KEITHLEY

Application Note Series

Number 2608

Increasing Production Throughput of Multi-pin Devices with Keithley Series 2600 System SourceMeter® Instruments

Introduction

Electronic component manufacturers have always been under intense pressure to minimize the cost of their products. As device tolerances and specifications have become increasingly stringent, the level of pressure has risen. Qualifying components to tight specifications using traditional test and measurement equipment can be difficult, simply because many instruments and modular test systems don't fully address the fast cycle times and flexibility required to meet throughput goals. Most instruments require constant back-and-forth communications with a controlling PC because many systems lack control and test sequence capabilities. Today's ideal test and measurement equipment must combine solid, repeatable measurement capabilities with minimal bus traffic in order to execute complex test procedures with short cycle times and higher accuracies.

Most test and measurement instruments communicate continuously with a controlling PC. Instrument setup, range changes, source values, etc. are packaged up and delivered over a communications bus to the instrument, one command at a time. Then, the data is returned to the PC in the same fashion. Each packaged command sent via the PC/instrument link takes time, which can range from hundreds of milliseconds per bundle for an RS-232 communication link to tens of milliseconds for GPIB (General Purpose Interface Bus). Even a fast bus like a 100 Base-T Ethernet interface can add considerably to the test time. Data evaluation, calculations, and handler control all increase the test time still further.

The obvious question becomes: Is there some way to streamline the communications process between the PC and the instrument?

This Application Note explores the advantages of using Keithley's Series 2600 System SourceMeter instruments in production environments to enhance test performance and throughput. Specifically, it discusses how to implement and optimize the Series 2600's embedded Test Script Processor (TSP) and on-the-fly pass/fail capabilities to decrease the communications time and increase throughput. It includes a step-by-step illustration of a real-world example—production testing a BJT device.

Simple Test Description: Transistor Testing

BJT transistors are multi-pin devices made up of three sections: a Collector, an Emitter, and a Base. ***Figure 1*** illustrates a common test configuration for a BJT. Two channels must be controlled during characterization: the Base/Emitter (B/E) channel and the Collector/Emitter (C/E) channel. Source-Measure Units (SMUs) offer a convenient way to address this configuration. An SMU is a powerful instrument that can source and measure simultaneously. It's ideal for applications that require a programmed source of current/voltage coupled with integrated measurement and control. Keithley Instruments developed one of the world's first SMUs, as well as the popular Series 2400 SourceMeter© line. These instruments have emerged as powerful production test tools, replacing many older systems built from multiple instruments such as power supplies and separate DMMs for the measurement function. The Series 2600 extends this concept, integrating cutting-edge control and test sequencing with additional advances that leverage and expand on the traditional SMU architecture.

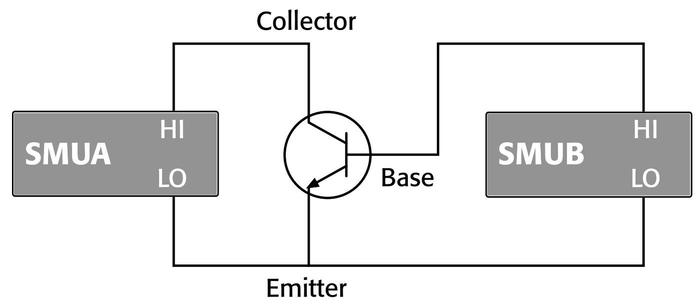

Figure 1. SMU to NPN Transistor schematic.

The Model 2602 contains two SMUs in one half-rack instrument case, so it's a very convenient instrument for testing three-leaded devices like BJTs. ***Figure 2*** shows how to connect a Model 2602 to a transistor. In this configuration, SMUA handles sourcing and measurement for the Collector/Emitter (C/E) channel, while SMUB is used for sourcing and measurement for the Base/Emitter channel (B/E).

The following test sequence provides a basic set of measurement steps for a transistor; the range and source values have been specified especially for the common 2N3904 NPN BJT. Many different types of transistors and an even greater number of tests can be used to classify and bin these devices, but the core test requirements involve sourcing a known value on the B/E and C/E channels and performing basic voltage or current measurements. Before attempting to test devices, be sure to read and understand the documentation for the Series 2600 hardware and ensure you have selected the appropriate range and source values.

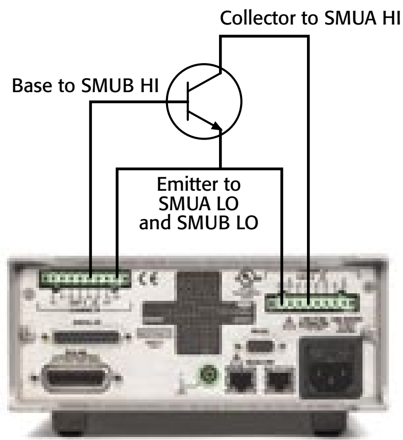

Figure 2. Model 2602 connections to an NPN transistor (2N3904).

Test Sequence - Instrument Setup

Basic Source/Measurement functions

The set-up step reconfigures an instrument from its default state into a state that's optimized for the application. The set-up portion of the test sequence typically configures the instrument's source and measurement ranges, source output modes, and compliance/limits. Optimizing the set-up sequence can significantly increase test speed. For example, choosing appropriate fixed ranges for source and measurement, disabling beepers, and turning off displays can decrease test time considerably.

The following code snippets illustrate actual commands as sent to a Keithley Series 26XX System SourceMeter© Instrument. Comments are denoted by "--" .

2602 TSP code for Setup

```
function setup() --Define function "setup"
 smub.reset() -- Reset SMUB (base)
 smua.reset() -- Reset SMUA (collector)

 smub.source.func = smub.OUTPUT_DCVOLTS -- Set to source voltage
 smub.measure.autozero = smub.AUTOZERO_ALWAYS
 smub.measure.nplc = 1 -- Set integration rate

 smub.source.rangei = 0.01 -- Set source range
 smub.source.levelv = 0 -- Set source value
 smub.source.output = smub.OUTPUT_ON -- Enable SMUB

 smua.source.func = smua.OUTPUT_DCVOLTS -- Set to source voltage
 smua.measure.autozero = smua.AUTOZERO_AUTO --Set Autozero to Auto
 smua.measure.nplc = 1 -- Set integration rate

 smua.source.rangev = 40 -- Set source range
 smua.source.levelv = 0 -- Set source value
 smua.source.output = smua.OUTPUT_ON -- Enable SMUA
end --end function "setup"
```

Test 1: VCEO (Open Base)

Basic Source/Measure functions

The VCEO step is used to test the open base voltage of the transistor and is a figure of merit that helps describe the maximum voltage levels the C/E junction can withstand without damage.

SMUA: Source a specified current on C/E channel, measure voltage, and evaluate vs. Pass/Fail criteria

SMUB: Open Base- Source 0mA on B/E channel

202x TSP code for VCEO measurement

```
function VCEO() -- Start function "VCEO"
VCEOlimit = 40 -- Local variable for VCEO limit

 smub.source.func = smub.OUTPUT_DCAMPS -- Set to source current

 smub.measure.rangev = 40 -- Set measurement range
 smub.source.limitv = 40 -- Set source limit (compliance)
 smub.source.rangei = 100E-9 -- Set current range
 smub.source.leveli = 0 -- Set source value

 smua.source.func = smua.OUTPUT_DCAMPS -- Set to source current
 smua.source.leveli = 0.01 -- Set source level
 smua.measure.rangev = 40 -- Set measurement range
 smua.source.limitv = 40 -- Set source limit (compliance)
```

```
  VCEO_data = smua.measure.v() -- Measure VCEO

  if (VCEO_data > VCEOlimit) then -- Evaluate Pass/Fail criterion
      Pass = 1 --Pass is True
  else
      Pass = 0 --Reinitialize Pass
  end

end --End function "VCEO"
```

Test 2: VCEsat/VBEsat

The VCEsat and VBEsat test the voltage across the C/E channel, as well as the B/E channel, when the transistor is "ON" and conducting an appreciable current (Ic). They are figures of merit that describe the required voltage consumed by the device when it has been activated, specifically when used as a switch.

Basic Source/Measure functions

SMUA: Source current on C/E channel, measure voltage (VCEsat), and evaluate vs. Pass/Fail criteria

SMUB: Source current on B/E, measure voltage (VBEsat), and evaluate vs. Pass/Fail criteria

2602 TSP code for VCEsat/VBEsat measurement

```
function VCEsat() --Define function "VCEsat"
  smua.measure.rangev = 100E-3 -- Set measurement range
  smub.measure.rangev = 100E-3 -- Set measurement range

  smua.source.leveli = 10E-3 -- Set source range
  smub.source.leveli = 1E-3 -- Set source range

  VCEsat_data = smua.measure.v() -- Measure VCEsat
  VBEsat_data = smub.measure.v() -- Measure VBEsat

  if (VCEsat_data < limitVCEsat) then -- Evaluate Pass/Fail criterion
      Pass = 1 --Pass is True
  else
      Pass = 0
  end

  if (VBEsat_data < limitVBEsat) then -- Evaluate Pass/Fail criterion
      Pass = 1 --Pass is True
  else
      Pass = 0
  end

end --End function "VCEsat"
```

Test 3: hFE(Beta)*

Transistors are also used as amplifiers. The hFE or Beta of a BJT represents the amplification of the transistor under specific drive conditions. This figure of merit is primarily used to select devices with appropriate amplification levels for a given application.

Basic Source/Measure functions

SMUA: Source voltage on C/E channel, and measure current

SMUB: Binary Search for current source value on B/E such that C/E current is within Pass/Fail limits

The most common technique for determining Beta is known as Binary Search. In this technique, a fixed voltage is sourced on the C/E channel while the B/E channel sources a current that lies halfway between a Hi and Lo limit. At this B/E source value, the C/E current draw (Ic) is measured. If the C/E current measurement (Ic) is above a set target value, then the current B/E source value becomes the new Hi Limit and a new B/E current that lies halfway between the Lo and the new Hi limit is sourced. This process is repeated until the target Ic current is measured.

---

* hFE (Beta) is a calculation of the gain of an amplifier defined by this equation:

$$Beta = Ic/Ib$$

where Ic = current through C/E and Ib = current through B/E

2602 TSP code for Beta using a Binary Search

```
function searchBinary() --Defines the start of a function. Function can then be called at any time.

 k = 0 -- Variable to count loops in search
 VCESource = 1 -- Variable for source value
 HIGHIb = 10e-7 -- Variable for High source limit on B/E channel
 LOWIb = 1e-9 -- Variable for Lo source limit on B/E channel
 HFE1limit = 40 -- Variable for hFE limit
 TARGETIc = 100e-6 -- Variable for target current measurement on C/E channel

   smua.source.func = smua.OUTPUT_DCVOLTS -- Set to source voltage
   smua.source.rangev = 6 -- Set to source range
   smua.source.limiti = (5 * TARGETIc) -- Set source limit
   smua.measure.rangei = 10e-3 --Set measure range

   smub.source.func = smub.OUTPUT_DCAMPS -- Set to source current
   smub.measure.rangei = 100e-6 -- Set measurement range
   smub.source.rangev = 6 -- Set source range
   smub.measure.rangev = 6 -- Set measurement range
   smub.source.limitv = 6 -- Set voltage source compliance

--Start binary search
   smua.source.levelv = VCESource -- Set source value
   smub.source.leveli = 0 -- Set source value

   repeat -- Repeat following code until conditions are met
      k = k + 1 -- Increment
     Ib = ((HIGHIb-LOWIb)/2) + LOWIb -- Establish source current value
      smub.source.leveli = Ib -- Source new current value for B/E channel
      delay(0.001) -- Source delay
     IcMeas = smua.measure.i() -- Measure C/E current

      if (TARGETIc < IcMeas) then -- Evaluate measurement vs. target
         HIGHIb = Ib -- If measurement is greater than target, new source value equals hi limit
      else
         LOWIb = Ib -- Else new source value equals lo limit
      end

   until ((math.abs(IcMeas - TARGETIc) < (0.05*TARGETIc))or(k>10)) -- Conditions to continue loop

   BETA1_data = IcMeas/Ib -- Calculate Beta (hFE)

   if BETA1_data > HFE1limit then --Evaluate Pass/Fail criterion
      Pass = 1 --Pass is True
   else
      Pass = 0
   end
end -- End of function
```

Downloading the script and retrieving the data

Downloading the script to the 2602 is simple. Using the provided software, Test Script Builder, or by simply passing the script to the instrument via another language, such as Visual Basic®, C, or the LabVIEW® programming environment. Script management and optimization are covered in detail in the 2602 User's Guide, as well as in the Help Files Associated with the Keithley Test Script Builder.

The following guidelines are useful for organizing test scripts and may be helpful during code troubleshooting:

1. Set 2602 parameters that will be common to all tests (e.g., autozero, data format, etc.).
2. Define each step in the test as a function. This aids in code reuse, as well as readability.

   With scripting, it's possible to re-use the function any time. To program efficiently, it's good practice to write code so that as many functions as possible can be re-used.

   In the above example, it's possible to name multiple functions, one for each part of the test sequence. The code used to call the functions could be written as follows:

```
setup() --Call function "setup"
VCEO() --Call function "VCEO"
VCEsat() --Call function "VCEsat"
searchBinary()--Call function "searchBinary"
```

3. Set limit values and digital output bit patterns for each pass/fail outcome. Allowing the 2602 to control decision-making makes it possible to decrease the communications overhead even more significantly.

Increased Throughput: Why the 26xx?

As mentioned previously, the source and measure operations for these types of tests are usually addressed with SMUs. To automate and increase throughput, these more traditional test stands include a PC and two SMUs configured for remote communications through a link such as Ethernet, GPIB, or USB. In this configuration, the PC is the master of the test and is responsible for running the test sequence, evaluating the pass/fail criteria, as well as controlling any binning/sorting operations that may be available. The test sequence may contain source values, range settings, and other configuration information. ***Figure 3*** shows a BJT test sequence and its various elements. ***Figure 4*** shows the standard implementation of the test, where a controlling PC is in almost constant communication with the instrumentation.

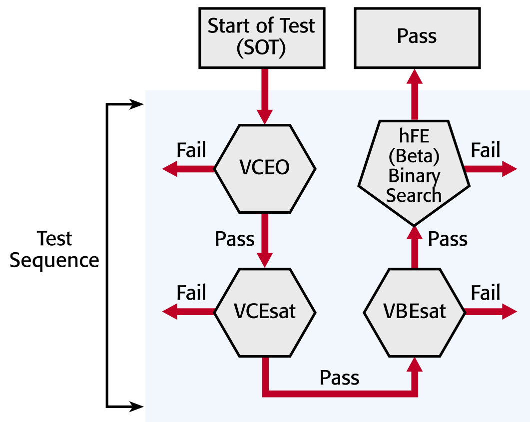

Figure 3. Elements used in the BJT test example, compiled into a test sequence.

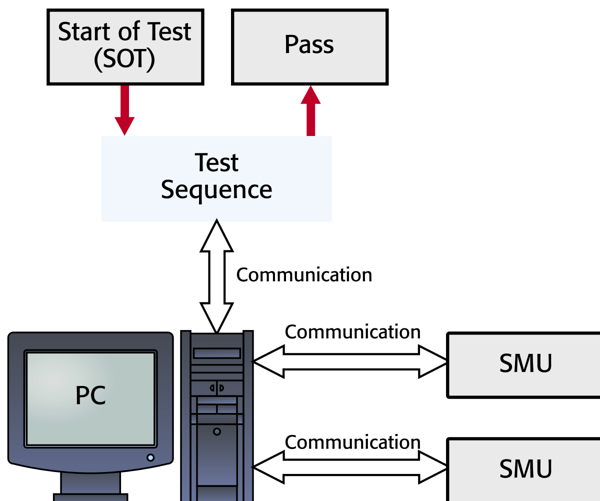

Figure 4: Traditional PC control of a test sequence. Note high level of communications traffic.

In each element of a test sequence, the instruments must be configured for each test, perform the desired action, and then return the data to the controlling PC. The controlling PC then must evaluate the pass/fail criteria and perform the appropriate action for binning the device under test. Each command sent and executed consumes precious production time and lowers throughput. Obviously, a large percentage of this test sequence is consumed by communicating information to and from the PC. This represents a significant opportunity to increase throughput. Migrating the test sequence to the 2602 TSP has shown 2–10× throughput gains over systems that lack embedded processing.

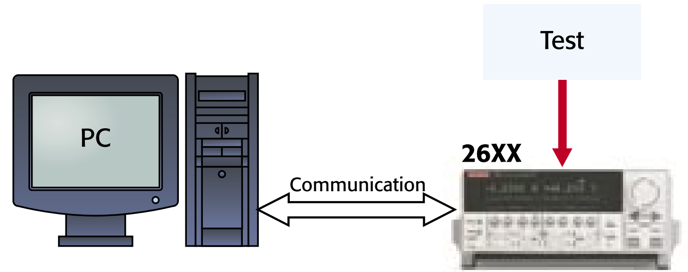

Figure 5: Use of the embedded Test Script Processor (TSP) in the Model 2602 to store the test sequence. Note decreased communications traffic.

Series 2600 instruments offer the unique ability to increase the throughput of complicated test sequences dramatically by decreasing the amount of traffic over the communications bus. In these instruments, the majority of the test sequence is embedded in the powerful, flexible, on-board Test Script Processor (TSP). The TSP is a full-featured test sequence engine that allows unprecedented control of the test sequence, with internal pass/fail criteria, math, calculations, and control of digital I/O (see the Test Sequence with 2602 illustrated in ***Figure 5***). The TSP can store a user-defined test sequence in memory and execute it on command. This limits the "set-up" and configuration time for each step in the test sequence and increases throughput by decreasing communication time.

The Series 2600's TSP can provide other throughput advantages. The on-board processor can evaluate the test results in real time.

In this BJT test sequence, the following set of code was used to evaluate Pass/Fail criteria:

Evaluation of measurement vs. Pass/Fail Criterion

```
if (VCEO_data > VCEO_limit) then --Evaluate
Pass/Fail criterion
       pass = 1 --Pass is True
else (pass = = 0)
end
```

In this case, *the instrument* evaluates the data in real time and can determine whether the device passes or fails. With the addition of a simple digital I/O control, the 2602 can be used to operate the handler interface directly as well.

Evaluation of measurement vs. Pass/Fail Criterion

```
if (VCEO_data > VCEO_limit) then --Evaluate
Pass/Fail criterion
       pass = 1 --Pass is True
    write Handler(1) -- Write "pass" to handler[1]
else
    writeHandler(0) -- Write "fail" to handler[1]
end
```

[1] Each handler's interface is different. Please consult Keithley's Applications Group or your handler's manufacturer for details.

The Series 2600 also has a very large buffer, capable of storing readings, math calculations, pass/fail limits, as well as statistics on the data collected.

Summary

Series 2600 System SourceMeter instruments represent a flexible test platform that can revolutionize the way component tests are performed. In head-to-head testing of BJTs, Series 2600 instruments provided 2–3× higher throughput than competitive products, including even mainframe systems with test sequencing capabilities.

Series 2600 advantages:

- Embedded Test Script Processor (TSP) invests enormous test control flexibility in the instrument, not the PC, lessening communications lag time and increasing throughput.
- Full-featured scripting language allows on-board instrument calculations and complex math.
- Large buffer allows minimizing communications with the PC.
- 14-bit digital I/O can be accessed "on the fly," increasing throughput by allowing instrument and binning equipment such as handlers (not included) to run without PC interference.

Sources of error

Lead Resistance

A common source of voltage measurement error is the series resistance from the test leads running from the instrument to the diode. This series resistance is added into the measurement when making a two-wire connection (see ***Figure 6***). The effects of lead resistance are particularly detrimental when long connecting cables and high currents are used, because the voltage drop across the lead resistance becomes significant compared to the measured voltage.

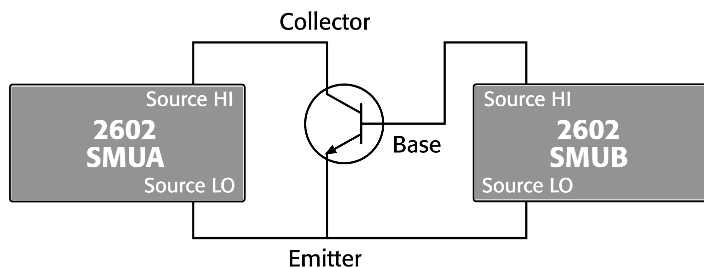

Figure 6. 2602 channel local sense (two-wire) connection.

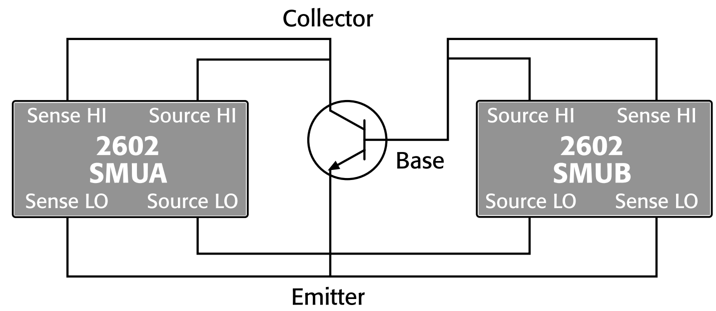

Figure 7. 2602 channel SMU remote sense (Kelvin) connection.

To eliminate this problem, use the four-wire remote sensing method rather than the two-wire technique. With the four-wire method (***Figure 7***), a current is forced through the DUT using one pair of leads and the voltage across the DUT is measured through a second set of leads. As a result, only the voltage drop across the diode is measured.

Leakage Current

Stray leakage in cables and fixtures can be a source of error in measurements involving very low currents, such as for leakage currents. To minimize this problem, construct test fixturing with high resistance materials.

Another way to reduce leakage currents is to use the built-in guard of the SourceMeter instrument. The guard is a low impedance point in the circuit that is nearly the same potential as the high impedance point to be guarded. This is best illustrated by example (***Figure 8***).

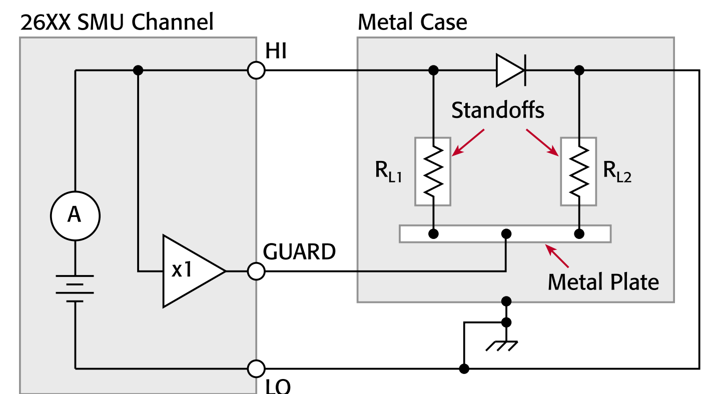

Figure 8. Series 2600 guarding technique

In this example, the diode to be measured is mounted on two insulated standoffs (R_L). Guarding is used in this circuit to ensure all the current flows through the diode and not through the standoffs. In general, cable guard should be used when sourcing or measuring currents of less than 1μA. This circuit is guarded by connecting the guard terminal of the instrument to the metal plate. This puts the bottom of insulator R_{L1} at almost the same potential as the top. Since both ends of the insulator are at nearly the same potential, no significant current can flow through it. All the current will flow then through the diode as desired.

WARNING: Guard is at the same potential as output HI. Therefore, if hazardous voltages are present at output HI, they are also present at the Guard terminal.

Electrostatic Interference

High resistance measurements may be affected by electrostatic interference, which occurs when an electrically charged object is brought near an uncharged object. To reduce the effect of electrostatic fields, a shield can be built to enclose the circuit being measured. As shown in ***Figure 8***, a metal shield connected to ground surrounds the diode under test. The LO of the SourceMeter instrument must be connected to the metal shield to avoid noise due to common mode and other interference. This also acts as a safety shield because the metal plate is at guard potential.

Example Script

Keithley has developed an example TSP script to demonstrate a fully functional BJT test suite. At the end of the test, an output report is produced that gives the test voltages, currents and pass/fail status. Be aware that this program may need to be modified, especially to ensure proper communications to a handler, if used for binning tested parts. To obtain a copy of this script as a digital file, access Keithley's World Wide Web site (http://www.keithley.com).

Equipment List

The following equipment is required to assemble a BJT production test system and run the example programs available from Keithley:

1. Keithley Model 2602 Dual Channel System SourceMeter® instrument
2. PC with KPC-488.2 Interface Card or KUSB-488 USB-to-GPIB Adapter
3. 2N3904 BJT
4. Component handler with test fixture
5. Keithley 7007 IEEE-488 interface cable
6. Custom DB-9 digital I/O handler interface cable to interface the instrument to the handler
7. Test leads to connect the instrument to the test fixture

Test System Safety

Many electrical test systems or instruments are capable of measuring or sourcing hazardous voltage and power levels. It is also possible, under single fault conditions (e.g., a programming error or an instrument failure), to output hazardous levels even when the system indicates no hazard is present. These high voltage and power levels make it essential to protect operators from any of these hazards at all times. Protection methods include:

- Design test fixtures to prevent operator contact with any hazardous circuit.
- Make sure the device under test is fully enclosed to protect the operator from any flying debris. For example, capacitors and semiconductor devices can explode if too much voltage or power is applied.
- Double insulate all electrical connections that an operator could touch. Double insulation ensures the operator is still protected, even if one insulation layer fails.
- Use high-reliability, fail-safe interlock switches to disconnect power sources when a test fixture cover is opened.
- Where possible, use automated handlers so operators do not require access to the inside of the test fixture or have a need to open guards.
- Provide proper training to all users of the system so they understand all potential hazards and know how to protect themselves from injury.

It is the responsibility of the test system designers, integrators, and installers to make sure operator and maintenance personnel protection is in place and effective.

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