On-Aircraft Wiring Characterization and Validation of Handheld Diagnostic Equipment

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ABSTRACT

The U.S. Air Force recognizes the importance in shifting from a reactive to proactive mode in improving aircraft wire system integrity and in transforming the maintenance approach in the inspection and repair of aging aerospace systems (Figure 1). For the past several years, AFRL has conducted extensive in-laboratory evaluations of multiple wiring diagnostic technologies aimed at assisting field users in identifying and locating aircraft wiring system faults quickly and as simply as possible (Refs 1, 2, 3, 5). Until recently, the majority of all test and evaluation conducted on these technologies has been performed under controlled conditions and in concert with equipment manufacturers. Initial in-laboratory evaluation goals were to advance these technologies to a level where they would be ready for on-aircraft evaluation and then transitioned to the field.

This paper focuses on the performance of handheld wiring diagnostics equipment when tested on a decommissioned T-1A aircraft. Results of these tests are expected to be used as part of a qualification process for the selection of wiring diagnostic equipment for use within the Air Force. The combination of laboratory evaluation, on-aircraft testing by laboratory personnel, and a future secondary evaluation by Air Force maintenance personnel on the T-1, should result in selection of one or more handheld units that can provide a useful diagnostics tool for Air Force users.

Figure 1. Photos of on-aircraft wiring diagnostics and in-laboratory evaluation of diagnostics technologies.

BACKGROUND:

In November of 2004, AFRL and the T-1 System Squadron at Wright Patterson AFB obtained a decommissioned T-1A Jayhawk aircraft that had been involved in a mishap at Keesler AFB in August of 2003 (Figure 2). The aircraft was built in 1993 and had accumulated 5218 flight hours prior to the incident. The T-1

System Squadron hoped to utilize the Keesler aircraft for aging and reliability data to assist in strategic financial planning and risk management of the fleet over the expected lifetime of the aircraft.

Figure 2. Photos of a T-1 Jayhawk and delivery of mishap aircraft to Wright Patterson AFB, OH.

AFRL/MLSA has led an effort to assess the aging and reliability characteristics of the T-1 through various evaluations of the aircraft's structural and electrical systems, components, and materials. Characterizing the aging properties of the wiring system and testing diagnostic equipment is just one of the aging and reliability focal areas MLSA is working in support of the T-1 System Squadron.

TECHNICAL APPROACH

TEST BED

The T-1A aircraft was used to establish the wiring test bed used in the evaluation of handheld wiring diagnostic equipment. The forward avionics compartment (Figure 3), containing wiring harnesses for the Weather Radar, Stall Warning System, and some flight control functions, was selected as the aircraft area to build the test bed for this effort.

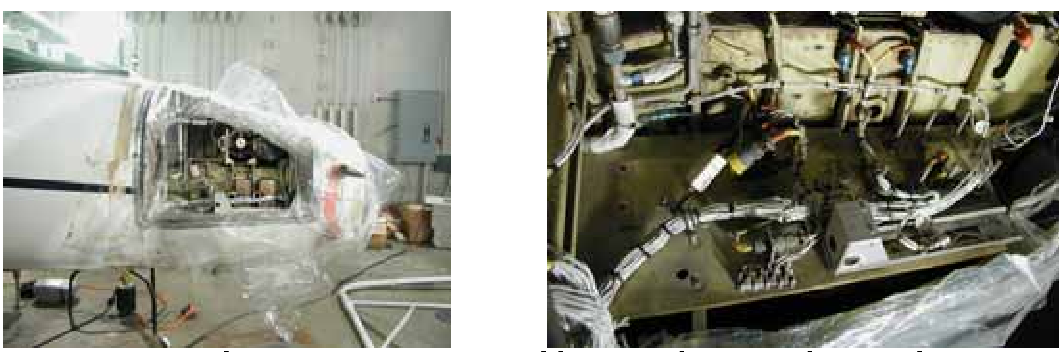

Figure 3. Forward avionics compartment and location of on-aircraft wiring diagnostics test bed.

The majority of the wiring in the forward avionics compartment is tin plated, polytetrafluoroethylene (PTFE) insulated, single conductor wire, or tin plated, PTFE insulated, twisted pair shielded wire, both manufactured to MIL-W-22759/16. All wiring selected for this evaluation was 22 gauge. All faults were constructed privately in an effort to allow for a "blind" evaluation of wiring diagnostic equipment by the test team. The fault development "team" decided on the type of faults to produce, the techniques to be used to develop them and the location of each. Ten faults were produced in three different wiring harnesses within the test bed. Several of the fault types produced are shown in Figure 4. All

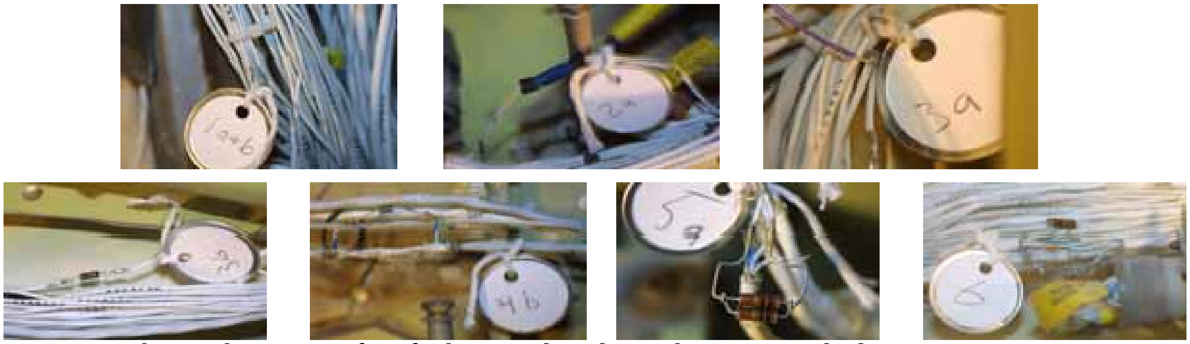

Figure 4. Photos showing 7 of 10 faults introduced into the T-1A test bed.

harnesses within the T-1 are open harnesses with tie wraps spaced along the length of the harness. This differs from other military aircraft that utilize braided harnesses which keep all enclosed wires in close proximity to each other with little relative movement with respect to one another. Movement of these wires, with respect to one another and with respect to bulkheads or other grounded structure, can vary the impedance of each.

After the faults were created and tested electrically, the avionics compartment covers were reattached and wax sealed. The tested harness ends and connectors extended from the sides to allow access by the test team (Figure 5).

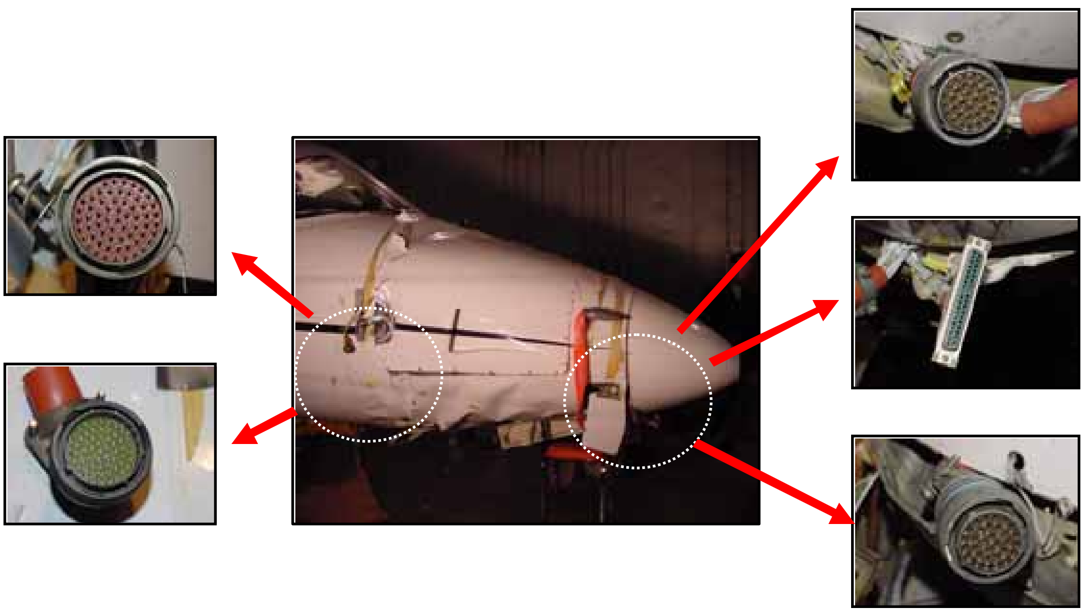

Figure 5. Forward avionics compartment, sealed for "blind testing. Connectors used to locate faults are also shown (arrows).

<u>TEST TEAM</u>

The testing of a variety of handheld or portable wiring diagnostic equipment on the T-1 test bed was conducted by the same engineers and technicians from the Air Force Research Laboratory and AT&T Government Solutions that performed a majority of the in-laboratory evaluations conducted over the previous 5+ years at AFRL (Refs 2, 4, 5). Over that time, the test team became familiar with the operation and various features of each unit and the various settings and options available to produce the most reliable test results. The in-laboratory test beds allowed for controlled testing. The in-laboratory wiring harnesses and test patches containing the various faults were stationary allowing for good variable control. During in-laboratory testing, the test team was also aware of the fault types and location as testing was conducted. This allowed for interaction with the equipment manufacturers who produced equipment upgrades and modifications that yielded results which improved over time.

Testing on the T-1 was conducted without the test team having knowledge of fault type or location. Their expertise and knowledge of the equipment has allowed multiple test techniques to be tried in an effort to find those that produce the best results and ultimately provide another tool in determining the performance of each piece of equipment.

EVALUATION PROCESS

As mentioned, ten different faults were introduced in three different wiring harnesses within the front avionics compartment of the aircraft. The ten faults were created to simulate what might be written up by flight crews as actual problems experienced during normal operations. The "simulated" fault write ups, corresponding to actual faults added to the test bed, included:

- **Flap indicator is always in COMMAND position**
- **Intermittent stall warning fail, AOA indicator has small fluctuations**
- **Stall warning signal sounds while in INHIBIT mode**
- **Stall identifying light does not come on with stall horn, light works in test**
- **Weather radar will not start self test**
- **Weather radar will not finish self test**
- **Weather radar passes self-test, no weather tracked**
- **Weather radar passes self-test intermittently, weather tracked intermittently as well**
- **Flight controls fault, AOA indicators inop**
- **Flap indicator inop during take off**

The test team was asked to use this information and T-1 Technical Orders (TO) to try and determine which circuits and corresponding harnesses, connectors, and pins should be tested to isolate the fault. This was done to again simulate procedures that might be followed in the field. The test team was provided a wiring schematic (Figure 6) containing the harnesses, connector numbers, wiring types, and pin numbers found within the test bed. The ten faults were produced among these wires.

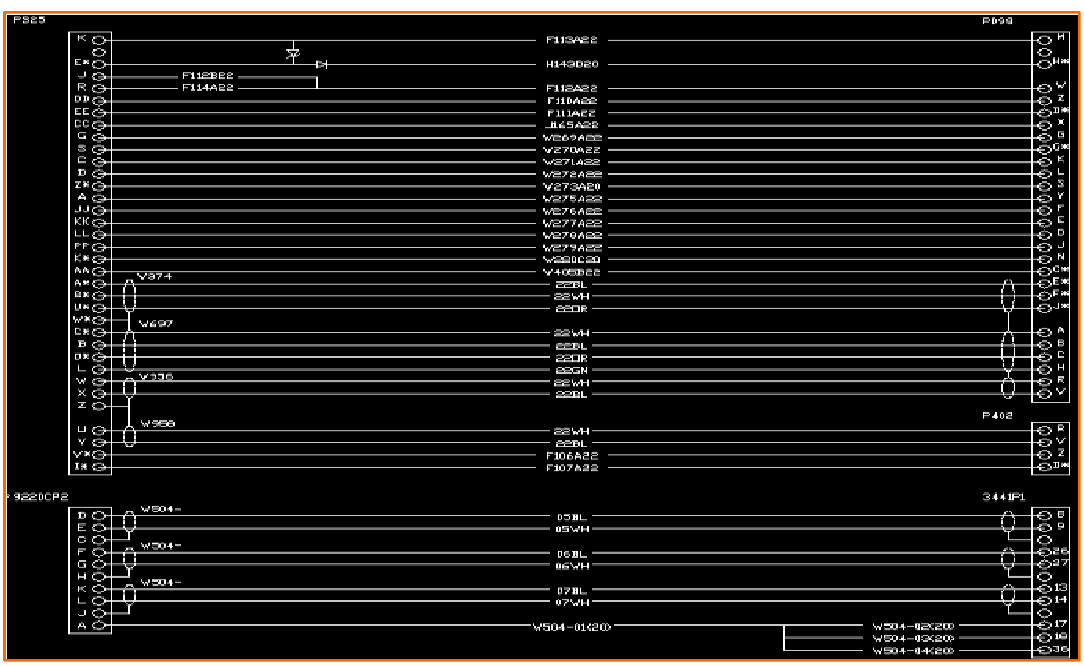

Figure 6. T-1 Test Bed Wiring Schematic.

The test team was also allowed to use a standard multimeter and a 4-wire bond integrity meter (4 point probe) similar to what is currently available to field personnel to assist in locating aircraft wiring faults.

Using the aircraft TO schematics and fault write-ups the test team was able to determine which harnesses, connectors, and pin combinations corresponded to which fault. The multimeter was used to verify the faults existed and that the suspected pin combinations containing the faults were correct.

Two hand held diagnostic technologies were used for the testing conducted in this study and have shown significant promise in laboratory testing. They are based on Standing Wave Reflectometry (SWR) and Time Domain Reflectometry (TDR). Both TDR and SWR technologies rely on reflected signals that detect an impedance change located between the meter's signal source and some location on the wire under test. A typical TDR measurement employs a step generator and an oscilloscope in a system. A voltage step is injected into the wire under test, and the incident and reflected voltage waves are monitored by the oscilloscope at a particular point on the wire. TDR reveals at a glance the distributed characteristic impedance of the wire, and it shows both the position and the nature (i.e., resistive, capacitive, or inductive) of each discontinuity, or defect, within the wire. While this technique has been very successful on controlled impedance wires such as coax and twisted pair, it has limited use on single conductors with uncontrolled impedance and variable ground plane proximities. Velocity of propagation (Vop) is the ratio of the velocity of a wave in a transmission line to the speed of light in vacuum; the number is 1 or less. The Vop varies with the transmission media (i.e. wire type) and is a key constant used by TDR and SWR technologies in distance to fault calculations. Various Vop constants exist based on different references. It can also be calculated, by the equipment itself if the length of the transmission line being tested is known.

The test bed developers discovered, at least in the case of the T-1, that the TO listed harness length was significantly different than the measured value. It is likely that this is the case for most Air Force platforms since excess wiring is sometimes left when an aircraft is wired to allow for modifications or subsequent repairs later on. Hence, the test team could not use the TO to reliably determine harness length.

Without knowing the harness length, the test team had to determine Vop either as a constant from one of a variety of sources, or allow the equipment to calculate it once the length was known. For this paper, two Vop values were used. The first was 0.67, also referred to as the Kuzniar Number (Ref 6), KN, a nominal value selected by the test team from prior in-laboratory wiring diagnostic technology evaluations. KN is most effective when testing controlled impedance wire types like twisted pair shielded wire found on the T-1.

The second method used was to establish the Vop value by testing a known "good" pair of wires, preferably from the same harness as the fault under test. For the shielded twisted pair wiring faults, an undamaged twisted pair from a different harness had to be used to establish the twisted pair Vop since there were no remaining undamaged shielded twisted pairs available. The length of the undamaged wiring was determined by measuring the resistance (4-wire measurement technique) from end to end and dividing by the known resistance per unit length (specification value) based upon the wiring size of the undamaged wiring. If the manufacturer's method for establishing a Vop value from a known length of wiring failed to establish a Vop, then an alternate method was used to calculate the Vop. The alternate method used was to test the undamaged wiring using a Vop value of 1, and then dividing the known length of wiring by the length reported when tested with the Vop set to 1. Once a Vop is known and entered into the tested unit, it calculates the distance to fault either automatically or manually by allowing the user to interpret an on-screen waveform.

During the testing process, it was observed that when establishing a Vop on a known "good" pair of wires, the value obtained often differed depending upon which end of the connector was used to establish the Vop. Because of this, a Vop value was established from both ends of the connector (same two wires) and the damaged wiring was evaluated using the Vop value established from that end of the connector.

Six different handheld or portable wiring diagnostic technologies were evaluated in this study. All were evaluated in the laboratory under controlled conditions prior to the T-1 testing (Figure 7). In-laboratory test results varied for all units.

The in-laboratory results showed that most of these diagnostic systems were capable of consistently measuring a short or open in an unshielded twisted pair wire within 12 inches. Faults that were associated with an electrical ground did produce larger errors than 12 inches. Fault distance measurements to single conductor wires shorted or open varied considerably between evaluated equipment. This was expected for equipment that uses waveform reflections since the measurements are being made on wires with uncontrolled impedance. Of particular note was equipment that could display a waveform. An experienced user could determine if a reading had a high confidence level based on observing where the fault was placed on the displayed waveform. (Ref 6)

The test team followed a test sequence that involved testing each fault with each piece of test equipment before proceeding to the next fault. Three readings were taken for each fault for each piece of test equipment with the average value or mode reported in this paper. For those units that provided two similar distance to fault readings and one that was significantly different, the reported value was based on the average of the two similar numbers. In most cases (~95%), the instruments provided similar values for all three readings. Each fault was evaluated on the same day so that temperature and humidity was similar for each piece of equipment tested for a given fault. For this paper only seven of the ten test bed faults were evaluated due to time constraints. The remaining three faults are presently being evaluated.

Figure 7. Handheld or portable wiring diagnostic technologies evaluated

Each piece of diagnostic equipment evaluated was operated as defined by the manufacturer. All but one of the units automatically removed the test lead length from the distance to fault readings obtained. That unit required the test lead length be subtracted from the values obtained. The test team utilized various features offered by each manufacturer to obtain the best results possible. The basic function of each unit was well understood by the test team based on their experience in operating the equipment during several years of in-laboratory evaluations and other independent testing. This paper does not cover the unique features or capabilities of each piece of equipment tested. The test team documented all findings during the test process through notes and data sheets.

TEST RESULTS

The results of the T-1 testing to date are shown in a table in the Appendix. The first column of the table shows the fault number, wire type, connectors and pins associated with that fault number. The temperature and humidity on the day of the test are also included. Only seven of the ten test bed faults are shown in the table. Column 2 provides the manufacturers tested, shown as Manufacturer A through F, with two manufacturers represented in both automatic and manual modes.

Columns 3 through 6 provide the fault detection performance data for all six equipment manufacturers from the left and right connectors of the harness containing the fault.

Columns 7 through 10 provide the distance to fault performance data for all six equipment manufacturers from the left and right connectors of the harness containing the fault. The distance to fault data is coded with green, yellow, and red colors and no numbers. This is done to keep the actual fault distances from each connector "unknown" for future testing. The colors provided represent equipment performance. Green indicates that the average of the three readings taken for that fault produced a distance error within 10%. Yellow represents an error of between 10 and 20% while red represents an error of greater than 20%. This percentage was calculated by subtracting the actual fault distance from the connector from the tested distance and dividing that number by the total length of the harness. The performance criteria selected can be explained with an example. Assume a wire harness of 100 inches in length is being evaluated. A fault is introduced 35 inches from the left connector. If Manufacturer A provides a distance to fault of 20 inches, the performance of that instrument would be 15% (i.e. 35-20÷100 x 100) signifying a color code of yellow. Using this method normalizes the data based on harness length and allows the "blind" nature of the T-1 test bed to be preserved.

Reviewing the data we can see that most of the equipment technologies tested performed well in diagnosing the fault, specifically as an open or short. In most cases, 100% fault detection was observed.

Distance to fault data was considerably more inconsistent. Generally, all of the technologies performed better when diagnosing faults within wire types having controlled impedances. It can also be observed that determining the length of the harness (Ω/unit length) using the calculated Vop provided better distance to fault results than using a nominal Vop, KN, in controlled impedance wires such as twisted shielded pairs. Using a nominal Vop of 0.67 (KN) is quick and easy but it's use appears to be instrument dependent. If field personnel can measure the resistance of the harness being tested and determine the length using a standardized Ω/unit length constant for a given wire type, calculation of a Vop by the instrument and the resulting distance to fault appears to provide better results for all instruments.

Of the data taken to date, collectively all manufacturers diagnosed controlled impedance faults to within 20% of the harness length nearly 80% of the time when using the known harness length method for determining Vop. Of all manufacturers in this category, manufacturers B (auto), D (auto and manual), E, and F performed the best. Performance for all manufacturers diminished when a nominal Vop, KN, was used. When KN was used as the Vop, collectively all manufacturers diagnosed controlled impedance faults to within 20% of the harness length 65% of the time.

Single conductor wires (uncontrolled impedance) also posed significant challenges for most of the technologies evaluated. For single conductor faults, collectively all manufacturers were able to diagnose to within 20% of the harness length slightly less than 75% of the time using the known harness length method for determining the Vop. Of all manufacturers in this category, manufacturers B (manual), C, D (auto and manual), and F performed the best. Performance for all manufacturers diminished when a nominal Vop, KN, was used when testing uncontrolled impedance wires. When KN was used as the Vop, collectively all manufacturers diagnosed uncontrolled impedance faults to within 20% of the harness length 50% of the time.

The test data also shows in some cases that testing from one end of the connector yielded good results, yet testing from the other end of the connector yielded less than desirable results. One possible explanation for this phenomenon, particularly for units whose test leads are not zeroed out or not completely zeroed out, might be due to the relative length of the test leads in relation to the actual distance to fault; given the Vop is a composite of the total conductive path. In some cases, the test lead length may approach or exceed the actual distance to fault from one end of the cable and be much shorter than the actual distance to fault when testing from the other end of the cable. Another possibility might be that different impedance might be seen from each end of the connector. Even in the case of a twisted pair wiring example, it may be that the amount of wiring untwisted near the connector, just before the wiring enters the connector from each end, varies from end to end, thus impacting the impedance seen from that connector.

Generally, all of the technologies tested performed less effectively when tested on an actual aircraft than when being evaluated in a laboratory under controlled conditions. Several variables may contribute to the decreased performance. Movement of the tested connectors to connect the equipment test leads could significantly change the impedance of wires with uncontrolled impedance (single conductors) and, therefore, impact the wave transmission characteristics of a given piece of equipment, which in turn impacts the distance to fault readings. The test method used for this study, however, did not introduce harness movement unlike procedures that might be used in the field to diagnose wiring faults.

Additional methods exist that can be used with the equipment tested to determine distance to fault. They include the use of other standardized Vop values in equipment calculations of fault distance, the use of fault distance ratios to determine fault distance based on readings obtained from both ends of a particular harness, and the use of resistance and capacitance data to calculate fault distance. These methods can and will be employed in future tests.

The data presented within this report is independent of involvement by the manufacturers themselves. Manufacturers will be invited in future testing to ensure the methods used by the test team are consistent with recommended manufacturer methods. Any data taken in these cases will be documented and published in subsequent reports.

SUMMARY

Over the past several years, the Air Force Research Laboratory has been committed to advancing wiring diagnostics technologies to a level that can help the warfighter more easily diagnose costly wiring faults on aircraft. AFRL has worked in unison with a consortium of government agencies, academia, and industry to achieve higher levels of wire system integrity.

Handheld wiring diagnostic equipment has advanced to a level where fault detection is nearly 100% accurate regardless of the manufacturer selected. Distance to fault characterization by the equipment manufacturers has also advanced but not yet to a level where field personnel can “push a button” and get a reliable fault location.

This paper has attempted to provide objective information regarding the performance of these technologies on an actual aircraft containing typical wiring faults. Prior research, though extensive, lacked any significant or in-depth on aircraft testing that needs to be done prior to actual procurement of this equipment. The risk associated with using equipment that performs poorly can be substantial if it means that aircraft will be disassembled to find a fault with a piece of equipment providing less than desirable results.

Users should be cautioned that while the in-laboratory test results have been instrumental in bringing technologies forward, actual use of these technologies currently requires a full understanding of the limitations of each and specific techniques that must be used to get meaningful results. The data taken and provided in this paper are a good “first step” in understanding how each technology performs on an actual aircraft. More testing is required to determine which technology provides the best results while still allowing for ease of use by the warfighter.

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APPENDIX

T-1 A Preliminary Test Results

Fault #	Hand Held Diagnostic System Manufacturer	Fault Detection: Nominal VOP 0.67 – From Left Connector	Fault Detection: Nominal VOP 0.67 – From Right Connector	Fault Detection: VOP by Ω/unit length – From Left Connector	Fault Detection: VOP by Ω/unit length – From Right Connector	Distance to Fault: Nominal VOP 0.67 – From Left Connector	Distance to Fault: Nominal VOP 0.67 – From Right Connector	Distance to Fault: VOP by Ω/unit length – From Left Connector	Distance to Fault: VOP by Ω/unit length – From Right Connector
Fault # 1 Single Conductor P098 pins J - M short P325 pins PP - K short 57.7F 9.6%RH	A	Short	Short	Short	Short				
	B (auto)	Short	Short	Short	Short				
	B (manual)	Short	Short	Short	Short				
	C	Short	Short	Short	Short				
	D (auto)	Short	Short	Short	Short				
	D (manual)	Short	Short	Short	Short				
	E	Short	Short	Short	Short				
	F	Short	Short	Short	Short				
Fault # 10 Single Conductor P098 E open P325 KK open 60.2F 42.3% RH	A	Open	Open	Open	Open				
	B (auto)	Open	Open	Open	Open				
	B (manual)	Open	Open	Open	Open				
	C	Open	Open	Open	Open				
	D (auto)	Open	Open	Open	Open				
	D (manual)	Open	Open	Open	Open				
	E	Open	Open	Open	Open				
	F	Open	Open	High Impedance	No Trace			No Trace	
Fault #3b Single Conductor P098 C* open P325 AA open 58.5F 9.5%RH	A	Open	Open	Open	Open				
	B (auto)	Open	Open	Open	Open				
	B (manual)	Open	Open	Open	Open				
	C	Open	Open	Open	Open				
	D (auto)	Open	Open	Test Incmplt	Test Incmplt			Test Incmplt	Test Incmplt
	D (manual)	Open	Open	Test Incmplt	Test Incmplt			Test Incmplt	Test Incmplt
	E	Open	Open	Open	Open				
	F	Short	Open	Open	Open				
Fault #4b Twisted Shielded Pair 3441P1 8 open 9220CP2 D open 58.9F 49% RH	A	Open	Open	Open	Open				
	B (auto)	Open	Open	Open	Open				
	B (manual)	Open	Open	Open	Open				
	C	Open	Open	Open	Open				
	D (auto)	Open	Open	Open	Open				
	D (manual)	Open	Open	Open	Open				
	E	Open	Open	Open	Open				
	F	Low Impedance	Open	Open	Open				
Fault #5a Twisted Shielded Pair 3441P1 26-27 short 9220CP2 F,G short 60.7F 39.5% RH	A	Short	Short	Short	Short				
	B (auto)	Short	Short	Short	Short				
	B (manual)	Short	Short	Short	Short				
	C	Short	Short	Short	Short				
	D (auto)	Short	Short	Short	Short				
	D (manual)	Short	Short	Short	Short				
	E	Short	Short	Short	Short				
	F	Short	Low Impedance	Short	Low Impedance				
Fault # 4a Twisted Shielded 3441P1 13-GND short 9220CP2 K-J short 60.7F 39.5% RH	A	Short	Short	Short	Short		No shield pin		No shield pin
	B (auto)	Short	Short	Short	Short		No shield pin		No shield pin
	B (manual)	Short	Short	Short	Short		No shield pin		No shield pin
	C	Short	Short	Short	Short		No shield pin		No shield pin
	D (auto)	Short	Short	Short	Short		No shield pin		No shield pin
	D (manual)	Short	Short	Short	Short		No shield pin		No shield pin
	E	Short	Short	Short	Short		No shield pin		No shield pin
	F	Short	Short	Short	Short		No shield pin		No shield pin
Fault #5b Twisted Shielded Pair 3441P1 No pin available 9220CP2 C-GND open 65.7F 39.2% RH	A	Open	Test Incmplt	Test Incmplt	Test Incmplt		Test Incmplt	Test Incmplt	Test Incmplt
	B (auto)	Open	Test Incmplt	Test Incmplt	Test Incmplt		Test Incmplt	Test Incmplt	Test Incmplt
	B (manual)	Open	Test Incmplt	Test Incmplt	Test Incmplt		Test Incmplt	Test Incmplt	Test Incmplt
	C	Open	Test Incmplt	Test Incmplt	Test Incmplt		Test Incmplt	Test Incmplt	Test Incmplt
	D (auto)	Open	Test Incmplt	Test Incmplt	Test Incmplt		Test Incmplt	Test Incmplt	Test Incmplt
	D (manual)	Open	Test Incmplt	Test Incmplt	Test Incmplt		Test Incmplt	Test Incmplt	Test Incmplt
	E	Open	Test Incmplt	Test Incmplt	Test Incmplt		Test Incmplt	Test Incmplt	Test Incmplt
	F	High Impedance	Test Incmplt	Test Incmplt	Test Incmplt		Test Incmplt	Test Incmplt	Test Incmplt

Key

Fault Detection:
- 100% Detected
- <100% Detected or Alternate Display
- No Faults Detected

Distance to Fault:
- Within 10% of Total Harness Length
- Between 10 and 20% of Total Harness Length
- Greater than 20% of Total Harness Length