Failure Mode and Effects Analysis (FMEA): A Guide for Continuous Improvement for the Semiconductor Equipment Industry

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Abstract: This paper provides guidelines on the use of Failure Mode and Effects Analysis (FMEA) for ensuring that reliability is designed into typical semiconductor manufacturing equipment. These are steps taken during the design phase of the equipment life cycle to ensure that reliability requirements have been properly allocated and that a process for continuous improvement exists. The guide provides information and examples regarding the proper use of FMEA as it applies to semiconductor manufacturing equipment. The guide attempts to encourage the use of FMEAs to cut down cost and avoid the embarrassment of discovering problems (i.e., defects, failures, downtime, scrap loss) in the field. The FMEA is a proactive approach to solving potential failure modes. Software for executing an FMEA is available from SEMATECH, Technology Transfer Number 92091302A-XFR, SEMATECH Failure Modes and Effects Analysis (FMEA) Software Tool

Keywords: Failure Modes and Effects Analysis, Reliability, Functional, Risk Priority Number

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1 EXECUTIVE SUMMARY

1.1 Description

Failure modes and effects analysis (FMEA) is an established reliability engineering activity that also supports fault tolerant design, testability, safety, logistic support, and related functions. The technique has its roots in the analysis of electronic circuits made up of discrete components with well-defined failure modes. Software for executing an FMEA is available from SEMATECH, Technology Transfer #92091302A-XFR, SEMATECH Failure Modes and Effects Analysis (FMEA) Software Tool.

The purpose of FMEA is to analyze the design characteristics relative to the planned manufacturing process to ensure that the resultant product meets customer needs and expectations. When potential failure modes are identified, corrective action can be taken to eliminate or continually reduce the potential for occurrence. The FMEA approach also documents the rationale for a particular manufacturing process. FMEA provides an organized, critical analysis of potential failure modes of the system being defined and identifies associated causes. It uses occurrence and detection probabilities in conjunction with a severity criteria to develop a risk priority number (RPN) for ranking corrective action considerations.

2 INTRODUCTION

For years, failure modes and effects analysis (FMEA) has been an integral part of engineering designs. For the most part, it has been an indispensable tool for industries such as the aerospace and automobile industries. Government agencies (i.e., Air Force, Navy) require that FMEAs be performed on their systems to ensure safety as well as reliability. Most notably, the automotive industry has adopted FMEAs in the design and manufacturing/assembly of automobiles. Although there are many types of FMEAs (design, process, equipment) and analyses vary from hardware to software, one common factor has remained through the years—to resolve potential problems before they occur.

By taking a functional approach, this guide will allow the designer to perform system design analysis without the traditional component-level material (i.e., parts lists, schematics, and failure-rate data).

2.1 The Use of FMEA in the Semiconductor Industry

Ford Motor Company requires their suppliers to perform detailed FMEAs on all designs and processes [1]. Texas Instruments and Intel Corporation, suppliers to Ford Motor Company, have implemented extensive training on FMEA as part of their total quality educational programs [2].

The emphasis on FMEA is cited in much of the literature of Japanese system development [3]. In the late 1980s, the Japanese semiconductor manufacturing equipment industry began experimenting with FMEA as a technique to predict and improve reliability. At Nippon Electronics Corporation (NEC), the FMEA process became the most important factor for improving equipment reliability during the design of new systems. In 1990, FMEA became part of NEC's standard equipment design document. The FMEA allowed NEC's equipment engineering group to accumulate design knowledge and information for preventing failures that were fed back to design engineering for new equipment [4]. The chart in Figure 1 shows a correlation between reliability improvement (solid line) and the application of FMEA by the

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NEC-KANSAI engineering team on wafer etching equipment from 1990 to 1991. The reliability growth has been traced back to the standardization of the FMEA. Having a documented process, for the prevention of potential failures has allowed NEC-KANSAI to continue to improve on their reliability.

In today's competitive world market, users of semiconductor equipment should require from their suppliers that FMEAs be initiated, to a minimum, at the functional level of new equipment design. This should allow for a closer, long lasting user/supplier relationship.
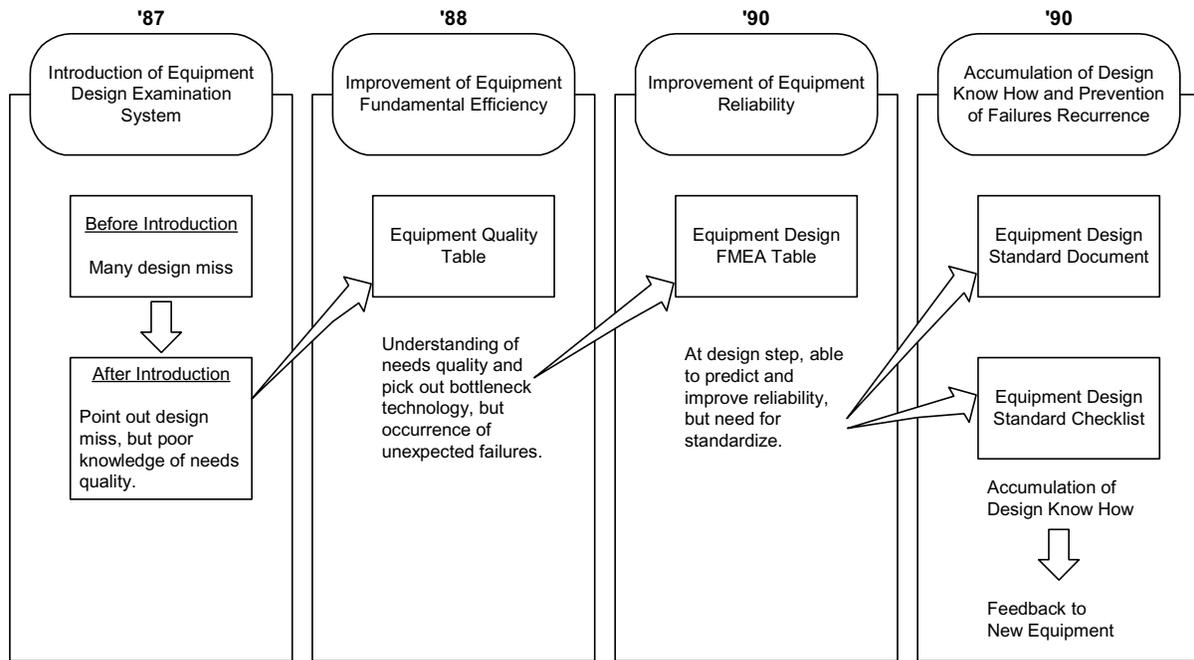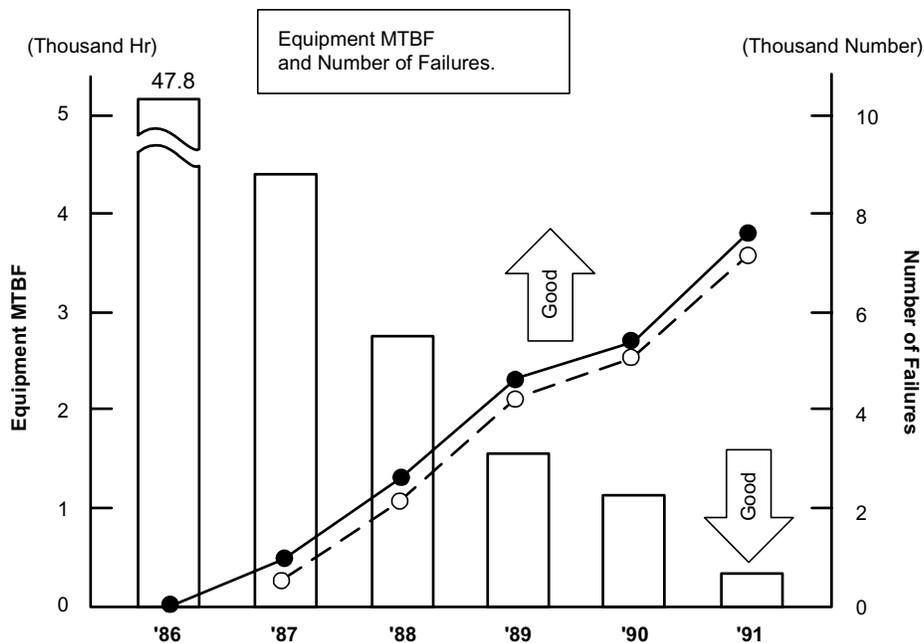
Figure 1   Wafer Etching Equipment Reliability

3   DESIGN OVERVIEW

3.1   Purpose of FMEA

The purpose of performing an FMEA is to analyze the product's design characteristics relative to the planned manufacturing process and experiment design to ensure that the resultant product meets customer needs and expectations. When potential failure modes are identified, corrective action can be taken to eliminate them or to continually reduce a potential occurrence. The FMEA also documents the rationale for the chosen manufacturing process. It provides for an organized critical analysis of potential failure modes and the associated causes for the system being defined. The technique uses occurrence and detection probabilities in conjunction with a severity criteria to develop a risk priority number (RPN) for ranking corrective action considerations.

The FMEA can be performed as either a hardware or functional analysis. The hardware approach requires parts identification from engineering drawings (schematics, bill of materials) and reliability performance data, for example mean time between failure (MTBF), and is generally performed in a part-level fashion (bottom-up). However, it can be initiated at any level (component/assembly/subsystem) and progress in either direction (up or down).

Typically, the functional approach is used when hardware items have not been uniquely identified or when system complexity requires analysis from the system level downward (top-down). This normally occurs during the design development stages of the equipment life cycle; however, any subsystem FMEA can be performed at any time. Although FMEA analyses vary from hardware to software, and from components (i.e., integrated circuits, bearings) to system (i.e., stepper, furnace), the goal is always the same: to design reliability into the equipment. Thus, a functional analysis to FMEA on a subassembly is appropriate to use as a case study for the purposes of this guideline.

3.2   When to Perform an FMEA

3.2.1   Equipment Life Cycle

The recommended method for performing an FMEA is dictated by the equipment life cycle. The early stages of the equipment life cycle represent the region where the greatest impact on equipment reliability can be made. As the design matures, it becomes more difficult to alter. Unfortunately, the time, cost, and resources required to correct a problem increase as well. Toward the end of the design/development life cycle, only 15% of the life cycle costs are consumed, but approximately 95% of the total life cycle costs have already been locked-in [5]. (see Figure 2).

3.2.2   Total Quality

Under the seven assessment categories of The Partnering for Total Quality Tool Kit, FMEA is recommended along with Process Analysis Technique, Design of Experiments and Fault Tree Analysis, as a part of quality assurance that a company should use systematically for total quality control [6]. All indicators from the total quality management perspective and from examination of the equipment life cycle tell us that the FMEA works best when conducted early in the planning stages of the design. However, the FMEA is an iterative process that should be updated continually as the program develops.

3.3 Who Performs the FMEA

The FMEA should be initiated by the design engineer for the hardware approach, and the systems engineer for the functional approach. Once the initial FMEA has been completed, the entire engineering team should participate in the review process. The team will review for consensus and identify the high-risk areas that must be addressed to ensure completeness. Changes are then identified and implemented for improved reliability of the product. The following is a suggested team for conducting/reviewing an FMEA.

- Project Manager
- Design Engineer (hardware/software/systems)
- Test Engineer
- Reliability Engineer
- Quality Engineer
- Field Service Engineer
- Manufacturing/Process Engineer
- Safety Engineering

Outside supplier engineering and/or manufacturing could be added to the team. Customer representation is recommended if a joint development program between user/supplier exists.
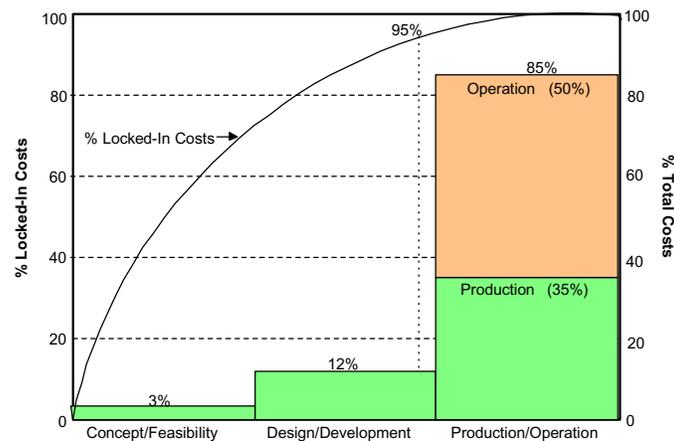
Figure 2   Percent of Total Life Cycle Costs vs. Locked-in Costs

3.4 FMEA Process

Since the FMEA concentrates on identifying possible failure modes and their effects on the equipment, design deficiencies can be identified and improvements can be made. Identification of potential failure modes leads to a recommendation for an effective reliability program. Priorities on the failure modes can be set according to the FMEA's risk priority number (RPN) system. A concentrated effort can be placed on the higher RPN items based on the Pareto analysis obtained from the analysis. As the equipment proceeds through the life cycle phases, the FMEA analysis becomes more detailed and should be continued. The FMEA process consists of the following (see Figure 3):

1. FMEA Prerequisites
2. Functional Block Diagram
3. Failure mode analysis and preparation of work sheets
4. Team Review
5. Corrective action

3.4.1 FMEA Prerequisites

a) Review specifications such as the statement of work (SOW) and the system requirement document (SRD). The type of information necessary to perform the analysis includes: equipment configurations, designs, specifications, and operating procedures.

b) Collect all available information that describes the subassembly to be analyzed. Systems engineering can provide system configuration (i.e., equipment types, quantities, redundancy), interface information, and functional descriptions.

c) Compile information on earlier/similar designs from in-house/customer users such as data flow diagrams and reliability performance data from the company's failure reporting, analysis and corrective action system (FRACAS). Data may also be collected by interviewing: design personnel; operations, testing, and maintenance personnel; component suppliers; and outside experts to gather as much information as possible.

The above information should provide enough design detail to organize the equipment configuration to the level required (i.e., wafer handler, pre-aligner, computer keyboard) for analysis.

6

Start

Review
Requirements

Review
FRACAS
Data

Get System
Description

3.4.1   FMEA Prerequisites

Design Detail

Functional Block
Diagram

3.4.2   Functional Block Diagram

Determine Failure
Modes

3.4.3   Failure Mode Analysis and
Preparation of Worksheets

Severity

Occurrence

Detection

FMEA
Worksheets

Team Review

3.4.4   Team Review

Yes   Changes
Proposed?   No

3.4.5   Corrective Action

Corrective
Action Required

No Change
Required

Distribute to Users:

Design
Engineering

Technical
Support

Manufacturing

Reliable
Equipment

Figure 3   FMEA Process

3.4.2   Functional Block Diagram (FBD)

A functional block diagram is used to show how the different parts of the system interact with one another to verify the critical path.

The recommended way to analyze the system is to break it down to different levels (i.e., system, subsystem, subassemblies, field replaceable units). Review schematics and other engineering drawings of the system being analyzed to show how different subsystems, assemblies or parts interface with one another by their critical support systems such as power, plumbing, actuation signals, data flow, etc. to understand the normal functional flow requirements. A list of all functions of the equipment is prepared before examining the potential failure modes of each of those functions. Operating conditions (such as; temperature, loads, and pressure), and environmental conditions may be included in the components list. An example of an FBD is given in Figure 4 [7].
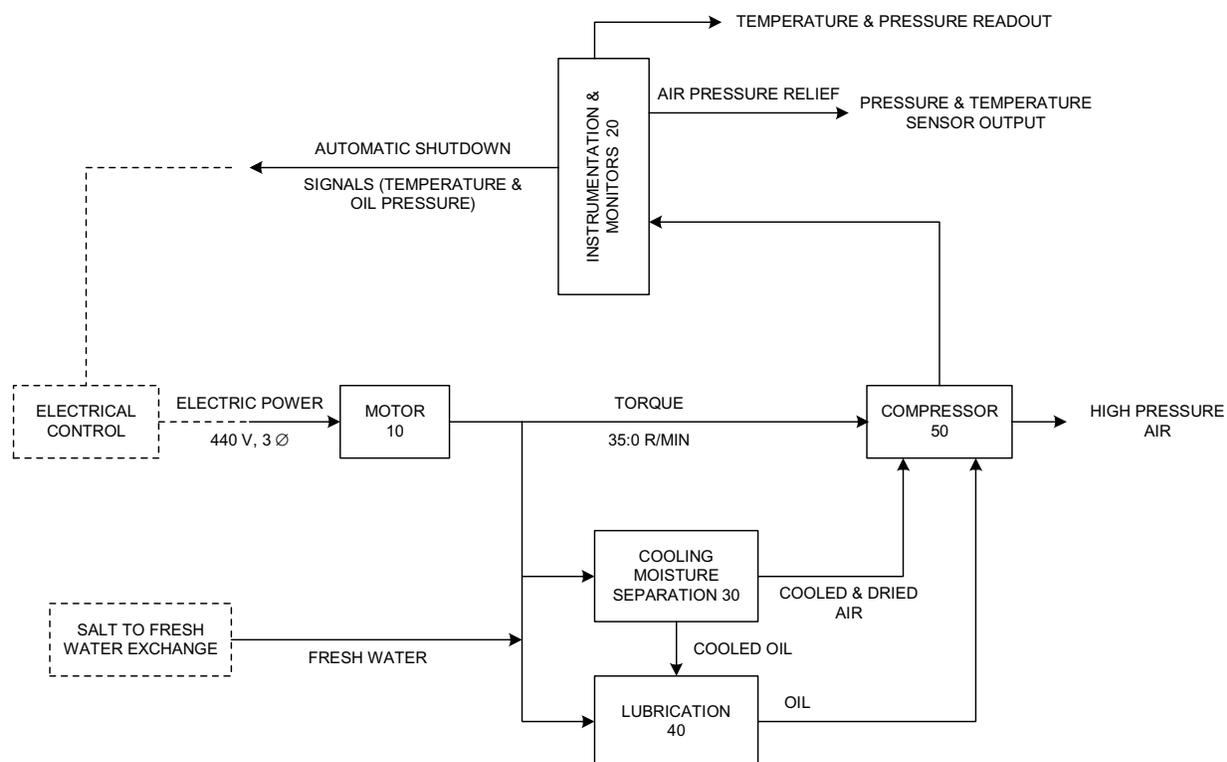
Figure 4   Example of an FBD

3.4.3   Failure Mode Analysis and Preparation of Worksheets

a)   Determine the potential failure modes:

Put yourself in the place of the end user by simply asking, What can go wrong? Assume that if it can it will! What will the operators see?

- Subassembly examples of failure modes
  - Mechanical load positions out of tolerance
  - Multiple readjustments
  - Unspecified surface finish on wafer chuck

- Assembly examples of failure modes
  - Inadequate torque
  - Surface wear
  - Loose/tight fit
  - Interference
- Manufacturing/Process examples of failure modes
  - Over/undersize
  - Cracked
  - Omitted
  - Misassembled
  - Improper finish
  - Rough
  - Eccentric
  - Leaky
  - Imbalance
  - Porous
  - Damaged surface
- Component examples of failure modes
  - Semiconductor open/short (stuck at 0 or 1)
  - Detail parts—Broken wire/part (permanent fault)
  - Worn part (intermittent/transient fault)
  - Noise level (intermittent/transient fault)

The Reliability Analysis Center (RAC) has developed a document designed solely to address component failure mechanisms and failure mode distributions for numerous part types including semiconductors, mechanical and electromechanical components [8].

b) **Determine the potential effects of the failure mode:**

The potential effects for each failure mode need to be identified both locally (subassembly) and globally (system). For example, a local effect on the malfunction of a wafer handler–flip arm could be a wafer rejection, but the end effect could be system failure resulting in equipment down-time, loss of product, etc. Customer satisfaction is key in determining the effect of a failure mode. Safety criticality is also determined at this time based on Environmental Safety and Health (ES & H) levels. Based on this information, a severity ranking is used to determine the criticality of the failure mode on the subassembly to the end effect.

Sometimes we tend to overlook the effects of a failure by focusing on the subassembly itself rather than the overall effect on the system. The end (global) effect of the failure mode is the one to be used for determining the severity ranking. Table 1 and Table 2 are suggested for determining the severity ranking. Refer to Section 4.1 for details.

c)   Determine the potential cause of the failure:

Most probable causes associated with potential failure modes. As a minimum, examine its relation to:
–   Preventive maintenance operation
–   Failure to operate at a prescribed time
–   Intermittent Operation
–   Failure TO cease operation at a prescribed time
–   Loss OF output or failure during operation
–   Degraded output or operational capability
–   Other, unique failure conditions based upon system characteristics and operational requirements or constraints.
–   Design causes (improper tolerancing, improper stress calculations)

For each failure mode, the possible mechanisms and causes of failures are listed on the worksheet. This is an important element of the FMEA since it points the way toward preventive/corrective action. For example, the cause for the failure mode "unspecified surface finish" could be "improper surface finish." Other causes for example on the failure for the mode "excessive external leakage" of a valve might be "stress corrosion resulting in body structure failure."

Other Design causes are:
–   Wall thickness
–   Improper tolerancing
–   Improper stress calculations

Table 3 is suggested for determining occurrence ranking. Refer to Section 4.3.

d)   Determine current controls/fault detection:

Many organizations have design criteria that help prevent the causes of failure modes through their design guidelines. Checking of drawings prior to release, and prescribed design reviews are paramount to determining compliance with design guidelines.

Ask yourself: How will faults be detected? Some detection methods may be through hardware, software, locally, remotely, or by the customer? Preventive maintenance is another way of minimizing the occurrance of failures.

Typical detection methods might be:
–   Local hardware concurrent with operation (i.e., parity)
–   Downstream or at a higher level
–   Built-in test (BIT), on-line background, off-line
–   Application software exception handling
–   Time-out
–   Visual methods
–   Alarms

Determining the detection methods is only half of this exercise. Determining the recovery methods is the second part. Ask yourself: How will the system recover from the fault?

Typical recovery methods:
- Retry (intermittent/transient vs. permanent)
- Re-load and retry
- Alternate path or redundancy
- Degraded (accepted degradation in performance)
- Repair and restart

Table 4 is suggested for determining the detection ranking. Refer to Section 4.3 for more details.

e) Determine the Risk Priority Number (RPN):

The RPN is the critical indicator for determining proper corrective action on the failure modes. The RPN is calculated by multiplying the severity (1–10), occurrence (1–10) and detection ranking (1–10) levels resulting in a scale from 1 to 1000.

$$RPN = Severity \times Occurrence \times Detection.$$

The smaller the RPN the better; therefore, the larger, the worse. A pareto analysis should be performed based on the RPNs once all the possible failure modes, effects and causes, have been determined. The high RPNs will assist you in providing a justification for corrective action on each failure mode.

The generation of the RPN allows the engineering team to focus their attention on solutions to priority items rather than trying to analyze all the failure modes. An assessment of improvements can be made immediately. Priorities are then re-evaluated so that the highest priority is always the focus for improvement.

For example, for a failure mode of:
SEV = 6 (major)
OCC = 7 (fails once a month)
DET = 10 (none)

The RPN is 420 (prior to performing corrective action).

But after performing corrective action, the RPN on the same failure mode becomes 48 as follows:
SEV = 6 (major—no change)
OCC = 2 (fails once every 2 months)
DET = 4 (Preventive maintenance in place)

f) Preparation of FMEA Worksheets

The FMEA worksheet references the "Fault Code Number" for continuity and traceability. For example, the code I-WH-PA-001 represents the following:
I: system I
WH: wafer handler subsystem
PA: pre-aligner subassembly
001:   field replaceable unit

The data that is presented in the worksheets should coincide with the normal design development process, (system hardware going through several iterations). Therefore, the worksheet should follow the latest design information that is available on the baseline equipment block diagram.

The outcome of the worksheets leads to better designs that have been thoroughly analyzed prior to commencing the detailed design of the equipment.

Other information on the worksheet should include:

- System Name
- Subsystem Name
- Subassembly name
- Field Replaceable Unit (FRU)
- Reference Drawing Number
- Date of worksheet revision (or effective date of design review)
- Sheet number (of total)
- Preparer's name

Note that the worksheet is a dynamic tool and becomes labor intensive if it is paper-based. Therefore, an automated data base program should be used. Refer to Figure 5, FMEA Worksheet, for the following field descriptions:

- FMEA Fields Description
- Function – Name or concise statement of function performed by the equipment.
- Potential Failure Mode – Refer to Section 3.4.3.A
- Potential Local Effect(s) of Failure – subassembly consideration. Refer to Section 3.4.3.B.
- Potential End Effect(s) of Failure – Refer to Section 3.4.3.B.
- SEV – Severity ranking as defined in Table 1 and Table 2.
- Cr – A safety critical (Cr) failure mode. Enter a "Y" for yes if this is a safety critical failure mode on the appropriate column.
- Potential Causes – Refer to Section 3.4.3.C.
- OCC – Occurrence ranking based on the probability of failure as defined in Table 3.
- Current Controls/Fault Detection – Refer to Section 3.4.3.D.
- DET – Detection ranking based on the probability of detection as defined in Table 4.
- RPN – Refer to Section 3.4.3.E.
- Recommended Action(s) – Action recommended to reduce the possibility of occurrence of the failure mode, reduce the severity (based on a design change) if failure mode occurs, or improve the detection capability should the failure mode occur.
- Area/Individual Responsible and Completion Date(s) – This area lists the person(s) responsible for evaluation of the recommended action(s). Besides ownership, it provides for accountability by assigning a completion date.
- Actions Taken – Following completion of a recommended action, the FMEA provides for closure of the potential failure mode. This feature allows for design robustness in future similar equipment by providing a historical report.

Reassessment after corrective action

- SEV—Following recommended corrective action.
- OCC—Following recommended corrective action.
- DET—Following recommended corrective action.

- SEV—Following recommended corrective action.
- OCC—Following recommended corrective action.
- RPN—Following recommended corrective action.

3.4.4   Team Review

The suggested engineering team provides comments and reviews the worksheets to consider the higher ranked different failure modes based on the RPNs. The team can then determine which potential improvements can be made by reviewing the worksheets. If the engineering team discovers potential problems and/or identifies improvements to the design, block diagrams need to be revised and FMEA worksheets need to be updated to reflect the changes. Since the FMEA process is an iterative process, the worksheets need to reflect the changes until final design of equipment. When the design is finalized, the worksheets are then distributed to the users, design engineering, technical support and manufacturing. This assures that the recommended improvements are implemented, if appropriate. The worksheets may also provide information to other engineering areas that may not have been aware of potential problems.

It is recommended that the team employ problem solving techniques during their reviews. Basic problem solving tools cited in the *SEMATECH Total Quality Tool Kit* [9] such as brainstorming, flow charts, Pareto charts and nominal group technique are very effective and useful in gaining insight into all possible causes of the potential problems. Team reviews can be structured in accordance with the format found in the *SEMATECH Guidelines for Equipment Reliability* [10].

3.4.5   Determine Corrective Action

3.4.5.1 Design Engineering

Design engineering uses the completed FMEA worksheets to identify and correct potential design related problems. This is where the FMEA becomes the basis for continuous improvement. Software upgrades can also be performed from the worksheet information.

3.4.5.2 Technical Support

From the FMEA worksheets, the engineering team can suggest a statistically based preventive maintenance schedule based on the frequency and type of failure. A spares provisioning list can also be generated from the worksheet. Field service benefits as well as the design engineers.

3.4.5.3 Manufacturing

From the FMEA worksheets, the team could suggest a process be changed to optimize installations, acceptance testing, etc. This is done because the sensitivities of the design are known and documented. FMEA proliferates design information as it is applied. The selection of suppliers can be optimized as well. Statistical process control on the manufacturing floor can also be aided by the use of the FMEA. FMEA can be a way to communicate design deficiencies in the manufacturing of the equipment. If the equipment being manufactured has workmanship defects, improper adjustments/set-ups, or parts that are improperly toleranced, input can be to the FMEA which will in turn make the problem visible to the design engineer. These issues relate to design for manufacturability (DFM). This is one effective way that FMEA can be used to affect DFM since many failure modes have origins in the manufacturing process.

SYSTEM: FAILURE MODE AND EFFECTS ANALYSIS (FMEA)   DATE:
SUBSYSTEM: FAULT CODE #   SHEET:
REFERENCE DRAWING: PREPARED BY:

Subsystem/ Module & Function	Potential Failure Mode	Potential Local Effect(s) of Failure	Potential End Effects(s) of Failure	SEV	Cr	Potential Cause(s) of Failure	OCC	Current Controls/Fault Detection	DET	RPN	Recommended Action(s)	Area/Individual Responsible & Completion Date(s)	Actions Taken	SEV	OCC	DET	RPN
Subsystem name and function	"How can this subsystem fail to perform its function?" "What will an operator see?"	The local effect of the subsystem or end user.	Downtime # of hours at the system level. 2. Safety 3. Environ-mental 4. Scrap loss			"How can this failure occur?" Describe in terms of something that can be corrected or controlled. 2. Refer to specific errors or malfunctions		"What mechanisms are in place that could detect, prevent, or minimize the impact of this cause?"			"How can we change the design to eliminate the problem?" "How can we detect (fault isolate) this cause for this failure?" "How should we test to ensure the failure has been eliminated?" "What PM procedures should we recommend?" 1. Begin with highest RPN. 2. Could say "no action" or "Further study is required." 3. An idea written here does not imply corrective action.	"What is going to take responsibility?" "When will it be done?"	"What was done to correct the problem?" Examples: Engineering Change, Software revision, no recommended action at this time due to obsolescence, etc.				
		Critical Failure symbol (Cr) Used to identify critical failures that must be addressed (i.e., whenever Safety is an issue).						Detectioin Ranking (1-10) (see Detection Table)									
		Severity Ranking (1-10) (see Severity Table)		7	1		5		6	210				6	1	1	6
		Occurrence Ranking (1-10) (see Occurrence Table)											How did the "Action Taken" change the RPN?				
						Risk Priority Number RPN = Severity * Occurrence * Detection											

Figure 5   FMEA Worksheet

4 RANKING CRITERIA FOR THE FMEA

4.1 Severity Ranking Criteria

Calculating the severity levels provides for a classification ranking that encompasses safety, production continuity, scrap loss, etc. There could be other factors to consider (contributors to the overall severity of the event being analyzed). Table 1 is just a reference; the customer and supplier should collaborate in formalizing a severity ranking criteria that provides the most useful information.

Table 1   Severity Ranking Criteria

Rank	Description
1–2	Failure is of such minor nature that the customer (internal or external) will probably not detect the failure.
3–5	Failure will result in slight customer annoyance and/or slight deterioration of part or system performance.
6–7	Failure will result in customer dissatisfaction and annoyance and/or deterioration of part or system performance.
8–9	Failure will result in high degree of customer dissatisfaction and cause non-functionality of system.
10	Failure will result in major customer dissatisfaction and cause non-system operation or non-compliance with government regulations.

If using the severity ranking for safety rather than customer satisfaction, use Table 2 (refer to Section 4.1.1).

4.1.1 Environmental, Safety and Health Severity Code

The Environmental Safety and Health (ES&H) severity code is a qualitative means of representing the worst case incident that could result from an equipment or process failure or for lack of a contingency plan for such an incident. Table 2 lists the ES&H severity level definitions used in an FMEA analysis.

Table 2   ES&H Severity Level Definitions

Rank	Severity Level	Description
10	**Catastrophic I**	A failure results in the major injury or death of personnel.
7–9	**Critical II**	A failure results in minor injury to personnel, personnel exposure to harmful chemicals or radiation, a fire or a release of chemicals in to the environment.
4–6	**Major III**	A failure results in a low level exposure to personnel, or activates facility alarm system.
1–3	**Minor IV**	A failure results in minor system damage but does not cause injury to personnel, allow any kind of exposure to operational or service personnel or allow any release of chemicals into environment.

ES&H Severity levels are patterned after the industry standard, SEMI S2-91 Product Safety Guideline. All equipment should be designed to Level IV severity. Types I, II, III are considered unacceptable risks.

4.1.2   Definitions

–   Low level exposure: an exposure at less than 25% of published TLV or STEL.

–   Minor injury: a small burn, light electrical shock, small cut or pinch. These can be handled by first aid and are not OSHA recordable or considered as lost time cases.

–   Major injury: requires medical attention other than first aid. This is a "Medical Risk" condition.

4.2   Occurrence Ranking Criteria

The probability that a failure will occur during the expected life of the system can be described in potential occurrences per unit time. Individual failure mode probabilities are grouped into distinct, logically defined levels. The recommended occurrence ranking criteria for the FMEA are depicted in Table 3.

Table 3   Occurrence Ranking Criteria

Rank	Description
1	**An unlikely probability of occurrence** during the item operating time interval. Unlikely is defined as a *single failure mode (FM) probability < 0.001* of the overall probability of failure during the item operating time interval.
2–3	**A remote probability of occurrence** during the item operating time interval (i.e. once every two months). Remote is defined as a *single FM probability > 0.001 but < 0.01* of the overall probability of failure during the item operating time interval.
4–6	**An occasional probability of occurrence** during the item operating time interval (i.e. once a month). Occasional is defined as a *single FM probability > 0.01 but < 0.10* of the overall probability of failure during the item operating time interval.
7–9	**A moderate probability of occurrence** during the item operating time interval (i.e. once every two weeks). Probable is defined as a *single FM probability > 0.10 but < 0.20* of the overall probability of failure during the item operating time interval.
10	**A high probability of occurrence** during the item operating time interval (i.e. once a week). High probability is defined as a *single FM probability > 0.20* of the overall probability of failure during the item operating interval.

NOTE: Quantitative data should be used if it is available.

For Example:

    0.001 = 1 failure in 1,000 hours
    0.01   = 1 failure in 100 hours
    0.10   = 1 failure in 10 hours

4.3   Detection Ranking Criteria

This section provides a ranking based on an assessment of the probability that the failure mode will be detected given the controls that are in place. The probability of detection is ranked in reverse order. For example, a "1" indicates a very high probability that a failure would be detected before reaching the customer; a "10" indicates a low – zero probability that the failure will be detected; therefore, the failure would be experienced by the customer. Table 4 ranks the recommended criteria.

Table 4   Detection Ranking Criteria

Rank	Description
1–2	Very high probability that the defect will be detected. Verification and/or controls will almost certainly detect the existence of a deficiency or defect.
3–4	High probability that the defect will be detected. Verification and/or controls have a good chance of detecting the existence of a deficiency or defect.
5–7	Moderate probability that the defect will be detected. Verification and/or controls are likely to detect the existence of a deficiency or defect.
8–9	Low probability that the defect will be detected. Verification and/or controls not likely to detect the existence of a deficiency or defect.
10	Very low (or zero) probability that the defect will be detected. Verification and/or controls will not or cannot detect the existence of a deficiency or defect.

5   FMEA DATA BASE MANAGEMENT SYSTEM (DBMS)

The FMEA worksheet can become labor-intensive if performed manually on paper. A relational database management system (DBMS) is recommended for performing an FMEA (i.e., PARADOX, DBASE, FoxPro, ALPHA4, etc.)

The DBMS should be resident on a local area network (LAN) so that the engineering team can have easy and immediate access to the FMEA information.

An FMEA software tool has been developed, based on this guideline, at Silicon Valley Group, Inc. Lithography Division (SVGL). SVGL has given SEMATECH the rights to distribute the software tool to member companies and SEMI/SEMATECH members. Refer to Appendix A for sample input screens and reports from the SEMATECH FMEA software tool.

6   CASE STUDY

6.1   Functional Approach Example

The following example FMEA of an Automated Wafer Defect Detection System is demonstrated performing a functional FMEA. Prior to performing an FMEA make sure the following items have been satisfied: (Refer to Appendix A for a "Process-FMEA" example.)

- Construct a top-down (similar to a fault tree) block diagram of the equipment. Assign control numbers or a code that makes sense to you to the different blocks (see Figure 6 for a Level II example). A Level II FMEA consists of analyzing each of the subsystems included in the system. Lower levels could be addressed in the same manner.

- Create a function output list from the functional block diagram (Figure 7) and subassembly to be analyzed. See Table 5 for a Level III example.

- From Table 1, select the most appropriate severity ranking for the specific function.

- From Table 3, select the most appropriate ranking for probability of failure for the same function.

- From Table 4, select the most appropriate ranking of probability of detection for the same function.

- Calculate the RPN of each particular failure mode (prior to corrective action).

- Construct an FMEA worksheet according to the information gathered in the analysis. Figure 8, Typical FMEA Worksheet, shows the information gathered from the Automated Wafer Defect Detection example for one failure mode and the associated causes.

- For a quick comparison of RPNs for the different causes to a specific failure mode, generate a Pareto chart. This Pareto chart clearly demonstrates where management should focus efforts and allocate the right resources. Refer to Figure 9 for typical Pareto chart examples.

- At this level, as reflected in the RPN columns of the FMEA worksheet, corrective action was initiated only on the high RPN. Management has clearly implemented the corrective action based on cost, time, and resources. The effects of specific failure modes have been minimized. For this example, the RPN for the potential cause of failure "a-3" changed from 150 to 6 (refer to Figure 8).

LEVEL I

AUTOMATED WAFER DEFECT DETECTION SYSTEM II

LEVEL II

| Wafer Environment WE | Wafer Handler WH | Wafer Motion WM | Microscope MS | Image Sensor IS | Computer CP | Operator Interface OI |
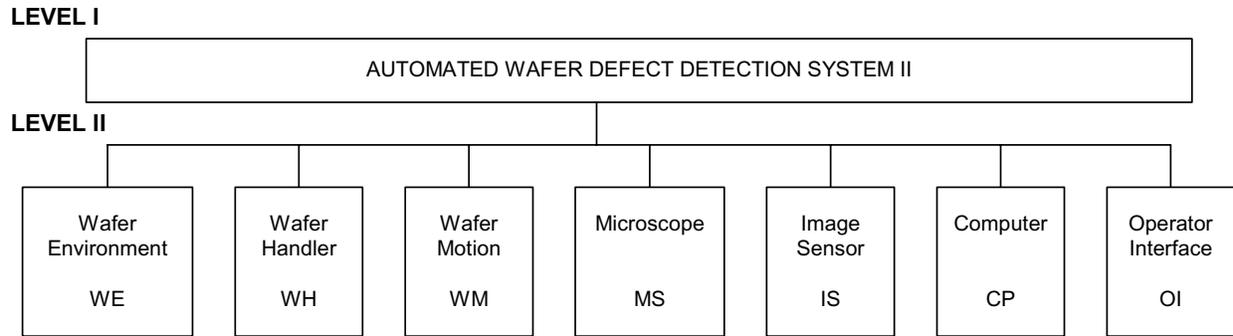
Figure 6   Level II Equipment Block Diagram

Operator Interface II-OI

| Operator Input II-OI-OP | Video Display II-OI-VD | Review Option II-OI-RO | Data Link II-OI-DL |
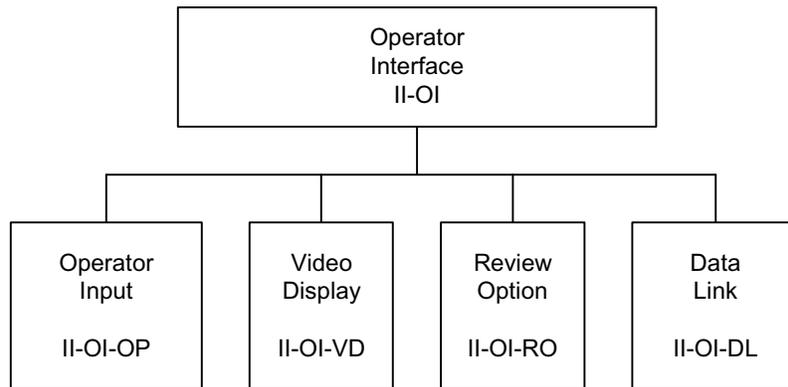
Figure 7   Level III Functional Block Diagram (Simplified)

Table 5   Function Output List for a Level III FMEA

Fault Code No.	Function	Output
II-OI-OP	Operator Input	The main operator interaction is a traditional keyboard for entering key parameters. A mouse is also provided for interaction with the window display.
II-OI-VD	Video Display	There are two color monitors: a 16-inch diagonal high-resolution monitor provides for text and graphical data presentation; a 14-inch color monitor provides for image presentation.
II-OI-RO	Review Option	For review purposes, the 8-bit red, green, blue (RGB) color generation option of the microscope can be used. A joystick is also provided for stage motion control during manual review and program creation.
II-OI-DL	Data Link	Program transfer is accomplished either through RS-232 data link, magnetic floppy disks, or tape drives located in front of the keyboard.

SYSTEM: Automated Wafer Defect Detection   FAILURE MODE AND EFFECTS ANALYSIS (FMEA): FUNCTIONAL ANALYSIS   DATE: May 14, 1991
SUBSYSTEM: Video Display   FAULT CODE # 11-0I-VD   SHEET: 1 of 13
REFERENCE DRAWING: AWDD-S1108237-91   PREPARED BY: M. Villacourt

Subsystem/ Module & Function	Potential Failure Mode	Potential Local Effect(s) of Failure	Potential End Effects(s) of Failure	SEV	Cr	Potential Cause(s) of Failure	OCC	Current Controls/Fault Detection	DET	RPN	Recommended Action(s)	Area/Individual Responsible & Completion Date(s)	Actions Taken	SEV	OCC	DET	RPN
a. 16-inch Color Monitor	a. Loss of video	a. Unable to display operator's input	a. Loss of text and graphical data representation	6		a-1. CRT component failure	2	a-1. Loss of video	1	12	a-1. Recommend the 14-inch monitor be used as a backup to provide operator interface. However, graphical data representation will become degraded due to the loss of high resolution.	a-1. R. Sakone (electrical) and D. Tren (software) will evaluate proposed configuration by 6/15/91.	a-1. Not accepted by the Reliability Review Team. See report AWDD-120.	6	2	1	12
				6		a-2. Graphics PCB failure	3	a-2. System alert	3	54	a-2. Recommend a 16-inch monitor be replaced for the existing 14-inch monitor; so that complete redundancy will exist.	a-2. R. Sakone (electrical) and D. Tren (software) will evaluate proposed configuration by 6/15/91.	a-2. Not accepted by the Reliability Review Team. See report AWDD-121.	6	3	3	54
				6		a-3. Power supply failure	5		5	150	a-3. Recommend multiplexing the two CRT power supplies so that power failures be almost eliminated.	a-3. R. Sakone (electrical) has already reviewed this option. Report is available through BK Barnolli. Date of completion 4/25/91.	a-3. Due to cost and time this option has been accepted by the Reliability Review Team. An Engineering Change will occur on 7/25/91 for the field units S/N 2312 and higher	6	1	1	6

Figure 8   Typical FMEA Worksheet
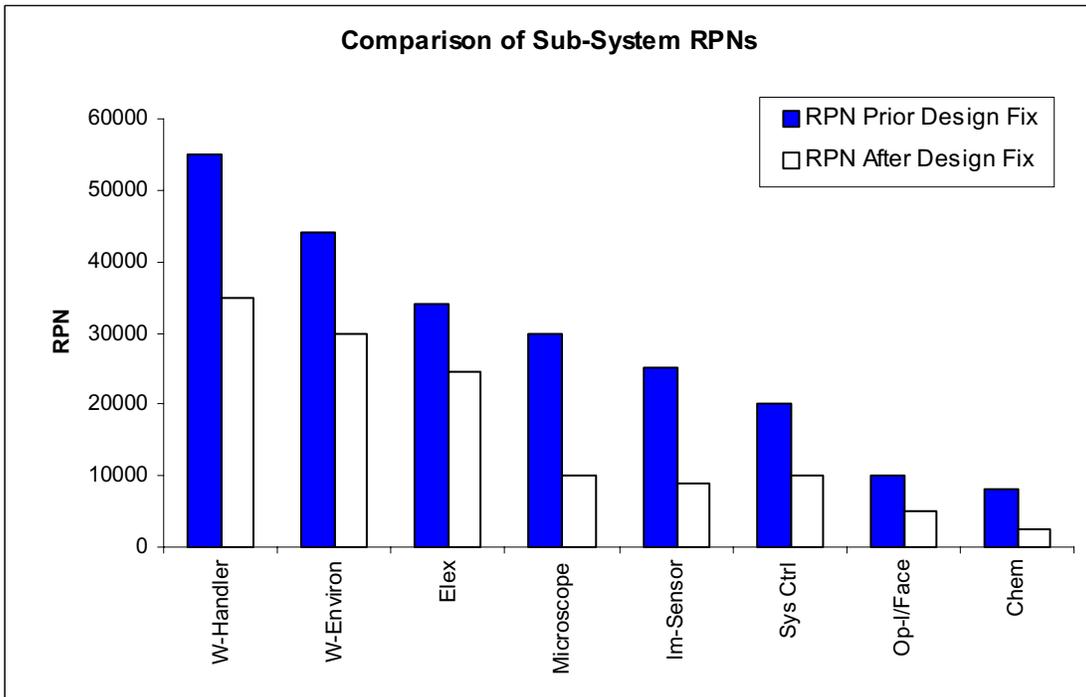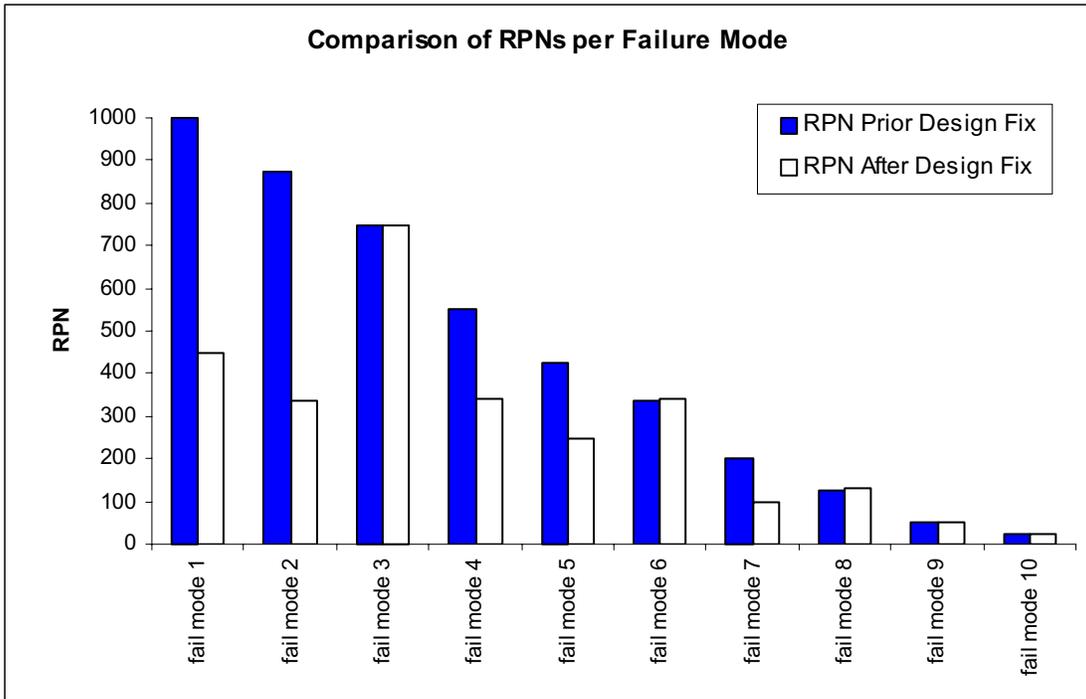
Figure 9   Pareto Charts Examples

7   SUMMARY/CONCLUSIONS

The failure modes included in the FMEA are the failures anticipated at the design stage. As such, they could be compared with Failure Reporting, Analysis and Corrective Action System (FRACAS) results once actual failures are observed during test, production and operation. If the failures in the FMEA and FRACAS differ substantially, the cause may be that different criteria were considered for each, or the up-front reliability engineering may not be appropriate. Take appropriate steps to avoid either possibility.

8   REFERENCES

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[3] Ciraolo, Michael, "Software Factories: Japan," *Tech Monitoring by SRI International,* April 1991, pp. 1–5

[4] Matzumura, K., "Improving Equipment Design Through TPM," *The Second Annual Total Productive Maintenance Conference: TPM Achieving World Class Equipment Managemen*t, 1991

[5] SEMATECH, *Guidelines for Equipment Reliability,* Austin, TX: SEMATECH, Technology Transfer #92039014A-GEN, 1992

[6] SEMATECH, *Partnering for Total Quality: A Total Quality Tool Kit,* Vol. 6, Austin, TX: SEMATECH, Technology Transfer #90060279A-GEN, 1990, pp. 16–17

[7] MIL-STD-1629A, Task 101 "Procedures for Performing a Failure Mode, Effects and Criticality Analysis," 24 November 1980.

[8] Reliability Analysis Center, 13440–8200, *Failure Modes Data,* Rome, NY: Reliability Analysis Center, 1991

[9] SEMATECH, *Partnering for Total Quality: A Total Quality Tool Kit,* Vol. 6, Austin, TX: SEMATECH, Technology Transfer #90060279A-GEN, 1990, pp. 33–44

[10] SEMATECH, *Guidelines for Equipment Reliability,* Austin, TX: SEMATECH, Technology Transfer #92039014A-GEN, 1992, pp. 3–15, 16

APPENDIX A
PROCESS – FMEA EXAMPLE

```
                    SAMPLE SCREENS FROM FMEA SOFTWARE TOOL
                              FOR PROCESS FMEA


Input screen 1:

MASTER DATA EDIT SYSTEM FOR FMEA:
Fields in yellow – Lookup [F1].   Fields in purple – Help [F3].
******************************************************************************
                              FMEA DATA EDIT
                                (Process)        Fault Code:  III-APEX-DEV-001
System:        III (cluster)                         Date:  9/24/92
Subsystem:     APEX (process)              Prepared By:  M. Villacourt
Subassembly:   DEV
FRU:                                       SEV * OCC * DET    = RPN
Refer Draw:    345-D23                       7    4    8      = 224


Process:       DEVELOP
Operation:


Potential:     POOR DEVELOP
Failure Mode:

*****************************************************************************<More>******
[F2] – Save/Quit   [Del] – Delete record   [F10] – Print   [PgDn] – Next Screen
[F5] – Corrective Action




Input screen 2:

MASTER DATA EDIT SYSTEM FOR FMEA:
Fields in yellow – Lookup [F1].   Fields in purple – Help [F3].
******************************************************************************
Potential
Local Effect:  REWORK OF WAFER


Potential      SCRAP OF WAFER
End Effect:
SEV:           7


Safety Critical (Y/N):  N


Potential      TRACK MALFUNCTION – PER HOT PLATE UNIFORMITY
Cause:
OCC:           4


Current:       INSPECTION VIA SEM
Controls/Fault:
Detection:
DET:           8
*****************************************************************************<More>******
[F2] – Save/Quit   [Del] – Delete record   [F10] – Print   [PgUp] – Previous Screen
[F5] – Corrective Action
```

```
help screen 1:
                          SEMATECH, INC.
            Press [Esc] to exit or use normal editing keys to move.

+----------------------------------------------------------------------+
   SEVERITY RANKING CRITERIA
  --------------------------------------------------------------------
   1-2  Failure is of such minor nature that customer (internal) will
        probably not detect failure. Example: Wafer substrate has bad
        pattern.
        --------------------------------------------------------------
   3-5  Failure will result in slight customer annoyance and/or slight
        deterioration of wafer. Example: Not correct thickness; Bad
        coat quality; Not uniformly baked; Wrong dose focus reticle.
        --------------------------------------------------------------
    6   Failure will result in customer dissatisfaction/deterioration
        of part. Example: HMDS has empty canister; Too much Vapor Prime.
        --------------------------------------------------------------
   7-8  Failure will result in high degree of customer dissatisfaction.
        Example: Does not bake properly; Does not develop properly;
        Causes CD problems.
        --------------------------------------------------------------
   10   Failure will result in major customer dissatisfaction and cause
        wafer to be scrapped.
     ====================================================================
   (IF USING)  EH&S Severity Level Definitions      (PRESS PAGE/DOWN)
+----------------------------------------------------------------------+



help screen 2:
                          SEMATECH, INC.
            Press [Esc] to exit or use normal editing keys to move.

+----------------------------------------------------------------------+
   OCCURRENCE RANKING CRITERIA
  --------------------------------------------------------------------
    1   An unlikely probability of occurrence during the item operating
        time interval. Probability < 0.001 of the overall probability
        during the item operating time interval (1 fail in 1000 hours).
        --------------------------------------------------------------
   2-3  A remote probability of occurrence during the item operating
        time interval (i.e., once every two months). Probability
        > 0.001 but < 0.01 of the overall probability of failure.
        --------------------------------------------------------------
   4-6  An occasional probability of occurrence during the item
        operating time interval (i.e., once a month). Probability
        > 0.01 but < 0.10 of the overall probability of failure.
        --------------------------------------------------------------
   7-9  A moderate probability of occurrence during the item operating
        time interval (i.e., once every two weeks). Probability > 0.10
        but < 0.20 of the overall probability of failure.
        --------------------------------------------------------------
   10   A high probability of occurrence during the item operating time
        interval (i.e., once a week). Probability > 0.20 of the overall
        probability of failure.
+----------------------------------------------------------------------+
```

LITHOGRAPHY PROCESS

WAFER SUBSTRATE → HMDS → COAT → PAB → RETICLE LOAD → MICRASCAN (EXPOSE) → PEB → DEVELOP → SEM → ETCH (SCRAP) → YIELD FAILURE
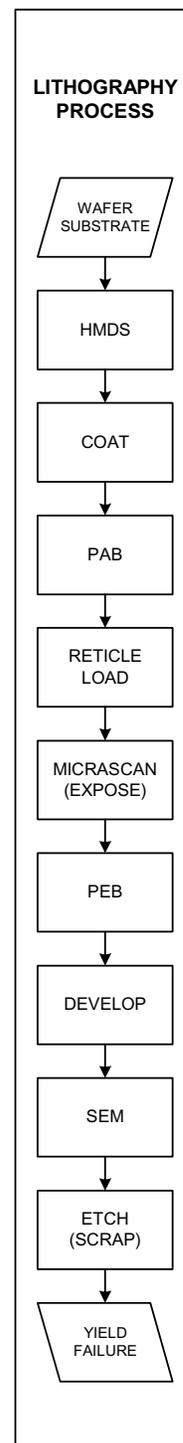
```
help screen 3:
                              SEMATECH, INC.
             Press [Esc] to exit or use normal editing keys to move.

+------------------------------------------------------------------+
   DETECTION RANKING CRITERIA
  ------------------------------------------------------------------
   1-2  Very high probability that the defect will be detected.
        Defect is prevented by removing wrong reticle in STEPPER, or
        removing bad wafer via VISUAL inspection prior operation.
        ----------------------------------------------------------
   3-5  High probability that the defect will be detected.
        Defect is detected during COAT, PAB, or DEVELOP.
        ----------------------------------------------------------
   5-6  Moderate probability that the defect will be detected.
        Defect is detected during PEB or DEVELOP.
        ----------------------------------------------------------
    8   Low probability that the defect will be detected.
        Defect is only detected during SEM.
        ----------------------------------------------------------
   10   Very low (or zero) probability that the detect will be
        detected. Defect is only detected in ETCH or YIELD.
+------------------------------------------------------------------+
```

```
screen 3:

MASTER DATA ENTRY SYSTEM FOR FMEA CORRECTIVE ACTIONS:
Fields in purple - Help [F3].
*******************************************************************************
                        FMEA CORRECTIVE ACTIONS

System:       III          Fault Code:  III-APEX-DEV-001     Date: 9/24/92
Subsystem:    APEX                                  Prepared By:  M. Villacourt
Subassembly:  DEV          FRU:
*******************************************************************************
Recommended:
Actions:        INSTITUTE A WEEKLY UNIFORMITY PREVENTIVE MAINTENANCE PROCEDURE.


Actions:        TRACK COMPANY TO EVALUATE RECOMMENDATION AND PROVIDE RESPONSE
Taken:          TO SEMATECH BY 10/31/92.


Area/Individual Responsible: JOHN JOHNSON, TRACK COMPANY SOFTWARE DIRECTOR
SEV * OCC * DET = RPN
(7) * (2) * (5) = 70
*******************************************************************************
          [F10] - Print        [F2] - Save/return      [Esc] - Quit/no save
```

Report date: 9/24/92   FAILURE MODE AND EFFECTS ANALYSIS: PROCESS FMEA

SYSTEM: III   DATE: September 24, 1992
SUBSYSTEM: APEX-E PROCESS   FAULT CODE: III-APEX-DEV-001
SUBASSEMBLY: DEVELOP   PREPARED BY: M. Villacourt

Function	Potential Failure Mode	Potential Local Effect(s)	Potential End Effects(s)	SEV	Cr	Potential Cause(s)	OCC	Current Controls/Fault Detection	DET	RPN	Recommended Action(s)	Area/Individual Responsible	Actions Taken	SEV	OCC	DET	RPN
DEVELOP	POOR DEVELOP	REWORK OF WAFER	SCRAP OF WAFER	7	N	TRACK MALFUNCTION	4	INSPECTION VIA SEM	8	224	REWRITE TRACK SOFTWARE CODE 123 TO INCLUDE PROCESS RECOGNITION INSPECTION DURING PEB AND WHILE IN DEVELOP	JOHN JOHNSON	TRACK COMPANY TO EVALUATE RECOMMENDATION AND PROVIDE RESPONSE TO SEMATECH BY 10/31/92.	7	4	5	140

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