450 mm Demonstration Test Method (DTM)
Abstract: The 450 Demonstration Test Method (DTM) is a guideline for characterizing the process performance and reliability of semiconductor IC process and metrology equipment at any stage of development maturity. It provides a method for experimentation scaled to the maturity of the tool or process being tested. The 450 DTM assesses the maturity of the tool or process to be tested, it executes the appropriate testing based on that maturity, and it enables test results to be reported in standardized formats. This document incorporates the experience of conducting previous demonstrations during the 300 mm transition as well as early dry runs of specific 450 mm DTM test elements.

Keywords: Demonstration, Equipment, Equipment Testing, Maturity, Reliability, Test Methods

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<th>Definition</th>
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<tr>
<td>DFM</td>
<td>Design for Maintainability, development activities that support serviceable designs.</td>
</tr>
<tr>
<td>DOE</td>
<td>Design of Experiments, statistically based experimentation that reduces risks from traditional trial and error-based experimentation.</td>
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<tr>
<td>DTM</td>
<td>Demonstration Test Method, the high level procedure by which equipment is demonstrated.</td>
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<tr>
<td>ECA</td>
<td>Engineering Capability Assessment, an assessment of the documentation, engineering change control loops, and roadmaps for issues found during the physical portion of the EMA.</td>
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<tr>
<td>ECAG</td>
<td>Equipment Class Application Guideline, an interface document between the EPMs and the DTM.</td>
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<tr>
<td>ECC</td>
<td>Engineering Change Control, revision approval infrastructure necessary to control modifications.</td>
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<tr>
<td>EMA</td>
<td>Equipment Maturity Assessment, an assessment of equipment maturity that is necessary to perform test scaling as well as metric goal scaling.</td>
</tr>
<tr>
<td>EPM</td>
<td>Equipment Performance Metrics, metric goals necessary as expected results in the DTM process.</td>
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<tr>
<td>FIMA</td>
<td>Factory Integration Maturity Assessment, a hardware assessment of factory integration components necessary for 450 mm material handling.</td>
</tr>
<tr>
<td>FINs</td>
<td>Fault Insertion test, physical testing used to confirm assumptions present in the paper-based FMEA.</td>
</tr>
<tr>
<td>FMEA</td>
<td>Failure Modes Effect Analysis, industry standard practice to determine the effects of system/subsystem failure as well as their severity.</td>
</tr>
<tr>
<td>GS</td>
<td>Gauge Study, a calibration of the metrology system.</td>
</tr>
<tr>
<td>HVM</td>
<td>High Volume Manufacturing, the end user’s production or fab environment.</td>
</tr>
<tr>
<td>MDC</td>
<td>Mechanical Dry Cycle, similar to a marathon test, but limited to the cycling of equipment mechanical components. No wafer processing is performed; gases and other consumable are not required.</td>
</tr>
<tr>
<td>MTBF</td>
<td>Mean Time Between Failures, a typical reliability metric used for repairable systems.</td>
</tr>
<tr>
<td>OHT</td>
<td>Overhead Transport, the automated system that delivers wafers to equipment for processing.</td>
</tr>
<tr>
<td>PDC</td>
<td>Passive Data Collection, a stability study of the equipment’s process.</td>
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<tr>
<td>PMP</td>
<td>Performance Metrics Profile, the supplier’s current list of equipment performance consistent with ISMI’s metrics.</td>
</tr>
<tr>
<td>SA</td>
<td>Sensitivity Analysis, process optimization and in some cases a screening design that helps support demonstration projects. Otherwise known as Design of Experiments (DOE).</td>
</tr>
<tr>
<td>SOW</td>
<td>Statement of Work, contractual document that states the work to be performed.</td>
</tr>
<tr>
<td>SRC</td>
<td>Software Revision Control, infrastructure necessary to control software modifications.</td>
</tr>
<tr>
<td>SU</td>
<td>Software Usability, the ability of software to be used by an operator.</td>
</tr>
<tr>
<td>UI</td>
<td>User Interface, the screen or terminal where data is entered or information is accessed.</td>
</tr>
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1 EXECUTIVE SUMMARY

The SEMATECH 450 mm Demonstration Test Method (DTM) is a guideline for characterizing process performance and reliability of semiconductor IC process and metrology equipment, at any phase of development. It provides a method for experimentation scaled to the maturity of the equipment being tested. The 450 DTM is used to understand and quantify the functionality and performance of a tool or process while reducing test variability. It incorporates experience from multiple demonstration tests during the 300 mm transition using the 300 mm DTM.

The time and resources to perform a demonstration test on a tool largely depend upon the maturity of the tool under investigation. For example, a more mature tool would typically be tested more rigorously using goals and statistical confidence levels closer to manufacturing requirements than a tool in an early developmental stage. On the other hand, a less mature tool may have more extensive designed experiments for process characterization and no requirement to establish utilization statistics. Because of resource or time constraints, a tool or process often meets many, but not all, of the goals and objectives of a test. It is very important that both customers and suppliers agree on realistic goals and objectives before the test plan is developed. Success criteria for a demonstration test should be defined before conducting the test.

The 450 DTM is useful for characterizing new or existing tools, conversions, or line re-qualifications. This demonstration methodology applies to any type of manufacturing characterization at any phase of the development cycle for equipment or processes. Within the context of the 450 mm transition, early performance testing and characterization of the tools and processes that accelerate development, selection, and implementation of pilot line and production 450 mm capabilities are highly desired.

The 450 DTM assesses the maturity of the tool or process to be tested, it executes the appropriate testing based on that maturity, and it enables test results to be reported in standardized formats. The methodology is complex; however, it can be envisioned as a simple set of relationships as presented in Figure 1.

Figure 1 Taxonomy of the 450 mm Demonstration Test Method (DTM)
1.1 450 mm Equipment Maturity Assessment
The first step of the DTM is to determine the development maturity of the equipment to be tested. The capability of the tool to meet the requirements for different levels of testing is evaluated. The proper test level is selected to ensure that appropriate testing is done for valid and meaningful results. Program requirements for standards conformance are also assessed.

A review of the supplier’s program to meet standards conformance requirements is a precursor to determining the maturity of a tool for testing. The tool is then physically inspected to determine its current development maturity so that its capability to meet the requirements of a specific level of testing can be determined. The inspection also provides input for the test planning process. The findings are documented in an equipment maturity assessment (EMA) report.

1.2 Demonstration Testing
Demonstration testing is the next step of the 450 DTM; it is composed of Test Planning, Baseline Characterization, and actual Demonstration Testing.

1.2.1 Demonstration Test Planning
The test planning establishes the extent, goals, and statistical confidence levels for the demonstration test. An iterative planning process using all available data is used to ensure that the test will produce statistically valid results for the maturity of the tool and industry requirements.

A test plan is developed to define its scope, requirements, schedule, cost, resources (including wafers needed), timeline, and performance goals. This planning activity includes evaluating any pre-knowledge to modify the test requirements, length, and cost and to improve statistical confidence levels, as well as test scaling to ensure that the appropriate testing is done for the development maturity of the tool or process. The test plan is then reviewed to verify that the test parameters and goals are in line with industry requirements and to seek the ratification and support of all participants.

1.2.2 Baseline Characterization
Baseline characterization establishes the stability and/or functionality of the tool or process. The performance baseline characterization profile evaluates certain minimum functional performance and verifies that the process results are stable. This ensures that statistically valid and representative results can be produced from the demonstration test.

A gauge study is performed first to identify the precision and accuracy of the measurement systems to be used in the demonstration test so that gauge variability can be removed from the process results. Mechanical dry cycling (MDC) evaluates tool functionality without the complexity of wafer processing. Then passive data collection (PDC) establishes that the process results are consistent and repeatable, which provides the basis for statistically valid testing. Finally, the results are compared to the test requirements to determine that the tool is stable and to make any necessary revisions to the test plan. It is possible that the results could indicate that the test should be terminated at this point, before committing the bulk of the test resources in the next step.
1.2.3 Demonstration Testing

Demonstration testing focuses on process parametric and manufacturing environment performance. This step generates select statistics as specified by SEMI E10, Reliability, Availability, and Maintainability.

To characterize the process, designed experiments are conducted to systematically analyze input parameters. This analysis identifies key inputs, then quantifies performance and relationships between them. Next, the tool is operated in an environment that simulates full manufacturing as closely as possible to quantify overall manufacturing performance. Finally, all the testing materials, data, and results are dispositioned to close the test.

1.3 Demonstration Test Outputs

The output stage of the DTM describes the method, format, content, and requirements for the documentation of a demonstration test. SEMATECH produces five reports for a full demonstration test. The final demonstration report is an overall summary of the demonstration test results detailed in the four interim reports. Supplier comments and inputs on the test process, results, or improvement plans and roadmaps will be included in the final report.

The 450 DTM provides a rational structure for performance testing based on experience and statistically valid methods. This document, however, does not and cannot address deployment requirements or strategies in any meaningful way. The 450 DTM does not provide a checklist of items required by a particular test or for a particular tool. The test team and other participants, using the 450 DTM, must develop their own checklist of requirements on a case-by-case basis. Use of the 450 DTM enables valid testing of early development stages and significantly improves the return on investment (ROI) for statistically valid testing.

The results of a demonstration test represent the measured performance of a tool or process at one point in time. Any evaluation or comparisons that are based upon that data must consider the tool maturity as well as the rigor and extent of the testing performed. It would be invalid to make comparisons among the results of tools at different levels of maturity. The 450 DTM does not include any consideration or mechanism to forecast future performance, infer results that were not measured, or imply any behavior or performance in the past or future outside of the test results.

2 INTRODUCTION

2.1 Document Scope

This document provides process engineers, development engineers, and their managers a basic understanding of the requirements of a testing methodology that emphasizes quality, completeness, and decision-making with statistically valid data at any stage of development. The SEMATECH 450 mm Demonstration Test Method (see Figure 2) is intended to be used to characterize complex integrated systems capable of independently performing a process function. While a specific test will depend upon the development maturity of the tool, the document is generic enough to enable broad application of the methodology. It is also updated periodically to reflect any change in the methods.
Figure 2  Flowchart of the DTM
This document is not a process or hardware development procedure. Although it emphasizes definitions and requirements, it cannot replace formal statistical analysis, engineering training, or competent management. Although the document does not address infrastructure, it fundamentally assumes a commitment to project management, decision-making based on data, and the total quality process.

Throughout this document, the methodology is sequentially deployed; however, concurrent testing may be possible or even desirable. SEMATECH encourages evaluators to take full advantage of concurrent testing, acceleration techniques, and any other methods that reduce the resource requirements and cost of testing while maintaining the integrity of the test results.

Each test element (or modular test activity) includes a section on test results, output, and documentation. The intent is that statistically valid, objective results based on data will be reported for each test element. A demonstration test report should be produced that provides a comprehensive summation of the demonstration test results.

The requirements and any examples in this document apply specifically to semiconductor equipment and processes and concentrate on the necessary test and statistical methods for proper interpretation of results in that industry. The fundamentals of the methodology also apply to other manufacturing industries.

3 REFERENCE DOCUMENTS

Companion documents to the DTM are available on the web at http://www.ismi.sematech.org.

- 450 mm Equipment Maturity Assessment (EMA) Handbook, ISMI, Technology Transfer #10065106B-ENG, January 2012
- 450 mm Factory Integration Maturity Assessment, Technology Transfer #10065100B-ENG, June 2010

The following SEMI standards are available at www.semi.org:

- SEMI S2, Safety Guidelines for Semiconductor Manufacturing Equipment
- SEMI S8, Safety Guidelines for Ergonomics Engineering of Semiconductor Manufacturing Equipment
- SEMI M27, Practice for Determining the Precision over Tolerance (P/T) Ration of Test Equipment

4 SEMATECH DEMONSTRATION TEST METHOD

The SEMATECH 450 DTM is a guideline for efficient, effective characterization of equipment process performance as well as hardware and software reliability in integrated systems. It provides a method for experimentation and goal setting appropriate to the maturity of the tool or process being tested. The 450 DTM is used to determine the variability, functionality, and reliability of a particular piece of equipment or process that is valid and representative within the context of its development maturity.
The 450 DTM evolved from the SEMATECH Qualification Plan, Intel Corporation’s burn-in methodology, and the International 300 mm Initiative (I300I) DTM.\(^1\) Before these test methodologies were developed, new and upgraded equipment and processes underwent varying degrees of testing. The testing ranged from rigorous statistical tests and improvement efforts to limited acceptance testing that consisted of production-ready status upon installation. In most cases, the testing was done without considering the developmental maturity level of the tool. This kind of non-rigorous characterization often led to months attempting to stabilize the equipment, resulting in confusion about whether or not goals were met. The 450 DTM demands the practice of sound statistical methods to establish a baseline for a tool or process. The methodology operates in a cost-effective manner, using the minimum resources that can perform statistically valid data collection activities and produce valid, representative, and meaningful results.

While the terms “qualification” and “characterization” are frequently used interchangeably, they are, however, very different. Qualification implies a wider base of activities than a characterization. A qualification includes describing the tool or process performance, comparing the tool or process to a pre-defined set of goals and specifications, and stressing the tool or process in a manufacturing environment. In addition, from a user’s point of view, qualification can also mean readying the equipment to perform in integrated manufacturing.

Characterization refers to the subset of the qualification activities involved in exploring the performance of the tool or process to quantify the behavior intrinsic to the design. Characterization often occurs in a non-manufacturing environment and generally focuses on process performance. Characterization can be performed at any point in the development cycle; it is usually only a small part of a qualification.

The following are some of the target outcomes of a full, rigorous demonstration test:

- Identification of
  - Development maturity of the tool or process
  - The proper DTM test level
  - Key input and output parameters of the process and equipment
  - Major sources of variation for each key output variable
  - Significant interactions between variables
  - Effects of input variations on the distributions of the outputs
  - Opportunities for improving output variables
  - Opportunities for improving equipment reliability
  - Variables to monitor and initial control limits to implement the control system
  - Major modes of failure and their root causes and solutions

- Determination of
  - Repeatability and stability of metrology tools and systems
  - Process capability, stability, and variability of each key output variable
  - Load recommendations, test wafer locations (batch), and sample size requirements for the control system

\(^1\) I300I was a subsidiary of SEMATECH during the 300 mm transition.
Reliability numerics
Cost of ownership estimate

Information on
Maintenance and repair procedures and frequencies
Optimum process operating windows
Consumable parts and supplies

4.1 Test Method Prerequisites

To implement the 450 DTM effectively, certain infrastructure requirements must be met. At a minimum these include the appropriate skill set, customer and industry information sources, test resources, and the identification of and conformance to relevant standards.

4.1.1 Technical Skill Set

The demonstration test requires a broad set of skills in a variety of disciplines. In many cases, test team members will have expertise in several areas, providing a resource pool from which to draw during the test. A typical demonstration test team requires knowledge in the following categories:

- Process technology
- Project management
- Equipment development
- Process development
- Manufacturing operations
- Statistics
- Technology transfer
- Environment, safety, and health
- Equipment reliability

4.1.2 Customer and Industry Requirements

Planning and reviewing the goals of the demonstration test must involve the customers, since customers define whether the test was a success. Industry requirements and customers’ needs must be understood before the test is defined. As a precursor to the demonstration test, reliable sources of customer and industry information must be identified. The customers and supplier must agree on realistic goals and objectives before developing the test plan. What constitutes a test’s success must be defined before execution begins. A common definition of what constitutes a “failure” is critical to setting and meeting the test success criteria. Reaching a mutual understanding of these issues is often facilitated by the development of consensus models of the equipment and its operation and processes as well as the metrology systems and materials interactions involved.

4.1.3 Test Resources

The resources that are available to support and execute the test must be identified and adequate. Key areas to evaluate include personnel allocation, wafers, process materials, equipment support, and the test site facility. The availability of test resources will fundamentally affect the test design and schedule. In extreme cases, a demonstration test may fail due to the lack of adequate staff and physical resources.
The suitability of the test site and the facilities that will support the tool must be ensured. Safety issues that could result from incompatibility should be considered. The tool, test site, and facilities should be evaluated independently and as a unit to identify potential problems. The evaluation should consider industrial hygiene, equipment safety, and environmental impact at a minimum. Note: SEMATECH will not perform an evaluation of a supplier’s development facility. Equipment suppliers are responsible for operating factories according to applicable laws and regulations.

4.1.4 Relevant Standards

Standards that will affect and shape the demonstration test must be identified before the test is defined. The supplier will generally be aware of the applicable standards requirements for the technology of the test tool. All demonstration tests will report conformance to specific 450 mm standards of interest and generic industry standard requirements such as the SEMI S2 safety standard; SEMI S8 ergonomic standard; and SEMI E10 reliability, availability, and maintainability standard.

For SEMATECH demonstration tests, emphasis will also be placed on standards that are materially linked to 450 mm wafer capability. SEMATECH’s member companies have established a set of expectations and supplier guidance for factory integration and configuration and have ratified a common set of required SEMI standards for equipment of this generation. Conformance to these standards is assessed during the EMA and included in the 450 EMA report.

5 450 EQUIPMENT MATURITY ASSESSMENT

The first step of the 450 DTM is to evaluate the maturity of a target test tool to determine its capability to perform at different levels of testing (see Figure 3). Testing can be performed at any stage in the development cycle to produce valuable characterization data so that data-driven management and engineering can be applied to decision-making and further development.

Assessors should reference the 450 Equipment Maturity Assessment (EMA) Handbook (Technology Transfer #10065106A-ENG), which provides extensive checklists to support data collection during the EMA.

Each level of testing has different requirements relating to the type, extent, and rigor of the testing to be performed. Four incremental levels of increasingly rigorous testing collect data on the ongoing development of a tool throughout the development cycle. Each level of testing requires additional capabilities from the tool to meet the testing requirements. A principle of the demonstration test method is to perform only the testing that is valid and useful for the development maturity of the test tool or process.

Equipment characteristics are assessed to compare the functional tool capabilities to those required for the most rigorous testing level. These characteristics (Appendix A) are assessed by physically inspecting the tool to be tested. Some characteristics can be evaluated only by looking into the engineering systems or capabilities that produced them. The development maturity of the tool affects not only the level of testing to be performed, but the test goals and statistical confidence requirements. See Section 6.1 for more information.
SEMATECH has identified specific standards that are directly applicable to the development of and requirements for 450 mm equipment. During the EMA, the plans, progress, and level of current conformance will be investigated for inclusion in the EMA report.

### 5.1 450 EMA Review

At the conclusion of the EMA, a preliminary test level can be suggested by the EMA team; however, a formal EMA review must be held within two weeks of the EMA to provide assessment feedback to SEMATECH and supplier management teams. The purpose of this is to complete the Statement of Work (SOW) such that scaled demonstration test goals are stated in the demonstration contract.

### 5.2 Demonstration Test Levels

As a tool progresses through the development cycle, it achieves capability thresholds where it can meet the requirements of additional levels of testing. The 450 DTM establishes three thresholds that define significantly different testing levels. These levels represent differences in the scope, extent, rigor, and overall quality of the test results compared to the expectations and requirements for a manufacturing application.
5.2.1 Level 1 Test

Level 1 testing is a preliminary investigation of a process, usually used for proof of concept on a new process or for investigating the stability and boundaries of a technical approach before further product development. The results of a passive data collection (PDC) could indicate that a sensitivity analysis through designed experiments is valuable and should be performed.

A Level 1 test includes the following test elements:

- Test Planning
- Gauge Studies
- PDC
- Sensitivity Analysis (if appropriate)

Level 1 testing is generally performed very early in development maturity, such as a “development test bed” or “unit level development.” Candidate tools for Level 1 testing must produce process results, be safe to operate throughout the test, and be documented within a design specification.

The documentation of Level 1 test results should provide a quantitative summary of the process stability of the tool. The following SEMATECH reports are typically generated from it:

- EMA report
- Baseline characterization report
- Demonstration test report

5.2.2 Level 2 Test

Level 2 testing gathers information on the process performance space to provide statistically valid characterization. It is generally used to characterize tools for which the process capability is more advanced than the general tool maturity, but sufficient product integration in material handling and processing have been achieved to eliminate external sources of variation. In some cases, the material handling function may be advanced and similar enough to the final design to allow preliminary manufacturing performance screening by MDC.

A Level 2 test includes the following test elements:

- Test planning
- Gauge studies
- Mechanical dry cycle (if appropriate)
- PDC
- Sensitivity Analysis (DOE)

Level 2 testing is generally performed at an early development maturity as soon as the platform is capable of integrated operation, such as the alpha development stage. Candidate tools for Level 2 testing must meet the appropriate EMA characteristic requirements, must be integrated platforms with all material handling and process functions as defined by the design specification, and use an automated recipe to produce process results that are reproducible (stable). Remote support functions must be identified.

The documentation of Level 2 test results should summarize the process stability of the tool and significant levels of detail about the overall process results and capabilities. The following
SEMATECH reports are typically generated from it:

- EMA report
- Baseline characterization report
- Sensitivity analysis report
- Demonstration test report

### 5.2.3 Level 3 Test

Level 3 testing includes extensive testing and characterization of the process and manufacturing performance capabilities of a tool. The results represent a thorough investigation of the performance characteristics as they relate to use of the tool in a manufacturing environment.

A Level 3 test includes the following test elements:

- Test planning
- Gauge studies
- Mechanical dry cycle (MDC)
- PDC
- Sensitivity analysis (DOE)
- Marathon

Level 3 testing is generally performed on more mature tools, typically those that are in the beta stage of development. Candidate tools for Level 3 testing must meet the appropriate EMA characteristic requirements, have every function described by the design specification, are capable of fully automated product processing (pod-to-pod), and produce statistically stable process results. More mature tools, those that are in late stages of development, will generally not undergo significant changes to fundamental design attributes such as footprint size and layout or software platform. At this maturity, the tool is expected to be under closed-loop engineering change control.

The documentation of level 3 test results should provide significant information about the process behavior of a tool, as well as quantify the performance in a manufacturing environment. The output of a level 3 test should provide an overall view of all tool characteristics. The following SEMATECH reports are typically generated from it:

- EMA report
- Baseline characterization report
- Sensitivity analysis report
- Marathon test report
- Demonstration test report

### 5.3 Standards Conformance

SEMATECH’s member companies have ratified a common set of standards representing the expectations and requirements for 450 mm semiconductor equipment. During the EMA, candidate test tools are investigated for standards conformance by the EMA team. The supplier’s program on each of the standards is reviewed. The review will consist of determining the progress, current state, and plans for conformance to each standard. SEMATECH will not perform conformance audits or certification to any of the standards. Standards conformance is the sole responsibility of the supplier.
The evaluation of conformance to the standards is an interactive review conducted before the physical inspection of the candidate tool during the EMA. The assessors will look for evidence of conformance to the standards. Findings of standards conformance will be included in the EMA report and in the final demonstration test report.

5.4 Preparation and Execution

Before an EMA, certain prerequisites should be reviewed. The tool should be ready for the assessment and results expected to meet the requirements for one of the test levels. The evaluation team members should be identified, and the team should have all the requisite skills.

The assessment is a cooperative effort among representatives of the test team and the supplier, who will work together to establish the maturity level of the tool and determine the correct testing level. The assessment team must include the following skill sets as a minimum:

- Process technology engineering
- Development engineering
- Equipment reliability
- Safety
- Equipment engineering

The supplier’s program for standards conformance is reviewed. The team then physically inspects the tool to be tested, systematically investigating the current performance and capabilities of each characteristic in the EMA characteristics matrix (see Appendix A). As each characteristic is evaluated, documentation or other information that clarifies capabilities is considered. All EMA characteristics required for a particular test level must be achieved; otherwise, the equipment will not be tested at that level.

In some cases, a characteristic can be evaluated only by investigating the engineering data and systems that produce that functionality. An engineering capability assessment can substantiate findings and quantify current developmental progress and maturity. The engineering capability assessment ensures that all available data sources are considered to determine the appropriate testing level.

During the EMA, factors that could affect the testing should be identified and investigated. Other factors may be identified that would provide early direction for test planning. These testing recommendations should be captured and included in the EMA report.

5.5 Documentation

The following information should be included in an EMA report:

- Equipment model number, serial number, options, configuration, and software release
- Development maturity of the tool
- Determination of the DTM test level
- Standards conformance
- Summary of tool characteristics
- Engineering capability assessment results
- Testing recommendations
- Opportunities for improvement
6 DEMONSTRATION TESTING

Demonstration testing is done to quantify the performance of a tool or process through systematic testing that produces statistically valid results. It can be performed on any tool or process, at any development stage. Three major activity groups make up a demonstration test:

1) Test planning, using an iterative process making use of all available data, assures that the proper, cost-effective testing is done to adequately test the tool or process. The goal is to produce statistically valid results given the capabilities of the tool and industry requirements.

2) The baseline characterization ensures the stability and/or functionality of the tool or process. It serves as the foundation for the statistical validity of the demonstration test results.

3) The demonstration test focuses on characterizing the process and demonstrating manufacturing performance. The results of the demonstration test are always evaluated with respect to the goals and within the context of the tool maturity.

The demonstration test is designed to produce a characterization of a tool or process performance at the time of testing. A tool may be tested several times throughout its development cycle as it matures to document its growth and performance improvements.

6.1 Demonstration Test Planning

The test planning step sets the goals and procedures to be used for the demonstration test, helps predict potential problems, and provides a framework for decision making if problems occur. If planning is not completed before the test begins, problems during the execution may affect the results and timeline. The review process may require updating the test plan, but creation of its basic framework happens here. During test planning, the output of the EMA and any available pre-knowledge are used for test scaling. Test planning is an iterative process that continues until a test plan is established that is consistent with the maturity of the tool and that meets the test level requirements. The test plan must have acceptable goals and well defined test procedures. Finally, it must be able to be performed within the timeline and resource constraints. The plan review is held with customers to ensure that the test outcome aligns with industry needs.

6.1.1 Plan Demonstration Test

During test planning, the team members solidify the goals and procedures for the test. One test can have many goals, which should specifically state the metrics to be used and the basis for evaluation. Proper planning clearly defines specification metrics, establishes the methods of data collection, and defines the method of data reporting. Baseline metrics are developed, if necessary, to determine the success of the demonstration test.

A sampling plan is established to allow an estimate of resources required for the test. For each of the testing activities, the sample must be sufficient to meet the statistical confidence level required. The sampling plan may change during the execution of the demonstration test as the team develops a better understanding of the variability of the tool or process. Accurate estimates of the quantity of material and data that the test and team can produce within the test time are generated. Artificially minimizing sampling can reduce the technical quality of the test results while artificially maximizing sampling can reduce the capability to support the demonstration test.
The subject matter experts on the test team may identify important test metrics in addition to the equipment performance metrics. These additional metrics are communicated to the supplier as soon as possible. The test team is responsible for estimating the goals of any additional metrics used in testing.

6.1.1.1 Establish Test Goals and Procedures

A comprehensive set of goals should be determined. Since they will influence the extent and rigor of testing as well as the procedures to be used, all the test requirements and outputs should be reflected in the test goals. Goals should include the following:

- Equipment performance metrics
- Process parametrics
- Key process input factors
- Manufacturing and reliability
- Cost of ownership

The test procedures define the way the test will be executed, the way resource requirements will be met, and any logistical requirements. The procedures should also include any contingency plans required by special circumstances. Some factors to be considered in generating the procedures are as follows:

- Test location
- Facilities requirements
- Environmental factors
- Metrology and support equipment requirements
- Manpower available
- Data collection methodology
- Logistics
- Cost constraints
- Pre-processed wafer requirements
- Joint development with another supplier or IC company

6.1.1.2 Analyze Pre-knowledge

Pre-knowledge refers to the amalgam of all available data from the tool and process development activities and any previous testing. This could consist of unit level test results, process characterization runs, and any other data. Performance data on the previous generation of the tool can be used if they are very similar, especially when the same subsystems are used. In the absence of data on the test tool, the best guess and worst case estimates derived from the experience of knowledgeable engineers can be used as pre-knowledge.

By applying a Bayesian statistical design technique to the pre-knowledge, valid testing can be performed in a shorter time or with higher statistical confidence while lowering resource requirements. This technique is applied by the following:

- Using past data or experience, construct a previous distribution (probability density function) of the failure rates from which to derive the failure rate of the upcoming test.
- Select a test time (T) and use the previous distribution to list the most likely test results.
• Combine the previous distribution and likely results to construct confidence intervals for each likely result. Compare with the goals of the test.

• The design technique is complete if each likely result produces approximately the required confidence. If the likely confidence intervals are well above or below the test goal, select another test time (T) and repeat the process.

In SEMATECH-sponsored demonstration tests, a staff statistician will be responsible for the application of pre-knowledge. When a supplier applies pre-knowledge as part of its development activities, sufficient documentation should be captured to support the use of previous data.

6.1.2 Test Scaling

Test scaling involves reducing the scope, extent, and rigor of a demonstration test based upon tool maturity, DTM test level, and other factors. This allows tools to be tested at any development stage and ensures that only meaningful testing is performed. Well executed test scaling will produce the most value in test results for the least investment of test resources. Scaling the test goals and statistical confidence levels within the test elements ensures that the appropriate extent and rigor of testing is done. The recommendations of the EMA are also considered when making scaling adjustments.

The test element may be combined with another element to provide data on both elements concurrently. Care should be taken in combining elements to avoid increased variability and to preserve the integrity of a decision making capability based on data analysis.

6.1.2.1 Goal and Statistical Confidence Level Scaling

Scaling the test goals and statistical confidence levels ensures that the appropriate extent and rigor of testing is done. Each test goal and its corresponding statistical confidence will be scaled individually. To provide consistency from test to test, a systematic method should be used to scale the test goals and statistical confidence levels. This method will be based on the current measured performance of the test tool.

The test goal and statistical confidence level scaling has four steps:

1) The supplier provides a Performance Metric Profile (PMP) summarizing the current performance of the target test tool. The Performance Metric Profile is comprised of a measure for each SEMATECH and other test metrics defined in advance by the test team. The supplier will also provide as much test and raw data as possible to validate the PMP. Note that “no metric” or “no data” can sometimes be an acceptable input, depending upon the development stage.

2) The test and raw data provided by the supplier is reviewed to validate the PMP. The validated results are used to create the derating factor insofar as the data substantiate the PMP measures.

3) Each PMP measure is individually reconciled with the requirement. The level to which the PMP measure fails to meet the goals is used to generate a derating factor for each metric.

4) The derating factors are applied to establish the initial test goals and statistical confidence levels.
The output of this scaling process establishes the initial test goals and statistical confidence levels for demonstration testing. These goals could be modified through the iterative test planning process as other factors, such as the EMA recommendations and resource limitations, are considered.

### 6.1.2.2 EMA Recommendations

The output of the EMA includes recommendations to be considered during the demonstration test planning. These recommendations are a direct product of the physical assessment of the tool and the engineering systems that produced it. A formal review of the EMA recommendations should be conducted and the test methods and procedures modified if appropriate. Modifying the test plan as a result of the EMA recommendations is a form of test scaling.

### 6.1.3 Generate Test Plan

The test plan is the formal documentation of the demonstration test goals and procedures. The test plan should not only establish and quantify the test parameters and resources, but also include the documentation of decisions and background information that will validate the goals, operational parameters, and DTM test level to be executed.

The completed test plan is reviewed for conformance to industry and customer requirements to ensure that the demonstration test will produce adequate value for the invested resources. If the test plan does not adequately meet industry needs and requirements, the test planning process should be repeated until an acceptable test plan has been defined.

The test plan should be continually updated as the test progresses to reflect changes in the test environment, goals, procedures, or other external factors.

### 6.1.4 Test Plan Review

The role of the test plan review is to ratify the test goals, procedures, and resources as well as provide a formal venue for customer input and validation. Once the formal test plan has been completed, a meeting should be scheduled with key customers, marketing, engineering, and any other appropriate participants. Each of the goals, procedures, constraints, and resources should be reviewed.

The test plan review is used to solicit wide support and acceptance of the test plan and to avoid unforeseen or unnecessary changes during test execution that may result from oversights.

### 6.2 Baseline Characterization

The baseline characterization establishes the stability and/or functionality of the tool or process. The baseline characterization evaluates certain functional performance and verifies that the process results are stable so that statistically valid and representative results can be produced from the demonstration testing.

A gauge study is used to identify the precision and accuracy of the measurement systems to be used in the demonstration test, so that gauge variability can be removed from the process results. Mechanical dry cycling evaluates tool functionality without the complexity of wafer processing. A passive data collection experiment establishes that the process results are consistent and repeatable, which provides the basis for statistically valid testing. Finally, the results are reviewed to assess performance to test requirements and to make any revisions to the test plan. It
The results could indicate that the test should be terminated after characterization baseline testing before committing the bulk of the test resources in the next step.

SEMATECH provides software data collection and analysis tools that meet the requirements and constraints of the 450 DTM to provide standardization and productivity improvement benefits.

6.2.1  Gauge Studies

A gauge study determines whether the metrology tool is stable and estimates the accuracy and precision of the system and establishes control systems for it. The gauge study, which the metrology systems used to support a demonstration test must undergo, is not intended to provide a comprehensive characterization of the metrology tool. It represents the qualification of the specific measurement capability needed for the demonstration test.

A metrology system includes the measurement tool, the transfer standards, and control systems to be used and the procedures or methods used to make measurements on the tool. The study consists of statistically planned activities that identify and quantify the major sources of variability in the measurement process.

For 450 mm demonstration tests, if the measurement system to be used has undergone a gauge study or demonstration test that includes the range of output results for a test and is under statistical process control (SPC), the study does not need to be repeated. The capability and contribution to variability of test results will be understood and applicable to all testing that uses the measurement system.

A comprehensive gauge study methodology is outside the scope of this document. While the minimum requirements are described below, a more rigorous method should typically be used.

6.2.1.1  Preparation and Execution

The test team identifies the following components of the execution plan:

- Sampling plan
- Possible sources of variation for measurement system
- Input and output parameters to monitor
- Analysis plan
- Staffing assignments to specific tasks

A sampling plan includes the number, frequency, and types of measurements for the gauge study. Regardless of the statistical confidence level selected for the test plan goals and parameters, the gauge study requires a high confidence level, typically >95%. Estimating accuracy requires a sample size of at least 16 independent replications. Estimating the repeatability of the metrology tool requires a sample size of at least 30 independent replications. The sources of variation to be explored determine the type and number of measurements used to estimate reproducibility.

If the test involves more than one type of product (e.g., different film types or thicknesses), then a separate gauge study for each type of product is performed. In most cases, these studies are performed concurrently. The gauge study is performed on transfer standards or artifacts of each product type, if possible. If transfer standards do not exist, the gauge study should still be conducted. A reference product can be created and used throughout the test. The final report should state the origin of the reference products tested.
The team identifies possible sources of variability that can affect the measurements. Examples of sources of variability are operator-to-operator variability and drift over time. A repeatability study does not investigate any sources of variation, whereas a reproducibility experiment exposes the metrology system to all relevant sources of variability.

A gauge study occurs in three steps. First, the necessity of calibrating the tool is explored, then repeatability of the measurement tool is estimated, and finally the reproducibility of the measurement system is evaluated.

The first step of the gauge study identifies any need to calibrate the measurement tool. If a transfer standard is available, the gauge accuracy is determined using repeated measurements. If a transfer standard is not available, direct accuracy may not be possible. However, measuring a reference product allows tool drift ("relative accuracy") to be tracked.

Repeated measurements (30 minimum) over a short time using a transfer standard or reference product provide estimates of the repeatability and short-term stability of the measurement tool. The contributions of external sources of variability should be minimized. For example, measure a single site repeatedly without moving the object being measured. Or, if the study requires measuring multiple sites several times, group the replicates by site to allow the standard deviation to be estimated properly.

A reproducibility experiment includes all likely sources of variation in the measurement system. The number and types of these sources guide the design of the sampling plan used to capture the variability of the system. Adherence to this sampling plan is crucial for data integrity.

6.2.1.2 Analysis and Decisions

The measurement data are analyzed to determine whether the tool needs calibration; a 95% confidence interval for the observed bias is also calculated. The bias is the standard value minus the mean of the measurements taken. If zero is within the confidence interval, a calibration is unnecessary. The tool should be calibrated only if the mean of the data is sufficiently far away from the standard value. Unnecessary calibration may add variation to the measurement process.

Summary statistics generated from the initial data estimate repeatability. A comparison of the repeatability to the process specifications determines whether the magnitude is acceptable. A trend plot of 30 readings estimates the stability of the tool.

A trend chart of the data resulting from the reproducibility experiment can estimate the stability of the measurement system. If the measurement system is stable, the variance components are calculated and analyzed. The total variance of the measurement system (precision) is compared to a measure or estimate of the variation in the process. When reporting the precision of the measurement system, the number of standard deviations is cited. The precision-to-tolerance ratio (P/T, see SEMI M27) is then calculated, using the precision of the measurement system and the process specifications.

The yes/no decisions made during a gauge study include the following:

- The tool needs calibration
- The metrology tool is stable
- The measurement system is stable
- The total error is acceptable
- The components of the total error are understood
If the total error is unacceptable, the test can continue with the current measurement system with revised sampling plans, a new measurement system can be identified, or the test goals can be modified to take into account the actual measurement capability.

6.2.1.3 Test Outputs and Documentation
Gauge study reports should include the following:

- General test information
- Goals of the study
- Development maturity of the metrology tool or process
- Equipment model number, options, configuration, software release
- Source for transfer standards, manufacturer’s certification of the standards
- Any issues or special factors that limit the scope or applicability of the study
- Data collection method
- Accuracy statement
- Pre-calibration bias (with 95% confidence interval)
- Linearity graph (before calibration) if multiple products were measured
- Precision statement
- Repeatability
- Trend plot of the data
- Explanation of any patterns in the trend plot
- Reproducibility
- Sources of variability investigated and those found to be significant
- Components of variation table/graph
- Box plots of sources
- P/T ratio, including specifications
- Comparative studies with a 95% confidence interval of the differences for bias and precision
- Long-term stability
- Control chart
- Reaction plans for out-of-control situations
- Decisions and reasons to use an unstable system or one with a high P/T value (if applicable)

6.2.2 Mechanical Dry Cycle
The MDC test quantifies the mechanical performance and identifies those problems that occur from handling the wafers or production materials. The process should start by operating the wafer-handling and mechanical components of the tool without the complexity of wafer processing. This provides a cost-effective way to estimate the mechanical performance of the tool.

6.2.2.1 Preparation and Execution
The test team identifies the following components of the execution plan:

- Test goal and statistical confidence
- Wafers or wafer surrogates to be used in the test
- Acceleration techniques
• Data collection method
• Analysis plan

The rigor and extent of this testing should be based upon the maturity of the test tool and the test goals established. Note that mean time between failures (MTBF) may not be testable with any great confidence within the time allotted for the test. An estimate of the MTBF can be established by converting the number of cycles completed in the test based on the tool throughput. In this case, mean wafers between failures (MWBF) may provide a better metric. An MDC goal of 5000 MWBF with some level of statistical confidence is typical.

The time during which continuous cycling is performed may vary if acceleration techniques are used, the equipment is modified, or failures are being diagnosed. The test time can be minimized by good planning and disciplined test execution.

A data collection method should be established to collect the test data. It should include the number of machine cycles or wafers, number of failures, and specific failure data. A logbook or other formal method to record unusual events during testing should be maintained. Available software data collection and analysis tools are used to support the SEMATECH demonstrations.

6.2.2.2 Test Outputs and Documentation

Mechanical dry cycle reports should include the following:
• Test level
• General test information
• Goals of the study
• Equipment model number, options, configuration, and software release
• Acceleration techniques used, if any
• Summary of mechanical functions tested
• Data collection method
• Reliability numerics
• Pareto charts of failures
• Analysis of failures
• Repairs or unplanned events logged during the test
• Any issues or special factors that limit the scope or applicability of the study

6.2.3 Passive Data Collection

A PDC specifically establishes process stability. The PDC accumulates information for a defined duration without process or equipment adjustments (“tweaks”). Normal maintenance procedures are allowed, but should be documented. Analysis of the data determines stability, capability, sampling efficiency, and relationships among variables.

A PDC can be run concurrently with a gauge study; however, this involves some risk. The analysis of results cannot begin until the data analysis and interpretation of the gauge study has been completed. If the data from the gauge study show an unstable system, then the PDC must be repeated (or the products remeasured) after the metrology system has been stabilized.

The objectives of a PDC are to determine the capability of a process, to estimate the sources of variability in the process, and to set the direction of future experimentation.
6.2.3.1 Preparation and Execution

The test team identifies the following components of the PDC execution plan:

- Sampling plan that captures the most likely sources of variability
- Input and output parameters to monitor
- Possible sources of variability for each response
- Incoming material requirements
- Data analysis plan
- Staffing assignments for specific tasks
- Format for a logbook or formal system to record unusual events during processing

The sample size for a PDC should include at least 30 completely independent replications. The number of replications may be reduced if lower confidence level results are acceptable. A replication captures all the variability inherent in an equipment cycle. For example, in a vertical furnace evaluation, a replication may be a complete furnace load; in a stepper evaluation, a replication may be a single wafer.

During a PDC, intentional oversampling is recommended, such as using 11 wafers per load instead of three or measuring 49 sites on a wafer instead of 13. Data from oversampling support informed choices about reducing sampling efforts on subsequent data collection activities and during the demonstration testing. The number of input parameters monitored during sampling should be as large as practical, consistent with test scaling and resource constraints. This is to promote understanding of which input parameters drive the equipment response.

The team measures process outputs and collects the resulting data, including the input parameter values. Detailed documentation during the execution of a PDC can help explain patterns or anomalies discovered during the analysis.

Process or equipment deviations from the normal operating procedures are not allowed during a PDC. If a problem occurs during a PDC, the PDC should be stopped and an analysis conducted to find and correct the problem, then a new PDC started.

6.2.3.2 Analysis and Decisions

Trend plots are used to estimate the stability and capability of the equipment or process. Statistical analysis of the PDC data identifies relationships between variables. Variance components are analyzed to establish sources of variability and their relative contributions to the total variability in the system. The analysis often suggests opportunities for process improvements. If the PDC used a relatively large sample size, the analysis may also suggest an appropriate smaller sampling plan for future work.

Some of the yes/no decisions resulting from a PDC are as follows:

- The process output is stable
- The equipment is stable and repeatable
- Reasons for instability have been identified

If the answers to these questions are “no,” further work may be needed before proceeding to subsequent test elements.
6.2.3.3 Test Outputs and Documentation

PDC reports should include the following:

- Test level
- General test information
- Goals of the study
- Input and output parameters that were measured
- Sampling plan
- Process settings used
- Equipment configuration
- Repairs or unplanned events logged during the PDC
- Stability and capability
- Trend charts
- Explanations of special causes of variation
- Histograms
- Conclusions
- Relationships between process variables
- Graphical displays (box plots, scatter plots, etc.)
- Analysis of statistical significance
- Autocorrelations/cross-correlation in time
- Improved sampling plan development
- Variance component analysis
- Table of percentages
- PDC conclusions
- Recommendations for further investigation
- Opportunities for improvement

6.2.4 Baseline Characterization Review

The baseline characterization review assesses the results of the gauge study, mechanical dry cycling, and passive data collection elements to ensure that the next test plan steps are still valid.

The bulk of the resource consumption and cost of demonstration testing is incurred during the sensitivity analysis and marathon test (step 3). The baseline characterization review provides for a critical point at which a data-driven decision to continue, modify, or terminate the test can be made by evaluating the tool or process results from the performance baseline testing.

The recommended items to review at this time are as follows:

- Quantitative results and decisions from the gauge study
- Quantitative results and decisions from the mechanical dry cycle study
- Quantitative results and decisions from the passive data collection test
- Tool performance during the PDC, including anticipated or expected hardware or software reliability issues
- Requirements for incoming material, process tolerance, and resource allocation

Plans presented and discussed during the review should include the following:

- Resources required to complete
- Updated demonstration test schedule and budget
• Required buy-in from management and project customers to support dependencies
• Continuation or cancellation of the test

6.2.5 Test Termination

A demonstration test can be terminated for several reasons, primarily associated with poor process performance if the equipment under test cannot meet expectations, which renders further testing invalid. If the test is terminated, the test team documents the achievements and failures of the testing completed. If the test does not continue to demonstration testing, current tool performance is reported. The project continues to close out all tests and demonstration test reporting.

6.3 Demonstration Testing

At the end of the baseline characterization, the review will have established whether or not the equipment and process are stable. If so, testing continues with the sensitivity analysis and marathon (manufacturing performance) testing. However, the main focus of the Demonstration Test Method is simply demonstration testing. It is during this step that tests will fully characterize the process and measure the manufacturing performance of the test tool.

6.3.1 Sensitivity Analysis

Complete process characterization is done most effectively with a DOE. The DOE methodology uses a series of experimental designs that manipulate several process inputs simultaneously to deliberately perturb a process to develop cause-and-effect relationships between inputs and outputs.

A sequential experimental design strategy uses resources most efficiently. Screening experiments are used to determine the most significant inputs and explore possible interactions between inputs. Response surface characterization designs are then used to explore the effects of these remaining significant inputs on the responses. The number of inputs investigated should be managed, as they affect the resources and time required to complete the sensitivity analysis.

The level of test team knowledge about a process and the data gathered during the PDC dictates the type of experiment first used. Screening designs are used when the team has limited knowledge of the process and the process has many input variables with unknown or uncertain influences. Initial screening designs assume the relationships between inputs and outputs are linear rather than curvilinear. These designs can detect curvature in a response, but cannot estimate it. Screening designs can explore many inputs. All potentially significant inputs should be included in the initial screening design; however, a design would rarely include more than 20. The final number of test combinations depends upon the information desired. For the SEMATECH program, the number of inputs tested will generally be less than ten.

Characterization is used when the test team has moderate to considerable knowledge about the process and previous experiments have defined the relatively few important input variables and possible interactions among these inputs. Characterization designs are applied when previous experiments have detected statistically significant curvilinear relationships between inputs and outputs. These designs should usually be restricted to no more than five inputs because of the large number of test combinations needed to estimate curvature.
6.3.1.1 Screening Experiments

If the process tool has demonstrated stability, the tool undergoes characterization using designed experiments to identify the inputs that influence the responses. If the process tool has demonstrated an unstable process with acceptable hardware reliability, a method for obtaining stable results must be determined. Screening experiments are used to determine the inputs that affect stability.

Process characterization typically involves investigating the effects of a possibly large number of inputs on several outputs. Establishing cause-and-effect relationships between the variation of an input variable and change in process outputs is the primary objective. The most efficient way to establish these relationships is through designed experiments. Characterization may also include purely engineering activities used to reach stability, such as refining the quality of consumables.

In a screening experiment, omitting process inputs to reduce the number of experiments is unwise since important relationships will be overlooked. As many input variables as practical are included. A design matrix is used that isolates the main effects of the investigated inputs and the estimation of likely interactions. The types of experimental designs used here are screening experiments.

6.3.1.1.1 Preparation and Execution

The project team identifies the following components of the screening experiment execution plan:

- Inputs and the ranges of their settings
- Likely interactions among the inputs
- Responses to measure
- A sampling plan (number of replications to include, etc.)
- Restrictions on the execution of the experiment
- Staffing assignments for specific tasks
- A plan for analyzing the experimental data
- Decisions based on performance baseline results

The team generates or acquires updates on

- Timeframe for the experiment (include analysis and documentation)
- Test cost
- Metrology system stability

Screening experiments generally use two levels of inputs: low and high, with added center points. There are several types of screening designs: factorial, fractional-factorial, and D-optimal. The type of design chosen depends upon the number of inputs, results required, and tool constraints. D-optimal designs are suitable when tool constraints on input prevent some combinations of those inputs, as may be likely in early development cycle tools. However, D-optimal designs are not as straightforward to design and analyze as factorial and fractional-factorial designs.²

² Statistics for Experimenters, George Box, William Hunter & Stewart Hunter, Wiley (1978)
A correct sampling plan for a screening experiment will include sufficient monitor wafers per batch to detect and measure the variation among wafers. The number of points taken per wafer must be sufficient to estimate the within-wafer variance component. In a screening experiment, attempting to quantify possible non-linear relationships between input settings and outputs is premature. At this point, the experimental design is used only to detect the existence of such non-linearity. It is important that the test team follow the experimental design and execute all the test combinations in the correct order for the experimental design chosen.

6.3.1.1.2 Analysis and Decisions

A detailed description of the analysis of a DOE is beyond the scope of this document. In general, the analysis should be based on multiple regression analysis and should include suitable graphical representations. The analyst should graph the data obtained using a variety of graph types (e.g., histograms, box plots, scatter plots, and trend plots) to detect unusual or maverick observations and to identify possible cause-and-effect relationships between input and output parameters. Properly designed scatter plots (two-way interaction plots) help identify interactions between inputs that affect an output. Multiple regression analyses quantify the relationships and identify statistically important input variables (and likely interactions among them) that the team can exploit to improve the process output or to decrease its variability.

The analysis may reveal opportunities to improve the process by changing certain input settings. Process changes must be analyzed for impact on established safety systems or environmental controls. An additional PDC at the new input settings should be run to confirm predictions. The changes observed in the process must have both engineering and statistical significance.

Some of the yes/no decisions made from the results of screening experiment include the following:

- The process or equipment has achieved stability
- The correct input factors and their ranges were explored
- The project should continue; a management review is required for this decision

6.3.1.1.3 Test Outputs and Documentation

Screening experiment reports should include the following:

- Description of the screening experiment
- Goals of the study
- Input factors and ranges explored
- Responses measured
- Experimental method
- Design matrix
- Data collection methods
- Results of experiment
- Model for each response
- Graphical display of results
- Conclusions and future activities
6.3.1.2 Characterization Experiments

The screening experiments determined which input factors were significant, established the interactions among them, and checked for any curvilinear effects. However, the designs used could only detect such curvature and not estimate it. The characterization experiments therefore explore the process response space.

The number of input factors to be explored should be carefully considered, as it will significantly influence the time and resources for the characterization experiments. In the SEMATECH program, the number of input factors will generally be limited to five or fewer. Blocking designs should also be considered to reduce irrelevant sources of variation. Matched pair designs can also be considered to improve the experimental efficiency.

6.3.1.2.1 Preparation and Execution

The test team identifies the following components of the characterization plan:

- Experimental strategy (goals of experiment)
- Response variables of interest
- Input factors and range of settings
- Number of replications to include
- Restrictions on the execution of experiment
- Staffing assignments for specific tasks
- Plan for analysis of experiment
- Decisions based on results

The team acquires updates on

- Timeframe for the experiment (include analysis and documentation)
- Test cost
- Sampling plan
- Metrology system stability

Experiments to model curvature require a response surface design. These designs require three to five levels of each input variable and are able to quantify any curvilinear relationships between inputs and outputs detected in the screening experiments. Response surface design matrices include Central Composite Box-Behnken, and D-optimal designs. Again, D-optimal designs are most suitable when tool constraints on input factors prevent some combinations of those inputs.

6.3.1.2.2 Analysis and Decisions

A detailed description of the analysis of designed experiments is beyond the scope of this document. In general, the analysis should be based on multiple regression and include suitable graphical representation. Graphical diagnostic tools can be valuable for assessing the quality of the regression model. The statistical analysis will identify significant inputs, their input interactions, and any quadratic terms (curvilinear effects) if appropriate for the design matrix. Graphical representations expedite the interpretation of the final regression models obtained from response surface test designs.

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3 Statistics for Experimenters, George Box, William Hunter & Stewart Hunter, Wiley (1978)
Response surface models and associated contour plots are the most widely accepted representation of a process window in which several critical responses have acceptable values and stability to minor changes in process inputs. Several replications at the predicted process optimum confirm the values of the actual responses under those conditions and allow more refined estimates of confidence intervals for those responses.

Some of the yes/no decisions made during this element are as follows:

- The experiment is monitoring the correct inputs and responses
- The process window has acceptable width at acceptable performance
- Environment, safety, and health factors have been evaluated
- The project is ready to continue to the next element

### 6.3.1.2.3 Test Outputs and Documentation

DOE reports should include the following:

- Description of characterization experiment
- Fixed factors during each experiment or between experiments
- Experimental objective and strategy
- Design factors
- Responses monitored
- Compromises
- Stability of metrology
- Stability of process under investigation
- Data analysis
- Interaction plots
- Cube plots
- Contour plots
- Models and fits to data
- Decisions
- Process window verification
- Conclusions
- Opportunities for improvement

### 6.3.2 Marathon Test

The marathon test establishes the manufacturing performance of a tool, including the reliability, cost of ownership, and throughput, and generates the information required for valid performance estimates. These statistics are generated in a simulated manufacturing environment called a marathon test. The test environment should replicate a production manufacturing environment as closely as possible. Cleanroom floor space, production materials and delivery systems, preventive maintenance, and any other attributes that materially contribute to the simulated production environment should be executed as well as is practical within the resource and cost constraints of the test. The type of wafers or product to be used during the marathon test is determined by the extent and type of information required for the test.

The marathon test (or manufacturing demonstration) quantifies the intrinsic availability and utilization capability of the tool design. The simulated manufacturing environment should be optimized to eliminate standard fab constraints, such as process material shortages, upstream and downstream dependencies, facility peculiarities, operations manpower, and other issues. The
resulting metrics reflect the performance limitations and behaviors of the test tool without the variability of external influences. Preparation is extensive, and the resources are significant. The tool and process must run continuously, with all the required support in place for the 24 hours a day/7 days a week operation. The objective of the marathon test is to determine tool performance in a simulated manufacturing environment.

6.3.2.1 Plan for Marathon Test

A resource and planning review should be held before the marathon test. Potential problems are identified and solutions proposed. The resource and plan review should include reviewing and finalizing decisions, verifying support systems, and assuring availability of required resources.

Plans and decisions include the following:

- Length of marathon—determined by statistical methods but subject to cost and resource constraints
- Type of wafers to use
- Maintenance plans defined, frequency determined, and schedules established
- Failure modes defined
- Equipment subsystems defined
- Conditions for aborting the marathon defined
- Detailed agreements on what is out of control
- Reaction plans to out-of-control situations
- Procedures to be used in the test
- Logistics

Support systems and commitments include the following:

- Commitment of 24-hour/7-day operation capability. Note: 24/7 is preferred; however, in some cases, 24/7 testing may not be feasible for some companies
- Engineering commitment for 24/7 operation. Note: 24/7 is preferred; however, in some cases, 24/7 testing may not be feasible for some companies
- Supplier commitment for resource support
- On-line control charts for all appropriate responses and metrology systems
- Measurement capacity and data analysis capability available
- Equipment utilization/failure reporting hardware links and software

Review of resources examined, ratified, and/or adjusted:

- Cost estimate and assumptions
- Training and certification of team members
- Logs generated to document reactions to excursions
- Adequate supply of test wafers—dummies as well as monitor wafers
- Required spare parts list generated and crucial spare parts on site

There must be a consistent approach to running the equipment and reacting to excursions or failures by all members of the equipment team.

6.3.2.2 Resource Review

A resource review should be completed before the marathon. This review obtains management and test team approval, which is crucial because the resources involved in a marathon test are
significant. Representatives from the customer and supplier will decide whether to continue the
project based on the relationship among project achievements, the cost of continuing, and future
benefits. The team presents the decisions made, problems identified, support systems necessary,
and resource availability for the marathon.

6.3.2.3 Preparation and Execution

The execution of a marathon test must simulate a manufacturing environment as closely as
possible. The intent is to replicate the normal operating environment of a production tool,
eliminating external sources of variability. This allows for the accurate measurement of tool
performance, limited only by intrinsic design capabilities.

Data collection must consistently and accurately record and classify downtime following
established procedures. Maintaining backup records is recommended, since they may become
important in resolving classification issues correctly. Equipment software and computer records
should be uploaded and maintained at regular intervals.

The team should detail operating procedures, responses, and activities permitted during the
marathon test. The marathon should include normal activities such as preventive maintenance
(PM) and statistical process control (SPC) or process adjustments that would be permitted in a
normal mode of operation.

Once the marathon test has been started, the test team must maintain constant communication to
resolve problems quickly and must document any unplanned events and reactions in detail. One
of the principles of marathon testing is to eliminate external sources of variability so that the
metrics represent only the performance of the tool. Material control, logistics, and data
management should be routinely reviewed as the test progresses.

The marathon test is either time or performance-terminated, depending upon its test design.
When the test concludes, a test team meeting is recommended to review the test plan
requirements to ensure completion and to prepare for the test close-out and documentation step.

6.3.2.4 Analysis and Decisions

The results of the marathon are analyzed in two segments: process capability performance and
tool performance. Confidence intervals for both should be calculated when appropriate. Process
results are analyzed through statistical methods in the same manner as the sensitivity analysis.

The equipment performance is analyzed using SEMI E10 guidelines, using the utilization
information gathered during the marathon test. Statistics on tool utilization, such as reliability,
availability, and maintainability (RAM), are calculated. Other utilization statistics can be
calculated using throughput information:

- Mean time between failures productive (MTBFp) or mean wafers between failures
  (MWBF)
- Equipment-dependent uptime
- Operational uptime
- Mean time to repair (MTTR)
- Operational utilization
- Total utilization

The information gathered on the failure modes is summarized and displayed in graphical format.
The failure frequency by type or “reason down” should be graphed on a Pareto chart. Summary
statistics, such as subsystem failure average frequency and subsystem failure MTTR, are calculated for each of the identified subsystems.

Data obtained during the marathon test are used to calculate the cost of ownership. Some yes/no decisions made during the marathon test include the following:

- The equipment and process met the goals stated in the project plan. If not, which goals were not met and why
- Further work is needed to improve tool or process performance
- The cost of ownership estimate is acceptable
- The dominant failure modes are identified
- Solutions for the failures can be implemented

6.3.2.5 Test Outputs and Documentation

Marathon test reports should include the following:

- Marathon plan
- Sampling scheme
- Timeline
- Support systems
- Control charts used and reaction plans
- Other preparation plans
- Process performance
- Statistical analysis
- Graphical analysis
- Data influences
- Analysis of out-of-control conditions and their relationship to hardware/software reliability
- Tool performance
- Pareto of failure modes
- RAM statistics
- Utilization statistics
- Cost of ownership input parameters
- Cost of ownership results
- Conclusions
- Opportunities for tool or process improvement

6.3.3 Test Close-Out and Documentation

After the marathon test concludes, a test close-out review discusses all three steps of the demonstration test plan. Each test goal is compared with the results from the test. Unachieved goals are examined in detail to capture the most likely causes of failure. During this review, the customer and supplier discuss whether the project was a success and may suggest future activities. Future activities might include additional studies, redesigns of equipment or process, or releases to manufacturing. If the test is to be closed out, the demonstration test output is documented and all other activities associated with the test are closed. Equipment and materials must be dispositioned, results and data sources consolidated, and artifact materials (wafers) archived, if appropriate.
7 DEMONSTRATION TEST REPORTS

Any demonstration testing produces results that must be formally documented. The final demonstration report is a comprehensive summary of all the test results from the maturity-based tests that generated the data. It provides a high level overview of the tool performance, with a minimum of detailed data. Four corollary reports are also produced to document in detail the specific results, performance, and data from the primary testing activities. SEMATECH can provide detailed content outlines for each report.

Note: The demonstration test final report is an internally published document only; the report requirements are therefore beyond the scope of this document. Notation Convention

Demonstration testing of tools and processes at different maturity levels presents a challenge in ensuring accurate representation of reported metrics. To facilitate clarity in reporting test results, a special notational convention is used.

7.1.1 Test Level Notation Convention

For demonstration testing, any result reported must represent the most rigorous test element that can produce that output. The level of testing performed is therefore the single critical modifying factor to the metric identifier:

\[ \text{Metric ID}_{\text{Test Level}} \]

The notation for demonstration test results of a test level involve annotating the metric ID with a trailing subscript indicating the level of DTM testing performed. The alternative flat text representation places the metric ID first, followed by brackets that contain the metric modifier. Examples can be found in Table 1.

<table>
<thead>
<tr>
<th>Example Case</th>
<th>Convention Notation</th>
<th>Flat Text Notation</th>
</tr>
</thead>
<tbody>
<tr>
<td>MTBFp of a tool completing Level 3 testing. The result of the Marathon element is most rigorous for MTBFp in Level 3.</td>
<td>MTBFp \text{Level 3}</td>
<td>MTBFp [Level 3]</td>
</tr>
<tr>
<td>Uniformity of a tool completing Level 2 testing. If a sensitivity analysis was performed it is most rigorous for uniformity and would be reported. Otherwise, PDC results are reported for Level 2.</td>
<td>Uniformity \text{L2}</td>
<td>Uniformity [Level 2]</td>
</tr>
<tr>
<td>or, Uniformity\text{L2}</td>
<td>or, Uniformity [L2]</td>
<td></td>
</tr>
</tbody>
</table>

7.1.2 Equipment Maturity Notation Convention

For demonstration testing, both the DTM test level and 450 DTM test element used must be indicated. This includes references to specific equipment performance metrics. The convention incorporates the DTM test level of the test tool or process and the type of test that produced the results as modifiers to the metric identifier.

\[ \text{DTM Test Level}^{\text{Metric ID}}_{\text{Test Element}} \]

The notation for demonstration test results annotates the metric ID with a leading superscript, which is the DTM test level, and a trailing subscript, which is the test element applied. The alternative flat text representation places the metric ID first, followed by brackets that contain the metric modifiers in order separated by a comma. Examples are shown in Table 2.
### Table 2  Maturity Notation Examples

<table>
<thead>
<tr>
<th>Example Case</th>
<th>Convention Notation</th>
<th>Flat Text Notation</th>
</tr>
</thead>
<tbody>
<tr>
<td>A Level 3 tool that completed a Marathon test</td>
<td>$\text{Level }^3 \text{MTBF}<em>{P</em>{\text{Marathon}}}$</td>
<td>MTBFp [Level 3, Marathon]</td>
</tr>
<tr>
<td>producing MTBFp results</td>
<td>or, $L^3 \text{MTBF}<em>{P</em>{\text{MAR}}}$</td>
<td>or, MTBFp [L3, MAR]</td>
</tr>
<tr>
<td>A Level 2 tool that completed a PDC producing</td>
<td>$\text{Level }^2 \text{Uniformity}<em>{P</em>{\text{DC}}}$</td>
<td>Uniformity [Level, PDC]</td>
</tr>
<tr>
<td>uniformity results</td>
<td>or, $L^2 \text{Uniformity}<em>{P</em>{\text{DC}}}$</td>
<td>or, Uniformity [L2, PDC]</td>
</tr>
</tbody>
</table>

#### 7.2 Reports

Because the demonstration test aims to produce valid objective results that are representative of the tool at its current maturity level, the output reports can be considered the product of a demonstration test and should be as complete as possible for the level of testing that was completed.

Test results should be documented as the testing is performed or as soon as possible thereafter. All 450 DTM testing should be summarized in five reports, which represent the major test activity groups. The order of reporting normally follows the testing progressions: EMA, Baseline Characterization, Sensitivity Analysis, Marathon, and the Final Demonstration Test Report.

#### 7.2.1 Equipment Maturity Assessment Report

The EMA report documents the findings and results of an EMA. The maturity of the test tool, selection of level for testing, opportunities and recommendations as well as standards conformance are included. The EMA report also provides inputs to subsequent test planning and scaling.

An outline of the content and structure is as follows:

- Executive summary
- Introduction
  - Purpose and scope
  - Assessment information
- Standards conformance
- Description of the equipment
- Summary of findings
  - Characteristic matrix results summary
  - Engineering capability assessment (ECA)
  - Opportunities for improvement
- Demonstration test recommendations
7.2.2 Baseline Characterization Report

The baseline characterization report documents the results of the baseline test elements and includes the test plans, gauge study, MDC, PDC, and baseline review.

An outline of the content and structure is as follows:

- Executive overview
- Introduction
  - Purpose and scope
  - Reference documents
  - Tool description
  - Equipment maturity assessment
- Baseline characterization
  - Test planning
    - Test prerequisites
      - Pre-knowledge
      - Site requirements and preparation
      - Definition of failure
      - Test termination
    - Test scaling
    - Cost of ownership
    - Test preparation
      - Resources
      - Logistics
      - Test data collection
      - Test review schedule
    - Gauge studies
    - Mechanical dry cycle (MDC) test
      - MDC preparation, settings and procedures
      - MDC results
    - Passive data collection (PDC)
      - Test preparation
        - Parametrics
        - Methods
        - Process recipe
      - PDC results
      - PDC analysis and conclusions
    - Baseline characterization analysis, conclusions, and review
      - Analysis and conclusions
      - Baseline review
7.2.3 **Sensitivity Analysis Report**

The sensitivity analysis report documents the results of the screening and characterization DOE that explore the process operating space.

An outline of the content and structure is as follows:

- Executive summary
- Introduction
  - Purpose and scope
  - EMA statement
  - Description of the equipment
  - Metrology error statement
- Experiment methodology
  - Unplanned events
  - Test wafer preparation
  - Input and output parameters
  - Sampling plan
  - Randomization procedures
  - Responses measured
- Experiment results
  - Variance component analysis
  - Significant relationships between process variables
  - Significant differences between the test variables
  - Response surface analysis
- Conclusions
- Recommendations
- Opportunities for improvement

7.2.4 **Marathon Test Report**

The marathon test report documents the results of the marathon test.

An outline of the content and structure is as follows:

- Executive summary
- Introduction
  - Purpose and scope
  - Reference documents
  - EMA statement
  - Description of equipment
- Marathon methodology
  - Test plan overview
    - Preparation and settings
    - Special factors limiting scope of test
    - Goals of the test
• Sampling plan
• Procedures
• Data collection and processing
• Analysis plan

• Marathon results
  – Overall results
    • MTBFp or MWBF
    • MTTR
  – Equipment utilization
    • Total utilization
    • Operational utilization
  – Equipment uptime
    • Operational uptime
    • Equipment dependent uptime
  – Repairs or unplanned events
  – Definition of failures
  – Cost of ownership
    • Input parameters
    • Results

• Conclusions
• Recommendations and opportunities for improvement

7.2.5 Demonstration Test Report

The demonstration test report provides a composite report on tool or process performance. The final report draws data from all testing performed and integrates it into an overall representation of the demonstration test results.

Since the demonstration test will be scaled to the maturity of the test tool, not every test will produce data in every area. The final report format is based upon a full demonstration test, in which every test element was executed. The final report for a test should always include results for every test element for the DTM test level in effect.

An outline of the content and structure is as follows:

• Executive summary
• Introduction
  – Purpose and scope
  – Reference documents
  – Tool description
• Demonstration test results
  – Baseline characterization
    • Test planning
    • Gauge study
• MDC results
• PDC results
• Baseline review
  – Sensitivity analysis
  – Marathon results
  – Cost of ownership
  – Summary and conclusions
• Supplier input

8 CONCLUSION

The SEMATECH 450 DTM is a method for quantifying the performance of a tool or process through systematic testing that produces statistically valid results. The value to the industry of a consistent, standardized test approach that meets the needs of the IC companies and reduces the cost of redundant testing cannot be overstated. Common pre-competitive requirements provides a more positive and productive development environment.

The 450 DTM includes several unique approaches and methods. The incorporation of a method for effectively testing early development stage tools throughout the test scaling process allows for streamlined, cost-effective development testing. The minimization of resources required for test execution by scaling and the application of Bayesian statistical methods while preserving the integrity of the results allows for effective data-driven decisions.

Testing done now, and as part of the development of 450 mm capability for the industry, will create the foundation for even more effective testing, development, and implementation.
Appendix A – 450 EMA Characteristic Matrix

The 450 EMA is performed by conducting a physical inspection of the test tool and its supporting engineering development systems. The evaluation of selected equipment characteristics in comparison to the maturity required for the most rigorous testing level provides the basis for determining the appropriate testing level.

The equipment characteristics listed below are assessed to compare the functional tool capabilities to HVM goals. These characteristics are assessed by physical inspection; some characteristics can be evaluated only by looking into supporting engineering systems. The conformance of each characteristic for each DTM test level, as described in Table A-1, provides the basis for consistent test level determination.

Table A-1 Characteristic Evaluation Matrix

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>450 DTM Test Level</th>
<th>Assessment Performed at Equipment or Offline</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Level 1</td>
<td>Level 2</td>
</tr>
<tr>
<td>Design Specification</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Measurable Process Results</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Safe Operation</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Material Handling Functions</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reproducible Process Results</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Automated Process Recipe</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Remote Functions (Support Equipment)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Equipment Footprint</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Support Module Footprint</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Facilities Layout</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Continuous Processing</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Equipment Functionality</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Automated Operation</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Error Handling/Recovery</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Informal Design for Maintainability (DFM)</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Ease of Operator Use &amp; Software Usability (SU)</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Process and System Stability</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Engineering Documentation</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Engineering Change Control (Hardware)</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Software Revision and Release Control (SRC)</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Environmental Impact Analysis</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Factory Integration Maturity Assessment (FIMA)</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Wafer Process Characterization</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Manufacturing Performance</td>
<td>X</td>
<td></td>
</tr>
</tbody>
</table>

1 – Directly related to process/equipment maturity or demonstration success
2 – Used to detect equipment immaturity
3 – Used to detect supplier development capability immaturity