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## Chapter 1

### Company Information

Founded in 1982, Reedholm Instruments, Co., specializes in making automatic test systems. Reedholm's technical knowledge, flexibility, and commitment to forward compatibility have contributed to many advancements in the area of dc test for the semiconductor industry and have led to a world-wide customer base.

### Instrumentation and Fixturing

Instrumentation of Reedholm systems that connects to device test fixtures, such as probe cards and load boards, uses a cross point switching matrix. Even more significant than instrumentation specifications, test fixtures are an integral part of dc semiconductor test systems. In fact, test fixtures represent the limiting factors in accuracy and sensitivity of automatic test systems. To construct trustworthy data gathered with Reedholm tools, analog cabling, probe cards, and load boards are developed and/or characterized specifically for use with these test systems.

### Test System Solutions

With an installed base of over 400 test systems, the scope of Reedholm test services and solutions does not stop with test systems. In fact, test structure design, analysis, and characterization are all aspects of these testing products. Moreover, Reedholm's entire product line is aimed at various aspects of test structures in one of five categories:

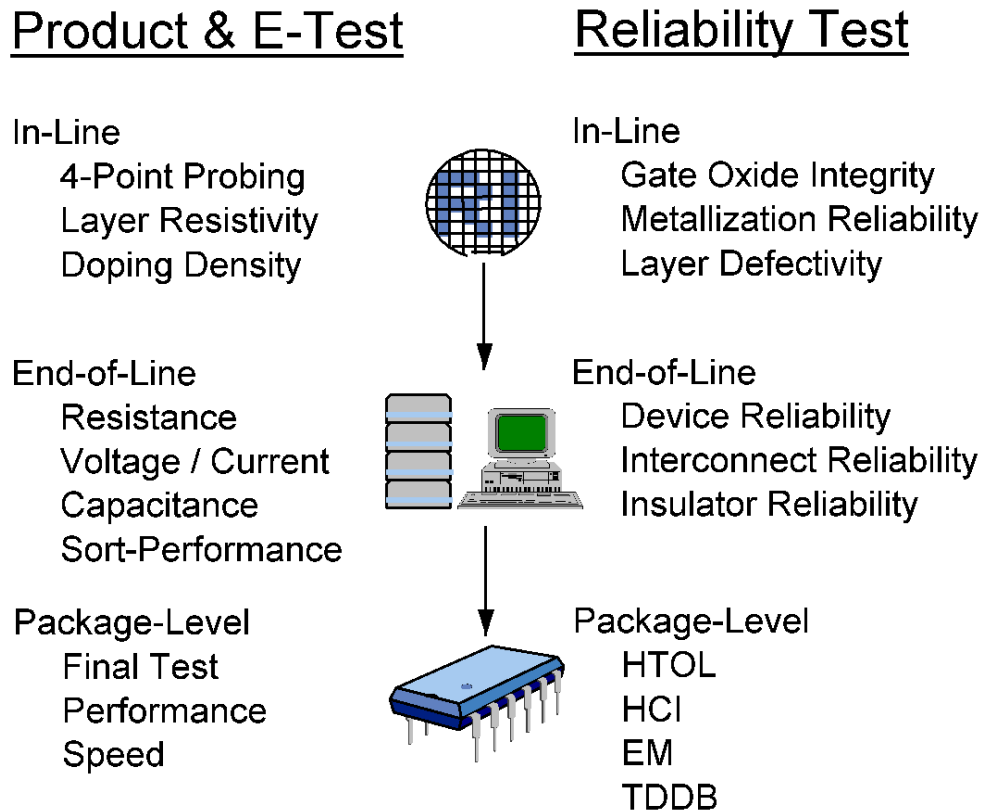
- DC Parametric Systems
- Fast Wafer Level Reliability (WLR) Systems
- Customized Fast WLR Structures
- Packaged Level Reliability (PLR) Systems
- Test Systems for CHARM<sup>®</sup> Wafers

While for years parametric testers have been able to perform tests adequately, the materials measured in testing can limit sensitivity. Often, these limitations are interpreted as being caused by equipment becoming outmoded. However, new software may be all that is needed to accommodate these limitations. Reedholm concentrates on applications software and on continual improvement of existing test structures. As a result, new instruments are developed only when they are required for new applications. In addition, to avoid planned obsolescence of its systems, Reedholm provides upwards compatibility with new instruments so that test plans written in years past integrate and are adaptable with the latest product offerings.

## Chapter 2

### Quality Assurance Elements

Reliability, product, and parametric tests are performed at certain intervals during the manufacturing process. For example, some tests are done before wafers are fully processed, some after full processing, and some after devices are packaged. As Figure 1 shows, product and E-test measurements are made to assure quality and functionality. Like packaged reliability tests, fast WLR tests verify the sustained functionality of the product or process over time



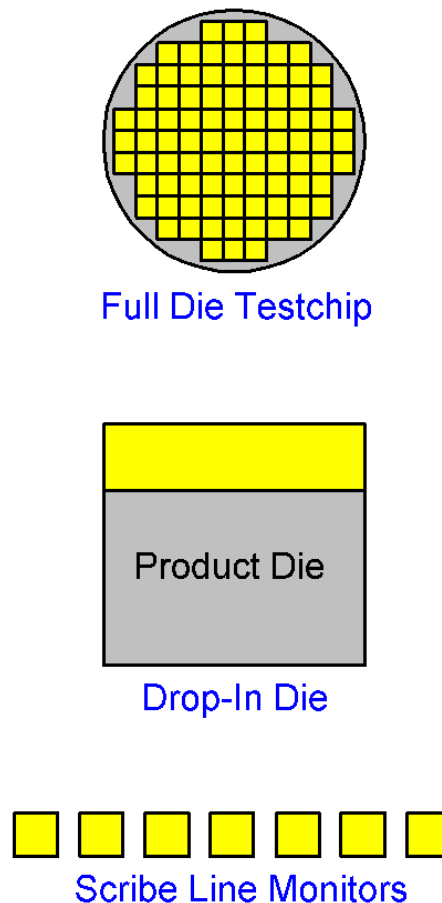
*Figure 1 — Methods of Quality Assurance*

However, WLR allows for detection of specific failure mechanisms—like gate oxide wear-out, metal migration, or excessive hot carrier injection—measured throughout wafer fabrication on discrete process layers. The advantage of fast WLR is that material can be tested quickly after a given process step. As a result, WLR enables lot screening and process monitoring measurements to take place quite early in the manufacture of the wafer. Through this timely evaluation of device, interconnect, and insulator stability, fast WLR testing serves both as a process improvement tool and as a maverick lot identifier.

## Chapter 3

### Process Improvement Sequence

Over time, test programs may be developed and refined as knowledge is gained on the effectiveness of test structures. This process leads to the use of progressively fewer electrical tests (ET) and WLR structures, lowering test times and cost of test.



*Figure 2 — Test Area Declines as Technology Matures*

#### Development

As with any new test structure, all WLR test structures must be characterized for their sensitivity to problems with the targeted process. Ascertaining this sensitivity is typically done using a full-die test chip to evaluate all structures under varied process conditions. WLR structure characterization is best performed during the development phase of a process when test chips are available and many splits can be evaluated.

Structures can also be used to sort among many process options to determine the optimal subset of line widths, of thicknesses, or of alloys to use for a particular process step. This sorting minimizes the number of design iterations during the process development cycle.

**Production Ramp/Maturity**

Information collected from the development stage is used to select structures to be placed in drop-in die or scribe lanes. As information is progressively gathered from many lots, WLR testing of these structures is used to establish a signature, to verify process control limits, and to monitor the process. When a process reliability problem is detected, the identifying structures can be used to highlight suspected process steps and to perform evaluations to help resolve the problem.



# Chapter 4

## Process Reliability Factors

Every reliability issue involves different problems at specific processing steps; therefore, each mechanism needs to be assessed individually. WLR testing allows a single mechanism to be stressed and monitored in order to determine the mechanism’s stability. Through this approach, WLR provides the fab line with rapid, direct feedback concerning process reliability degradation and maverick lot detection. The following diagram helps to illustrate the complex possibilities of process induced reliability failures. The major branches shown in Figure 3 indicate different process components. These lead to failure mechanisms of key interest.

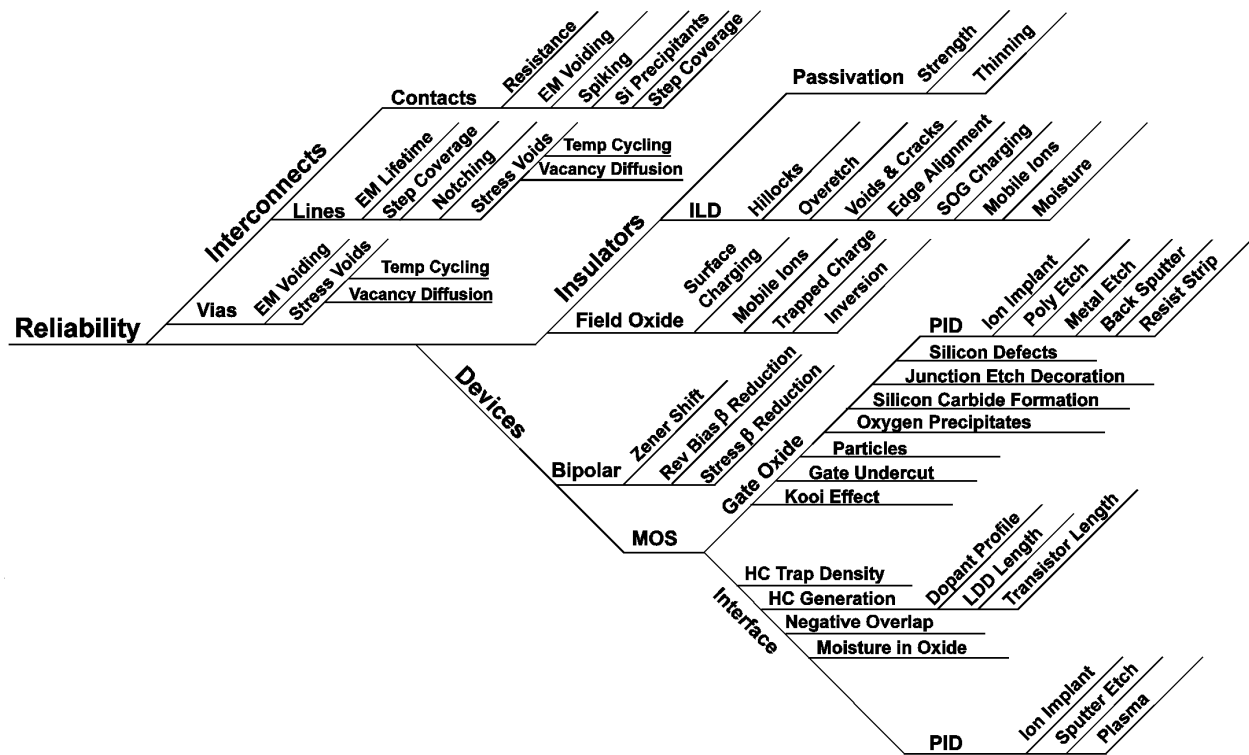


Figure 3 — Process Reliability Factors

## Chapter 5

### Reliability Improvement with Fast WLR

In order to establish a successful WLR program, a detailed analysis of test needs must be performed. Also, continual monitoring of all aspects of the program is required to minimize necessary resources and to produce useful data.

#### WLR Structure Engineering

An effective WLR program has its basis in failure mechanism physics rather than in simplistic design-as-you-go methods. Some commercial approaches propose drop-in type solutions, which assume that successful WLR implementation on one process implies functionality of the same WLR design on all process geometries and features. However, beneficial implementation calls for treatment of WLR as a program that requires further refinement as production is ramped up.

One important element that assists in this refinement is the use of a reference structure, whenever possible, to augment test results. Reference structures need to be carefully designed so that they are insensitive to process reliability effects. Following this approach allows results from reliability monitor structures to be normalized against a reference to reduce the effects of normal process variation. In turn, the sensitivity of the test structures to detect changes in the process reliability increases.

To create a sound WLR program, one needs to follow several steps. First, process reliability concerns are identified and understood through the use of selected failure physics models. Next, test structures that accelerate failures are designed to make them failure mechanism specific. Such designs provide unambiguous electrical test results that correlate directly to the mechanism being evaluated. Designs that include multiple mechanisms within one structure require lengthy physical analysis before the suspected failure mechanism and process step can be identified. This lessens the value provided from WLR monitoring as a rapid process feedback tool. To ensure that a sound WLR program is attained, the response to stressing each structure needs to be evaluated in three ways:

- To verify that the structure is capable of achieving the desired stress conditions.
- To ascertain if meaningful shifts or failures occur.
- To determine if the results are stable enough for process monitoring.

To be successful, this approach requires much information about the structure and the software design. As data becomes available, this information will allow for monitoring and for improving the various structures. However, until enough data accumulates to provide for statistical evaluation, the effectiveness of WLR is inconclusive.

#### Process Development and Monitoring

After the selection of test structures, the WLR program must undergo further refinement as production ramps up. A consideration of real production problems allows for the careful selection and prioritization of test structures that will offer the most pertinent information about the processes being monitored. The goal of this assessment is to turn these observations into actionable data that will assist in the optimization of the WLR structures for production use.

## Chapter 6

### WLR Successes

Two published success stories, those of National Semiconductor and of ST Microelectronics, assist in exemplifying the value of well-engineered WLR programs.

#### National Semiconductor

Performing a review of fab-line problems, this company calculated the costs of issues that were actually averted by using WLR testing. The review consisted of a comparison of potential costs WLR testing prevented and of the total expense that was actually incurred. As Figure 4 conveys, National Semiconductor experienced ample savings using WLR.

Year	WLR Tests Used	Scrap Costs	
		Actual	Potential
1	HV ILD, Qbd, Bubble Test	\$ 60K	\$ 5.05M
2	SWEAT, HV ILD, Qbd, Bubble Test	100K	8.35M
3	Via Voiding, EM	0K	2.00M
4	CHARM, SOG Vt, Mobile Ion	30K	6.20M
5	Mobile Ion, Junction Integrity, Via Voiding	25K	5.60M
<b>Total Incurred/Potential Cost:</b>		<b>\$215K</b>	<b>\$27.20M</b>

*Figure 4 — National Semiconductor's Testing Costs Review*

## ST Microelectronics

Performing a similar study to gauge the value of their use of WLR, ST Microelectronics reviewed processing problems as far back as five years prior to the implementation of their WLR program. Costs were assigned in terms of arbitrary units to represent expenses incurred in scrap, screening, customer interactions, and other steps of production. Data gleaned from this exercise conveyed that on average, a similar number of crises occurred after WLR as occurred before WLR. However, problems were identified at the earliest during the burn-in phase. With a WLR program, all problems were discovered in-line. This early detection eliminated unnecessary costs associated with processing irregularities. Figure 5 summarizes the considerable savings provided through this approach.

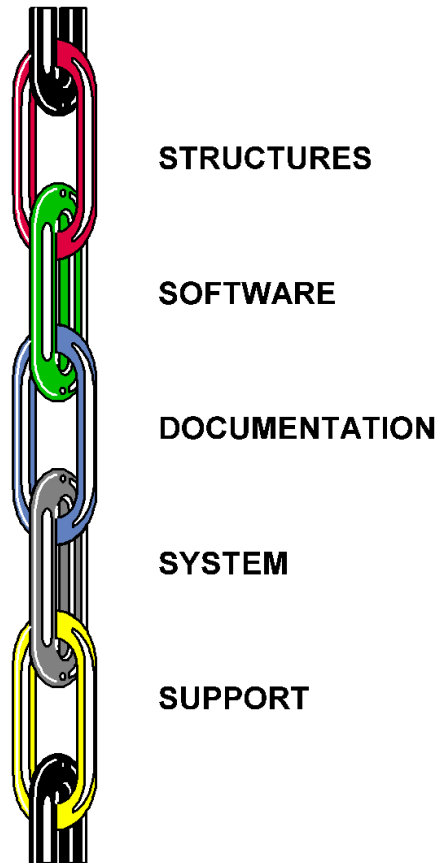
Year	Crisis	Problem ID Location	Cust. Returns	Cust. Visits	Scrap	Special Screen	Man Hours	Total
-5	Metal Corrosion	Final Test	11	1	105	21	5	143
-4	Ion Contamination	Burn In	11	2	105	53	11	182
-3	Metal Shorts	Field Failure	105	5	105	63	11	289
-2	Metal Corrosion	Final Test	11	1	105	32	11	160
-2	Plasma Charging	Final Test	0	0	11	16	5	32
-2	Metal Cracks	Product Qual	421	11	527	53	21	1,033
-1	Bond Failures	Customer Qual	32	1	11	7	5	56
-1	Via Failures	Customer Qual	0	2	32	21	5	58
0	Contact Failures	Field Failures	0	32	0	12	11	55
<b>Total Before WLR:</b>			<b>591</b>	<b>55</b>	<b>1,001</b>	<b>278</b>	<b>85</b>	<b>2,010</b>
2	Low BVox	In-Line	0	0	0	5	5	10
2	Contact Failures	In-Line	0	0	0	2	2	4
2	Milky Metal	In-Line	0	0	0	5	3	8
<b>Total After WLR:</b>			<b>0</b>	<b>0</b>	<b>0</b>	<b>12</b>	<b>10</b>	<b>22</b>

*Figure 5 — ST Microelectronics' Savings Generated through a WLR Program*

## Chapter 7

### Interlinking Elements

A fast WLR program consists of more than a test system, software, and structures. As Figure 6 illustrates, the success of such a plan relies on a variety of elements working in unison.



*Figure 6 — Elements of a WLR Program*

Each link in this chain contributes to the value of the entire reliability program. For example, structure and software design documentation provides necessary background information that enables customers to decide which structures best suit their requirements and to judge whether data retrieved offers actionable information. Realizing the important interconnection between various parts, Reedholm aims to provide customers with tools through which they may optimize their WLR programs. Included in this approach is the option to expand testing capabilities over time. Also, in using an external supplier's support, like that offered by Reedholm, customers enjoy the benefit of the supplier's ample knowledge from experiences with many WLR programs.

## Chapter 8

### FSA 0.35 $\mu$ m Project

The Fabless Semiconductor Association (FSA) consists of over 200 members who generate annual sales beyond twelve billion dollars. The FSA supports projects and activities that lead to the mutual benefit of fabless and foundry members. One of these activities involves standardizing the use of WLR within the foundry community for process monitoring and maverick lot detection.

#### Project Overview

Highly interested in determining the value of WLR as a wafer level testing method, Reedholm has remained extremely involved with the FSA. Through this interaction, Reedholm, a pre-eminent provider of WLR test structures, was selected as the sole supplier for the “FSA 0.35 $\mu$ m Standard Wafer Level Reliability Test Chip Project.” In 1997, Reedholm was awarded the contract to manage the implementation of this project that is targeting formation of guidelines for the standardized use of WLR throughout the industry. In support of this project, Reedholm performs the following activities:

- Customizes Reedholm developed WLR structures for each foundry.
- Coordinates foundry experiments.
- Tests the WLR structures fabricated by each foundry.
- Furnishes raw data from each foundry that provides approval.

For each participating foundry, Reedholm provides structure layout and complete documentation to clearly communicate the theory behind the operation of each structure. Also, detailed data on stress and test methodology is included to relate test setup, execution, and result information. Customizing structures to match each foundry’s unique design rules, Reedholm develops test plans after wafers are received.

Recognizing the efforts of the FSA to institute WLR, foundries wish to participate in this shared effort to evaluate fast WLR. Also, foundries consider WLR as offering the possibility of a consistent testing means that will simplify their ability to report reliability data to their customers. In addition, after WLR has been implemented in production, each foundry will receive certification that acknowledges compliance with FSA WLR requirements.

#### Project Goals

Reedholm and other participants in the FSA project hope to show that a WLR program can accomplish several goals:

- Reliability testing on every lot.
- Maverick lot identification.
- Quick identification of reliability problems.

As an advocate of WLR and the FSA, Reedholm continues to receive support and encouragement from many foundries, IC companies, and associations, such as JEDEC.

## Chapter 9

### Reedholm WLR Structures

A test structure is an extension of a dc measurement system that is used to measure specific elements in order to evaluate a discrete process step for a specific reliability failure mechanism.

#### Number of Structures

The number of structures Reedholm designs for the WLR programs implemented in each foundry depends on the process complexity. For example, 34 pad arrays are delivered for a single poly, three metal process.

#### Layout Format

Reedholm test structures are delivered in GDSII file format set up in 1 by 12 pad arrays that allow these devices to fit in 100 $\mu$ m scribe lanes or in test element groups. Individual pads measure 75 $\mu$ m by 75 $\mu$ m, and are spaced on 200 $\mu$ m centers.

#### Test Structure and Test Plan Development

Structure behavior varies with different processes. To insure that WLR test results are controllable and are limited to the failure mechanism of interest, Reedholm customizes each foundry's structures per process. Then, Reedholm characterizes key structures and develops the test plans for the WLR structures only after a foundry's wafers are received.

#### Documentation per Structure

To clarify the intention of each structure, Reedholm supplies documentation on each one. This documentation includes Reedholm customization directions and theories of structure operation so the foundry can implement them on other processes. Additional information provided includes structure design features, formulas for dimension calculations, layouts, and stress and test methodologies.

An understanding of all aspects of each test structure assists in the implementation of a successful WLR program. For this reason, transferring the knowledge behind WLR structure design, test, and results is a focus of Reedholm's WLR offering.

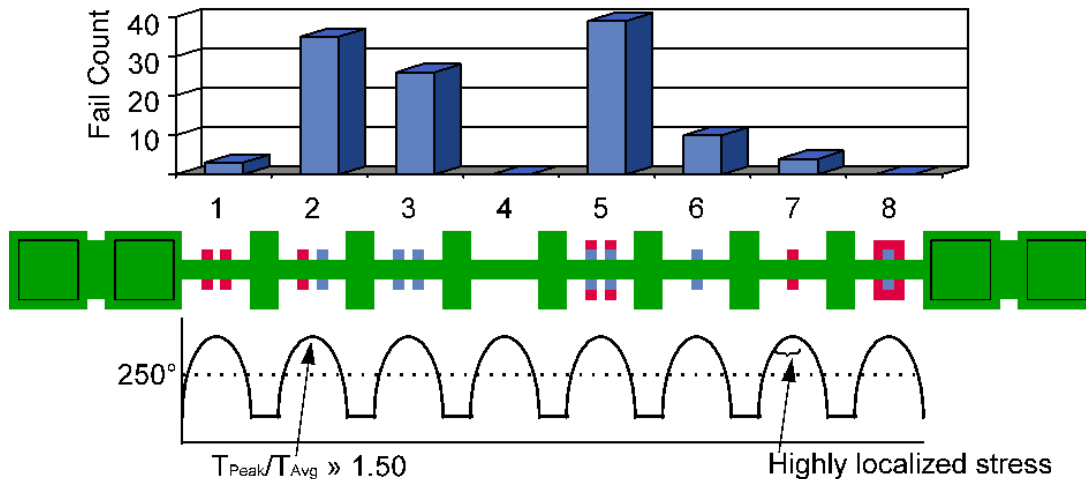
## Chapter 10

### Electromigration (EM)

A standard wafer-level electromigration acceleration test, or SWEAT structure, exemplifies some of the difficulties that might occur as a result of an improper WLR engineering. Several problems are prevalent:

- Unknown failure location.
- Ambiguous test results.
- Peak temperature becomes much greater than the average temperature.
- Multiple failure mechanisms in one structure.

The temperature profile in Figure 7 illustrates how narrow sections can be heated to high temperatures under current stress while the wide sections stay near ambient. Temperature in a short line has a peak near the center that produces much higher acceleration than in the cooler parts. While a problem exists with very high temperatures in narrow SWEAT segments, this occurrence may be considered acceptable since statistical data can be taken so quickly. However, making structures so complicated that failures become ambiguous is not acceptable.



*Figure 7 — Optical Wafer Inspection Chart*

As depicted at the top of Figure 7, the histogram of failure location shows dominance by a few sections, so no conclusion about the failure mechanism can be reached without knowing the relative failure rates. Furthermore, the failure rates of some segments are so low that orders of magnitude degradation in those sections could occur without being detected.



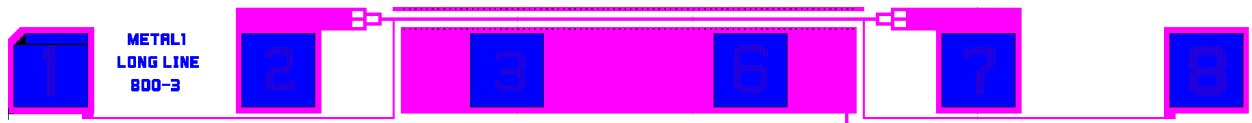
## Chapter 11

### Reedholm Electromigration Structures

Used with either the SWEAT or Isothermal EM test routines, Reedholm's EM structures have a qualitatively different design approach than the method used for combination SWEAT structures.

#### Long Line for Metal Electromigration

Used to provide continuity to the ASTM standard, a long line measuring 800 $\mu$ m provides good thermal stress control ( $T_{PEAK}/T_{AVG} \cong 1.04$ ).

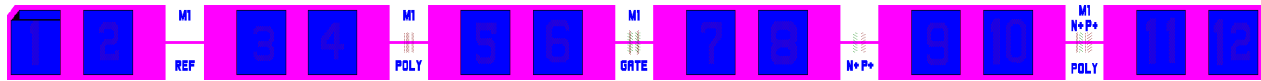


*Figure 8 — Reedholm Metal EM Structure*

With this design, testing lasts only slightly longer than with SWEAT. The temperature remains constant over most of the line.

#### Short Lines for Step Coverage

The use of a short line allows for the evaluation of step coverage by maximizing stress at patterned intervals. Figure 9 depicts a Reedholm short line step coverage structure.



*Figure 9 — Reedholm Step Coverage Structures*

These step coverage structures illustrate use of the good features of SWEAT while isolating failure mechanisms. Representing each type of topography, the design of the short line test in Figure 9 includes probe pads set between step areas that enable individual testing or electrical determination of the failure location after stress. In addition, a reference line with no steps can also be tested to normalize the test results. Through reference elements, feature effects can be isolated from metal quality issues.

## Chapter 12

### Software

A fundamental goal of Reedholm is to provide continual improvement of its products. Following this aim, one important aspect of the Reedholm WLR applications software is that it does not become obsolete. For over twelve years, Reedholm's software developers have worked to design products that maintain forward compatibility of test plans. Test sequences generated from earlier versions of the applications software require little or no conversion to be compatible with the latest software versions. This plan of non-obsolescence has enabled Reedholm to incorporate years of software improvements and application enhancements.

Moreover, Reedholm's software is easy to use. Capable of creating and executing test plans in the form of ASCII files, Reedholm software furnishes graphical user interfaces (GUI) that are all menu driven. Also, this software does not require programming or compiling to execute new test plans. Elements like pin numbers, test conditions, and exit criteria may be entered into fields configured to provide every level of flexibility required for each test type. In addition, users have the ability to extend their library of test choices.

The design of Reedholm software provides the fastest execution possible while it simultaneously offers users the most control over test options. In fact, if new tests not included with the software are desired, low level instrument drivers are available and are documented to allow source-code access to the test system. Thus, this capability allows a test sequence to include standard menu choices and user written tests.

Figure 10 shows the input grid for the WLR isothermal EM test.

#### EMPAC WLR ISOTHERMAL EM INPUT SCREEN

TEST PARAMETERS	
Test Name	M1 800x3 IsoTTF
Create PRN	<input checked="" type="checkbox"/>
PRN Name	M1800X3I
Ext. Supply	<input type="checkbox"/>
PINS	STRESS PARAMETERS
Force High Pin	2
Sense High Pin	1
Force Low Pin	7
Sense Low Pin	8
Temp Adj. Time	45
	Stress Temperature
	400
	Cross Section Area
	1.5
	Resistance Change
	20
	Maximum Length
	600
	Voltage Compliance
	15
	Activation Energy
	-600m
	I Density Exponent
	2
	Test Structure TCR
	3.7n
	TCR Temperature
	21
	Ambient Temperature
	23
	Intermediate 1
	2
	Intermediate 2
	1

Figure 10 — Isothermal EM Test Set-Up Grid

# Chapter 13

## Documentation

Several pieces of information contribute to documentation on the various aspects of test structures. One important part is Reedholm’s design customization guidelines, which employ these elements:

- Design rules.
- Special considerations for particular process features (i.e., poly vs. salicided poly).
- Calculations for design features.
- Layouts and cross sections.

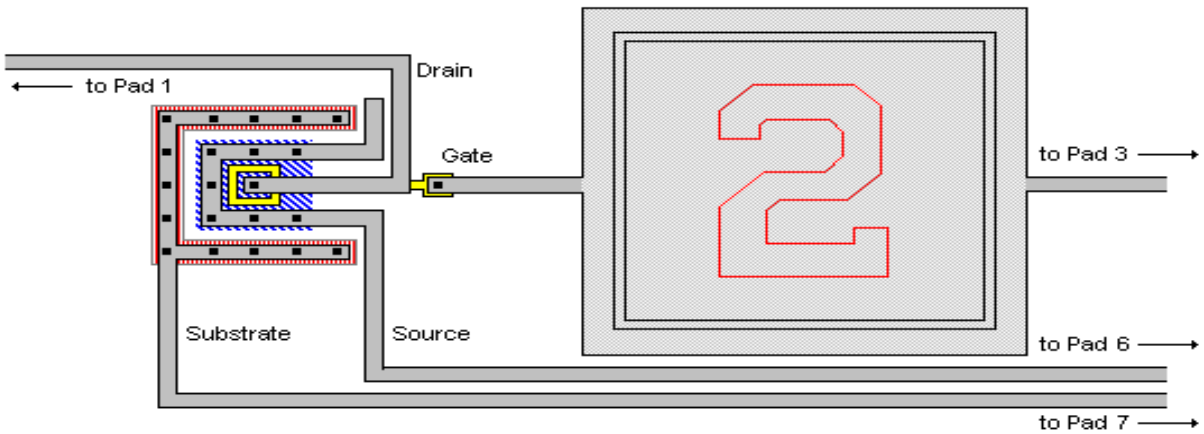


Figure 11 — Typical Layout Detail Drawing

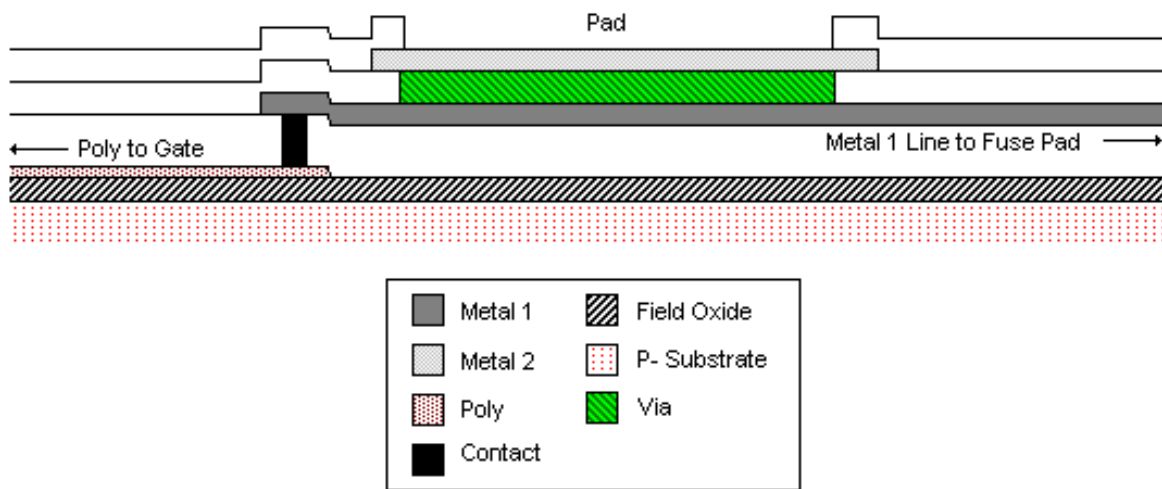
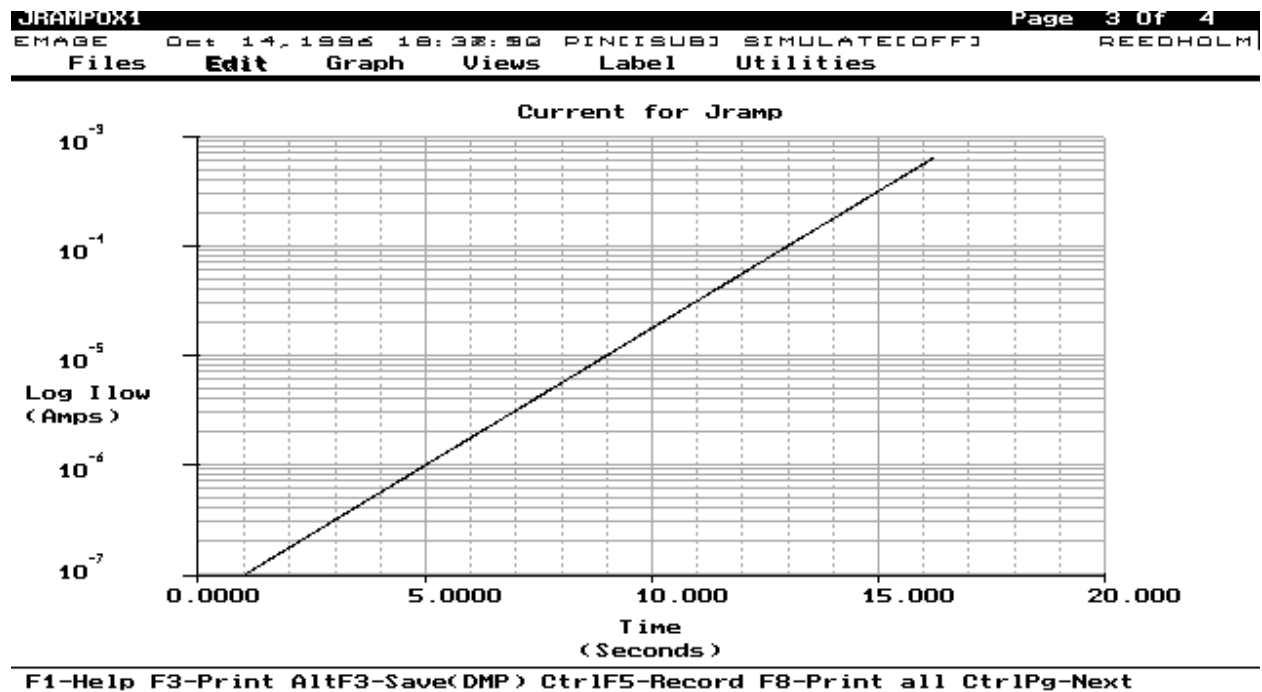


Figure 12 — Typical Cross Section Drawing

In addition, software and structure manuals provide information on all test structure issues so that customers may maintain test designs themselves. Structure design documentation includes these elements:

- Test structure design philosophy.
- Testing concepts.
- Recommended test sequence.
- Schematic representation of the testing.

Also included is information on test setup, execution, and expected results. This thorough documentation provides a complete understanding of Reedholm's WLR test structures and of how to successfully implement them. Figure 13 exemplifies test information that is provided in this documentation



*Figure 13 — Plot of WLR Current Ramp Test*

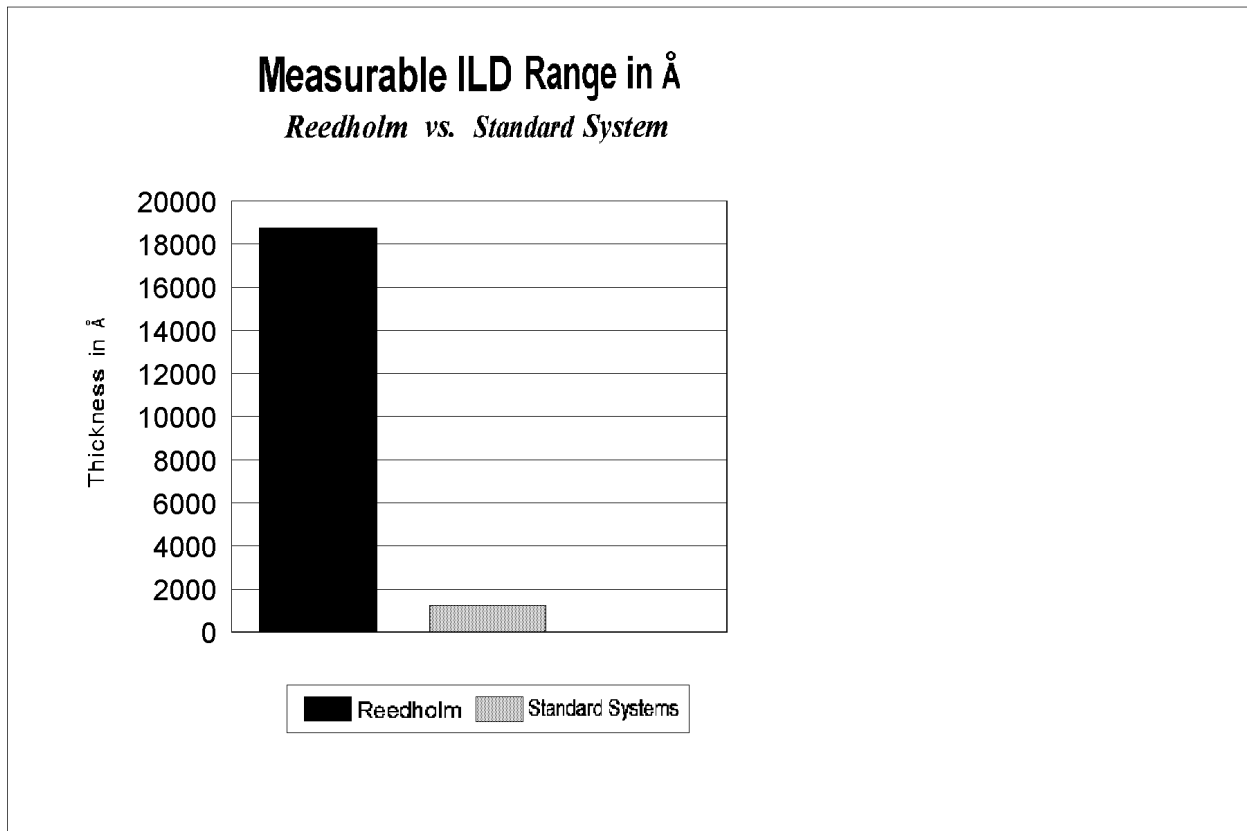
## Chapter 14

### Parametric Test Equipment

In addition to standard dc parametric test performance, Reedholm systems provide the power speed, sensitivity, and accuracy required for true reliability testing at the wafer level.

#### Power

Many WLR tests use heat as an acceleration factor. As a result, high current is needed since doubling the current quadruples power and hence heating. Reedholm systems provide 400mA for on-chip heaters and 550mA at 100V for self-heated structures. An optional 2A supply can also be routed through the switching matrix when higher currents are required

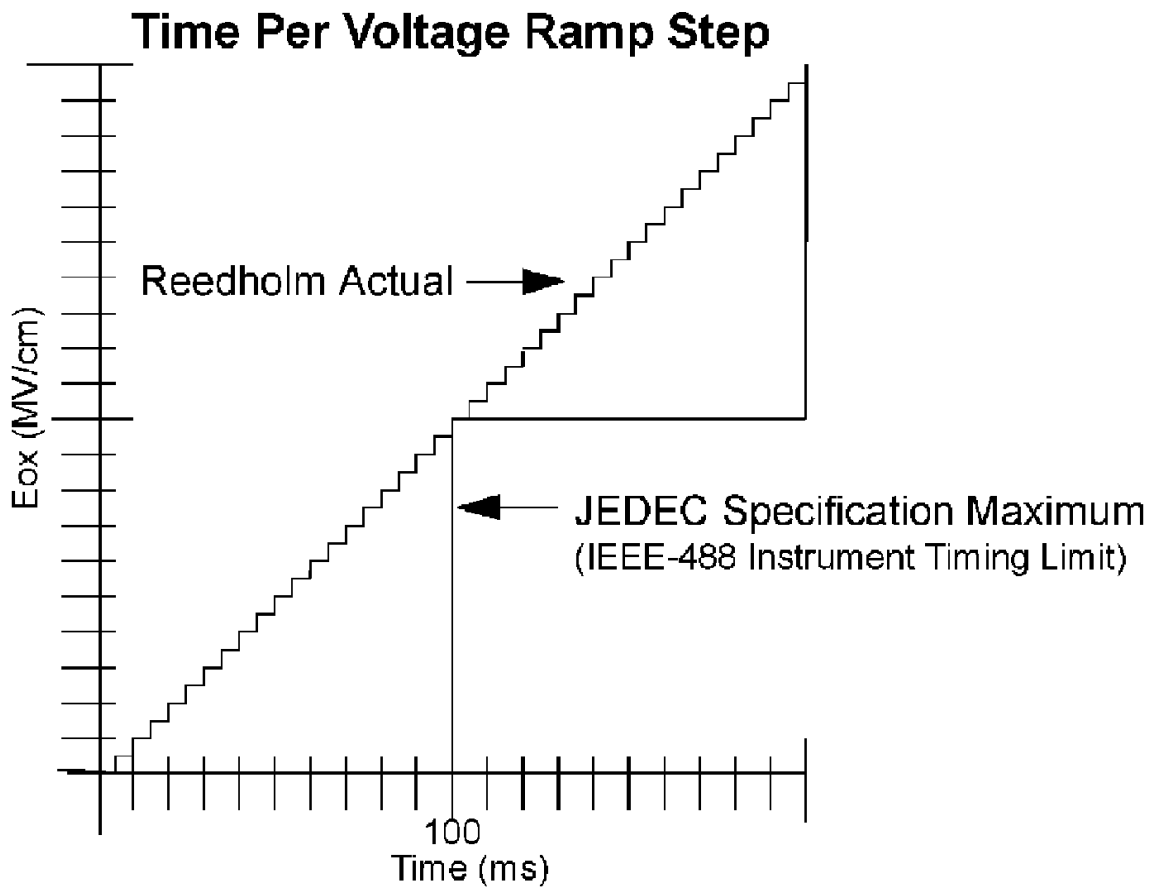


*Figure 14 — Measurable ILD Thickness in Å*

The graph in Figure 14 exemplifies Reedholm's ability to measure thick films like ILD, which in even the most advanced processes may be up to a micron thick. As the graph conveys, standard dc systems lack sufficient power to render accurate measurements for such a thickness. A 1500V option is available to properly evaluate interlayer dielectrics (ILD) with true ILD breakdown measurements.

## Speed and Accuracy

System speed impacts WLR data accuracy and leads to better data quality. For example, Reedholm's fast instrument communication and low timing uncertainty allows for high resolution in detecting breakdown events in oxides.

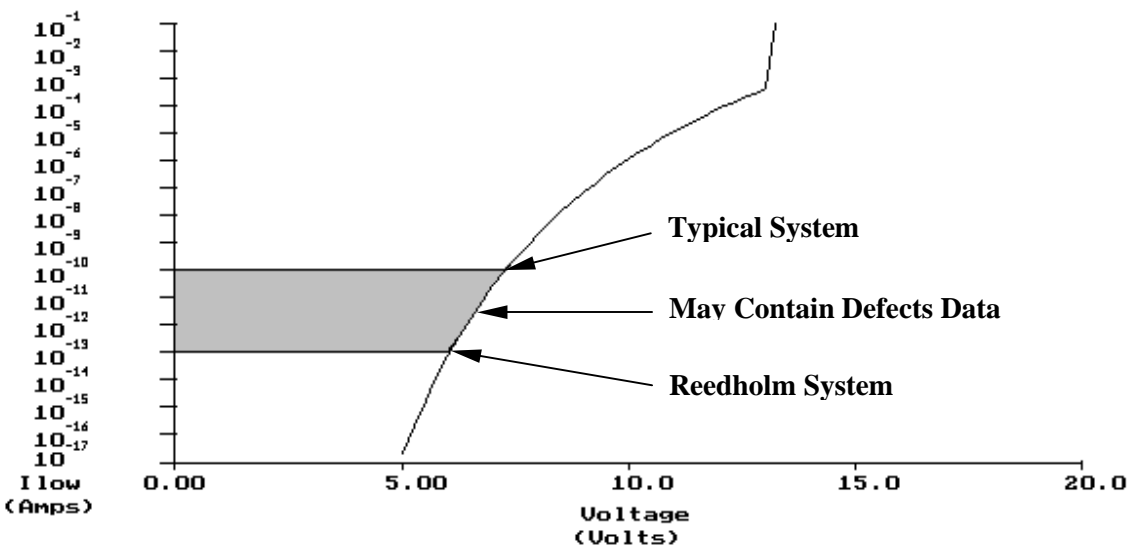


*Figure 15 — Ramped Breakdown Comparison*

Figure 15 shows how the Reedholm approach minimizes timing uncertainty and maximizes communications speed, which is accomplished through the use of a real time operating system for control.

## Sensitivity

Also, Reedholm systems lend themselves to oxide testing because traps that manifest themselves at sub-pA levels are often missed with other parametric testers. A typical tester and probe card combination may provide only 0.1nA sensitivity at the probe tips. Heightened sensitivity increases the information derived from improved measurements. For this reason, Reedholm systems can include special probe cards and analog cabling to obtain orders of magnitude more sensitivity. Measuring with 0.05pA/V or lower resolution, Reedholm systems have the ability to detect problems with thinner oxides and with smaller transistors earlier and more accurately. The gray area on the graph in Figure 16 shows this difference in current sensitivity.



*Figure 16 — Comparison of Reedholm and Other Test Hardware on a Typical Fowler Nordheim Tunneling Plot*

## Chapter 15

### Support

Reedholm views training and support as important opportunities to provide customers with information that will contribute to the success of their WLR programs.

### Training

During training, Reedholm concentrates on guiding customers through the startup and implementation process. A primary concern is for customers to understand the structures they will be using. So Reedholm focuses on details of structure designs, characterization methods, and customization guidelines. In addition, Reedholm also gives direction on test system use and maintenance and instruction on WLR software operation.

### Lifetime Support

Through phone, fax, or email communications, Reedholm's support ensures immediate resolutions for any testing difficulties that may transpire. In the event that a detailed test issue occurs, Reedholm uses software installed at the factory to quickly duplicate the test conditions so that the problem can be identified and a solution communicated.

### Customization

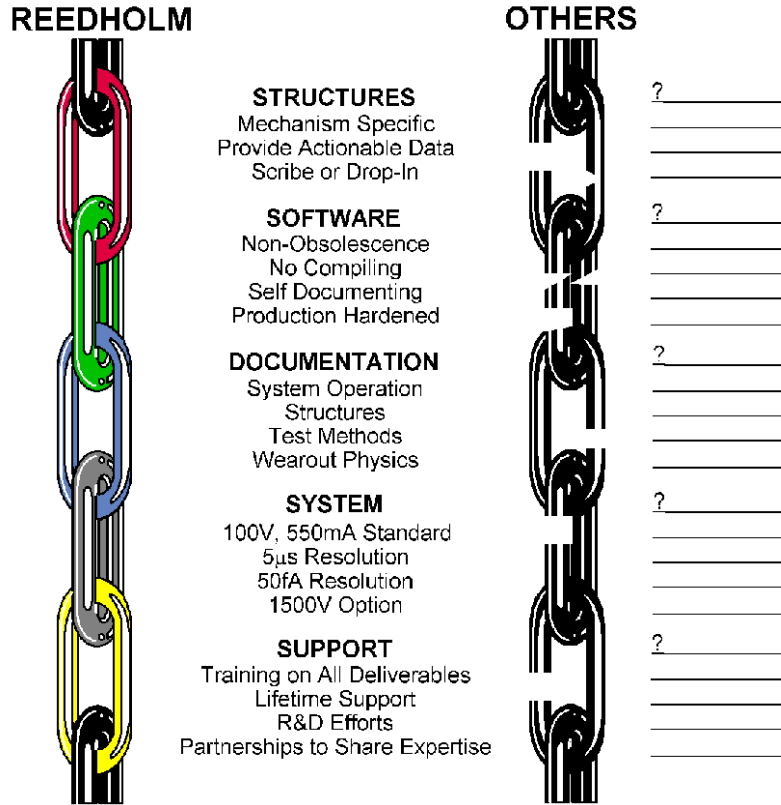
Reedholm can supply and support customized fixturing, hardware, or software. This tailoring includes low leakage probe cards for use on a variety of probers. In addition, Reedholm configures instrumentation and software to provide unique test capabilities.



## Chapter 16

### Why Compromise?

Many elements contribute to the success of a WLR program. Reedholm comprehends the importance of every aspect that goes into sound WLR testing. For a solid WLR program that is cost effective, Reedholm Instruments offers solutions.



*Figure 17 —Reedholm Instruments Offers Solutions*