

CHAPTER 9

Building and Testing Prototypes

LEARNING OBJECTIVES

When you have completed this chapter you will be able to

- Describe why companies build and test parts and or products
- Describe various product and part tests to validate form, fit, and function
- Characterize traditional prototyping methods
- Describe various prototyping methods
- Explain the overall rapid prototyping process
- Describe the components of a test plan

9.1 INTRODUCTION

Many technical and economic issues arise during the development of a new product. For example, will the:

1. new product work at extreme temperatures and humidity?
2. housing appear old-fashioned to the customer?
3. newly added part actually work as predicted by the equations.
4. product have a good "feel" in the hands of the user?
5. customer be satisfied with the overall size?
6. fabricated parts assemble without interference?
7. finished product satisfy industry-mandated safety tests?
8. new housing material be compatible with the intended lubricants?
9. customer be able to easily replace worn parts?
10. new part be stiff (flexible) enough?
11. new part have an acceptable wear rate?
12. new product present an electric shock hazard?
13. part be more attractive with a mirror finish?
14. finished product meet minimum performance requirements?
15. manufacturing group be able to fabricate the part to acceptable tolerances?
16. the new part easily assemble with the mating part?

The economic viability of a company hinges upon the intelligent expenditure of time and money, especially as it relates to product development. Companies can spend millions, for example, during the design phase and especially when tooling-up to launch a new, mass-produced product. The product development team, therefore, must establish a sound plan of tests, to be conducted at various stages, to ensure that the final product will be economically and technically successful.

In the next sections we will examine the types of tests that companies carry out using models and/or prototypes and how they are fabricated by traditional and rapid prototyping methods.

9.2 PRODUCT AND PART TESTING

Product and part tests can be separated into three major categories that focus on validating form, fit, and/or function. Concerns about the form of a part or product relate to its overall appearance, including shape and relative size. Concerns about fit relate to how precisely the parts are fabricated and how well they fit together in the assembly, or how they "fit" the user. Finally, parts and products must function, or perform as expected, last a long time, and be easy to maintain. Let's regroup the list of concerns from the previous section into form, fit, and function categories.

- **Form test**—Will the part and/or product have an acceptable appearance?
 1. housing appear old-fashioned to the customer?
 2. customer be satisfied with the overall size?
 3. part be more attractive with a mirror finish?
- **Fit test**—Will the parts fit together and also fit the user, with an acceptable precision?
 4. product have a good "feel" in the hands of the user?
 5. fabricated parts assemble without interference?
 6. manufacturing group be able to fabricate the part to acceptable tolerances?
 7. the new part easily assemble with the mating part?
- **Function test**—Will the part and/or product perform as required?
 1. new product work at extreme temperatures and humidity?
 2. newly added part actually work as predicted by the equations?
 3. finished product satisfy industry mandated safety tests?
 4. new housing material be compatible with the intended lubricants?
 5. customer be able to easily replace worn parts?
 6. new part be stiff enough?
 7. new part have an acceptable wear rate?
 8. product present an electric shock hazard?
 9. finished product meet minimum performance requirements?

9.2.1 Product Development Tests

Most of the questions regarding form, fit, and function can be tested at earlier phases in the development cycle, before the final product rolls off the production line. For example, we can test the appearance of a product by showing customers a reduced-size scale model, made of clay or balsa wood. Another typical situation arises for a product that has many standard parts, but only a few special-purpose parts. Samples of those parts could be made and tested for function by using planned materials and manufacturing processes.

A **physical prototype** is a tangible replica of the part showing principal geometric features, such as length, width, height, holes, fillets, rounds, projections, slots, cavities, and surface texture. Prototypes may be reduced-scale, expanded-scale, or full-scale representations of the part. Prototypes may be made of materials similar to or exactly like the intended product. They can be fabricated with manufacturing processes that are similar to, different from, or exactly the same as those to be used on the intended product. As a consequence, prototypes will vary in their cost and ability to be tested for form, fit, and function. Effective development teams will use the right type of prototype to test critical aspects at the right time, thereby saving the company time and money.

Let's examine the different types of tests and prototypes that are typically used during the various development phases of a product as shown in Figure 9.1.

1. **Product concept tests.** A reduced-scale or full-scale model of a new product or "product concept" is fabricated to look like the "finished" product. Usually only the exterior of the product is fabricated and shown, illustrating existing or newly improved features that compose the product concept. This appearance prototype is then shown to potential customers to obtain their reactions and their willingness to ultimately purchase the product. Product concept tests are usually done early in the development cycle, to make sure that the product will have the right look, or appearance, and have the right combination of features. An automobile manufacturer would use a clay scale model of a new sports car to examine the acceptability of a two-seat, rear-engine convertible. A large appliance manufacturer would "mock-up" a new laundry washing machine, to examine the customer appeal of enhanced digital controls, or the acceptance of top loading versus side loading. An electronics firm would prototype the case of a new cell phone to examine the effects of various colors and overall shape.
2. **Proof-of-concept tests.** The model or prototype is built to prove that it will function or perform according to the function concept, i.e., the physical principle, material and geometry that were selected. Bench-top, pilot-plant, and/or laboratory experiments are performed to prove that the physical principle will work in the final product. For example, an office printer manufacturer could machine parts for a bench-top "working-model" of a new electrostatic paper feeder to replace the mechanical roller-feeder in its new line of printers. An electronics manufacturer would test the concept of a newly improved circuit using a prototype board.

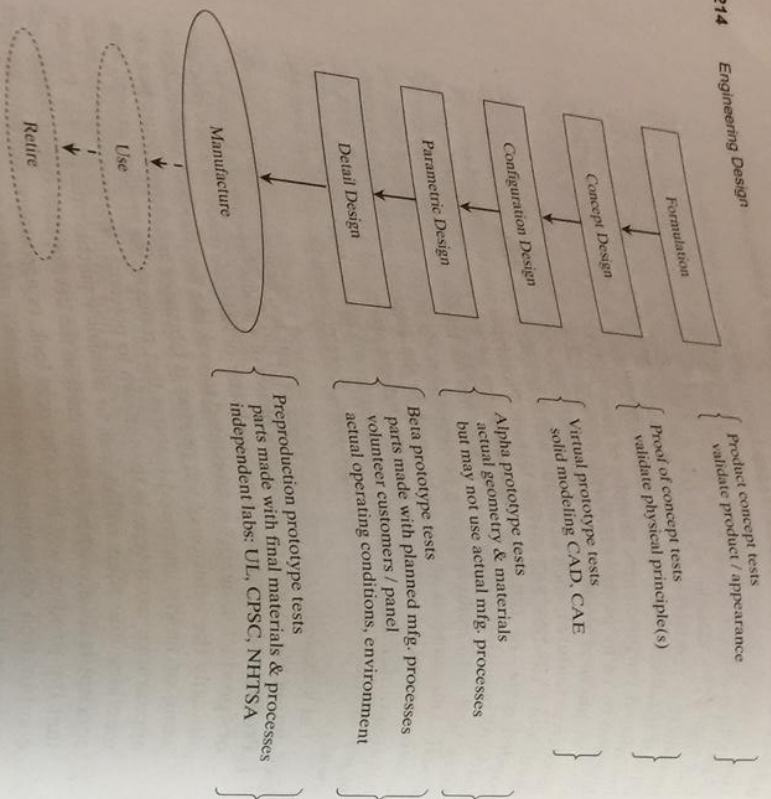


FIGURE 9.1 Prototype testing throughout the product development process.

3. **Virtual prototype tests.** A part or product can be prototyped or modeled inside the memory of a computer as a non-real replica or virtual prototype using computer-aided design packages, which can create and analyze three-dimensional, solid models. Solid modeling is often used to develop the form of a part and examine the mobility and/or potential interference of mated parts in an assembly. The solid-model data file is also used to analyze forces, moments, motions, stresses, and strains, among other things. A construction equipment manufacturer would use solid modeling and finite element analysis to develop a CAD model or virtual prototype of its new gearbox and analyze its strength and/or rigidity. A small-appliance manufacturer would build a solid model of its new high-power

hand-held hair blower, then generate realistic pictorial renderings, to assess customer acceptance of the new housing shape and size.

4. **Alpha-prototype tests.** A reduced-scale or full-scale part or product is prototyped using the same geometric features, materials, and layout as the intended final assembly (Otto and Wood, 2001). Alpha prototypes are not usually prototyped using the same manufacturing processes that will be used in the final production. Alpha-prototype tests are conducted in a company's laboratories and focus on a part or product's appearance and/or its functional performance. A screwdriver manufacturer would fabricate an alpha prototype by machining plain carbon steel to examine the "feel" of its newly shaped handle, even though in final production stainless steel and stamping would be used. The parts for a new desktop printer case could be machined from a production polymer to prove its functionality, even though injection molding would be used in final production.

5. **Beta-prototype tests.** A full-scale, functional part or product is prototyped using similar materials and manufacturing processes that will be used in production. Beta prototypes can be tested in the company's laboratories but are often tested by volunteers or potential customers in their home or work environment (Crawford and DiBenedetto, 2003). The tests confirm intended mass-production and assembly processes and demonstrate the approximate performance of the product. Results from the beta-prototype tests are used to make the last remaining changes to the product, complete the production planning and initiate the production tooling. Groups of potential customers, called "customer panels," are often used to evaluate beta prototypes of new vacuum cleaners, kitchen appliances, hand tools, and sports equipment. Potential customers are also used to test and evaluate Beta version software on their home or work computers.

6. **Preproduction prototype tests.** A full-scale part or product made and assembled with final materials and actual production processes is tested. Therefore, the tests are made on "finished" products similar to ones that customers purchase. The tests confirm and document production and assembly processes and demonstrate the actual performance of the "final" product. Test results are used to make last-minute revisions to the production tooling and assembly processes and to make minor design revisions to comply with state and federal codes. The tests are also used to verify and document that the products have no defects in design or manufacture, which could be tested in a product liability lawsuit. An electric toaster manufacturer has the Underwriters Laboratories (UL), a nonprofit independent organization, conduct electrical shock and fire safety tests. A baby stroller manufacturer has its new product tested in an independent laboratory before sending production-run samples to the Consumer Product Safety Commission (CPSC). An automobile manufacturer has production prototypes tested for crash-worthiness by the National Highway Transportation Safety Administration.

9.3 BUILDING TRADITIONAL PROTOTYPES

Craftsmen have been making models for thousands of years using simple hand tools and a variety of materials. Traditional materials include woods, clay or ceramics, construction papers, and more recently with the availability of machine tools, metals and polymers (Otto and Wood, 2001). Traditional prototype examples include:

- clay models of new auto-body styles,
- wood models of heavy-equipment cardboard and paper materials,
- product mock-ups made of decorated facilities, to examine equipment layout,
- reduced-scale balsa wood models of large facilities,

As mentioned in Chapter 5, materials and the processes used to shape them are interdependent. Some materials are incompatible with certain fabrication methods. For example, metals in general cannot be carved with a sculpting knife, as wood can be. Nor can construction papers be welded; rather they must be glued or adhesively taped together. Also, some materials are poorly suited for function testing, such as a paper wing that could deform under load in a wind tunnel. Therefore, the choice of material and fabrication method will largely depend on:

- *Shape-generating compatibility.* Can the material be formed into the needed geometric features to adequately represent the part?
- *Function-testing validity.* Are the material properties representative or scalable such that the part when reduced (or expanded) in size can be validly tested?
- *Fabrication costs.* Will the prototype costs for materials and labor be acceptable?
- *Fabrication time.* How long will it take to fabricate the original prototype and one or more duplicates?

9.4 BUILDING RAPID PROTOTYPES

Traditional prototypes use tools and fabrication methods that are labor-intensive, often require significant mechanical or artistic skills, and take a long time to fabricate an original or its duplicates. **Rapid prototyping** is an alternative technology that uses computers and computer-controlled equipment to automatically and rapidly fabricate prototypes (Jacobs, 1996; Wood, 1993). Rapid prototyping processes include the following:

Numerical Control Machining (NC/CNC). The earliest of these is numerically controlled machining of prototypes, otherwise called **NC/CNC machining**. Beginning around the early 1960s, if we wanted to make a prototype using an NC lathe or milling machine, we would give our drawing to an operator who would interpret the drawing and create a "program" of machine

control codes, which were punched as holes on a paper tape. The tape would then be read by the NC machine to control the precise feeds and speeds of the workpiece and tool, thereby generating the various part features. Since a prototype can be made from strong metals, such as steel, it can be used for function testing under simulated loads.

More recently, computer numerically controlled machines (CNC) now have on-board computers, which generate and store their own programs. Software packages make efficient use of files generated by CAD solid-modeling software. The CNC software generates the appropriate tool paths and tool changes from the solid model file with a minimum of operator attention. It can be argued that NC/CNC is not fully "automatic," because a skilled operator must still be involved in running the machine and making fixture changes. However, multiple copies of a part can be made quickly and with a high level of precision. An example part is shown in Figure 9.2.

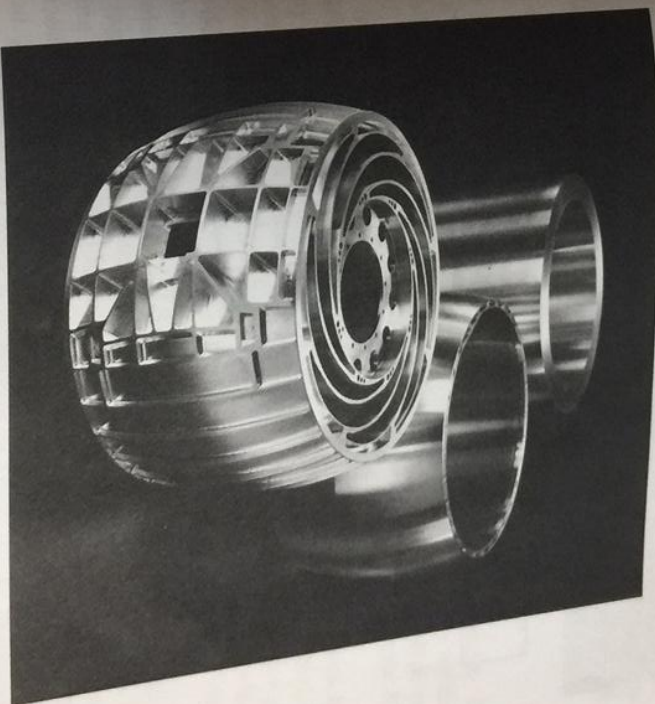


FIGURE 9.2 Example CNC part, a wheel made for the Mars rover. (Courtesy of Haas Automation, Inc.)

NC/CNC machines remove material from circular or rectangular base parts. Mills, for example, are used to cut out slots and trim parts to their final

engineering Design

NCCNC lathes can be used to cut various cylindrical shoulders dimensions. A principal advantage of machining (by hand or steps onto shafts. being able to make prototypes out of strong, hard, NCCNC) is, of course, tolerances are the best of all the prototype. Accuracies and tolerances can be subjected to operating methods. As such, the resulting prototypes can be subjected to loading loads approaching the actual in-use conditions.

(SLA) is a material additive process in na-... identify a liquid photopolym...

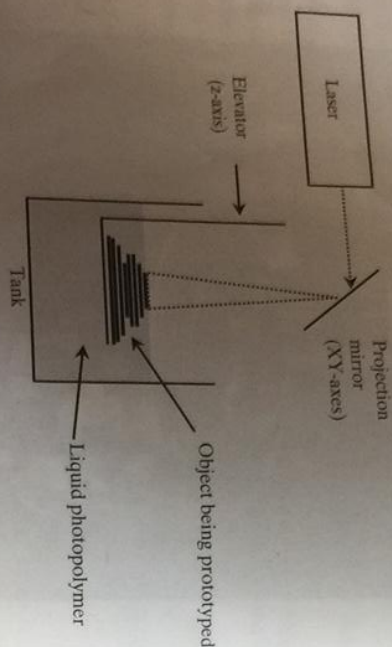
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FIGURE 9.3 The SLA process uses a powerful laser to cure a photosensitive polymer, layer by layer, as the elevator lowers into the tank.

Fused-deposition modeling (FDM) is a process that deposits a thin filament of melted (fused) material in precise locations on a horizontal layer, using numerically controlled positioners. As the material solidifies, a prototype model is built, layer by layer, typically up to 10 inches by 10 inches in cross section and up to 16 inches high. Parts can be made from a number of materials, including: high-strength ABS plastic in multiple colors, impact-resistant ABS, polycarbonate, and polyphenylsulfone. No special room air



FIGURE 9.4 Example of an SLA part for rapid tooling. (Courtesy of 3D Systems.)

vents or exhausts are required, and the process is fully automated. The materials are nonhazardous and nontoxic. Parts are postprocessed by mechanical agitation in a water solution to remove support structures. Prototype parts are used by companies to verify form, fit, and function. An example FDM product is shown in Figure 9.5.

Laminated-object manufacturing (LOM) is a process that builds each prototype by laminating together thin layers of paper, polymer, or sheet steel, which have been cut using a numerically controlled laser. LOM prototypes can be sanded to reduce jagged edges, but may not be able to be fully function-tested, such as for stress or strain, owing to the anisotropic material properties of the laminate.

Selective laser sintering (SLS) is a process that uses a high-power laser to sinter together fusible materials, such as powdered metals, layer by layer. Sintering is the heating and fusing of small particles resulting in a hard bonded material block. The unsintered powder supports the part as the layers are sintered.

3-D inkjet prototyping is a process that selectively deposits a glue-like binder onto a layer of dry powder, layer by layer, which dries into a solid prototype. A similar process uses a print head to deposit a thermoplastic material, layer by layer. The processes work well as concept modelers (Smith, 2001). Each prototype has limited dimensional tolerances and is somewhat fragile unless coated with a hardener to help to maintain part integrity. An example types made with this process are typically not function-tested. An example shown in Figure 9.6 shows how prototyping can be used for rapid tooling.



FIGURE 9.5 Example FDM motorcycle cowling. (Courtesy of Stratasys Inc.)

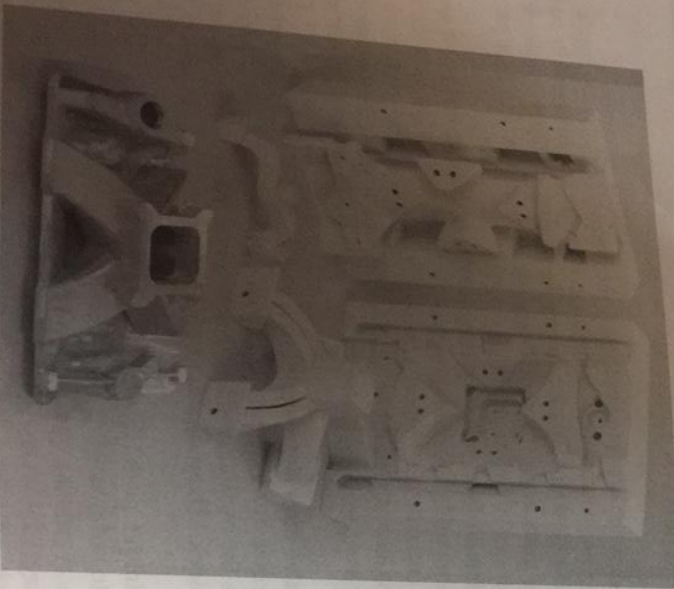


FIGURE 9.6 Example of 3-D Inkjet prototyping used to create the patterns for a set of mold halves and cores for the manifold casting. (Courtesy of Z Corporation.)

The rapid prototyping process begins with the creation of a virtual part created in the memory of a computer, as shown in Figure 9.7. Using 3-D solid modeling software, we can design the virtual part to include features such as: walls, ribs, holes, bosses, fillets, slots, chamfers, and rounds. Sizes are entered as parameters, that is, variables, which can be conveniently modified at any time during or after the creation of the part. The resulting image can be viewed in any of the orthographic views along with a variety of oblique and isometric views. The image can also be rendered with various colors and surface textures, for worker training and/or marketing purposes, etc. Bills of materials and dimensioned views are also produced with similar ease. The part shape is stored as numerical data and is archived on computer disks as **solid-model part files**.

Next, all the surfaces of the part are converted to very small triangular facets. Each facet is represented by geometric data, including the x, y, and z coordinates of the three vertices and an outward-facing normal vector. The data are stored with the as ***.STL file extension**. The *.STL file is read by a computer program for the specific rapid prototyping machine, such as a numerical controlled milling machine. The program slices the virtual solid into layers and a set of codes that instruct the prototyping machine to fabricate the part layer by layer.

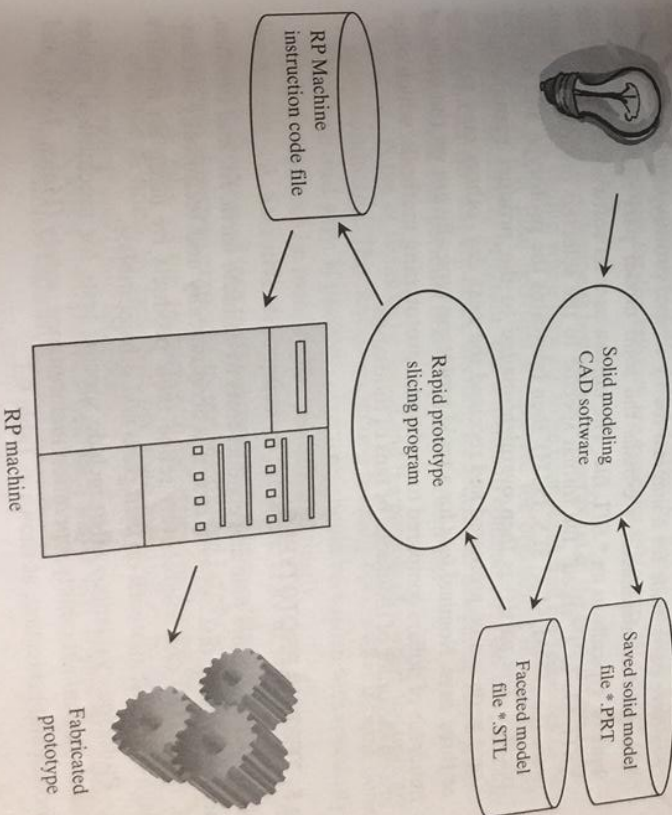


FIGURE 9.7 The rapid prototyping process.

Advantages/Disadvantages of Rapid Prototyping. The advantages of rapid prototyping typically outweigh the disadvantages, specifically:

- **Time.** The overall time from hand sketches to physical prototype can be on the order of hours or days, compared to traditional methods, which can require days, weeks, or even months.
- **Duplication ease and costs.** Duplicate prototypes can be fabricated quickly, less expensively, and with greater precision than with traditional methods.
- **Flexibility.** Changes to the virtual model and subsequent generation of revised prototypes are facilitated with rapid prototyping, because the data are stored parametrically.
- **Rapid tooling.** Prototype models and data can be conveyed electronically, and easily, to downstream departments, such as production and facilities planning, to communicate tooling concepts to mold makers, or generate master patterns for tooling, or generate tooling inserts.

The principal disadvantages are the costs of purchasing and setting up the rapid prototyping equipment and the fact that some prototyping materials are not suitable for function testing.

Rather than investing in prototyping equipment, product manufacturers can have parts made for a nominal fee by a rapid prototyping **service bureau**. The product manufacturer e-mails the solid model part file to the service bureau, typically as an *.STL file. The bureau uses its software to convert the *.STL file to a "sliced" file format specific to the selected prototyping hardware (i.e., FDM, SLA, SLS, LOM), then fabricates the prototype and any duplicates. The part(s) is then overnight-mailed to the product manufacturer. Some parts can be processed and received the next day, others may take two or three days. Nominal fees for a rapid prototype typically are on the order of hundreds of dollars compared to traditional prototyping methods, which often are on the order of thousands or tens of thousands.

9.5 TESTING PROTOTYPES

Successful companies plan and conduct tests to validate form, fit, and function, thereby ensuring that any new design is economically and technically successful. Companies can progressively refine their products by using an iterative design-build-test approach on their parts and subassemblies.

Prototype evaluations often include specific tests for mechanical modes of failure, manufacturability, operation/maintenance, safety (Hales, 1993), and environmental protection, as shown in Table 9.1.

TABLE 9.1 Specific Tests for Part and Product Prototypes

1. Mechanical modes of failure:	3. Operation/maintenance concerns:
static strength	styling/aesthetics
fatigue	ergonomics
deflection/stiffness	maintenance
creep, impact	repairs
vibration	4. Safety concerns:
thermal/heat transfer/fluid	risk to user, products liability
energy consumption / production	risk to consumer/society
friction	safety codes, standards (UL, NHTSA)
wear	risk to production worker (e.g., OSHA)
corrosion	5. Environmental protection concerns
life, reliability	air quality, noise
2. Manufacturability concerns:	water - quality, quantity
process compatibility/precision	solid waste - hazardous materials
process technology readiness	radioactivity - fallout
raw material quality	
assembly	

In some cases, test plans are required. For example, in the food and drug industry, test plan requirements are mandated by the Food and Drug Administration. And, products for the military are typically subject to "Mil-Spec" test plan requirements.

A product development **test plan** is a description of the type of tests to be performed, the timing when they are to be completed, and the resources to be expended. A test plan provides a structure for organizing, scheduling, and managing the testing program, and a means to communicate the test program details to all the stakeholders, eliciting feedback and delegating responsibilities. The basic components in a test plan document are:

Objectives. A list of items to be tested and the purposes for which the tests are being conducted. The objectives section basically covers what is being done for whom and why. If possible, objectives should be written with specificity. They should also be measurable, realistic, and timely.

Workscope. A narrative description of the work tasks to be performed, including the type of tests, test descriptions, experimental setup, experimental controls, design of experiments test matrix, and list of deliverables.

Budget. A tally of the resources to be expended, including items such as number of hours by task, cost per hour, materials to be consumed, equipment rental costs, and total costs.

Schedule. A chart that shows when each major task begins and ends, with major milestones indicated.

EXAMPLE

Range scientist, Dr. Pat Clark, develops animal tracking collars for the Agricultural Research Center of the United States Department of Agriculture. His latest project involved the design and testing of an electronics package enclosure for small animals. The enclosure needs to house: a GPS unit, a satellite modem, a CPU-transceiver board and batteries. The standard collar enclosure, shown in Figure 9.8, is somewhat bulky. While it "fits" cattle, it is less ergonomic for animals such as wolves and coyotes. The new enclosure would be compact and watertight.



Figure 9.8 GPS collar used to track cattle. (USDA)

Senior design engineering students Tyler Brown, Emily Perrin, and Brad Vawter from the Mechanical and Biomedical Engineering Department at Boise State University, were selected to design the enclosure. The team considered many alternative configurations to provide for mold draft and no undercuts. They finally decided upon a "batteries on the side" arrangement.

The electronic components were individually modeled using actual dimensions of the existing parts. The virtual parts were then mated in the enclosure. The resulting solid models, as shown in Figure 9.9 and Figure 9.10, acted as virtual "fit" tests, indicating that the new compact design should "fit."

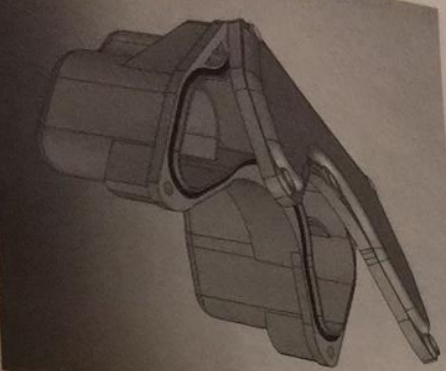


Figure 9.9 Solid models of enclosure lid, o-ring and base, are virtually assembled in the computer.

Figure 9.10 Solid models of mated enclosure base, o-ring, batteries, GPS and CPU cards

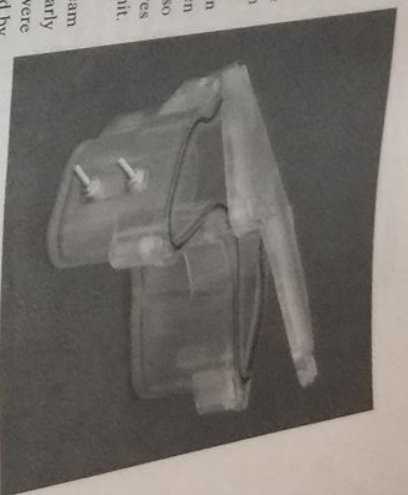
FIGURE 9.11 Physical SLA prototype of enclosure base with lid and o-ring.

The team decided to fabricate an SLA prototype for water immersion testing. The SLA prototype base and lid are shown assembled in Figure 9.11.

Immersion tests were conducted in water at 3 ft depths at temperatures between 40 F and 100 F. The enclosure was also subjected to simulate hydrodynamic pressures related to animal swimming or splashing the unit. A small leak was detected.

Upon closer examination, the team found that the lid was bending irregularly against the o-ring, as the fasteners were tightened. The leak was temporarily sealed by shortening the o-ring diameter, which reduced the cross section area, reducing the spring force of the o-ring, reducing the warpage, and stopping the leak. However, the team decided that increasing the final design lid thickness was a better and more permanent fix.

The virtual solid model and physical SLA prototype proved instrumental in validating the design's fit and function.



9.6 SUMMARY

- > Companies build and test prototypes to ensure form, fit, and function.
- > Product development tests include: product-concept, proof-of-concept, virtual, alpha, beta, and preproduction.
- > Prototypes can be built using traditional and rapid-prototyping methods and materials.
- > Rapid-prototyping methods include NC machining, stereolithographic apparatus, fused deposition modeling, laminated object manufacturing, selective laser sintering, and 3-D inkjet printing.
- > The overall rapid-prototyping process takes advantage of computer-aided design automation.
- > Part and product testing can include tests for: mechanical modes of failure, manufacturability, user operation and maintenance, safety, and environmental protection.
- > Comprehensive product development requires the preparation and completion of a detailed test plan.

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KEY TERMS

Additive process	Proof-of-concept test
Alpha prototype test	Rapid prototyping
Beta prototype test	Rapid tooling
Fit test	Selective laser sintering (SLS)
Function test	Service bureau
Fused-deposition modeling (FDM)	Solid-model part file
Laminated-object manufacturing (LOM)	Stereolithographic apparatus (SLA)
NC/CNC machining	* STL file
Physical prototype	Test plan
Preproduction prototype test	3-D inkjet prototyping
Product concept test	Virtual prototype

EXERCISES

Self-Test Write the letter of the choice that best answers the question.

1. C Which of the following tests are usually done early in the developmental cycle to make sure that the product will have the right appearance and have the right combination of features: a. beta-prototype b. preproduction-prototype c. product concept d. alpha-prototype tests
2. A Tests which use a prototype having the same geometric features, materials, and layout as the intended final assembly, but not the final manufacturing processes: a. alpha-prototype b. virtual prototype c. beta-prototype d. preproduction-prototype
3. C Tests in which a full-scale, functional part or product is prototyped using materials and manufacturing processes that will be used in production are called: a. alpha-prototype b. virtual-prototype c. beta-prototype d. preproduction-prototype

Tests in which a full-scale part or product is made and assembled with the final materials and actual production processes are called: a. visual-prototype b. proof-of-concept c. alpha prototype d. preproduction-prototype

An technology that uses computers and computer-controlled equipment to automatically fabricate prototypes is called: a. rapid prototyping b. alpha prototyping c. visual prototyping d. beta prototyping

The rapid-prototyping process that uses a high-power laser to selectively solidify a liquid photopolymer, layer by layer, into the shape of the finished prototype is called: a. fused-deposition modeling b. laminated-object manufacturing c. selective laser sintering d. stereolithography

The rapid-prototyping process that deposits a thin filament of melted material on a horizontal layer, using numerically controlled positioners, is called: a. laminated-object manufacturing b. fused-deposition modeling c. CNC prototyping d. stereolithography

The rapid-prototyping process that builds each prototype by laminating together thin layers of material, which have been cut using a numerically controlled laser, is called: a. laminated-object manufacturing b. CNC prototyping c. 3-D-inkjet prototyping d. fused-deposition modeling

The rapid-prototyping process that uses a high-power laser to sinter together fusible materials, such as powdered metals, layer by layer, is called: a. laminated-object manufacturing b. selective laser sintering c. fused-deposition modeling d. stereolithography

The rapid-prototyping process that selectively deposits a glue-like binder onto a layer of dry powder, layer by layer, which dries into a solid prototype is called: a. CNC prototyping b. fused-deposition modeling c. laminated-object manufacturing d. 3-D-inkjet prototyping

The rapid-prototyping process that begins with the creation of a virtual part created in the memory of a computer is called: a. overall rapid-prototyping process b. fused-deposition modeling c. stereolithography d. NC machining

The following are advantages of rapid prototyping except: a. rapid tooling b. low capital equipment cost c. duplication ease and costs d. flexibility

All of the following are basic components in a product development test plan except: a. production b. work scope c. objectives d. schedule

The heating and fusing of small particles resulting in a hard bonded material block is called: a. depositing b. laminating c. sintering d. modeling

Non-real, electronic replica of a part or product is called: a. physical prototype b. virtual prototype c. scale model d. NC/CNC

Type of test to determine whether a part and/or product will have an acceptable appearance is: a. form b. fit c. safety d. function

Type of test to determine whether a part and/or product will fit the user, with an acceptable precision is: a. form b. fit c. safety d. function

A process that builds a part by adding layers of material is: a. subtractive b. additive c. gluing d. machining

CHAPTER 10

Design for X: Failure, Safety, Tolerances, Environment

LEARNING OBJECTIVES

When you have completed this chapter you will be able to

- Identify product failure modes, their effects and severity
- Establish failure mode causes, occurrence likelihood, and detectability
- Determine risk priority numbers to focus remedial actions
- Identify hazards associated with the product manufacture, use, and retirement
- Describe and apply the safety hierarchy fundamentals
- Explain the difference between dimensions and tolerances
- Understand and implement worst-case and statistical tolerance design
- Design environmentally friendly products

10.1 INTRODUCTION

Design for X (DFX) is a term used to describe any of the various design methods that focus on specific product development concerns. For example, X can stand for safety, reliability, assembly, manufacture, tolerances, robustness, or the environment.

Since DFX methods address specific issues, they implement customized procedures that take advantage of specific information available at different phases of design. Design for assembly and design for manufacture, for example, were introduced in Chapter 7 "Configuration Design," because those methods utilize changes in product form, such as shape and configuration, to improve assembly and manufacture. Design for robustness was introduced in Chapter 8 "Parametric Design," since most methods depend on quantitative information available at that phase.

Tolerance design is especially useful during and after parametric design, as the final manufacturing specifications are being prepared. Design for safety,

10.2.2 Calculating the Risk Priority Number (RPN)

The risk priority number is a metric used to assess the risk of a failure mode. The RPN for a part failure mode is the product of three factors: a **severity rating**, an **occurrence rating**, and a **detection rating**. $RPN = (S) \cdot (O) \cdot (D)$. Each factor is a numerical rating that ranges between 1 (good) and 10 (bad), as shown in Tables 10.3 thru 10.5. Note that lower rating numbers are better. Consequently, the smaller the RPN, the smaller the risk. In other words, a part with almost no risk would have a severity rating of 1, an occurrence rating of 1, and a detection rating of 1, resulting in an RPN equal to 1. Similarly, a part having the most risk of failure would have a $RPN = 10 \cdot 10 \cdot 10 = 1000$.

Step 1: Determine the failure modes.

Identify the way in which the component might fail to perform its desired function(s). Consider how a function transforms matter, energy, and signal. Review information sources such as the House of Quality, function decomposition diagrams, free-body diagrams, the product engineering design specification, process flow diagrams and configuration sketches, part-detail drawings, and assembly drawings. And in the case of an existing product, obtain service and/or test records.

Step 2: Determine potential effects of each failure mode.

Establish the effects of each failure mode in terms of what the user or the product might be subjected to.

Step 3: Select a severity (S) rating for each effect.

Determine possible injury to users, damage to product, personal, or real property, and or harm to the environment. Select an appropriate rating number from Table 10.3.

TABLE 10.3 Severity Rating for the Effects of a Failure Mode, Based on the Injury or Damage to People, Property, or the Environment

Severity (S) Rating	Type of effects	Description
10	CATASTROPHIC	Injury to people, or damage to property or environment
9	Extremely Harmful	Damage to product, property or environment
8	Very Harmful	Damage to product
7	HARMFUL	Major degradation of function
6	Moderate	Partial malfunction of product
5	Significant	Performance loss causes customer complaints
4	ANNOYING	Loss of function is annoying, cannot be overcome
3	Minor	Some loss of performance, but can be overcome
2	Insignificant	Very little function degradation
1	NONE	No noticeable effects in function or harm to others

Step 4: Determine the possible causes for each effect.

Brainstorm mechanical, electrical, chemical, and other physical mechanisms that could cause each effect. Consider common causes for similar products.

Step 5: Select an occurrence (O) rating for each effect.

Estimate the probability each cause will occur and select an occurrence rating from Table 10.4.

Step 6: Determine design and manufacturing controls.

List design activities such as calculation checks and engineering tests used to validate the design. Also, identify and list inspection or product testing controls that may detect possible manufacturing defects.

Step 7: Select a detection (D) rating for each cause.

Estimate the likelihood that the controls will detect each cause and select an appropriate detection rating value from Table 10.5.

TABLE 10.4 Occurrence Rating Based on the Likelihood That a Cause Will Occur

Occurrence (O) Rating	Likelihood of cause	Description
10	EXPECTED	>30 %
9	Very likely	30 % (3 per 10)
8	Probable	5 % (5 per 100)
7	OCCASIONAL	1 % (1 per 100)
6	More plausible	0.3 % (3 per 1,000)
5	Plausible	
4	REMOTE	0.006 % (6 per 10 ⁵)
3	Unlikely	0.00006 % (6 per 10 ⁷)
2	Very unlikely	
1	IMPROBABLE	< 2 per 10 ⁹ events

TABLE 10.5 Detection Rating Based on the Probability that Design and or Manufacturing Controls Will Detect the Cause

Detection (D) Rating	Detectability of cause	Description
10	IMPOSSIBLE	Impossible to detect, or no inspection
9	Very rare	
8	Rare	
7	POSSIBLE	Some chance of detecting, or 50% inspection
6	Quite possible	
5	Somewhat likely	
4	LIKELY	Quite likely to detect, or 75% inspection
3	Quite likely	
2	Almost certain	
1	CERTAIN	Will be detected, or 100% inspection

Step 8: Calculate the risk priority number for each failure mode.

Compute the product of the severity, occurrence, and detection ratings,
 $RPN = (S) \cdot (O) \cdot (D)$.

Step 9: Recommend and take action.

Rank the failure modes and determine which failure mode has the greatest risk. Generate, analyze, and evaluate alternative action plans that eliminate the potential cause(s), reduce the severity of their effects, or increase the frequency of detection. Recommend and implement the best alternatives.

Step 10: Recalculate the risk priority numbers.

After remedial action has been implemented, revise the RPN's for the "corrected" failure mode. Reiterate steps 9 and 10.

The 10-step FMEA method uses a tabular layout to organize the information and facilitate the calculations, as shown in Table 10.6.

TABLE 10.6 Failure Modes and Effects Analysis Template Used to Calculate Risk Priority Number Based on Ratings for Severity, Occurrence, and Detection

Failure mode	Severity (S)		Occurrence (O)		Detection (D)		RPN	Recommended Action
	Effects	S Rating	Causes	O Rating	Controls	D Rating		
(step 1)	(step 2)	(step 3)	(step 4)	(step 5)	(step 6)	(step 7)	(step 8)	(step 9)

Example

A portable log splitter has been designed for home use. A 10-horsepower gasoline engine has been selected to drive a hydraulic pump that connects to the piston and ram by a wire-reinforced rubber hose. The product development team has identified that a fluid leak is a possible failure mode for the hose. Fluid leaks have been caused in the past by poor hose material supplied by vendors. Also, during manufacture, an automated assembly machine has been known to occasionally cut the hose. The team estimates that the likelihood of a "poor material" is about 5 percent and a "cut" is about 0.5 percent. When a poor-material hose leaks it reduces the pressure to the piston/ram resulting in poor splitting, in other words, a partial malfunction of the log splitter. When a cut hose leaks it damages the pump as the oil empties onto the ground. It also causes an oil spill harming the ground. The company will inspect 50 percent of the rubber hoses as they are delivered from the vendor. Also, it is quite likely that a cut hose will be detected because the assembly machine usually jams when it cuts.

Use the FMEA method to determine the risks associated with a leaky hose and recommend corrective actions.

Based on the given information we select a "moderate" severity rating = 7 for the poor material cause, and an "extremely harmful" severity rating = 9 for the cut-hose.

We select a "probable" occurrence rating = 8 for the poor material, and a "probable" occurrence rating = 7 for the cut hose. Finally, we select detection ratings of 7 and 4, respectively. We enter the data into the template and calculate the RPN's as shown in Table 10.7.

In discussions with the development team, we establish a new inspection procedure to test 100 percent of the incoming hose material. And we will modify the assembly machine to reduce the cut size, thereby producing effects (i.e. leaks) with a similar severity to that of poor hose material. Revised RPN calculations result in Table 10.8.

The new pressure test procedure will make a significant reduction in the risk of a poor material causing a leak. Similarly, the risk for a cut hose will be reduced. In the first case, we changed the detectability, and in the second case we changed the severity.

TABLE 10.7 FMEA Analysis of Log-splitter Hose

TABLE 10.7. FMEA of a log splitter								
Failure mode	Effects	Severity (S)	Occurrence (O)		Detection (D)		RPN	Recommended Action
		S Rating	Causes	O Rating	Controls Tests	D Rating		
hose leaks	poor log splitting	7	poor material	8	inspect 50%	7	392	establish new pressure test
	oil mess pump damage	9	cut hose	7	none	4	252	modify assembly machine

Table 10.8 Revised FMEA Analysis with Revised Risk Priority Number for hose leak failure mode

Table 10.8 Revised FMEA Analysis with Revised Risk Priority Number for hose leak and pump damage								
Failure mode	Effects	Severity (S)	Occurrence (O)		Detection (D)		RPN	Recommended Action
		S Rating	Causes	O Rating	Controls Tests	D Rating		
hose leaks	poor log splitting	7	poor material	8	test 100%	1	56	none further
	some oil spill no pump damage	7	cut hose	7	none	4	196	none further

A failure mode-and-effects analysis can be completed beginning as early as the configuration design phase. Existing products can also be evaluated. The method has also been used to reduce the risk of failure within processes.

10.3 DESIGN FOR SAFETY

An unsafe product may cause injury to people. It may also cause damage to personal or real property. A defective automobile brake system, for example, could result in a collision that might injure the driver, passengers, other

drivers and pedestrians. The collision could cause damage to vehicles, buildings, and/or other facilities. Similarly, an unsafe industrial product or system could injure employees or damage manufacturing facilities. For example, an unguarded machine tool could entrap an operator's hand, crushing it severely, or improperly vented fumes could explode or start a fire, injuring workers and damaging valuable equipment and the building.

Design for safety is a term used to describe design methods which aim to reduce the risk and severity of personal injury or property damage. Designing and manufacturing an unsafe product can lead to customer and employee lawsuits and criminal penalties. It is also unethical. The American Society of Mechanical Engineers Code of Ethics, for example, places the safety, health, and welfare of the public as the paramount responsibility of an engineer.

10.3.1 Safety Hazards

Injuries may occur to employees or customers at any stage in the life of a product, including during:

- manufacture—when components are fabricated, assembled, and distributed,
- use—when the user sets up, operates, repairs, and maintains the product,
- retire—when the user takes down, disassembles, recycles, and disposes.

Therefore, as we design a product it is our paramount responsibility to consider the hazards that may be dangerous for anyone coming into contact with the product or its components during its lifetime. Wherever possible, we must design-out, eliminate or reduce the risk of injury or property damage.

A **hazard** is a source of danger. Hazards have the potential to injure people or damage property or the environment. Let's consider the types of injuries to people, including cuts, burns, broken bones, poisoning, and radiation. Some hazards act through direct contact. Others act indirectly via inhalation (of gases or vapors) or radiation. We also recognize that injury and damage can result from the dissipation of the kinetic energy of moving machine components or the potential energy stored in chemicals and mechanical equipment. Lindbeck (1995), for example, describes six basic types of hazards:

1. **Entrapment.** **Entrapment hazards** cause injuries when machine parts move toward each other to create pinch points where fingers, hands, or other body parts can get pinched or crushed. Examples include roller chains and sprockets, belts and pulleys, pivoting levers, meshing gears, and lifting platforms.
2. **Contact.** **Contact hazards** cause injuries merely by coming into contact with body parts. These hazards include hot surfaces, sharp edges, or electrically charged parts, either moving or stationary. Examples include gasoline engine mufflers, welding equipment, stamped metal parts with burrs, rotating or reciprocating saw blades, and exposed electrical wires or contacts.

3. **Impact.** **Impact hazards** cause injuries as translating, rotating, or reciprocating machine parts collide with body parts. Examples include hammer blows to the hand and gear hub collars with projecting bolts.
4. **Ejection.** **Ejection hazards** cause injuries as debris particles are flung from moving machine parts. Examples include grinding-wheel disintegration chunks and circular-saw wood particles.
5. **Entanglement.** **Entanglement hazards** include rotating shafts or moving work pieces that can catch hair or loose clothing. Examples include entangling hair on a rotating shaft such as a lathe and catching loose clothing in a wood chipper.
6. **Noise and vibration.** Loud noises can result in temporary or permanent hearing loss. Examples include unprotected exposure to noise from engine exhausts and stamping machines. Extended exposure to vibrating hand tools can cause numbness in the limbs, referred to as hand-arm vibration syndrome (HAVS).

Hazards also include fire, explosion, electromagnetic radiation, and exposure to toxic, hazardous, or radioactive substances. Finally, we can include environmental hazards such as extremes in temperature, humidity, wind, ice, snow, and lightning.

Conditional Circumstances We should also distinguish conditions associated with hazards. For example, a grinder has a rotating abrasive wheel. If a chunk of the wheel breaks off, unexpectedly, during use, it may have sufficient kinetic energy to penetrate unprotected human skin tissues and is also very likely to cause eye injury. This is a circumstance when the abrasive failed to hold the wheel together. Sparks caused by normal grinding, on the other hand, are a "normal" hazard that is inherent in the operation of the machine. Misuse by the user is another conditional circumstance. For example, consider how a user might pick up a bench grinder to grind an I-beam that is elevated 10 feet off the floor, rather than using a portable grinder.

Finally, we have the condition due to regular maintenance. For example, a service person may be exposed to electrical shock when removing a protective cover from a machine. Improper maintenance and failure to properly maintain equipment are additional circumstances that may create hazards. Lack of exhaust muffler maintenance, for example, might lead to carbon monoxide poisoning. We can define six conditional circumstances as follows:

1. Hazard is inherent during normal use.
2. Hazard originates from a component failure.
3. Hazard is caused by user misuse.
4. Hazard exists during normal maintenance.
5. Hazard is created by improper maintenance.
6. Hazard stems from lack of maintenance.

We are responsible for design and manufacture of safe products. Therefore, we must consider not only those inherent hazards that occur during normal use, but also those hazards that may occur under all six conditions.

10.3.2 Legal Responsibilities

As professionals we are ethically bound to hold paramount the safety, health, and welfare of the public. Under local, state, and federal laws, we are also legally responsible for the safety of our customers and employees. Products liability deals with customer product safety while the Occupational Safety and Health Act(s) (OSHA) deals with employee safety.

Products Liability is a phrase used to describe our legal responsibility to our customers under criminal or civil actions (Blinn, 1989). **Criminal actions** are legal proceedings directed at individuals or companies who may have committed a crime. For example, an individual negligent in the performance of his duties may be charged with negligent homicide and ultimately face prison time. **Civil actions** are those taken by the injured party (plaintiff) against the manufacturer or seller (defendant) to recover damages for personal injury or loss to property caused by defect(s) in design or manufacture.

The attorney(s) for the plaintiff in a civil action will try to prove that the product had a defect in design or defect in manufacture (Himmelfarb, 1985) and that the defect occurred because of the negligence of the manufacturing company or the designer(s) in that they failed to:

- perform appropriate analyses,
- comply with published standards,
- make use of state-of-the-art technology, owing to ignorance,
- include reasonable safety features or devices,
- take into account how the user might misuse the product,
- consider hidden dangers that might surprise the user,
- consider variations in materials, manufacturing processes, or effects of wear,
- carry out appropriate testing, or interpret results correctly,
- provide adequate warnings.

It is important to note that in addition to diligently designing and manufacturing safe products we must also document our efforts in order to prove that we were not negligent in our duties.

Occupational Safety Employees are protected with regard to **occupational safety** under local, state, and federal laws, the most notable being the federally mandated Occupational Health and Safety Act of 1970. Employers are therefore legally responsible for ensuring that their employees are protected from a



Recall notices are used to alert consumers of potential product defects and their modes of failure before they happen. Then, after repair or replacement, the product can be relied upon to perform its required function.

variety of workplace hazards, including: hazardous chemicals, noise, vibration, heat, cold, dust, radiation, inhaled fibers, bacteria, molds, fungi, insects, bites, inadequate lighting, repetitive movements, and lifting.

10.3.4 Guidelines for Safe Products

A number of guidelines result directly from the discussion above:

1. Perform appropriate analyses. All analysis calculations should be completed thoroughly, checked, signed, and dated. Analyses should be as comprehensive as those typically performed in the practice.
2. Comply with published standards. Obtain, review, and implement relevant industry and government standards.
3. Use state-of-the-art technology. We must keep our knowledge up to date. Ignorance of newer, safer technology is not an excuse.
4. Include reasonable safety features or devices. Design-in safety features and devices to eliminate or protect against the hazard.
5. Take into account how the user might misuse the product. Consider how the user could misuse or abuse the product. Try to eliminate opportunities for the user to misuse the product.
6. Consider hidden dangers that might surprise the user. Consider sudden loud noises or vibrations or unusual modes of operation that might startle the operator, causing loss of control and injury.
7. Consider variations in materials or manufacturing processes, or effects of wear. Analyze the robustness of the product. Design-in allowances for wear and environmental deterioration.
8. Carry out appropriate testing and interpret results correctly. Conduct a thorough test plan of individual parts and completed assemblies. Con-

consider all modes of failure and the hazards originated by each mode. Thoroughly document your findings and judge your results conservatively.

9. Provide adequate warnings. Include appropriate warning labels on the product and in the user/owner manual. Also consider warning devices such as audible or visible alarms.
10. Implement superior quality control. Implement a program of part and assembly inspection and function testing that is commensurate with the nature of the hazards and the probabilities of occurrence.
11. Document everything. Check, sign, date, and archive relevant documents.

Safety Hierarchy. Over the last 30 years, a method has evolved that prioritizes design for safety efforts. It is called the safety hierarchy (Pahl and Beitz, 1996; MIL-STD-1472F, 1999). The **safety hierarchy** establishes the priorities for risk reduction as follows:

1. *Eliminate the hazard.* This is a proactive approach that recognizes that it is often more effective to just "design-out" the hazard. Redesigning the cover to eliminate access to the moving parts is an example.
2. *Protect against the hazard.* This is a passive or indirect approach, which does not eliminate the hazard, but eliminates the opportunity for the user to come into contact with the hazard. Examples include machine guards, safety interlock switches, light curtains, seatbelts, and locked equipment rooms.
3. *Warn against the hazard.* This does not eliminate the hazard or the opportunity. It is a weak remedy, but in some cases the only effective alternative. Examples include warning labels, passive barriers, and alarm systems.
4. *Provide training.* Provide and require appropriate operator training.
5. *Provide personal protection.* Provide the operator or user with protective clothing or protective devices such as safety glasses, nonflammable welding aprons, or rubber gloves to handle chemicals.

Example

Our team is designing a machine tool housing for a large and expensive tool that will run 24 hours a day, seven days a week. The current design will require removal of a cover panel during servicing, exposing moving gears and links, which could cause pinching, crushing, or cutting injuries. Use the Safety Hierarchy to suggest a prioritized list of re-design efforts.

The team is considering the following alternatives:

- Design an "open-access-cover" alarm horn and flashing light.
- Include a lockable disconnect switch, and have the operator "red-tag" the switch to alert other personnel from re-starting the machine.
- Provide an instruction manual describing the hazard of removing the access panel.
- Relocate the access cover such that moving parts are not exposed.

- Design the machine to never need maintenance during its lifetime.
- Provide the operator with wire-mesh safety gloves, to reduce finger cuts.
- Place a warning label on the access cover and in the user manual.

Using the Safety Hierarchy we would consider redesign efforts in the following order.

1. Eliminate the hazard. For example, we could design the machine to never need maintenance during its lifetime? Some bearings are "lubricated-for-life." Upon further investigation, the team might be able to design the machine as "no-maintenance-required". Perhaps the parts needing service are not moving, and can be accessed from a different path away from the exposed moving parts. This alternative could be safe and economical.
2. Protect against the hazard. Depending on the electrical connection, designing a lockable disconnect switch alternative might be easy and inexpensive.
3. Warn against the hazard. Placing a warning label on the machine or designing an "open-access-cover" alarm horn and flashing light does not eliminate the hazard. But, labels and alarms alert the operator to possible injury.
4. Provide training. Providing an instruction manual is useful, but should not be relied upon to prevent injury. Manuals get lost and operators forget what they have read. Also, in-person training is somewhat helpful but is not a good way to prevent injury.
5. Provide personal protection. Safety gloves would help reduce cuts but may not prevent pinching and or crushing injuries.

Note that the team is responsible for designing-in safety. The "safety, health and welfare of the public is paramount..." Considerations of increased costs and or reduced profits resulting from safety improvements are not paramount. National and local codes and standards, management and our company's legal staff will help guide us in factoring in these aspects.

Safe Design Principles. Three fundamental design principles are used to design safe products and systems: safe-life design, fail-safe design, and redundant design.

1. **Safe-life design principle.** Product components are designed to operate for their entire predicted useful life without breakdown or malfunction. Examples include hammers, screwdrivers, bridges, buildings, and electric hand drills. Product design, based on this principle, requires the designers to identify and specify: all operating conditions, misuses and abuses of the product, and appropriate maintenance and repair schedules.
2. **Fail-safe design principle.** Product is designed such that upon failure of a component, some critical functions are still performed. Failure of the component should be discernible such that the product can be shut down safely. Examples include using a castle nut and a cotter pin to prevent a nut from falling off a bolt and separating the connection, or a boiler feed-water valve failing in the open position, a "failed" roller bearing generating vibration and noise while providing some function.

3. **Redundant design principle.** Additional components or systems, configured in parallel or series, take over the principal function of the failed component or system. Examples include multiengine airplanes, standby electric generators, dual in-line oil filters, and emergency brakes.

Safety is no accident.

10.4 TOLERANCE DESIGN

As part of our parametric design activities, we determine appropriate values for the design variables such as lengths, widths, heights, hole diameters, thicknesses, fillet radii, chamfers, and slot widths. These values are shown on detail drawings as dimensions. A **dimension** is any quantity that *sizes, locates, or orients* geometric features on a part.

Many products are composed of multiple components. Some of the components may be standard parts, which we purchase from a variety of vendors. Others may be special-purpose parts that we manufacture, or outsource for manufacture by another company.

The success of our product ultimately depends on how well the components fit and function together. Rotating or translating parts, for example, need clearances to allow for motion. Some fastened parts need interferences such as press fits and snap fits. Assuming that we are mass-producing the product, we can benefit by making interchangeable parts. Interchangeable parts fit and function together during original assembly without trimming or patching operations. They also provide for convenient replacement during routine servicing.

We can tolerate just so much variation before the fit or function becomes unacceptable.

Example

The part shown on Figure 10.1 has dimensions A–F. Which of these are used to size a feature, locate a feature, or orient a feature?

Dimension A, D, and E are size dimensions that specify the width and height of the part and the diameter of the hole, respectively. Dimensions B and C are location dimensions that determine the center of the hole. Dimension F is an orientation dimension that specifies the angle of the inclined surface.

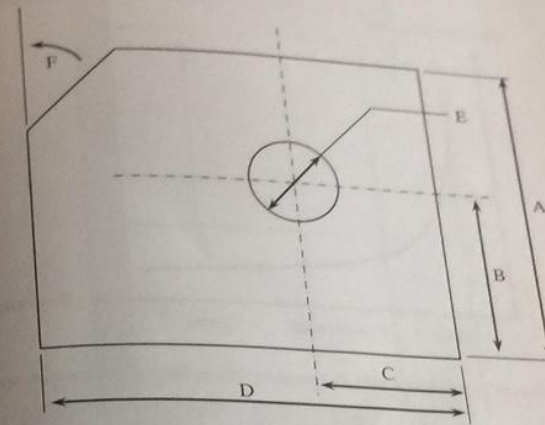


FIGURE 10.1 Example part showing size, location, and orientation dimensions.

To maintain control over dimensional variation, we specify upper and lower limits on part dimensions, that is, maximum and minimum sizes. The specified difference between maximum and minimum size limits of a part feature is called a **tolerance**.

To achieve part-interchangeability we might be tempted to specify small tolerances. But the realities of manufacturing are that interchangeable parts are not easy to make. Sand-casting processes, for example, can achieve only rough dimensional precision. Investment casting is better, and machining processes are better yet.

The reasons for dimensional variations in machining, for example, include how fast we remove material, the mechanical properties of the material, the quality of the tool, and the rigidity of the clamping fixtures. All of the manufacturing processes, in fact, have similar limitations. Of course, if we handcraft each part, we can achieve fine tolerances. For example, we can slow down the feed rate during machining, use the most rigid fixture, or use the best tools. In general, we find that the cost of producing a part increases rapidly as we specify finer tolerances that are beyond the typical ability of commercial equipment, as shown in Figure 10.2.

Our goal as a product development team, therefore, is to design a part that balances the costs of finer tolerances with the benefits of improved interchangeability. In other words, the parts fit and function as expected.

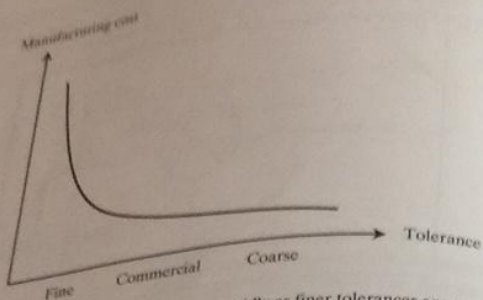


FIGURE 10.2 The cost to produce a part increases rapidly as finer tolerances are specified.

10.4.1 Worst-Case Tolerance Design

Worst-case tolerance design is an approach that assures that almost all of the parts fit together. It assumes that each manufacturing process will produce parts with the "worst" precision within its capability. If, for example, a machine produces parts to within ± 0.005 inches and we need the part to be big, the method assumes that the part will be made short (-0.005 inches), rather than big ($+0.005$ inches). It is considered to be a conservative method because it ignores the many parts that are made with little or no deviation from the nominal.

Consider the three-part assembly having a clearance fit shown in Figure 10.3. Parts designed for a **clearance fit** are specified with an intended space between mating parts. A clearance fit is needed for a bolt to fit into a hole, for example. Sometimes clearance fits are specified to make parts easier to assemble. An **interference fit**, on the other hand, is specified with an intended lack of space between mating parts, such as a gear press-fitted onto a shaft. We note that parts B and C are assembled into part A. Assume that a 0.015 clearance fit is required and that the nominal dimensions for A, B, and C are 3.000, 1.650, and 1.300 inches, respectively. Furthermore, assume that part A can be made to within ± 0.015 inch, B within ± 0.003 inch, and C within ± 0.020 inch. Will the assembly have the desired clearance fit? If not, how should we specify the tolerances?

We can define the manufactured lengths of A, B and C as the sum of a nominal dimension and a tolerance as $d_A = 3.00 \pm 0.015$, $d_B = 1.650 \pm 0.003$ and $d_C = 1.300 \pm 0.020$. The clearance gap d_g can be obtained from:

$$d_{gap} = d_A \pm t_A - (d_B \pm t_B + d_C \pm t_C) \quad (10.1)$$

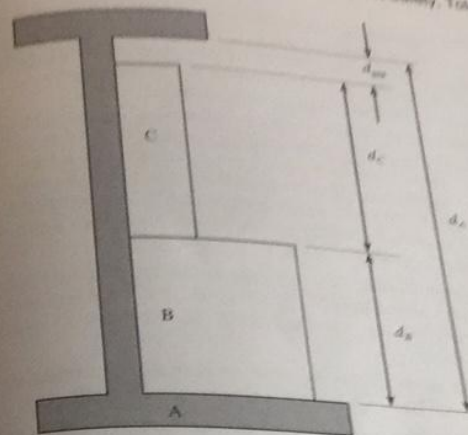


FIGURE 10.3 Assembly consisting of parts B and C mating in part A.

We rearrange the equation to separate the nominal dimensions from the tolerances to obtain equation (10.2). We see that the clearance is equal to the nominal gap minus the tolerance stack (within the summation sign).

$$d_{gap} = (d_A - d_B - d_C) - (\pm t_A \pm t_B \pm t_C) = d_{gap \text{ Nominal}} - \sum \pm t_i \quad (10.2)$$

We find that the worst case of clearance gap is found by substituting the maximum material condition (MMC) dimension of each part into equation (10.1). The worst clearance or smallest gap, results from having the smallest part A to mate with the largest parts B and C. This results in a clearance gap value of:

$$d_{gap} = d_A - t_A - (d_B + t_B + d_C + t_C) \quad (10.3)$$

Substituting the numerical values, we determine the clearance gap as:

$$d_{gap} = 3.000 - 0.015 - (1.650 + 0.003 + 1.300 + 0.020) \quad (10.4)$$

$$d_{gap} = 2.985 - (1.653 + 1.320) = 2.985 - 2.973 \quad (10.5)$$

$$d_{gap} = 0.012 \text{ in.} \quad (10.6)$$

Since the minimum clearance required is 0.015, this is not an acceptable situation. We see that even under the worst circumstance for part A and the worst circumstance for parts B and C, we still cannot guarantee that the

assembly will fit together. In this situation we would need to remanufacture or dispose of some of the ill-fitting parts. Either alternative is expensive. In all likelihood, the worst-case assembly does not occur that often. In fact, the major drawback of this method is that it may be too conservative.

We can remedy this situation a couple of ways:

Tighten some tolerances. We can ask manufacturing engineering to estimate the impact of tightening the tolerance on one of the parts. If, for example, we squeeze out 0.003 inch by improving the manufacturing processes for part A, and or part C, we would have the desired clearance. This may mean spending more time and labor to produce either part, which adds cost to the assembly. We might be able to afford a higher-precision machine. But, until we ask, we won't know what the facts are.

Redesign the nominal values. We can reexamine the nominal sizes for the parts. Can A be 0.003 inch larger? Can either B or C be 0.003 inch smaller? This may not be possible for standard parts. So we have to dig in to the circumstances and find out.

Redesign some of the parts. If the top wall of part A, for example, could be eliminated, we would not have a need for a clearance gap at all.

Consider selective assembly. Assume that during assembly, larger B and C parts could be separated from the smaller ones. Using selective assembly they could be selected and assembled onto larger A parts (Stoll, 1999). This, of course, would require inspection and inventory costs. It also may not be suitable for parts that need replacement in the field.

10.4.2 Statistical Tolerance Design

The **statistical tolerance design method** uses stochastic measures of each manufacturing process to estimate the probability that parts will fit and/or function based on the actual statistical capability of the processes. It is not as conservative as the worst-case method and is considered to be the most widely used method in industry (Creveling, 1997).

The statistical method assumes that dimensions and their tolerances are random variables, x_i and s_i . We can approximate the mean value of a function of those variables $\phi(\mathbf{x})$, such as clearance gap, by the function evaluated at the mean values of the random variables as

$$\bar{\phi}(\mathbf{x}) = \phi(\bar{x}_1, \bar{x}_2, \bar{x}_3, \dots, \bar{x}_n) \quad (10.7)$$

The standard deviation can be similarly estimated by taking the square root of the sum of the squared deviations as

$$s = (s_1^2 + s_2^2 + \dots + s_n^2)^{1/2} = \left(\sum_{i=1}^n s_i^2 \right)^{1/2} \quad (10.8)$$

We can estimate the mean value of the clearance gap by substituting the mean values of the part dimensions, that is the nominal values, as shown in equation (10.9) and (10.10) resulting in a clearance gap mean value of 0.050 in.

$$\bar{d}_{gap} = \bar{d}_A - (\bar{d}_B + \bar{d}_C) \quad (10.9)$$

$$\bar{d}_{gap} = 3.000 - (1.650 + 1.300) = 0.050 \text{ in.} \quad (10.10)$$

The upper limit for a manufacturing process is typically assumed as three standard deviations above the mean value that is $t = +3s$ and the lower limit is assumed to be $t = -3s$. Rearranging the variables, we find that $s = t/3$. The equation for the standard deviation of the gap can be obtained as:

$$s_{gap} = (s_A^2 + s_B^2 + s_C^2)^{1/2} \quad (10.11)$$

$$s_{gap} = [(t_A/3)^2 + (t_B/3)^2 + (t_C/3)^2]^{1/2} \quad (10.12)$$

$$s_{gap} = [(0.015/3)^2 + (0.003/3)^2 + (0.020/3)^2]^{1/2} \quad (10.13)$$

$$s_{gap} = 0.008393 \text{ in.} \quad (10.14)$$

Transforming the random variable d_{gap} to the standard unit normal distribution z , we obtain a measure of the probability that the clearance is less than 0.015 in. We know that for normally distributed random variables we can find the probability that $x \leq x^*$ by numerically integrating the probability density function as follows.

$$p(x \leq x^*) = \int_{-\infty}^{x^*} f(x) dx = \int_{-\infty}^{x^*} \frac{1}{\sqrt{2\pi} \sigma} e^{-\frac{1}{2} \left(\frac{x^* - \mu}{\sigma} \right)^2} dx \quad (10.15)$$

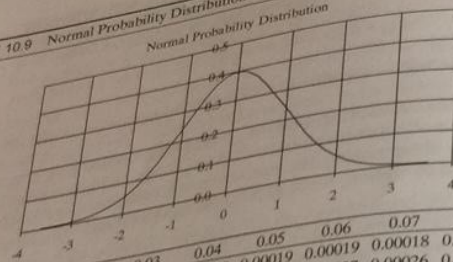
Rather than integrating equation (10.15) for every problem, we can transform a normally distributed random variable x , to the unit normal distribution variable z , using equation (10.16).

$$z^* = \frac{x^* - \bar{x}}{s} \quad (10.16)$$

$$p(z \leq z^*) = \int_{-\infty}^{z^*} f(z) dz = \int_{-\infty}^{z^*} \frac{1}{\sqrt{2\pi}} e^{-\frac{1}{2} z^2} dz \quad (10.17)$$

Probability values derived from equation (10.17) are shown in Table 10.9.

TABLE 10.9 Normal Probability Distribution



Z	0.00	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
-3.5	0.00023	0.00022	0.00022	0.00021	0.00020	0.00019	0.00018	0.00017	0.00017	0.00017
-3.4	0.00034	0.00032	0.00031	0.00030	0.00029	0.00028	0.00027	0.00026	0.00025	0.00024
-3.3	0.00048	0.00047	0.00045	0.00044	0.00042	0.00040	0.00039	0.00038	0.00036	0.00035
-3.2	0.00069	0.00068	0.00066	0.00064	0.00062	0.00060	0.00058	0.00056	0.00054	0.00052
-3.1	0.00097	0.00094	0.00092	0.00089	0.00087	0.00084	0.00082	0.00079	0.00076	0.00074
-3.0	0.00135	0.00131	0.00126	0.00122	0.00118	0.00114	0.00111	0.00107	0.00104	0.00100
-2.9	0.00187	0.00181	0.00175	0.00169	0.00164	0.00159	0.00154	0.00149	0.00144	0.00139
-2.8	0.00256	0.00248	0.00240	0.00233	0.00226	0.00219	0.00212	0.00205	0.00199	0.00193
-2.7	0.0035	0.0034	0.0033	0.0032	0.0031	0.0030	0.0029	0.0028	0.0027	0.0026
-2.6	0.0047	0.0045	0.0044	0.0043	0.0041	0.0040	0.0039	0.0038	0.0037	0.0036
-2.5	0.0062	0.0060	0.0059	0.0057	0.0055	0.0054	0.0052	0.0051	0.0049	0.0048
-2.4	0.0082	0.0080	0.0078	0.0075	0.0073	0.0071	0.0069	0.0068	0.0066	0.0064
-2.3	0.0107	0.0104	0.0102	0.0100	0.0099	0.0096	0.0094	0.0091	0.0089	0.0088
-2.2	0.0139	0.0136	0.0132	0.0129	0.0125	0.0122	0.0119	0.0116	0.0113	0.0110
-2.1	0.0179	0.0174	0.0170	0.0166	0.0162	0.0158	0.0154	0.0150	0.0146	0.0143
-2.0	0.0228	0.0222	0.0217	0.0212	0.0207	0.0202	0.0197	0.0192	0.0188	0.0183
-1.9	0.0287	0.0281	0.0274	0.0268	0.0262	0.0256	0.0250	0.0244	0.0239	0.0233
-1.8	0.0359	0.0351	0.0344	0.0336	0.0329	0.0322	0.0314	0.0307	0.0301	0.0294
-1.7	0.0446	0.0436	0.0427	0.0418	0.0409	0.0401	0.0392	0.0384	0.0375	0.0367
-1.6	0.0548	0.0537	0.0526	0.0516	0.0505	0.0495	0.0485	0.0475	0.0465	0.0455
-1.5	0.0668	0.0655	0.0643	0.0630	0.0618	0.0606	0.0594	0.0582	0.0571	0.0559
-1.4	0.0808	0.0793	0.0778	0.0764	0.0749	0.0735	0.0721	0.0708	0.0694	0.0681
-1.3	0.0968	0.0951	0.0934	0.0918	0.0901	0.0885	0.0869	0.0853	0.0838	0.0823
-1.2	0.1151	0.1131	0.1112	0.1093	0.1075	0.1056	0.1038	0.1020	0.1003	0.0985
-1.1	0.1357	0.1335	0.1314	0.1292	0.1271	0.1251	0.1230	0.1210	0.1190	0.1170
-1.0	0.1587	0.1562	0.1539	0.1515	0.1492	0.1469	0.1446	0.1423	0.1401	0.1379
-0.9	0.1841	0.1814	0.1788	0.1762	0.1736	0.1711	0.1685	0.1660	0.1635	0.1611
-0.8	0.2119	0.2090	0.2061	0.2033	0.2005	0.1977	0.1949	0.1922	0.1894	0.1867
-0.7	0.2420	0.2389	0.2358	0.2327	0.2296	0.2266	0.2236	0.2206	0.2177	0.2148
-0.6	0.2743	0.2709	0.2676	0.2643	0.2611	0.2578	0.2546	0.2514	0.2483	0.2451
-0.5	0.3085	0.3050	0.3015	0.2981	0.2946	0.2912	0.2877	0.2843	0.2810	0.2776
-0.4	0.3446	0.3409	0.3372	0.3336	0.3300	0.3264	0.3228	0.3192	0.3156	0.3121
-0.3	0.3821	0.3783	0.3745	0.3707	0.3669	0.3632	0.3594	0.3557	0.3520	0.3483
-0.2	0.4207	0.4168	0.4129	0.4090	0.4052	0.4013	0.3974	0.3936	0.3897	0.3859
-0.1	0.4602	0.4562	0.4522	0.4483	0.4443	0.4404	0.4364	0.4325	0.4286	0.4247
0.0	0.5000	0.4960	0.4920	0.4880	0.4840	0.4801	0.4761	0.4721	0.4681	0.4641

The likelihood that the clearance is smaller than the required amount, can be stated as $p(d \leq d^*)$, for $d^* = 0.015$ as shown in (10.17).

$$p(x \leq x^*) = p(d_{gap} \leq 0.015) = p(z \leq z^*) \quad (10.18)$$

$$z^* = \frac{x^* - \bar{x}}{s} = \frac{d^* - \bar{d}}{s_d} = \frac{0.015 - 0.05}{0.008393} = -4.170 \quad (10.19)$$

Therefore

$$p(d_{gap} \leq 0.015) = p(z \leq -4.170) \approx 0. \quad (10.20)$$

Using the unit normal distribution table, we find the probability, that the clearance gap is smaller than 0.015 inches, is not even listed on the table because it is so small. Using a spreadsheet function to evaluate the unit normal distribution integral, we find the computed probability is 0.0000152. This is equivalent to 15.2 occurrences per million assemblies. We now see why the worst-case method is considered conservative. Based on this very small probability, the existing design is acceptable.

Using **sensitivity analysis**, we can examine the stack of tolerances to see which specific parts contribute the most variation (Ullman, 1997). We rearrange equation (10.8) as follows:

$$s^2 = s_1^2 + s_2^2 + \dots + s_n^2 \quad (10.21)$$

Then by dividing through by s^2 , we obtain equation (10.22) where P_i are the percentage contributions to the assembly variance.

$$1 = \frac{s_1^2}{s^2} + \frac{s_2^2}{s^2} + \dots + \frac{s_n^2}{s^2} = P_1 + P_2 + P_3 \dots P_n \quad (10.22)$$

Using the values from the example, we can create a summary shown in Table 10.10. We see that part C contributes 63.1 percent of the variation and part A contributes 35.5 percent. Therefore, if we were out of tolerance, we would focus our tolerance design attention on part C.

Table 10.10 Sensitivity Analysis Of Three-Part Assembly

Part	t	s	s^2	P_i
A	0.015	0.00500	2.50E-05	35.5
B	0.003	0.00100	1.00E-06	1.4
C	0.020	0.00667	4.44E-05	63.1
				100.0

Example

A 5-inch-diameter pin will be assembled into a 5.005-inch journal bearing. The pin manufacturing tolerance is specified as 0.003 inch. A minimum clearance fit of 0.001 inch is required for the hole such that 0.1 percent of the pins are normal normal probability table. Assume that the manufacturing process is normally distributed. The mean value of the clearance gap can be found from:

$$\bar{d}_{\text{pin}} = \bar{d}_{\text{hole}} - \bar{d}_{\text{min}} = 5.005 - 5.000 = 0.005 \text{ in.}$$

$$\text{Using the normal distribution, we find that for a 0.1\%, } z = -3.90$$

$$z = \frac{\bar{x} - \bar{x}}{s} = \frac{d - \bar{d}}{s_d} = \frac{0.001 - 0.005}{s_d} = -3.90$$

$$s_d = \frac{0.001 - 0.005}{-3.90} = 0.00129 \text{ in.}$$

$$s_d = (s_{\text{hole}}^2 + s_{\text{pin}}^2)^{1/2} = 0.00129 \text{ in.}$$

$$s_d = (s_{\text{hole}}^2 + s_{\text{pin}}^2)^{1/2} = 0.00129 \text{ in.}$$

$$s_d = (s_{\text{hole}}^2 + s_{\text{pin}}^2)^{1/2} = 0.00129 \text{ in.}$$

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$$s_d = (s_{\text{hole}}^2 + s_{\text{pin}}^2)^{1/2} = 0.00129 \text{ in.}$$

Then solving for the tolerance, we obtain: $t_{\text{hole}} = 0.0025 \text{ in.}$

10.4.3 Tolerance Design Guidelines

The following guidelines can be used to make tolerance design decisions.

- Consider which dimensions, if any, are critical to the fit and function of the assembly. Not all dimensions will have an impact. Quantitatively examine tolerance stacks using worst-case or statistical tolerancing methods.
- amine tolerance stacks using worst-case or statistical tolerancing methods.
- Consider whether any critical parts can be redesigned to become noncritical.
- Consider the feasibility of selective assembly.
- Consider revising nominal dimensions before specifying tighter tolerances.
- If a tighter tolerance is needed, use sensitivity analysis to identify prospects.
- Specify commercial tolerances when possible.
- Reduce the number of fine-tolerance specifications.

DESIGN FOR THE ENVIRONMENT

Our personal health and well-being is intimately linked to the environment in which we live. We are dependent on the air we breathe, the water we drink, and the raw materials we consume. As the world population increases, more people share the same environment, encouraging us to find better ways to protect the world we share. It is our moral obligation. And as a member of the engineering profession, it is our ethical responsibility. **Design for the Environment (DFE)** is a group of design methods that aim to minimize the use of raw materials, increase recyclability, improve remanufacture, increase energy efficiency, and improve the workplace environment.

Design for Minimal Use of Materials. Let's examine the effects of material waste, by starting with the finished product. Was it packaged carefully to protect it during shipping? Broken or damaged products are often disposed of, that is, wasted. As the product was assembled, were any parts damaged, or thrown away because they were not within specifications? Could these parts have been designed better? During the fabrication of the parts, how much waste material was manufactured as scrap? Was the scrap recyclable? Upon receipt of the raw materials, were any damaged in transit, or spoiled owing to aging? Imagine if we could reduce our raw material usage 10 percent. Imagine the impact that would have on fuel used to ship the raw materials. Imagine the reduction of air pollution and highway repairs because of the reduction in raw materials shipping, and so on. To minimize materials use we can design lighter, less dense parts with reduced manufactured waste. Similarly, we should try to use renewable, non-toxic and abundant materials.

Design for Recyclability. These design efforts focus on returning recyclable materials back into the product stream. Non-recyclable materials are sent to waste disposal sites and should be designed with reduced volume or toxicity. Polymers, such as polyethylenes and polystyrenes, and metals, such as steel, copper, silver, and brass, are very recyclable assuming they can be economically separated from the non-recyclable materials. A separate field called design for disassembly considers aspects such as identifying parts with recyclable content and selecting appropriate fasteners that facilitate disassembly (Otto and Wood, 2001).

Design for Remanufacture. Not all products are composed of components that simultaneously fail. The typical laser printer, for example, has a replaceable toner cartridge that can be reused if appropriately remanufactured. **Remanufacturing** includes disassembly, inspecting, cleaning, and replacement of worn or broken parts. Product design efforts should focus on facilitating these activities, especially design for disassembly.

Design for Energy Efficiency. Products should be designed to be manufactured and used with less energy. Less electrical use during manufacture

means less heat generated by inefficient motors and devices. Also, using less electricity means less fossil fuel consumed, less air pollution, and possibly less global warming. Similarly, energy efficiency during, and also improves, the environmental hazard, noise, and thermal pollution. We also need to recognize and remedy the exposure of our co-workers and community to the environmental hazards, such as air pollution, chemicals, Close adherence to sure of our co-workers and community to the environmental hazards, such as air pollution, chemicals, Close adherence to exposure to toxic and/or hazardous materials is a must. We should also consider alternative materials and manufacturing processes that are more environmentally friendly.

10.6 SUMMARY

- > FMEA is used to identify potential failure modes, causes, and effects.
- > FMEA is used to eliminate or reduce the occurrence of failures and/or mitigate the severity of the effects of failures.
- > Hazards that can injure people or damage property exist in the manufacture, use, and retirement of products.
- > Engineers have legal and ethical responsibilities regarding the safety, health, and welfare of employees, customers, and the general public.
- > Design-for-safety practices include the safety hierarchy, safe-life design, fail-safe design and redundant design.
- > Tolerance design ensures part interchangeability.
- > Tolerance tolerance design is a conservative method that may be costly.
- > Worst-case tolerance design makes effective use of fundamental probability mathematics and manufacturing process data to specify tolerances that are more realistic but less conservative.
- > Design for the environment methods consider minimal use of materials, recyclability, remanufacture, energy efficiency, and workplace conditions.

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KEY TERMS

Civil actions	Fail-safe design	Risk priority number
Clearence fit	Failure Modes & Effects Analysis (FMEA)	Safe-life design
Contact hazards	Failure mode	Safety hierarchy
Criminal actions	Hazard	Selective assembly
Design for the Environment	Impact hazards	Sensitivity analysis
Design for safety	Interference fit	Severity rating
Design for X	Occupational safety	Statistical tolerance
Detection	Occurrence rating	design method
Detection rating	Products liability	Tolerance design
Dimension	Recyclable	Worst-case tolerance
Ejection hazards	Redundant design	design method
Entanglement hazards	Remanufacturing	
Entrapment hazards		

EXERCISES

Self-Test. Write the letter of the choice that best answers the question

1. B In the failure modes and effect analysis method, the reason why a part fails owing to a defect in design or manufacture is called the:
 - a. effect
 - b. cause
 - c. severity
 - d. detection
2. C The adverse consequences that the customer might experience is called:
 - a. severity
 - b. causes
 - c. effects
 - d. detection
3. D The risk priority number is the product of the following factors except:
 - a. severity rating
 - b. defects
 - c. occurrence rating
 - d. detection rating
4. B All of the following are examples of prevailing part failure modes except:
 - a. binding
 - b. rotating
 - c. leaking
 - d. fracturing
5. C What "likelihood" would rate a 10 on the occurrence rating chart?
 - a. occasional
 - b. remote
 - c. expected
 - d. improbable
6. D At what stage in the life of a product may injuries occur to employees or customers:
 - a. manufacture
 - b. use
 - c. retirement
 - d. all of these
7. A Injuries received by touching hot surfaces, sharp edges or electrical charged parts are caused by:
 - a) contact hazards
 - b) entrapment hazards
 - c) impact hazards
 - d) entanglement hazards
8. B Injuries received from hammer blows are called:
 - a. contact hazards
 - b. impact hazards
 - c. ejection hazards
 - d. entanglement hazards