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Aircraft Age-Related Degradation Study on Single- and Three-Phase Circuit Breakers

November 2002

Final Report

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16. Abstract

This report provides technical data and brief observations generated for a controlled series of tests on circuit breakers removed from an aging Boeing 727-232 and a McDonnell Douglas DC-10 aircraft. The test program is divided into two groups (Process 1 and Process 2). Sixty circuit breakers in Process 1 were tested for 200% and 500% current overloads. Two hundred forty circuit breakers in Process 2 were tested for voltage drop at rated current, minimum and maximum limits of ultimate trip, 150% and 200% low current overload, and 400% to 500% high current overload. The low voltage contact resistance and temperature rise were continuously monitored. This report also contains a summary of results generated by the FAA Airworthiness Assurance Nondestructive Inspection Validation Center located at Sandia National Laboratories on circuit breakers removed from three aged aircraft.

The results of the tests protocols indicated that circuit breakers installed in aircraft with extended service life will continue to protect the electrical wire provided the maintenance procedures recommended in the report are performed annually. The report also recommends proposed changes to SAE Aero-Space Standards to improve circuit protection on future aircraft.

This report also contains technical data generated by the FAA Airworthiness Assurance Nondestructive Inspection Validation Center on circuit breakers removed from three retired aircraft. The most significant result of this study is a 39% failure rate in the 114% to 138% current overload ranges. The value and impact of this study still needs to be determined.

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EXECUTIVE SUMMARY

This report provides technical data and brief observations generated for a controlled series of tests on circuit breakers removed from an aging Boeing 727-232 and a McDonnell Douglas DC-10 aircraft. The test program is divided into two groups (Process 1 and Process 2). Sixty circuit breakers in Process 1 were tested for 200% and 500% current overloads. Two hundred forty circuit breakers in Process 2 were tested for voltage drop at rated current, minimum and maximum limits of ultimate trip, 150% and 200% low current overload, and 400% to 500% high current overload. The low voltage contact resistance and temperature rise were continuously monitored. This report also contains a summary of results generated by the FAA Airworthiness Assurance Nondestructive Inspection Validation Center located at Sandia National Laboratories on circuit breakers removed from three aged aircraft.

The results of the tests protocols indicated that circuit breakers installed in aircraft with extended service life will continue to protect the electrical wire provided the maintenance procedures recommended in the report are performed annually. The report also recommends proposed changes to SAE Aero-Space Standards to improve circuit protection on future aircraft.

1. INTRODUCTION.

1.1 PURPOSE.

The purpose of the test program is to provide data needed to determine to what extent circuit breakers removed from aging aircraft have degraded from their original performance specification parameters. The data will be used to help the Federal Aviation Administration (FAA) to determine causes of breaker degradation, to determine to what extent degradation may affect the continued safe operation of the wiring component protected by the breaker, and to determine the impact of the degradation on aircraft performance.

1.2 BACKGROUND.

In response to several mishaps in which the cause was determined or suspected to be failures of the electrical interconnection system (wiring), the FAA established the Aging Electrical Systems Research Program. The program is intended to conduct research into aging electrical interconnection systems and to develop the means for insuring the continued safety of those systems in aging aircraft. Specifically, the research will determine the mechanisms, which drive the aging process, develop tools to better inspect and maintain wiring, and develop technologies that eliminate or mitigate the hazards associated with wiring failure.

In the spring of 2000, the FAA sponsored a small test program to evaluate the performance of circuit breakers removed from several retired large transport aircraft. The FAA Airworthiness Assurance Nondestructive Inspection Validation Center located at Sandia National Laboratories in Albuquerque, New Mexico, conducted the testing. Results are provided in appendix J. The results of the study indicated that a more intensive and controlled evaluation of circuit breaker aging was necessary, which is the topic of this report.

1.2.1 Components.

Generally, wiring components are expected to safely perform the intended function throughout the design life of the aircraft. It has generally been assumed that components will not normally require replacement during the design life of the aircraft. When an aircraft has been extended beyond the original design life limit, it is important to understand the aging characteristics of wiring components and to insure that the components will continue to perform safely. If the continued aging of the components degrades the electrical distribution system performance, control measures must be adopted. The measures may either control the level of degradation (which may include inspections, repairs, maintenance, and in extreme cases, complete replacement of components) or mitigate the hazards associated with the failure modes created by the degradation.

1.2.2 Inspection.

Electrical wiring components are passive in function, thus providing little or no feedback on the degree of degradation. Wiring components typically do not exhibit functional or visual signs of degradation until the electrical system no longer distributes the required information or power. Generally, there are no provisions made for regular test and evaluation beyond general visual

inspection (GVI). For some electrical components, such as circuit breakers, GVI may not be sufficient. In addition, there are no clear maintenance requirements, no means for easy inspection and, in general, no defined life limits for these devices (other than clearly recognizable failures). Just how age and environment relate to performance degradation or failure of circuit breakers is the subject of this research.

1.3 RELATED ACTIVITIES AND DOCUMENTS.

SAE Aerospace Recommended Practice (ARP) 1199, "Selection, Application, and Inspection of Electrical Over-current Protection Devices," provides circuit breaker application guidance to aircraft electrical systems designers. The basic principles established in ARP 1199 are discussed in generalities in ARP 4404, "Aircraft Electrical Installation." ARP 4404 was used as a baseline for requirements specified in Chapter 11 (Electrical Systems) of FAA Advisory Circular 43.13-1B, Acceptable Methods, Techniques, and Practices – Aircraft Inspection and Repair. Discussions of the data generated by the protocol specified herein shall assume breakers were installed in the aircraft in accordance with ARP 1199. Technical definitions used herein shall also be based on definitions provided in ARP 1199. SAE Aerospace Specification (AS) 50881 (previously MIL-W-5088), "Wire Aerospace Vehicles," has been the baseline for commercial aircraft for many years. AS 50881 defined how the wiring system (wire, connectors, terminals, etc.) are assembled and installed in the aircraft. Discussion of the data herein assumes the wires and terminals attached to breakers are installed in accordance with AS 50881 guidelines.

The philosophy of ARP 1199 is that the electrical circuit protection should, in general, provide automatic protection to a single circuit and more importantly minimize smoke and fire to the electrical components, equipment, and wire. The breaker's primary purpose is to protect the wire. In general, equipment protection requires a separate protection device. ARP 1199 assumes, "circuit breakers will be applied within the electrical rating, environmental conditions, and other parameters as described in the applicable specification or specification sheets." ARP 1199 implies that the most predominate specification used for aircraft circuit breakers components is MIL-C-5809, "Circuit Breakers, Trip Free, Aircraft." The test protocol outlined in appendix D is based on MIL-C-5809.

MIL-C-5809, Circuit Breakers, Trip-Free, Aircraft, General Specification For, has been used since the late 1960s as a worldwide standard and is presently being converted to a commercial SAE AS 5809 Standard. The test protocols were performed in accordance with MIL-C-5809 test methods, except as modified by the test plan shown herein.

The test procedures used in this project were developed from procedures used by Raytheon Technical Services Company (RTSC) to qualify manufacturers to MIL-C-5809 for the Naval Air System Command Qualified Product List (QPL) 5809. The procedures used are as follows.

2110 – FAA_TERM_STRENGTH: Circuit Breaker Strength of Terminals

2012A – FAA_CLEAN: Circuit Breaker Cleaning

2012 – FAA_VISUAL_INVENTORY: Inventory, Visual Examination, and Data Recording

2097A – FAA_OP_FORCE: Circuit Breaker Operating Force

3001G – FAA_VOLTAGE_DROP: Voltage Drop at Rated Current

3005M – FAA_DWV_CLOSED: Breaker Dielectric Withstanding Voltage for Closed Breakers (Line & Load to Ground)

3005N – FAA_DWV_OPEN: Breaker Dielectric Withstanding Voltage for Breakers In The Trip or Open Position (Line to Load)

3008C – FAA_150_200%_OL: 150% or 200% Overload Calibration

3008D – FAA_400_500_600%_OL: 400%, 500%, or 600% Overload Calibration

3009H – FAA_LVCR: Low Voltage Contact Resistance for FAA Aged Aircraft Circuit Breakers

3011N – FAA_IR: FAA Circuit Breaker Insulation Resistance

3015 – FAA_MIN_TRIP: Minimum Limit of Ultimate Trip

3015A – FAA_90%_TRIP: 90% of Minimum Limit of Ultimate Trip

3015B – FAA_MAX_TRIP: Maximum Limit of Ultimate Trip

3015C – FAA_110%_TRIP: 110% of Maximum Limit of Ultimate Trip

4000G – FAA_FA_REPORT: FAA Failure Analysis Submittal to Manufacturers

4004 – FAA_XRAY: Procedure for Taking an X-Ray Radiograph of a Circuit Breaker

2. AIRCRAFT SAMPLE INFORMATION.

The circuit breakers were removed from 12 panels provided from two aircraft. Eight panels were provided from a Boeing 727-232 and four panels from a McDonnell-Douglas DC-10. Panels designated “A” through “D” came from the DC-10 aircraft, and panels designated “E” through “L” came from the B727-232 aircraft.

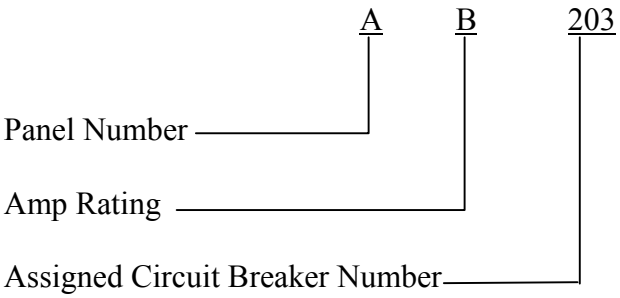
Photographs of both the front and back of each panel (see appendix A) recorded the physical conditions of the panels. The overall conditions of the panels were good, although some panels were relatively dirty compared to the others.

The aircraft deployment history, provided by the FAA, is included in appendix A. The DC-10 aircraft’s first flight was June 6, 1975 and averaged 2.84 hours flight time per cycle. The aircraft was parked for modifications in November 1999. It is assumed that the panels were removed in the spring of 2001, just prior to their delivery to the RTSC test facility. The B727-232 aircraft’s first flight was April 3, 1974, and averaged 1.13 hours flight time per cycle. The aircraft was retired in October 1999. It is assumed these panels were also removed in the spring of 2001.

2.1 CIRCUIT BREAKER SAMPLE INFORMATION.

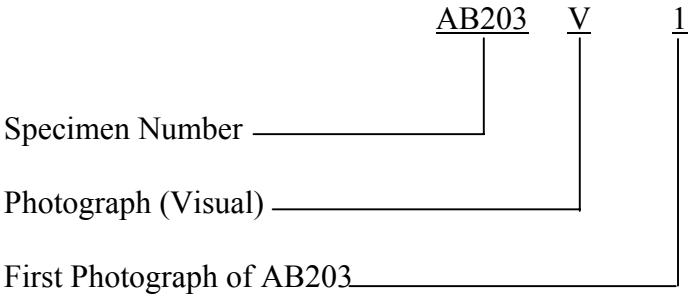
The circuit breakers were sampled from the panels in accordance with the guidelines provided in appendix B. An inventory and physical examination record of each breaker sampled from the panels is also provided in appendix B. The information includes a visual description of each breaker and all associated panel or wiring information. Typical information, such as circuit breaker manufacturer's part numbers, which are coded (see appendix I), date codes, circuit identification numbers, circuit breaker terminating wire and terminal conditions, etc., were recorded.

Each circuit breaker sample was assigned a unique specimen number in accordance with the following format.



Three-phase circuit breakers are three, single-phase circuit breakers bonded together with a single reset button. Three-phase circuit breakers were recorded as three, one-phase circuit breakers for sampling purposes. To distinguish the phases, the sample number in the example above would be AB203A, AB203B, and AB203C. The last letter on the sample number represents each phase (A, B, and C).

When warranted, photographs were taken. The photographs were assigned a unique number as follows.



2.2 CIRCUIT BREAKER REQUIREMENTS AND PART NUMBER CODES.

Three circuit breaker manufacturers and 20 different part number families were included in the test program. Each part number family was coded with an alpha character (i.e., A, B, C, etc.) followed by the breaker's ampere rating (i.e., -5, -10, -50, etc.). Within a family of parts, there may be various ampere ratings. Many of the part numbers have different performance

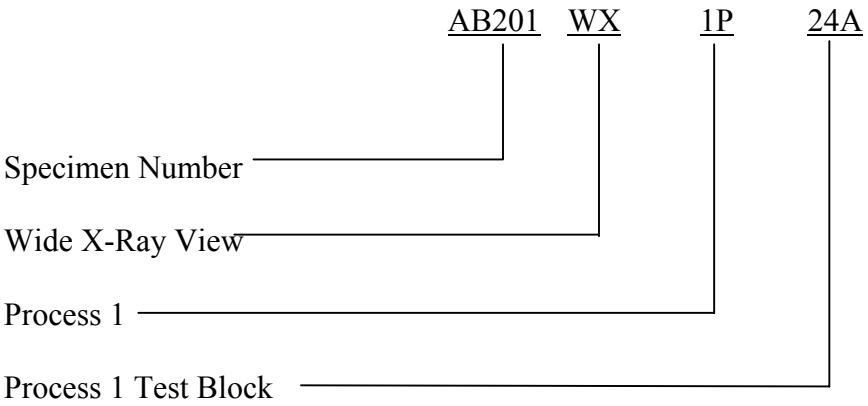
requirements. A list of the coded part numbers and the specification performance requirements for each breaker is provided in appendix C.

3. TEST PROTOCOL.

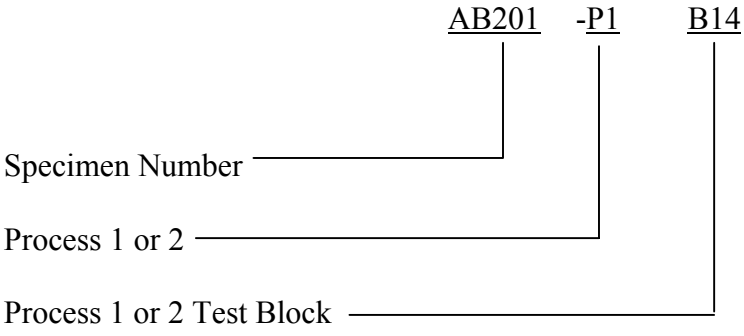
3.1 TEST PROTOCOL PROCEDURES.

The FAA developed the test protocol in conjunction with the circuit breaker manufacturers. The protocol is based on the MIL-C-5809 specification requirements. The MIL-C-5809 specification has been accepted as the worldwide circuit breaker standard since its conception. The test protocol outlined in appendix D required 300 breakers be divided into two test groups. Twenty percent (60 breakers) were tested in accordance with the Process 1, and 80 percent (240 breakers) were tested in accordance with the Process 2.

Each x-ray photograph was designated with the following code.



When warranted, the samples were submitted to the manufacturer for failure analysis. Each sample had a designated failure analysis report number. The failure analysis report number was designated as follows.



3.2 TEST PROTOCOL PROCEDURE DEVIATIONS.

Deviations from the test protocol outlined in appendix D were required. The following paragraphs discuss the deviations in detail.

3.2.1 Low Voltage Contact Resistance.

The Low Voltage Contact Resistance (LVCR) test was initially performed with a constant-current power supply using an open-circuit, 26-volt direct current. This approach was used to minimize anticipated circuit variables that would need adjustment during the test, to reduce expected test time, and to meet the precise current requirement of 200 mA. A point paper, provided in appendix D, was written to demonstrate that a constant-current approach would provide the same results as the test method specified in the Process 1 and Process 2 procedures. During the LVCR modified testing, it was noted that the constant-current approach provided initial current surges that open the 0.5 amp breakers. The open-circuit voltage was reduced to 1.0 volt to minimize the surges, but the 1.0-volt value was insufficient to overcome the contact resistance in large amp breakers. Even at 1.0 volt, a slight surge was also noted. The LVCR circuit was then setup in accordance with Process 1 and Process 2 procedures. The current surges were virtually eliminated, and a current of 200 ±0.100 mA was maintained. Although, theoretically, the constant-current approach is valid and there should be no affect on the subsequent 200% and 500% current overload tests, a partial group of new samples was removed from the panels and subjected to the LVCR test in accordance with Process 1 procedures. For the Process 2 protocol, all the LVCR tests were performed in accordance with the original test procedure. The current value was recorded after the last cycle of the LVCR voltage drop value was recorded.

3.2.2 Button View X-Rays.

The test procedure specified x-ray photographs be taken of each breaker in three axes. The x axis (wide side view) and the y axis (narrow side view) were x-ray photographed when required by the procedure. During the initial x-ray investigation, it was found that the z axis (button end view) provided little or no distinguishable information. As a result, the "button view" was only taken when a failure occurred.

3.2.3 Process 1 and 2 X-Rays.

In Process 1, each x, y, and z axis was exposed to a 90-pulse x-ray energy of 3.1 milliroentgens. In Process 2, each x and y axis was exposed to 90 pulses, and the z axis was exposed to 396 pulses of energy. The increased number of pulses in the z axis provided a clearer internal view of the circuit breaker.

3.2.4 Process 2 Block 20 Correction.

Process 2 has a missing decision test block and a failure analysis block after test block 20 (dielectric test/terminal-to-ground). This report presumes that the missing decision blocks would be designated 20a and 20b respectively.

3.2.5 Process 2 Block 47a Correction.

Test block 47a presumes the breaker to be in an open position after the minimum limit of ultimate trips required by test blocks 44 or 44a. The minimum limit of ultimate trips requires the breaker to remain in a closed position after completion of the test. If the breaker opens, it is

considered failed and submitted to test block 46 for failure analysis. In order to perform the required test block 47a test, the breaker would have to be manually opened then closed to measure the reset forces. Opening and closing the breaker, except when specified, violates the protocol, thus test block 47a was removed.

3.2.6 Process 2 Unused Test Blocks.

Although not a direct protocol deviation, numerous test blocks in the test protocols were not performed because all the circuit breakers passed prior test requirements. Further information on when these test blocks were not used is provided in section 4.

3.2.7 Voltage Drop and Temperature Rise Monitoring.

The test procedure specified the voltage drop and temperature rise of the breaker to be continuously monitored during the test program. The procedure did not specify how this information was to be reported. Since the maximum voltage drop and maximum temperature rise are the most significant result of these measurements, only the maximum values were reported.

3.2.8 Current Overload.

Process 1 test blocks 6 and 12, as well as test blocks 55 and 59, presume that all circuit breakers would have 200% and 500% current overload requirements. As indicated in appendix C, this is not the case. The current overload percentages used were in accordance with the circuit breaker's specified requirements, and those values were recorded in appendix F.

Detailed comparisons of the circuit breaker performance must take into account the variation in current overload requirements.

3.2.9 Three-Phase Breaker.

In some cases, the test requirements specified in appendix F for the three-phase breakers require one phase (one of three tandem breakers) to maintain a different current overload than for the other two phases (two of three tandem breakers). The requirement does not specify which of the three breakers (A, B, or C) should be tested at the higher overload current. It is presumed that the high current overload requirement must be applied to all three of the phases in order to verify that any one phase overload will activate the breaker. To perform the test as specified, would require three sets of power supplies and timers wired in parallel with an activation switch that would turn the current on for each phase at the same time. The test would also triple the number on times needed to complete the test blocks. To minimize the impact on cost and schedule, the test was performed at the maximum current overload for all three phases at the same time. The test result reported in paragraph 4.3.8 indicates that the presumption is acceptable.

3.2.10 Terminal Strength.

The "strength of threaded parts" test, which includes "strength of terminal" (paragraph 4.7.5.2 of MIL-C-5809), was not included in the original test protocols. As a result of visual observations

and preparation of samples, it was determined the properties of the circuit breaker terminals should be examined. The test was performed on the breakers after all other protocol requirements were completed. The results were recorded as part of the physical inventory data and are provided in appendix B.

4. DISCUSSION.

4.1 BASIC CIRCUIT BREAKER CHARACTERISTICS.

There are several different designs of circuit breakers, but the most commonly used type is the thermal circuit breaker that depends on a thermal-sensing element to release. Typically, the sensing element is a bimetal strip, which opens the electrical circuit at a predetermined calibration point based on a temperature rise caused by load current heating. Since the breaker is a thermal reactive device, the calibration will also depend upon the heat sink connected to the breaker terminal (i.e., conductor size, electrical busses, etc.), and the breaker mounting location (i.e., proximity of other breakers, components, panel size, etc.). The circuit breaker specification will specify the calibration characteristics at specific temperatures. The three most common temperature points are at room ambient (25^{o}C), the lowest operating temperature, and the highest operating temperature designed for the breaker in free air. The electrical system designer must take into account the change in calibration due to heat sink characteristics surrounding the breaker in application and the temperature environment of the circuit breaker location.

The electrical designer must choose a circuit breaker rating that matches the wire size the breaker is trying to protect. If the wire size is too small or too big for the breaker, the heat sink characteristics of the wire will shift the calibration curve up or down, respectively. If the wire is too big, the breaker will respond more slowly to a current overload, thus inadequately protecting the wire. If the wire is too small, the breaker will open earlier than designed, potentially causing electrical system malfunctions. Although it is generally not recommended, when multiple wires are used on the same breaker for protecting noncritical circuits, the breaker must be chosen to protect the smallest wire size connected to the breaker, and the heat sink characteristics caused by the multiple conductors must be taken into account. This is not the only reason, but it is one of the principle reasons why wire is always design-controlled and is always replaced with the same size wire. Any modification by the aircraft user, involving circuit protection, must consider the heat sink characteristics of the breaker in order to prevent safety problems.

If the protection requirement of an electrical circuit cannot tolerate large changes in the calibration curves of the breaker, due to changes in the temperature surrounding the breaker location, the electrical designer should consider using a temperature compensated thermal circuit breaker. The temperature-compensated thermal circuit breaker typically has an additional sensing element that minimizes distortion in the calibration curve due to external temperature surrounding the breaker. Additionally, the performance characteristics of single-phase, temperature-compensated thermal circuit breakers are typically specified to higher application temperatures, due in part to this temperature compensation mechanism. The calibration curve of a temperature-compensated thermal circuit breaker generally allows for less variation due to ambient temperature changes than for a non-temperature-compensated thermal circuit breaker.

Temperature-compensated breakers have been more widely used in recent years to protect the electrical wire, and were not originally designed into the aircraft, which were tested in this program. The use of temperature-compensated thermal breakers is a choice of the design engineer, but is generally consistent across a platform. It is expected that since most applications typically use wire well below the temperature and current ratings, the wire can tolerate slightly wider calibration curves that may be present with the temperature-compensated thermal circuit breaker.

Most breakers evaluated in this test program are non-temperature-compensated thermal circuit breakers. ARP 1199 provides guidelines on how to take into account application of the circuit breaker. The calibration characteristics at 25°C for each breaker tested are provided in appendix C.

4.1.1 Circuit Protection.

The circuit protection of an electrical system is accomplished by controlling the following three major circuit breaker performance characteristics.

a. Voltage drop at rated current. The electrical designer must consider the total voltage drop at a rated current for each electrical circuit. This includes the electrical distribution system (wire, connector, splice, etc.) and the circuit breaker. The voltage drop must not exceed the voltage loss permitted to properly operate the electrical load. Typically, the wire size is conservatively chosen at 50% of its rated current capability to minimize circuit voltage loss effects and current overloads. In other words, the bigger the wire size the smaller the voltage loss. The designer must balance the voltage loss tolerance against the added weight and required space needed for a bigger wire. The required voltage drops for the breakers tested ranged from 0.15 to 2.0 volts (see appendix C).

b. Minimum and maximum limit of ultimate trip. The circuit breaker minimum ultimate trip limit is designed to keep the electrical circuit closed during periods of slightly increased load current. The circuit breaker maximum limit of ultimate trip limit is designed to open the circuit to protect the wire from high steady-state load current. The minimum ultimate trip limit prevents the circuit breaker from tripping for at least one hour when a slightly increased steady-state load current (typically 115% increase) is applied. The maximum ultimate trip limit causes the breaker to trip within 1 hour when a steady-state high current (typically 138% increase) is applied. The ultimate trip characteristic varies for different type breakers to accommodate different load requirements. The tested circuit breaker's ultimate trips varied from 105% to 115% for 1-hour minimum trip limits and 138% to 145% for less than 1-hour maximum trip limits (see appendix C). Because the breakers are thermal circuit monitoring devices, the ultimate trip limits will drift with time and the number of encountered on and off cycles. This is commonly known as the circuit breaker's endurance requirement. Typically, this drift is a ±10% deviation from the initial ultimate trip limit. The designer must accommodate this drift, if the breakers are to be applied for the life of the aircraft.

c. Overload current trips. The current overload requirements are designed to prevent nuisance trips caused by short duration current load surges, while at the same time,

protect the wire from current overload caused by direct shorts. The breaker will stay closed for a very short period to accommodate a current surge but open quickly enough to protect the wire. Typically, current overloads are performed at 200% and 500% of rated circuit breaker current. The lower limit typically maintains the breaker in a closed position for a longer period than does the higher limit. In some cases, the circuit breaker is designed with only a lower overcurrent trip requirement. The tested breakers had 150% and 200% lower limits with trip times ranging from 2 to 70 seconds. The upper limit of the tested breakers ranged from no limit to 600% with trip times varying from 0.16 to 15 seconds (see appendix C).

4.1.2 Circuit Breaker Cycling.

A circuit breaker is design to provide some on and off circuit characteristics, but it is not recommended to be used as a switch. A circuit breaker typically requires 2,500 on and off cycles with an inductive load, 5,000 cycles with a resistive load, or 10,000 cycles with no load. A switch is typically designed for endurances four times that of circuit breaker on and off cycles. If a circuit requires on and off action, the electrical designer should provide an electrical switch.

4.1.3 Calibration Test Temperature.

To achieve repeatable results, calibration tests must be performed under controlled temperature conditions. Calibration characteristics will vary slightly depending on the test temperature. In this project, all calibration tests were performed at 25° ±2°C. Circuit breakers with smaller amp ratings are more sensitive to calibration test temperatures than larger rated breakers. MIL-C-5809 has a very detailed test procedure including a "still" air control box to permit precise calibration measurements at specific temperatures. Schedule and cost did not permit the tested breakers to be performed individually at the precise temperature of 25° ±0°C and at zero airflow conditions.

4.1.4 General Assumptions.

The following general assumptions were used to analyze the results of the test protocols.

a. The circuit breakers were installed in the aircraft in accordance with ARP 1199.

b. The circuit breakers performance characteristics were established in accordance with MIL-C-5809 test methods.

c. The circuit breakers' calibration characteristics deviate insignificantly for a temperature change of ±2°C and in low airflow conditions.

d. Wires attached to the breakers were installed in accordance with AS 50881 (previously MIL-W-5088).

e. The wide variety of tested breakers typically represents the types of breakers used in aging commercial aircraft.

Specific detailed assumptions are included for each test discussion.

4.2 VISUAL OBSERVATIONS.

The following significant observations were noted from the visual inspections.

4.2.1 Contamination.

Appendix B data indicate that roughly 50 percent of the circuit breakers removed from the panels were exposed to dust or small particles. In most cases, the foreign or extraneous material was easily removed from the breakers. The data also indicated 11 breakers from two panels were exposed to some type of liquid as well as dust and small particles. Three breakers (1 three-phase breaker) were exposed to what appears to be copper particles. Some panels are dustier than others. The contamination may have caused circuit breaker IE228 to fail voltage drop at rated current although this could not be established conclusively (see appendix F). Seven breakers appeared to be new (very clean), although the breakers had old date codes.

4.2.1.1 Assumptions.

The assumptions for the contamination results are.

a. The dust and debris accumulated over time after aircraft delivery.

b. The liquid and copper particle exposures occurred during maintenance, since it was found with the dust and small particles.

c. The panels with the most contamination were overhead panels that provided traps for dust and small particles.

d. The breakers that appeared to be new were replaced after the majority of dust or small particle exposures already occurred.

4.2.1.2 Conclusions.

Maintenance manuals do not clearly specify that panels be routinely cleaned and protected when exposed to maintenance activity behind or above the panels.

4.2.1.3 Recommendations.

ARP 1199 states that unsealed circuit breakers exposed to contamination may develop voltage arc-over, current seepage, internal corrosion, and dry closure problems. The aircraft circuit breaker installer and maintenance personnel must take into account the impact of these issues. Although the overall results of the protocols indicated contamination has little affect, the following actions are recommended.

a. Aircraft maintenance manuals should include clear instructions on how to protect the panels during maintenance actions.

b. Maintenance schedules should be established to vacuum and clean the rear of panels at least once a year.

4.2.2 Terminal Lug Applications.

Appendix B data indicate that a significant number of breakers may be protecting multiple circuits. There were 142 wires, each with different circuit identification, attached to the 316 breakers that were evaluated. Many of the dual lug terminations were probably bussed circuits connected on the line side of the breakers and, thus, do not represent multiple circuits. Many of the lugs containing two wires had two different size conductors. In two cases, a terminal had three wires, and in one case, a terminal had four wires. A summary of the results is provided in table 1. The summary is based on the circuit breaker panel designations. The circuit information is grouped into five categories. Depending on amp rating, the categories would include signal and power circuits.

TABLE 1. MULTIPLE CIRCUITS DETAILS

Circuits Category	System Types Being Supported	Breaker Termination Method Load and Line Side	Notes
Passenger	Lights AMPL Bty Gallery Air Conditioner Telephone Service	2 Lug/Terminal: 5 2 Wire/Lug: 32 3 Lug/Terminal: 2	(1)
Fire	Agent Extinguisher Body/Well Detection Gage	2 Lug/Terminal: 3 2 Wire/Lug: 2	
Engine	Gage Ignition Trim Generator Fuel	2 Lug/Terminal: 0 2 Wire/Lug: 16	(1)
Flight	Trim Wiper Land Gear Navigation Pressure Communication Window Auto Pilot Yaw Stick Pitch DIR	2 Lug/Terminal: 8 2 Wire/Lug: 22 4 Wire/Lug: 1	(2)
Instruments/ Miscellaneous	Gage Pump Sensor APU Radio DME Service TR Changer Switch	2 Lug/Terminal: 6 2 Wire/Lug: 25 3 Lug/Terminal: 2	(1) (2) (1)

(1) Includes one three-phase companion-trip, multiple-pole breaker with two lugs or one lug with two wires on three of the phase terminals (six possible circuits).

(2) Includes one three-phase companion-trip, multiple-pole breaker with two wires on one of the phase terminals (four possible circuits).

4.2.2.1 Discussions.

FAR 25.1357 clearly states each circuit for essential loads has an individual circuit breaker, but one breaker is not required for all types of circuits (i.e., string of lights). The philosophy of ARP 1199 states that "For reliable circuit protection, the design should provide automatic protection that will limit the fault to a single circuit..." The scope of ARP 4404 states that, "it is desirable that all circuits, including emergency circuits be equipped with an appropriate protective device." Both of these documents imply each circuit should have its own breaker, especially flight critical circuits. Unfortunately, neither ARP 1199 nor ARP 4404 provides additional guidance on when multiple circuits on a single breaker should be used. The guideline needed for determining how to crimp multiple conductors in the same terminal is not included in AS 50881. The SAE AE-8 committee responsible for AS 50881 is now addressing this issue with a draft ARP 5576, "Multi-Wire Crimp Terminations, Recommendations For." There are no guidelines on how to mount multiple terminals on a single breaker in AS 50881 or AS 5809. AS 5809 defined the breaker's type of screw and the strength of the terminals. These parts of the breaker may be impacted by multiple lugs, as well as the operation of the breaker as discussed in section 4. Table 1 results indicate there is a high probability that some circuits are attached to breakers with other circuits.

4.2.2.2 Assumptions.

The assumptions for multiple-circuit applications on single breakers are:

a. The choice of multiple wires in the same terminal is based on the total circular-mil-area of the conductor range permitted for the terminal crimp barrel.

b. The choice of circuit breaker for multiple-circuit applications is based on the smallest wire being used in the terminal lug.

c. The applications of the breakers are in accordance with FAR 25.1357.

4.2.2.3 Conclusions.

A detailed circuit analysis would need to be performed to verify multiple circuits are monitored and to determine the impact of multiple circuits on each breaker. This type of analysis is beyond the scope of the test program.

4.2.2.4 Recommendations.

To address multiple circuits on a single breaker, the following actions are recommended.

a. Request the SAE AE-8 committee, who is responsible for ARP 1199 and ARP 4404, to develop clear guidelines on when multiple circuits on the same breaker should and should not, be permitted.

b. Request the SAE AE-8 committee, who is responsible for AS 50881 and AS 5809 (formerly MIL-C-5809), to define when and how multiple wires in one lug or multiple lugs on one terminal should be applied to circuit breakers.

4.2.3 Circuit Breaker Interconnecting Components.

The physical condition of the circuit breaker terminals, mechanical locking hardware (lugs and wires), and the electrical components are summarized in tables 2 through 4 respectively.

4.2.3.1 Discussions.

4.2.3.1.1 Circuit Breaker Terminals.

The most significant result shown in table 2 is darkening breaker terminals indicating excessive heating and signs of electrical arcing indicating loose terminals. The darkened areas may be due to chemical oxidation, which can occur when the materials are exposed to high temperatures. Metal oxides are often nonconductive or semiconductive films that increase the resistance or voltage drop of the circuit, in turn increasing the potential for localized resistive heating. Some of the worst-case examples are shown in photographs JD247V1, CD071V2, and CD071V4 in appendix A, but insufficient evidence was present to indicate why the overheating or arcing occurred. A breaker would detect the excessive heating, only if sufficient heat was transferred to the breaker to cause the current element of a thermal breaker to open according to the calibration curve. A temperature-compensated thermal circuit breaker element may not be opened until much higher temperature rises occur. The calibration curves of temperature- and non-temperature-compensated breakers are often very similar, although depending on the location of the heat source, in relation to the compensating element, the temperature-compensated breaker may be a little less sensitive to some low level or extremely short heating events. It should be noted that varying levels of discoloration are expected under normal operating conditions. There were signs of some corrosion on several breakers, but the corrosion appeared to be insignificant compared to the number of samples inspected. The loose terminals noted for one manufacturer (CBMB) were due to the lack of epoxy between the terminal and the breaker housing. Nonepoxy terminal breaker types are no longer manufactured.

TABLE 2. CIRCUIT BREAKER TERMINALS CONDITION

Observations	Number of Incidents(1)
Loose(2)	10
Corroded/Black Speckle	10
Black/Arcing/Discolored	26
Clinch Nut Broke/Corroded	4

(1) Total number of terminal incidents (may include two terminals on one breaker.
(2) Terminals not epoxy bonded to case (only manufacturer CBMB).

4.2.3.1.2 LJ295 Circuit Breaker Case.

The circuit breaker sample LJ295's case cracked when mounting the test leads with an electric screwdriver. The screwdriver may have applied too much torque on the terminal. As a result of this occurrence, the breaker was replaced with another sample and all test leads were firmly tightened to the circuit breaker terminals by hand from that point forward.

4.2.3.1.3 Circuit Breaker Terminal Strength.

The "strength of threaded parts" test that includes "strength of terminal" (paragraph 4.7.5.2 of MIL-C-5809) were not included in Process 1 or Process 2 protocols. Because of the results of table 2 and the failure of LJ295, a terminal strength test was performed on 16 specimens. The results were recorded with the physical inventory in appendix B. All breakers withstood the compression force without damaging the housing. The threads on nine breakers stripped, and the housing on two breakers cracked when the minimum required torque load was applied. A quality issue or an aging issue, or both, may have caused the failures.

4.2.3.1.4 Circuit Breaker Electrical Hardware.

The most significant results noted in table 3 are the securing hardware not specifically designed for the breaker and the inconsistent application of the hardware. In some cases, not all, the required hardware was used. Cross threading of the circuit breaker terminal will cause the lug to become loose, see photograph HD182V3 in appendix B. Stripped terminal thread will also cause lugs to become loose, but none were noted during the physical inspection. Loose lugs can cause hotspots and over heating at the terminal/lug interface, similar to those shown in photographs JD247V1, CD071V2, and CD071V4 in appendix B.

TABLE 3. CIRCUIT BREAKER HARDWARE CONDITION

Hardware Issue	Number of Incidents(1)	Observations(2)
Screws	12	- Stainless Material - Brass Material - Short Length - Flat Head - Cross Threaded - Dark Color
Flat Washers	41	- Washer Against Terminal Not Lug (20) - Washer Not Specified by MIL-C-5809 (21)
Lock Washer	15	- Lock Washer Broken (7) - Lock Washer Under Lug (1) - No Lock Washer on Terminals (7)
Circuit Breaker Washer/Separator (Heat Shield)	1	- Heat Shield Missing

(1) Total number of terminal incidents (two may be on same breaker).

(2) Assumes all breakers are standardized with MIL-C-5809 screw (typically MS31957-41) and lock washer (typically MS35338-137) for each terminal.

4.2.3.1.5 Circuit Breaker Electrical Component.

The most significant result noted in table 4 is the misapplication of terminal lugs. The number of misapplications is small compared to the number of circuit breakers inspected, but the impact on the electrical system could be significant. Crimping the conductor with the wrong size lug can cause heating of the lug, wire conductor and insulation, and the circuit breaker terminal and internal components. Crimping insufficient strands can also cause hotspots and possible separation of the wire conductor.

TABLE 4. ELECTRICAL DISTRIBUTION COMPONENTS

Electrical Component	Number of Incidents	Observations
Terminal Lug	6	- Dirty (4) - 16 AWG Wire in Terminal Size (18-22/Red) - 3 Strands of Wire Crimped to a Load side Lug
Wire	13	- Numerous Wires Dirty - New Wires (7) - Red Wires (1) - Translucent Gray (1) - Gooey Substance (4)

4.2.3.2 Assumptions.

The assumptions for the interconnecting component results are:

a. The circuit breakers were originally connected to the lugs, using the securing hardware provided by the breaker manufacturer.

b. The original circuit breaker securing hardware is the standard hardware specified in MIL-C-5809 related drawings, which are one MS31957-41 screw and one MS35338-137 lock washer for each terminal post.

4.2.3.3 Conclusions.

The conclusions based on the interconnecting component results and assumptions are:

a. Aircraft maintenance manuals do not clearly specify that securing hardware should be replaced with identical parts, and there is no established process to permit substitutions until such time that the identical part can be added.

b. Aircraft maintenance manuals do not require routine inspection of circuit breaker panels to examine for loose, misapplied, or broken securing hardware and faulty electrical components.

c. Aircraft maintenance manuals do not require inspection of circuit breaker panels for signs of overheating or arcing of electrical circuits.

d. Aircraft maintenance manuals do not provide cautionary notes in regards to cross threading or over torquing mounting screws.

4.2.3.4 Recommendations.

The recommendations based on the results, assumptions and conclusions for interconnecting components are:

a. Establish routine maintenance schedules to inspect the back of circuit breaker panels for misapplied interconnecting hardware.

b. Change the aircraft maintenance manuals to include the following:

    1. Examine for loose, broken, or misapplied securing hardware.

    2. Provide guidance on what to do when signs of overheating or arcing are observed.

    3. Clearly define circuit breaker securing hardware and require identical replacement, unless there is a process permitting temporary substitution, until the part can be properly replaced.

    4. Provide cautionary notes to prevent cross threading or thread stripping and to require circuit breakers to be completely replaced when such incidents occur.

    5. Change ARP 1199, paragraph 5.8.1.b.4, to recommend circuit breaker terminal securing parts be replaced with identical parts and not permit substitutions without a process for appropriate replacement at a scheduled maintenance period.

4.2.4 Date Code Variability.

4.2.4.1 Discussions.

The circuit breaker date code methodology varied from manufacturer to manufacturer. In some cases the date, which is typically four digits, is provided with the week or month first, followed by the year. In other cases, the year and the week or month was reversed. There are also cases where the date code included alpha characters such as 0474A or Jan-74. Typically, the circuit breaker date code is specified in the component specification or drawing.

4.2.4.2 Assumptions.

None

4.2.4.3 Conclusions.

Based on the results and assumptions for date code variability, it can be concluded that, at the time the breakers were originally installed, there was no aircraft standard that recommended a specific date code format.

4.2.4.4 Recommendations.

Based on the results, assumptions and conclusions for date code variability, the following is recommended.

a. ARP 1199 should be revised to include a reference to EIA-476-B, "Date Code Marking." EIA-476-B specifies a four digit code, the first two digits are the calendar week and the second two digits are the calendar year that the component was produced.

b. Request SAE AE-8 to institute the EIA-476-B date code concept into all future circuit breaker specifications.

4.3 DISCUSSIONS OF PROCESS 1 TEST RESULTS.

The results of Process 1 testing are provided in appendices B and F. Radiographs of the breakers are provided in appendix E. Only 4 of the 60 breakers failed the Process 1 protocol tests.

4.3.1 Open Breaker Test Results.

4.3.1.1 Discussions.

The circuit breaker, HD213, was the only failed breaker that began the test in an open position. HD213 continued to pop open during routine preparation for the LVCR tests. It was considered a failure at that point and returned to the manufacturer for failure analysis (see appendix F). The results of the analysis indicated excessive wear of the latching mechanism that may be caused by excessive on and off cycling of the breaker. The breaker case was cracked at one of the bushings. The design requirement of the HD213 breaker includes 5,000 on and off cycles with an inductive load, and 10,000 cycles with no load without failure. HD213 was designated on the panel as WINDOW HEAT/RIGHT NO. 2/AC CONTROL. Similarly, circuit breakers HD181, HD182, and HD185 were respectfully designated on the panel as WINDOW HEAT/RIGHT NO. 2 DC CONTROL, WINDOW HEAT/RIGHT NO. 1, and WINDOW HEAT/RIGHT-5. HD181, HD182, and HD185 circuit breakers passed all the process 2 tests.

4.3.1.2 Assumptions.

The assumption concerning the HD213 mechanical failure is that circuit breakers with similar circuit designations would have been subjected to a similar number of on and off cycles during service life.

4.3.1.3 Conclusions.

Based on the results and assumption for the HD213 circuit breaker failure, it can be concluded that HD213 was a premature mechanical failure possibly caused by mechanical damage. If the assumption is invalid, an alternate possible conclusion is that the breaker is being used as a switch.

4.3.1.4 Recommendations.

Based on the results, assumption, and conclusions, instructions should be provided to maintenance personnel on the Boeing 727-232 aircraft to review the procedures incorporating circuit breaker designated WINDOW HEAT/RIGHT NO. 2/AC CONTROL on panel serial number 65-55630-2. If the breaker is being routinely cycled on and off, schedule a breaker replacement based on the design requirements of the breaker.

4.3.2 Lower and Higher Current Overload Results.

4.3.2.1 Discussions.

4.3.2.1.1 Lower Current Overload.

Three breakers failed the lower overload test at 200% rated current. Two of the breakers, EE191 and GE200, had borderline failures. The results indicated that both breakers opened slightly quicker than the required performance time. The two breakers also failed the lower current overload test after five on and off cycles.

EE191 and GE200 were returned to the manufacturer for failure analysis (see appendix F). The manufacturer found both breakers would pass the 200% overload when performed in accordance with MIL-C-5809 (still air, 25°C environment). Although not required, these breakers also pass the minimum and maximum limit of ultimate trip tests when performed by the manufacturer.

The third breaker, EE312, opened immediately at the 200% current overload. EE312 also failed after five on and off cycles. EE312 was returned to the manufacturer for failure analysis. The manufacturer noted that EE312 passed the 200% overload when performed in accordance with MIL-C-5809, but had slight increases in voltage drop at rated current.

4.3.2.1.2 Higher Current Overload.

All remaining breakers that passed the lower overload test also passed the higher overload test at 500% when required. For certain types of breakers, the higher current overload test was not performed because it was not specified as a requirement. Since there were no higher current overload failures, test block 14 was not performed.

4.3.2.2 Assumptions.

The following assumption is made for the lower and higher current overload results.

- All of the Process 1 tested breakers will provide similar results as noted in Process 2 testing.

4.3.2.3 Conclusions.

Based on the lower and higher current overload results and assumptions, it can be concluded that the breakers in aging aircraft continue to protect the wire from current overload when

periodically cycled on and off with no load. The breakers may cause some nuisance trips. See Process 2 discussions (section 4.4) for overload requirements for further validation of this conclusion, as well as recommendations based on these conclusions.

4.4 DISCUSSIONS OF PROCESS 2 TEST RESULTS.

The results of Process 2 testing (see appendix D) are provided in appendices B and I. Radiographs of the breakers are provided in appendix E. For ease of discussion, the Process 2 results are grouped together by the type of test performed.

4.4.1 Dielectric Withstand Voltage Test Results.

All tested circuit breakers passed the various dielectric withstand voltage tests. Therefore, Process 2 test blocks 5 through 9, 12 through 16, 32 through 36, 37 through 41, 42, and 43 were not performed (see appendix D). Although the leakage current for the dielectric voltage test was not required, it was recorded for information.

4.4.2 Insulation Resistance Test Results.

All tested circuit breakers passed the insulation resistance test (see blocks 17 and 29 of appendix D).

4.4.3 Operating Force Test Results.

All tested circuit breakers passed the button pullout and reset force requirements (see blocks 18, 24, 30, 54a, 58a, and 63 of appendix D).

4.4.4 Voltage Drops at Rated Current Test Results.

Although several breaker types have no voltage drop requirement at rated current (see appendix C), all the breakers were tested as specified in block 43a of appendix D. Those breakers that failed a specific voltage drop requirement were submitted to test block 43c for failure analysis, otherwise the breakers were submitted to the next test block in the protocol. Because there were only a few three-phase breaker specimens, only 1 three-phase breaker was submitted for failure analysis. The results of the voltage drop at rated current before and after opening and closing the breakers five times (blocks 43a and 43c respectively) are summarized in table 5.

4.4.4.1 Voltage Drop Comparison.

Counting the three-phase breakers as three separate breakers, the results indicated that 45 out of 240 breakers failed voltage drop at rated current, showing a 19% failure rate. When cycled on and off five times, seven out of the ten breaker types had decreased voltage drops at rated current, the improvement ranging from 3 to 193 percent. Breaker type A-5 showed no change, and breaker type B-10 experienced a 3 percent increase in voltage drop. There was no data for the tenth breaker type (D-7.5). Seven out of 31 breakers tested to block 43c passed the voltage drop requirement after being cycled on and off five times. Based on the averages after five on

and off cycles, the voltage drop at rated current was only 3 to 11 percent over specification requirements for five of the breaker types and was passing for the other four breaker types.

TABLE 5. VOLTAGE DROP COMPARISONS

Measured Voltage Drop at Rated Current in Volts (Initial in Block 43a)					Measured Voltage Drop at Rated Current in Volts (After Five Open and Close Cycles in Block 43c)					Notes
Breaker Type	Reqd. V Max	Number of Failures	Voltage Range (Min–Max)	Initial Average Voltage	Number of Failures	Voltage Range (Min/Max)	Average Voltage After Cycling	Percent Improve-ment	Average % Over Reqt.	
A-10	0.15	10	0.16-0.20	0.175	10	0.124-0.230	0.169	3%	7.5%	1
A-3	0.33	3	0.34-0.36	0.347	2	0.283-0.355	0.324	7%	(1.8)%	
A-5	0.25	4	0.26-0.26	0.26	3	0.249-0.271	0.260	0%	4%	
B-10	0.15	5	0.16-0.17	0.164	4	0.146-0.179	0.167	(2)%	11%	2
B-3	0.33	2	0.34-0.36	0.35	2	0.339-0.340	0.34	3%	3%	
B-5	0.25	3	0.26-0.37	0.30	3	0.266-0.270	0.268	12%	7%	3
C-3	0.55	1	0.66	0.66	0	0.225	0.225	193%	(59)%	
D-7.5	0.30	14	0.31-0.34	0.315	-	-	-	-	-	4
E-8	0.30	2	0.31-0.81	0.56	0	0.179-0.268	0.224	150%	(25)%	5
J-3	0.79	1	0.97	0.97	0	0.772	0.772	25%	(2)%	

1. DH149 tripped during test (value not recorded).

2. JH251 tripped during test (value not recorded).

3. IE238 had very high LVCR values (voltage drop at rated current not recorded)

4. D-7.5 represents 5 three-phase tandem breakers (15 single phase breakers). One single-phase breaker passed. One breaker at 0.61 volt was considered as an anomaly and not included in the average.

5. Three-phase tandem breaker, LG291, with one phase passing.

4.4.4.2 Voltage Drop Design Criteria.

The limited data obtained from the design information survey (see appendix A) indicates a typical aircraft critical circuit is designed to have a required maximum voltage drop at rated current of up to:

a. 2 volts direct current (Vdc) for 28 Vdc electrical power,
b. 4 volts alternating current (Vac) for 115 Vac electrical power, and
c. 7 Vac for 200 Vac electrical power.

A comparison of the differences between the design maximum electrical power voltage drop at rated current and the maximum increase in voltage drop measured after five on and off cycles for each circuit breaker type is provided in table 6. Only the five circuit breaker types that failed the average voltage drop requirement after five on and off cycles are listed.

The results of table 6 indicate that the increase in measured voltage drop at rated current will only cause a maximum of 4%, 2%, and 1.1% increase respectively in circuit voltage drop for 28 Vdc, 115 Vac, and 200 Vac electrical systems. These higher values seem to be related only to the A-10 breaker type. The more typical range of circuit voltage drop increase is 1% or less.

TABLE 6. VOLTAGE DROP DESIGN COMPARISONS AFTER ON AND OFF CYCLES

Breaker Requirement		Voltage Drop/Current Measured Values		Difference (Requirement– Measured)	Percent of Voltage Design Maximum allowable		
Type	Voltage Drop (V)	Voltage Range (V)	Maximum Voltage (V)	(V)	28 Vdc (2 V)	115 Vac (4 V)	200 Vac (7V)
A-10	0.150	0.124-0.230	0.230	0.080	4.0%	2.0%	1.1%
A-5	0.250	0.260-0.260	0.260	0.010	0.5%	0.25%	0.14%
B-10	0.150	0.146-0.179	0.179	0.029	1.5%	0.73%	0.41%
B-3	0.330	0.339-0.340	0.340	0.010	0.5%	0.25%	0.14%
B-5	0.250	0.266-0.270	0.270	0.020	1.0%	0.5%	0.29%

Based on the results and discussion for the voltage drops at rated current, the following is assumed.

a. The breaker, after one on and off cycle, will typically provide the same voltage drop results as five on and off cycles (see LVCR discussions for further details).

b. The circuit voltage drops in table 6 typically represent most commercial aircraft design requirements.

c. Circuit breakers that have very high voltage drops at rated current after cycling would typically be expected to generate heat that will cause a non-temperature-compensated thermal circuit breaker to trip at a lower current. A temperature-compensated thermal circuit breaker may be less sensitive to this type of temperature rise. This assumes that the heat from the contacts will be transferred roughly equivalently to the heat sensitive strips and the compensating member. A non-temperature-compensated thermal circuit breaker strip would detect the increased heat as an artificial increase in current. A temperature-compensated thermal circuit breaker would detect the heat as increased environmental temperature, rather than an artificial increase in current. In other words, depending on how the breakers are calibrated and designed, a non-temperature-compensated thermal circuit breaker would typically be expected to open sooner than a temperature-compensated breaker when resistive heating occurs.

d. All electrical circuits are designed to permit small rises in voltage drop at rated current.

e. Cycling breakers periodically will not generally cause the breaker to reach the trip cycle design limit during its service life.

4.4.4.3 Conclusion.

Based on the results and assumptions for the voltage drops at rated current test, the following is concluded.

a. Cycling the breaker on and off improves the voltage drop at rated current.

b. Small rises in voltage drop (1% to 4%) at rated current in aging aircraft does not have a significant impact on the electrical system.

4.4.4.4 Recommendation.

Based on the results, assumptions, and conclusions for the voltage drop at rated current test, it is recommended the breakers not be replaced but periodically cycled on and off.

4.4.5 Minimum and Maximum Limit of Ultimate Trip Test Results.

4.4.5.1 Minimum Limit.

Thirty-nine circuit breakers out of 204 tested failed the minimum limit of ultimate trip, but all circuit breakers tested passed the 90% minimum of ultimate trip.

4.4.5.2 Maximum Limit.

Twelve circuit breakers out of 206 breakers tested failed the initial maximum limit of ultimate trip. Only one breaker failed the ±10% endurance limit of ultimate trip.

4.4.5.3 110% Maximum Failure Limit.

Only one circuit breaker, (DA112) failed after the 110% maximum limit of ultimate trip was submitted to five on and off cycles then retested. DA112 still failed the 110% requirement. DA112 was then submitted to the manufacturer for failure analysis. DA112 passed the manufacturer's test, but it was noted that the button-cam extension spring was no longer attached to the spring insulator. The manufacturer indicated that the disconnected spring did not affect the result. The failure is considered an anomaly. For this reason, it was not included as part of the minimum and maximum limit of ultimate trip analysis.

4.4.5.4 Design Requirements (Initial Limits).

As discussed in section 4, the minimum and maximum limit of ultimate trip requirements are designed to prevent breaker trips caused by slight increases in load current on the wire. The range of minimum limit of ultimate trip required for the tested breakers to remain closed for at least 1 hour is 5% (denoted as the 105% minimum trip test) to 15% (denoted as the 115% minimum trip test) of the breaker's rated current. The range of maximum limit of ultimate trip required for the tested breakers to open within 1 hour is 38% (denoted as the 138% maximum trip test) to 45% (denoted as the 145% maximum trip test) of the breaker's rated current. These percentages vary with the breaker type. Since the wire is designed to perform for the life of the

aircraft (see SAE specification AS 50881), the electrical system designer had to choose a wire size for the tested breakers that minimized the wire aging caused by a possible continuous 5% to 15% increase in load current over the rated current. The designer had to also choose a wire size that minimizes the effects of multiple occurrences of an increased current load for 1 hour of at least 38% to 45% above the tested circuit breaker's current rating.

4.4.5.5 Design Requirements (Aging Endurance Limits).

In addition to the initial limited increases in load currents, the tested breakers are also designed to permit the minimum and maximum limits of ultimate trip to change by an additional ±10% as the breakers age (see MIL-C-5089). The ±10% change permits the minimum limit of ultimate trip to be 90% of the initial minimum required value and the maximum limit of ultimate trip to be 110% of the initial maximum required value. The ±10% change is permitted after the breaker has been aged by on and off cycles. The on and off cycle requirements for most thermal breakers are 5,000 cycles with a resistive load, 2,500 cycles with an inductive load, or 10,000 cycles with no load (see MIL-C-5809). The test protocol presumes the tested breakers have been aged to less than this ±10% endurance requirement, and therefore, the on and off cycles were not performed as part of the protocol. The change in breaker calibration due to aging had to be considered by the electrical system designer to avoid trips caused by current load increases because of the aging equipment and circuit breaker. Since the tested breakers (depending on the type) permit an initial 38% to 45% increase in rated current then another 10% increase as the breaker ages, the designer had to choose a wire size that carried the load currents 41.8% (110% of 38%) to 49.5% (110% of 45%) above the breaker's rated current. The results obtained from an aircraft manufacturer indicate the electrical designer typically choose a wire size that carried a current load 100% greater than that expected to be required by the equipment load. The 41.8% value is well below the conservative 100% margin designed for the wire.

4.4.5.6 Assumptions.

Based on the results and discussion of the minimum and maximum limit of ultimate trip the following statements are assumed.

a. The wire is designed for the life of the aircraft.

b. The breakers were designed for a ±10% change in ultimate trip requirements as the breakers age.

c. The electrical system is designed for a conservative, maximum wire current load of at least 50% of the wire current rating.

4.4.5.7 Conclusion.

Based on the results and assumptions for the minimum and maximum limit of ultimate trip test, the following is concluded.

- The circuit breakers in aging aircraft have not exceeded their design limits for protecting the wire from slight increased current levels caused by aging of the electrical distribution system.

4.4.5.8 Recommendation.

Based on the results, assumptions, and conclusion for minimum and maximum ultimate trip tests, it is recommended the breakers not be replaced.

4.4.6 Lower Current Overload Test Results (150% and 200%).

The 200% lower current overload test was performed on all circuit breaker families except the family designated as manufacturer code L-0.5 (see appendix C). The L-0.5 family of circuit breakers only has a 150% lower current overload requirement.

4.4.6.1 Lower Current Overload, 200% Results.

Eleven out of 182 circuit breakers failed the 200% lower current overload test specified in block 55 for a failure rate of 6%. This failure rate correlates with the 5% failure rate (3 out of 60 breakers) noted for the 200% lower overload performed on the first 60 breakers in Process 1. Seven of the 14 combined Process 1 and Process 2 breakers tripped below the minimum trip time and seven tripped above the required maximum trip time. After subjecting the 11 Process 2 failures to five on and off cycles, seven of the breakers passed the lower current overload requirement. The five remaining failures all exceeded the maximum trip time required to open the breaker. All breakers were submitted to the manufacturer for failure analysis (see appendix F). Only one breaker passed when tested by the manufacturer in accordance with MIL-C-5809. The failing breaker, GE174, tripped 0.3 seconds earlier than the required 15 seconds minimum tripped time.

4.4.6.1.1 Assumptions.

The wire size is conservatively rated at 50% of the required load current.

4.4.6.1.2 Conclusion.

Based on the results and assumption for the 200% current overload test, the following may be concluded.

a. Cycling the breaker on and off improves the breaker's 200% lower current overload characteristics.

b. The circuit breakers in aging aircraft have not exceeded their design limits for protecting the wire from current surges or shorts caused by aging of the electrical load or the distribution system.

c. The unlikely, worst-case scenario for some breakers is a nuisance trip caused by load current surges. Maintenance personnel will replace nuisance trip breakers.

4.4.6.1.3 Recommendations.

Based on the results, assumptions, and conclusions for 200% current overload tested breakers, it is recommended the breakers not be replaced but periodically cycled on and off.

4.4.6.2 Lower Current Overload, 150% Results.

Fourteen out of 23 circuit breakers failed the 150% lower current overload for the L-0.5 family of circuit breakers for a failure rate of 64%. The L-0.5 breaker type is a 0.5-amp-rated breaker and has no higher current overload requirement. The smaller the amp rating for a breaker the more sensitive the breaker becomes to slight changes in test currents. The L-0.5 breaker is required to open between 1 and 8 seconds at a 150% current overload. Thirteen out of 14 failed breakers open in less than 1 second (0.6 to 0.9 second). The remaining breaker exceeded the 8-second maximum requirement. After five on and off cycles, the breaker that exceeded the 8-second requirement passed the 150% overload test. Twelve out of the remaining 13 breakers still had values below the 1-second requirement. The thirteenth breaker had a borderline passing value of 1.1 seconds (0.1 second above the minimum requirement). The manufacturer performed the 150% test three times on the 14 failing breakers. Four breakers failed the first two times and five the last time. Different breakers passed or failed each time the test was performed. In all cases, the breakers tripped before the minimum 1-second requirement.

4.4.6.2.1 Assumption.

The breakers are replaced, if nuisance trips occur.

4.4.6.2.2 Conclusions.

Based on the results and assumptions for the L-0.5 breaker types, the following may be concluded.

a. The high failure rate of 61% indicated L-0.5-amp breakers are not used in circuits that generate current surges exceeding 150% of current rating, otherwise these would be nuisance trip breakers that would have been replaced by maintenance requirements.

b. Cycling the breaker on and off may improve the breaker's 150% lower current overload trip characteristics.

c. The circuit breakers in aging aircraft have not exceeded their design limits for protecting the wire from current surges or shorts caused by aging or failure of the electrical load.

4.4.6.2.3 Recommendation.

Based on the results, assumptions, and conclusions for 150% current overload tested L-0.5 breakers, it is recommended the breakers not be replaced but periodically cycled on and off.

4.4.7 Higher Current Overload Test Results (400%, 500%, and 600%).

4.4.7.1 Single-Phase Breakers.

As reported in section 4.2.2, there were no failures as a result of the 400%, 500%, and 600% higher-current overload tests performed on the breakers in Process 1. For the Process 2 tests, 5 out of 168 breakers failed for a failure rate of 3%. The percentage of current overload used for a particular breaker type was determined by the circuit breaker requirement provided in appendix C. The high-current calibration curve requires the breaker to stay closed for a very short period of time (minimum time) and then open within a maximum period of time. Three of the five breakers tripped before the required minimum time, and two breakers tripped after the required maximum time. After five on and off cycles, two breakers out of five passed the overcurrent requirement. Of the three remaining breakers that failed, two failed the required minimum time, and one failed the required maximum time. When the failed breakers were tested by the manufacturer in accordance with MIL-C-5809, all the breakers passed the higher-current overload requirement. The circuit breaker failures by ampere rating are as follows.

Ampere Rating (amps)	Number of Failures
1	1 (500%)
8	1 (400%)
5	2 (600%)
10	1 (500%)

4.4.7.2 Three-Phase Breakers.

The three-phase breaker designated as LG291A, LG291B, and LG291C (see section 2.1) failed 500% current overload on phase A (LG291A). Phases B and C (LG291B and LG291C respectively) were not tested after failing the voltage drop at rated current. All the other three-phase circuit breakers were tested on all phases and passed all the tests, except the voltage drop at rated current test, as reported section 4.3.4. The low rate of failure for three-phase breakers indicates the presumption in the protocol deviation noted in section 3.2 is acceptable.

4.4.7.3 Assumptions.

None

4.4.7.4 Conclusions.

Based on the results and assumptions for the 400%, 500%, and 600% current overloads the following is concluded.

a. Cycling the breaker on and off improves the breaker's 400%, 500%, and 600% higher-current overload characteristics.

b. The circuit breakers in aging aircraft have not exceeded their design limits for protecting the wire from current surges or shorts caused by the aging of the electrical load or the distribution system.

4.4.7.5 Recommendation.

Based on the results, assumptions, and conclusions for 400%, 500%, and 600% current overload, it is recommended the breakers not be replaced but periodically cycled on and off.

4.4.8 Low Voltage Contact Resistance Test Results.

The low voltage contact resistance (LVCR) test is designed to monitor the changing resistance of the circuit breaker's mated contacts as the contacts are exercised on and off (refreshed) by mechanical wiping or electrical wiping. Circuit breakers either have one or two mated contact pairs. For each breaker tested, the average of 10 LVCR readings was recorded after each major test event in both protocols. The LVCR was also monitored as a part of the failure analysis (FA). For each FA, a single LVCR reading was recorded followed by an on and off cycle for a total of five cycles followed by a final LVCR reading. These results are recorded and summarized in appendix F. The data is condensed as shown in table 7.

TABLE 7. LOW VOLTAGE CONTACT RESISTANCE COMPARISONS

	LVCR Averaged by Breaker Type (millivolts)							
Breaker Type	Initial	After 2 Cycles	After Min. Trip	After Max. Trip	After 150%/200% Trip	After 500% Trip	After 5 FA Cycles	Note
A-10	18	26	5	18	5	3	54	1
A-3	23	77	55	78	53	38	130	
A-5	44	48	23	27	24	21	102	
B-1	262	266	233	268	234	196	271	
B-10	16	43	19	28	16	5	380	
L-0.5	466	468	461	461	461	N/A	461	2

1. Sampling size dropped from 17 to 5 specimens (after 2 cycles).
2. Breaker only has a 150% overload current requirement. Sampling size dropped from 23 to 9 specimens (after max. trip).

A review of the average LVRC results for the breaker types shown in table 7 indicated the LVCR value in relative terms changes very little after on and off cycles with or without loads. The increased values (after 5 FA cycles in table 7) indicate breakers that failed a specific performance requirement did have slightly higher LVCR values, but there is insufficient data to establish this increase as a trend.

4.4.8.1 Assumptions.

None

4.4.8.2 Conclusions.

Based on the results and assumptions for the LVCR, it can be concluded that the conditions of the contacts have little or no affect on the circuit breaker performance.

4.4.8.3 Recommendations.

None

4.4.9 Temperature Rise Test Results.

The temperature rise was monitored during all calibration tests. A general review of the data indicated that temperature rise typically increases with the current rating of the breaker. A temperature rise is expected, since more current generates more heat; however, there were exceptions to this proportionality. There appeared to be little or no relationship between the temperature rise and a particular failure mode.

4.4.9.1 Assumptions.

None

4.4.9.2 Conclusions.

There is insufficient data to indicate a relationship between temperature rise and circuit breaker test characteristics.

4.4.9.3 Recommendations.

None

4.4.10 Date Code Test Result Comparisons.

Table 8 was developed to try to determine if there is a relationship between the age of a circuit breaker and its failure rate. The combined date codes of all the breakers tested indicated the breakers varied in age from 1968 to 1996. The numerous breaker types in the test program contains a variety of manufacturing dates, but those provided in table 8 were chosen because the breaker types had a significant number of specimens and the date codes covered a broad period of time. The results indicated a 47% failure rate occurred for the L-0.5 breaker for date codes 1972 to 1993. The L-0.5 breaker result is skewed by the fact that 41% of the failures are only in the 1974 date code. The B-3 breaker had a 14% failure rate for date codes 1969 to 1991. The B-10 breakers had a 13% failure rate for date codes 1973 to 1986. The results indicate that the failures do occur in the earlier date codes.

4.4.10.1 Assumptions.

The assumption for date code analysis is that, in general, all breakers types will change similarly over time in a benign environment.

4.4.10.2 Conclusions.

The conclusion based on the date code analysis results is that the oldest breakers have a tendency to deviate further from the original specification requirements than the newer ones.

TABLE 8. DATE CODE COMPARISONS

P1 and P2 Combined			Failures				
Breaker Type	Date Code	Number of Breakers	90% Minimum Trip	110% Maximum Trip	150% or 200% Overload	400%, 500%, or 600% Overload	Voltage Drop at Rated Current
L-0.5	1972	1					
	1974	22		1	10		
	1982	1					
	1988	1					
	1991	3			3		
	1992	1			1		
	1993	3					
B-3	1969	15*					2
	1973	2					
	1983	1					
	1987	1					
	1988	1					
	1989	1					
	1990	1					
	1991	1					
B-10	1973	22			1	1	3
	1974	7					
	1984	1					
	1985	4					
	1986	2					

*One Breaker would not stay closed.

5. SUMMARY OF PROCESS 1 AND PROCESS 2 CONCLUSIONS AND RECOMMENDATIONS.

5.1 CONCLUSION.

The results of the tests protocols indicate that circuit breakers installed in aircraft with extended service life will continue to protect the electrical wire provided the maintenance procedures recommended in sections 5.2 to 5.4 and in paragraph 5.8 of SAE ARP 1199 are performed at least once a year.

5.2 MAINTENANCE MANUAL RECOMMENDATION.

The results indicate that the aircraft maintenance manuals should be reviewed and updated to reflect the following actions:

a. Provide instruction to cycle all breakers off and on once a year.

b. Provide instruction on how to protect the back panels during routine maintenance actions.

c. Provide instruction on how to clean the back panels.

d. Provide instruction to examine all panels for loose, broken, misapplied circuit breaker wire termination hardware, and require replacement with the correct hardware.

e. Provide clear instructions on how to avoid cross-threading screws or thread-stripping breaker terminals and require complete replacement of the breaker when it occurs.

f. Provide instructions on how to inspect for overheating and electrical arcing as well as defines what repairs are needed to minimize hotspots and prevent future occurrences.

g. Provide instruction that clearly defines the circuit breaker's wire termination hardware, and permit no substitutions unless there is a process that provides clearly define alternatives until direct replacements can be performed.

h. Provide instructions to maintenance personnel to review all processes that may be using breakers as on and off devices. If a breaker is routinely cycled on and off, establish a breaker replacement schedule based on the design requirements of the breaker or redesign the circuit to include a switch.

5.3 SAE STANDARD RECOMMENDATIONS.

The results indicate that the SAE AE-8 Committee, "Aero Electrical/Electronic Distribution Systems," be requested to perform the following.

a. Revise ARP 1199, paragraph 5.8.1 b4, to recommend circuit breaker termination-securing parts be replaced with identical parts and permit no substitutions without a process for appropriate replacement at a scheduled maintenance period.

b. Revise ARP 1199 to include a reference to EIA-476-B, "Date Code Marking." EIA-476-B specifies a four-digit code, the first two digits are the calendar week and the second two digits are the calendar year in which the component was produced.

c. Revise ARP 1199 and ARP 4404 to include more definitive guidelines on when multiple circuits can be used with one circuit breaker.

d. Revise AS 50881 and AS 5809 to include when and how multiple wires in one lug or multiple lugs on one circuit breaker terminal can be applied.

5.4 FAA ADVISORY CIRCULARS.

It is recommended that the appropriate FAA Advisory Circulars refer to SAE ARP 1199, ARP 4404, and AS 50881 for Electrical Distribution System Guidance.