Chapter 10: Qualification Testing Protocols for MEMS

B. Stark and S. Kayali

This guideline has offered detailed physical analysis of the distinct parts and materials used to manufacture a MEMS device. In this chapter, all the information presented will be tied together through the common thread of space qualification. It must be primarily understood that this guideline is not, and was never intended to be, a rigid set of specifications. It is instead a recommendation of qualification methods. Clearly with the vast array of devices used in the industry, it would be difficult to qualify the individual tests needed on a given device.

The proper use of this guide requires referencing to all the chapters. The specifics of qualifying a device depend upon the specifics of the process, materials, and structures in a device. The reason that specific standards were not set for MEMS in space is that many people within the electronics community have complained that these standards limit their device development and do not recognize that some tests on some devices are unnecessary. A further problem with standards is that they often do not take into account mission requirements. It is the ultimate job of the mission designers to determine the thermal ranges and radiation levels expected during the mission. To set these ahead of time, without this foreknowledge, can require expensive overdesigning of parts on short term missions and be too lenient on parts used on longer missions.

In order to improve reliability, qualification should begin as early as possible. History has shown that the reliability of a device will fluctuate over its development cycle as shown in Figure 10-1.

The initial low reliability of prototypes can be attributed to a myriad of causes from design flaws to manufacturing process problems, with a number of other environmental and handling issues having an impact. After this initial period, reliability improves from refinements in device manufacture and from the identification and eradication of predominant failure modes. Once a device is placed into production, there is a regression of reliability stemming from the compromises made to transfer a device from research production to a full scale manufacturing line. With eventual improvements in production processing, reliability should approach the potential device reliability.

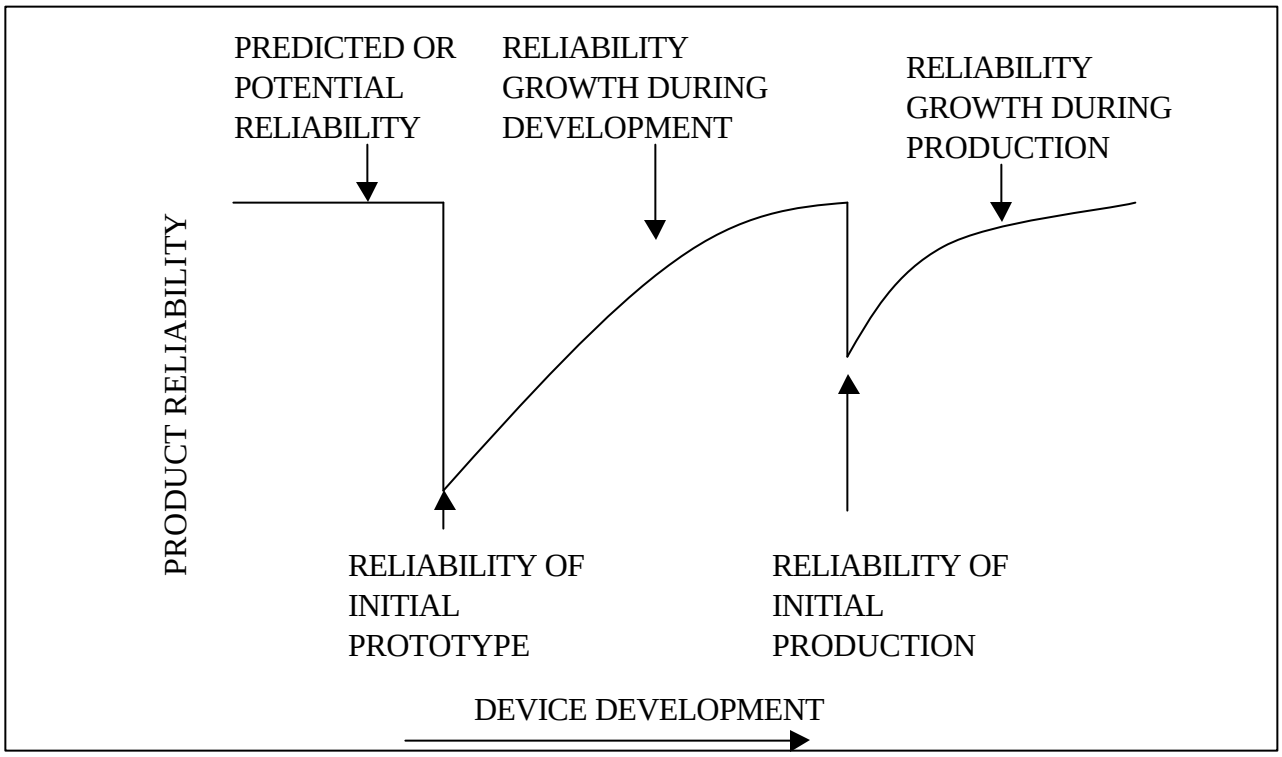

Figure 10-1: Reliability over the development cycle.

These reliability fluctuations from design to production can be minimized by incorporating statistical process control methodologies into device fabrication and by performing life-testing. This step will force reliability improvements to coincide with device production and will ultimately lead to a more reliable device that can be brought to market much quicker than would be otherwise expected. As such, this chapter provides the methods necessary to both limit this reliability swing during device development and to improve long term device reliability.

There is a four-step procedure followed by most satellite manufacturers which includes some practices recommended by Qualified Manufacturers Listing, or QML, programs. These steps of Process Qualification, Product Qualification, Product Acceptance, and Company Certification, are summarized in Figure 10-2. Process Qualification concerns a procedure the

manufacturers should follow to assure the quality, uniformity, and reproducibility of MEMS from a specific fabrication process. Product Qualification encompasses a set of simulations and measurements to establish the mechanical, electrical, thermal, and reliability characteristics of a particular device. Product Acceptance is a series of tests performed on the deliverable device that are designed to ensure that a part meets the program requirements and to provide specific reliability information pertinent to that product. Company Certification focuses on the procedures and management controls that a manufacturer should have in place to assure the quality of their MEMS devices.

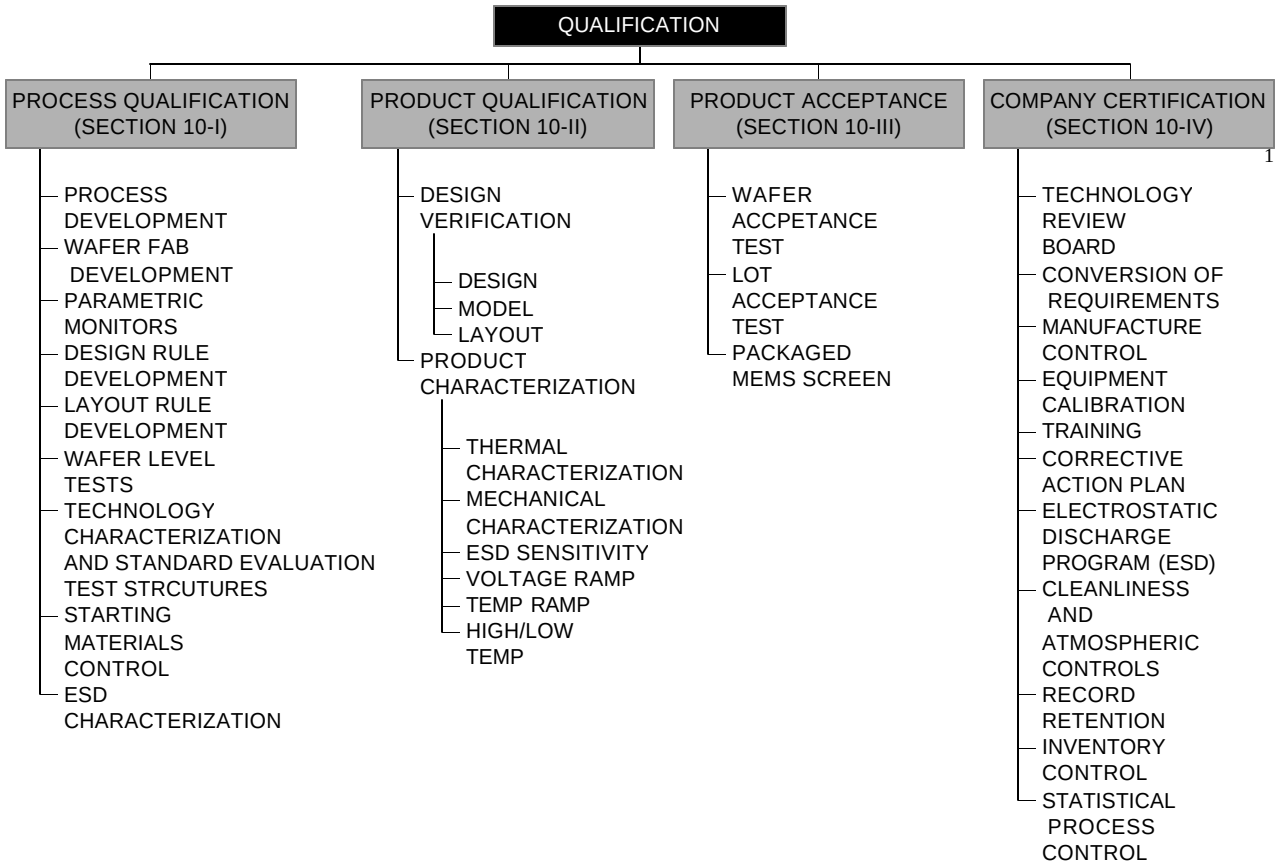

Figure 10-2: Recommended qualification methodology.

Before these four steps are presented in any detail, one important aspect of MEMS qualification must be addressed. Although the manufacturer is ultimately responsible for delivering a reliable MEMS, the overall system reliability is the domain of the MEMS user. For

[1] Company Certification is a process that may only be possible in mature industries. Given the paucity of MEMS foundries, it is uncertain if Company Certification is realizable. For this reason it is suggested, but certainly not required that Company Certification be performed.

this reason, it is in the interest of both parties to understand the expected performance requirements of both the MEMS and the system into which it will be inserted.

I. Process Qualification

Manufacturers who have standardized their production to a single technology will often try to qualify their entire production line. Through this process, the manufacturer attempts to show that its entire production line is under control and operating efficiently. Furthermore, this process enables the manufacturer to establish an electromechanical baseline to use in measuring performance and reliability for all products coming off the line. The benefits of this process are twofold. The manufacturer saves costs and time in the development of future devices, since the reliability and performance characteristics of the constituent parts of a device will have already been established. The user gains both the comfort of procuring parts from an established line with a history of producing qualified parts and the cost savings inherent to a reduced qualification time.

The procedure of qualifying a production line is called process qualification. This is generally defined as the set of procedures that a manufacturer follows to demonstrate that they have control of the entire process of designing and fabricating a MEMS device using a specific process, which will usually be one of the processes listed in Chapter 5. This act addresses all aspects of production, including the acceptance of starting materials, documentation of procedures, implementation of handling procedures, and the establishment of lifetime and failure data for devices fabricated with the process. Since the goal of process qualification is to provide assurance that a particular process is under control and known to produce reliable parts, it needs to be performed only once, although a routine monitoring of the production line is standard. It is important to understand that only the process and basic structures are being qualified and that no reliability information is obtained for a particular MEMS design.

Although process qualification is intended to qualify a defined fabrication procedure and device family, it must be recognized that MEMS technology is evolving at an astounding rate, which requires the continual updating of fabrication procedures. Furthermore, minor changes in the fabrication process to account for environmental variations, incoming material variations, continuous process improvement, or minor design modifications may be required. All of these changes are permitted and frequently occur under the direction of the TRB. Thus, maintaining the status quo does not guarantee maintaining qualification.

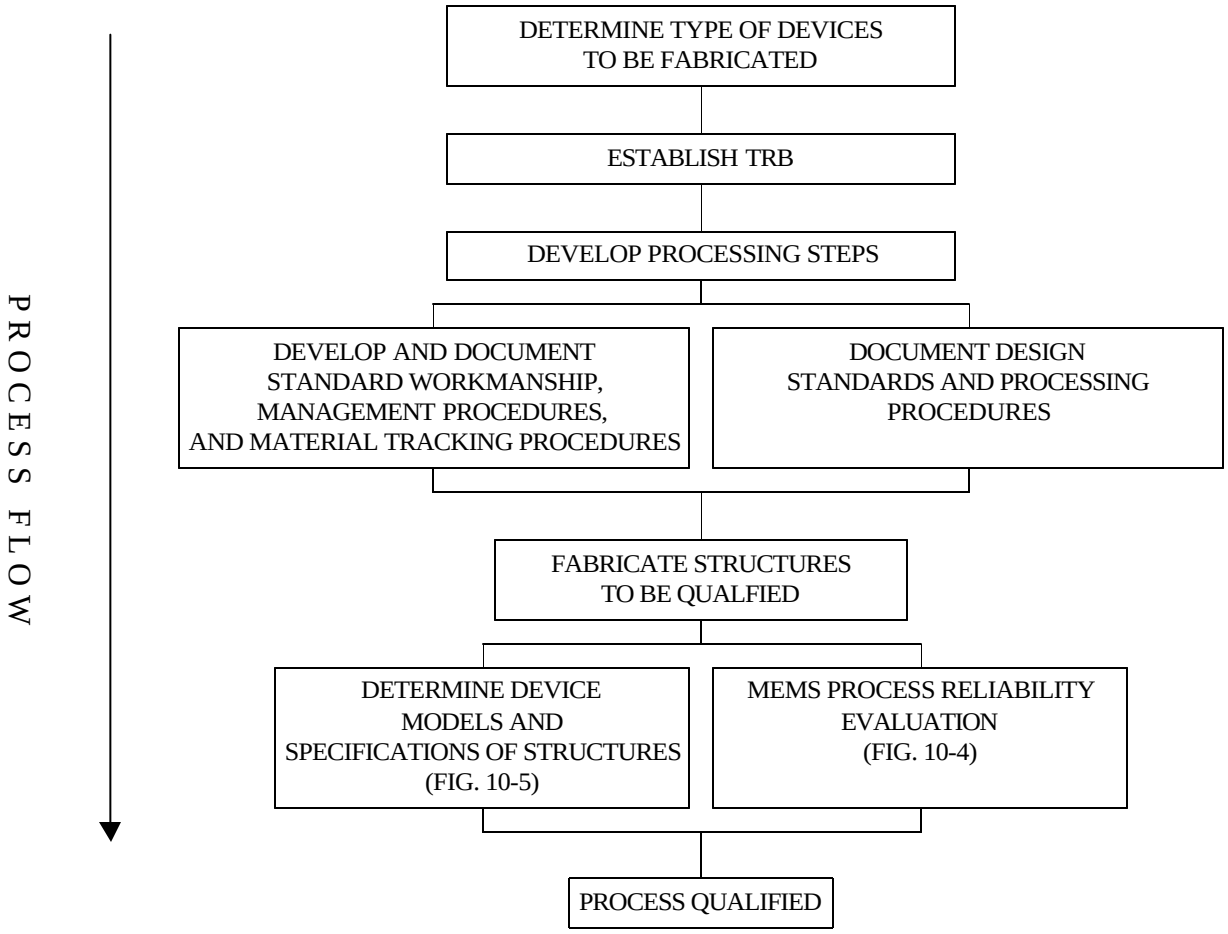

Figure 10-3: MEMS process qualification steps.

The internal documents and procedures used by most manufacturers are summarized in Figure 10-3. In addition to this, the QML program provides guidelines for process qualification. The first step in this procedure is to determine the family of devices to be fabricated and the technology that will be used in the fabrication. After this, the manufacturer will establish a TRB to control the process qualification procedure. After the processing steps have been defined and documented, the workmanship, management procedures, material tracking procedures, and design procedures should be documented. The information contained in the documentation described the process domain that is being qualified.

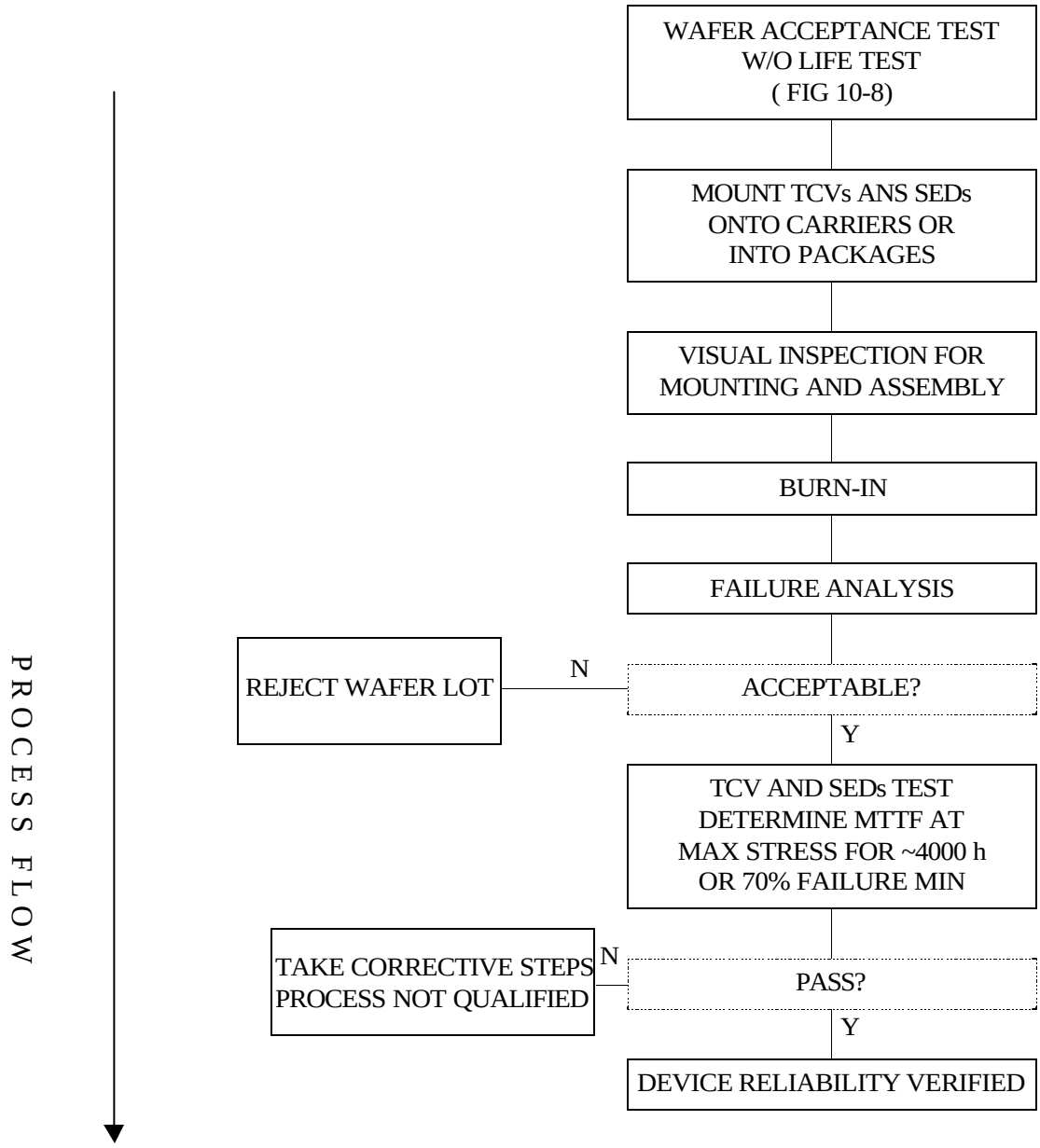

Figure 10-4: MEMS process reliability evaluation.

The qualification process also involves a series of tests designed to characterize the technology being qualified. This includes the properties and the reliability characteristics of components being fabricated on the line. Some of these tests are performed at wafer level, while other tests require the mounting of structures onto carriers. All of these tests and the applicable procedures are an integral part of the qualification program and provide valuable reliability and performance data at various stages of the manufacturing process. Figure 10-4 outlines a recommended series of tests for MEMS process reliability evaluation. The number of devices subjected to each test will normally be determined by the TRB and the rationale for their decision will become part of the process qualification documentation. Clearly a higher level of

confidence exists if more structures are tested, but this must be balanced by the understanding that, after a certain point, the incremental gain in confidence is more than offset by the increase in cost related to the testing. Since the stability of the process is being determined as part of the process qualification, the manufacturer will typically fabricate and test components from several wafer lots. Figure 10-5 provides a series of tests that are recommended to characterize the electromechanical limitations of devices. The performance limitations obtained from these tests often become the basis for limits incorporated into the design and layout rules.

One of the aspects of the processes qualification procedure to note is that the procedure is QML-like and therefore addresses topics similar to those of company certification. The major difference between the two is that company certification is performed by the customer, whereas process qualification is self-imposed by the manufacturer, often before customers are identified. Items particular to process qualifications are described below.

A. Process Step Development

Although the Company Certification process is also fundamental to the process qualification procedure, the actual task of turning a bare wafer into a processed device is often the only task associated with process qualification. While process qualification is actually more involved, processing is the most critical step in process qualification and requires the most time and resources to develop, In addition to this, it is important to recognize that the fabrication procedures and devices processed on the line are the factors that separate one process from another. The first step towards process qualification is the documentation of all the steps necessary to produce a MEMS device. Although all of the steps in the fabrication process should be documented, the details are typically considered proprietary by the manufacturer. Therefore the MEMS customer can expect to see a generalized process flow, but not a detailed account of each step necessary to reproduce a given product on another line.

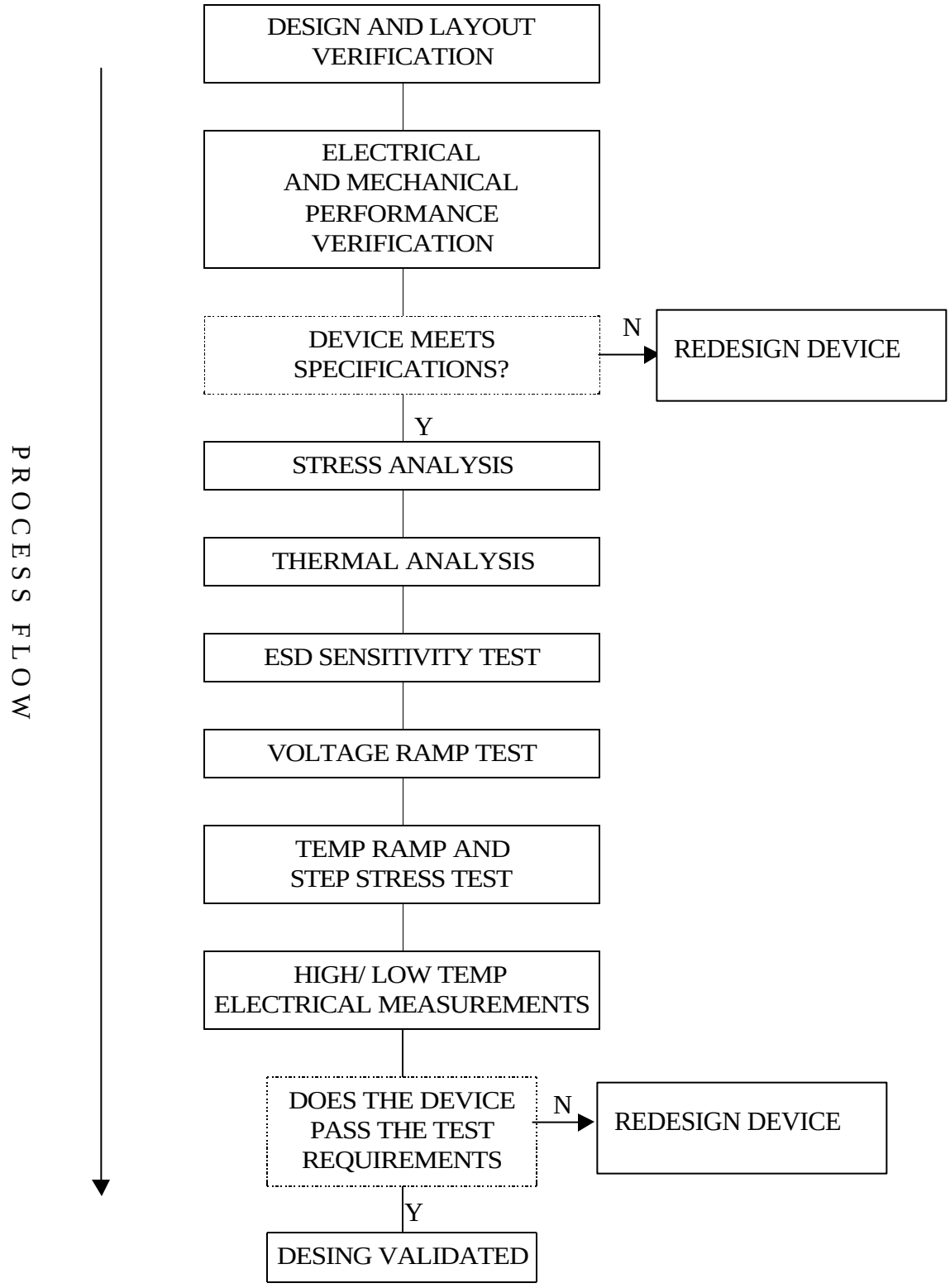

Figure 10-5: Device design validation.

B. Wafer Fabrication Documentation

Once a process is qualified, reliability concerns may still arise from minor variations in the process flow, environment, or starting materials. For this reason, all wafer fabrication steps and conditions should be recorded by the manufacturer to maintain the repeatability of the product. Documentation of these steps and fabrication conditions should be maintained to trace any future quality or reliability concerns to a specific step. Although process travelers can be used to document the fabrication and manufacturing steps, they usually lack the detail necessary to trace quality or reliability problems to specific fabrication steps. The wafer fabrication steps themselves and the documentation describing them are usually considered proprietary by the manufacturer.

C. Parametric Monitors

Parametric monitors are essential for monitoring a production line's quality or continuous improvement. PMs were fully described in Chapter 8; they are mentioned here only to emphasize the fact that the choice of the test structures is dependent on the process and technology being monitored. Therefore, this choice is a critical element in the process qualification procedure. The complete list of parametric monitors is usually combined into a single list that is included on all wafers. The data obtained from the test structures will be normally stored in a database that permits the quick comparison of each wafer fabricated on the line to all of the other wafers. This permits determination of the process stability.

D. Design-Rule and Model Development

The reliability of MEMS fabricated on a qualified process will greatly depend on whether or not they are fabricated from qualified structures according to prescribed rules. In addition to this, the standardization of the structures brings a certain degree of cost reduction. For this reason, part of the process qualification procedure is to determine and document design rules that are specific to the process. Typical information included will be the minimum feature size, maximum etch hole separation, thickness of thin film materials, required overlap in layers, depth of dry etching. While individual processes will compile their own design rules, the list must contain all information necessary to produce a working device. In addition to this information, manufacturers should compile information on the properties of all the materials in the process. Information such as Young's modulus, fracture strength, intrinsic resistivity, stray stress, and thermal characteristics, should be maintained by the manufacturer.

To use standard components in MEMS designs, models must be developed. Although some commercial packages may include models, they need to be altered to fit measured characteristics. Once standardized models are constructed, the chances of design success are greatly increased.

E. Wafer Level Tests

The semiconductor industry strives to reduce production costs by shifting as much testing as possible to the earliest possible point in the production cycle in order to weed out bad wafer lots before more time, and thus money, has been spent on them. The best strategy performs wafer level tests that includes electromechanical characterization, test structure characterization, and environmental performance. Limitations may exist in the level of test detail depending upon the device design and the manufacturer's test capabilities. In general, wafer-level tests are performed, but they must be supplemented with other verifications, such as test fixture or in-package tests. Once agreement between the wafer-level and the package-level tests has been established, the manufacturer may rely on the wafer-level tests for production monitoring.

F. TCV and SED Tests

One of the most important steps in the process-qualification procedure is to determine the electromechanical, environmental, and reliability characteristics of devices fabricated within the domain of the process. This data is obtained through the characterization of TCV and SEDs, as shown in Figures 10-5 and 10-6. All data gathered from these tests should be stored by the TRB. In most cases, the success of a manufacturer in the qualifying process will depend on the data from these tests.

G. Starting Materials Control

The manufacturer should have a mechanism to assure the quality and characteristics of every starting material, from the wafers and chemicals used in the processing steps to the shipping containers used for die/wafer transportation and storage, since they all have a direct impact on the quality and reliability of the final product. Analyses of the chemicals and gases used in processing devices is normally performed by the device manufacturer or the supplier of the chemicals. Traceability and documentation of the characterization results to the individual wafer process lot is essential in resolving any process variation or concerns. The facility audit program can be the vehicle used to determine the manufacturer's level of control.

Most device manufacturers procure wafers from outside suppliers. Procurement requirements imposed by the device manufacturer identify the dislocation density, type of starting material, resistivity, crystalline orientation, and other characteristics that are important to the user. This information can help determine the suitability of the starting material to the process and the material's capabilities. The traceability and documentation of the procurement requirements and wafer characterization can be used to resolve any process variation concerns. Wafer preparation steps, such as initial surface cleaning, can also alter device characteristics and are an important aspect of process control.

Integral to the complete process flow is the mask preparation and the method of identifying changes to the mask sets. The repeatability and quality of the masks should be assessed and documented prior to initiation of the fabrication process.

H. Electrostatic Discharge Characterization and Sensitivity

If not handled properly, several elements used in MEMS can be damaged by ESD. Therefore, every process and design should be characterized to determine ESD sensitivity. Regardless of these results, all MEMS devices should be treated as sensitive to ESD damage. An ESD handling and training program is essential to maintain a low level of ESD-attributed failures.

Inspection, test, and packaging of MEMS should be carried out in a static-free environment to assure that delivered products are free of damage. Devices should be packaged in conductive carriers and delivered in static-free bags. All handling and inspection should be performed in areas meeting "Class 1" handling requirements. Both the manufacturer and the user share the responsibility of assuring that an adequate procedure is in place for protection against ESD.

In general, the following steps can help reduce or eliminate ESD problems in device manufacturing and test areas:

- Ensure that all workstations are static free.
- Handle devices only at static free workstations.
- Implement ESD training for all operators.
- Control relative humidity to within 40 to 60%.
- Transport all devices in static-free containers.
- Ground yourself before handling devices.

II. Product Qualification

Product qualification is the process by which a manufacturer proves that a given device performs its specified task as required by the consumer. To do this, a manufacturer must test a device under a wide range of conditions and collect data proving that the device performed adequately. Every MEMS device, before it is introduced into the market, needs to pass product qualification. Since the process is device specific, even products developed on qualified lines need to go through product qualification. Figure 10-6 shows a product qualification procedure that addresses issues critical to MEMS. Although the exact sequence of tests is not critical, it is recommended that the first two tests, design and performance verification, are conducted first, since unacceptable performance at this stage will require

redesign. Ultimately the exact tests conducted will depend upon the device being tested, which makes it the job of the manufacturer and end-user to determine what tests are necessary. However, the next several sections describe recommended steps that will be common to most MEMS qualification efforts.

A. MEMS Design and Layout Verification

One of the best ways to reduce MEMS engineering cost and improve reliability is to verify the design and layout of the device before fabrication. This is usually done by design reviews conducted both internally and externally by the customer. Commonly this involves structural analysis of all the mechanical subcomponents of the device. With Chapter 6 offering a solid introduction to the mechanical limits of specific structures, it should be evident that the entire device needs to be analyzed to insure that there are no parts experiencing stress over the fracture limits and that there are no unstable device configurations. This analysis should also lead to the development of a structural safety factor, f_s:

$$f_s = \frac{\text{actual stress}}{\text{maximum allowable stress}} \tag{10-1}$$

This analysis will determine a confidence level for a device based upon its design. Clearly, the higher the factor of safety, the better a part is suited for high-rel applications. However, a high factor of safety often impedes both device cost and performance. Ultimately it is up to the user to determine what safety margins are acceptable. Typically the verification process involves representatives from different departments working together to make sure that both the theoretical design and the actual on-chip implementation are sound. These reviews should be conducted after design, after layout, but before mask making, and after final MEMS characterization.

B. Electromechanical Performance Verification

After a device has been fabricated, but before any of the expensive qualification tests have been conducted, it is recommended that a basic performance evaluation is conducted. This involves taking a device and subjecting it to normal operating conditions. The output should be measured and compared with expected values. If the device cannot operate as expected, then there is no need for further evaluation of it. Upon passing these basic tests, more extensive tests can be conducted.

C. Thermal Analysis

Thermal analysis is an important part of determining the expected lifetime of any ASIC sub-components of a MEMS device. Since electronic components' expected lifetime is exponentially related to temperature, it is important to look for any hot spots on a device that

could significantly impinge device lifetime. This can be done analytically through the equations of thermodynamics, but it is more often done through external examination. This test needs to be conducted over the operating range of the device. For structural components, this test can reveal areas of high stress, as there is a mechanical dissipation of stress through heat. It is also important to perform this test in thermally activated devices.

D. ESD Sensitivity Tests

It is quite conceivable that some MEMS devices will be sensitive to ESD damage, and therefore the ESD characterization given in reference [38] should be conducted to determine the sensitivity of the design. While literature on ESD and MEMS is essentially nonexistent, certain electrostatic components of MEMS would appear to be susceptible to ESD. Until more tests are conducted on the ESD sensitivity of MEMS, these devices should be treated as "Class 1" devices.

E. Voltage Ramp

The sensitivity of a MEMS device to voltage overstress and the absolute maximum voltage ratings are determined during the voltage ramp test. Testing is normally done by ramping the power supply until a catastrophic failure occurs. Ramp rates and step duration are a function of the design limitations, but the test should allow the device to stabilize at each step. After the test, an analysis is recommended to determine the exact failure site. Failure-point definition should be in conservative agreement with the device data sheet and design limits

F. Temperature Ramp

A temperature ramp is a useful test to run on a device slated for space insertion. This involves ramping temperature up and down from ambient until failure or severe output degradation occurs. The duration of the individual steps may vary, but they should be long enough to insure that the device reaches thermal equilibrium. This will allow a determination of the allowable operating limits of the device, keeping in mind that high temperature operation can significantly weaken the lifetime of electrical subsystems and is not recommended, even if it is possible. As with voltage ramping, failure analysis is recommended after the test and failure points should be in conservative agreement with the device data sheet and design limits.

III. Product Acceptance

MEMS that are designed by qualified engineers, fabricated on process qualified lines, and verified to meet design goals may still exhibit poor reliability characteristics. This can be due to a myriad of reasons including variations in the fabrication process, undetected materials flaws, and packaging induced stress. No matter what the actual cause, these devices must be screened out before they are integrated into high-rel systems. For this reason, manufacturers of

all high-rel systems require devices to pass a series of product acceptance tests, in order to increase the confidence in device reliability. It is this step in the qualification process that is significantly different for space qualified MEMS as opposed to commercial grade devices.

The level of testing performed during product acceptance is a function of the form of the deliverable. For example, the first level of acceptance testing, called "wafer acceptance test" is performed at the wafer level to assure the uniformity and reliability of the fabrication process through a wafer to wafer comparison. The lot acceptance test for die is a second level test that provides further reliability information, but only on a sample of MEMS, due to the difficulty in performing full characterization on unpackaged devices. It is used if the MEMS user has requested the MEMS to be delivered in die form for integration into a larger module. This sample testing will provide the user with only an estimate of device reliability, with no knowledge of the impact packaging will have upon final device reliability. If packaged parts are requested instead, a full screening can be performed and the user should have the assurance that the delivered parts are reliable. The acceptance testing procedure is summarized in Figure 10-6.

The recommended product acceptance test for die deliverable is shown in Figure 10-7. Note that there are three levels of testing within the procedure and each starts with the wafer acceptance test shown in Figure 10-8. The lowest level of testing is required for MEMS that have already been product qualified and have been manufactured on a qualified process line, whereas the highest level of testing is required for a new circuit design that is processed on an unqualified line. Whichever level of testing is required, the same level of reliability assurance should be granted to the MEMS device upon completion of the lot acceptance test. The cost and time advantage of buying MEMS from manufacturers with qualified processes and validated circuit design should be both self evident and substantial.

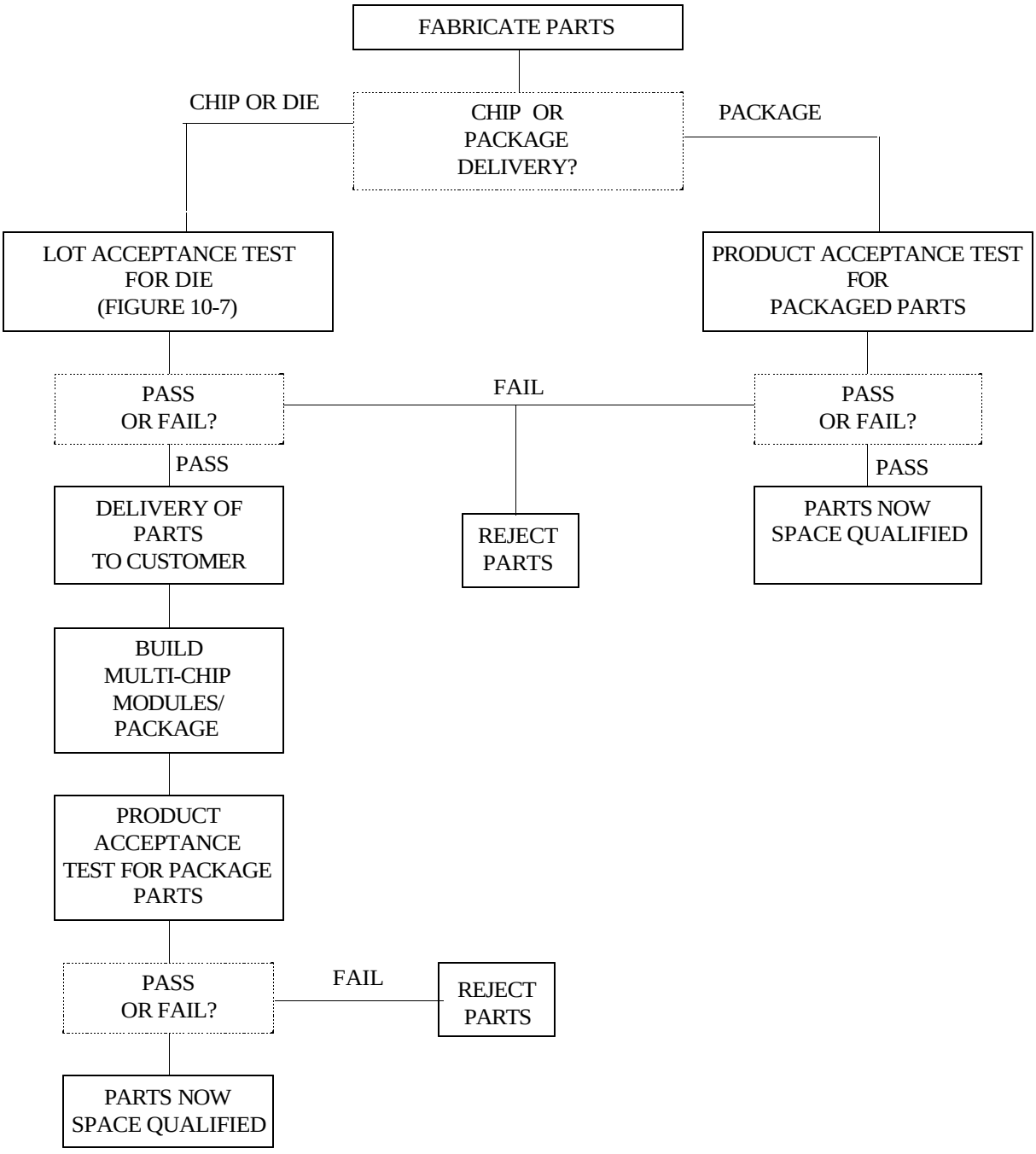

Figure 10-6: MEMS part qualification overview.

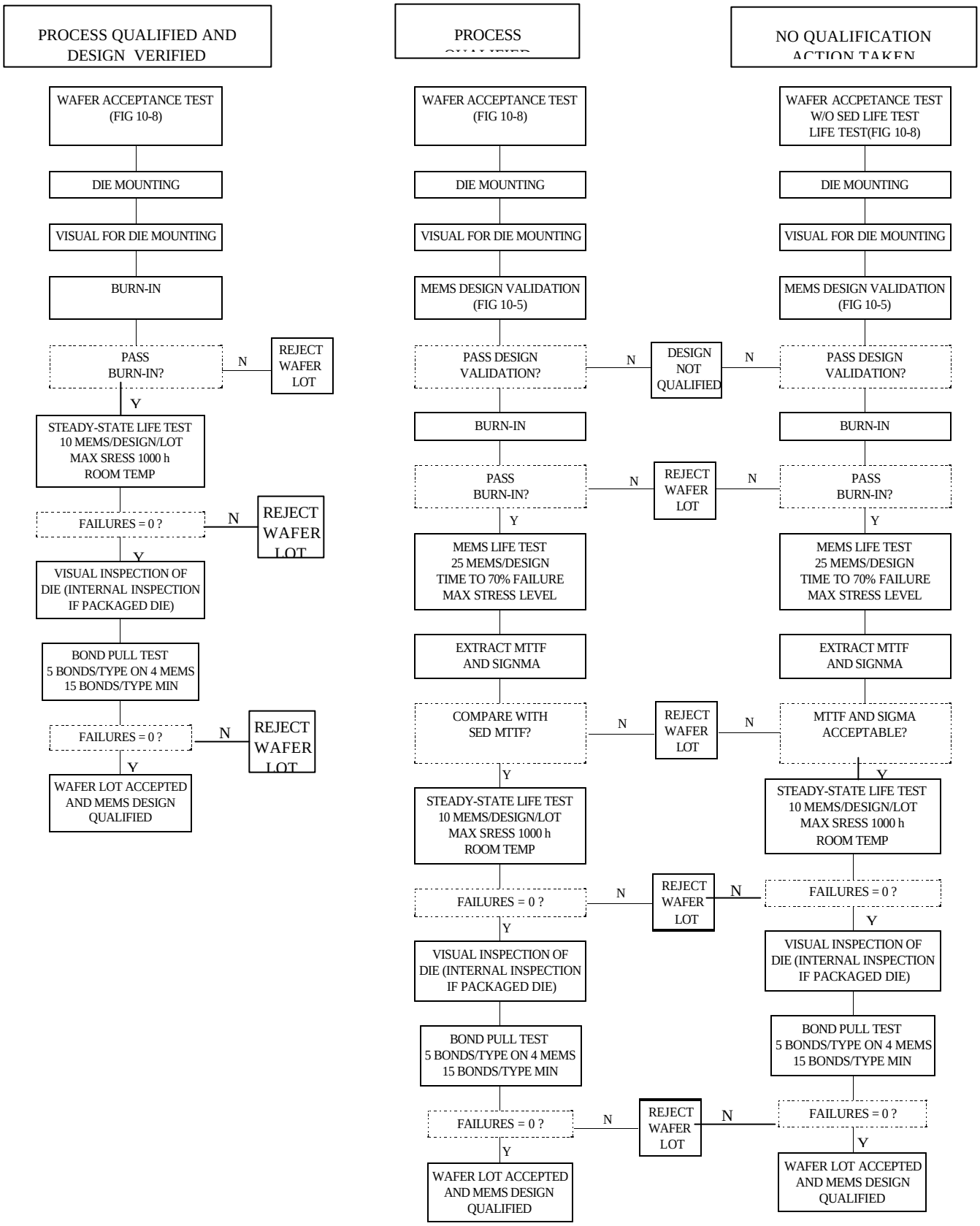

Figure 10-7: Lot acceptance test for die.

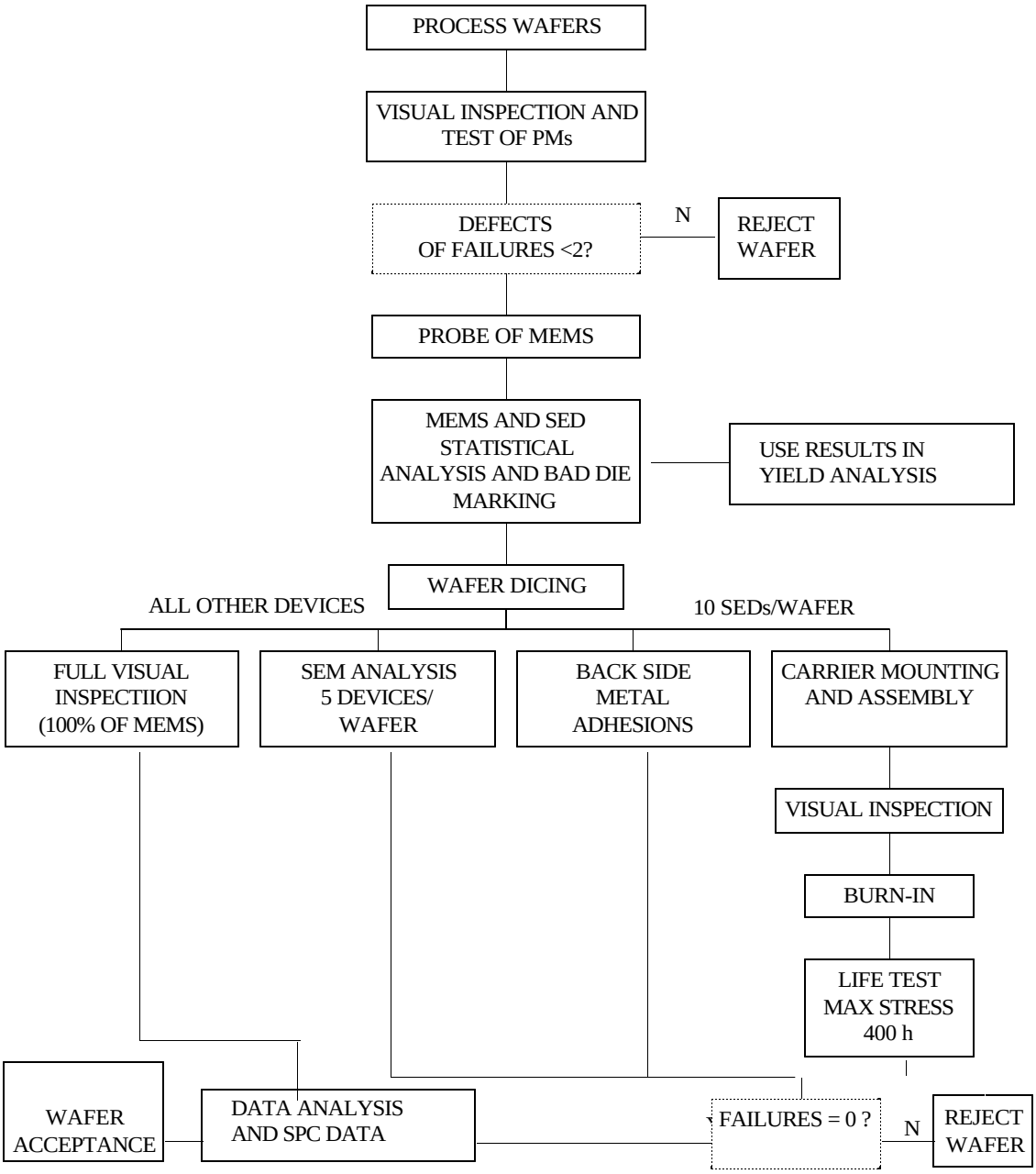

Figure 10-8: Wafer acceptance test.

It is assumed either that a product acceptance of die deliverables is performed on the devices before they are inserted into the packaging process or that a subgroup of the parts can be removed from the packaged parts and life testing performed on them in a way similar to that recommended for the die deliverables. Thus, this screen adds further reliability information to the data obtained from the wafer and lot acceptance tests. 100% of the packaged MEMS devices are recommended to be screened using the packaged parts screen. It must be

understood that this is only a recommended screen and not all tests will be necessary for all devices.

Table 10-1 shows the recommended screening tests that can be used for MEMS packaged devices and the reference for the screen. This information is modified from MIL-PRF-38534 Class K requirements and should be applied after careful consideration of the applicability and mission requirements. It should be kept in mind that these tests are designed for microelectronic circuits and may need to be modified for specific applications of MEMS.

Test	Reference
Nondestructive bond pull	MIL-STD-883, Method 2023
Internal visual inspection	MIL-STD-883, Method 2017
IR-scan (prior to seal)[1]	JEDEC Document JES2 [39]
Mechanical Shock	MIL-STD-883, Method 2002
Constant Acceleration	MIL-STD-883, Method 2001
Temperature cycling	MIL-STD-883, Method 1010
Thermal shock	MIL-STD-883, Method 1011
Particle impact noise detection	MIL-STD-883, Method 2020
Electrical	Customer's specifications
Burn-in	MIL-STD-883, Method 1015
Electrical (high/low) temp	Customer's specifications
Fine leak Gross leak	MIL-STD-883, Method 1014 MIL-STD-883, Method 1014
Radiographic	MIL-STD-883, Method 2012
External visual	MIL-STD-883, Method 2009

Table 10-1: Typical packaged device screening.

Throughout the rest of this chapter, a brief description of, and the rationale for, each product acceptance test or screen will be given.

A. SEM Analysis

Scanning Electron Microscopy analysis can provide valuable information regarding the step coverage and quality of the metallization and passivation on device. Thus, this tool is required as part of the wafer acceptance tests. Some accept/reject criteria are provided in MIL-STD-883, but they may need some modification to cover different MEMS technologies.

[1] This test may only be necessary if a MEMS device has on-chip electronics.

B. Nondestructive Bond Pull Test

The integrity of wire bonds cannot always be judged through visual and electrical tests. Therefore, some qualification procedures recommend the implementation of a nondestructive bond pull test of each bond. The pull force selected for this test is generally dependent on the material and wire diameter in question. MIL-STD-883, Method 2023, is normally used for this application. Obviously selecting the required pull force is critical and must be decided by the manufacturer and the user.

Mechanical damage to good bonds as a result of the test is possible. Due to this problem, some manufacturers have removed this step from their qualification and screen procedures and resorted to in-process controls and testing to provide the necessary information. The decision to require this test must be made by the MEMS user after careful consideration of the system application and workmanship of the manufacturer.

C. Visual Inspection

Many defects in MEMS, such as substrate cracks, poor wire bonds, and foreign materials, reduce device reliability. Cracks can separate devices that are designed to be mechanically coupled, thus changing the mechanical characteristics of the device. Poor wire bonds increase the resistivity of the device, which can change the anticipated electrical output. Conductive particulates can short out devices, causing huge current flow through tiny fingers of comb drives. To prevent these and any other obvious flaws from impinging upon device performance, a visual screen of a device is performed during wafer acceptance tests for defects of the die and during the packaged device screens for packaging and bonding defects.

D. Laser Profile

Since some MEMS will have unacceptably high residual stresses, it is useful to measure the warping in a device caused by these stresses. One method of doing this is to use a laser profiling system to examine surface contour. These systems record non-planar displacements through the use of laser interferometry and have proven useful in the analysis of MEMS. One limitation to these systems is that they do not distinguish between surface contour and internal stress. The only tactic that has proven effective for differentiating between these two effects is to use differential measuring of surface profiles on devices that are etched on both sides. For devices suspended above the substrate, there is no method available for directly measuring internal stress.

E. IR Scan

Some defects, such as substrate cracks and die-attach voids, must be detected, whether or not they are visible. Since these types of defects have a different thermal conductivity than

the surrounding defect free region, they may be detected through thermal mapping. The baseline for comparison is the thermal profile of the MEMS device that was made as part of the product or design verification step. Typically a 5 ^{o}C variation in thermal output is enough for a device to be considered a reject. However, this step may not prove that informative if the temperature of the MEMS device does not vary much from the ambient temperature. Thus the applicability of this test will be design dependent and will likely require enough on-chip electronics to noticeably heat the device.

Although infrared microscopes are expensive, require calibration, and have a minimum resolution of approximately 15 μm, they are the best method of mapping a device's thermal characteristics, since they do not damage the device. While this screening step is not typically imposed as a requirement following MIL-PRF-38534, it is a good idea for any high power applications or application, such as those involving thermal actuators, that require good thermal stability. This step should be performed after die attach and before attachment of the package lid.

F. Mechanical Shock Screen

This screen is intended to detect weak parts that are required to undergo severe shocks during transportation, handling, satellite launch, or other operations. The test subjects the packaged MEMS to a number of short shock pulses with a defined peak. Failures are detected during final visual and electrical screens.

G. Constant Acceleration

This screen is intended to detect failures due to mechanical weaknesses by subjecting the packaged MEMS to a constant acceleration. Typical failures occur in the bonds and die attach, and these are detected during the final visual and electrical screens. This screen is an effective tool to detect poor workmanship. The appendix to this section describes methods for producing mission specific dynamic tests for MEMS and can be used either as a supplement or a replacement for the military standards.

H. Temperature Cycling and Shock Screen

Failure in mechanical devices can be accelerated by applying thermal stress. These tests detect structural defects or weak points in packaging that would normally result in early failures. Temperature cycling consists of cycling a packaged MEMS between extreme temperatures many times. Typically the temperatures used are –65 to 200 ^{o}C and the number of cycles is 15. The temperature shock screen is similar to the temperature cycle screen in that the test involves subjecting the packaged MEMS to extreme low and high temperature, usually -65 to 150 ^{o}C, over many cycles. The difference is that the rate of change in temperature with respect to time is much greater. Temperature shock screens are typically done between baths of hot and cold

materials, while cycling screens use conductive air cooling to change temperature. Failure detection for both screens is done in a final electrical and visual inspection. These tests are also discussed in great detail in MIL-STD-883, Methods 1010 and 1011.

I. Particle Impact Noise Detection

During encapsulation, thermal stress screens, and mechanical tests, particles may break off from either the MEMS device or the package. These loose particles may mechanically damage the MEMS or short out part of the circuit. That particle impact noise detection screen, or PIND, is a nondestructive test used to find parts that have this defect. During the test, the part is vibrated and a sensor is used to detect anomalous noise. Failure criteria are given in MIL-STD-883, Method 2020.

J. Burn-In

In an ideal world, devices that were substandard would be eliminated by a well controlled process line before they ever reach the customer. However, it is unrealistic to assume that a manufacturer can detect or predict which devices will fail with 100% accuracy. Therefore, to eliminate the device discussed in Chapter 2 as being part of the infant mortality group in a given production population, the burn-in screen must be performed.

The burn-in screen stresses devices above their normal operating conditions to accelerate any early failure that would occur from latent defects. For electronic circuits, burn-in is typically done at elevated temperatures to accelerate early failure mechanisms. For MEMS, the import of elevated temperatures will be device dependent. Far more likely to be of use is the practice of supplying a voltage that is above the normal operating regime for a device.

The difficulty in the burn-in test is to select a level of testing that will weed out weak devices while not damaging good ones. An implicit trade off in burn-in is that the confidence that a device will not suffer infant mortality comes at the expense of its long-term life expectancy. Thus, running the test for too long can be as problematic as running it in an abbreviated manner. The exact details of the burn-in will be up to the manufacturer and customer to decide in trying to balance the two conflicting goals of confidence and lifetime with the mission requirements. Devices that fail burn-in, which is usually defined as a pre-determined shift in output characteristics, should be discarded, rather than have any attempts made to salvage them.

K. Leak Test

There was a fair amount of information devoted to the subject of contamination and induced failure mechanisms in Chapter 3. To eliminate many of these problems, many MEMS devices are hermetically sealed in their packages and for these devices, their reliability is

dependent upon the integrity of these seals. The thermal and mechanical tests were intended to detect defects in packaging but often a leak test is required to find failed devices.

Fine leak tests consist of placing the packaged device in a chamber pressurized with a known gas, which will enter the package through any cracks that have developed. Usually helium or nitrogen gas with a small concentration of a radioactive isotope is used, since these gases can be detected in small concentrations using commercially available equipment. After a time, the chamber is cleansed by circulating air and the packages are tested to determine if gas leaks from them. Although the use of radioactive isotopes sounds somewhat extreme, it is the preferred method in high-volume production lines due to the fact that it is easier to detect for a longer period of time. The disadvantage of this method is that the gas will escape from a gross leak before it has time to be detected. Therefore, a gross leak test is used that is similar to the fine leak test except that it is conducted with a pressurized liquid bath instead of the gas.

L. Radiographic

The final screen is usually a radiographic picture of the inside of the sealed package taken with an x-ray machine. This nondestructive test uses radiation to penetrate the package walls and produce a shadow image on a photographic plate. It is useful for checking the location and position of wire bonds and for detecting loose particles that may have moved or broken off during the screening process. In some cases, this screen can also be useful in determining the presence of die-attach voids.

IV. Company Certification

Procurement of MEMS will often be the result of long-term partnerships between the customer and manufacturer in which both parties collaborate in order to assure the reliability and performance specifications of the flight ready device. This close relationship between the two parties evolves through mutual trust. In a new partnership, the best way for a manufacturer to establish trust is to show that it has good control over the facilities, processes, and personnel used to make these devices. Typically these controls, which include documentation, procedures, and management practices, are part of a Quality Management Program. This step of proving that the company has these processes in place is referred to as “company certification” and is usually verified by the MEMS user through a written or facility audit. It is recommended that the audit and company certification be completed before the contract for a deliverable MEMS device is signed. In some cases, the MEMS user may make this requirement a paramount consideration in selecting a company from which to buy parts. A company that does not have tight quality controls installed should not be allowed to supply MEMS for high-rel applications.

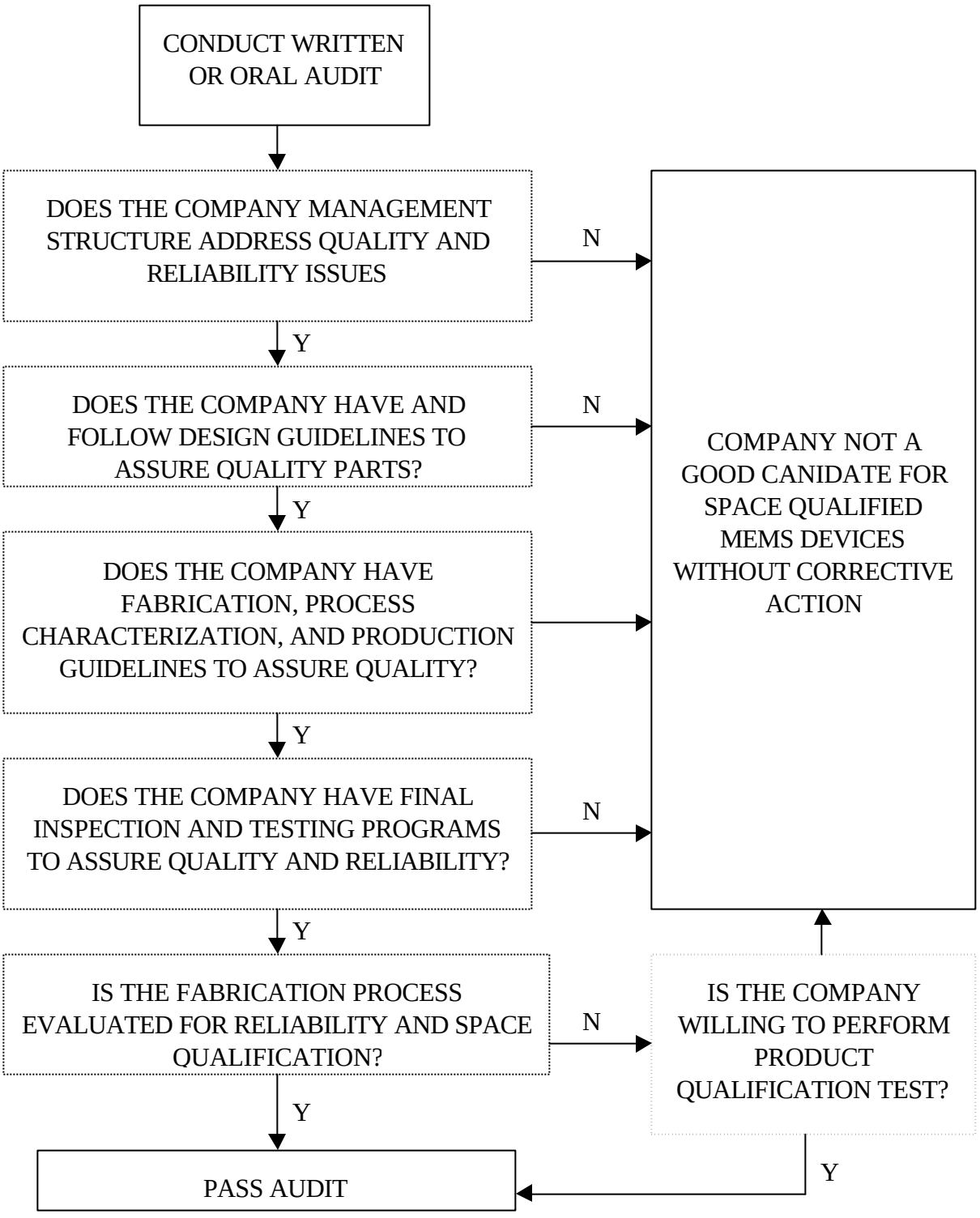

Figure 10-9: Reliability audit.

Since most of the information sought during company certification is based upon established quality control programs and standard industry methodologies,[1] the audit should be easy and inexpensive for both the user and manufacturer. Manufacturers should keep this information available and ready for distribution at all times. This whole process may be facilitated if the manufacturer has passed previous qualification audits, in which case this step may only require an update from previous audits.

A simplified version of the audit is shown in Figure 10-9. The audit for a specific MEMS must be developed on a case-by-case basis. The major items in the Quality Management Program are presented in the rest of this section, but it must be remembered that this is only a partial list. As stated before, the end goal of a reliable MEMS device is ultimately in the hands of the user. Any additional device specific tests must be specified by the user as needed.

A. Technology Review Board

In order to assure the quality and reliability of MEMS, manufacturers will usually have a permanent committee in place with authoritative knowledge of the entire fabrication process. If the quality of the process is not maintained, this committee, called the Technology Review Board, or TRB for short, will have power to change the process to improve quality. The TRB is responsible for the following measures:

- The development, implementation, and documentation of the manufacturer's Quality Management Program and Quality Management Plan.
- The development, implementation, and documentation of the manufacturer's Process Qualification, Product Qualification, and Product Acceptance Plans.
- Compiling and maintaining all records of the fabrication process, statistical process control (SPC) procedures, SPC data, certification and qualification processes, reliability data analysis, and corrective actions taken to remedy reliability problems.
- Examining test structures and MEMS reliability data and establishing and implementing corrective actions when the reliability of the devices decreases.
- Notifying customers when the reliability of a wafer lot is questioned and supplying the customers an evaluation of the problem and any corrective action required.
- Supplying reliability data to customers.

Because of these great responsibilities that cover such a broad area of knowledge, the members of the TRB should have good hands-on knowledge of device design, technology development, wafer fabrication, assembly, testing, and quality assurance procedures. While the

members of the TRB board are usually from the manufacturing company, it is not unusual for a customer to request a seat on the board for their products.

B. Conversion of Customer Requirements

Not all customers express their specifications in the same way, and not all MEMS manufacturers publish their performance specifications and operating guidelines in the same way. Normally a user will ask for a device with specific characteristics, such as an accelerometer with a dynamic range of +/- 50g and a resolution of .1g instead of saying that they want a bulk micromachined device with a cantilever beam accelerometer. It is the job of the manufacturer to use the requirements of the user to determine the device design. It is through the conversion of the customer's specifications to the manufacturer's designs that the manufacturer can determine the cost and reliability concerns of the device. It is recommended that the procedure by which a customer's requirements are converted to the manufacturer's working instructions be documented. A typical document will describe the procedure a company performs, the order in which they are performed, and the typical schedule. Some of the items typically included in this conversion are:

- Relating customer device requirements to manufacturer device requirements.
- Converting the device requirements to a device design, using controlled design procedures and tools (i.e. established electric, geometric, mechanical, and reliability design rules).
- Establishing a design review team.
- Selection of test structures.
- Mask generation procedure within the controlled design procedure.
- Wafer-fabrication-capabilities baseline.
- Circuit fabrication procedure in accordance with approved design, mask, fabrication, assembly, and test flows.
- Incoming inspection and supplier procurement document covering design, mask, fabrication, and assembly.
- Establishment of screening and traveler documents.
- Technology Conformance Inspection, or TCI, procedures.
- Marking requirements.

- Rework procedures.

C. Manufacturing Control Procedures

MEMS manufacture is a complicated process that involves multiple materials and steps, each of which are critical to final device performance and reliability. Only a properly controlled manufacturing line can be expected to routinely produce quality MEMS devices. For this reason, the customer needs to be assured that the manufacturer is using only certified processes and qualified technologies at every step of the manufacturing process. To obtain that level of assurance, the company certification audit should review the manufacturer's procedure for:

- Traceability of all materials and products to the wafer lot.
- Incoming inspection to assure conformance to the material specification.
- Electrostatic discharge, or ESD, control in handling the material in all stages of manufacturing.
- Conformance with design requirements at:
    1. Device procurement specification
    2. Layout verification
    3. Testability and fault coverage verification
    4. Electrical and mechanical parameter performance extraction
    5. Archived data
- Conformance with fabrication requirements at:
    1. Mask fabrication
    2. Mask inspection
    3. Wafer fabrication
- Assembly and package requirements.
- Electrical and mechanical testing.

Most of this information can be obtained by examining the manufacturer's process flow.

D. Equipment Calibration and Maintenance

In order to maintain device quality, the processing equipment must be maintained. For this reason, all equipment used in the manufacturing process must be kept to the equipment

manufacturer's specifications. In addition to routine maintenance, the equipment must also be calibrated on a regular basis. Documentation showing the maintenance and calibration schedule, departures from this schedule, and corrective action taken due to these departures should be kept by the manufacturers. This documentation will also highlight any major discrepancies found in the calibration and maintenance of a piece of equipment, since it could affect the reliability of the MEMS. The TRB will review this documentation to determine if any corrective action is required. Further information on equipment calibration can be found in Reference [31].

E. Training Programs

Even well maintained and calibrated equipment cannot produce quality devices without skilled operators. To assure the skills of the personnel employed in the design, fabrication, and testing of devices, each engineer, scientist, and technician should have formal training relative to their tasks. Furthermore, retesting and retraining should be provided regularly to maintain the worker's proficiency, especially if new equipment or procedures are introduced into the manufacturing process. It is therefore recommended that the work training and testing practices employed to establish, evaluate, and maintain the skills of personnel engaged in reliability-critical work be documented with respect to form, content, and frequency.

F. Corrective Action Program

One of the best ways to continuously improve the reliability of manufactured parts is to test and analyze failed parts from all stages of manufacturing and, based on these findings, make corrective actions to the manufacturing process or to the education of the end users. The plan that describes these corrective actions is normally documented and should detail the specific steps followed by the manufacturer to correct any process that is found to be defective. The documentation should also include the mechanisms and time frames involved in informing customers of potential reliability problems.

G. Self-Audit Program

To promote continual quality improvement, manufacturers regularly review their manufacturing procedures through an independent internal self-audit program under the direction of the TRB. The self-audit program should identify the critical review areas, their frequency of audit, and the corrective action system to be employed when deviations from requirements are found. Typical areas included in a self-audit are:

- Calibration and preventive maintenance,
- Fabrication procedures,
- Training programs,
- Electrical and mechanical tests,

- Failure analysis programs,
- Test methods,
- Environmental control,
- Incoming inspection,
- Inventory control and traceability,
- Statistical Process Control and
- Record Retention.

The self-audit checklist, the date of the previous audits, and all the findings from the audits are typically maintained by the TRB, which will use these findings to recommend corrective actions and prepare a self-audit follow-up.

H. Electrostatic Discharge Handling Program

Because of the catastrophic failure caused by ESD, all personnel that work with MEMS should be trained in the proper procedures for handling the devices. Furthermore, these procedures should be documented and available for reference. Typically, the procedures include the methods, equipment, and materials used in the handling, packaging and testing of MEMS. Further guidance for device handling is available in the Electronics Industry Association JEDEC Publication EIA 625 [33] and MIL-STD-1686.[34]

I. Cleanliness and Atmospheric Controls

The quality of MEMS and the yield of the fabrication line is directly linked to the manufacturer's control over the cleanliness of the environment in which the parts are fabricated. Therefore, manufacturers often spend a large amount of their resources to guarantee that devices are fabricated in ultraclean rooms where the atmosphere is tightly controlled. Since the yield of the fabrication process is so strongly dependent on the success of maintaining those conditions, regular measurements are taken to assure the temperature, humidity, and cleanliness of the fabrication areas. In addition, during transit and storage prior to seal, the die/wafer should be protected from human contact, machine overspray, or other sources of contamination. All of these procedures and measurements are recorded and compiled into a single document by the clean-room manager for future reference.

J. Record Retention

Documentation is the only method available to gauge the reliability of MEMS as a function of time, which is critical to spotting faults in the process line. Although many sections in this guide recommend the documentation of certain data or procedures, it is helpful if a list of

documents and the period of retention for each document is made. Furthermore, the list should contain a record of when each document was last changed, who is responsible for maintaining the document, and where the document is stored. The typical documents to be retained are those that relate to

- Inspection operations,
- Failure and defect report and analysis,
- Initial documentation and subsequent changes in design, materials, or processing,
- Equipment calibration,
- Process, utility, and material controls,
- Product lot identification,
- Product traceability,
- Self-audit report,
- Personnel training and testing and
- TRB meeting minutes.

K. Inventory Control

The proper inventory of all incoming materials and outgoing parts is not only required for the management of a profitable company but also for the manufacture of reliable MEMS devices. Many materials and chemicals used in the fabrication of MEMS have shelf lives that must be tracked if process yield and reliability are to be maintained. The tracking of in-process and completed MEMS is essential for the establishment of MEMS history, which is critical in failure analysis. Therefore, the methods and procedures used to control the inventory of all materials related to MEMS manufacturing should be documented. This documentation typically includes:

- Incoming inspection requirements and reports.
- Identification and segregation of non-conforming materials.
- Identification and control of limited-life materials.
- Control of raw materials.
- Data retention for required receiving reports, test reports, certification, etc.

- Supplier certification plan.

L. Statistical Process Control

The establishment of a statistical baseline for judging the continuous improvement of a manufacturer's process is an important task. To establish that baseline, the manufacturer should develop an SPC program using in-process monitoring techniques to control the key processing steps that affect device yield and reliability. As part of the SPC process, every wafer lot typically has built-in control monitors from which data are gathered, which should then be analyzed by appropriated SPC methods to determine the effectiveness of the company's continuous improvement plans. Additional information on SPC analysis can be found in the Electronics Industry Association JEDEC EIA 556A [35] and in MIL-I-38535.[36]

V. Additional Reading

Microelectronics Failure Analysis Techniques, A Procedural Guide, E. Doyle, Jr., and B. Morris, Editors, report written for Air Force Systems Command, Rome Air Development Center under contracts F30602-78-C-0339 and F30602-78-C-0281

MIL-STD-1540C, *Test Requirements for Launch, Upper-Stage and Space Vehicles*, United States Air Force Military Standard, 1994.

Thomson, W. T., "Theory of Vibration with Applications," 2nd ed., Prentice-Hall, Inc., Engelwood Cliffs, New Jersey, 1981.

Kinsler, L. E. and A. R. Frey, "Fundamentals of Acoustics," 2nd ed., John Wiley & Sons, Inc., New York, 1962.

Markstein, H. W., "Designing Electronics for High Vibration and Shock," *Electronic Packaging & Production*, April 1987, pp. 40-43.

MIL-STD-462, *Electromagnetic Emission and Susceptibility, Test Methods for*, United States Department of Defense Military Standard.