DESIGN PRACTICES FOR HIGHER EQUIPMENT RELIABILITY

GUIDEBOOK

A PARTNERING FOR TOTAL QUALITY DOCUMENT

SEMATECH

“Reliability is a race without end. And the formula to improved reliability is to build it into every stage of development.”

William J. Spencer,
President and Chief Executive Officer,
SEMATECH, Inc.

“The Best Practice to achieve high reliability is building reliability into products at the earliest stages of design.”

Texas Instruments, Inc.
Product Design Guide for Reliability Assurance

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External Total Quality and Reliability
SEMATECH

ABBREVIATIONS

AGREE	Advisory Group on Reliability of Electronic Equipment
EMC	electromagnetic compatibility
EMI	electromagnetic interference
FMEA	failure mode and effect analysis
FTA	fault tree analysis
I/O	input/output
LC	inductance-capacitance
MCBF	mean cycles between failures
MTBF	mean time between failures
MVT	majority voting technique
PM	preventive maintenance
RC	resistance-capacitance
RFI	radio frequency interference
SM	scheduled maintenance
SEMI	Semiconductor Equipment and Materials International, Inc.

INTRODUCTION

Today's competitive environment demands an increasing level of reliability in semiconductor manufacturing equipment. All semiconductor manufacturing equipment suppliers are becoming more aware of this demand. The industry has made some strides in the last five years in improving reliability. But, as with so much of this business today, reliability improvement is a race without an end. The equipment must satisfy customer reliability requirements *at a cost* the customer is *willing* to pay.

The "best practice" to achieve the higher reliability is to build reliability into products at the earliest possible stages of the design phase.[1] The majority of reliability problems could be designed in an early phase if recognized by the designers.

This guidebook is a tool to assist semiconductor manufacturing equipment suppliers in meeting the higher reliability demand. It is intended to influence the equipment design practices to design reliability into new products and upgrades of older products. It is essential that design engineering personnel practice these principles to ensure that new designs achieve the higher reliability.

The focus of this guideline is on system reliability, realizing that hardware and software are integral parts of the semiconductor manufacturing equipment. However, other guidelines exist[2] that address the issue of software reliability. Thus, the software reliability topic is discussed only briefly.

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[1] SEMATECH. *Guidelines for Equipment Reliability.* 92031014A-GEN. Austin, TX: SEMATECH, Inc. May 1992.

[2] SEMATECH. *Software Process Improvement for Semiconductor Equipment Suppliers: A General Approach.* 92111377A-TR Austin, TX: SEMATECH, Inc. Dec. 4, 1992.

The reliability improvement techniques outlined in this guidebook are not intended to compromise safety or regulatory agency requirements. If a conflict arises, safety and regulatory agency requirements will have priority.

This guidebook is developed with the lessons learned while helping the semiconductor manufacturing equipment suppliers improve the reliability of their equipment. This guidebook will be revised as the necessity arises.

SCOPE

The design practices outlined in this guidebook apply to all the new product lines of semiconductor manufacturing equipment and to upgrades of older product lines, although the guidelines are generic enough to be applied to any equipment or system.

RELIABILITY DEFINITION

Reliability, one of the most important measures of a system's performance, has been used widely in industry for a long time. This section defines reliability and measures of reliability commonly used in the semiconductor manufacturing equipment industry.

Reliability is the probability that a part (or system) will perform its intended functions for a specific period of time, when operated under the stated operational conditions and following a specific preventive maintenance (PM) policy.

SEMI E10[3] contains definitions for several measures of reliability used in the semiconductor manufacturing industry. From these, two popular measures of reliability in the semiconductor manufacturing equipment are as follows:

1. Mean Time Between Failures (MTBF) — the average time the part (or system) performed its intended functions between failures; productive time divided by the number of failures during that time.
2. Mean Cycles Between Failures (MCBF) — the average number of part (or system) cycles between failures; total part (or system) cycles divided by the number of failures. Sometimes, the number of wafers processed is used instead of the number of part cycles.

One *part cycle* is one operational sequence of processing, manufacturing, or testing steps for a part (or system). In some situations, the number of cycles equals the number of product units (e.g., wafers) processed.

A *failure*, as defined in SEMI E10, is any interruption or variance from the specification of equipment operation that requires the replacement or repair of a component (other than a specified consumable) because of degradation or failure. Failures also include any assists that interrupt operation and take longer than six minutes.

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[3] SEMI E10, Guidelines for Definition and Measurement of Equipment Reliability, Availability, and Maintainability.

PROCESS OVERVIEW

The process of designing-in reliability consists of six interrelated steps as shown in Figure 1. The equipment design engineers must use these process steps during the design phase of the overall life cycle phases as shown in the figure. Each step will enhance the reliability; however, maximum benefit is derived only if all the steps are followed. The process starts with knowing the reliability requirements. It has four parallel reliability improvement steps focused around the design step.

The following sections describe these six steps in detail.

KNOW RELIABILITY REQUIREMENTS

If what is required is not known, then it cannot be achieved. Therefore, the first step of designing reliability into a system or a part is to know the reliability requirements. At the beginning of each equipment development program,[4] determine the system-level uptime and MTBF requirements based on the market survey or other input. The requirements should include the following:

- Measure(s) of reliability, e.g., MTBF, MCBF
- Time factor, such as the age of the equipment or the equipment program (e.g., fifth production unit, 2 months after installation, etc.)
- Operational conditions
  - Duty cycle, e.g., 4 hrs / day
  - Throughput rate, e.g., 10 wafers / hr.

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[4] The concept phase is defined in the *Guidelines for Equipment Reliability.* See footnote 1 for a complete bibliographic reference.

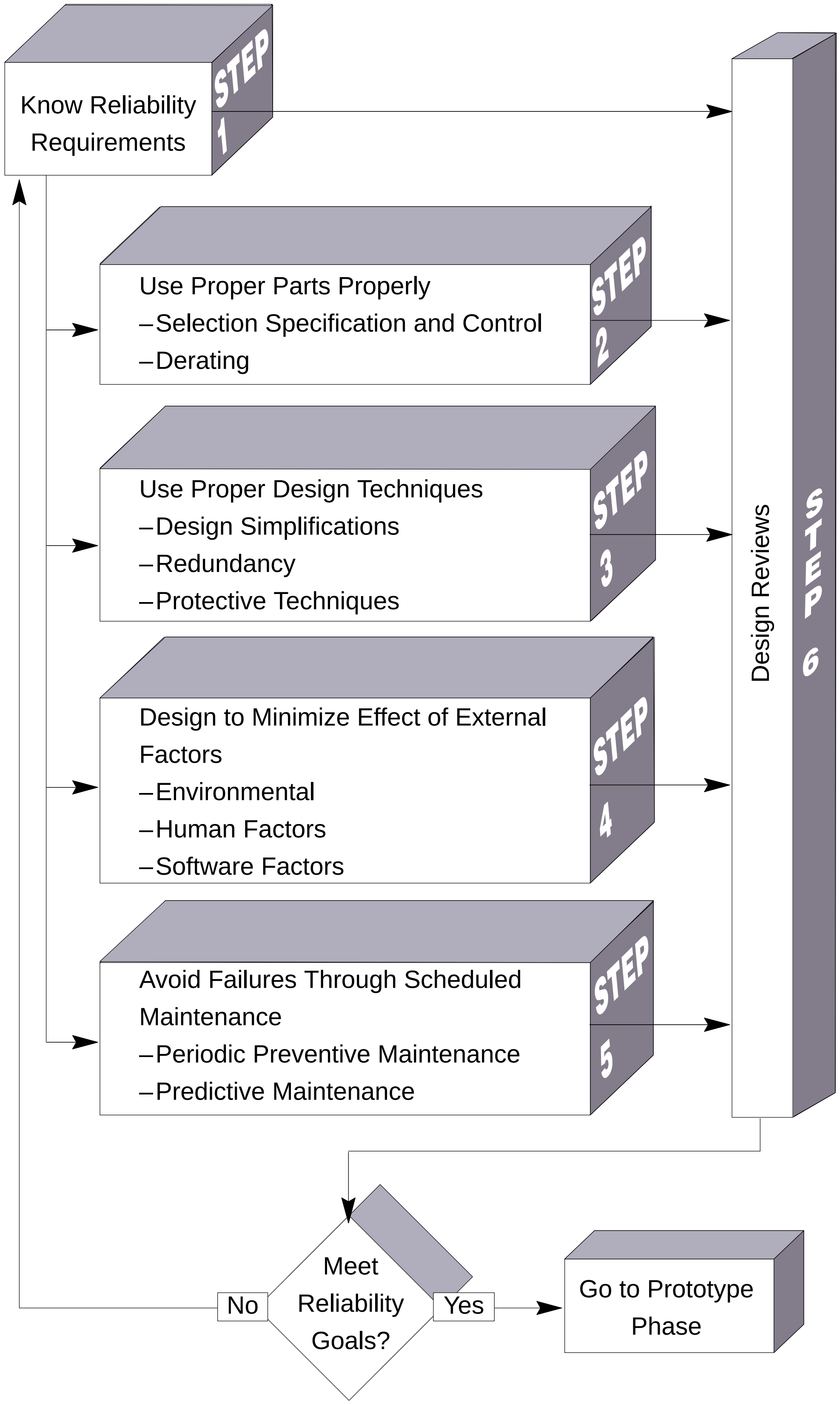

Figure 1 Process of Designing-In Reliability

  - Process to be used, e.g., HFC etch
  - Operator skill level, e.g., grade 12
  - PM policies to be followed, e.g., daily, weekly
- Shipping and installation limitations
- Confidence level for the measure of reliability, e.g., 70%, 90%

Once the system-level MTBF requirement is firmed up, that value is used to develop a reliability budget (allocation) for subsystem and part-level reliability (MTBF) requirements through the AGREE Allocation Method[5] or any other method appropriate for the system.

Example: Reliability Goal and Its Allocations

Goal: System level $MTBF_s$ of the dry etcher system will be 500 hours with 70% confidence, 2 months after installation, when it is shipped by a truck, installed following the installation manual, and operated in Class 10 cleanroom under the following operational conditions:

- Power on: 24 hrs / day, 7 days a week
- Throughput rate: 15 wafers / hr
- Plasma etch process
- Operator skill level: grade 12
- Daily, weekly, and monthly PM policies to be followed

This dry etcher system consists of four modules and software with the following weight factors (based on the module complexity):

Module 1 $W_1 = 6$
Module 2 $W_2 = 10$
Module 3 $W_3 = 3$
Module 4 $W_4 = 6$
Software $W_5 = 5$

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[5] ARINC Research Corporation. *Reliability Engineering.* Englewood Cliffs, NJ: Prentice-Hall, 1964.

Module-level $MTBF_i$ allocation for each individual module is given by:

$$MTBF_i = MTBF_S \times \left(\sum_{i=1}^{5} W_i \right) / W_i$$

Substituting the above values for MTBF and W_i produces the following results:

$MTBF_1 = 2{,}500$ hrs
$MTBF_2 = 1{,}500$ hrs
$MTBF_3 = 5{,}000$ hrs
$MTBF_4 = 2{,}500$ hrs
$MTBF_5 = 3{,}000$ hrs

The module-level MTBF can be allocated to submodule levels or part levels using the above methodology (during the detailed design).

The part-level MTBF requirement becomes a basis for the part specification and selection and for all the reliability techniques outlined in this guidebook. Design engineers should use these values as a basis for (i) continuing system-level MTBF evaluations using reliability modeling, (ii) performing sensitivity analysis, and (iii) developing a scheduled maintenance policy.

USE PROPER PARTS PROPERLY

Parts are the basic building blocks of systems (equipment). A system cannot be more reliable than the building blocks from which it is built. Therefore, the most crucial step of the process to design-in reliability is to select proper parts and apply them properly. This step is divided into two substeps: (i) part selection, specification, and control and (ii) application of the selected parts in the system.

Part Selection

The general rule for part selection is that, whenever possible, the designer should strive to use standard and proven parts in the system design and select a supplier who will meet or exceed the reliability requirements.

Before selecting any part and its supplier,

- Determine the part type needed to perform the required function and the environment in which it is expected to operate.
- Consider this part a reliability-sensitive part if any of the following criteria applies:
  - The part operation is necessary for system operation.
  - The part performs critical functions such as process stabilization or safety.
  - The part has limited life.
  - If the part fails, it would it be difficult to repair.

Select each reliability-sensitive part using the process shown in the Figure 2.

Part Specification

Detailed procurement specifications should include:

- Reliability requirements for the intended application(s)
- Details of intended application(s)
- Reliability qualification procedure
- Capability and accuracy requirements of the part to stabilize the process

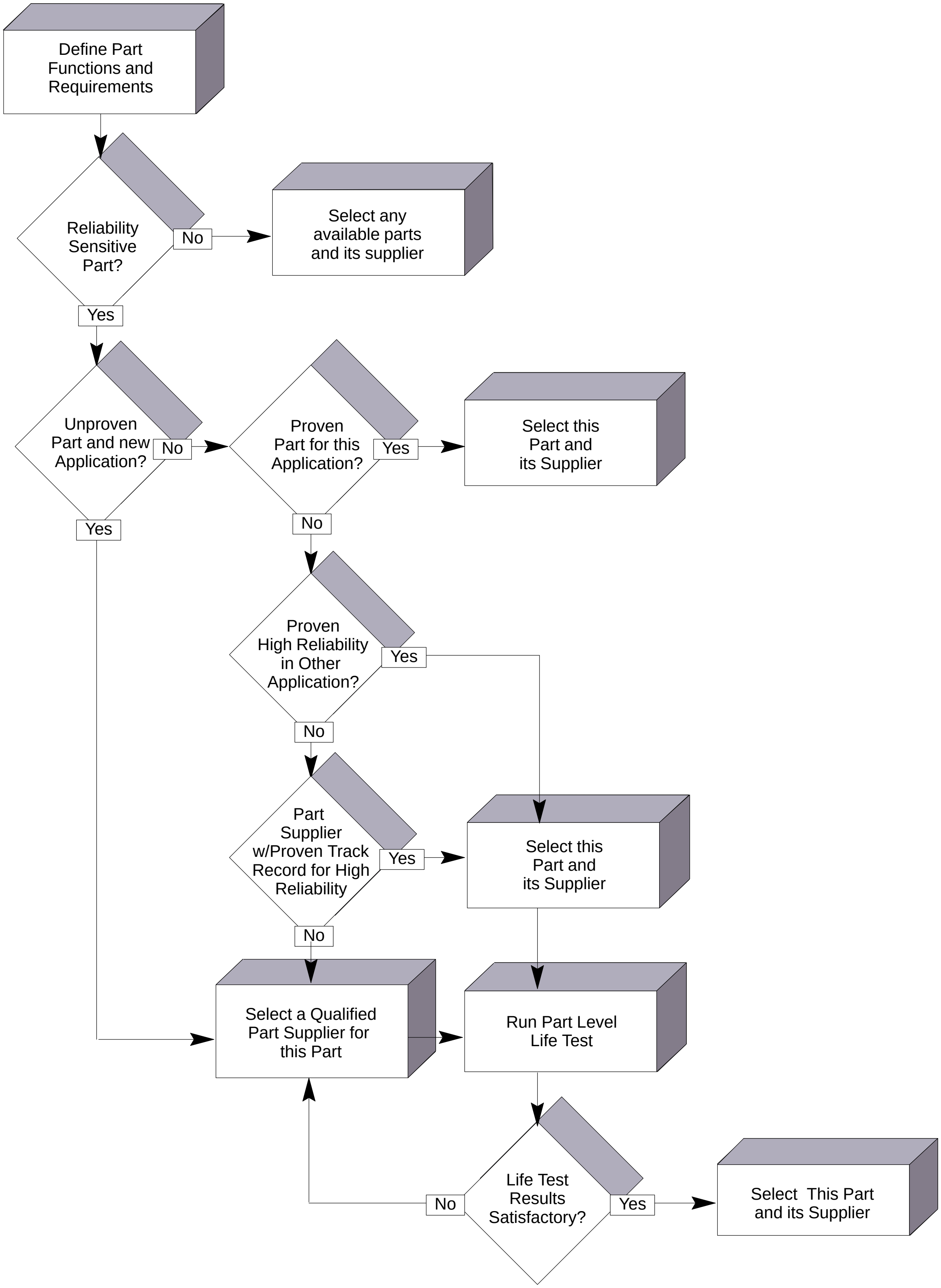

Figure 2 Selection Process for Reliability-Sensitive Part

Part Control

All part suppliers should perform appropriate screening tests during their production to remove defective parts from the production lines. All the defective parts should be tagged and disposed of properly so they do not enter the production line.

Part Application/Derating

Once the part is selected, perform an analysis to compare the expected stress levels of the intended applications with those of the part's rated (capacity) stress levels.

A technique known as *derating* is used to improve inherent reliability of the equipment. In this technique, a part is selected so that it will be operated at less severe stress than the stress level at which it is rated capable of operating.

Select the reliability-sensitive parts that are rated (voltage, power, temperature, corrosive environment, vacuum level, power dissipation, etc.) capable of operating at significantly higher than the respective expected stress levels (at least 100%, safety factor=2).

Use the appropriate derating factors for various electronics components given in Appendix A.

If derating is not feasible, use other alternatives such as preventive maintenance and predictive maintenance (described on page 22) to enhance reliability.

USE PROPER DESIGN TECHNIQUES

Design Simplification

The reliability of any system is a function of its complexity. Anything that can be done to reduce complexity will, as a rule, improve reliability. Put simply, if a part can be eliminated from the design, the effects of its failure are eliminated also. (Figure 3 provides an example of design simplification.) Use the following procedure during the design.

1. During the design review, determine that all parts are required to perform the intended function(s). If a part is not required, eliminate it from the design.
2. If possible, reduce the number of parts through combining functionality. However,
   - Ensure that higher stresses are not imposed on the remaining parts.
   - Do not replace proven reliable parts by unproven or unknown parts in order to perform multiple functions.

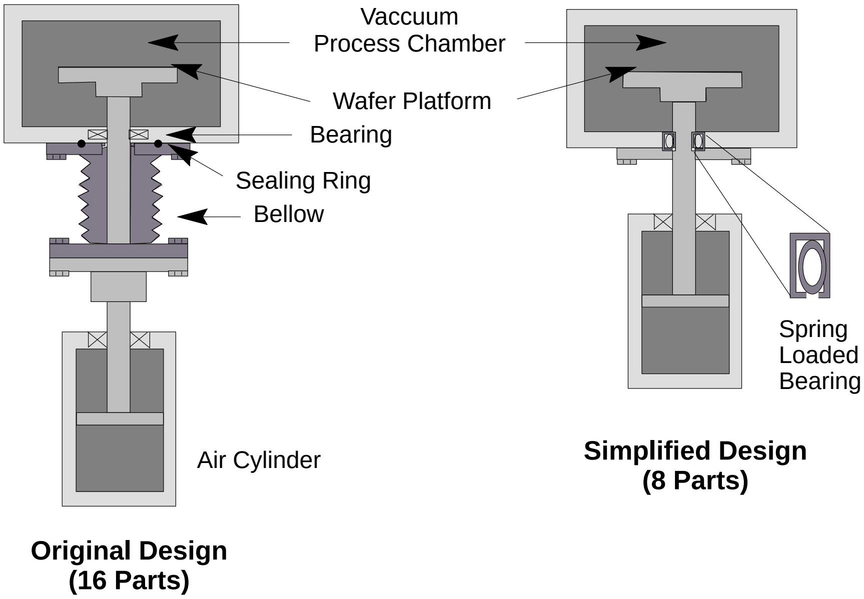

Figure 3 Example of Design Simplification

Redundancy

Contrary to design simplification, redundancy increases the number of parts. However, it is one of the most popular methods in electronics design to achieve the needed level of reliability. *Redundancy* is the provision of more than one part / module for accomplishing a given function so that all parts / modules must fail before causing a system failure. Redundancy, therefore, permits a system to operate even though certain parts / modules have failed, thus increasing system reliability and availability.

For example, if we have a simple system consisting of two identical parallel (redundant) parts / modules, the system MTBF will be 1.5 times that of the individual part / module (using the formula given in the *Electronic Reliability Design Handbook*[6]).

Provide the redundant parts whenever the improved reliability justifies the increased cost. Appendix B depicts the most commonly used redundancies. The *Electronic Reliability Design Handbook* describes many other types of redundancies available to improve reliability.

The application of redundancy will increase weight, space requirements, complexity, cost, and time to design. Both the advantages and disadvantages of redundancy must be carefully considered before a part is incorporated in a system design. It should be used only if the increase in reliability justifies the additional cost.

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[6] Department of Defense. *Electronic Reliability Design Handbook*, Vol. 1. MIL-HDBK-338. Washington, D.C.: Department of Defense. October 15, 1990. Pages 7-45 through 7-73.

Protective Techniques

A *protective technique* is one that includes a means in the design that prevents a failed (or malfunctioning) part from causing further damage to other parts (or system). The following examples of protective techniques should be used in the system design wherever possible:

- Fuses or circuit breakers to sense excessive current drain, to cut off power to the failed parts, and to prevent complete system shutdown
- Thermostat to sense over-temperature conditions and shut down the part or system operation until the temperature returns to normal
- Mechanical stops to prevent mechanical parts from traveling beyond their limits
- Pressure regulator and accumulator to prevent pressure surges
- Surge protectors to prevent damage from power surges
- Interlocks to prevent inadvertent operations
- Route plumbing so that if a leak occurs, the leaking fluid will not damage other parts or the system
- Self-checking circuitry and software to sense abnormal conditions and operate adjustments to restore to normal conditions or to activate switching mechanisms to compensate for the malfunction
- An hour meter to track and display cumulative time

MINIMIZE EFFECT OF EXTERNAL FACTORS

The operating environment is neither forgiving nor understanding; it methodically surrounds and affects every part of a system. If a part cannot sustain the effects of the expected environment, then reliability suffers. First, semiconductor manufacturing equipment suppliers must understand the operating environment and its potential effects. Then, they must select designs and materials that counteract these effects or provide methods to alter or control environmental conditions within acceptable limits.

The design engineers must consider the following external factors affecting reliability.

Heat Transfer

It is known that the temperature significantly changes the physical properties of almost all materials and the rate of almost all chemical reactions. Therefore, poor heat transfer is a major factor affecting reliability.

The following steps minimize detrimental heat effects.

- Use a substitute part that is equally reliable but generates less heat or is capable of withstanding the temperature that occurs.
- Locate the heat generating parts so that their placement results in minimum heat effect on other parts.
- Provide passive heat sinks to remove excess heat by conduction and radiation.

- For high heat-generation areas, provide a proper active heat removal technique such as[7]
  - forced air cooling
  - liquid cooling
  - evaporative cooling
- Insulate surrounding parts from very high heat-generating parts. Each high heat-generating part should have an adequate means to dissipate heat.
- Avoid thermal stress from nonuniform temperatures. Match expansion coefficients of mating parts. Design flexibility into the parts.
- Avoid thermal cycling of the parts. Provide adequate clearance between moving parts to accommodate material expansion and contraction when the temperature changes.
- Provide heat sensors to detect component failures that generate heat.

Shock and Vibration

Typically, equipment will experience shock during shipment and low amplitude random vibration during operation.

Protective measures against shock and vibration are generally determined by an analysis of the deflection and mechanical stress produced by these factors. If deflection or stress exceed safe levels, then take the following corrective measures for the affected parts.

- Isolate the equipment from shock and vibration by incorporating damping devices and stabilizers in the design.

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[7] These methods are explained in detail in “Good Thermal Design,” a tutorial of the 1990 Annual Reliability and Maintainability Symposium, Las Vegas, NV, January 1990.

- Stiffen a support member, and locate and orient the part on the support member so that natural frequency is high and shock and vibration effects are minimized.
- Use self-locking fasteners to mount the part.
- Provide shock mounts or magnetic bearings wherever required.
- Provide shock absorbing buffers between mating parts.

Moisture

Moisture occurs everywhere; therefore, it is the most important chemical deteriorative factor of all. In addition to its chemical effects, such as corrosion of many metals, condensed moisture also acts as a physical agent, such as when it locks mating parts together. It also reacts with some process gases.

Design engineers must use the following design techniques, singly or combined, to counteract the detrimental effects of moisture:

- Eliminate moisture traps by providing drainage or air circulation.
- Use desiccant devices to remove moisture when air circulation or drainage is not possible.
- Apply protective coating wherever required.
- Use materials that are resistant to moisture effects, fungus, corrosion, etc.
- Hermetically seal the parts that are affected by moisture.
- Separate dissimilar metals or materials that might combine or react in the presence of moisture.
- Purge with dry nitrogen to expel ambient moisture.
- Avoid any fluid near the vacuum seal and exposure of any cool component to atmosphere.

Explosion

Semiconductor manufacturing equipment may explode when gases are inadvertently released, creating an explosive mixture. Therefore, the design must

- Provide adequate interlocks and safeguards to avoid any possibility of a gas explosion.
- Purge the process chamber, gas lines, and gas box with nitrogen. Connect the gas box to the plant exhaust system.

Electromagnetic Compatibility

Semiconductor manufacturing equipment must neither cause nor be susceptible to electromagnetic disturbances such as electromagnetic interference (EMI) or radio frequency interference (RFI) in a facility. The equipment, hardware and software, must be designed and installed to assure electromagnetic compatibility (EMC). Take the following precautions to minimize the EMI and RFI effects.

- Hardware Design — Component selection, layout, interconnection, and packing should assure EMC. Locate EMI sources and shield them with EMI shielding material. Locate RFI sources and make sure that they do not leak; use braided wires in the areas where the RFI field strength is strong.
- AC Power — Interfaces should have proper grounding for safety and noise control, power loss protection, and harmonics control. Add fine wires to drain static charges. Use appropriate filtering (such as RC and LC network filters) to lower the interference when sensitive components and signal lines are unavoidably near to EMI/RFI sources.
- Software — The operating system should have automatic fault recovery routines, timeout loops for critical functions, software noise filters, and frequent reverification of status at critical I/O points.

High Vacuum

Some of the semiconductor manufacturing equipment system parts will be exposed to high vacuum. In a high vacuum, material with high vapor pressure sublimates or evaporates rapidly, particularly at high temperature. A chemical atmosphere produced by outgassing and sublimation may have corrosive or poisoning effects. Also, solid sliding surfaces can become cold-welded after losing adsorbed gases. Consider the following design factors for the parts exposed to high vacuum.

- Use material with low sublimation rate.
- Use material that avoids hazardous outgassing atmosphere.
- Use vacuum grease for sliding surfaces.
- Avoid rapid pumping of moist air from any isolated areas.

Human Factors

Equipment failures are caused by both human and equipment malfunctions. Designing human factors into a system is intended to improve human and machine performance during operation, control, maintenance, and support activities. Thus, the overall equipment reliability is influenced not only by the equipment and its associated procedures, but also by the people who use them. The equipment design must consider human reliability factors and their effects on overall equipment reliability. When the interface between the human and the equipment is complex, the possibility of human error increases with an accompanying increase in the probability of equipment failure.

Human Factors Design (*ergonomics*) is a discipline concerned with designing equipment, operations, and work environments to match the range of human capabilities and limitations. Ultimately, everything that one designs has an impact on a human in one way or another. For this reason, designers should be constantly alert to the human factors implications of their proposed design. Keep in mind that the ultimate success of the equipment depends on how well the user performs the tasks associated with it.

The methodology of human factors design is based on a logical and systematic process of

- Understanding and establishing the proper role of the man-machine interface
- Designing the human-equipment interfaces to fit the human's capabilities and limitations
- Evaluating and testing to see that the design fits human capabilities and limitations
- Properly training the humans on the equipment

Consider the following human factors to make sound human-equipment interface designs:

- The equipment must conform to population stereotypes and user expectations.
- It should be easy to learn how to operate the equipment; the human-machine interface should be easy for a typical operator to understand . Orient all controls for operations in a logical order so that operator errors are minimized.
- The equipment must alert the operator when he or she requests a non-normal function. The equipment must bar functions that could create a safety hazard or could damage either the environment or the equipment.
- There should be a simple means to indicate when critical parts of the system are functioning properly. Provide easily perceived displays and simple controls to allow effective and efficient communication between humans and the equipment. When the

system does not perform properly, an alarm or signal should alert the operator and indicators should be provided so the operator can detect malfunctions.

- The tasks allocated to humans and the equipment are based on known relative strengths and weaknesses. Make the combined user-equipment involvement as safe as possible. Neither human nor equipment failures should compromise the user's health, damage the hardware, cause injury to others, or damage adjacent hardware.
- The parts expected to fail during the equipment life must be easily accessible. Subsystems that are difficult to repair must be more reliable.
- Relevant information should be easily accessible so the user avoids relying on memory.
- The performance of equipment functions should be effective and efficient. Maximize the acceptability of the equipment to allow a user to use it efficiently and keep it in good working order with a minimum of effort.
- Minimize the stress that the equipment imposes on the user during use, operation, service, or maintenance. This includes such stress as an undue energy demand, frustration dealing with the equipment, and worry about whether one is using the equipment properly.

Whenever practicable, human factors design engineering specialists must help to identify and solve human factors design problems.[8]

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8. For more detail, refer to W. Woodson's *Human Factors Design Handbook Information and Guidelines for the Design of Systems, Facilities, Equipment, and Products for Human Use* (New York:McGraw-Hill, 1981).

Software Design Factors

Just like the human factor, software design factors are intended to increase and preserve hardware and software performance during operation, control, maintenance, and support activities.

To increase system reliability, consider the following software factors in the hardware and software designs.

- Provide confirmation signals for all the movements.
- Use standard hardware so standard software can be used.
- Use proven software routines whenever possible.
- Design the software system in an evolutionary fashion.
- When possible, design functionality in software rather than hardware.
- Involve software engineers in the requirement definition and design review processes.

The software design must be harmonious with the hardware. Follow the software design guidelines in the *Software Process Improvement for Semiconductor Equipment Suppliers* (see footnote 2) during the software development.

AVOID FAILURES THROUGH SCHEDULED MAINTENANCE

One sure way to improve reliability is to minimize the number of failures that occur during operation. This can be achieved two ways:

1. Select parts that fail less often.
2. Replace a part that is expected to fail soon, before it fails.

The latter method is known as *scheduled maintenance* (SM). When it is not feasible to find a part that fails less often and the reliability requirements are not met, SM can achieve the reliability goals.

If these two situations are properly comprehended during the design phase, they can be avoided through one of the following policies.

Periodic Preventive Maintenance

This is a fixed-period-driven preventive maintenance procedure that is performed to enhance reliability and availability of a system. To implement this policy, choose a predetermined period of operation of the part or of the system, and

- Replace the parts that are partially worn out or aged with new parts before they are expected to fail.
- Inspect, readjust, or clean the parts that require adjustment or become contaminated before they are expected to fail.

This way, system failures are forestalled during the system operation reducing the average failure rate and increasing system uptime. Any failure during the operation is much more expensive than SM, since failures interrupt the operation at an undesirable time. A failing part may also damage other parts, causing system reliability and uptime to further degrade. Thus, it is often economically advantageous to implement a policy of preventive part replacement / maintenance, if a part's reliability is not adequate for the intended operational life of the system.

This procedure applies to a few selected reliability-sensitive parts that have exemplified a sudden increase in their failure rates at predictable times during operation. These parts should be identified and their replacement / maintenance period should be determined based on past semiconductor manufacturing equipment experience or supplier recommendations. Perform a cost trade-off study before recommending that a particular part be included in the system SM policy.

In certain situations, SM reduces scrap and rework in addition to enhancing the reliability.

Predictive Maintenance

Predictive maintenance is a condition-driven scheduled preventive maintenance program. Instead of relying on fixed period-of-life units to schedule maintenance activities, predictive maintenance uses direct monitoring of the mechanical condition, system efficiency, and other indicators to determine the proper time to perform the required maintenance activities. Design engineers must select parts that are appropriate to using this technique.

Any of the following five nondestructive techniques are normally used for predictive maintenance:[9]

- *Vibration monitoring technique* — Monitoring the vibration signature analysis to predict the failure modes that have a distinct vibration frequency or amplitude components.
- *Process parameter monitoring technique* — Monitoring the process efficiency, heat loss, or other nondestructive aspect to predict imminent failure.
- *Thermography technique* — Monitoring the emission of infrared energy (e.g., heat) to detect incipient failures.
- *Tribology technique* — Monitoring lubrication oil analysis, wear particle analysis, and ferrography to predict failure of the bearing-lubrication-rotor support structure system.
- *Visual inspection technique* — Conducting routine visual inspection of all the critical equipment and its parts to detect irregular operation.

DESIGN REVIEWS

Design reviews are an essential element of the design-in reliability process. The main purposes of a design review are to assure that

- Customer requirements are satisfied.
- The design has been studied to identify possible problems (FMEA or FTA).
- All necessary improvements are made using cost trade-off studies.

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[9] These techniques are described in detail in R. K. Mobley's *An Introduction to Predictive Maintenance* (New York: Van Nostrand Reinhold, 1990).

- The alternatives have been considered, and the most satisfactory design has been selected to meet the specified requirements based on cost trade-off studies.
- Feedback is provided to all concerned with the product.

Conduct design reviews on a regular basis as soon as the design feasibility study starts and continue through the production phase. An effective design review team should have representation from each functional area. Table 1 contains the make-up of an effective design team and the responsibilities of each team member.

During the feasibility phase, conduct system-level design reviews using the checklist in Table 2. As the design progresses to the design phase, start conducting part-level design reviews using the checklist in Table 3. Continue both types of design reviews throughout the prototype, pilot production, and production phases.

A design review must be conducted as a checkpoint to release:

- Marketing requirement statements
- Module specifications or engineering specifications
- Key plans such as reliability, quality, etc.
- Engineering drawings to the fab
- The production ramping

TABLE 1 DESIGN REVIEW TEAM MEMBERS AND THEIR RESPONSIBILITIES

Member	*Responsibilities*
Team Leader*	Coordinate and conduct meetings, issue minutes of the meeting and interim and final reports
Design Engineers (Mechanical, Electrical, and Industrial)	Prepare and present design and substantiate decisions with data from tests or calculations
Reliability Engineer	Evaluate design for optimum reliability, consistent with goals
Manufacturing Engineer	Ensure that the design is producible at affordable cost and schedule
Service (Field) Engineer Maintainability Engineer	Ensure that installation, maintenance, and operation considerations are included in the design
Procurement Representative	Assure that acceptable parts and materials are available to meet cost and delivery schedule
Quality Engineer	Ensure that the functions of inspection, control, and test can be efficiently carried out
Material Specialist	Ensure that the material selected will perform as required
Process Engineer	Ensure that the hardware and software will be capable of meeting process requirements
Software Engineer	Ensure that the hardware and software will be compatible and will optimize reliability
Safety Engineer	Ensure that safety issues are resolved
Tool Engineer	Evaluate design in terms of the tooling costs required to satisfy tolerance and functional requirements
Packaging and Shipping Specialist	Assure that the product is capable of being handled without damage
Marketing Representative	Assure that the customers' requirements are met
Toughest Customer (optional)	Include ultimate users' concerns

* Preferred Team Leader is manager of Design Engineering or Reliability Engineering.

TABLE 2 SYSTEM-LEVEL CHECKLIST FOR DESIGN REVIEW TEAM

#	*Item*
1.	Have specific design criteria for system level reliability been established?
2.	Have acceptance, qualification, sampling, and reliability assurance testing been established?
3.	Have specific maintenance criteria for maintainability been established?
4.	Is the design simple? Does it have a minimum number of parts?
5.	Is it designed as a unified overall system rather than an accumulation of parts, etc.?
6.	Are standard high-reliability parts being used?
7.	Are high failure-rate parts identified? Has a PM policy been developed for these parts?
8.	Have limited-life parts been identified and PM requirements specified?
9.	Have critical parts that require special procurement, testing, or handling been identified?
10.	Has redundancy been provided where needed to meet specific reliability goals?
11.	Are there adequate indicators to verify critical functions?
12.	Is there a provision for improvements to eliminate design inadequacies observed in tests?
13.	Have adjustments been minimized and made accessible?
14.	Have stability requirements for all parts associated with each adjustment been established?
15.	Is there a concentrated effort to make the developmental model as near to the production model as possible?
16.	Are there adequate safety precautions taken to satisfy the safety requirement?
17.	Is the design of software control and user interface correct and appropriate?

TABLE 3 PART-LEVEL CHECKLIST FOR DESIGN REVIEW TEAM

#	*Item*
1.	Is the part compatible with the system to be designed?
2.	Are the following requirements established for each reliability sensitive part? – Reliability level (failure rate, MTBF, etc.) – Reliability test – MTTR – Stress levels – Process capability and accuracy requirements for the process stabilizing parts
3.	Is the part a standard high reliability part? If not, can the selected part meet the reliability requirements?
4.	Is the reliability (MTBF) of the part based on actual application of the part?
5.	Has a shelf life of the part been determined?
6.	Have levels of different stress factors been determined?
7.	Have derating factors been used in application of the part?
8.	Have safety factors and safety margins been used in application of the part?
9.	Are the best available methods for reducing the adverse effect of operational environments on the part being utilized?
10.	Have normal modes of failure and the magnitude of each mode for the part been identified?
11.	Have the PM requirements for the part been identified?
12.	Is the part properly integrated and installed in the system?

APPENDIX A: DERATING FACTORS FOR ELECTRONICS PARTS

Component[10]	*Stress Category*	*Derating Factor*
Capacitors, General	Voltage	0.5
Ceramic Capacitors	Voltage	0.5 at < 85°C 0.3 at < 125°C
Supermetallized, Plastic Film, Any Tantalum Capacitors	Voltage Temperature	0.5 at < 85°C less than 85°C
Glass Dielectric, Fixed Mica Capacitors	Voltage Temperature	0.3 at < 85°C less than 85°C
Connectors	Current Voltage Temperature	0.5 0.5 less than 125°C
Quartz Crystals	Power	0.25
Diodes	Voltage Current	0.75 0.5
EMI & RFI Filters	Voltage Current	0.5 0.75
Fuses	Current	0.7 at < 25°C 0.5 at > 25°C
Integrated Circuits (All Kinds)	Voltage Current Power	0.7 0.8 0.75
Resistors (All Kinds)	Voltage Power	0.8 0.5
Thermistors	Power	0.5
Relays & Switches	Current	0.75 for resistive load 0.4 for inductive load 0.2 for motors 0.1 for filament
Transistors	Breakdown Voltage Junction Temp	0.75 less than 105°C
Wires and Cables	Current	0.6

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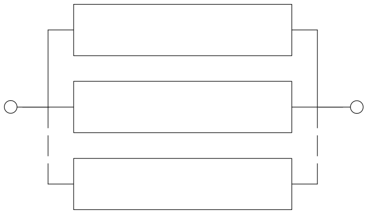
[10] Factors derived from *Electronic Parts, Materials, and Processes for Space Launch Vehicles* (MIL-STD-1574A USAF, December 1987).

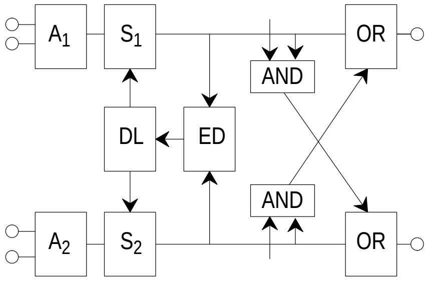
APPENDIX B: MOST COMMONLY USED REDUNDANCY TECHNIQUES

Simple Parallel Redundancy[11]



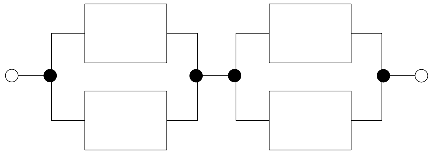
In its simplest form, redundancy consists of a simple parallel combination of elements. If any element fails, identical paths exist through parallel redundant elements.

Duplex Redundancy

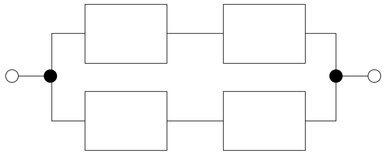


This technique is applied to redundant logic sections, such as A_1 and A_2 operating in parallel. It is primarily used in computer applications where A_1 and A_2 can be used in duplex or active redundant modes or as separate elements. An error detector at the output of each logic section detects noncoincidental output and starts a diagnostic routine to determine and disable the faulty element.

(a) Bimodal Parallel/Series Redundancy



(b) Bimodal Series/Parallel Redundancy



A series connection of parallel redundant elements provides protection against shorts and opens. A direct short across the network is prevented by a redundant element in series. An open across the network is prevented by the parallel element. Network *a* is useful when the primary element failure mode is open. Network *b* is useful when the primary element failure mode is short.

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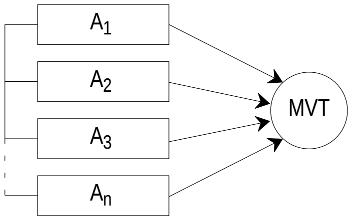
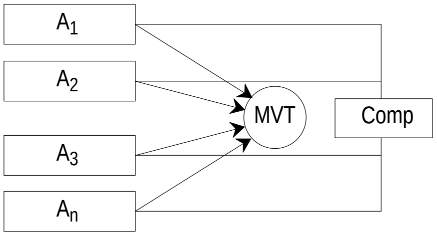
[11] Examples from the Department of Defense *Electronic Reliability Design Handbook*, Vol. 1. See footnote 6 for a complete bibliographic reference.

Majority Voting Redundancy



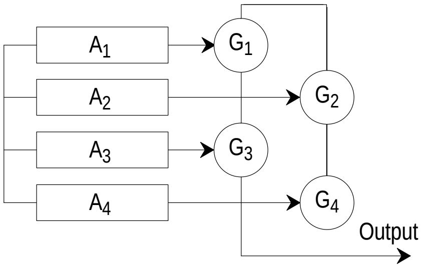
Decisions can be built into the basic parallel redundant model by inputting signals from parallel elements into a voter to compare each signal with remaining signals. Valid decisions are made only if the number of useful elements exceeds the failed elements.

Adaptive Majority Logic



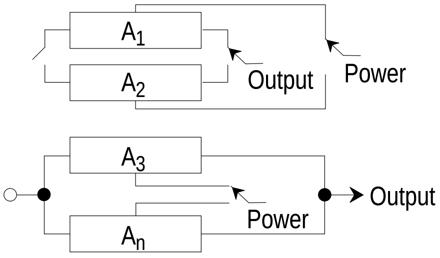
This technique exemplifies the majority logic configuration discussed previously with a comparator and switching network to switch out or inhibit failed redundant techniques.

Gate Connector Redundancy



Similar to majority voting, redundant elements are generally binary circuits. The output of the binary elements is fed to switch-like gates that perform the voting function. The gates contain no components that, if failed, would cause the redundant circuit to fail. Any failure in the gate connector acts as though the binary element were at fault.

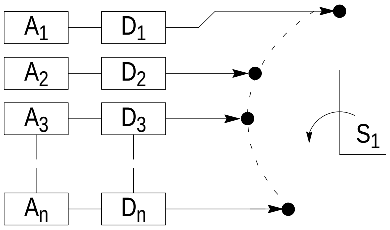
Standby Redundancy



A particular redundant element of a parallel configuration can be switched into an active circuit by connecting the output from each element to switch poles. Two switching configurations are possible.

1. The element may be isolated by the switch until switching is completed and power is applied to the element in the switching operation.
2. All redundant elements are continuously connected to the circuit and a single redundant element is activated by switching power to it.

Operating Redundancy



In this application, all redundant units operate simultaneously. A sensor on each unit detects failures. When a unit fails, a switch at the output transfers to the next unit and remains there until failure.

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2706 Montopolis Drive
Austin, Texas 78741
(512) 356–3500

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