NBSIR 75-672

A Preliminary Approach to Performance Requirements and Criteria for Electrical Connections in Residential Branch Circuit Wiring

William J. Meese, Ramon L. Cilimberg
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Final Report

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U. S. DEPARTMENT OF COMMERCE, Frederick B. Dent, Secretary
NATIONAL BUREAU OF STANDARDS, Richard W. Roberts, Director

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ABSTRACT

During the Operation BREAKTHROUGH Research and Demonstration program the U.S. Department of Housing and Urban Development became concerned with the inability to properly evaluate innovative electrical connections. Innovation in electrical connections has been very slow because of the long-life requirements, stringent fire safety requirements, long established conventional practices and evaluation procedures and lack of a performance base for describing requirements. This preliminary report presents the framework for a proposed method to evaluate electrical connections on a performance basis and supplements information contained in a previous report on current technology of electrical connections used in residential branch circuit wiring. Innovations involving electrical connections may lead to significant advancements in housing construction if it can be demonstrated that functional and safety requirements over the expected life of electrical connections were adequately satisfied. Research is needed to enable prediction of long-term performance of electrical connections based on the results of accelerated performance tests.

Key Words: Branch circuits; electrical codes; electrical connections; fire safety; housewiring; contact resistance; performance testing.

1. INTRODUCTION

In 1969 the U.S. Department of Housing and Urban Development initiated Operation BREAKTHROUGH, with one of the purposes of the program being to encourage and demonstrate innovations in housing. In the Operation BREAKTHROUGH program several innovations involving electrical connections were proposed. All such innovations would eliminate the use of the traditional "box" and in some cases would make connections inaccessible after completion of building construction. Taking cognizance of the potential fire hazard and the lack of durability and other technical information, approvals for innovations involving electrical systems were sparingly given with conservative stipulations. However, the possibilities of almost immediate significant benefits were recognized.

Subsequently the U.S. Department of Housing and Urban Development agreed to sponsor a long-term research project on electrical connections in residential branch circuit wiring at the National Bureau of Standards. The first publication of this project was a report on "Analysis of Current Technology on Electrical Connections Used in Residential Branch Circuit Wiring" [1].

This report, the second of the project, covers concepts to be used in generating performance requirements and criteria for evaluation of innovative electrical connections and identifies areas where research is needed.

1.1 Scope

This report contains preliminary performance requirements and criteria intended for the evaluation of electrical connections used in residential branch circuit wiring and identifies research needs.

"Branch Circuit" is defined by the National Electrical Code [2], as follows:

> A branch circuit is that portion of the wiring system between the final overcurrent device protecting the circuit and the outlet(s).
>
> A device not approved for branch circuit protection such as thermal cutout or motor overload protective device, is not considered as the overcurrent device protecting the circuit.

Branch circuits in housing are generally limited to nominal 115 or 230 volts with rated ampacity (current carrying capacity in amperes) of not less than 15 or more than 50. Generally wires involved are not larger than #6 AWG nor smaller than #14 AWG for copper conductors or smaller than #12 AWG for aluminum or copper clad aluminum conductors. Tap conductors for lighting fixtures (fixture wiring) and similar equipment connected to branch circuits may be as small as #18 AWG for copper conductors.

Both wire-to-wire and wire-to-terminal (such as wire-to-terminals on receptacles, switches, lighting fixtures or permanent appliances), connections which are made in the field or in a housing or mobile home factory are covered. Connections which are normally made as a part of the manufacturing process of electrical equipment are not covered.

1.2 The Performance Approach

A goal of this project is to develop requirements and criteria based on performance. Performance requirements should state functions and operational characteristics needed. Performance criteria should state at what level the item must perform when tested in a prescribed manner. The criteria should not state how a connector should be designed, what materials it should be made of, its size or other quantities not directly related to performance.

1.3 Definitions of Special Terms

To assist in common understanding, special terms used throughout this report are defined below.

1.3.1 Electrical Connection Component:

All parts of the hardware directly concerned with the proper functioning and safety of the electrical connection. As described below, this would include the continuous current path elements, the dielectric element and the enclosure element.

1.3.2 Continuous Current Path Element:

The electric connection point or area and electric wire and other metal parts in the vicinity of the connection point through which current is intended to flow and which are directly involved in the proper functioning and safety of the connection. In conventional construction this would include metal portions of "wire-nuts" in wire-to-wire connections and wire-binding screw terminals on wire-to-terminal connections.

Also included is the grounding connection point or area and wire and metal parts in the vicinity directly involved in the proper functioning and safety of the grounding connection. In this report "continuous current path elements" are generally referred to in the plural because an electric connection usually involves more than one joint or connection.

1.3.3 Dielectric Element:

Insulating material in the vicinity of the electric connection point or area. Insulating material must completely surround the continuous current path elements. The dielectric element may be "air". This is the case where receptacles or switches are rigidly held in place within an outlet box and electrical connections are made by means of wire-binding screws.

1.3.4 Enclosure Element:

Rigid metallic or non-metallic material which surrounds an electrical connection and prevents persons, other building components or other objects from coming in contact with the continuous current path elements. In conventional construction a switch, outlet or junction box is the enclosure.

The same piece of hardware may perform both the function of the dielectric element, which is an electrical function, and the function of the enclosure, which is a mechanical function.

1.3.5 Other Building Components:

Parts of the building other than electrical connection components. This would include studs and other structural parts, nails, gypsum board, pipes, ducts, and wiring other than that included in definition 1.3.1.

1.4 Significant Traditional Requirements For Electrical Connections

Traditional requirements for electrical connections are discussed in detail in the report "Analysis of Current Technology of Electrical Connections Used In Residential Branch Wiring" [1]. Code requirements which have been the most constrictive to innovation are summarized below.

1.4.1 "Box" Requirements

It is the code requirements for a "box" and not the requirements directly related to electrical connections which have been the primary elements of non-compliance for nearly all recent innovative electrical connections. The performance requirements and criteria in this report do not directly, or indirectly, require that electrical connections be made in traditional "boxes."

1.4.2 Accessibility Requirements

A long established code requirement for all electrical connections is accessibility (without disturbing the structure or finish of a building after building construction has been completed) in addition to being located in boxes. There appears to be very little demand for inaccessible connections at the present time. However, some innovators and housing producers believe it to be unduly restrictive and an impediment to advances in the manufactured housing construction process. With advanced developments in housing construction the demand for inaccessible connections will probably increase. Subsection 4.8 of this report outlines a procedure to evaluate inaccessible electrical connections. Because of the lack of technical information and considering the long-life requirements which would be necessary for connections not accessible for repair or replacement purposes, a conservative evaluation of inaccessible connections is necessary.

2. SERVICE CONDITIONS

In the evaluation of electrical connections it is important that service conditions be known and well defined. Service conditions are conditions involving durability (time), environment (ambient temperature, humidity, chemical content of the surrounding atmosphere, etc.), mechanical stresses (vibration, wire bending, etc.) and electrical loading (current loads and cycling patterns). Tests to determine compliance with performance criteria should address applicable service condition.

Service conditions to be considered in the evaluation of innovative electrical connectors are (1) "design service conditions" and (2) "unusual or extreme service conditions." The term "applicable service conditions", as used in the presentation of criteria in Section 4, includes both conditions in accordance with the discussions below.

2.1 Design Service Conditions

Service conditions under which an electrical connection component is expected to perform satisfactorily (design service conditions) need to be determined. Design service conditions should be the most severe conditions which can be anticipated under normal usage in housing installations. These are, generally, the conditions to which an electrical connector should be designed.

2.1.1 Time

An electrical connection component should be designed to perform safely for the life of a house, the exception being that the occurrence of a failure must not cause a hazard and the electrical connection component must be readily repairable or replaceable.

2.1.2 Environment Subsequent to Installation

The temperature in the vicinity of the electrical connection may be more of a factor in the failure of electrical connections than current passing through it and the two are not necessarily directly related because of heat dissipation aspects. Temperatures of a connection and of components in the vicinity of a connection should be correlated with typical insulation types and configurations surrounding them.

Anticipated humidity and moisture conditions in the vicinity of the connection need to be determined. Also, the effect of different environments which come into contact with electrical connection components, such as marine or industrial environments, need to be determined. The influence of varying local conditions upon connector elements must be assessed in terms of the performance, degradation and increased hazards.

2.1.3 Environment Prior to Installation

The environment to which an electrical connector and electrical wire have been exposed prior to installation may produce or induce surface chemical reactions when connections are made and thereby affect subsequent performance. This may result from exposure to various environments of the connector and wire during manufacturing and storage operations. It appears that surface chemistry aspects need investigation.

2.1.4 Mechanical Stresses

Mechanical stresses, particularly those to which the connector and wire are subjected during installation and maintenance operations, need to be determined and defined. Wire breakage (at or in the vicinity of a connection) as a result of installing or making connections could be a major factor in connection failure. Mechanical properties such as bend ductility and tensile elongation of conductors may be important in the consideration of service conditions and potential for inducing failures.

Loosening of connections appears to be a major factor in their failure. Vibration may be a contributing cause of loose connections. Some types of housing, such as mobile homes, may require connections to be more vibration resistant. Vibrations to which electrical connections are subjected need to be determined.

2.1.5 Electrical Loading

In electrical connection testing, the amount of current and the number and length of "on" and "off" cycles under which the tests are conducted are specified and closely controlled. However, there appears to be no back-up information in the literature relating such tests to field performance [1]. In testing, it is the general practice to subject electrical components to considerable current overloads to accelerate failure. Establishment of a better relationship between short-term accelerated testing and long-term field performance is needed.

2.2 Extreme or Unusual Service Conditions

In the evaluation of electrical connections, severe service conditions under which connections may generally not be expected to operate satisfactorily, but to which a particular type of connection may be exposed or utilized, should be considered. The effect and probability of extreme or unusual service conditions as they relate to a particular connector should be determined. It is not the intent that specific tests under extreme or unusual circumstances be conducted except when those evaluating the connection determine that such tests are important to the evaluation.

2.2.1 Improper Installation

Improperly installed connectors should not be expected to perform satisfactorily. However, ways in which the connector may be improperly installed, the chances of such improper installation and the effect of improper installation should be considered.

2.2.2 Other Extreme or Unusual Service Conditions

The effect of temperatures beyond those normally expected and the effect of prolonged high humidity or moisture should be evaluated. Included in these evaluations are extreme environmental conditions to which connectors may be exposed in manufacturing and storage operations.

The effect of extreme vibrations and unusual stresses on electrical connections should be evaluated. For example, what would happen if the wire were bent over a smaller radius than required or expected? Other extreme or unusual service conditions, such as prolonged "on" current or different cycling patterns should be evaluated.

2.2.3 Evaluation for Extreme or Unusual Service Conditions

Performance under unusual or extreme service conditions must be evaluated and may result in the non-approval of connectors which perform satisfactorily under design service conditions. For example, if it could be determined that the probability of an incorrect installation is high, and such an installation would pose an extreme fire hazard, the connector should not be approved.

The results of the evaluation for unusual or extreme service conditions may result in restrictions on the use of the connector. Possibly, a connector which would perform poorly when subjected to extreme vibrations may be prohibited from use in mobile homes but not in conventional housing. Connectors made of certain material may be prohibited under certain conditions, such as a marine environment.

Evaluation of electrical connections under design conditions is principally a matter of determining conformance under specific conditions. For a complete and competent evaluation under extreme or unusual conditions, judgment supplemented by test data and other measurable criteria is necessary.

3. FRAMEWORK FOR PERFORMANCE EVALUATION OF ELECTRICAL CONNECTIONS

Figure 1 outlines a proposed framework for the evaluation of electrical connections on a performance basis. The key to this evaluation is "Performance of Essential Physical Elements" when subjected to "Applicable Service Conditions" shall be in accordance with necessary "Attributes."

An electrical connection has three essential physical elements which are: (A) a continuous current path element, (B) a dielectric element, and (C) an enclosure element. These terms are defined in Subsection 1.3.

FIGURE 1

PERFORMANCE EVALUATION OF ELECTRICAL CONNECTIONS

ATTRIBUTES / ESSENTIAL PHYSICAL ELEMENTS	4.1 ELECTRICAL FUNCTION	4.2 FIRE SAFETY	4.3 ELECTRICAL SAFETY	4.4 BURN SAFETY	4.5 MECHANICAL SAFETY	4.6 TOXICITY SAFETY	4.7 BUILDING ENVIRONMENT NON-INTERFERENCE	4.8 ACCESSIBILITY/ MAINTAINABILITY/ REPLACEABILITY
A CONTINUOUS CURRENT PATH								
B DIELECTRIC								
C ENCLOSURE								

- Performance of ESSENTIAL PHYSICAL ELEMENTS
  - When subjected to APPLICABLE SERVICE CONDITIONS (Tests)
  - Shall be in accordance with Necessary ATTRIBUTES

4. PERFORMANCE REQUIREMENTS AND PERFORMANCE CRITERIA

In Section 3 a framework for the performance evaluation of electrical connections was presented. This section, on performance requirements and performance criteria, details the concepts to be used in these evaluations.

For each attribute, the performance requirement(s) of each essential physical element is listed first. This is followed by the listing of performance criteria, which describe the performance requirements in more specific terms. This is followed by a description of applicable tests and commentaries which explain and discuss each requirement and criterion.

Section 5 further discusses and describes tests to evaluate electrical function and safety (fire, electrical and burn) attributes. In many cases the same tests may be used to evaluate two or more of these attributes.

4.1 Electrical Function Attribute

4.1-A Continuous Current Path Elements

Requirement 4.1-A

The continuous current path elements shall provide for adequate flow of current through the connection point or area.

Criterion 4.1-A

Under applicable service conditions the continuous current path elements shall permit rated current of connected wires or other specified current values to flow through the connection point or area without excessive voltage drop. Specific values for allowable voltage drops are to be determined.

Test 4.1-A

Evaluative test methods for determining performance need to be developed. See Subsection 5.1, Continuous Current Path Element Tests.

Commentary 4.1-A

Rule 210-6(d), Voltage Drop, of the National Electrical Code [2] states that the size of conductors for branch circuits should be such that the voltage drop will not exceed 3 percent to the farthest outlet for power, heating or lighting purposes or combination thereof. This rule also states that the maximum total voltage drop for feeders should not exceed 5 percent overall.

Voltage drop at the connection point will be in proportion to the effective contact resistance. However, experience indicates that high contact resistance will result in excessive heating and a fire hazard before there is any impairment of electrical function. Specific limits for voltage drop will probably be established in response to fire safety (temperature) requirements (see Requirement 4.2-A) rather than in response to electrical function requirements.

4.1-B Dielectric Element

Requirement 4.1-B

The dielectric element shall provide adequate electrical insulation between individual continuous current path elements and between the continuous current path elements and other building components.

Criterion 4.1-B

Under applicable service conditions, the dielectric element shall provide electrical insulation which will withstand, without breakdown, a suitable voltage between the continuous current path elements and the surface of the electrical connection enclosure element when the electrical connection component is properly installed.

Test 4.1-B

Evaluative test methods for determining insulation performance need to be developed. See Subsection 5.2, Dielectric Element Tests.

Commentary 4.1-B

Adequate electrical insulation is necessary for electrical function and safety requirements. Specific criteria need to be developed. Criteria do not exist for dielectric withstand tests for this application; however, as related items of interest, examples of starting points are cited below.

For attachment plugs and receptacles, Underwriters' Laboratories requires a dielectric withstand test as follows: [3]

> "The assembly of a cord and wiring device shall be capable of withstanding without breakdown, for a period of one minute the application of a 60-cycle-per-second (60 hertz) essentially sinusoidal potential of 1250 volts between the two conductors of the flexible cord."

For non-metallic sheathed cable Underwriters' Laboratories requires a dielectric withstand test as follows: [4]

> "After immersion in water at room temperature for 24 hours and while still immersed, speciments from finished cable wound around a mandrel shall withstand for one minute a 60-cycle-per-second (60 hertz) essentially sinusoidal potential of 5000 volts. The potential shall be applied from each conductor separately, to the other conductor or conductors, the grounding conductor if any, and the water/mandrel ground."

4.1-C Enclosure Elements

Requirement 4.1-C

The enclosure element shall provide adequate electrical protection from contact with the continous current path elements for persons and other building components.

Criterion 4.1-C

Under applicable service conditions, the enclosure element shall be so constructed and installed, and possess sufficient rigidty and strength so that any objects in contact with any part of the surface of an electrical connection component will have electrical insulation at least equal to that specified in Criterion 4.1-B between the object and the continuous current path elements.

Test 4.1-C

Evaluative test methods for determining protection performance need to be developed. See Subsection 5.3, Enclosure Element Test and Test 4.3-C.

Commentary 4.1-C

The enclosure element is needed to afford structural protection to the continuous current path elements as well as for safety purposes. U. L. performance tests for conventional outlet boxes [5], include tests for tensile strength, flexural strength, resistance to crushing, and resistance to impact. Innovative devices may require additional criteria.

4.2 Fire Safety Attribute

4.2-A Continuous Current Path Elements

Requirement 4.2-A

Under applicable service conditions, the continuous current path elements shall be capable of operating without causing overheating of proximate building materials.

Criterion 4.2-A

Under applicable service conditions the continuous current path elements shall exhibit connectability which will not permit overheating.

Test 4.2-A

Evaluative test methods for determining current path performance need to be established. See Subsection 5.1, Continuous Current Path Tests.

Commentary 4.2-A

Research is needed to establish specific values pertaining to heat generation, temperatures, contact resistance, metal-to-metal contact or other properties pertaining to overheating, or to characteristics which may result in overheating of the continuous current path elements. Therefore, the above criterion is stated in general terms. Heat generation, heat dissipation, and the ability of different materials to withstand the effect of heat need to be examined further. Subsection 5.1, Continuous Current Path Element Tests, further discusses the problems of connectability and wire breakage.

4.2-B Dielectric Element

Requirement 4.2-B

The dielectric element shall be fire resistive and prevent arcing between phases of the circuit or to ground.

Criterion 4.2-B

(a) Under applicable service conditions, the dielectric element shall be of non-combustible construction as defined by NFPA Life Safety Code [6].

(b) See Criterion 4.1-B.

Test 4.2-B

Test methods for determining performance of the dielectric element need to be developed. See Subsection 5.1, Continuous Current Path Tests.

Commentary 4.2-B

The dielectric element provides a fire safety function; by separating the conductors, and should not be constructed of combustible materials.

4.2-C Enclosure Element

Requirement 4.2-C

The enclosure element shall be fire resistive and shall be so constructed in combination with the dielectric and continuous current path elements and/or located, to prevent ignition of other building components as a result of the flow of current through the continuous current path elements.

Criterion 4.2-C

(a) Under applicable service conditions the enclosure element shall be of non-combustible construction as defined by the NFPA Life Safety Code [6].

(b) Temperature on the surface of the enclosure element shall be governed by Criterion 4.4-C.

Test 4.2-C

Evaluative test method to determine performance of enclosure elements need to be developed. See Subsection 5.3, Enclosure Element Tests.

Commentary 4.2-C

The enclosure element should protect people and other building components from heat generated in the continuous current path elements, and should be constructed of non-combustible materials.

4.3 Electrical Safety Attribute

4.3-A Continuous Current Path Elements

Commentary 4.3-A

Protection against electrical hazards is the function of the dielectric and enclosure elements.

4.3-B Dielectric Element

Requirement 4.3-B

The dielectric element shall provide adequate electrical insulation from the continuous current path elements to a person or building component which may come in contact with the surface of the enclosure element.

Criterion 4.3-B

Same as Criterion 4.1-B.

Test 4.3-B

See Subsection 5.2, Dielectric Element Test.

Commentary 4.3-B

Adequate insulation is needed for both electrical safety and electrical function purposes. It is anticipated the criteria and tests indicated by criteria 4.1.-B and 4.3-B, will cover both the electrical safety and electrical function attributes.

4.3-C Enclosure Element

Requirement 4.3-C

The enclosure element shall provide adequate physical protection to persons and other building components from the continuous current path elements.

Criterion 4.3-C

(a) See Criterion 4.1-C.

(b) Any exposed metal parts on the surface of the enclosure element shall have provisions for and, when installed, shall be grounded in accordance with the National Electrical Code [2].

Test 4.3-C

Inspection of enclosure element and of any nonmetallic material used in its construction, and of grounding provisions of any exposed metal parts for determination of electrical safety. Also, see Subsection 5.3, Enclosure Element Tests.

Commentary 4.3-C

In conventional construction, the enclosure element, which is the "box", performs the function described in Requirement 4.3-C when properly installed with covers in place. It is the intent that the electrical connection component have no exposed live parts, and when properly installed, any exposed metal parts be effectively grounded.

4.4 Burn Safety Attribute

4.4-A Continuous Current Path Elements

Commentary 4.4-A

Performance requirements concerning burn safety apply to the enclosure element only.

4.4-B Dielectric Element

Commentary 4.4-B

Performance requirements concerning burn safety apply to the enclosure element only.

4.4-C Enclosure Element

Requirement 4.4-C

The enclosure element shall not attain temperatures sufficient to burn persons or animals who may inadvertently touch the enclosure element.

Criterion 4.4-C

Under applicable service conditions, no part of the surface of the enclosure element shall exceed a temperature of 40°F above ambient temperature.

Test 4.4-C

See Subsection 5.3, Enclosure Element Tests.

Commentary 4.4-C

It is anticipated that many innovative connections will not have "free space" which is now required in conventional outlet boxes by the National Electrical Code [2]. It is the intent of this requirement that any heat generated by the connection be dissipated in such a way as to not burn persons or animals who may inadvertently touch the enclosure element. The above criterion, which is subject to further qualifications, is based on judgment following tests which were performed at the National Bureau of Standards.

4.5 Mechanical Safety Attribute

Requirement 4.5

All parts of the electrical connection component; including the continuous current path elements, the dielectric element and the enclosure element; shall present no unreasonable mechanical hazards.

Criterion 4.5

Under applicable service conditions and during installation and maintenance operations, all parts of the electrical connection component shall be so constructed and installed that no unreasonable mechanical hazards exist, such as cutting, pinching, abrasion, tripping or snagging.

Test 4.5

Physical inspection of electrical connection components and evaluation of methods of installing and maintaining electrical connection components should be conducted to determine mechanical safety.

Commentary 4.5

It is the intent that electrical connection components be examined for mechanical hazards to people which may exist in installation, maintenance or replacement operations or after installation.

4.6 Toxicity Safety Attribute

Requirement 4.6

Electrical connection components shall present no unreasonable potential toxic hazards.

Criterion 4.6

Under applicable service conditions including overheating conditions, all parts of the electrical connection component, including the continuous current path elements, the dielectric element and the enclosure element, shall be so constructed and installed that no unreasonable potential toxic hazards exist.

Test 4.6

Inspection and evaluation is required of electrical connection components and materials, including paints and finishes, used in their construction. In the event of any suspicion of toxic hazards, the opinion of experts in this field should be sought.

Commentary 4.6

While conventional materials used in electrical construction are not believed to be toxic, the possibility of toxic hazards should not be overlooked, particularly if new materials are introduced. Also, because electrical connection components, even under normal conditions, operate at higher temperatures than most building components, toxicity hazards should be considered.

4.7 Building Environment Non-Interference Attribute

Requirement 4.7

The electrical connection component shall not produce an environment that will interfere with building functions.

Criterion 4.7

Under applicable service conditions, all parts of electrical connection components, including the continuous current path elements, the dielectric element and the enclosure element, shall be so constructed and installed to prevent excessive air and moisture transmission and so that there is no unreasonable interference or unusual interactions with communication, acoustical or other building functions.

Test 4.7

Physical inspection of electrical connection components should be conducted to evaluate the potential for interference with building functions. Applicable tests, such as radio interference tests, should be conducted if interference with any building function is suspected.

Commentary 4.7

For tight well-made connections with low contact resistance, there appears to be little likelihood of interference with building functions. Therefore, specific tests, such as a radio interference test, to ascertain this criterion are not proposed. However, the evaluation of innovative electrical connections should consider the possibilities of such interference.

4.8 Accessibility, Repairability, Replaceability Attribute

Requirement 4.8

Inaccesible electrical connections should retain all necessary attributes for the expected life of the building in which they are installed. Otherwise electrical connection components, or parts of electrical connection components which contain the connection point or area of the continuous current path element shall be reasonably accessible and either reasonably repairable and/or replaceable.

Criterion 4.8

Inaccessible electrical connections should retain Attributes 1 through 7 for a minimum of 50 years. Other electrical connection components or parts of electrical connection components which contain the connection point or area of the continuous current path elements shall be:

(1) accessible without disturbing any building component other than the electrical connection component and

(2) either

(a) repairable with the entire electrical connection component restorable to its original condition, or

(b) replaceable with readily available hardware or with other readily available electrical connection components without major disturbance of other building components and with the electrical connection in conformance with the criterion listed above.

Test 4.8

Inspection to determine accessibility, repairability, replaceability aspects of electrical connection components should be conducted. For inaccessible electrical connections see commentary below.

Commentary 4.8

See Subsection 1.4.2, concerning the subject of "Accessibility" requirements in codes. Considerable research and test development is needed for the evaluation of inaccessible connections. Inaccessible connection development should be encouraged and any innovative connector, which on preliminary examination, appears to be suitable for use in inaccessible locations, should receive extensive evaluation for such use.

5. TESTS TO EVALUATE ELECTRICAL FUNCTION AND FIRE, ELECTRICAL AND BURN SAFETY ATTRIBUTES

It is anticipated that testing to evaluate the performance of electrical connections will, in general, address the first four Attributes shown in Figure 1, which are (4.1) Electrical Function, (4.2) Fire Safety, (4.3) Electrical Safety and (4.4) Burn Safety. It is anticipated that the other four attributes, which are (4.5) Mechanical Safety, (4.6) Toxicity Safety, (4.7) Building Environment Non-interference, and (4.8) Accessibility, Maintainability, Replaceability will, in general, be evaluated by inspection. If there is uncertainty about compliance with the criterion pertaining to any of these attributes, testing methodologies must be developed. See Subsection 4.8 for the evaluation procedures of inaccessible connections.

5.1 Continuous Current Path Element Tests

To evaluate Attributes (4.1) Electrical Function, (4.2) Fire Safety, and (4.4) Burn Safety, tests and research to determine both the performance of the continuous current path element and the performance of materials used in the continuous current path element are needed. As discussed in "Analysis of Current Technology on Electrical Connections Used in Residential BRANCH Circuit Wiring" [1] failures in electrical connections, after exposure to time, power cycling, mechanical stresses and environmental conditions usually occur for two basic reasons, which are:

(1) properties of the wire and connection, which promote loose connections and/or increased contact resistance, usually resulting in overheating. This is termed unsatisfactory "connectability", and

(2) wire breakage in the vincinity of the connection point or area, which may result from added stresses during installation or maintenance operations. This may also result in overheating.

Overheating of an electrical connection is caused by the resistance to the flow of current at the wire-connector interface. With an increase in resistance there will be an associated increase in temperature. The resistance will not increase unless certain changes occur in the wire-connector interface with time and exposure to various environments. The contact resistance will tend to increase with reduced contact pressure and with the formation of a nonconductive layer in the contact interface. Contact pressure may be reduced by manual movement of the wire, vibration, stress relaxation or creep of the wire and differential thermal expansion between the wire and the connector.

A performance test needs to be developed to simulate vibration and manual movement (wire disturbance). An accelerated short term test may not simulate stress relaxation or creep, which are long term mechanisms.

The contact resistance (and thus temperature) may tend to increase with time, and exposure of the wire-connector interface to oxygen, water, chloride, and sulfur compounds. Oxygen and water exist in nearly all environments while chloride is found in marine atmospheres and sulfur compounds are prevalent in industrial atmospheres. A performance test should be developed which will simulate the effects of these compounds on contact resistance for electrical connectors that will be used in building at sites which are exposed to the respective compounds.

The temperature of electrical contacts is also dependent on the tendency of the air or other materials surrounding the electrical connector to conduct heat away from the contact interface. A performance test should simulate the highest ambient temperature that may exist in the wall of a building.

A reliable performance test of an electrical connection would be the measurement of the temperature of the wire-connector interface of a device exposed to the worst conditions in a building for the life of the building. The time required for such a test under real life conditions is prohibitive for performance testing. However, long-term tests should be performed in an electrical connector research program to establish the validity of acceleration factors for performance testing.

On a practical basis acceleration factors must be assumed, to conduct performance tests. Since these factors have not been established, tests should be performed for various factors and attempts made to extrapolate these short term results to estimates of long term performance. However, validation of the acceleration factors is needed.

An example of an interim performance test of an innovative electrical connector is the power cycling with wire disturbance test performed by Underwriters' Laboratory [7]. The acceleration factors are current (53 amperes for a device rated 20 amperes) cycle rate (3-1/2 hours current ON, 1/2 hour current OFF), total cycles (500), wire disturbance (bend wire from horizontal to vertical), and ambient temperature (25°C). Bulk terminal temperatures are measured during the test and failure is based on a single reading in excess of 175°C or a temperature rise greater than 10°C of any one data point above the average temperature rise of eleven data points of one test connection.

To determine reasons for failure of materials and properties necessary for acceptable connections, tests and research on characteristics of materials are needed. Testing is needed to determine that installation and maintenance operations will not deteriorate mechanical properties to the extent that wire breakage will subsequently occur. Testing is also needed to determine properties affecting the connectability of an electrical connection.

Wire strength criteria may be needed to ensure that mechanical property modifications to meet connection criteria do not lower the wire strength sufficiently to cause failure during installation. Wire ductility criteria may be needed to ensure that the wire can be manipulated before and after making a connection without breaking or impairing heat cycle performance. The ductility of the wire can be lowered by the stress produced in making mechanical connections. Subsequent bending of the wire for connector replacement or other repairs can result in wire breakage if the ductility is too low. Possibly, some innovative connectors may require less manipulation and, therefore, less ductile wire than conventional connections.

Connectability is usually a function of the properties of the wire and the properties of the connector which will promote metal-to-metal contact at the interface between the wire and the connector. Metal-to-metal contact can generally be assured by designs which break the oxide layers on the surfaces of the wire and the connector and provide sufficient normal force or pressure to effect cold welding of the metal in the wire to the metal in the connector. Metal-to-metal contact is measured destructively by metallographic techniques such as scanning electron microscopy. Contact resistance measurements may give non-destructive indication of metal-to-metal contact. The relationship between the number of micro-contacts, contact resistance, contact pressure, and subsequent heat cycle temperature rise may need to be established for electrical connectors.

There may be correlations between mechanical properties such as wire yield strength and creep strength and the heat cycle performance of electrical connectors. Tests may need to be performed to determine if quantitative values should be established for mechanical properties.

There may be correlations between the chemistry of the wire-connector interface and the heat cycle performance of electrical connectors. Tests may need to be performed to determine if quantitative performance values should be established as a function of surface chemistry.

A test program should be developed to determine the causes of overheating which is apparently the most critical factor in connector evaluation. The ultimate goal will be to determine the approximate service life and conditions of an electrical connection before failure, particularly failure resulting in overheating, on the basis of relatively short term tests.

Tentatively, it has been determined that tests or research in the areas listed below are needed for the evaluation of the continuous current path elements. Specific test conditions and methods for testing need to be established.

(1) Power cycling with wire disturbance

(2) Power cycling with vibration

(3) Environmental exposure

Humidity	Expose wire and connector separately to each environment and then connect and perform power cycle test.
Salt Spray	Connect wire and connector, then expose to each environment, then perform power cycle test.

(4) Creep strength of wire

(5) Surface chemistry of wire, connector and wire-connector interface

(6) Contact pressure of interface

(7) Contact resistance of interface

(8) Coefficient of expansion of wire and connector

(9) Bend ductility

(10) Bend test in a simulated wall

(11) Effect of high ambient temperature

(12) Effect of temperature rise on various structural arrangements.

5.2 Dielectric Element Tests

To evaluate Attribute (4.1) Electrical Function, (4.2) Fire Safety, and (4.3) Electrical Safety, determination of the dielectric element performance characteristics is necessary. Reasonable assurances are needed that the dielectric elements, after exposure to time, heat cycling, mechanical stresses and environmental exposures, will retain needed electrical and fire resistance properties. In some tests performed on the continuous current path elements, such as the power cycling and environmental tests, the dielectric element will be subjected to simulated performance, after which satisfactory dielectric withstand and fire resistance properties should be unaffected.

Tentatively, it has been determined that tests or research in the areas listed below are needed for the evaluation of the dielectric element. Specific test conditions and methods of testing need to be established.

(1) Dielectric withstand

(2) Fire resistance

Performance criteria for the dielectric element can probably be established without extensive research. The required performance of the dielectric element in the vicinity of connections is not significantly different from its required performance near other parts of an electric circuit.

5.3 Enclosure Element Tests

To evaluate Attributes (4.1) Electrical Safety, (4.2) Fire Safety, (4.3) Electrical Safety and (4.4) Burn Safety, determination of the enclosure element performance characteristics is necessary. Reasonable assurances are needed that the enclosure element, after exposure to time, heat cycling, and mechanical and environmental absuses, will retain its structural, fire resistive and surface temperature properties and that insulation between the continuous current path elements and the enclosure element be kept intact. In some tests performed on the continuous current path element, the enclosure element will be subjected to simulated performance, after which satisfactory properties of the enclosure element should be retained.

Tentatively, it has been determined that tests or research in the areas listed below are needed for the evaluation of the enclosure element. Specific test conditions and methods of testing need to be established.

(1) Strength

(2) Deflection

(3) Surface temperature

(4) Insulation from continuous current path elements

Performance criteria for the enclosure element can probably be established without extensive research. The required performance of the enclosure element in the vicinity of connections is not significantly different from its required performance near other parts of an electric circuit.

6. SUMMARY

This report presents the framework for generating methods of evaluation for determing performance of electrical connections used in residential branch circuit wiring. Figure 1 summarizes this approach. This is a "black box" approach. Determining satisfactory performance regardless of materials, design geometry, methods of installation or other specification type requirements is the aim of this project.

Information on environmental and other service conditions under which electrical connections operate, as well as the effect of these service conditions, is required for the development of performance criteria. Information on some materials properties of electric cable and connectors, and the effect of these properties on performance may also be needed. Tests sufficiently representative of real exposure will then be developed. Such tests will need to be supplemented by judgment because of the many attributes and unusual service conditions which may be encountered.

The thermal performance of the continuous current path elements under various service conditions appear to be the most significant performance aspect to be determined in evaluating electrical connections. The methods of evaluation which must be developed are dependent upon accelerated testing to accomplish in a reasonable time the determination of long term characteristics. Additional research should be undertaken to relate real exposure to acceleration factors.

Suitable performance criteria for the dielectric element (electrical protection) and for the enclosure element (structural protection) can probably be developed without extensive research. The dielectric and the enclosure elements are essential physical elements for electrical connections but they are also essential physical elements for all other parts of branch circuits. However, unlike the performance of the continuous current path elements, the performance of the dielectric and enclosure elements are not significantly different in the vicinity of the connections.

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USCOMM NBS DC

NBS-114A (REV. 7-73)

U.S. DEPT. OF COMM. BIBLIOGRAPHIC DATA SHEET	1. PUBLICATION OR REPORT NO. NBSIR 75-672	2. Gov't Accession No.	3. Recipient's Accession No.
4. TITLE AND SUBTITLE A PRELIMINARY APPROACH TO PERFORMANCE REQUIREMENTS AND CRITERIA FOR ELECTRICAL CONNECTIONS IN RESIDENTIAL BRANCH CIRCUIT WIRING			5. Publication Date March 1975 6. Performing Organization Code
7. AUTHOR(S) William J. Meese, Ramon L. Cilimberg, and Adolfo A. Camacho			8. Performing Organ. Report No. NBSIR 75-672
9. PERFORMING ORGANIZATION NAME AND ADDRESS NATIONAL BUREAU OF STANDARDS DEPARTMENT OF COMMERCE WASHINGTON, D.C. 20234			10. Project/Task/Work Unit No. 4628492 11. Contract/Grant No.
12. Sponsoring Organization Name and Complete Address *(Street, City, State, ZIP)* Office of Policy Development and Research Department of Housing and Urban Development Washington, D.C. 20410			13. Type of Report & Period Covered FINAL 14. Sponsoring Agency Code
15. SUPPLEMENTARY NOTES			

16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

During the Operation BREAKTHROUGH Research and Demonstration program the U.S. Department of Housing and Urban Development became concerned with the inability to properly evaluate innovative electrical connections. Innovation in electrical connections has been very slow because of the long-life requirements, stringent fire safety requirements, long established conventional practices and evaluation procedures and lack of a performance base for describing requirements. This preliminary report presents the framework for a proposed method to evaluate electrical connections on a performance basis and supplements information contained in a previous report on current technology of electrical connections used in residential branch circuit wiring. Innovations involving electrical connections may lead to significant advancements in housing construction if it can be demonstrated that functional and safety requirements over the expected life of electrical connections were adequately satisfied. Research is needed to enable prediction of long-term performance of electrical connections based on the results of accelerated performance tests.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Branch circuits; electrical codes; electrical connections; fire safety; housewiring; contact resistance; performance testing.

18. AVAILABILITY	19. SECURITY CLASS (THIS REPORT)	21. NO. OF PAGES
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	20. SECURITY CLASS (THIS PAGE) UNCLASSIFIED	22. Price