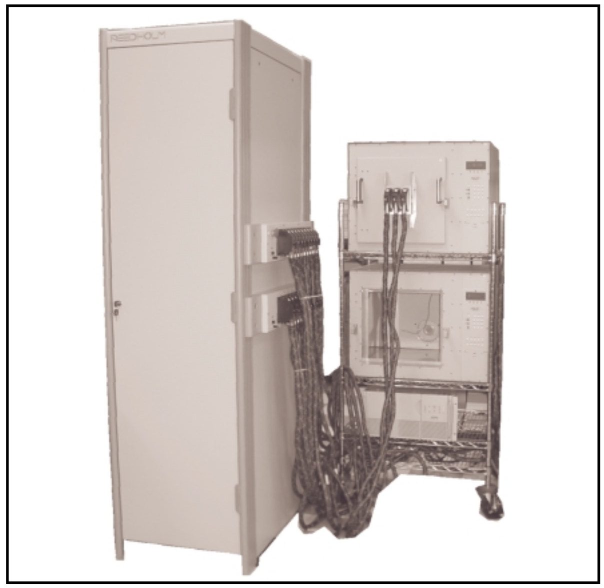
Metal Migration Reliability Analyzer

Model RI-52

- **Up to 400°C EM Stressing**
- **Selectable Temperature Ramp Control**
- **Uncompromised Oven Performance**
- **Simple, Rugged Oven Interface**
- **Microvolt Sensitivity**
- **<1% Load Board Temp. Uniformity**
- **Accurate, Unambiguous Data**
- **Open ASCII Data Files**
- **PC and Tester Error Recoveries**
- **Post-Test Selection of Failure Criteria**



Meeting Advanced Processing Needs

The reliability of advanced interconnect systems is so high that accelerated testing to failure or changes in resistance of several per cent is not practical. Copper interconnects are especially reliable, even at temperatures so high that other failure mechanisms are introduced. Thus, isolating copper interconnect failure mechanisms means that thermal and electrical stresses are restricted to levels so low that extrapolations to use conditions have to be done from device resistance changes that are quite small.

Such a change in metal interconnect reliability testing not only requires excellent voltage sensitivity, it also requires that thermal and electrical stress conditions be highly controlled and uniform. Otherwise, small changes or differences in stress conditions might be falsely interpreted as interconnect degradation.

The RI-52 consists of hardware and software integrated into a metal migration test system providing a wide temperature range, outstanding measurement quality, and excellent stress uniformity. Accuracy and precision are optimized through the use of four terminal resistance measurements. These features assure that metal lifetime predictions are due to structures under stress, and are not a function of the test system.

Base RI-52 System

The base system consists of one oven which can handle three experiments of 32 devices each. Thus, 96 devices may be stressed within one oven. There is a stress current supply and a device scanner dedicated to each experiment. Experiments can be configured with:

- Up to 32 devices per experiment.
- Up to 16 devices per load board.
- Up to 3 experiments per oven.

Expanding the RI-52

The system pictured above is a configuration used by one of the pioneers in copper metallization development. Its configuration of six ovens permits simultaneous stressing of 576 devices at six different temperatures and 18 different current densities. The RI-52 configuration can be doubled in capacity to 1152 devices in 12 ovens.

Socketless Load Boards

One major improvement that results in long lifetimes is the elimination of device sockets and the card edge connector from the load board.

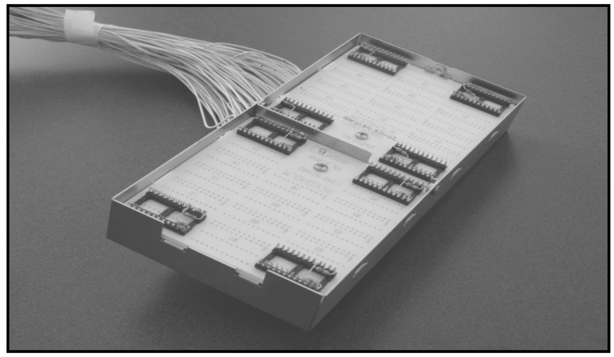
Device fixtures in the RI-52 are capable of sustained operation at 350^{o}C due to a unique design approach that either eliminates or significantly alters those elements which caused wearout in previous reliability test systems.

The ongoing operating costs for other packaged reliability systems can be quite high, primarily because the sockets are prone to powder after being subjected to high temperatures for an extended period of time. It is not uncommon to have to replace sockets on an annual basis. Since the Reedholm load boards eliminate sockets, and even metal traces, the expenditures for board replacement is drastically reduced if not eliminated altogether.

Configuring Experiments

Up to 16 devices can be stressed on each board. The devices can be packaged in either 300 mil, 16-pin or 600 mil, 24-pin dual in-line packages. Standard configuration supports package pin diameter/diagonal dimension of 15-25 mil. There are two load boards, or 32 devices, per experiment. Custom pin-out configurations are available if necessary. Whether custom or not, diagnostic test headers are provided for verification of the system signal pathways.

Only three experiments are conducted in one oven, thereby providing for the loading and unloading of devices without impacting other experiments being performed in the rest of the ovens.



Reedholm Oven Loadbox

Optimizing Temperature Uniformity

The commercial high temperature environmental chambers/ovens supplied with the RI-52 provide the best available temperature uniformity and stability. As with other Reedholm reliability systems, the chambers are not modified in any way that would compromise performance or reliability. For instance, Reedholm avoids the common practice of extending circuit boards through slots in the door since such an approach seriously degrades temperature uniformity and increases the thermal load on the chamber.

Integrated Oven Door Assembly

All of the hardware for three experiments is mounted to the oven door, yet the entire assembly is lightweight for easy removal and replacement. Robust cables connect the force, measure, and extrusion signals from the scanner cards inside the RI-52 instrument chassis to a rugged bracket on the oven door. Analog cables—with insulation capable of continuous operation at temperatures above 400°C—route through a small hole in the oven door to ceramic plugs.

The chamber door assembly provides several benefits to the RI-52 user. It protects the six load boards from mechanical damage, permits unrestricted lateral movement of load boards due to thermal expansion or contraction, and serves as a stable platform for insertion and removal of test devices.

Making Oven Uniformity Even Better

Additionally, the assembly acts as a plenum chamber that routes the convection heating/cooling gas directly to the load boards and creates turbulence for maximum temperature uniformity.

Preventing Load Board Heat Flow

While it is easier to build a reliability system with load boards protruding through, or connected to, an oven wall, doing so severely compromises temperature uniformity along the load board. That is because the thermal conductivity of suitable materials for load boards is much higher than the thermal conductivity of convection gas providing heating or cooling of the oven.

The wires used in the RI-52 to provide analog connections to the load boards have much lower thermal conductivity than the equivalent load boards, so thermal equilibrium is reached along the wires within a couple of inches of the oven wall. Several more inches of wire are used to make sure that there is no thermal gradient in the wire when connections are made to the load board. This conservative approach eliminates the possibility of temperature non-uniformity on the load boards due to heat conduction to the test system electronics.

Assuring Measurement Quality

The RI-52 makes use of Reedholm dc parametric test instrumentation to provide the accuracy, repeatability, and sensitivity necessary for detection of small resistance changes. Equally important for assessment of interconnect reliability is the elimination of system level error sources. This is done through auto-zeroing software, by compensating for common mode errors and by recording the actual stress current. These types of solutions are the legacy of Reedholm experience with dc parametric and fast WLR software.

Voltage and Current Measurements

As shown in Figure 1, a single, precision digital multimeter is used to sequentially measure the voltage drop across a string of test structures connected in a series. A resolution of <8µV on the lowest voltage range provides sensitivity of 30ppm, or 0.003%, of the 250mV range.

The high and low inputs of the multimeter are buffered by independent high power JFET input op amps. These present extremely high input resistances of $>10^{11}\Omega$ and offset currents of <10pA over the range of ±100V. These characteristics mean that the multimeter has no deleterious effects on voltage or current measurements. Furthermore, the excellent common mode rejection ratio

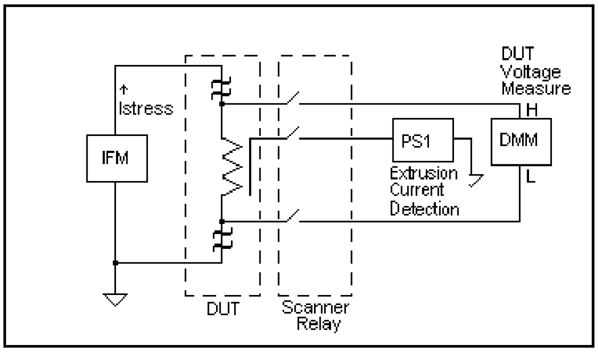


Figure 1 - Single DUT Stress/Measure Schematic

(CMRR) of 106db means that small voltages and currents can be measured independently of the voltage on a particular device in the stack of devices under stress.

The multimeter has a monolithic 16-bit successive approximation A/D converter capable of sampling at >20kHz. During system initialization, a self-linearizing calibration routine automatically executes and produces full 16-bit linearity. Voltage is measured on one of nine voltage ranges spanning 250mV to 100V.

In addition to the digital voltmeter, a programmable power supply is used as a voltage reference for extrusion current detection.

Scanner Modules

Each RI-52 experiment uses a separate scanner module that multiplexes the multimeter among the devices being stressed. From one to 32 devices can be stressed per experiment. One relay per device is used to connect the multimeter to the device sense terminals.

Scanner modules also provide the means for current to bypass failed devices. A zener diode is used in parallel with each device to provide a current path in case of a possible device open circuit between measurement cycles. After a device failure, a relay is used to provide a short circuit across the device on the subsequent measurement cycle and thus remove the stress current. The high quality, dry reed relays used on the scanner modules provide excellent isolation, low thermal emf, and long life. Each is expected to have <200mΩ static resistance well past 10^8 cycles.

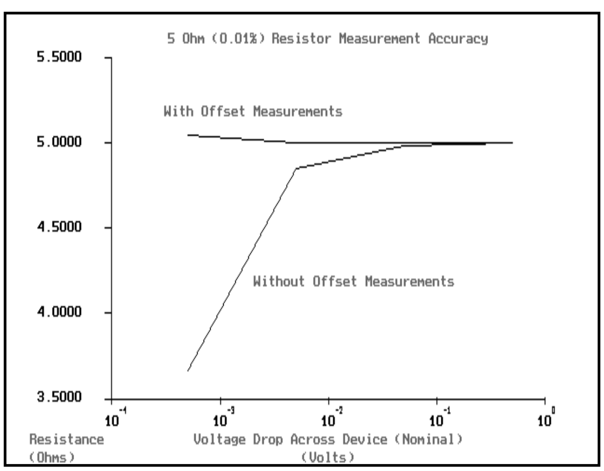


Figure 2 - Accuracy Maximized

Accuracy Enhancement

Signal path resistance is one of the largest contributors to EM measurement errors. Fortunately, these can be effectively eliminated by the use of four terminal measurements. Multimeter input impedance and input currents reduce possible sense voltage drops below detectable levels. Use of a true current source for stressing assures that the voltage drop across each device is solely a function of the device resistance.

Errors are also caused by the thermal electromotive forces (emf's) generated at junctions of dissimilar metals. These can be quite large when connections have to be made in a high temperature chamber. By auto-zeroing during the experiment, the RI-52 eliminates thermal emf's that plague other approaches. Figure 2 shows the accuracy improvement possible using this technique.

AC Noise Reduction

Another major error contribution comes from sources of ac noise, of which power line frequency is the largest component. The analog cabling is shielded to minimize noise pickup, with the low impedance of the shield providing a high bandwidth. A single ground point for the shield ensures that current from ground loops are not included in the measurements.

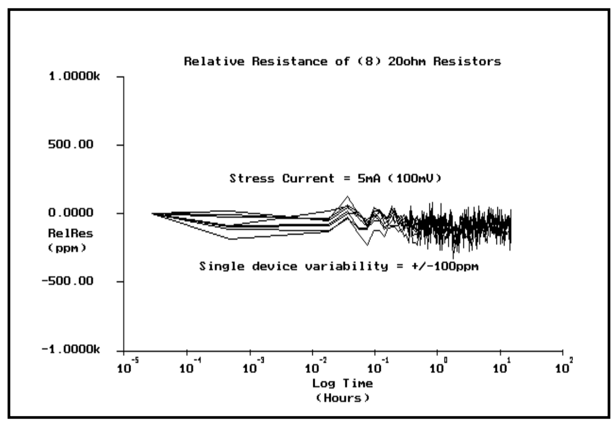


Figure 3 - Measurement Repeatability Data

As good as the shielding is, digital averaging techniques can be employed to further reduce the effects of ac line noise. By averaging hundreds of meter readings over one ac line cycle, the ac component of the noise is nearly eliminated. Of course, precise timing is required to identify how many conversions fit within one line cycle. The improvement gained through the use of digital averaging comes with a modest time penalty of just 17ms for 60Hz or 20ms for 50Hz.

Achieving Electrical Stress Uniformity

Just as important as maximizing measurement accuracy is ensuring that the stress current through each device is equal.

Identical Current in All Devices

The RI-52 uses a single supply per experiment to provide the desired stress current to each of the devices connected in series as illustrated in Figure 4.

Each supply is a programmable current stress module (ISM) that can supply a load current of 100mA at output voltages of up to ±100V with respect to ground. The analog circuitry consists of two precision DACs, an error amplifier, a precision voltage clamp, a voltage controlled current source (VCCS), a power output stage, and precision feedback components. Short circuit protection is provided by heat dissipaters on the output stage that permit indefinite operation at maximum load.

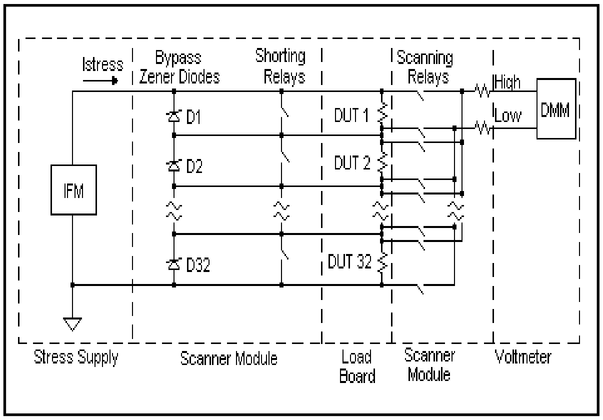


Figure 4 - EM Stressing

Stress Continuity

A concern with series stressing is what happens when one of the devices in an experiment opens. Zener diodes on the scanner modules provide an alternate path for the stress current. Figure 5 shows that stress is interrupted for <1ms when this occurs. Since there is a maximum of 32 devices in an experiment, the total interruption over the life of an experiment is <31ms.

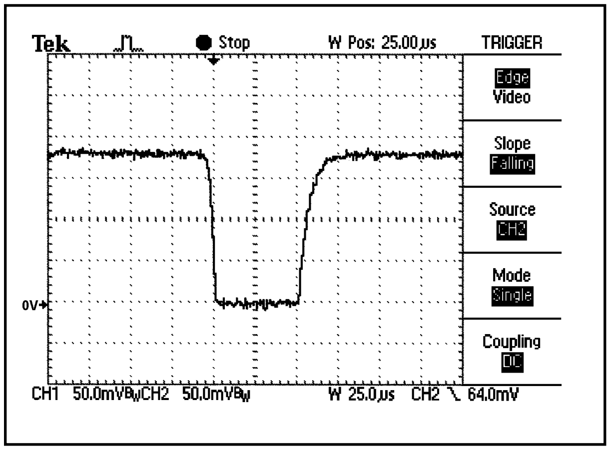


Figure 5 - Voltage When Device Opens

A second potential current stress interruption can occur when the scanner module relay is closed to short out a failed device. During that time, the stress current is reduced for <10ms. Again, since there are a maximum of 32 devices per experiment, the total stress interruption would be <310ms.

EM, Joule Heat, and Stress Migration Testing

A measurement cycle or scan is performed at periodic intervals on each valid device remaining in an experiment. In sequence, the test algorithm:

- Stresses, measures, records results, and shorts out failed samples.
- Optionally scans without storing results.
- Terminates when specified criteria are met.

The only difference between the EM and stress migration testing is that while the EM test uses both temperature and current flow to accelerate metal electromigration, only temperature is used to accelerate stress migration void generation.

Another experiment type available on the RI-52 allows characterization of the time constants associated with Joule heating. Resistance measurements are made with respect to time at specified temperatures and currents.

This test sequence is used during each scan:

1 DUT resistance is measured by connecting the voltmeter to the DUT sense terminals to measure the voltage drop. The relay contacts are closed during the measurement.

2 For EM tests, a check for electromigration induced metal extrusions can also be made during each scan. For this test, a programmable power supply is programmed to a fraction (usually 1%) of the test current at a voltage 0.5V below the voltage measured DUT low sense lead. Current limit detection circuitry on the power supply is used to identify an extrusion.

3 The voltage offset of each set of connections is determined by measuring the voltage drop a second time with no current flowing. Voltage measured without current flow is subtracted from the initial voltage, enhancing the accuracy of the measurement. This step is optional for EM tests, but is automatically executed for stress migration and Joule heat tests.

4 Finally, failed devices are removed from stress by closing the appropriate shorting relays. For EM tests, this step is optionally executed while under stress. Otherwise, relays are closed without current flow, and a current measurement is made to increase accuracy by taking into account common mode effects.

Infant Scans

At the start of an experiment, infant scans are performed so that all devices can be proven to be functional (within specified resistance limits). The first scan is done at ambient temperature. After the scan, any defective material can be replaced, and the scan repeated.

Once the thermal chamber and devices have reached the final stress temperature, the second infant scan is performed for EM and stress migration tests. Again, the user has the option to replace failing devices and retest. At high temperature, this may not be practical unless all devices fail.

Scheduled Scans

At user specified time increments, either logarithmically or linearly placed, a scheduled scan occurs and the test results are stored. After the scan, any failed devices are shorted out using relays on the scanner module. Complete control of device stress is achieved by optionally removing stress for less than 10ms while failed device relays are closed. In EM and stress migration tests, device failure is defined as a specified shift in resistance compared to the resistance measured in the first scheduled scan. In Joule heat tests, devices are removed from stress when successive resistance measurements become stable.

“No Data” Scans

The software provides an option to perform scans on EM and stress migration tests in between the scheduled scans, termed “no data” scans. Results of “no data” scans are stored when either of three possible events occurs:

- A device has failed due to resistance shift compared to the first normal scan.
- A user specified resistance increase from the previous scan is reached.
- A short to an extrusion monitor is detected.

Failed devices are also bypassed after “no data” scans.

Post Scans

In addition to infant and scheduled scans, post scans can be executed on EM and stress migration after an experiment has finished. This allows data to be gathered at different temperatures and compared to the infant data. During a post scan, all devices that did not fail the infant scans are tested.

Applications Software

EMREL is the interactive software tool used to perform oxide stressing and monitoring on the RI-52. It can control up to twelve independent experiments and is used for:

- Setting up and starting experiments.
- Performing scans on active experiments.
- Viewing logs and reports.
- Creating graphical representations of results.

EMAGE, the applications software with graphical analysis capabilities, can be used to display and analyze EMREL's graphical summary reports.

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Error Recovery

EMREL contains contingencies for recovery from a variety of conditions:

Loss of Computer Power
If the computer is turned off, or if the instrumentation is being used for diagnostic testing, scans cannot be performed. Once the Reedholm shell is restarted, scans are performed on all active experiments for which a scan is either due or overdue.

Loss of Tester Power
EMREL continuously monitors the voltage stress status for each active experiment and periodically checks all hardware. If any stress supplies or matrix pins are not set correctly, EMREL suspends the associated experiment, powers down its stresses, and unhooks its matrix pins. A single attempt is made to reset the experiment. If unsuccessful, it is powered down and flagged on screen with an error message.

Loss of the Experiment Scheduler
EMREL uses a file based approach to control active experiments. If either of the files is missing or corrupted, EMREL prompts the user as to whether the software should automatically rebuild the files. Once the files are rebuilt, all experiments are restarted.

Die Tracking

Another EMREL feature allows users to optionally record die information for each device so that test results can be tracked to their origin during analysis. The following information can be stored with the experiment results:

- Lot number
- Wafer number
- Die number
- X & Y location

Maintenance Software

A variety of maintenance tools are delivered with an RI-52. The main system diagnostic checks the standard Reedholm instrumentation modules, and a second diagnostic checks the system elements unique to the RI-52. The diagnostics perform the following:

- Determine system configuration.
- Select modules to be tested.
- Select tests to be run.
- Test for system function and accuracy.
- Create error and/or summary reports.

The maintenance tools offer an automatic method of verifying function and accuracy of system modules and cable harnesses. They also offer self-repeating, error logging tools to detect specific problems.

Other tools allow real-time, analog troubleshooting, and step-by-step calibration of the Reedholm instrumentation. The real time debugger provides a means to connect device pins and instrumentation, to program voltages and currents, and to make measurements.

A digital troubleshooting tool allows bit level control and display of the instrumentation control registers. Additional tools provide system timing information and instrumentation checkout at the individual module level.

Setting up Experiments

Electromigration

Along with a few optional cells at the top of the input grid, shown in Figure 6, the subsections for EM test setup include:

- **General Set-up Parameters**
  The experiment bank number being used is entered along with the number of devices in the experiment. Whether to return to ambient temperature after the experiment has finished and whether to measure the optional offset voltages are also entered.
- **Time Parameters**
  The time parameters include the experiment duration, the initial stress time between scans, and a multiplier used to set a log or linear stress time step. In addition, the thermal soak time is included.
- **Stress Parameter**
  The stress parameters include the stress temperature and the current or current density used to accelerate the failure mechanism. The temperature ramp rate is also included along with a cell to indicate whether stress is removed while failed devices are shorted.

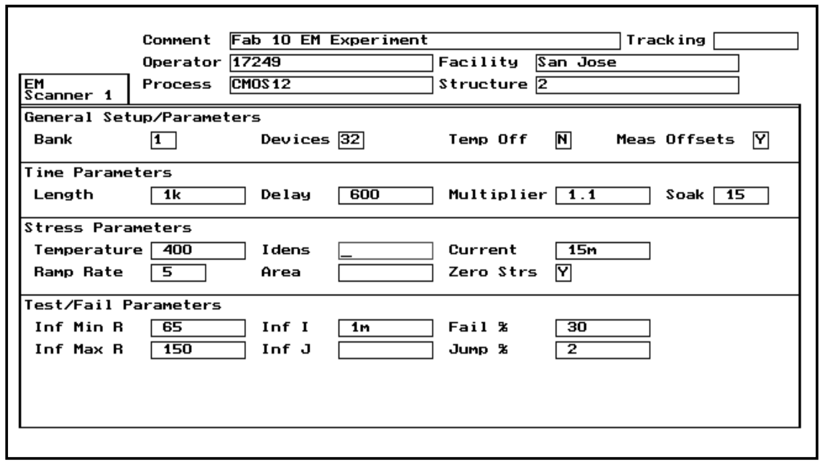


Figure 6 - Electromigration Input Grid

Stress Migration

Along with same optional cells at the top of the input grid, shown in Figure 7, the subsections for stress migration test setup include:

- **General Set-up Parameters**
  The experiment bank number being used is entered along with the number of devices in the experiment. Whether to return to ambient temperature after the experiment is also entered.
- **Time Parameters**
  The time parameters include the experiment duration, the initial stress time between scans, and a multiplier used to set a log or linear stress time step. In addition, the thermal soak time is included.
- **Stress Parameters**
  The stress parameters include the stress temperature and the temperature ramp rate.
- **Test/Fail Parameters**
  In this section, resistance limits used for the infant scans are entered along with the test current or test current density used during all scans. The failing resistance shift for each device under stress is also included, as well as the resistance increase that will cause “no data” scan test results to be stored.

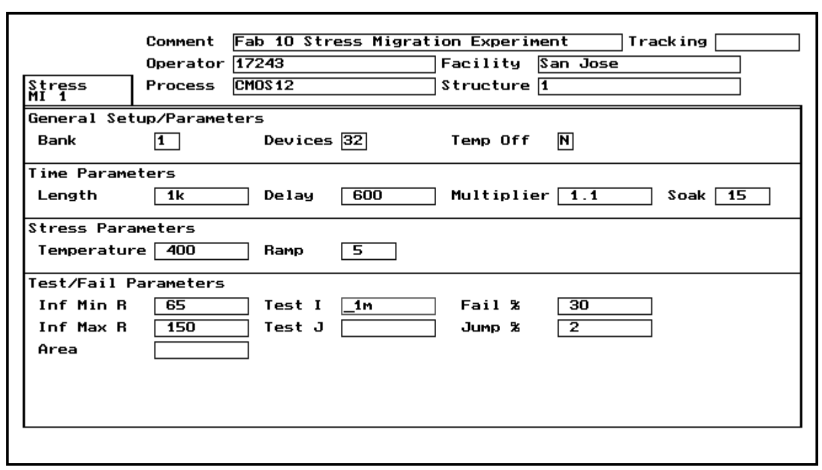


Figure 7 - Stress Migration Input Grid

Joule Heat

Unlike test setup for EM and stress migration tests, the Joule Heat test requires two input grids, which are shown in Figures 8 and 9. Along with a few optional cells at the top of the first input grid, it contains subsections for general setup and test parameters for a single experiment. The second grid contains a section for the temperature ramp parameters, which are used by all experiments in the same oven.

- **General Set-up Parameters**
  The experiment bank number being used is entered along with the number of devices in the experiment.
- **Test Parameters**
  The test parameters include the resistance limits used for the infant scans along with the test current used during the infant scans. The parameters include the start and stop stress current, as well as the current step size, to use at each temperature.

  The percentage shift, which defines the final resistance for each device under stress, is also included in this subsection of the grid, along with the time to wait for DUT cooling before making the next current or temperature step, the delay between resistance measurements, and the maximum time to wait for a failure at step.
- **Ramp Parameters**
  The ramp parameters include the start and stop temperature and the temperature step size. Also included are the temperature ramp rate, the length of time to wait at each temperature before current stress and DUT measurements begin, and whether to return the thermal chamber to ambient temperature at the end of the ramp.

  Lastly, the experiment setup file name(s) are specified for the three possible experiments sharing this Joule heat ramp input grid.

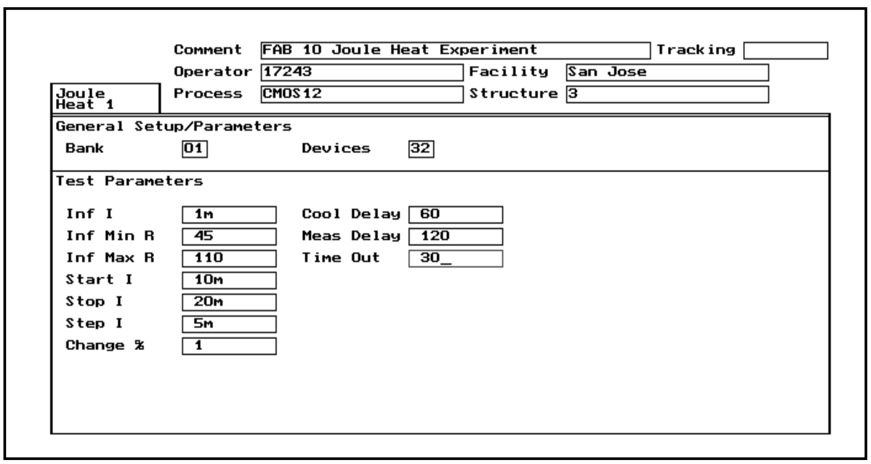


Figure 8 - Joule Heat Test Input Grid

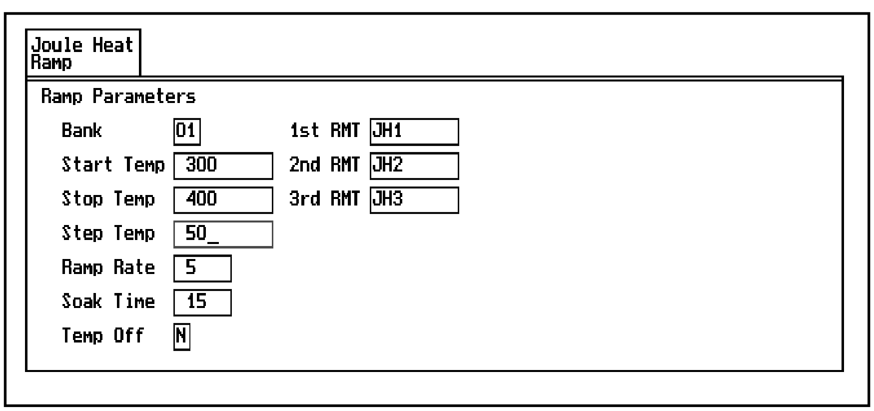


Figure 9 - Joule Heat Ramp Input Grid

Handling Data

Whether experiments are running or complete, information is available in the form of logs, reports, and summaries. Figure 10 exemplifies a graphical output.

For each EM or stress migration experiment, multiple data files can be generated by reprocessing the original data using new failure limits. Each new data file can then be analyzed separately.

- **Logs**
  A sequential log of each experiment contains dates and times of start-up, completion, and time each scan is taken. Other pertinent information is also recorded in the log.
- **Reports**
  Each report consists of an experiment description, the set-up conditions, and the information for each scan, which includes scan number, scan type (infant, scheduled, and post), elapsed time, number of devices failed, percentage of devices failed, temperature, measured voltage, and stress current. Reports can either be displayed on the monitor or sent to the printer.

  Reports can also be sent to disk for later retrieval and can include data from either individual devices or all devices in an experiment. Another option allows viewing results of only the first and last scheduled scans and the post scans.
- **Summaries**
  A summary can be generated in two different ASCII file formats: one in report format for printing and one in PRN format for graphing via EMAGE. The summaries available include: lognormal, cumulative failure, test result over time, and change in result from initial value over time.

  For Joule heat tests, summaries are generated in PRN format and include plots of resistance over time at each current and temperature and final resistance as a function of current at each temperature.

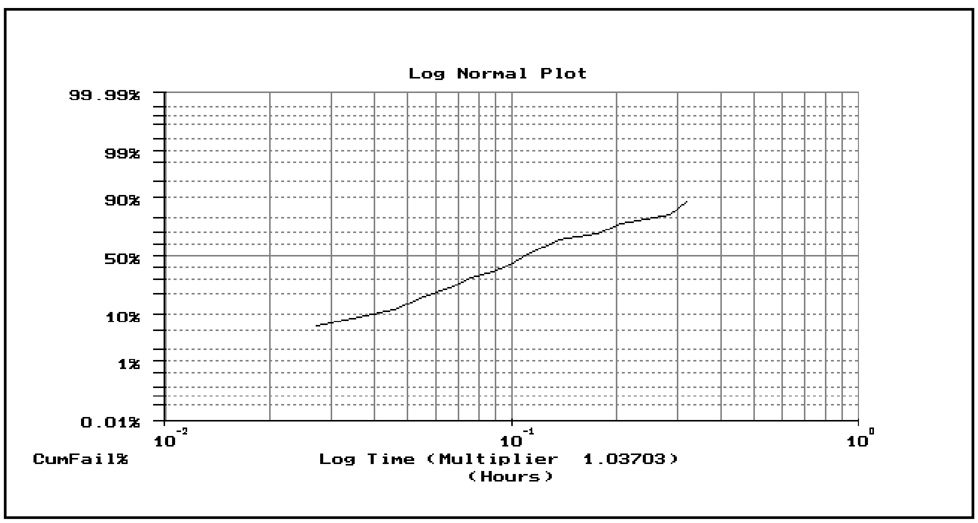
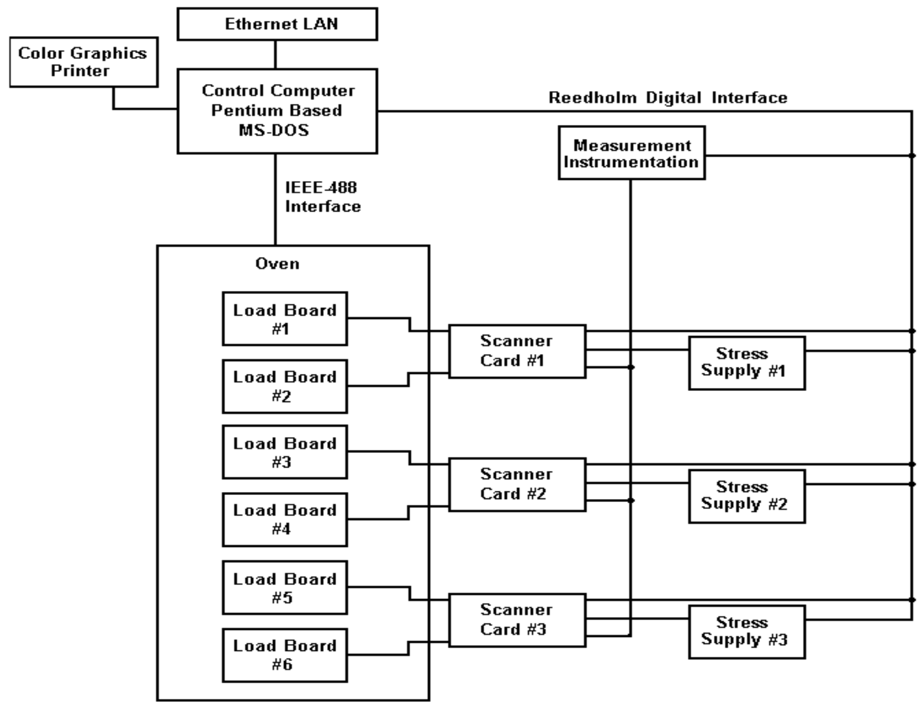


Figure 10 - EMAGE Cumulative Fail Plot

RI-52 System Block Diagram



Base Configuration:
- (3) 32 Device Experiments
- (6) Load Boards
- (1) Thermal Chamber

(96) Total DUT

Maximum Configuration:
- (36) 32 Device Experiments
- (72) Load Boards
- (12) Thermal Chambers

(1152) Total DUT

Base System Configuration

Instrument Enclosure
Floor Standing Dimensions:
L24" x W36" x H62"
L610mm x W914mm x H1575mm
Switching Instrument Supplies
(2) Backplane Assemblies

Tester Computer and Printer
Check with factory for present models.

Thermal Chamber
Check with factory for present model.

Stress Instrumentation
(3) ISM, Current Stress Modules

Test Instrumentation
(1) DMM, 16-Bit Digital Multimeter
(1) VFIF, Voltage/Current Forcing Module
(1) CPM, Crosspoint Matrix Module

Interconnection
(3) Scanner Modules
(1) Node Extender Module
(2) Node Terminator Modules
(6) 6' DUT Oven Analog Cables
(3) 6' Extrusion Oven Analog Cables
(3) 32" High Temperature Analog Cables

Load Boards
(6) Device Load Boards (16 DUT each)

Specifications

Use Conditions

Temperature: 18°C - 28°C
Humidity: 10% - 60% R.H. Non-Condensing
Nominal Power:
System 120V, 60Hz
Thermal Chamber 240V, 60Hz

Instrument Enclosure

For a standard configuration, the RI-52 enclosure is a seven foot, mobile rack with separate card files for scanner modules and measurement instrumentation. The test computer and printer are placed on a table adjacent to the instrumentation chassis.

Inside the test system, static power units provide dc voltages to the scanner and the instrument backplanes.

Switching System

A critical element of a dc reliability system is the switching sub-system. Reedholm has taken special care to develop low noise, high performance scanner modules. In addition, hazard detection software prevents “hot” switching of relays and thereby maximizes the operational life of the relays.

Maximum Stand-off Voltage ±600V
Maximum Carrying Current ±2A
Experiment Isolation Resistance $10^{11}\Omega$
Measurement Leakage Resistance
$10^{11}\Omega$/Total Number of Experiments in Group
Switching Speed (Including Software Delay) 1ms

Current Stress Module (ISM)

Mode	Range	Source Error Offset	Source Error % of Value	Resolution
Current	10mA	5µA	0.05	2.5µA
	100mA	50µA	0.05	25µA
Voltage	100V	100mV	0.05	50mV

Digital Multimeter (DMM) Module

Mode	Range	Measure Error Offset	Measure Error % of Value	Resolution
Voltage	0.25V	250µV (50µV)	0.03	7.8125µV
	0.5V	250µV (50µV)	0.03	15.625µV
	1V	300µV (75µV)	0.03	31.25µV
	2.5V	500µV (100µV)	0.03	78.125µV
	5V	1mV (200µV)	0.03	156.25µV
	10V	2mV (400µV)	0.03	312.5µV
	25V	5mV (1mV)	0.03	781.25µV
	50V	10mV (2mV)	0.03	1.5625mV
	100V	20mV (4mV)	0.03	3.125mV
Current	100nA	100pA*	0.20	3.125pA.
	1µA	300pA*	0.15	31.25pA
	10µA	2nA*	0.05	312.5nA
	100µA	20nA	0.05	3.125nA
	1mA	200nA	0.05	31.25nA
	10mA	2µA	0.05	312.5nA
	100mA	20µA	0.05	3.125µA
	1A	200µA	0.10	31.25µA

Voltage/Current Forcing (VFIF) Module

Mode	Range	Source Error Offset	Source Error % of Value	Resolution
Voltage	2.5V	500µV(100µV)	0.05	78.125µV
	5V	1mV (200µV)	0.05	156.25µV
	10V	2mV (400µV)	0.05	312.5µV
	25V	5mV (1mV)	0.05	781.25µV
	50V	10mV (2mV)	0.05	1.5625mV
	100V	20mV (4mV)V	0.05	3.125mV
Current	100nA	200pA*	0.20	3.125pA
	1µA	700pA*	0.15	31.25pA
	10µA	2nA (700pA)	0.05	312.5pA
	100µA	20nA (6nA)	0.05	3.125nA
	1mA	200nA (60nA)	0.05	31.25nA
	10mA	2µA (600nA)	0.05	312.5nA
	100mA	20µA (6µA)	0.05	3.125µA
	1A	200µA (60µA)	0.10	31.25µA

Notes:
1. ISM Voltage compliance maximum 100V.
2. DMM and VFIF current accuracy on two lowest ranges is measured with line cycle integration.
3. DMM Range Error in parenthesis ( ) applies for eight-hour period after auto-zero and for ± 1°C.
*4. Accuracy is determined with digital averaging approximating line cycle integration.

Support

Warranty

Each system comes with a twelve-month factory warranty covering defective parts and workmanship. Extended warranty and service contracts can be negotiated.

User Training

Training on the use of the system and software can occur at the factory or on site during installation. The training includes the starting of simple experiments.

Documentation

Complete documentation is delivered with the test system. This includes comprehensive user’s manuals describing hardware and software along with schematics of all instrumentation, load boards, and cabling.

Technical Support

Technical phone, fax, and e-mail support is available from the U.S. Monday through Friday, excluding holidays:

- Phone: (512) 869-1935
- FAX: (512) 869-0992
- E-mail: support@reedholm.com.