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CRIMP CONNECTION RELIABILITY

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Martin Marietta Corporation

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ROME AIR DEVELOPMENT CENTER
Air Force Systems Command
Griffiss Air Force Base, New York 13441

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Martin Marietta has conducted a 12 month program to collect and analyze crimp connection reliability data. More than 3.8 billion part hours of data were collected. A failure rate mathematical model for crimp connections has been developed for inclusion in MIL-HDBK-217B. Also included in the report is a discussion of the physical characteristics of crimped connections and guidelines for their selection and application.

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EVALUATION

This effort supports RADC TPO R-5-B, Solid State Device Reliability. Appendix A of the report, which includes a prediction model and updated crimp connection base failure rates, will be included in the next revision of MIL-HDBK-217B, "Reliability Prediction of Electronic Equipment." Use of this revised and updated model and updated base failure rates will greatly improve the accuracy of crimp connection reliability predictions.

The model developed consists of a base failure rate modified by multiplicative factors for environment, type of crimping tool, and quality procedures. The failure rate calculated from the model for a crimp termination in a fixed ground environment is approximately one order of magnitude less than the value of 0.0073 failures/10^6 hours presently given in MIL-HDBK-217B.

John E McCormick

JOHN E. McCORMICK
Solid State Applications Section
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SUMMARY

This report comprises the results of a 12 month program conducted by Martin Marietta Aerospace, to develop a crimp connection failure rate mathematical model for inclusion in MIL-HDBK-217B.

To develop the required model, an extensive data collection effort was conducted in conjunction with other on-going RADC study efforts. Private contractors, Government facilities, and research and educational institutions throughout the country were contacted and many were personally visited.

More than 3.8 billion part hours of collected data were analyzed and grouped over five operational environments. Table 1 lists collected crimp connection part-hour quantities by environment. Crimp connection data from environments such as space flight (S_F), missile launch (M_L) and ground mobile (G_M) could not be obtained although requested and sought. Environmental k-factors were derived through application of qualitative data and engineering analyses.

Table 1. Summary of Crimp Connection Data Collected

Environment	MIL-HDBK-217B Symbology	Part Hours x 10^6
Ground Benign	G_B	3590.000
Ground Fixed	G_F	16.181
Naval Sheltered	N_S	5.499
Airborne Inhabited	A_I	6.903
Airborne Uninhabited	A_U	249.453
	Total	3868.036

The failure rate model developed for crimp terminations consists of a base failure rate modified by multiplicative factors for environment, type of crimping tool, and quality procedures. The failure rate calculated from the model for a crimp termination in a fixed ground environment is approximately one order of magnitude less than the value of 0.0073 failures/10^6 hours given in MIL-HDBK-217B.

A good crimp connection can withstand high levels of temperature and vibration, has excellent performance in corrosive environments, and is reliable. Minimum technician skill is required to perform the crimping operation. Reliable crimp connections result from good planning that includes selecting the correct type of terminations, conductors, and tools for optimizing electrical conductivity and connection tensile strength to crimp indent depth, together with following established procedures during the crimping process to maximize product quality.

PREFACE

The Crimp Connector Reliability Report was prepared by the Orlando Division of Martin Marietta Aerospace, Orlando, Florida, and is submitted in response to CDRL Sequence No. A002. The purpose of the study was to develop a failure rate mathematical model for use in MIL-HDBK-217B from collected and analyzed crimp connection data.

This contract was issued in September 1976 by Rome Air Development Center (RADC). Mr. John McCormick (RBRM) was the RADC Project Engineer.

Technical consultation in the preparation of this report was provided by Messrs. Edward French and Joe Mavrides of Martin Marietta, Orlando, Florida, and by AMP Incorporated, Harrisburg, Pennsylvania.

Assistance in the acquisition of data was provided by Messrs. Thomas Gagnier, George Guth, and William Maynard. Other study team members were Lynn Mercer, Sharon Molnar, Bradley Olson, Aaron Penkacik, Betty Thomas, Robert Whalen, Lynn Westling, and Thomas Young.

CONTENTS

1.0 INTRODUCTION

Crimping is the most widely used method of pressure connection for permanent electrical contact between a wire conductor and a wire conductor terminating device, such as a connector pin. An estimated 70 billion crimp-type wire terminations are used every year in the United States.

The method's popularity can be attributed to its overall versatility. The most widely used type of crimp connection is the removable contact used in connectors. Another class of crimp connections includes terminals designed for attachment to board, bus, or block with some type of mechanical fastener. Low cost, high application speed, compatibility with a wide range of wire sizes, good mechanical strength, and high reliability are achievable with a crimp connection system.

The objective of this study program was to develop a crimp connection failure rate mathematical model based on contemporary data from military systems that experience varied conditions of application and environment. The developed model provides a means for deriving failure rates for crimp connections under variable conditions and applications. Variables comprising the model require no more information than is normally available to engineers during the equipment design phase.

More than 3.8 billion part hours of crimp connection data were collected and evaluated. These data were used as the basis for developing a failure rate model which includes factors for environment, tool type, and quality procedures. This model, with associated quantitative values for each factor, is presented in Appendix A in a format suitable for insertion into MIL-HDBK-217B.

Crimp connection performance and reliability are affected by many factors that could not be quantified by failure rate model variables. These factors include material, finish or plating, conductor size, crimp depth, and tensile strength. Effects of these factors are discussed, and guidelines are given for proper selection and application of crimp terminations and tools.

2.0 PROPERTIES OF CRIMP CONNECTIONS

The theory behind crimp connection is establishment of contact between two or more electrical conductors by applying mechanical force to deform metals past their elastic limits. The mechanical force establishes large area metal-to-metal contact and locks the conductors together through the process of cold welding and the action of residual elastic stresses in the conductors. Cleaning contaminants and oxides from conductor surfaces is also accomplished by a combination of high pressure, metal flow, and gross deformation of the conductors.

Although crimp connections are oriented toward electrical applications, design of crimp connection devices and associated tooling is basically a mechanical engineering problem. It involves elastic and plastic deformation of metals, cold welding of metals, and forging of metals into shapes that sustain residual contact forces for electrical effectiveness.

Crimp connection performance is best appreciated through understanding the interrelationships of the various elements that comprise the connection. These interrelationships include the effects of electrical wire size and tensile strength, crimp termination material and plating, and crimp depth versus tensile strength. These interrelationships and associated problems in making good crimp connections are discussed in sections 2.1 through 2.3.

2.1 Physical Characteristics and Parameters

The right crimp system, i.e., the proper combination of wire, termination, and tooling, must be used to obtain the optimum crimp geometry. The curves in Figure 1, from Reference 1, represent generalized variations of crimping parameters such as crimp joint conductivity, tensile strength, and wire conductor cross section area reduction, all with respect to the crimp indentation depth variable.

Figure 1 illustrates the effects of crimp depth. As crimp depth increases, tensile strength and electrical conductivity increase to an optimum point from where they then decrease because of the reduced cross section of the crimped members. The optimum crimp depths for tensile strength and conductivity usually do not coincide and a design compromise is required.

Reference 1. Whitley, J. H., "The Mechanics of Pressure Connections", AMP Incorporated, 1964.

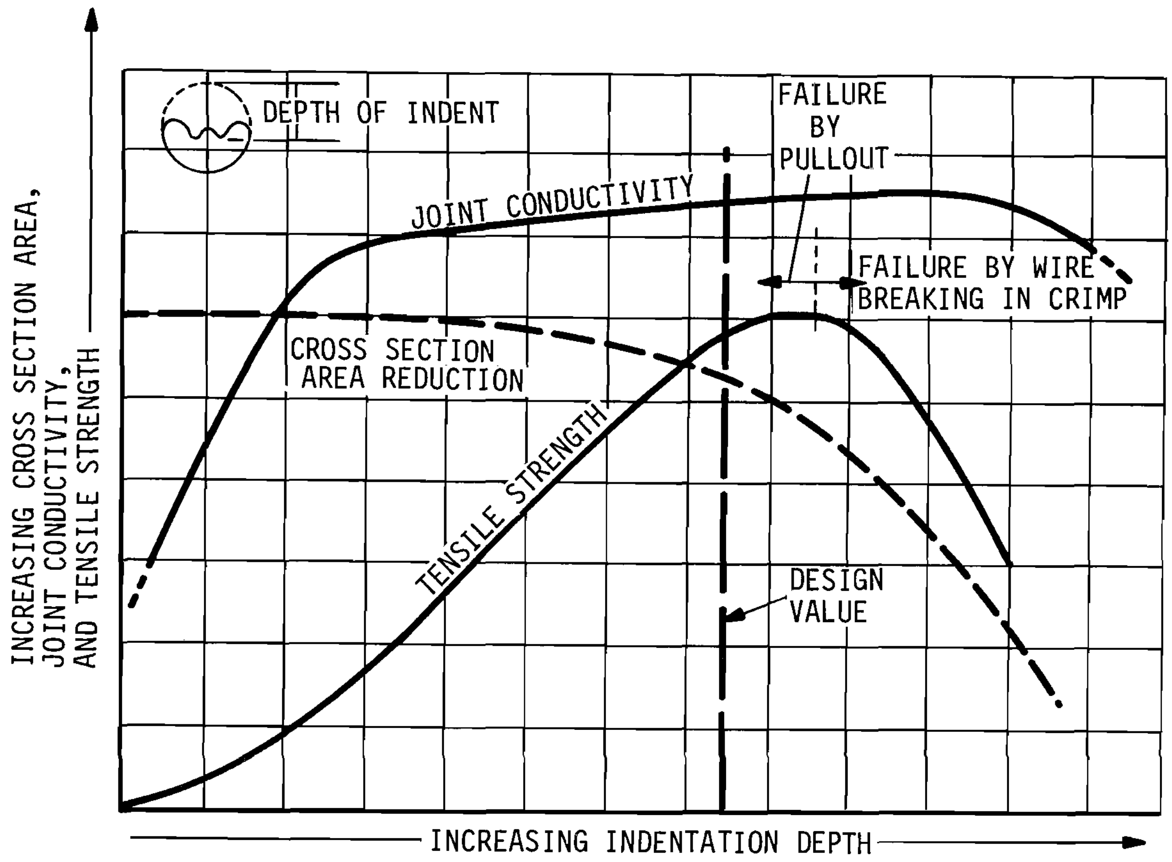

Figure 1. Variation of Crimped Connection Characteristics with Indentation Depth

The design value for indentation depth in a crimp system is usually chosen to fall on the undercrimped side of the tensile strength curve and on the overcrimped portion of the conductor cross sectional area of the curve (Figure 1). Figure 1 also shows that the effects of joint conductivity at the design value indentation depth is basically flat or at the "inverted bathtub" portion of its curve, However, tensile strength is considered to be the prime factor in the optimization and selection of the crimp indentation depth. Indentation depth is normally chosen on the undercrimped side of optimum tensile strength to compensate for build-up of production tolerances on crimp terminations, wire, and tooling, Thus, spillover to overcrimped portions of the tensile strength curve is prevented. The tensile strength curve is peaked and falls off quickly and crimped terminations weaken quickly at the peak of the curve. As tensile strength decreases, the connections are susceptible to vibration and shock, with resultant wire breakage in the crimp area.

Operation in the overcrimped area is preferred in some cases, such as when both wire and termination are molded to the point at which the mechanical cleaning action is better. The improved cleaning action enhances electrical conductivity which in some instances is preferred to lowered mechanical strength.

As a rule, spliced or crimped conductors, such as a wire and terminal or wire and connector pin, or even wire to wire, should have an electrical resistance no greater than an equivalent unspliced or uncrimped length of conductor; also, mechanical strengths of joints should not be significantly less than the conductors.

Figure 2, from Reference 1, compares the wire strengths of various gauges of wire by military and commercial specifications and requirements. For smaller wire gauges, approximately 90 percent wire strength is maintained in a crimp connection. For larger wire sizes and cables, the specifications allow greater reduction to the crimp connection strength/wire ratio. Some applications such as power utilities require higher tensile strengths in the connections used in overhead power lines. These higher strength requirements are usually accomplished by multiple crimping, i.e., forming several indents on a longer connection.

Although there is some disagreement on this point, it is generally believed that the high electrical conductivity and mechanical strength of crimp connections are a primary result of cold welding. The degree of welding is not that of a full-area cold weld achieved by bringing together two freshly cleaned metal surfaces under high pressure causing large plastic deformations. The crimping operation does not start with freshly cleaned surfaces, although the crimping action does clean the surfaces to some extent. Also, the plastic deformation in crimps is much less than with a normal cold weld. However, there is a sufficient amount of pressure and associated plastic deformation involved to cause some degree of cold welding. This produces a gas-tight connection that assures high resistance to internal corrosion.

2.2 Materials used in Crimp Connections

The most commonly used base metals for making crimp connections are brass, copper, nickel, aluminum, and several high-performance alloys. Each metal varies in degree of electrical resistance, compatibility with other metals, and applicable temperature limit. High grade copper is one of the best metals as it has good conductivity, forming properties, and is compatible with copper conductors. Nickel is used for many high temperature applications as it performs well at temperatures in excess of 1200°F. Brass is used for certain types of terminals used on high-speed crimping machines. Aluminum terminals are compatible with aluminum conductors, but are susceptible to corrosion, oxidation, and creep.

Reference 1. Op. cit.

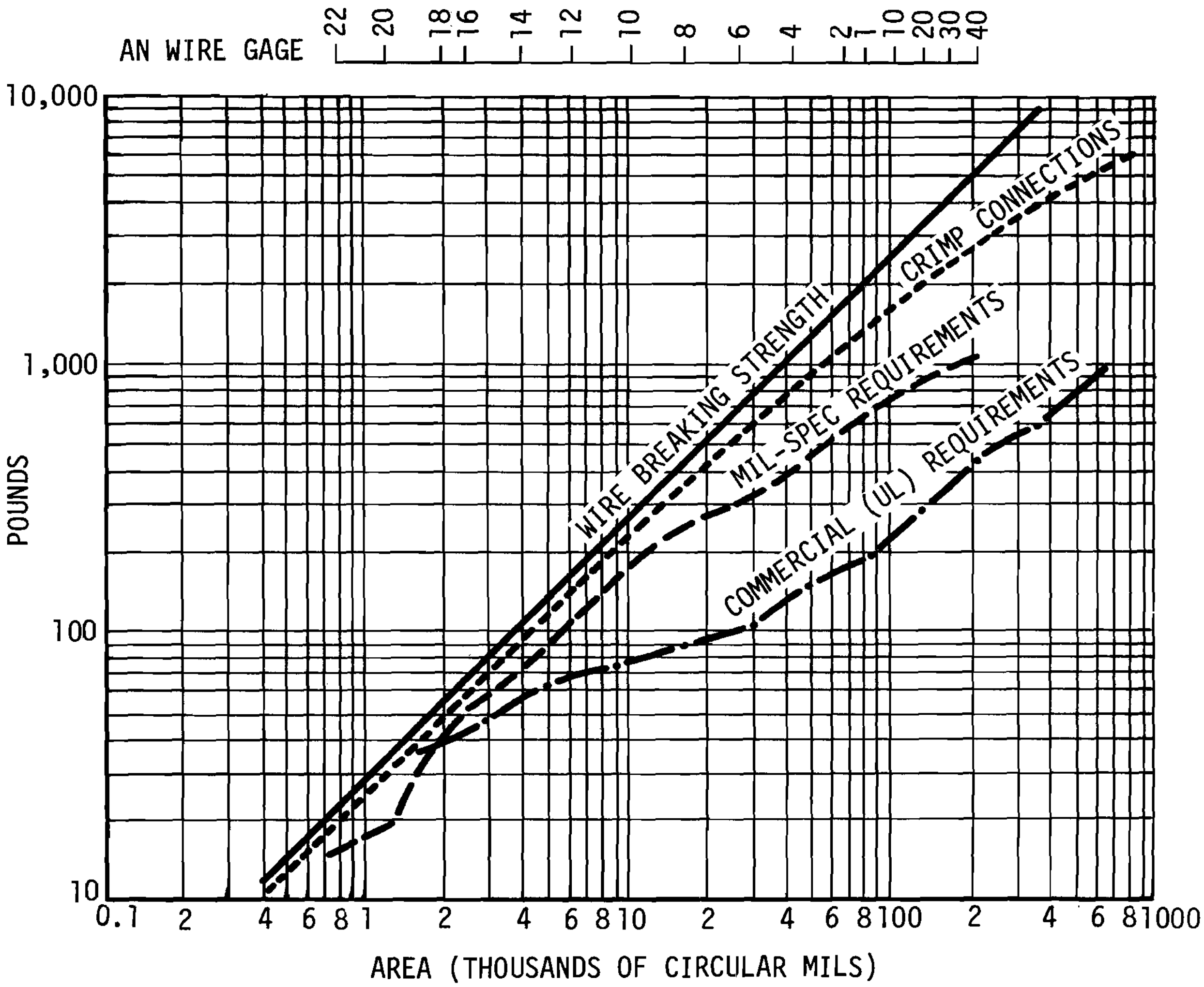

Figure 2. Tensile Strength of Wire and Wire Connections

Crimp contacts for connectors are usually made of alloys such as beryllium copper, phosphor bronze, and nickel. The beryllium copper alloys are widely used because of their good mechanical strength, high conductivity, and resistance to wear and corrosion. Phosphor bronze alloys are easily formed and have good corrosion resistance; however, their conductivity is not as good. In addition to good strength and corrosion resistance properties, nickel alloys offer lower stress relaxation at higher temperatures than copper alloys.

All metals have surface oxide films that provide protection against corrosion. Optimum corrosion resistance is offered by metals with the most cohesive and tough oxide films. Unfortunately, these oxide films also act as electrical insulators, causing the metal to lose its effectiveness as electrical contacts. Therefore, metal plating is required to improve electrical characteristics of the film on the surface of a contact or terminal.

Contact platings may be classified as either noble - gold, rhodium, palladium and platinum, or non-noble - tin, tin-lead, silver, and nickel. Silver is classified as non-noble because of its reaction with the large quantity of sulfur-bearing pollutants in modern industrial atmospheres. Gold is the most commonly used noble metal, while tin and tin-lead are the most often used non-noble platings. Although expensive, gold is practically oxide-free and requires little pressure to achieve good metal-to-metal contact. Crimp contacts for connectors in military systems are usually gold plated.

Certain types of crimp terminals can be obtained pre-insulated, i.e., the insulation is on the terminal before the crimping process. The most common insulating materials used on pre-insulated terminals are nylon and polyvinyl chloride (PVC). Both are rated at better than 220°F. At low temperatures, nylon is much more stable than PVC, however, PVC is recommended for most applications where moisture is present, as nylon tends to be hygroscopic.

2.3 Failure Causes and Prevention

The majority of crimp failures are caused by procedural problems, such as using the wrong indentation on the crimping tool or using an incorrect size termination for a given wire gauge. These failures are usually detected before the equipment is shipped through tensile strength tests or higher equipment level tests such as acceptance tests that include functional and limited environmental testing. The causes of these problems usually can be attributed to negligence and/or poor planning. These problems are evidenced by the causes of crimp connection failures that have been reported in the Government-Industry Data Exchange Program (GIDEP) ALERT files. GIDEP ALERT problems are summarized in Table 2.

Table 2. Typical Crimp Connection Failure Modes

Failure Mode	Causes
Increased Contact Resistance	Stress Relaxation: Creep Recrystallization
	Corrosion: Atmospheric Galvanic
	Undercrimping
Low Tensile Strength	Undercrimping
	Overcrimping
Wire Breakage Near Terminal	High Vibration
	Overcrimping

No failures occurred in any of the data collected during this study program, indicating that field failures of crimp connections are rare. However, most contractors contacted did not keep reliability records on crimp connections and had no data to report. The general consensus is that because of their low cost and ease of repair, failures of crimp connections usually go unreported.

A study of the physical characteristics of crimp connections indicates that if a crimp is properly made, i.e., with the proper combination of terminal, wire, and crimping tool and the application of correct crimp depth, the probability of a failure during field operation should be very small. However, there are some environmental and time-related failure modes which could occur, particularly in substandard or poorly designed crimps.

Typical Crimp Failure Causes

Figure 2 lists typical failure modes that can occur in crimp connections. A time-related failure mode that can be accelerated by temperature is high contact resistance due to stress relaxation. The crimping operation causes in the connection high internal or residual stresses that hold the termination and conductor together tightly. These residual stresses act as an elastic strain, with the same effect as holding the part in a tensile test machine under load. Stress relaxation, caused by creep or crystallization, reduces these residual contact pressures to a point where the terminal fails due to increased contact resistance.

When a metal is placed under high residual stresses, it tends to creep or "cold flow" away from the area of stress. This phenomenon is caused by slow atomic diffusion of the material to accommodate the crimped-in stresses and results in dimensional changes. High temperatures are required for this process to have significant effects in most metals; however, aluminum can creep at room temperatures.

Crimping can be considered a cold working process, i.e., plastic deformation below the temperature of full annealing. During cold working of a metal, the original crystal structure is broken down into a finer and and stronger structure. The dimensions of the resultant crystals are longer in one direction. As the crystal structure is broken down during cold working, energy is stored. When the metal is subsequently heated, the material tends to recrystallize to achieve a state of lower stored energy (Reference 2). This recrystallization process is the growth of new stress-free equiaxed crystals. (Equiaxed means the crystals have equivalent dimensions in all directions). Thus, recrystallization accelerates the effects of creep by relieving internal stress. The temperature required for recrystallization varies with the particular metal; recrystallization can occur in high purity copper at about 250°F and in lead at 25°F. Figure 3, from Reference 3, shows approximate recrystallization temperatures for several metals as compared to melting temperatures.

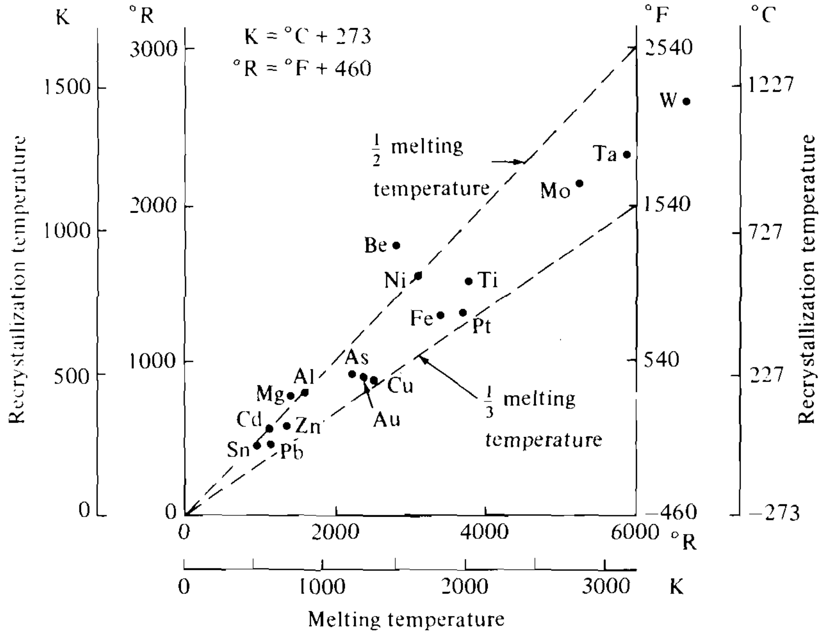

Figure 3. Metal Recrystallization Temperatures Compared with Melting Points

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Reference 2 - Mason, S. S., "Thermal Stress and Low-Cycle Fatigue," p. 255, McGraw-Hill Book Company, 1966.

Reference 3 - Van Vlack, L. H., "Elements of Materials Science," Figure 6-29, p. 154, 2nd ed., Addison-Wesley Publishing Company, 1964.

Corrosion of the electrical contact areas causes failure of the electrical interface. Atmospheric corrosion primarily depends upon the amount and types of contaminant present in the environment. This type of corrosion is not a serious problem if the crimp cross section is a true homogeneous mass and is gas tight, because the corrosive medium has no access to the contact area.

Galvanic corrosion results when two metals with different electrolytic potential are joined in the presence of a solution containing ionized salts. The metal with the most negative potential becomes anodic and will tend to go into solution with the presence of an ionized salt solution. The severity of the galvanic action depends on the electrochemical properties of the metals, concentration of the solution, temperature, and several other factors. The most common situation involves salt water as the electrolyte. Table 3, from Reference 4, lists the relative performance of various crimped couples in 1 percent salt spray.

An example of galvanic corrosion occurs when aluminum is joined with copper, the aluminum becomes anodic, and under proper conditions goes into solution and deposits on the copper in the form of hydrated aluminum oxides until the aluminum is completely consumed by the chemical process. This process results in total degradation of the electrical and mechanical interfaces of the termination.

Undercrimping effects on tensile strength are more apparent than overcrimping effects. The greater the crimping pressure, the stronger the connection, until the crimp indentation is too great, whereupon the cross section reduces and tensile strength decreases (see Figure 1).

A potential source of trouble in crimp terminals is wire breakage near the junction with the terminal, caused by the wire flexing as a result of environmental effects. An insulation-gripping sleeve added to the basic terminal will prevent many failures.

Failure Prevention in Crimp Connections

Adequate planning of each particular crimping operation is the most important factor in preventing crimp failures. Planning includes selecting the correct termination for the wire to be crimped, analyzing type and depth of indentation required, selecting the tool to be used, and establishing strict manufacturing practices and procedures. This section primarily addresses manufacturing practices. Procedures for selection and application of the correct terminations and tools to be used for given conductors is discussed in Section 4.0 of this report.

Reference 4. Ginsberg, G. L., Editor, "Connectors and Interconnections Handbook," Vol. 1, p. 5-11, Electronic Connector Study Group, Inc., Camden, New Jersey, 1977.

Table 3. Galvanic Corrosion in 1 Percent Salt Spray

	Copper	Nickel-Plated Copper	Silver-Plated Copper	Gold-Plated Copper	Tin-Plated Copper	Solder-Dipped Copper	Aluminum	Tin-Plated Aluminum (no undercoat)
Copper	1	1	2	1	2	2	4	4
Nickel-Plated Copper	1	1	1	1	1	1	4	3
Silver Plated Copper	2	1	1	1	2	3	4	4
Gold Plated Copper	1	1	1	1	2	3	4	4
Tin Plated Copper	2	1	2	2	1	1		
Solder Dipped Copper	2	1	2	3	1	1		2
Reflowed Tinned Copper	2							
Brass							4	
Nickel-Plated Brass							4	
Tin-Plated Brass							1	
Aluminum	4	4	4	4	1		1	1
Tin-Plated Aluminum (no undercoat)	4	3	4	4		2	1	1
Tin-Plated Aluminum (standard process)							2	
Solder-Dipped Aluminum							3	

1 = Completely Satisfactory; 2 = Slight Galvanic Corrosion;

3 = Moderate Galvanic Corrosion; 4 = Severe Galvanic Corrosion

Problems that occur in crimped terminations are usually caused by human error, particularilv when manual crimping tools are used. Instituting safeguards to ensure crimp quality is more economical in the long run than reworking bad terminations. Crimp connection reliability also is improved because of the resultant lower probability of a bad termination. Data acquired in a survey of contractors throughout the United States showed that the most successful safeguards that prevent human-oriented crimping problems are: 1) Certification of crimping technicians by a short training program; 2) color coding of tools, terminations, and wire; and 3) tensile strength tests performed at least once daily on samples crimped with each tool in use.

One advantage of using crimp connections over other types of permanent connections is the minimum skill level required to perform the operation. This does not mean that no training at all is required. A short training program should be given to each employee who will perform a crimping operation. In addition to being instructed on general crimping procedures, each employee should be monitored while using his working tools. After successfully completing the training program, each individual should be issued a card certifying that he is trained to work with crimping tools. Such a training program should require only a few hours.

A most successful means of preventing technicians from using the incorrect tool or tool setting is to color code the tools and terminations. Many manufacturers sell both tools and terminations already color coded.

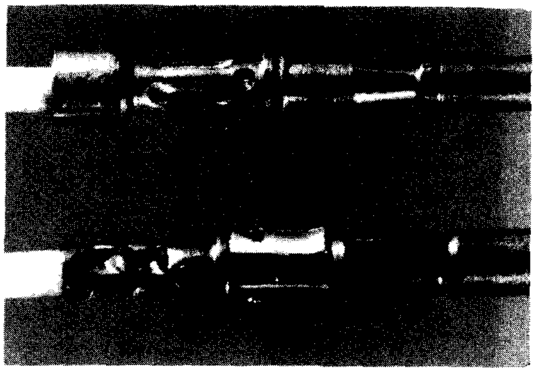
An additional method for ensuring that the technician is using the correct tool and procedures is to perform tensile strength tests (pull tests). The crimped connection is placed in a tensile tester and sufficient force applied to pull the wire out of the termination barrel or break the wire or termination device. The crimp barrel should not break nor become distorted to the extent of inoperability before the minimum specified tensile strength is reached. These tests should be performed at least once a day on samples from each tool; they are a check on both operator and tool.

Periodically crimping tools will go out of calibration, have cracked dies, or encounter other problems. These situations happen more frequently with manual than automatic (bench-mounted) tools. To maintain tool quality periodic tests should be performed, including: 1) Tool calibration check after a specified period of use (30 days recommended); 2) tensile strength test at least once daily on each tool in use; and 3) visual inspection performed daily on crimped samples from each tool.

Tool calibration is indirectly checked when tensile strength tests are performed; however, it is recommended that manual tools in particular be specifically checked for calibration periodically by measuring the distance between the indentors at a specific closure setting.

The tensile strength test, as well as being used to check for operator procedural problems, is also the primary means of checking tool performance. If more than one wire size is being crimped by a given tool, it is recommended that samples for maximum and minimum wire size be tested. Crimping of the samples should be performed by the normal operator for each tool, since this is a dual purpose test.

Prior to the tensile strength test, the samples should be visually inspected. As a minimum, the visual inspection should ensure that termination metal is not crushed nor torn; wire insulation is properly crimped and not crushed nor cracked; crimp indents are well formed and properly positioned; and the crimp terminations, wires, and insulation are properly interfaced. Examples of workmanship quality standards that should be applicable for most types of crimped connections are illustrated for solderless pins in Figure 4. The preferred and reject levels are compared by picture.



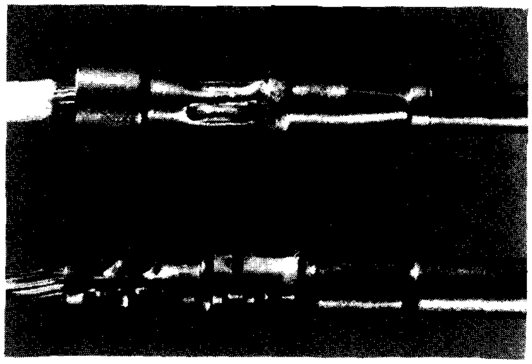
PREFERRED

Top Pin (with insulation support well): Insulation has been inserted to the depth of the insulation support well.

Bottom Pin (without insulation support well): Insulation has been stripped evenly and neatly and butts on the rear of the contact.

Conductors have bottomed in the support wells and are visible through the inspection hole.

Crimping indents are well formed and properly positioned.



REJECT

Top Pin (with insulation support well): Bare wire visible outside support well.

Bottom Pin (without insulation support well): Excess insulation strip. Exposed bare wire exceeds tolerance of 1X wire diameter plus 1/16 inch maximum from rear of contact crimp barrel.

Conductors have not bottomed in the support well and are not visible through inspection hole.

Top Pin: Crimping indents too low.

Figure 4. Examples of Good and Bad Workmanship for Crimped Solderless Pin Connections

3.0 FAILURE RATE MODEL DEVELOPMENT

3.1 Data Collection and Analysis

More than 3.8 billion part hours of data were collected on crimp connections during this study program. Table 4 summarizes the data collected for each environment. The data were obtained through an extensive data survey and collection effort. A total of 560 contractors, institutions, and Government agencies were sent a data survey letter explaining the purpose of the study program and requesting a response to a short questionnaire. Approximately 260 responses were received. Favorable responses were followed up by telephone calls, and where deemed necessary, personal visits were made. A total of 47 potential data sources were visited. Appendix B summarizes the data collection effort and lists the sources from which data were obtained for this study.

Table 4. Summary of Crimp Connection Data

Environment	Part Hours (x 10^6)	Failures	Failure Rate* (Failures/10^6 hrs)
Ground, Benign (G_B)	3,590.00	0	0.000255
Ground, Fixed (G_F)	16.18	0	0.0566
Naval, Sheltered (N_S)	5.50	0	-
Airborne, Inhabited (A_I)**	6.90	0	-
Airborne, Uninhabited (A_U)**	249.45	0	0.00367

* *All failure rates are calculated at upper single-sided 60 percent confidence level.*

** Subsonic aircraft

The failure rates given in Table 4 are calculated at the upper single-sided 60 percent confidence level by using the part hours and the 40 percent chi-square value at 2r + 2 degrees of freedom. The general equation used for calculating the failure rates were obtained from Reference 5 and is as follows:

$$\frac{\chi^2\ (\alpha,\ 2r + 2)}{2T} \quad = \text{Upper single-sided confidence level}$$

where:

r = the number of failures and determines the degree of freedom coordinate used in determining chi-square (χ^2).

2r + r = total number of degrees of freedom

α = acceptable risk of error (40 percent in this study)

1 - α = confidence level (60 percent in this study)

T = total number of part hours.

As shown in Table 4, the collected data reported no failures. These results demonstrate the large quantity of part hours necessary to generate failures. Few sources contacted during the study recorded accumulated time or failures on crimp connections. Therefore, the collection of significant quantities of data were very difficult. Most data were obtained from connectors with crimped connections.

3.2 Failure Rate Model

A failure rate model has been developed for predicting crimp connection reliability. The model is patterned after other MIL-HDBK-217B models in that it has a base failure rate modified by three multiplicative factors. The factors represent environment, type of crimping tool, and quality standards. The model is as follows:

$$\lambda_T = \lambda_b (\Pi_E \times \Pi_T \times \Pi_Q)$$

where:

λ_T = total crimp connection failure rate

λ_b = base failure rate

Π_E = environmental factor

Π_T = tool type factor

Π_Q = quality factor.

Base Failure Rate

A single base failure rate is used for the model: $\lambda_b = 0.000255$ failures per million hours. This value is based strictly upon the data collected in the ground benign environment, since no other environment had sufficient part hours to obtain representative failure rates. Although the failure rate is based upon data with zero failures, it is a realistic value that yields a total failure rate significantly lower than the present handbook value.

Environmental Factors

The environmental factors developed for crimp connections are shown in Table 5. No sufficient quantity of data was obtained in any environment other than ground benign to derive factors. Therefore, these factors are based upon a comparative analysis of known solder joint environmental factors and engineering analysis of crimp characteristics as a function of

Table 5. Crimp Connection Environmental Factors (Π_E)

Environment	Symbol	Π_E
Ground, Benign	G_B	1.0
Ground, Fixed	G_F	1.5
Naval, Sheltered	N_S	1.5
Naval, Unsheltered	N_U	3.0
Ground, Mobile	G_M	3.0
Airborne, Subsonic, Inhabited	A_{IT}	3.0
Airborne, Supersonic, Inhabited	A_{IF}	6.0
Airborne, Subsonic, Uninhabited	A_{UT}	4.0
Airborne, Supersonic, Uninhabited	A_{UF}	8.0
Missile Launch	M_L	7.0

different environmental conditions. Data taken from Reference 6 were used to derive solder joint factors in these environments as shown in Table 6. The factors in the table were obtained by normalizing all failure rates to the ground fixed failure rate. Engineering analyses of potential crimp connection failure mechanisms indicated that crimps are significantly better than solder joints in dynamic environments and less susceptible to electrochemical failures. Therefore, the values in Table 6 were considered to be upper limits for crimp connections with realistic values being significantly lower.

Table 6. Derivation of Environmental Factors for Solder Joints

Environment	Part Hours* (x 10^6)	Failures*	Failure Rate ** (failures/10^6 hrs)	Environmental Factor
Ground, Fixed	162,329.44	634	0.0039	1.0
Airborne	5,995.55	135	0.0231	5.9
Shipboard	1,640.53	14	0.0095	2.4

* Data obtained from Reference 6

** Upper single-sided 60 percent confidence level.

Reference 6. Cottrell, D. F., Gagnier, T. R., Kimball, E. W., Kirejczyk, T.E., Martin Marietta Corporation, "Revisions of RADC Nonelectronic Reliability Notebook," p. 19, RADC-TR-74-268, Rome Air Development Center, 1974

The aircraft environment has been expanded to four categories from the two categories, Inhabited and Uninhabited, listed in MIL-HDBK-217B. The purpose of the expansion is to separate supersonic and subsonic aircraft environments. It is generally accepted that equipment on supersonic aircraft are exposed to higher levels of shock, vibration, and acoustic noise and to a more severe operating temperature range than equipment on subsonic aircraft. Also, since the mission duration is usually much shorter for supersonic aircraft, more cyclic problems result. Therefore, significant differences in equipment reliability would be expected and have been observed. Data results contained in References 7 and 8 indicate that the supersonic environment degrades reliability by about twice that of the subsonic environment. Thus, a factor of 2.0 was applied to the subsonic values to obtain the supersonic environmental factors.

Tool Type Factors

The factors for different types of crimping tools are shown in Table 7. In the table, the term "manual" includes all hand-held tools, even if they are power assisted. These factors were developed with the underlying philosophy that reliability increases as direct human involvement decreases. In addition to there being little or no human interface, the automated or bench mounted machines have hardened steel dies that wear less than many manual tool dies and maintain a more stable tolerance. However, the difference in reliability between a crimp made by a manual tool versus one by an automated tool was considered to be no greater than 2 to 1. The primary factor is the human element; such things as cracked or worn dies can be identified by proper inspection procedures. If the effects of the human element are essentially eliminated by proper quality procedures, manual crimping should be just as reliable as automatic crimping.

Table 7. Tool Type Factors, Π_T

Tool Type	Π_T
Automated	1
Manual	2

NOTE: Manual includes all hand-held tools.

Automated encompasses all bench mounted power tools.

Reference 7. Kern, G. A. and Drnas, I. M., Hughes Aircraft Company, "Operational Influences on Reliability," page 5-4, RADC-TR-76-366, December 1976.

Reference 8. Pearce, M. B. and Rise, G. D., Boeing Aerospace Company, "Technique for Developing Equipment Failure Rate K Factors," page 13, AD 916002, December 1973.

The biggest advantage of automated tools is their speed. A fully automated machine can produce more than 3000 crimps per hour. Automated tools require more setup time but are less likely to have their settings erroneously changed. On the other hand, manual tools are usually adjustable for many settings and sometimes mysteriously acquire the wrong setting during a period of use. Also it is possible for a technician to pick up the wrong tool by mistake. Good quality procedures help prevent these errors occurring.

Quality Factors

The values for the quality standards factor are shown in Table 8. Automated tools are more consistent and maintain more stable tolerance levels than manual tools. Therefore, a factor of 1.0 is used for all automated tools (except powered hand-held tools). As a minimum, it is recommended that a daily pull test be performed on samples from these tools. This test is also referred to as a tensile strength test and consists of measuring the force required to pull the wire out of the contact or break the wire at the termination interface. This force should not be less than some specified minimum tensile strength. Any tolerance problems with automated machines must be detected early, since thousands of defective crimps can be produced in a very short period.

Table 8. Quality Factors, Π_Q

Quality Grade	Π_Q	Comments
Automated Tools	1.0	Daily pull tests recommended.
Manual Tools:		
Upper	0.5	Only MIL-SPEC or approved equivalent tools and terminations, pull test at beginning and end of shift, color coded tools and terminations.
Standard	1.0	Only MIL-SPEC tools, pull test at beginning of each shift.
Lower	10.0	Anything less than standard criteria.

Table 8 also shows the quality factors for the manually operated tools. Usage of military standard tools is required by both the standard and upper grades, which ensures a full cycle tool being used that will not reopen until the entire crimp cycle is completed. This prevents premature release of pressure during the crimping action which would cause the crimp depth to be less than desired. The upper grade also requires additional pull testing and color coding of tools and terminations. One of the worst problems encountered during crimping is the erroneous mismatching of tool indentation setting with the gauge of wire and terminal being used. Many companies color code as standard practice on production programs to help prevent personnel errors, and have obtained excellent results. Quality procedures classified as lower grade include the use of non-full cycle tools and infrequent pull tests. These types of procedures are undesirable for obtaining reliable crimp connections; thus a factor of 10.0 has been assigned to this grade.

Comparison with MIL-HDBK-217B Failure Rate

Using the failure rate model for a crimp connection in a fixed ground environment, standard quality grade, and made with a manual tool, the failure rate obtained is:

$$\lambda_T = 0.000255\ (1.5 \times 2 \times 1) = 0.000765 \text{ failures}/10^6 \text{ hours.}$$

This failure rate is almost one order of magnitude lower than the value of 0.0073 failures per million hours presently in MIL-HDBK-217B.

4.0 APPLICATION AND SELECTION GUIDELINES

A crimp connection can be defined as a system comprised of components, tooling, and techniques. This system is designed as a unit that performs a specific job with a predictable outcome. Experience has shown that each crimp system must be selected to suit the particular application. Optimization for one condition or set of conditions is not necessarily correct for others. Untested and unproven combinations are likely to cause unexpected reliability problems. This section is intended to provide a basic understanding of the factors involved in the selection and application of the elements comprising a crimp connection system.

4.1 Comparison of Crimped Connections to Other Permanent Connection Techniques

A crimp connection is classified as a permanent connection, i.e., a connection meant to be installed and left alone. The one positive attribute all or most permanent connections possess is the nonexistance of contact wear. But the similarities end there; electrical and mechanical properties and quality of performance are a function of different variables such as operating voltage and current, mechanical stress, environment and service requirements. Table 9, from Reference 4, compares crimp connections to 17 other mechanical, chemical and thermal methods of making permanent connections. Performance and compatibility criteria are ranked for the various type permanent connections. As indicated by the table, the crimped connection method ranks high in all categories. Only horizontal comparisons should be made with Table 9. Desired performance characteristics should be selected in the left column and available types of connections compared for that category only. Vertically, the rating values are based on standards that differ too widely; hence, vertical comparison is not recommended.

If it is established that crimp connections are the type of permanent connection needed for a specific application, then the selection of crimp system elements to meet that particular application may begin.

4.2 The Selection of Crimp Connections

The large number of crimp connection types makes it relatively certain that any termination requirement can be met. The key to selection and application is to be aware of available configurations and materials and to correlate the specific combinations required for a particular application.

The primary function of crimp connections regardless of configuration is to provide excellent mechanical and electrical connection. It is essential in choosing terminations to consider whether crimping will be accomplished manually or automatically. Significant physical differences

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Reference 4. Op. cit., pp. 5-4 and 5-5.

Table 9. Comparison of Crimp Connectors to Other Mechanical, Thermal, and Chemical Connective Methods

PERFORMANCE AND COMPATIBILITY	CODE: 10=most applicable 5=acceptable 0=not recommended —=not applicable	MECHANICAL										
		CRIMP	WIREWRAP	METAL POWDER	COLD WELD	ULTRASONIC WELD	RIVETS	EYELETS	WIRE SCREWS	TERMINAL SCREWS	TWISTED WIRES	WIRE NUTS
ELECTRICAL PROPERTIES	Low Resistance	9	9	10	10	10	9	8	9	9	9	9
	Resistance Stability	9	9	10	10	10	9	5	7	9	5	8
	Low Voltage	9	9	10	10	10	10	5	8	9	5	8
	High Currents	9	8	9	10	10	9	5	9	9	8	9
MECHANICAL PROPERTIES	Pulloff Force	9	8	9	10	9	9	7	3	10	2	8
	Low Creep	9	7	9	10	10	9	8	3	8	2	8
	Strength	9	7	9	10	9	10	9	5	9	4	8
APPLICABILITY TO THESE CONDUCTORS	Solid Wire	10	10	9	10	10	5	5	10	—	9	10
	Stranded Wire	10	0	9	1	1	2	5	2	—	9	10
	Insulated Wire	10	9	9	9	9	9	9	9	—	9	9
	Aluminum Wire	8	1	5	8	8	4	4	4	—	1	6
	Tinsel Wire	8	0	5	0	5	6	6	4	—	0	0
	Bus Bars and Structures	7	—	—	8	8	10	10	—	10	—	—
JOINING WIRE TO:	Wire	9	—	9	9	7	3	3	4	—	10	10
	Component	8	8	7	7	7	8	8	10	10	10	10
	Separable Connector	9	7	3	3	6	8	8	10	10	—	—
WITH INSULATED CONNECTIONS	Pre-Insulation	10	0	7	4	5	1	5	10	10	0	10
	Post-Insulation	10	7	10	7	8	8	8	8	7	9	10
RESISTANCE TO ENVIRONMENTS	Hi-Temp	9	8	9	9	9	4	3	7	8	5	7
	Low-Temp	9	8	9	9	9	5	5	8	8	7	7
	Thermal Shock	8	7	8	9	9	4	3	2	8	2	8
	Vibration	9	3	8	9	9	5	5	2	9	1	7
	Salty and Humid Air	9	6	9	10	10	8	7	7	9	4	8
	Aging	8	8	9	10	10	8	7	7	8	7	8
	Hermetic	10	1	9	10	10	8	1	1	—	1	1
	Nuclear Radiation	9	9	9	10	10	9	9	9	9	9	9
COST ECONOMY	Tooling	8	7	2	4	1	7	8	9	10	10	10
	Connector	9	9	7	8	7	9	9	10	9	10	9
	Process	9	8	5	5	1	8	8	10	10	10	10
ACCESSIBILITY IN ASSEMBLY	Method Needs Little Space	9	8	7	7	7	8	9	9	9	10	8
	Ease of Repair	9	7	6	6	6	7	7	10	10	10	9

Table 9 (Continued)

PERFORMANCE AND COMPATIBILITY	CODE: 10=most applicable 5=acceptable 0=not recommended –=not applicable	THERMAL				CHEMICAL		
		SOLDER	BRAZE	GAS OR ARC WELD	SPOT WELD	PLATING	CONDUCTIVE ADHESIVE	AMALGAM
ELECTRICAL PROPERTIES	Low Resistance	9	10	10	10	8	3	8
	Resistance Stability	10	10	10	10	8	7	9
	Low Voltage	9	10	10	10	8	5	8
	High Currents	8	10	10	9	1	1	3
MECHANICAL PROPERTIES	Pulloff Force	9	10	10	10	1	1	8
	Low Creep	9	10	10	10	5	5	9
	Strength	9	10	10	7	3	4	4
APPLICABILITY TO THESE CONDUCTORS	Solid Wire	10	10	10	10	10	10	8
	Stranded Wire	9	9	8	0	10	9	9
	Insulated Wire	6	2	2	8	9	9	9
	Aluminum Wire	5	2	1	0	2	2	0
	Tinsel Wire	5	0	1	1	5	5	5
	Bus Bars and Structures	8	8	8	9	6	6	6
JOINING WIRE TO:	Wire	10	10	9	8	—	8	8
	Component	10	8	5	9	4	5	5
	Separable Connector	9	8	1	8	5	4	6
WITH INSULATED CONNECTIONS	Pre-Insulation	0	0	0	1	1	8	9
	Post-Insulation	8	8	8	8	8	8	10
RESISTANCE TO ENVIRONMENTS	Hi-Temp	5	9	10	10	6	1	3
	Low-Temp	9	10	10	10	9	5	8
	Thermal Shock	8	9	10	10	7	7	7
	Vibration	6	7	10	9	2	1	7
	Salty and Humid Air	9	10	10	10	5	5	8
	Aging	9	10	10	10	8	5	8
	Hermetic	10	10	10	1	9	9	10
	Nuclear Radiation	9	10	10	10	9	1	5
COST ECONOMY	Tooling	7	4	3	4	5	9	7
	Connector	9	8	6	9	5	8	5
	Process	6	5	5	5	4	8	8
ACCESSIBILITY IN ASSEMBLY	Method Needs Little Space	8	5	4	8	5	8	8
	Ease of Repair	8	6	5	9	7	9	7

in configuration exist for those terminations designed for manual applications and those designed for automatic applications. Most terminations designed for automatic applications can also be used in manual tooling operations; however, those designed for manual use cannot normally be used in high-speed automatic machinery.

The type of crimp connection used most frequently is the contact for connectors. One end of the contact is the crimpable wire barrel, and the other end is the male or female portion of the connector. Examples of several sizes of crimpable connector contacts are shown in Figure 5. For each pair of contacts shown, the pin end faces the respective socket end with the crimp barrels on the extreme right and left. Figure 6 is a cut-away view of a military connector showing how the crimp contacts are arranged internal to the connector. Selection criteria for connector contacts are more dependent upon the particular connector characteristics and requirements than the crimping portion of the contact.

Crimp terminals, regardless of how they are configured or how they are crimped, are made up of two basic parts: the tongue and the wire barrel. The function of the tongue is to provide electrical contact and high mechanical strength. The two most popular crimp terminal designs are the rectangular and the basic ring configuration, or some variation of these two designs. Figure 7, based upon data in Reference 9, shows the common terminal tongue styles with application notes.

Terminal wire barrels fall into two basic categories: open barrel and closed barrel. Open barrel terminals have traditionally been best suited to high speed automatic applications. They are readily available in strip form on reels for automatic application and also are available loose for manual application. Closed barrel terminations offer a wider variety of terminal types and also are available for machine application.

Figure 8 shows two common forms of closed-barrel terminal: brazed and solid. Brazed terminals are especially reliable for use with solid wire. The open barrel terminals shown in the figure alleviate the need to strip wiring before mating the terminal barrel and wire during the crimping process. Insulation piercing lances are provided on one type of terminal; sharp serrations are on the other.

Figure 8 also illustrates insulation gripping and insulation supporting terminals. A sleeve has been added to the base of these terminals to help prevent the breakage of the wire near its junction with the terminal. The inside diameter of the sleeve is slightly larger than the inside diameter of the barrel. When the barrel is fastened to the end of the wire in the crimping operation, the insulation-supporting sleeve is fastened around the insulation. This additional support prevents excessive bending of the wire at the point where it enters the barrel of the terminal, and also prevents fraying of the wire insulation. These terminals are especially useful in environments where severe vibration is expected.

Reference 9. "A Purchasing Man's Guide to Wire Terminals," p.2, AMP Inc., Harrisburg, Pennsylvania.

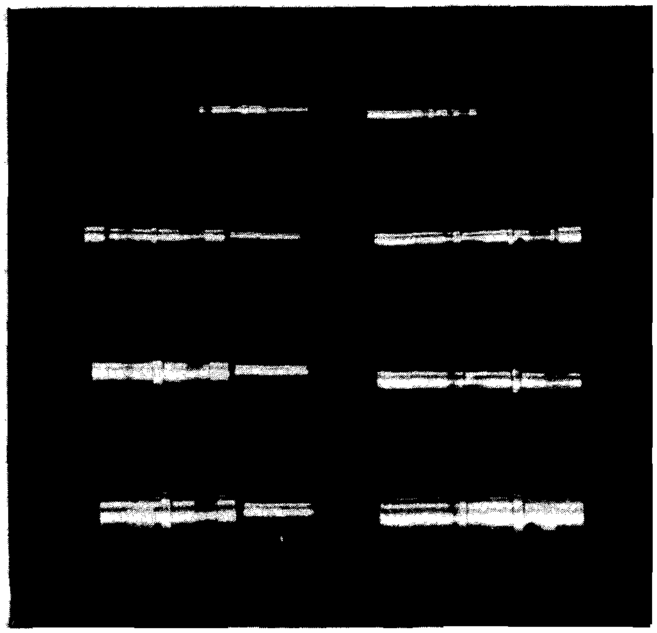
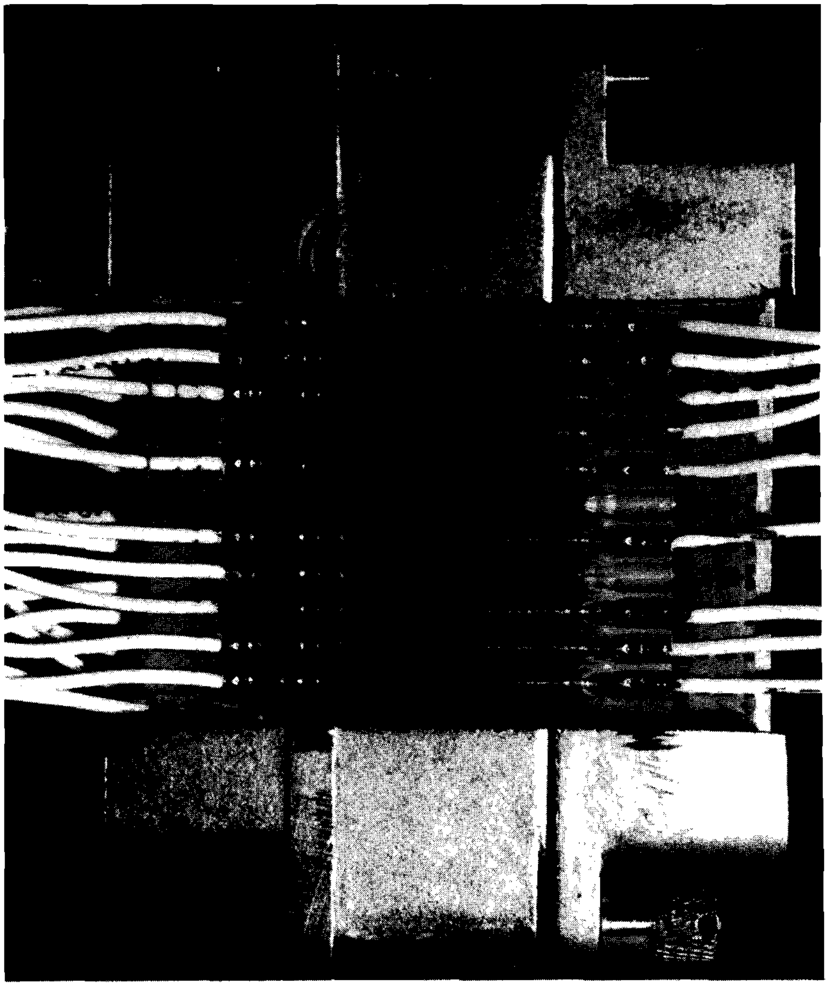
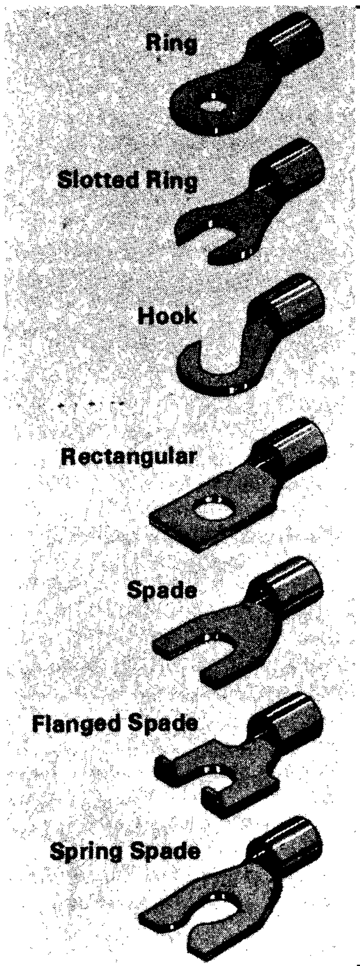


Figure 5. Crimpable Contacts Used in Connectors

Figure 6. Cutaway View of Contacts Within a Connector





Screw applies high contact forces to 360 deg. of the closed-loop surface, providing exceptionally low electrical resistance. For low voltage applications plating is recommended if little or no contact wipe exists to penetrate oxide film. Best suited for terminals not frequently removed and installed. Wear is seldom a problem.

Easily removed and installed without complete removal of screw. Under severe vibration the screw may become loose, and the tongue will offer little resistance to axial pulling forces.

Permits easy removal and installation of terminal without complete removal of screw. Axial pulling forces have no effect on the hook tongue under loose-screw conditions.

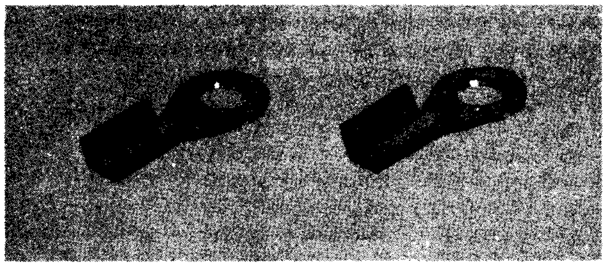
Best suited for infrequent removal and installation. Rectangular shape provides locking against lateral pulling forces.

Terminal removal and installation does not require complete removal of screw. Under severe vibration the screw may become loose, and tongue will offer little resistance to axial pulling forces.

For terminals subjected to severe vibration. Easy removal and installation.

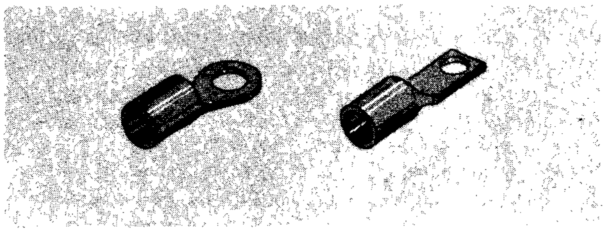
Easily removed or installed under loosened screw. Snap action of ends over screw prevents terminal from falling away from loose screw.

Figure 7. Common Terminal-Tongue Styles



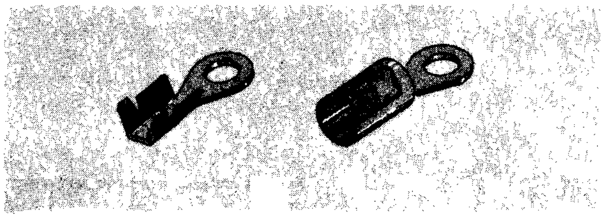
insulation-piercing lances sharp serrations

Open-barrel Terminals



brazed solid

Closed-barrel Terminals



insulation-gripping insulation-supporting

Terminals for Accomodating Insulation

Figure 8. Common Barrel Terminals

Table 10 lists various standards that may aid in the selection and application of connections and applicable tooling. The primary crimp and connection specification, MIL-C-39029A, covers removable crimp and solder type electrical contacts intended for use in multicontact connectors.

Table 10. Crimp Connection and Tool Specifications

Specification	Title
MIL-STD-1646 10 September 1973	Servicing Tools for Electric Contacts and Connections, Selection and Use of
MIL-C-39029A 2 August 1976	Contacts, Electrical Connector, General Specification for
MIL-T-7928/G 25 August 1976	Terminals, Lug and Splice, Crimp Style, Copper, General Specification for
MIL-C-22520F 19 March 1976	Crimping Tools, Terminal, Hand or Power Actuated, Wire Termination, and Tool Kits, General Specification for

Base Materials

The properties of contact materials most used for connector crimp contacts can be compared in Table 11 (reprinted from Reference 4). Connector manufacturers favor phosphor bronze, especially the composition of 95 percent copper, 4.75 percent tin, and 0.25 percent phosphorus. Properly designed beryllium copper contacts withstand more insertion and withdrawal cycles than most other nonferrous materials, but the cost per pound is much higher. The strength of beryllium copper allows the design of parts that withstand accidental high stresses without yielding or breaking, maintain high stresses for long periods of time without relaxation, and provide maximum force in a limited space.

Table 12 lists commonly used crimp terminal base materials, together with comments on applicability, significant characteristics, and constraints.

Reference 4. Op. cit., p. 6-29.

Table 11. Materials Used for Connector Crimp Contacts

Material	Relative Cost	Operative Temperature ^{o}F	Electrical Conductivity (% IACS @ $60^{o}F$)	Thermal Conductivity (BTU/FT/FT^2/ F/HR @ $68^{o}F$)	Modulus of Elasticity (psi x 10^6)	Fatigue Strength (Ksi @ 100 MM Cycles)
Cartridge Brass	1.00	250	25 min	70	16.0	16-24
Gilding Metal	1+	Not Available	56 min	135	17.0	21 @ 15 MM (spring temper)
Phosphor Bronze	1.8	275	10 min 20 min high Conductivity	40	16.0	30-35
Beryllium Copper	5.5	300	17-22 min	62-75	18.5	30-46
Nickel Silver (65-18)	1.47	650	6	27	18.0	Not Available

Table 12. Common Crimp Terminal Base Materials

Material	Attributes/Characteristics
Aluminum	High current applications Low weight Temperature constraints: 260°F maximum Susceptibility to oxidation, corrosion, and creep Compatibility with other aluminum conductors
Brass	Good conductivity Open barrel high speed machine applicability Temperature constraint: 225°F maximum Electrical resistance higher than some other metals
Copper 99.9 percent pure	Excellent conductivity Closed barrel application Excellent forming (malleability) properties Temperature constraints 600°F maximum
Nickel	Compatible with iron, manganese, nickel, and nickel-chromium Temperature constraints: with nickel-chromium up to 1200°F in highly corrosive environments High temperature application Relatively low conductivity
Steel	High mechanical strength Open barrel application Lower conductivity than most other terminals Suitable plating is required which cancels low initial cost

Plating Materials

As previously discussed, base metals used in crimp connections may have to be altered through plating to improve or change certain characteristics of the base metal. The most commonly used plating metals are described in Table 13.

Table 13. Common Crimp Terminal Plating Materials

Material	Attribute/Characteristics
Gold	Relatively oxide free Malleable Low voltage (dry circuit) and corrosive environment applications Good metal-to-metal contact with very little crimp pressure Extremely expensive
Nickel	Corrosion resistant Used to increase base metal temperature ratings High crimp forces required to provide good metal-to-metal contact because of hard oxide layers
Silver	Highly conductive Moderate crimp pressure required for metal-to-metal contact Expensive
Tin	Low cost High conductivity Reduces galvanic corrosion on copper and brass terminals Sufficient pressure provides good metal-to-metal contact

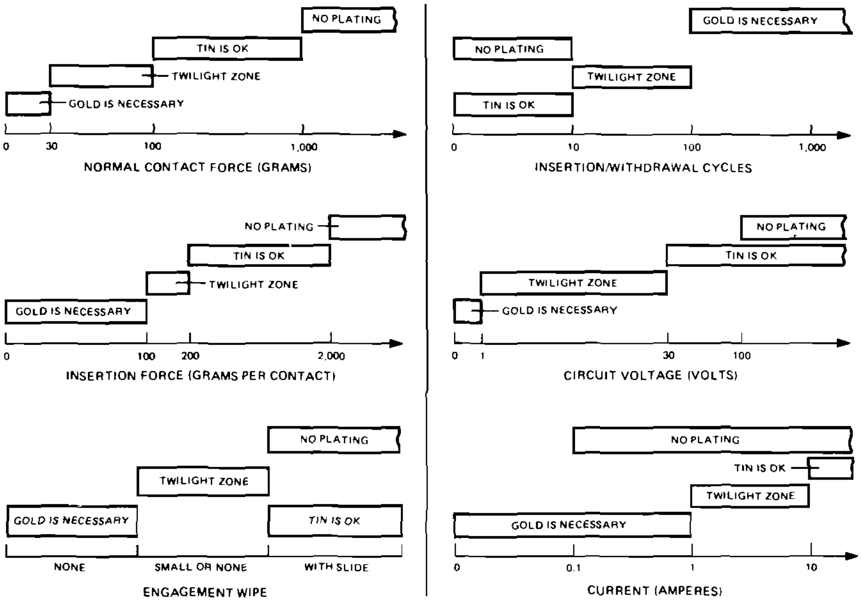
Plating criteria for the connector crimp contacts are based upon the required characteristics for the pin and socket portion of the contact rather than the crimp barrel. Pin and socket surfaces are subject to wear and exposure to chemical environments. Gold is primarily used for plating military connector contacts because of its oxidation resistance. The minimum thickness of gold plating required by MIL-C-39029A is 0.00005 inch.

An overplating of gold with an underplating of a less precious metal is often used as an added protective factor in the event that the gold overplating wears through. Nickel is an excellent underplating for wear resistance and hostile environments. Copper is also used as an underplating, but proper application must be considered as copper can diffuse to the surface of gold at high temperatures and form troublesome oxides. Silver can also diffuse and MIL-C-39029A does not permit its usage. Gold is never plated on brass or other zinc-containing alloys as zinc rapidly diffuses to the surface.

The high cost of gold has caused manufacturers to gain interest in a relatively new technique called selective plating. Several manufacturers have developed methods for plating only in those areas of the contact where plating is actually necessary. This concept is not new, but in the past the cost for selective plating has exceeded the value of the precious metal saved. In selective plating the crimp portion of the contact consists of the base metal or the undercoating materials and is not plated.

The primary alternate to gold plating on contacts is tin plating which is much less expensive. Although tin can become heavily coated with oxides or other nonconductive corrosion products, the coatings are relatively hard and brittle, and consequently easy to break through to form metal-to-metal contact. The minimum amount of force and mechanical motion required to accomplish this breakthrough of films is one of the primary considerations in selecting tin as a plating material. Guidelines to help choose gold, tin, or no plate for connector contacts have been reprinted in Table 14 from Reference 4.

Table 14. Guidelines for Selecting Gold, Tin, or No Plating Material for Connector Contacts



Reference 4. Op cit., p. 6-19.

Tin is probably the most common plating material. Tin can be used on brass, copper, and (over a layer of copper flash) on steel terminals; and is often used on copper or brass terminals that will be in contact with aluminum, to reduce galvanic corrosion.

Nickel is often used to plate copper and steel terminals to increase the temperature rating. Nickel is unsatisfactory on brass as severe corrosion can result.

Silver is normally used on copper and brass terminals. MIL-C-39029A specifies silver as the plating material to be used on certain copper and ferrous alloy contacts larger than size 12.

4.3 Crimping Tool Selection and Application

To obtain consistently reliable and cost effective terminations, a thorough analysis of factors involved should precede crimping tool selection. In many instances varied termination sizes and configurations can be crimped with a single multipurpose manual crimping tool. Multipurpose tools are extremely cost effective so long as the quantity of crimps required for any one type of termination is not excessive. Large volumes of specific terminations lend themselves quite effectively to automatic (bench mounted) tool applications where matching dies are inserted to crimp uniformly, reliably, and with great increase in speed. Listed below are guidelines in selecting the most appropriate tool for the job. In some areas, such as tool life and safety, it is recommended that personnel experienced with a particular tool be consulted during setup and initial tool operation. The following steps evaluate crimp tooling in terms of quality and cost:

<u>1</u> Itemize termination types and sizes to be crimped, thus narrowing the field of tools.

<u>2</u> Determine required crimping rates. The following rates may be used as a guideline for various tool types:

- <u>a</u> Manual (hand powered) - 100-150/hour
- <u>b</u> Automatic crimping machines - 100-3600/hour

<u>3</u> Evaluate tool life. Experience with manufacturer's specific tool is recommended. Die life averages are as follows:

- <u>a</u> Short - 5000-10,000 crimps
- <u>b</u> Average - 100,000-150,000 crimps
- <u>c</u> Long - 150,000-400,000 crimps

Optimum die life should exceed 250,000 crimps. This life is a function of termination material, proper setup, and general die maintenance.

4 Evaluate crimp connection quality. The quality and reliability of a crimp connection is extremely important. Various accessories, features, and conditions peculiar to crimping tools can be used to help assure a quality crimped connection. From Reference 4 the following list is provided:

a Locators that are positive stops against which terminations are inserted
b Wire locators that stop the wire end at the right position in the termination barrel
c Insulation grip terminals and associated crimping jaws that improve quality, provide the most positive insulation confinement, and act as a wire support. The insulation not only looks neater, but is crimped tighter.
d Die surfaces that are completely free of defects and burrs, highly polished, and in some cases hard chrome plated to assure smooth forming of the termination metal during the crimping operation.

Table 15 lists various types of crimping tools and their characteristics. Note that powered tools can be manual (hand held) as well as of the bench-mounted or automatic variety.

Reference 4. op. cit., page 5-18.

Table 15. Crimping Tool Types and Attributes

Plier crimping tool*	No full cycle action Inexpensive Useful for wide range of termination sizes and types Precision is user-dependent Has versatility for wire cutting, stripping, and bolt cutting
One hand scissor type full cycle tool	Produces controlled uniform crimp because of full cycle action Applicable to intermittent service Handles terminals from 26 to 10 AWG
Two-hand scissor type tool*	Similar to one hand; no full cycle mechanism Handles terminal size 8 to 2 AWG Has rotary die nests to handle various sized tools; are common options for two-handed tools
In-line hand tool*	Produces uniform crimping pressure across the entire terminal Produces highly reliable crimped connections May include full cycle action in sizes 26-10 AWG
Air powered crimping tool	Faster, easier crimping Less operator fatigue Scissor or inline applications
Hydraulic-powered tool	Can apply large force in small space Crimps large terminals Can handle wire sizes 8 AWG and larger Slow operation
Electromechanically powered tool	Motor driven Easily adaptable for strip fed crimping Very fast
Automatic machines	Tape or strip fed terminals Extremely fast Air, hydraulic, or electromechanically powered

*Some or all tools in this category are not full cycle and therefore not recommended for military production activities.

5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Crimped connections are the logical choice among permanent electrical connections for most applications because of their desirable characteristics, some of which are:

1. Stability at high temperatures
2. No heat involved in the process; possible damage to insulation prevented
3. Great tensile strength
4. High resistance to internal corrosion
5. High volume production capability
6. Minimum technician skill required
7. Reliability in high vibration environments
8. Repeatability; once inspected for proper setting, tool will provide identical production terminations.

Complex planning goes into making a good crimp connection. The basic configuration of the connection must be selected - size, shape, and material. The termination metal must be compatible with the type of wire used. The type of crimping tool to be used also affects termination decisions. After selection of the termination, the proper indent depth must be determined to optimize tensile strength and electrical conductivity. Procedures to be followed during the crimping operation must be established to help prevent workmanship or tool problems. Also, economics plays an important role in all these decisions. Thus, good planning is critical to a successful crimping operation.

A failure rate mathematical model developed for crimped connections will allow more precise reliability predictions for this type of termination. The model consists of a base failure rate modified by multiplicative factors for environment, type of crimping tool, and quality procedures. The failure rate for a crimped connection in the fixed ground environment is approximately one order of magnitude less when calculated from the model than the value in MIL-HDBK-217B. This is in line with both data and opinions received from sources surveyed during this study effort.

The collection of quantitative reliability data on crimped connections in fielded equipments was difficult. Most sources contacted kept no records of crimped termination failures and few even knew the quantity of crimps in their systems. Crimped connections exhibit such simplicity and are so inexpensive that they are basically overlooked, even though they may abound in great quantities in a system. If a field failure does occur, repair is so easy that no significance is attached to the failure.

5.2 Recommendations

The following recommendations are submitted for consideration and possible implementation:

1 Both Government agencies and contractors should develop a better awareness of the need for collecting data on crimped connections. Even though the failure rate for a single connection is small, the total contribution to the system failure rate can be significant because of the large quantities of crimped connections throughout the system.

2 Future data collection efforts directed toward crimped connections should be combined with connector study efforts. The most accessible data on crimped connections is associated with connectors.

3 Many high reliability programs have funding to collect reliability data on fielded equipments. These programs should be encouraged to include crimped connections in their data collection efforts.

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APPENDIX A

MIL-HDBK-217B, Section 2.14

CRIMP CONNECTIONS

2.14 Crimp Connections

Part failure rate model (λ_p):

$$\lambda_p = \lambda_b (\Pi_E \times \Pi_T \times \Pi_Q)$$

where:

λ_p = total crimp connection failure rate in failures/10^6 hrs.

λ_b = base failure rate (λ_b = 0.000255 failure/10^6 hrs.)

Π_E = environmental factor (Table 2.14-1)

Π_T = tool type factor (Table 2.14-2)

Π_Q = quality factor (Table 2.14-3)

Table 2.14-I. Environmental Factors (Π_E)

Environment	Π_E
G_B	1.0
G_F	1.5
N_S	1.5
N_U	3.0
A_{IT}	3.0
A_{IF}	6.0
G_M	3.0
A_{UT}	4.0
A_{UF}	8.0
M_L	7.0

Table 2.14-2. Tool Type Factors (Π_T)

Tool Type	Π_T
Automated	1
Manual	2

Notes: 1 Automated encompasses all powered tools not hand-held.

2 Manual includes all hand-held tools.

Table 2.14-3. Quality Factors (Π_Q)

Quality Grade	Π_Q	Comments
Automated Tools	1.0	Daily pull tests recommended
Manual Tools:		
Upper	0.5	Only MIL-SPEC or approved equivalent tools and terminals, pull test at beginning and end of each shift, color coded tools and terminations.
Standard	1.0	Only MIL-SPEC tools, pull test at beginning of each shift.
Lower	10.0	Anything less than standard critera.

APPENDIX B

DATA COLLECTION

A significant number of documents, journals, and technical papers were reviewed for information and data pertinent to the crimp connection reliability study. These documents were obtained from Government data sources and agencies, private contractors, and from the Orlando Martin Marietta Technical Information Center. Documents and reports that precipitated data and information for inclusion into this technical report are listed in the Bibliography.

More than 550 data sources were contacted by letter questionnaires in which personnel were requested to respond giving life test and field data that were accumulated in the past five years. Two hundred and sixty responses were reviewed for pertinent data. Potential data sources were then contacted by telephone and interviewed. More than forty-five potential sources of data were personnally visited in an effort to retrieve crimp connection failure rate data. The following sources contributed to this study program.

Autonetics
Anaheim, California

Lear Siegler
Grand Rapids, Michigan

Harris Corporation
Melbourne, Florida

Litton Data Systems
Van Nuys, California

Magnavox Company
Fort Wayne, Indiana

Martin Marietta
Orlando, Florida

Raytheon Company
Wayland, Massachusetts

GLOSSARY

Annealing	In general, a heat treatment in which a part is heated to soften the material; the treatment can lead to the recrystallization of cold-worked material.
Barrel	Cylindrical portion or portions of a terminal, splice. or contact accomodating the conductor or conductors.
Base Metal	Metal from which termination is made and on which one or more metals or coatings may be deposited.
Butt	Placement of two conductors together end-to-end (but not overlapping) with axes in line.
Clicker	Resistive crimped connections between wire and terminals that are intermittant in nature.
Cold working	The deformation of material below its recrystallization temperature.
Contact Area	Area in contact between two or more conductors such as crimped wire conductor and termination, permitting flow of electrical current.
Contact Crimp	A solderless contact whose hollow back portion accepts a bare wire; a swaging tool is then used to crimp the contact metal firmly against the wire. The front portion is the conducting member, usually a pin or socket for a connector.
Contact Inspection Hole	A hole in the cylindrical rear portion of contact used to check the depth to which a wire has been inserted.
Depth of Crimp	Thickness of the crimped portion of a connector measured between two opposite points on the crimped surface.
Dry Circuit	A mechanically closed circuit with no appreciable applied voltage during contacting.
Elastic Strain	The elastic displacement of atoms from their normal positions, as for example by applying a tensile or compressive stress. When the stress is removed, the atoms return to the normal spacing.
Ferrule	A short tube used to make solderless (crimped) connections to shielded or coaxial cables.
Insulation Grip	Certain crimp type contacts have extended cylinders at the rear designed to accept the bared wire and a small length of its insulation. When crimped, both wire and insulation are held firmly in place. This prevents the wire from being exposed by the insulation receding.

Insulation Support	An extension of the rear portion of the contact which gives the wire side support but not longitudinal support. This section is not crimped as is the insulation grip.
Migration	The movement of some metals, notably silver, from one location to another. It is felt that this results from a plating action in the pressure of moisture and an electrical potential.
Plastic Strain	The permanent displacement of atoms from a given starting position.
Plating	Plated on metal applied to the basic contact metal to provide the required contact-resistance and or wear-resistance.
Recrystallation	The growth of new stress-free equiaxed crystals in cold-worked material.
Terminals	Metal wire termination device designed to handle one or more conductors, and to be attached to a board, bus, or block with mechanical fasteners or clipped on.
Termination	(In this report) conductive device having a metal sleeve at one end which is secured to a conductor by mechanically crimping the sleeve. A crimp contact or terminal.
Yield strength	The stress at which a specified amount of plastic strain is produced, usually 0.2 percent.

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