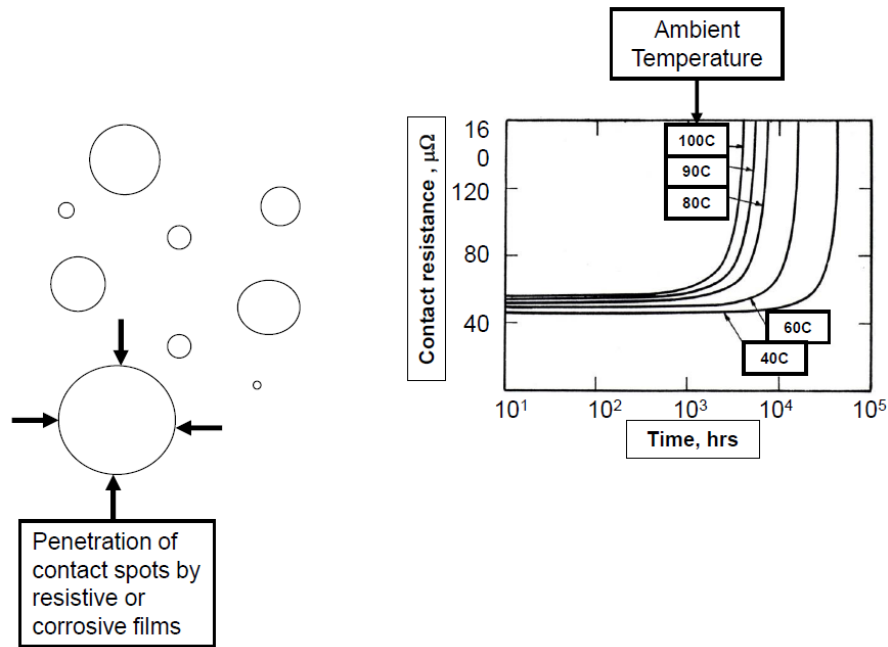


Figure 6-2
Runaway increases in contact resistance caused by ingress of corrosive or oxidizing gases as a function of time and ambient gas temperature

Fretting at the Bolted Joint Connection

When one conductor moves a small amount against a second conductor, it is possible for a buildup of resistance R_C to occur over time. For example, a motion as small as 5 μm is sufficient to break the gas-tight seal of an aluminum-to-aluminum interface. This phenomenon is called *fretting* [6]. With the bus connection, this can result from vibration, a mismatch of thermal expansion coefficients, metal creep, and relaxation. Figure 6-3 illustrates how fretting can result in a buildup of resistive material in a contacting region. Fretting can also be increased as the bolts joining the bus become looser.

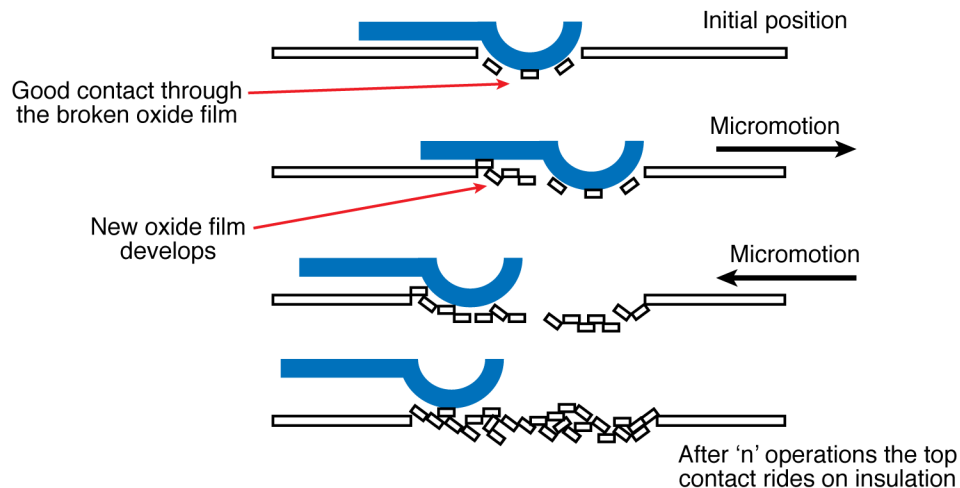


Figure 6-3
An illustration of fretting

The parameters that affect fretting are shown in Figure 6-4.

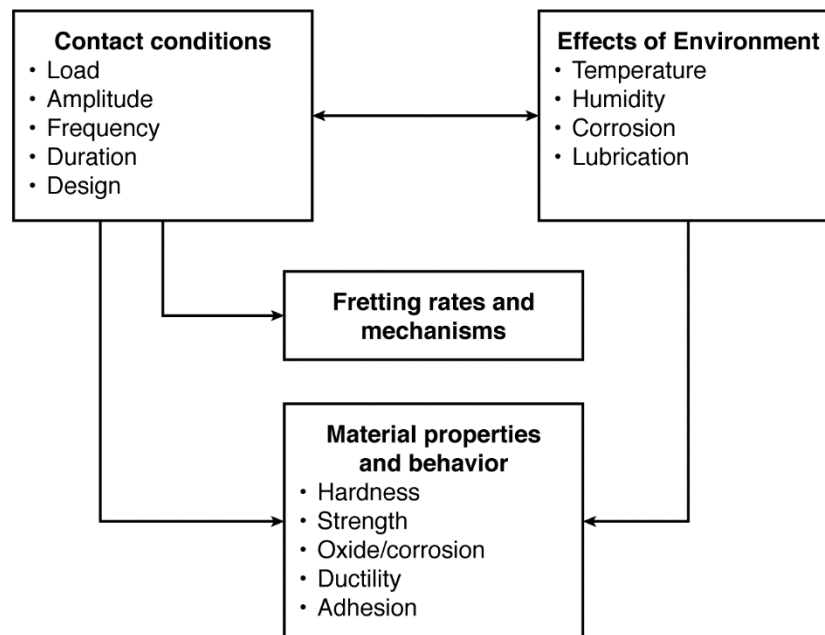


Figure 6-4
The parameters that affect fretting

Figure 6-5 shows an example from an experiment to show fretting for copper against aluminum (slip amplitude 25 μm ; contact force 2 N) [6]. Initially, the resistance R_C decreases as oxide is removed; a gradual increase continues after about 50 cycles. For copper against copper with the high contact forces expected for a bus connection, fretting does not usually occur. If, however, the bus joint is subjected to vibration, it is possible for fretting to occur even with a bolted joint. For aluminum against copper, the differences in thermal expansion can result in fretting corrosion. If moisture is present, it can initially help by lubricating the aluminum-to-copper joint, but moisture will eventually cause galvanic corrosion (described next).

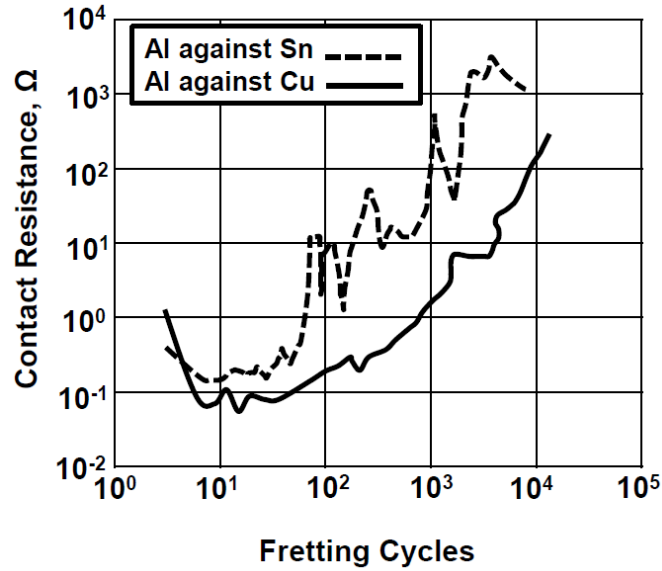


Figure 6-5
Fretting for aluminum (Al) against copper (Cu) and aluminum (Al) against tin (Sn) showing change in R_C as a function of fretting cycles

For aluminum-to-aluminum joints, thermoelastic ratcheting causes an increase in R_C when only disk washers are used. The effect is alleviated when Belleville spring washers are added to the joint [33]. The sequences of creep and ratcheting are illustrated in Figure 6-6.

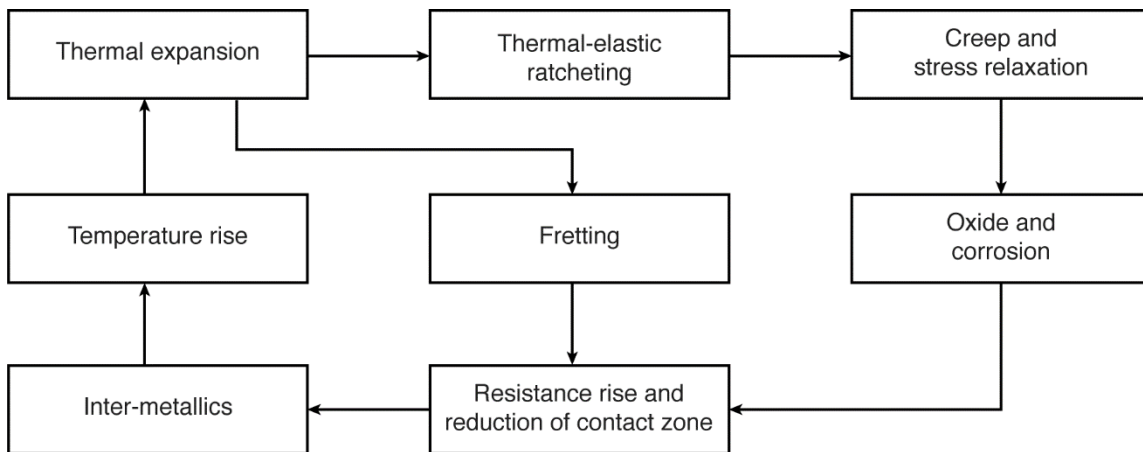


Figure 6-6
Possible sequences for creep and thermal-elastic ratcheting

A high contact force can reduce the fretting motion. However, the force should not exceed the yield strength of the bus or bolt materials.

Corrosion

The different modes of corrosion can be found in Reference [32]. One mode to consider here is galvanic corrosion. Galvanic corrosion can occur when two different metal are in contact with a thin layer of water. For aluminum in contact with steel or stainless steel, this does not typically occur to any great extent because their galvanic potentials are similar. However, galvanic corrosion is likely to occur for aluminum or steel in contact with copper—whose galvanic voltages are quite dissimilar. In these metal combinations, it is important to keep water from depositing at the joint to prevent corrosion. When inspecting a bolted connection, it is not necessary to identify the exact corrosion process. If it has occurred, corrosion is usually visually obvious [32].

For aluminum bus plated with silver (Ag), it is important to know the ambient atmosphere. If the atmosphere has high concentrations of SO_2 or H_2S , the Ag plate will form an oxide surface of AgS. This surface is a necessary precursor for the formation of Ag whiskers, which can grow long enough to short across adjacent bus runs [34]. Unleaded Sn plate will also form whiskers.

7

POWER CONNECTION FAILURES

As shown in Figure 2-1, a well-made joint can be reliable for a long time—indeed, for many years [5]. Once it begins to fail, it can fail in a relatively short time. It is entirely possible to measure a reasonable voltage drop across the connection and, a short while later, it will have failed. Figure 7-1 shows a cable connection to a motor contactor failure. This final visible evidence of failure occurred in just one or two days.

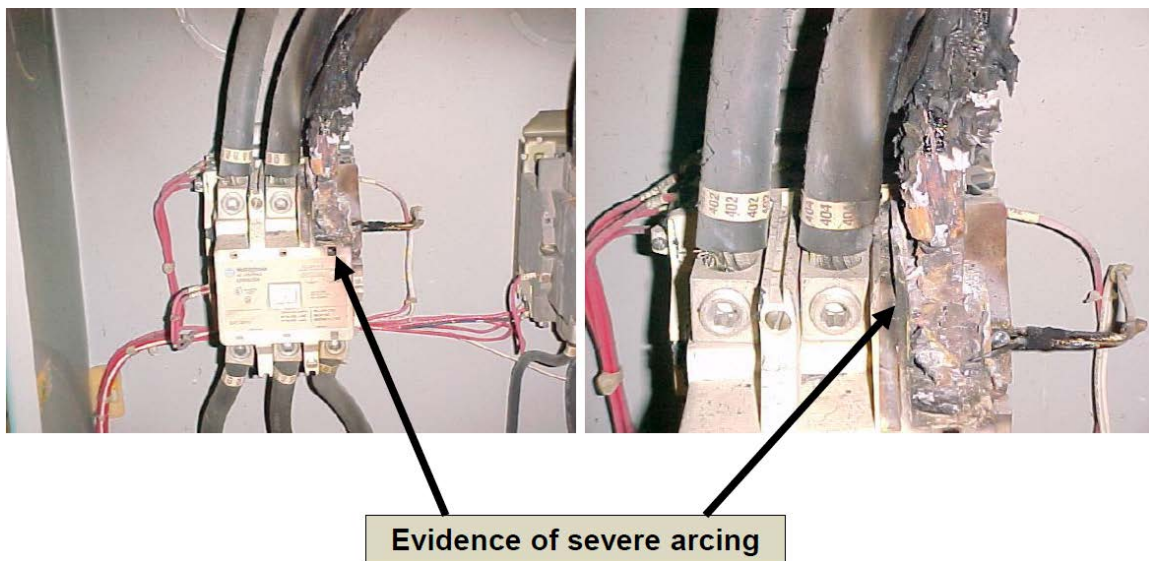


Figure 7-1
An example of a connection failure

Laboratory Experiment with an Example of a Bolted Bus Failure

Figure 7-2 shows the results of an experiment designed to make an aluminum bus connection carrying a current of 200 A fail in a reasonable time (in this case, 81 days). For example, the starting temperature at the contact spot is about 85°C, which—using Equation 3-13—gives a contact voltage of 65 mV. This is much higher than the recommended value of 10 mV for a well-made bolted joint given in Section 3, under Calculating Contact Temperature. The aluminum surfaces are mated with no preparation or inhibitor applied; in addition, the joint force is marginal. The temperature of the joint in this experiment is calculated using Equation 3-13. Here it can be seen that the failure occurred in just over 11.5 weeks [35].

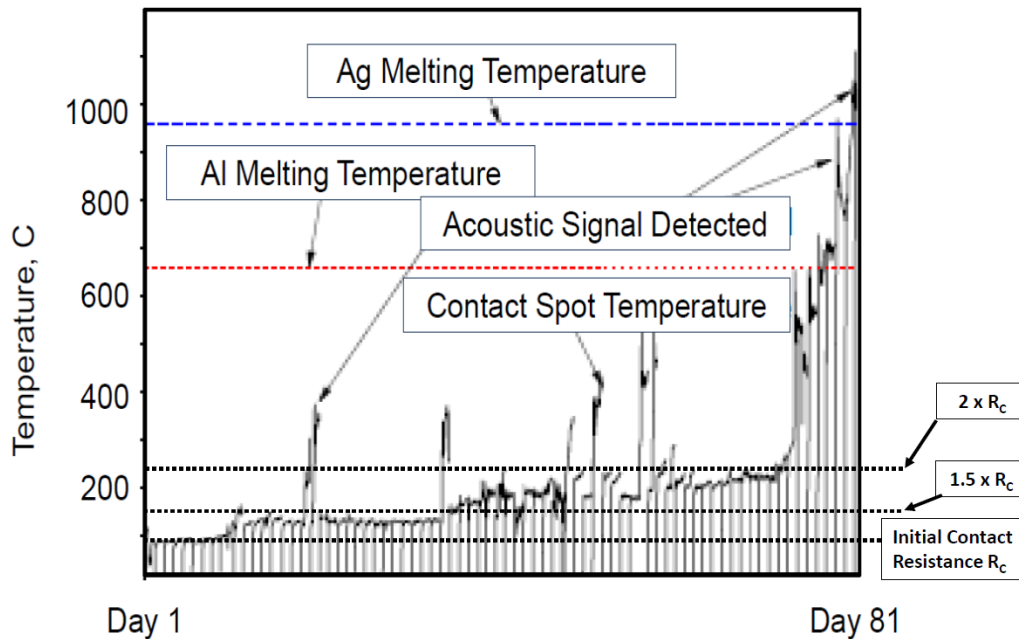


Figure 7-2
Failure of connected aluminum bus

Figure 7-2 also illustrates the difficulty of deciding whether the joint is beginning to fail if the voltage across the connection (the joint contact resistance times the current) is the only measurement taken. Figure 7-2 shows that, at Day 32, the resistance of the joint is 1.5 times the initial resistance. At this time, there are about 49 days before the contact joint exhibits extreme failure. On about Day 73, the resistance of the joint is now twice that at the experiment's initiation. Now there are only about 8 days before the extreme failure mode. The figure shows that, after this time, the temperature of the joint increases steadily to the initiation of the final runaway temperature after Day 75. Certainly a doubling of the contact resistance in this experiment should have given the experimenter knowledge that the joint was well into its failure mode. A more conservative indication that the joint is under stress occurs when the measured contact resistance is 1.5 times its initial value. It is therefore important to obtain a reasonable assessment of the true joint contact resistance, R_C , given in Section 5 (Equations 5-3 and 5-4 and Figure 5-3). For example, looking at Table 4-2, an increase of R_C from $1 \mu\Omega$ to $2 \mu\Omega$ would only increase the total joint resistance R_I in Figure 5-3 to $7 \mu\Omega$, that is, 1.4 times its initial value. Such a small increase could easily be ignored, but in reality a doubling of R_C is truly significant.

Long-Term Experiments Showing Bolted Bus Failures

Failure of Cu Bus Mated to Al Bus and Al Bus Mated to Al Bus

Figure 7-3 shows the results of long-term experiments on a Cu-to-Al and Al-to-Al bus with one steel bolt and flat steel washers but no Belleville washers [5]. These data are more representative of effects that can occur with a utility bolted bus connection. They show the runaway effect but over a longer period than is shown in Figure 7-2. The performance factor in these experiments is the measured joint resistance R_m , measured at a given time, divided by an initial joint resistance R_0' .

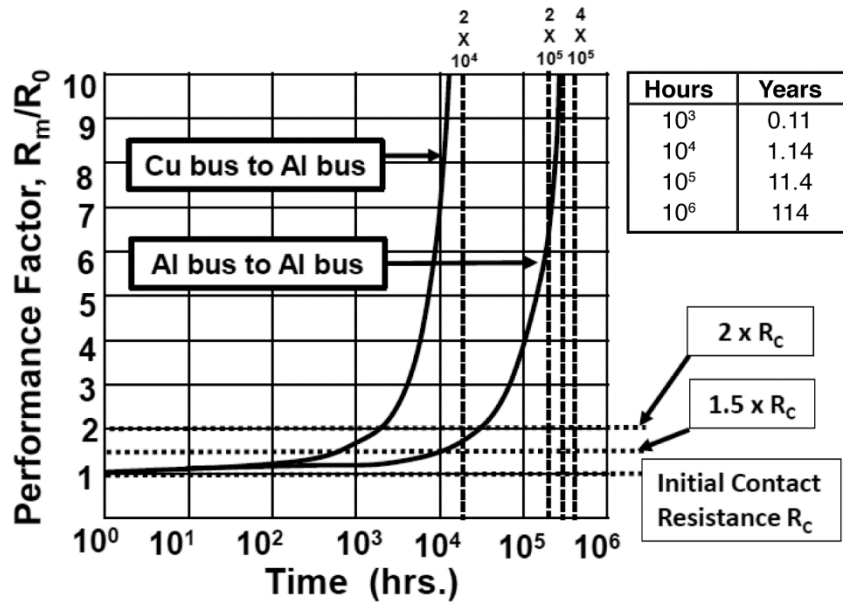


Figure 7-3
The aging behavior of a busbar joint for Cu-to-Al and Al-to-Al bus materials

Figure 7-3 shows the aging behavior of a busbar joint for an ambient temperature of 35°C and an initial contact temperature of 65°C passing a current of 560 A. This experiment shows that an aluminum-to-aluminum joint has nearly 20 times the life expectancy than the aluminum-to-copper joint. Figure 7-3 also shows that when the joint contact resistance is 1.5 times and twice the initial contact resistance, both joints show initiation of the runaway effect—that is, the ratio of the measured resistance (measured at a later time after installation) to the initial resistance (at installation) increases rapidly. The aluminum-to-copper joint shows a failure just over one year after the contact resistance is 1.5 times its initial value. The time to failure after the contact resistance is twice its initial value is about nine months. The aluminum-to-aluminum joint shows an unacceptable increase in contact resistance after about 10 years after the contact resistance has increased 1.5 times its initial value. The final runaway failure occurs at about 30 years. In this experimental example, a contact resistance of 1.5 times the initial value shows that there is some degradation of the joint. However, in this experiment, if the inspection period is 10 years, a second inspection at that time will be soon enough to prevent the runaway failure of the joint. When the measured contact resistance is twice its initial value, there is a shorter time before the final runaway failure of the joint occurs.

Failure of Al Bus Mated to Al Bus as a Function of Current

Figure 7-4 illustrates the aging behavior of the aluminum-to-aluminum bus with one steel bolt and flat steel washers but no Belleville washers in an indoor ambient of 35°C as a function of current passage through the joint [5]. This figure shows the effect of current on the aging of the busbar joint. In these experiments, the joint with 725 A current has a final life of about 20 years, but the same joint with a current of 225 A has a final life of about 60 years. Again, the figure shows the effect after the joint contact resistance is both 1.5 times and twice its initial value.

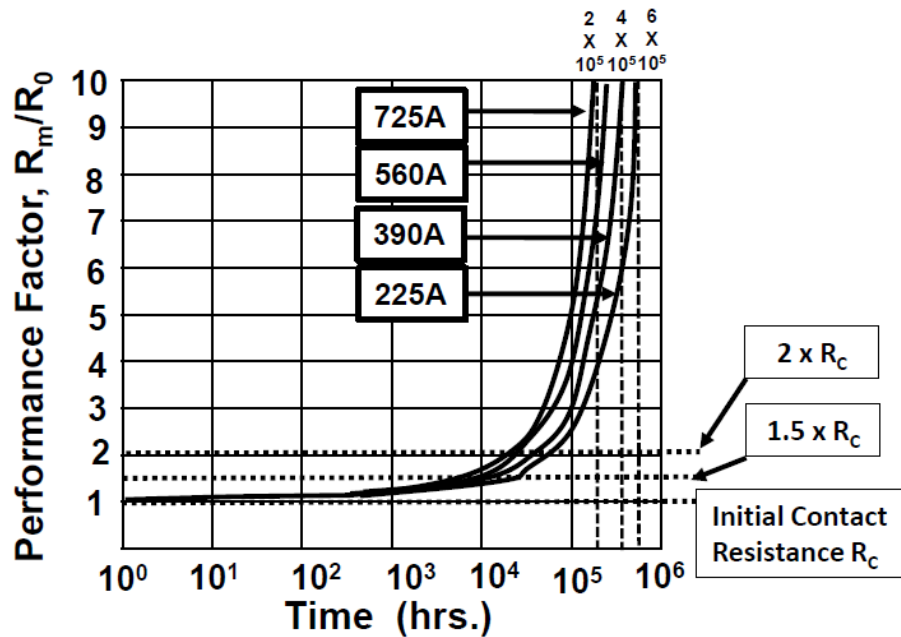


Figure 7-4
The aging behavior of an aluminum-to-aluminum bus as a function of current



Key Technical Point

During experimental testing of the aging behavior for an aluminum-to-aluminum joint as a function of current, doubling the current in the bus reduced the life of the joint by half.

Failure of Al Bus Mated to Al Bus as a Function of Ambient Temperature

Figure 7-5 shows the aging behavior of an aluminum-to-aluminum bus with one steel bolt and flat steel washers but no Belleville washers passing a current of 560 A as a function of the ambient temperature surrounding the busbar joint. This figure shows the effect of the indoor air temperature surrounding the busbar joint. It can be seen that this temperature can have a significant effect. The final life at 35°C is about 30 years but at 55°C is only 20 years. Again, this figure shows that when the contact resistance is 1.5 times the initial value, there is a period of about 10 years before the joint begins to show the initial stages of runaway failure.

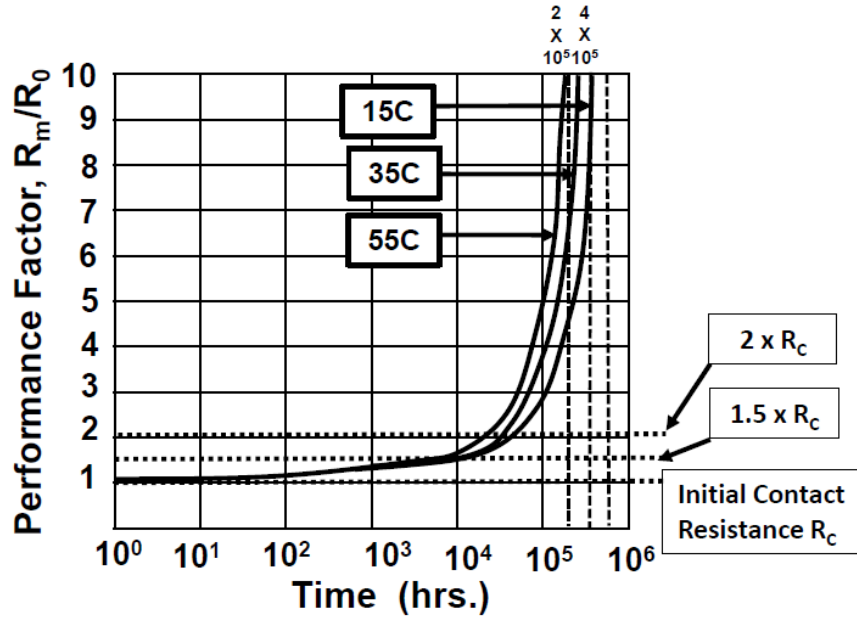


Figure 7-5
The aging behavior of aluminum-to-aluminum bus as a function of ambient temperature

Failure of Al Bus Mated to Al Bus, Al Alloy Bus Mated to Al Alloy Bus, and Cu Bus Mated to Cu Bus

Figure 7-6 shows the results of long-term experiments on a bus with one steel bolt and flat steel washers but no Belleville washers [24]. Here the aluminum-to-aluminum bus is bolted with a torque of 31 N.m and the aluminum alloy (Al-Mg-Si) joints and the copper joints with 60 N.m. The joints are subjected to city air for 8 hours. Current is then passed and switched off, and the joint is left exposed to city air for five years. During that time, the ambient temperature and humidity are not controlled.

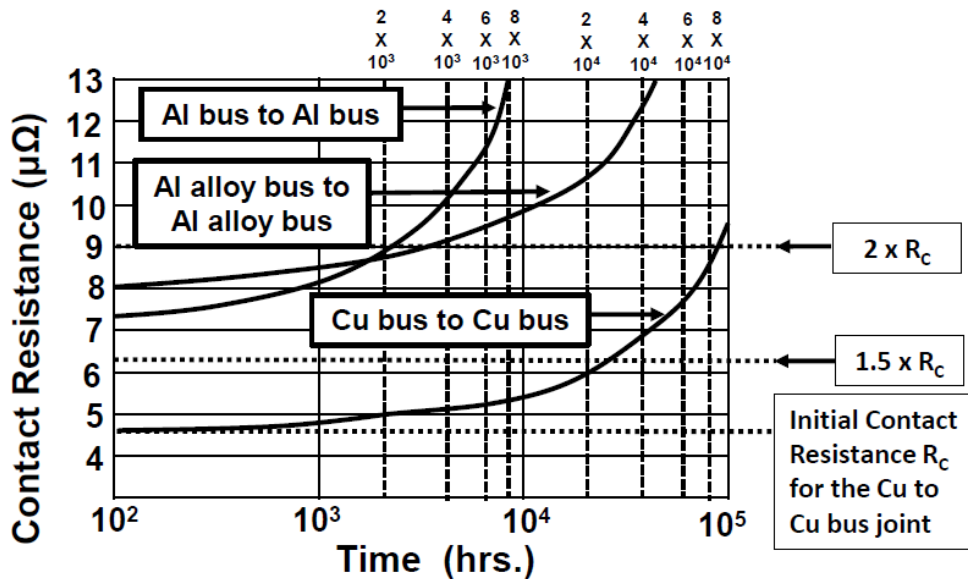


Figure 7-6
The aging behavior for different busbar joints

The aluminum alloy data give a R_m/R_0 value of about 1.24 at 10^4 hours (about 1.14 years). This is similar to the aluminum data in Figure 7-3, which give an increase of R_m/R_0 value of about 1.3 at 10^4 hours. The copper-to-copper busbar joint shows that this material aging performance is significantly greater than even the aluminum alloy joints. However, even these joints also show a significant increase in resistance after 10^5 hours (about 11.4 years). Again, in this figure, when the Cu-to-Cu joint shows a contact resistance of 1.5 times the initial value, the rise to the failure mode is evident.

Care must be taken in looking at the exact failure periods and applying these data to utility bus connections. From the experimental data, the failure period can be rapid as seen in Figure 7-2 for a badly made joint or a few years for the experimental conditions in Figures 7-3 through 7-5. Here the parameters of current level and ambient temperature are rigidly controlled unlike a typical utility environment. For Figure 7-6, the conditions cited in the paper [24] are not controlled—but for most of the time it seems that the joint carried no current. Figures 7-2 through 7-6 illustrate that once the performance factor (temperature in Figure 7-2; measured contact resistance/initial contact resistance [R_m/R_0] in Figures 7-3, 7-4, and 7-5; and contact resistance in Figure 7-6) in a bus connection shows an increase of about 1.5 times its initial contact resistance, the connection is in the initial stages of failure.



Key Technical Point

When the joint contact resistance of the bolted bus joint is equal to or greater than 1.5 times its initial value, the joint is in the initial stage of failure.

While Figure 7-1 shows evidence of arcing at the contact junction, this is not the cause of the failure but its final result. Following is the sequence of events that leads to the connector failure:

1. A gradual decrease of the contact region area.
2. A gradual increase in contact resistance.
3. A temperature rise in the contact region.
4. The higher temperature enhances any deterioration effects in the contact region and leads to a further increase in the contact resistance.
5. This will eventually result in a runaway temperature rise.
6. Melting can occur.
7. Intermittent contact may also result.
8. This can lead to arcing, material melting, and perhaps flashover to other conductors or to ground.
9. The result can be damage to the system and perhaps a fire.



Key Technical Point

Arc damage at a bolted bus joint is evidence that the connection is in the final stages of failure.

8

JOINT INSPECTION AND CORRECTIVE MEASURES

A well-made bus joint connection using the recommended bolt torque, joint compound, and Belleville washers will most probably outlast the lifetime of a generating station. However, a routine inspection of all bus joint connections is usually undertaken by utility maintenance engineers because if even one joint fails, the result can lead to a shutdown of the generating station. During a utility plant shutdown, there are six steps for assessing a bolted bus joint's performance and whether corrective measures must be undertaken:

1. Perform a visual inspection of the bolted bus joint.
2. Perform a visual check of the joint for arcing damage.
3. If there is no evidence of arc damage, check the joint for visible corrosion.
4. For booted joints or joints covered in insulation, check for overheating or other physical damage.
5. For Al-Al or Cu-Al bolted joints, check that a fillet of inhibitor is visible at each edge of the joint.
6. Check the bolts for proper torque.

Figure 8-1 illustrates the steps for this inspection process.

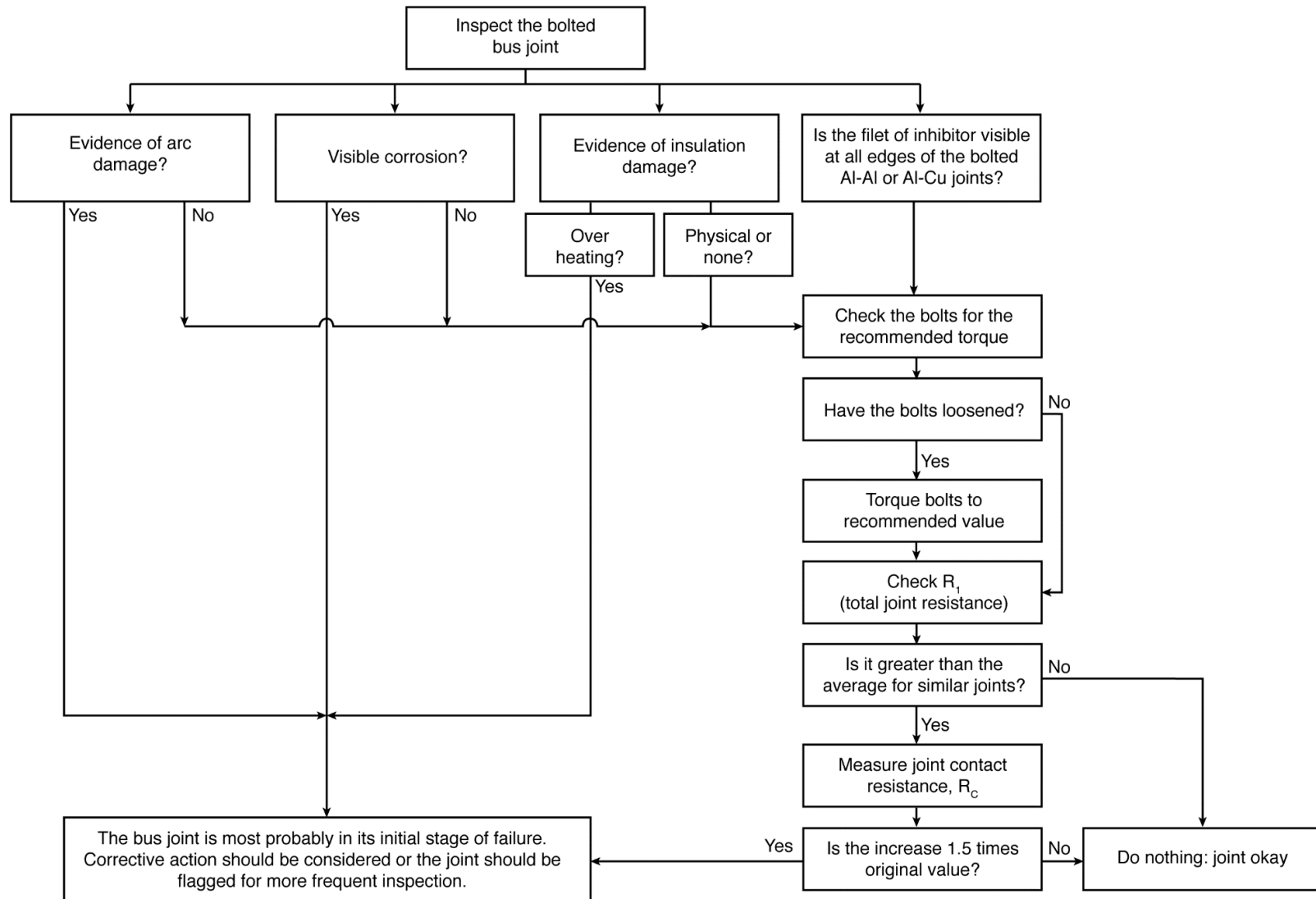


Figure 8-1
The inspection sequence and maintenance of bolted bus during a generating station shutdown

Note: The inspection sequence and corrective actions presented in Figure 8-1 conservatively recommend that if the total joint resistance, R_I (that is, the resistance across the entire bolted joint; see Equation 5-3) is greater than the average value of similar joints, the joint contact resistance, R_C , should be measured (see Equation 5-4). If its value is 1.5 times its original value, the joint is in the first stage of failure (see Section 7). It is, however, unlikely that the bus joints in a typical generating station have ever recorded the contact resistance of a freshly made bus joint. To obtain an estimate of the initial total joint resistance (R_I in Section 5), a sample of bus joints that appear satisfactory from visual inspection can be measured and an average value calculated. An alternative method would be to take the lowest value from this sample and use it as the standard one. Then, using the technique shown in Figure 5-3 and Equation 5-3, the initial total joint resistance can be calculated for this type of joint. The joint contact resistance can then be evaluated (Equation 5-4) for those joints whose total joint resistance is appreciably above the average value. The value of the joint contact resistance for the average or lowest value joint can then be compared with the joint contact resistance of any suspect joint.

The inspection sequence and corrective actions presented in Figure 8-1 are described as follows:

1. Perform a visual inspection of the bolted bus joint.
2. Perform a visual check of the joint for arcing damage. If there is any sign of arcing damage, the joint is progressing toward failure.
3. If there is no evidence of arc damage, check the joint for visible corrosion.
 - a. If corrosion is present at the joint, appropriate corrective action should be scheduled.
 - b. If there is no evidence of corrosion, check that the bolts have the correct torque (go to Step 6).
4. For bolted joints or joints covered in insulation, check for overheating or other physical damage.
 - a. If the insulation shows signs of heat damage, the joint is in the initial stages of failure, and corrective action should be scheduled.
 - b. If there is no heat damage but signs of physical damage—or no damage—test the bolts for the correct torque (go to Step 6).
5. For Al-Al or Cu-Al bolted joints, check that a fillet of inhibitor is visible at each edge of the joint. This presupposes that the joints were made correctly in the first place (see Section 4). Check the bolts for correct torque (go to Step 6).
6. Check the bolts for proper torque.
 - a. Torque to the recommended value.
 - b. Measure the total joint resistance, R_I (see Equation 5-3).
 - c. If R_I is significantly higher than the average for similar bolted joints, check the joint contact resistance, R_C (see Equation 5-4).
 - d. If R_C is greater than 1.5 times its initial value, the joint is in the initial stages of failure (see Section 7). Corrective action should be considered, or the bolted joint can be flagged for more frequent inspection.

- e. If during these more frequent inspections the contact resistance continues to increase, the joint is progressing toward failure, and corrective action should be scheduled.
- f. If the bolts retain their original torque value, measure the total joint resistance, R_I . If this is within the average value measured for similar bolted joints, the joint will perform satisfactorily to the next inspection period.
- g. If R_I is significantly higher than the average for similar bolted joints, go to Steps 6c and 6d above.

It is possible to perform a rough check on the bolted bus joint's status while there is current passing through the joint using infrared thermography or some other external temperature measurement. As discussed in Section 2, if this measurement shows a temperature increase over similar bolted joints, the joint is already in the initial stages of failure, and corrective action should be considered—or the bolted joint can be flagged for more frequent inspection. Figure 8-2 illustrates the steps for this inspection process.

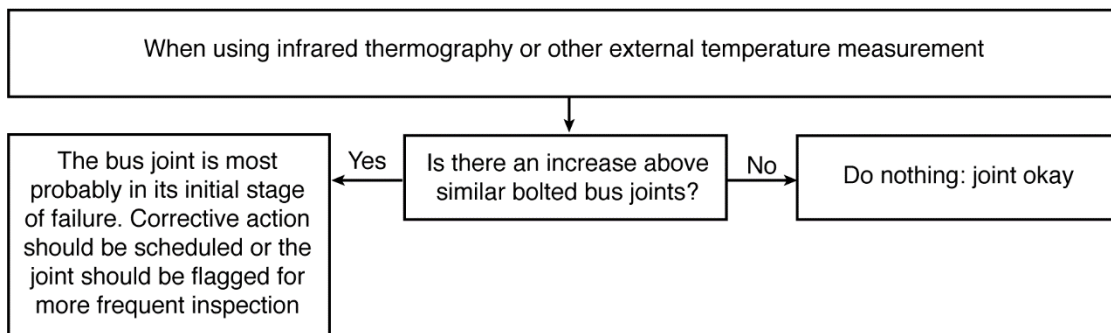


Figure 8-2
The inspection sequence and maintenance of bolted bus while passing current

Note: If there is no record of the joint's external temperature when passing its rated current, the lowest value from all similar joints examined should be used as a base value.

9

CONCLUSIONS

The following conclusions were reached as a result of this project:

- The joint contact resistance of a bolted bus joint is a function of the bus material's hardness and resistivity and the force applied to the joint by the bolt structure.
- Regular inspection of the utility's bolted bus joint is essential for continued reliability of the joint.
- FMEA identified seven degradation mechanisms that can result in the failure of a bolted bus joint:
 - Loose bolts.
 - Intermetallic formation at the contact spots.
 - Fretting.
 - Reduction of the individual contact spots by the ingress of oxidizing gases.
 - Corrosion at the joint.
 - Arcing at the joint.
 - Damaged insulation.
- Identification of the bolted bus joint under stress can be initially identified with visual inspection, but the best method is to use the joint contact resistance measurement (see Section 5).
- Use of infrared thermography shows only that a joint is in an imminent failure mode. It will not identify a joint that has the potential to fail in a period of a few years and before the next inspection period. It also cannot be used if the joint is booted or taped.
- When a joint shows a joint contact resistance ≥ 1.5 times its original value, the measurement indicates that the joint is in the initial stages of failure. Consider flagging the joint for more frequent inspection. If the joint contact resistance continues to increase, corrective action should be considered.
- When bolting an Al-to-Al bus or Al-to-Cu bus with steel or stainless steel bolts, the recommended torque should be used along with a conical spring washer such as a Belleville washer. Conservatively, the same washer can be used when joining a Cu-to-Cu bus with steel or stainless steel bolts.
- Use of an inhibitor material at the bus joint is also required to prevent the ingress of oxidizing or corrosive gases into the contacting region. When first making the joint with the inhibitor, a fillet of the inhibitor should be visible at each edge of the joint.

10

REFERENCES

1. *Lessons Learned from Exelon's Non-Segregated Bus Inspections*. EPRI, Palo Alto, CA: 2013. 30020000707.
2. Nuclear Regulatory Commission Information Notice 2010-25, Inadequate Electrical Connections. November 17, 2010.
3. Nuclear Regulatory Commission Information Notice 2000-14, Non-Vital Bus Fault Leads to Fire and Loss of Offsite Power. September 27, 2000.
4. Institute of Nuclear Power Operations Significant Event Report 5-09, 6.9-kV Non-Segregated Bus Failure and Complicated Scram. November 4, 2009.
5. Bergmann, H. Löbl, H. Böhme, and S. Großmann, "Model to assess the reliability of electrical joints." *Proc 42nd IEEE Holm Conf. on Electrical Contacts*, p. 180, 1996.
6. M. Braunovic, "Power Connections." *Electrical Contacts, Principles and Applications 2nd Edition*, 2014 (Ed. P. G. Slade), pp. 267–288.
7. Preface to the 2nd Edition, *Electrical Contacts, Principles and Applications*. 2014 (Ed. P. G. Slade).
8. B. Chudnovsky, A. Boris, and A. Chudnovsky, "Thermal Model of Electrical Contacts Based on Experimental Data." *Proc 54th IEEE Holm Conf. on Electrical Contacts*, p. 205, 2008.
9. K. Fandrem, M. Runde, and S. M. Helleso, "Condition assessment of overhead line connectors." *Proc. 28th International Conference on Electric Contacts*, pp. 411–415, June 2016.
10. C. Wilson, G. McIntosh, and R. Timsit, "Effect of a spot temperature on the temperature of external surfaces in electrical contacts." *Proc 59th IEEE Holm Conf. on Electrical Contacts*, p. 65, 2013.
11. R. Holm and E. Holm, *Electric Contacts, Theory and Applications 4th Edition*. pp. 7–17, 3rd printing, 2000.
12. R. Timsit, "Electrical contact resistance: fundamental principles." *Electrical Contacts, Principles and Applications 2nd Edition*, 2014 (Ed. P. G. Slade), pp. 5–18.
13. J. A. Greenwood and J.P. B. Williamson, "Contact of nominally flat surfaces." *Proc. Roy. Soc.*, A 295, p. 300. 1966.
14. P. Slade, *The Vacuum Interrupter, Theory, Design and Application*. CRC Press, 2008, p. 124.
15. F. Kohlrausch, "Über den Stationären Temperaturzustand eines elektrisch Geheizten Leiters." *Ann Phys*, 1:p. 132, 1900.
16. R. Timsit, Op. cit., pp. 57–63.

17. P. Slade, *Electrical Contacts, Principles and Applications*. CRC Press, 2nd Edition, 2014, p. 116.
18. P. Slade. Op. cit., p. 1198.
19. T. Fuhrmann, S. Schlegel, S. Grossmann, and M. Hoidis, “Studies on current-carrying connections with flat surfaces – relation between mechanical stress and electrical contact behavior.” *Proc Int’l Conf. on Electric Contacts*, pp. 3111–3117, 2016.
20. D. Nath, “Indian experience with aluminium busbars, links and cable terminations for use on low voltage systems up to 1000V.” *Proc. IEEE Holm Conf. on Electrical Contacts*, p. 93, 1985.
21. M. Braunovic, “Power Connections.” *Electrical Contacts, Principles and Applications 2nd Edition*, 2014 (Ed. P. G. Slade), p. 335.
22. P. Slade, Op. cit. p. 1199.
23. M. Braunovic, “Power Connections.” *Electrical Contacts, Principles and Applications 2nd Edition*, 2014 (Ed. P. G. Slade), p. 322–325.
24. Y. S. Vislennov and P. P. Kuzmin, “Evaluation of contact service life of electrical connections.” *Proc. 30th IEEE Holm Conf. on Electrical Contacts*, p. 521, 1990.
25. M. Braunovic, “Effect of different types of mechanical contact devices on the performance of bolted aluminum to aluminum joints under current cycling and stress relaxation condition.” *Proc 32nd IEEE Holm Conf. on Electrical Contacts*, p. 133, 1986.
26. M. Braunovic, “Effect of current cycling on contact resistance force and temperature of bolted aluminum to aluminum connectors of high ampacity.” *Proc Holm 26th Conf. on Electrical Contacts*, p. 103, 1980.
27. S. Schlegel, S. Grossmann, H. Lobl, M. Hoidis, U. Kaltenborn, and T. Magier, “Joint resistance of bolted copper - copper busbar joints depending on joint force at temperatures beyond 105°C.” *Proc Holm 56th Conf. on Electrical Contacts*, p. 444, 2010.
28. S.W. Melson and H. C. Booth, “The efficiency of overlapping joints in copper and aluminum-to-copper connections.” *J. IEE*, Vol. 60, No. 312, 1922.
29. R. Holm and E. Holm, Op. cit., p. 43.
30. [Digital Low Resistance Ohmmeters: http://us.megger.com/digital-low-resistance-ohmmeters-dlro10x](http://us.megger.com/digital-low-resistance-ohmmeters-dlro10x).
31. M. Braunovich, “Power Connections.” *Electrical Contacts, Principles and Applications 2nd Edition*, 2014 (Ed. P. G. Slade), pp. 288–298.
32. P. Slade, “Introduction to contact tarnishing and corrosion.” *Electrical Contacts, Principles and Applications 2nd Edition*, 2014 (Ed. P. G. Slade), pp.114–135.

33. M. Braunovic and M. Majanov, "Thermoelastic ratcheting effect in bolted aluminum to aluminum connections." *Proc 33rd IEEE Holm Conf. on Electrical Contacts*, p. 123, 1987.
34. B. Chudnovsky. "Degradation of power contacts in Industrial atmosphere: silver corrosion and whiskers." *Proc. 48th IEEE Holm Conference on Electrical Contacts*, pp. 140–147, October 2002.
35. X. Zhou and T. Schoepf, "Detection and formation process of overheated electrical joints due to faulty connections." *Proc. 26th Int'l Conf. on Electrical Contacts*, pp. 288–295, 2012.

A

KEY POINTS



Key Technical Point

Targets information that will lead to improved equipment reliability.

Page Number	Key Point
2-2	Once a bolted joint exhibits signs of accelerated aging, failure can occur in a relatively short time.
2-5	The most reliable performance factor measurement is contact resistance, R_C , and calculating the contact voltage, U_C . This measurement determines most accurately the state of the actual connection interface on all bolted connections—even those that are booted or taped. An external temperature measurement is often used but is less reliable in determining the state of the connection's interface.
2-6	Infrared thermography may not catch every possible failure. If it does show an increase in temperature, the joint is in its initial stage of failure.
3-4	The actual area of contact is a function of the contact load (bolt torque) and the material's hardness. It does not depend on the total area of the contact face. In other words, the actual area of contact is a function of the bolt torque and the hardness of the connection materials.
3-7	It is possible to estimate the temperature of a contact area by measuring the voltage drop across the contact surfaces by calculating it (using the joint contact resistance \times the bus current). A very small voltage drop across contact surfaces represents a very high temperature at the contact spots.
3-10	It is important to understand the significance of the metal melting and softening voltage when determining the bolt joint contact resistance, especially if there is a possibility that the bolted connection will be subjected to the passage of a fault or short-circuit current.
4-4	Aluminum oxidizes rapidly when exposed to air. When making connections with aluminum conductors, the effects of this thin insulating aluminum oxide layer must be overcome through the use of an abrading process under joint compounds to prevent aluminum oxides re-forming.
4-7	The difference in thermal expansion rates must be considered when mating different materials together. To alleviate problems from the different expansion coefficients among materials, it is important to use a Belleville washer.
5-3	This report discusses a method of measuring the joint contact resistance when the connections are covered with insulating covers (or "boots") or they are taped or wrapped with insulating materials.

Key Points

Page Number	Key Point
7-4	During experimental testing of the aging behavior for an aluminum-to-aluminum joint as a function of current, doubling the current in the bus reduced the life of the joint by half.
7-6	When the joint contact resistance of the bolted bust joint is equal to or greater than 1.5 times its initial value, the joint is in the initial stage of failure.
7-6	Arc damage at a bolted bus joint is evidence that the connection is in the final stages of failure.

Export Control Restrictions

Access to and use of EPRI Intellectual Property is granted with the specific understanding and requirement that responsibility for ensuring full compliance with all applicable U.S. and foreign export laws and regulations is being undertaken by you and your company. This includes an obligation to ensure that any individual receiving access hereunder who is not a U.S. citizen or permanent U.S. resident is permitted access under applicable U.S. and foreign export laws and regulations. In the event you are uncertain whether you or your company may lawfully obtain access to this EPRI Intellectual Property, you acknowledge that it is your obligation to consult with your company's legal counsel to determine whether this access is lawful. Although EPRI may make available on a case-by-case basis an informal assessment of the applicable U.S. export classification for specific EPRI Intellectual Property, you and your company acknowledge that this assessment is solely for informational purposes and not for reliance purposes. You and your company acknowledge that it is still the obligation of you and your company to make your own assessment of the applicable U.S. export classification and ensure compliance accordingly. You and your company understand and acknowledge your obligations to make a prompt report to EPRI and the appropriate authorities regarding any access to or use of EPRI Intellectual Property hereunder that may be in violation of applicable U.S. or foreign export laws or regulations.

The Electric Power Research Institute, Inc. (EPRI, www.epri.com) conducts research and development relating to the generation, delivery and use of electricity for the benefit of the public. An independent, nonprofit organization, EPRI brings together its scientists and engineers as well as experts from academia and industry to help address challenges in electricity, including reliability, efficiency, affordability, health, safety and the environment. EPRI members represent 90% of the electric utility revenue in the United States with international participation in 35 countries. EPRI's principal offices and laboratories are located in Palo Alto, Calif.; Charlotte, N.C.; Knoxville, Tenn.; and Lenox, Mass.

Together...Shaping the Future of Electricity

Programs:

Nuclear Power

Plant Engineering Program

© 2018 Electric Power Research Institute (EPRI), Inc. All rights reserved. Electric Power Research Institute, EPRI, and TOGETHER...SHAPING THE FUTURE OF ELECTRICITY are registered service marks of the Electric Power Research Institute, Inc.

3002011484

Electric Power Research Institute

3420 Hillview Avenue, Palo Alto, California 94304-1338 • PO Box 10412, Palo Alto, California 94303-0813 USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com