CHAPTER 28

Research & Development: More Innovation, Scarce Resources

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About This Chapter

This chapter discusses managing for quality in research organizations and in development processes. The material focuses on concepts, infrastructure, methods, and tools for simultaneously improving customer satisfaction and reducing costs associated with both research and development functions. Quality within the software development process is discussed in Chapter 29, Software and Systems Development: From Waterfall to AGILE.

High Points of This Chapter

1. The research and development function is positioned at the “fuzzy front end” of the innovation cycle and is subject to forces of both “market push” and “technology pull.” This sets the stage for unique problems and opportunities in managing for quality.
2. Producing high-quality research requires balancing the sometimes opposing needs of business risk management and control and creativity.

3. Cultural and organizational factors can be significant, unrecognized barriers to sustained high-quality research and long-term organizational success.
4. Measures of R&D quality continue to evolve toward true performance metrics that should entail a combination of lagging, concurrent, and leading indicators.
5. Quality planning concepts, tools and methods should be applied to help ensure that product design meets customer requirements. Traditionally, this includes designing for such attributes as reliability and maintainability, but new dimensions such as designing for ergonomics and ecological impact are emerging.

Introduction

Frequently the combined term "R&D" is used to describe cross-departmental processes that integrate new knowledge and technology emanating from the research function with the subsequent development of new (or improved) processes and products. However, because these activities remain distinct in most organizations, it will be useful in this chapter to distinguish between managing for quality in research processes and managing for quality in development processes. The primary objective is to impart to the reader an understanding of how various organizations have integrated quality concepts and, ultimately, activities to foster the development and launch of new and innovative products and services.

Pushmi-Pullyu: Managing the Forces

Dr. Joseph Juran's original spiral of progress in quality (see Gryna et al. 2007, pp. 15-16) focused on the cross-functional flow involved in "developing" a new manufactured product. In the context of the original spiral, requirements for the new product emanated from marketing research. The marketing organization conducted research to define customers' needs, as well as to obtain customers' feedback on how well the organization had met those needs with existing products. Based upon customers' feedback and changing customer needs, a new turn of the spiral began.

By analogy, however, the "bridge" between R&D and customers can be initiated by either customers or R&D, with marketing facilitating the building of the bridge. Although a predominant source, marketing research is not the only possible origin of new technology and product ideas. This is especially true with technology-based products because customers (end users in particular) do not or cannot always articulate unmet needs that technology can address. Strategy-directed research is another significant source of product ideas and leverages the concept behind the quote attributed to Louis Pasteur that "chance favors the prepared mind." For example, Post-it notes resulted from the "failure" of an experiment that was recognized by a researcher as an opportunity for a new product. The low-tack, pressure-sensitive adhesive that is the critical product characteristic languished for several years before another scientist took advantage of the 3M Company's bootlegging policy that allowed R&D scientists to unofficially pursue new ideas (Petroski 1992).

Although failure is not the most desired route, it is a necessary part of R&D success over the long run. Roussel et al. (1991) and, more recently, Miller and Morris (1999) emphasized the criticality of using exploratory research balanced with business discipline, conducted proactively to support an organization's strategic focus. Nussbaum (1997) quotes Thomson Consumer Electronics' vice president of consumer electronics for multimedia products as stating that design processes are being used "to address overall strategic business issues." More recently, Beall (2002) emphasized the need to encourage the indistinct "fuzzy front end" of the innovation cycle that supports landmark new products.

Strategic research increasingly is being focused on the delivery of concepts and technologies that will drive new or improved technologies, such as quantum computing and now-commercialized nanotechnology. Strategy-directed research often supports the development of new, breakthrough "platform" technologies that initially have no apparent market but can later generate multiple products and significant competitive advantage, especially where intellectual property is involved. The origins of marketing research and strategy-directed research for new technologies and product concepts can be characterized as "market pull" and "technology push," respectively.

Regardless of the means for identifying needs and opportunities, managing for quality in research organizations and development processes has become recognized as a critical activity. In addition to synthesizing information toward technology, goods, and services that are fit for use, an organization needs to operate with both speed and efficiency. This requires coordinated effort between research and development. Throughout this chapter are examples of tools and processes that can facilitate coordination, reduced cycle times, and costs, although few organizations excel in more than a few core areas. Dell computer vaulted to a top industry position on the conviction that velocity attained via the compression of time and distance backward into the supply chain and forward to the customer, is a driver of competitive advantage (Dell 2000). Speed has its limitations (see Thackara 2005 for a critique of the "need for speed" philosophy), but managing for quality in the R&D processes demonstrably can simultaneously reduce cycle times and costs. At a Shell Oil research center, Jensen and Morgan (1990) found that a quality team's project for improving the project requirements process resulted in decreasing project cycle times by 12 months. At Corning Laboratories (Smith 1991) $21 million of cost reductions were realized over a four-year period while new products were pushed out faster and with lower costs. A project to reduce researchers' idle time during experiments produced $1.2 million in "easy savings." Similarly, Hutton and Boyer (1991) reported on a quality improvement project in Mitel Telecom's Semiconductor Division that resulted in custom prototype lead times being reduced from 22 weeks to 6 weeks. More recently, Shankar et al. (2006) reported that TAP Pharmaceutical Products, Inc. attained a 68% reduction in documentation processing time (from 282 days to 90 days), thereby facilitating earlier product registration and launch. These are not small amounts, but as a last example consider Boeing's 787 Dreamliner and revamped 747-8 jumbo jet that, through delays, rework, and program management issues generated a combined total of approximately $3.5 billion in charges (Sanders 2009).

The Missions of Research and Development

Although research and development have common business goals, in order to manage the research function and development processes, it is critical to define and understand their respective, separate missions. To help distinguish among various types of research and development activities, the Industrial Research Institute (1996) provided the following definitions:

- "Basic" (or "fundamental") research consists of original experimental and/or theoretical investigations conducted to advance human knowledge in scientific and engineering fields.
- "Directed basic" (or "exploratory") research is original scientific or technical work that advances knowledge in relevant (to corporate business strategies) scientific and engineering fields, or that creates useful concepts that can be subsequently developed into commercial materials, processes, or products and, thus, make a contribution to the company's profitability at some time in the foreseeable future. It may not respond directly to a specific problem or need, but it is selected and directed

in those fields where advances will have a major impact on the company's future core businesses.

- "Applied" research is an investigation directed toward obtaining specific knowledge related to existing or planned commercial products, processes, systems, or services.
- "Development" is the translation of research findings or other knowledge into a plan or design for new, modified, or improved products/processes/services whether intended for sale or use. It includes the conceptual formulation, design, and testing of product/process/service alternatives, the construction of prototypes, and the operation of initial, scaled-down systems or pilot plants.

Building from Roussel et al. (1991), the following general definitions for the research and development processes are useful:

- Research: The process used by an organization to acquire new knowledge and understanding.
- Development: The process used by an organization to apply and connect scientific or engineering knowledge acquired from research for the provision of products and/or services commensurate with the organization's mission.

Although the latter definitions are broad, they are helpful. Both have been constructed to incorporate the word "process." One of the tenets of business management strategies and programs such as Six Sigma, Total Quality Management (TQM) and the Baldrige National Quality Program is to improve key processes that result in "products" that are "fit for use" by an organization's internal and external customers. In support of this perspective, Nussbaum (1997) stated: "At the leading edge of design is the transformation of the industry to one that focuses on process as well as product." Organizations easily can overemphasize product or process innovation to the detriment of the other (potentially suboptimizing the larger business) because they tend to shift in relative importance through a product's life cycle. Early in the life cycle, innovation is greatest in the product itself, whereas later in the life cycle, the product itself is relatively static, but the production process is tinkered with to provide improvement (Figure 28.1). Correspondingly, Himmelfarb (1996a) has suggested

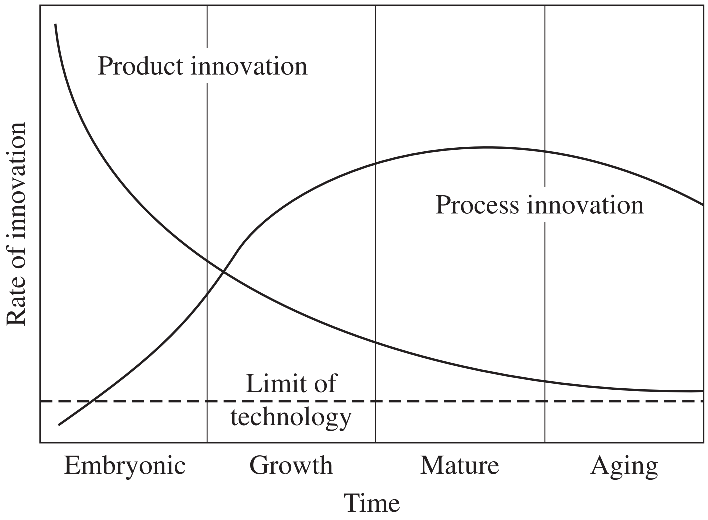

FIGURE 28.1 Shift in emphasis during research and development from product innovation to process innovation.

that one key responsibility of senior managers is to ensure that the product development process is well defined (via flowcharts), documented, understood, monitored, and improved. It is, therefore, useful to define the "products" and "customers" of the research and development processes, which, in turn, can be used to define, measure, plan, control, and improve process quality.

Products of Research and Development Processes

Juran (1992) defined a product as "the output of any process" and noted that the word "product" can refer to either goods or services. For the purpose of this chapter, product will be used to denote the intermediary or final outputs of either the research organization or the development process. The primary "products" of a research organization are information, knowledge, and technology. The products of the development process are new or improved processes, goods, or services that result from the application of the knowledge and technology. For example, the output of a research project may include a report containing the conclusions stemming from the project, or patent applications. Corresponding examples of final outputs of the product development process are designs and specifications released for production. Both the research and development processes also have intermediate or in-process outputs. Likely intermediate outputs of the research process are mathematical models, formulas, calculations, or the results from an experiment. Correspondingly, likely intermediate outputs of the development process are physical models, prototypes, or minutes from design review meetings.

Processes of Research and Development

Generically, the steps to product development are as follows:

- *Idea generation*. Sometimes called "ideation," this step involves the initial generation, development, and communication of ideas for new products. Ideas may come from virtually anywhere, including customers, R&D staff, sales staff, employees at large, focus groups, trade shows, and competitive intelligence.
- *Idea screening*. In this step, generated ideas are affinitized and filtered, ideally by concrete and objective criteria that may include technical feasibility, market fit and forecasts, competitor positions, intellectual property assessment, and overall profitability.
- *Concept development*. Typically, "proof of concept" is pursued by refining the target market, product attributes, likely production methods, and costs of both further development and manufacture. This phase may involve application of simulation, model building, and rapid prototyping.
- *Business case development*. Essentially, the expected selling price and sales volume are estimated to obtain anticipated revenues, and costs subtracted from these. Various metrics can be used for this, from straightforward breakeven points and net present value (NPV), to more complicated modeling and forecasting methods. Products often have a cross-functional team that reports to a program manager or similar senior person that is competent in bringing new products and technologies to market.
- *Beta testing*. Physical prototypes are produced in small quantities for testing under a range of conditions, focusing most on typical usage. Additionally, testing may include potential customer feedback via focus groups or preliminary release to the public (or a selected group) for evaluation, for example. Invitation to potential customers to participate in beta testing is especially common in the software world.

- *Technical development and implementation*. In this step, the procedural details are addressed to allow a product launch. This includes formalizing product specifications and engineering requirements, establishing supplier relationships, resourcing, scheduling, and logistics. In many industries such as pharmaceuticals, significant regulatory requirements also must be met. If it has not already been done, a product manager often is assigned to oversee the transition from development to commercialization.
- *Commercialization*. The product is launched, the distribution pipeline is filled, and ongoing maintenance activities (such as advertising) is initiated. Although this step usually is not considered a part of the development process, proactive organizations will continue to seek opportunities for product improvement, for example, by encouraging engagement of R&D staff with sales and marketing, and customers through to the end user.

Some processes do not fit neatly into any single step and may extend across multiple steps. Examples of important overlapping or interfacing research processes that were identified and improved at Eastman Chemical Company are provided by Holmes and McClaskey (1994) and include business unit organization interaction, needs validation and revalidation, concept development, technology transfer, and project management. Figure 28.2 (Holmes and McClaskey 1994), is a macrolevel process map of Eastman Chemical Company's "Innovation" process that follows the generic steps outlined above. Steps 1 to 4 represent the macrolevel research activities that generate the "new or improved product and process concept" stemming from step 4. The last step is the macrolevel development process that yields the processes and product designs for use in operations and markets, respectively.

Many organizations depict their product development processes through flowcharts reflecting their processes' major phases and "gates" (decision points). Altland (1995) discussed the use of a "phase-gated" robust technology development process used by Kodak to help ensure that process and product technologies are "capable of manufacture and are compatible with intended product applications." Gate reviews provide an excellent opportunity for the research, development, and marketing functions to come together periodically to plan a product pipeline. In the flowchart in Figure 28.3 (Boath 1993), the results are shown of "reengineering" an organization's new product development process. The new process led to a 25 percent increase in efficiency in "resource utilization."

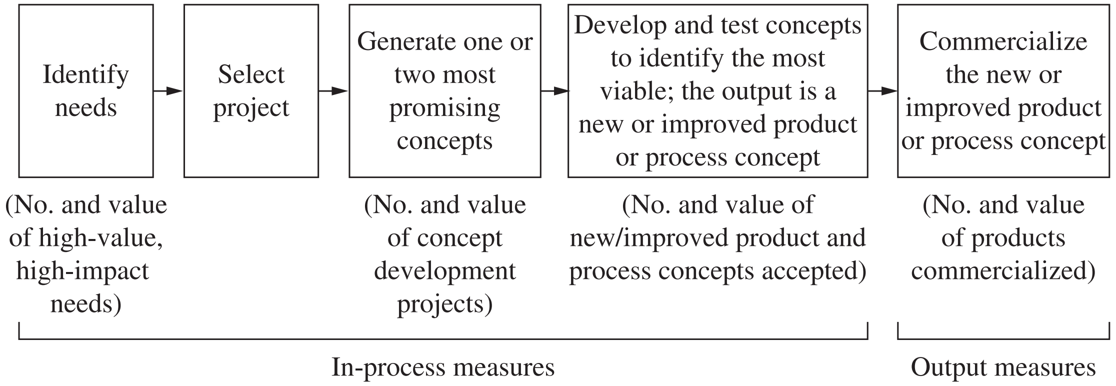

FIGURE 28.2 Eastman Chemical's Innovation Process. (*Holmes and McClaskey 1994.*)

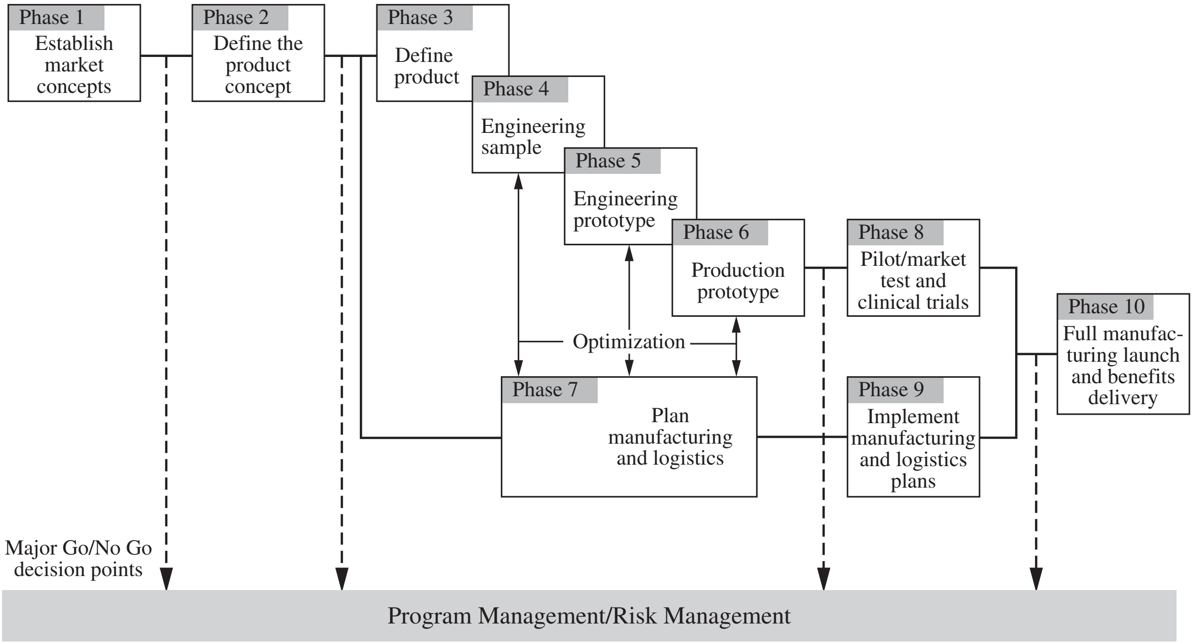

FIGURE 28.3 A development process for new products. (*Boath 1993.*)

Raven (1996), of Merrill Lynch's Insurance Group Services, Inc., provided an example of a project management process for product development in a financial service organization. The nine-step process, depicted in Figure 28.4, was cited by Florida's Sterling (Quality) Award Examiners as being an example of a "... role model for excellence." The activities associated with each of the nine steps are listed in Table 28.1 Himmelfarb (1996b) provides additional examples of new product development in service industries.

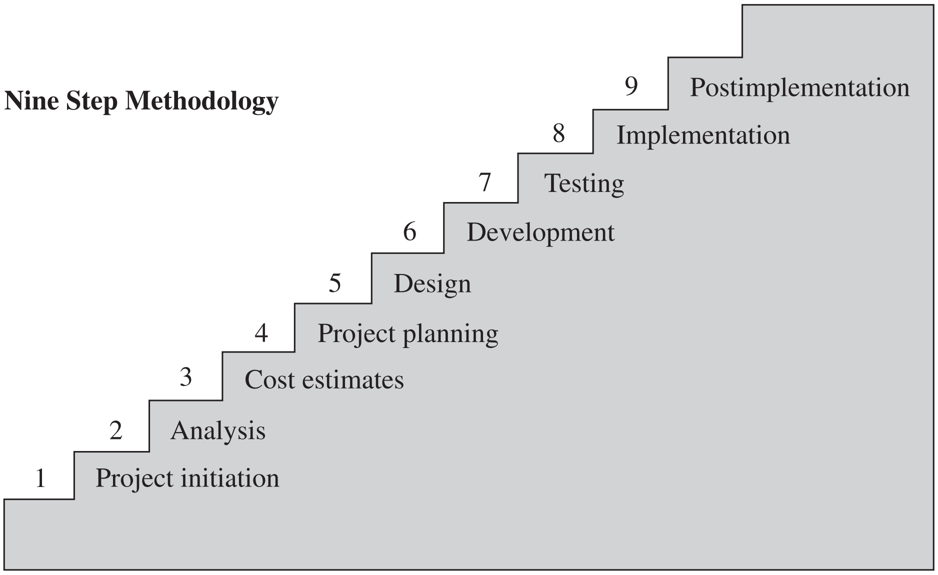

FIGURE 28.4 Merrill Lynch Insurance Group services project planning and development process. (*Raven 1996.*)

Step	Activities
1. Project initiation	a. Prepare recommendations b. Executive committee review c. Decide on approval (Yes/No)
2. Analysis	a. Determine scope b. Obtain sign off on scope c. Develop requirements d. Review requirements e. Conduct market research
3. Cost estimates	a. Determine cost estimates b. Conduct feasibility study
4. Project planning	a. Prepare timelines b. Develop action plans c. Schedule meetings
5. Design	a. Develop system design b. Develop business procedures
6. Development	a. Prepare SEC and state filings b. Complete system programming c. Develop test plan d. Develop work flows, policies, and procedure bulletins e. Prepare training, marketing, and sales materials f. Determine purchasing and print requirements g. Obtain sign-off
7. Testing	a. Conduct program testing b. Conduct system testing c. Conduct user acceptance testing d. Conduct regression testing e. Conduct quality assurance tests f. Conduct branch office testing g. Obtain sign-off
8. Implementation	a. Distribute policy and procedure bulletins, training materials, marketing, and sales materials b. Conduct operational training sessions c. Implement new systems, procedures, and processes
9. Postimplementation	a. Conduct Postproject reviews and surveys

(*Source*: Raven 1996.)

Table 28.1 Activities within Steps of Merrill Lynch Insurance Group Services Project Planning and Development Process

Defining the Quality of Research and Development

Just as quality products and services must be fit for use and free from deficiency, so should the processes responsible for bringing them to market. The many participants and dimensions contributing to quality make any clear-cut definitions tenuous (although one might say "I know it when I see it"); however, set out as follows are some practical considerations.

Defining Research Quality

In this section, research quality will be defined from the perspective of both customer satisfaction (effectiveness of features) and costs (efficiency of providing the features). Building from Wood and McCamey (1993) and Schumann et al. (1995), Kumar and Boyle (2001) created an operational definition of quality in R&D, stating:

> An understanding of who the R&D client is and what his or her values and expectations are, what the key technologies are and how they can be used to meet R&D clients' expectations and the needs of the entire organization, and who the R&D competitors are and how they will respond to emerging R&D clients' needs. This is achieved by doing things right once you are sure you are working on the right things, concentrating on continually improving the system, enabling people by removing barriers, and encouraging people to make their maximum contribution.

As examples of specific implementations of this, consider General Electric (Garfinkel 1990) that defined several dimensions of research quality: technical quality of research, impact of research ("game changer" versus incremental), business relevance, and timeliness (early or late relative to the targeted market requirements). At DuPont, Darby (1990) viewed R&D quality as "creating, anticipating, and meeting customer requirements," which required "continual improvement of knowledge, application, and alignment with business objectives."

The primary products of the exploratory and applied research process are information, knowledge, and technology. Godfrey (1991) provides a general discussion of information quality. Research product quality can therefore be defined both from the perspective of customers' satisfaction with the features of the information and the absence of deficiencies of the information (which decreases costs and cycle times, and thus increases efficiency). Features of research information include timeliness, utility, accuracy, and costs. Research deficiencies can either occur during the research process or be reflected in the end products of the research. Possible deficiencies in research products may be that the knowledge is late, inaccurate, irrelevant, or of relative poor value for the investment. Deficiencies in research processes are associated with process "rework" or "scrap," for example, having to reissue a section of a progress report because the wrong formula was used or having to redo an experiment because an audit revealed that reference samples had been contaminated.

Combining these perspectives, a simplified definition of research quality is the extent to which the features of the information and knowledge provided by the research function meet users' requirements. It is important to note, however, that expectations of quality may differ among researchers and customers. Take, for example, the need for failure as a part of research versus the need for success and the (potentially premature) "pull" by downstream processes of products that have, from the perspective of the scientific method, been inadequately tested. The dynamics of research and the typical business orientation towards stability and results can be a significant source of tension and conflict between business and research divisions, and disagreement as to research quality.

Defining Development Process Quality

The primary result of development is new or improved products and processes. The quality of a development process is defined as the extent to which the development process efficiently provides process and product features capable of repeatedly meeting their targeted design goals, for example, for costs, safety, and performance.

The resultant product and process features must be thought of from the perspective of "Big Q" thinking; that is, not only product and service quality but also the quality of processes, systems, organization, and leadership (Gryna et al. 2007). For example, Port (1996) discusses the early growth of environmentally friendly products and processes; being "green" has continued to increase in importance as a dimension of quality. In an economic analysis of green product development, Chen (2001) concluded that green products do not necessarily benefit the environment but that appropriate regulations could reverse this. Indeed, in recent years, regulators have compelled designers and manufacturers to address such issues as disposal, for example, battery disposal legislation in the United Kingdom, a German ordinance requiring manufacturers to assure the disposability of all packaging used in product transport, and, in the Netherlands, the rule that manufacturers must accept old and broken appliances for recycling.

Looking at internal, intermediate products, deficiencies and thus inefficiencies in the development process are associated with process rework or scrap. Berezowitz and Chang (1997) cite a study at Ford Motor Company, discussed by Hughes (1992), which concluded that although the work done in the product "design phase typically accounted for 5 percent of the ongoing total cost," it accounted for 70 percent of the influence on products' future quality. Boznak and Decker (1993) report that costs associated with deficiencies in product design and development processes can be very expensive. They reference one computer manufacturer whose costs "exceeded $21 million . . . (which) equated to 420,000 hours of non-value-added work . . . who lost nearly $55 million in gross margin opportunity on one product. Failure to effectively manage its product development processes put the company's entire $1.54 billion international business at risk." The authors suggest that the company's practices that caused this near catastrophe would have been precluded had those practices complied with the requirements of ISO 9000 (see Chapter 16, Using International Standards to Ensure Organization Compliance, for a discussion of ISO standards).

Examples of design "rework" include design changes necessitated by an outdated requirements package and partial redesigns necessitated by missing one or more design objectives (including schedules and costs). In many cases, the true costs of design rework are poorly understood; this is exacerbated by the trade-offs inherent to a compressed product development cycle. Arundachawat et al. (2009) address this topic with a literature review of published examples of design rework in concurrent engineering, including a compendium of factors implicated in causing rework. The authors cite three methods to estimate design rework: direct experimentation, mathematical modeling, and simulation but only report simulation as being used in published works.

More generally, Perry and Westwood (1991) measured development process quality by the extent to which technical targets are met, for example, "meeting specific process capability targets" and "the percent and degree of customer needs that are met, and the number of problems discovered at various stages of the product development process." At Motorola's Semiconductor Sector, Fiero and Birch (1989) reported that reducing development process deficiencies increased the percentage of fabricated prototypes passing all tests upon first submission from 25 percent to 65 percent. Furthermore, by involving 10 functional areas, Motorola was able to shorten development cycle times from 380 to 250 days. The reported investment of $150,000 resulted in potential additional revenues of $8 million per year.

Planning and Organizing for Quality in Research and Development

Quality does not just happen naturally; indeed, quite the opposite prevails (to quote from a Marvel comic book villain, "Entropy, entropy, all winds down"). To combat poor quality, it is imperative to understand the forces that tend to inhibit or promote quality including cultural barriers, infrastructure and organizational structure, and skill development. Managing for quality also necessitates knowing how one is performing, which is accomplished through measuring.

Identifying and Addressing Barriers

To successfully plan for and use the concepts required to manage for quality in research or development, management must first understand and then address potential implementation pitfalls and barriers associated with developing and implementing quality initiatives within R&D environments. Hooper (1990) and Endres (1992, 1997) discuss cultural and organizational barriers that must be addressed. For example, researchers' fear that quality initiatives will stifle individual creativity, resulting in bureaucratic controls, can be addressed through the choice of pilot projects. A project can be chosen to demonstrate the "what's in it for me?" in that improving research quality can provide researchers with better resources or processes for conducting more efficient research (e.g., reducing cycle times for obtaining reference articles; obtaining more information from fewer experiments using statistically designed experiments).

Hooper (1990) identifies as an organizational barrier to improving R&D quality R&D's traditional isolation from customers and business. Oestmann (1990) discusses how Caterpillar addressed the problem of researchers being isolated from their customers by moving ". . . experienced research engineers into the field, close to high populations of customers. Their assignment is to understand the customer—how he used his machines today and how he will use them in the future, what drives the customer to make buying decisions now and in the future. The objective of this is to envision what technologies will be needed to produce superior future products." After research evolved the most promising technologies, Caterpillar used cross-disciplinary teams to develop the required product concepts. Teams comprising representatives from marketing, engineering, manufacturing, and research develop concepts for solving customers' needs "and then rate each idea based on its value to the customer." Another solution to the isolation problem is to "bring the field to the staff" by means of a competitive intelligence program that extends beyond the usual audience of senior management, sales, and marketing to include topics of interest to R&D staff. Such a program can provide early identification of scientific or engineering breakthroughs that might take years to become manifest in marketing-driven reports, publications, patents, or competitor products (Murphy 2000).

For development personnel, Gryna (1999) discusses the importance of placing product developers in a state of "self-control." (See Chapter 20, Product-Based Organizations: Delivering Quality While Being Lean and Green, under Concept of Controllability; Self-control.) Prior to holding designers responsible for the quality of their work products the three major criteria (I, II, III) provided in Table 28.2 must be met. Gryna, using input from designers, developed the specific items listed under each criterion. The table may be used as a checklist to identify opportunities for improving designers' work products, and subsequently, their motivation for quality improvement.

Leadership and Infrastructure Development

For upper managers to successfully lead a quality initiative, they must understand their respective roles and responsibilities in managing for quality. Holmes and McClaskey (1994) stated that at Eastman Chemical:

> Top Research Management Leadership was the most significant and essential success factor. Research management changed the way it managed research by focusing on the major output

- I. Have designers been provided with the means of knowing what they should be doing?
  - *A.* Do they know the variety of applications for the product?
    - 1. Do they have complete information on operating environments?
    - 2. Do they have access to the user to discuss applications?
    - 3. Do they know the potential field mususes of the product?
  - *B.* Do they have a clear understanding of product requirements on performance, life, warranty period, reliability, maintainability, accessibility, availability, safety, operating costs, and other product features?
    - 1. Have nonquantitative features been defined in some manner?
    - 2. Do designers know the level of product sophistication suitable for the user involved?
  - *C.* Are adequate design guidelines, standards, handbooks, and catalogs available?
  - *D.* Do designers understand the interaction of their part of the design with the remainder of the design?
  - *E.* Do they understand the consequences of a failure (or other inadequacy) of their design on: (1) the functioning of the total system? (2) warranty costs? (3) user costs?
  - *F.* Do they know the relative importance of various components and characteristics within components?
  - *G.* Do they know what are the manufacturing process capabilities relative to the design tolerances?
  - *H.* Do they derive tolerances based on functional needs or just use standard tolerances?
  - *I.* Do they know the shop and field costs incurred because of incomplete design specifications or designs requiring change?
- II.Have designers been provided with the means for knowing what they are doing?
  - *A.* Do the have the means of testing their design in regard to the following:
    - 1. Performance, reliability, and other tests?
    - 2. Tests for unknown design interactions or effects?
    - 3. Mock-up or pilot run?
  - *B.* Is there an independent review of the design?
  - *C.* Have the detail drawings been checked?
  - *D.* Are designers required to record the analyses for the design?
  - *E.* Do they receive adequate feedback from development tests, manufacturing tests, proving ground tests, acceptance tests, and user experience?
    - 1. Are the results quantified where possible, including severity and frequency of problems and costs to the manufacturer and user?
    - 2. Does failure information contain sufficient technical detail on causes?
    - 3 Have designers visited the user site when appropriate?
  - *F.* Are designers aware of material substitutions, or process changes?
  - *G.* Do they receive notice when their design specifications are not followed in practice?
- III.Have designers been provided with the means of regulating the design process?
  - *A.* Are they provided with information on new alternative materials or design approaches? Do they have a means of evaluating these alternatives?
  - *B.* Have they been given performance information on previous designs?
  - *C.* Are the results of research efforts on new products transmitted to designers?
  - *D.* Are designersí approvals required to use products from new suppliers?
  - *E.* Do designers participate in defining the criteria for shipment of products?
  - *F.* May designers propose changes involving trade-offs between functional performance, reliability, and maintainability?
  - *G.* Are designers told of changes to their designs before they are released?
  - *H.* Have causes of design failures been determined by thorough analysis?
  - *I.* Do designers have the authority to follow their designs through the prototype stage and make design changes where needed?
  - *J.* May designers initiate design changes?
  - *K.* Are field reports reviewed with designers before making decisions on design changes?
  - *L.* Do designers understand the procedures and chain of command for changing a design?

(*Source:* Juran Institute, Inc. Copyright 1994. Used by permission.)

Table 28.2 A Self-Control Checklist for Designers

> and by personally leading the analysis and improvement of the key management processes which drive the output. Research management since 1990 has institutionalized QM (Quality Management) by making it the way Research is managed. The ECC Research success story is certainly another illustration of a quote by Dr. J. M. Juran (1992): *"To my knowledge no company has obtained world class quality without top managers taking charge."*

A key responsibility of upper management in leading a quality initiative within research or development is to organize and develop an infrastructure for initiating, expanding, and perpetuating quality in both research organizations and development processes.

Organizing for R&D Quality

Many R&D organizations have developed structures that facilitate the attainment of their goals for improving customer satisfaction and reducing the costs of poor quality. Predominating are administrative teams such as steering teams and quality councils. Wood and McCamey (1993) discuss the use of a steering team at Procter & Gamble for "maintaining momentum," representing all levels of the organization, and from which subgroups were spun off "to manage areas such as communication, training, planning, measurement," and team support. "The role of the steering team was to keep the division focused on business results and setting clear, measurable targets." Taylor and Jule (1991) discuss the role of the quality council at Westinghouse's Savannah River Laboratory, consisting of the laboratory chairman, department heads, two senior research fellows, and the laboratory's TQM manger. The council was supported by department/section councils in developing, implementing, and tracking an annual Quality Improvement Plan (QIP). The QIP was developed by a team of laboratory managers chartered by the director to assess quality progress during the previous year and "select topical areas for improvement in the coming year based on employee input. . . ." Each department manager was assigned a topical area and required to develop an improvement plan. The separate improvement plans were then reviewed and integrated into a quality improvement plan for the entire laboratory. Menger (1993) discussed the organization and activities of the World Class Quality (WCQ) Committee at Corning's Technology Group, consisting of representatives from five major groups reporting to Corning's vice-chairman. The WCQ identifies priorities and reviews progress in its group's members, establishing and improving key results indicators (KRIs) for cycle times, productivity, and customer and employee satisfaction. Figure 28.5 (Menger 1993), portrays the organization structure and process used to track and improve performance. As a final example, Figure 28.6 (Hildreth 1993) is a structure used to manage key business processes, for example, clinical research, development, and product transfer in manufacturing in R&D at Lederle-Praxis Biologicals. The Executive Quality Council is supported by a Business Process Quality Management (BPQM) Council and site-specific quality councils.

It is notable that organizing for R&D quality takes on a particularly troublesome aspect for organizations that have, typically through merger and acquisition activity (but also via strategic alliances), R&D facilities and staff that are physically remote from headquarters or each other. The healthcare products company Novartis, for example, has approximately 20 different R&D facilities spread across nine countries in Europe, Asia, and the United States. The trade-offs among centralized, decentralized, and hybrid R&D structures are onerous, and companies may shift considerably along the spectrum over time in response to changing economic conditions and corporate culture. The infrastructure elements cited above help instill and maintain quality and consistency across an organization while still allowing for the necessary freedoms that promote innovation. The role of R&D structural organization in quality and innovation remains a lively topic, and readers can find more detailed discussion

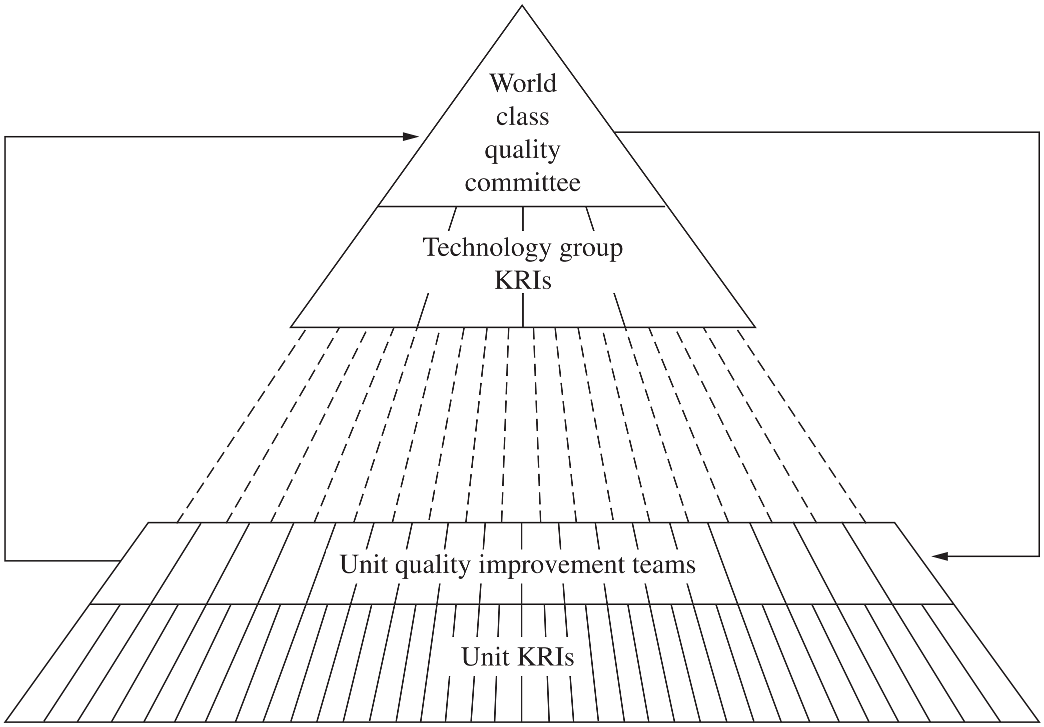

Figure 28.5 Corning's Technology Group quality organization and KRI improvement process. (*Menger 1993, pp. 1-14.*)

and recommendations in Richtne'r and Rognes (2008), Argyres and Silverman (2004), Mendez (2003), Gunasekaran (1997), and Ogbuehi and Bellas (1992).

In addition to organization structure, other elements of infrastructure are required to perpetuate R&D quality initiatives. These include training, project teams, facilitators, measurement systems, and rewards and recognition. Special considerations for training of R&D staff are discussed next.

Training for Quality in R&D

Before managers or researchers can lead or implement quality concepts, processes, or tools, their needs for education and training must be identified and met. Wood and McCamey (1993), of Procter & Gamble, discuss the importance of tailoring the training to the R&D environment:

> Our training had two key features: 1) it was focused on business needs and 2) it was tailored to the audience. These features reflected lessons we learned from other parts of the company; e.g., training that was not focused on real business issues lacked buy-in, and a training program developed for manufacturing could not be transplanted wholesale into an R&D organization.

Similarly, at Bell Laboratories, Godfrey (1985) reported that a key ingredient for successfully training design engineers in experimental design and reliability statistics is the use of case studies based upon real problems that "Bell Labs engineers have had . . . ." Training designers in modern technology can yield significant paybacks. At Perkin-Elmer, De Feo (1987) reported that training design engineers in Boothroyd and Dewhurst's (1987, 1994) design for assembly (DFA) methodology resulted in "weighted average" decreases of 48 percent in assembly times and 103 percent increases in assembly efficiencies.

Yoest (1991), reporting on a study conducted by Sverdrup Technologies at the Arnold Engineering Development Center, Arnold Air Force Base, concluded that teams whose

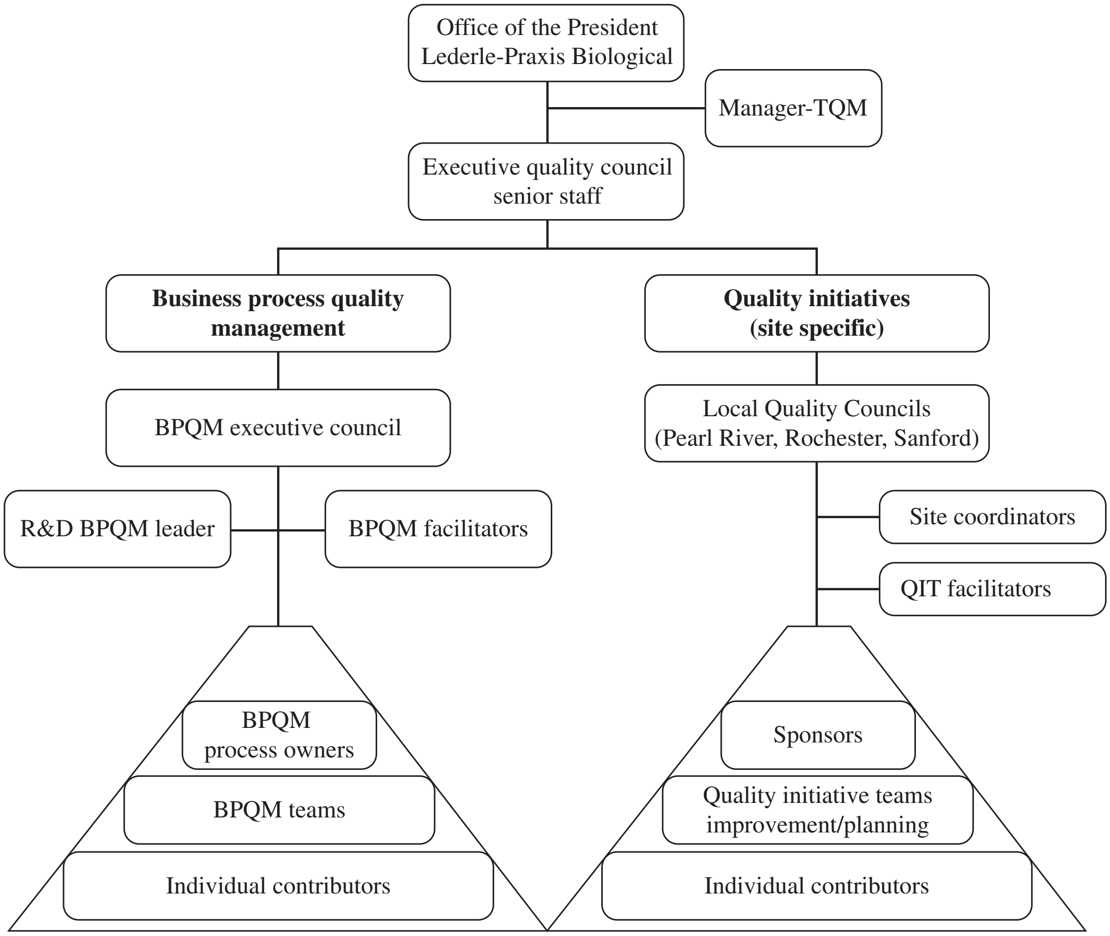

Figure 28.6 BPQM and site quality councils. (*Hildreth 1993, p. 2A-14.*)

facilitators and team leaders are specifically trained for their roles are more likely to successfully achieve their missions than teams whose leaders and facilitators did not receive training. Konosz and Ice (1991), at Alcoa's Technical Center, have similarly stated that "The successful implementation of problem-solving teams and quality improvement processes requires three critical components: (1) management leadership and involvement, (2) team training, and (3) process facilitation." They provide additional detail on the selection and training of team facilitators within an R&D environment. The above are consistent with the findings in Kumar and Boyle (2001) mentioned earlier; these authors provide a summary of best practices for achieving quality in applied R&D departments of manufacturing companies, with recommendations to promote good management practices, awareness by the R&D staff of the external environment, and quality culture.

Measuring R&D Quality Status

It has been said that in order to plan and improve, you must be able to control, and in order to control, you must be able to measure. Developing good measures for R&D quality has proven to be a key ingredient for improving the performance of research functions and development processes. To help distinguish among various types of measurements and measurement processes, it is useful to distinguish between measures used to manage the quality of specific R&D processes and products and measures used to assess overall R&D quality status.

Measuring Quality in R&D Processes and Products: Table 28.3 is a compilation of the top ten metrics reportedly in use at companies in 1998 and 2008. Although measures are relatively little changed, several trends appear to be forming (Teresko 2008a), including:

- *Commonality of metrics*. Definitions are converging, opening the way for greater opportunity for "apples to apples" benchmarking in the future.

Top 10 R&D Metrics Used by Industry, 1998	
1. R&D spending as a percentage of sales	76%
2. New products completed/released	68%
3. Number of approved projects ongoing	61%
4. Total active products supported	54%
5. Total patents filed/pending/awarded	51%
6. Current-year percentage of sales due to new products released in past x years	48%
7. Percentage of resources/investment dedicated	46%
8. Percentage of increase/decrease in R&D head count	43%
9. Percentage of resources/investment dedicated to sustaining products	39%
10. Average development cost per projects/product	39%

[*Source*: Goldense Group Inc., based on 1998 product development metrics survey (Teresko 2008a).]

Table 28.3(*a*) Metrics Used within Industrial R&D, 1988

Top 10 R&D Metrics Used by Industry, 2008	
1. R&D spending as a percentage of sales	77%
2. Total patents filed/pending/awarded/rejected	61%
3. Total R&D headcount	59%
4. Current-year percentage sales due to new products released in past *x* years	56%
5. Number of new products released	53%
6. Number of products/projects in active development	47%
7. Percentage resources/investment dedicated to new product development	41%
8. Number of products in defined/planning estimation stages	35%
9. Average project ROI—return on investment or average projects payback	31%
10. Percentage increase/decrease in R&D head count	31%

[*Source*: Goldense Group Inc., based on 2008 product development metrics survey (Teresko 2008b).]

Table 28.3(*b*) Metrics Used within Industrial R&D (2008)

- *Financial metrics*. This includes the rise in companies reporting use of current sales and profits (although not in the top 10) due to products released in prior years.
- *Intellectual property metrics*. Technology licensing and sales are of greater interest, possibly reflecting "open innovation" in which multiple parties are involved in the development, sale, or licensing of intellectual property.
- *True performance metrics*. Although a large proportion of metrics reported in 2008 remained focused on simple counts (risking a "hit the quota" mentality to hit numbers with quality a secondary consideration), efficiency (e.g., output per unit input), revenue, and profit-based measures are more prevalent.

The utility and types of measures for R&D process and product quality can be viewed from several perspectives. Gendason and Brown (1993) stated that for any metric to be "useful as a management tool, it must have three characteristics: it must be something that is countable; it must vary within a time frame that makes reaction to a 'downtrend' meaningful; and one must be able to define a goal value for the metric." While the metrics in Table 28.3 generally conform to this advice, it is useful to consider other attributes. Endres (1997) classified measures with respect to timeliness, application, and completeness; these factors are discussed in turn as follows.

Timeliness: Traditional measures for research quality have been lagging indicators, in that they report on what the research organization has already accomplished. By way of example, Mayo (1994) discusses Bell Labs' use of measures of new product revenues in a given year divided by total R&D costs in that year. Garfinkel (1990), at GE's Corporate R&D center, discussed GE's use of patents granted per million dollars invested in research as a benchmarking performance measurement. Although patent activity may be a leading indicator of future business (products and associated revenue streams), within R&D it is a lagging indicator because patents reflect work already completed (indeed, by the time a patent is published, it may be practically obsolete in rapidly moving technology environments).

Sekine and Arai (1994) provide tables of possible design process deficiency measures associated with management, lead times, costs, and quality. For example, a suggested measure for design quality is the ratio of the total costs of poor quality attributable to design problems to the total cost of poor quality caused by design, manufacture, or others. The authors state that, on the average, 60 percent of losses are attributable to design problems, 30 percent are attributable to manufacturing problems, and 10 percent to other areas, for example, installation. Goldstein (1990) suggested similar measures for design quality, for example, tracking the ratio of design corrective changes to the total number of drawings released for each new product.

Although they are commonly used, lagging indicators provide little preemptive control over ongoing quality. Examples of concurrent indicators and controls are the results of gate reviews, design reviews and peer reviews. Although all three help manage quality and risk, they each have different participants and objectives.

A gate review is a management-oriented assessment that ensures that a project is worth continuing in light of business risks and benefits. It may be a "hard" gate that represents a firm stop with formal passage required before resumption, or a "soft" review that permits at least some work to continue during the review. Because project prioritization and resourcing are components, a gate review usually will have not only technical and end-user representatives present but also financial decision-makers.

A design review is technically-oriented assessment conducted by independent, objective evaluators at pre-determined times to appraise a product's concept, requirements, product design, manufacturing process, and readiness for production. Hutchins (1999) recommends a minimum of three design review stages:

1. *Feasibility.* Existing knowledge of customer requirements is compared against known, feasible means of delivering against the requirements. This may include evaluation of initial specifications, drawings, or preliminary models.
2. *Intermediate*. Feasibility studies, prototypes, performance claims, and reliability data are assessed. Often, there are multiple intermediate design reviews.
3. *Final.* The completed product is in pilot production and evaluated for conformance with customer requirements. Production methods, materials, and the like are also assessed.

The three-stage process is a simplified version, and design reviews can be quite detailed. For example, the North American Space Administration (NASA) Program Formulation directive NPR 7123.1A cites 20 specific reviews from initial requirements and mission concept through launch, postflight, and decommissioning (NASA 2007). Most R&D organizations will find a happy medium in the level of detail between those cited above.

Gryna (1988) provides guidelines for structuring design reviews. Citing Gryna (1988) and Jacobs (1967), Table 28.4 summarizes design review team membership and responsibilities (Endres 1999). Kapur (1996) provides a similar design review responsibility matrix for a six-phase product design cycle. Prescribed attendance at the three phases identified by Hutchins (1999) include designers and quality engineers (all stages), production planners (intermediate and final reviews), specification and standards engineers (intermediate and final reviews), purchasing agents (final review), and safety officers (intermediate and final reviews).

A peer re view is an evaluation made by individuals that are familiar with the subject matter; in the case of R&D, this usually means scientists and engineers that are experienced in the technical details. Yamazaki et al. (2006) provide a general argument supporting the use of peer review as a tool in R&D management. Recognizing the limitations of traditional metrics (in particular, research outcomes may not be known for a considerable period of time and, being unknown, cannot be measured), the U.S. Army Research Laboratory (ARL) adopted peer review as a component to measuring R&D performance (the other components being customer evaluation and traditional performance measures) to answer three stakeholder questions (Oak Ridge Associated Universities 2005):

1. Is the work relevant? That is, does anyone care about what we are doing? Is there a target or a goal, not matter how distant, that our sponsor can relate to?
2. Is the program productive? That is, are we moving toward a goal, or at least delivering a product to our customers in a timely fashion?
3. Is the work of the highest quality? That is, can we back up our claim to be a world-class research organization doing world-class work?

Of the three methods of evaluation, it was concluded that peer review had the greatest utility in answering the third question regarding quality (Brown 2006). In other examples, Roberts (1990) discusses peer reviews used to verify progress by checking calculations, test data reduction, and research reports. Bodnarczuk (1991) provided insights into the nature of peer reviews in basic research at Fermi National Accelerator Laboratory.

Concurrent indicators can also be used to help develop leading indicators for predicting, and in some cases, controlling, R&D performance. The basic requirement is to identify coincident R&D process indicators that are demonstrably correlated, if not causative, with

		Type of Design Review*		
Group Member	**Responsibilities**	**PDR**	**IDR**	**FDR**
Chairperson	Calls, conducts meetings of group, and issues interim and final reports	X	X	X
Design engineer(s) (of product)	Prepares and presents design and substantiates decisions with data from tests or calculations	X	X	X
Reliability manager or engineer	Evaluates design for optimum reliability consistent with goals	X	X	X
Quality manager or engineer	Ensures that the functions of inspection, control, and test can be efficiently carried out		X	X
Manufacturing engineer	Ensures that the design is producible at minimum cost and schedule		X	X
Field engineer	Ensures that installation, maintenance, and user considerations were included in the design		X	X
Procurement representative	Ensures that acceptable parts and materials are available to meet cost and delivery schedules		X	
Materials engineer	Ensures that materials selected will perform as required		X	
Tooling engineer	Evaluates design in terms of the tooling costs required to satisfy tolerance and functional requirements		X	
Packaging and shipping engineer	Assures that the product is capable of being handled without damage, etc.		X	X
Marketing representative	Assures that requirements of customers are realistic and fully understood by all parties	X		
Design engineers (not associated with unit under review	Constructively reviews adequacy of design to meet all requirements of customer	X	X	X
Consultants, specialists on components, value, human factors etc. (as required	Evaluates design for compliance with goals of performance, cost, and schedule	X	X	X
Customer representative (optional)	Generally voice opinion as to acceptability of design and may request further investigation on specific items			X

[*Sources*: Gryna (1988), adapted from Jacobs (1967).]

*P = Preliminary; I = Intermediate; F = Final.

TABLE 28.4 Design Review Team Membership and Responsibility

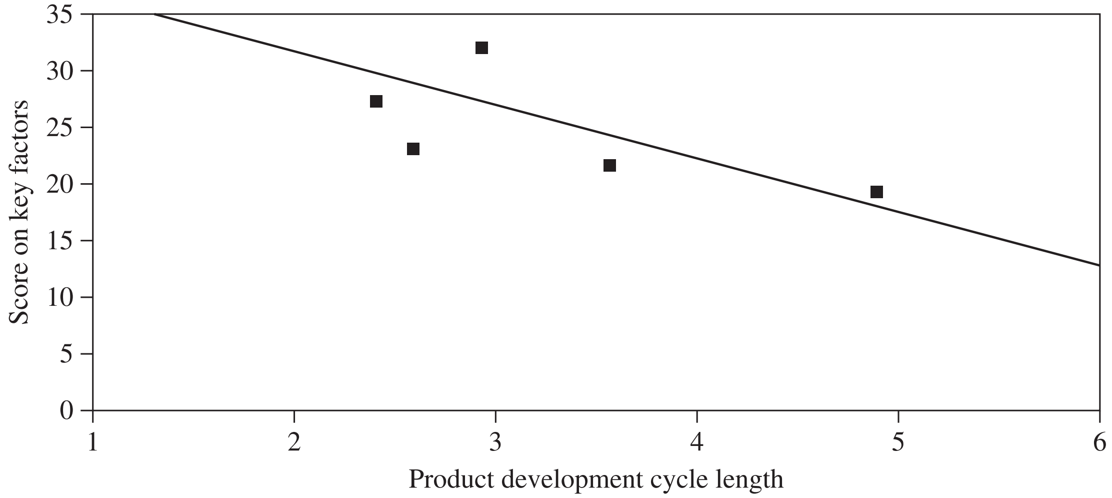

FIGURE 28.7 Correlation between development process compliance scores and cycle times at Kodak. (*Juran Institute. ©1994. Used with permission.*)

outcomes of research and development processes. For example, Figure 28.7 demonstrates the relationship between compliance scores during the product development projects and the length of the development cycle (Cole 1990). There is an obvious correlation that may be useful in identifying the major contributing factors (within the scoring system) to protracted development cycles.

Financial scores also prove useful as leading indicators for research effectiveness, for example, variations of net present value (NPV), expected net present value (ENPV), discounted cash flow, internal rate of return, and decision trees. Holmes and McClaskey (1994), at Eastman Chemical, showed the estimated net present value of new/improved concepts accepted (by business units for products, and manufacturing departments for processes) for commercialization. Figure 28.8 demonstrates that the effect of implementing TQM at Eastman Chemical Research virtually doubled research's productivity as measured by NPV (Endres 1997).

An additional method that has gained in popularity in recent years for the valuation of R&D effectiveness and technology created by R&D organizations is the use of real options (In simple terms, a real option provides the right, but not the obligation, to pursue some business undertaking; i.e., it represents a choice). For example, whereas the ultimate, future quality, and benefit of intellectual property created by R&D may be unknowable, it is estimable by applying concepts and principles of financial options pricing. That is, the possession of intellectual property (e.g., as exemplified by patents or trade secrets) provides a business with options. Options and the flexibility they afford can be estimated in financial terms (e.g., the choice to pursue internal technology to produce products unencumbered by royalties, or use established, third-party technology and pay licensing fees). Razgaitis (1999) provides core concepts in technology risk assessment, and valuation via real options; an applied example in automotive product development is supplied by Ford and Sobek (2005). Readers interested in a more comprehensive look at valuation of technology can refer to Boer (1999).

Applications: In addition to viewing each R&D measure (or measurement process, e.g., peer review) with respect to timeliness, it also is helpful to examine each measure with respect to its intended application. That is, is the measure intended to address customer satisfaction levels (in which case it will relate to the key features of the goods and services provided by R&D), or is the measure intended to address customer dissatisfaction and

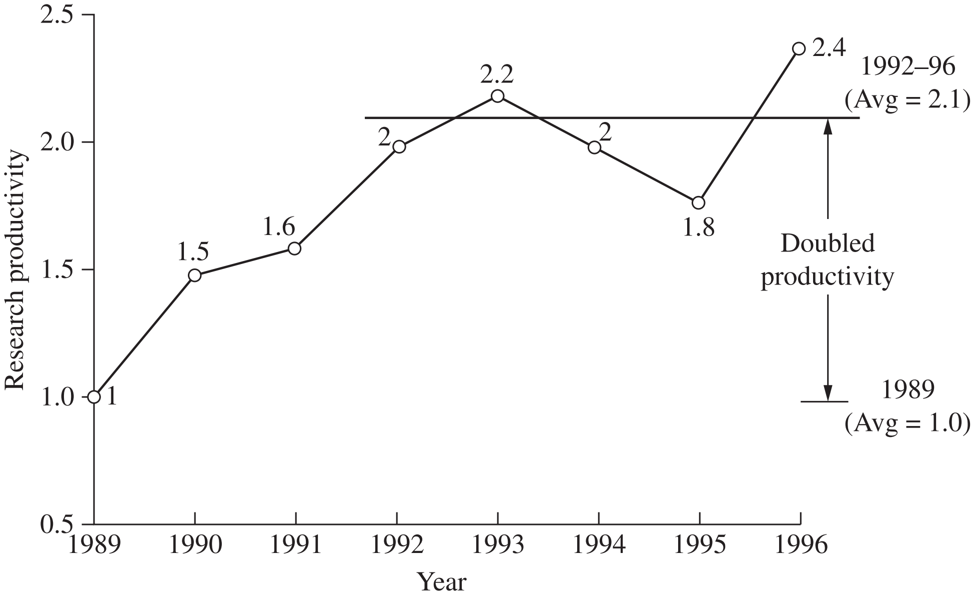

FIGURE 28.8 Eastman Chemical Research productivity as a ratio of 1989 NPV of improved concepts accepted and commercialized with major research input divided by total research expenditures. (*Juran Institute. ©1994. Used with permission.*)

organizational inefficiency (in which case it will relate to identification and quantification of key deficiencies of goods and services or of their R&D processes)? Juran (Chapter 1, Attaining Superior Results through Quality) discusses the relative effects of features and deficiencies on customer satisfaction and organization performance.

- *Process and Product Features*. Benchmarking the best practices of other R&D organizations is an important driver for measuring R&D quality. Lander et al. (1994) discuss the results of an industrial research organization benchmarking study of the best features of practices in R&D portfolio planning, development, and review. The study, by the Strategic Decisions Group, found that "best practice" companies exhibit common features; they:
  1. Measure R&D's contribution to strategic objectives
  2. Use decision-quality tools and techniques to evaluate proposed (and current) R&D portfolios
  3. Coordinate long-range business and R&D plans
  4. Agree on clear measurable goals for the projects

The study also revealed that "companies which are excellent at the four best practices:

1. Have established an explicit decision process that focuses on aligning R&D with corporate strategy and creating economic value
2. Use metrics that measure this alignment and the creation of value
3. Maintain a fertile organizational setting that supports decision quality and the implementation of change efforts"

Figure 28.9 represents, at a macrolevel, features of the process commonly used by the best-practice companies for R&D portfolio planning and review.

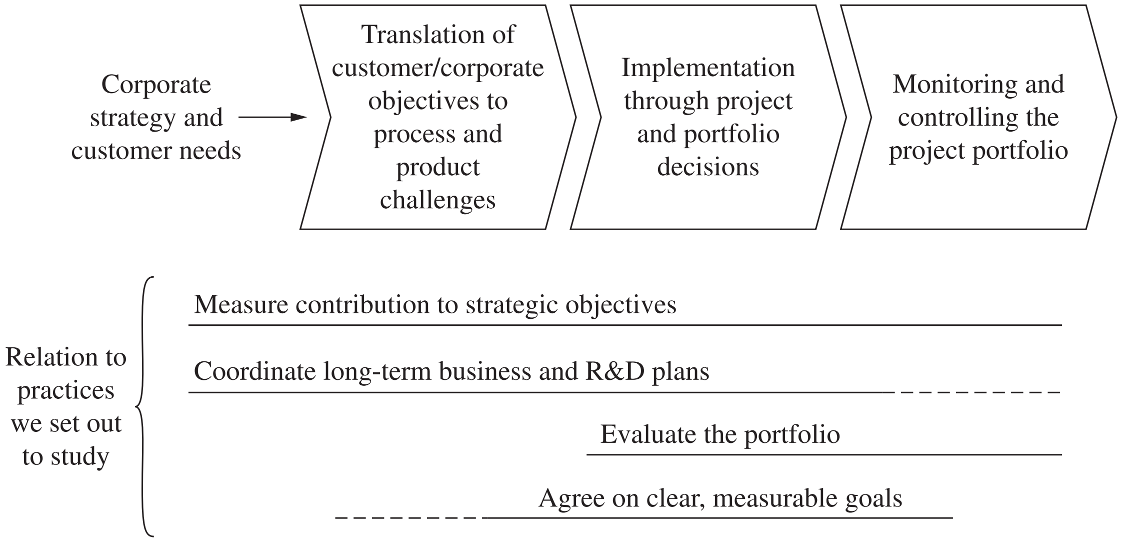

FIGURE 28.9 Common process for implementing best practices for R&D planning, implementation, and review. (*Lander et al. 1994, p. 3-14.*)

Among the organizations identified "for their exemplary R&D decision quality" practices were 3M, Merck, Hewlett-Packard, General Electric, Procter & Gamble, Microsoft, and Intel; it is notable that these companies have remained in dominant market positions over decades. Matheson et al. (1994) also provide examples of tools which organizations can use to identify their greatest opportunities for implementing and improving best practices in R&D planning and implementation. Hersh et al. (1993) discuss the use, in addition to the benchmarking for best practices, of internal customer surveys at Alcoa to identify and prioritize key R&D performance features at Alcoa's Technical Center. They used the survey results to establish four major categories of their customers' requirements:

1. Manage technology effectively
2. Link technology and business strategies
3. Build strong customer relationships
4. Provide socially and legally acceptable solutions

Each of these feature categories contained activities whose relative customer priority was also determined. For example, the first category—manage technology effectively—contained the highest priority requirement to "Assume accountability for attaining mutually determined project objectives," and the second-highest-priority requirement to "Meet customer cost and performance expectations." Wasson (1995) also discusses the use of the survey data in developing customer focused vision and mission statements for the Alcoa Technical Center. Endres (1997) provides additional details on the survey and its results.

- *Process and Product Deficiencies*. Identifying customers' requirements is necessary but not sufficient. R&D organizations also must define and implement methods for improving their customers' satisfaction levels and their process's efficiencies. Ferm et al. (1993) also discussed the use of business unit surveys at Allied Signal's

> Corporate Research & Technology Laboratory to "create a broad, generic measure of customer satisfaction . . . and then use the feedback to identify improvement opportunities, to assess internal perceptions of quality, and to set a baseline for the level of . . . research conformance to customer requirements." (In addition to surveying its business-unit customers, laboratory management gave the same survey to laboratory employees. The resulting data enabled them to compare employee perceptions of laboratory performance to the perceptions of external customers.) One of the vital few needs identified for action was the need to convince the business units that the laboratory was providing good value for project funding. Further analysis of the business units' responses revealed that the business units believed laboratory results were not being commercialized rapidly enough. However, the laboratory believed that the business units had accepted responsibility for the commercialization process. In response to this observation, a joint laboratory and (one) business-unit team was formed to clearly define and communicate responsibilities throughout the research project and subsequent commercialization and development processes.

Such tension between research and development groups is common. To help manage potential conflict, a dialog with clear delineation of expectations in handoff is suggested, for example, through the use of templates (similar to service level agreements) that specify deliverables needed from research to pull a product candidate into development. As mentioned earlier, one practice that can help is to cross-train staff between R&D, including movement of research staff into development to follow their inventions.

Finally, Wasson (1995) at Alcoa's Technical Center also provided several explicit measures used to determine customer satisfaction:

- Percentage of agreed-upon deliverables delivered
- Percentage of technical results achieved
- Results of customer satisfaction survey

Completeness. Endres (1997) uses the word "completeness" to indicate the degree to which measures are simultaneously comprehensive (i.e., taken together, they provide answers to the question: "Is the R&D organization meeting its performance objectives?") and aligned (i.e., there is a direct linkage between each variable measured and one or more of those objectives). Juran (1964) and Boath (1992) identified the need for a comprehensive hierarchy of measures. Figure 28.10 (Boath 1992) is an R&D performance measurement pyramid.

Although the concept of multiple levels of measures is useful, it is incomplete. To be complete, performance measures for research organizations and development processes must also be aligned. Menger (1993) discussed the development and use of key result indicators (KRIs) to drive progress in Corning's Technology Group, which contained research, development, and engineering. Corning's World-Class Quality Committee (WQC) defined the KRIs for the Technology Group. General areas for improvement and measurement used are

- Cycle time
- Productivity
- Customer satisfaction
- Employee satisfaction

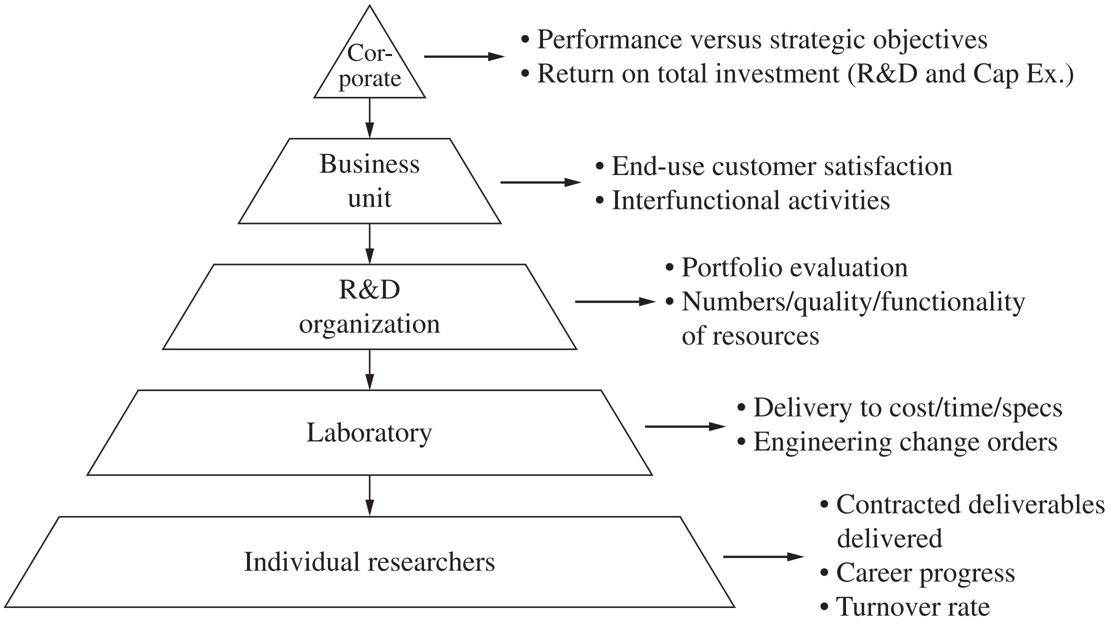

Figure 28.10 Boath's pyramid of R&D measures. (*Juran and Godfrey 1999, p. 19.9.*)

The WQC then requires each of the 15 major units in the Technology Group to define explicit performance measures for each of the previous general areas for improvement. "Twice a year the committee spends the better part of two days visiting each of the 15 units . . . (to) review the quality of their KRIs, consistency of unit KRIs with those of the technology group, progress made on the KRIs, and plans for improvement. . . ."

Additional examples of linking R&D performance measures are provided by Rummler and Brache (1995) who provided a comprehensive example of linking organizational-, process-, and job/performer-level measures for a product development process.

Assessing Overall R&D Quality Status

The previous discussions on measurement have focused on classifying and developing measures for research organizations and development processes. Gryna et al. (2007) define the benefits of determining the broad overall status of quality in organizations. This process has been defined as quality assessment. Assessment of quality consists of four elements:

1. Cost of poor quality
2. Standing in the marketplace
3. Quality culture in the organization
4. Operation of the company quality system

Examples of determining R&D customers' priorities and perspectives of performance have been discussed earlier. The assessment of some elements of quality culture in research has been discussed in an example presented by Holmes and McClaskey (1994). In 1989, the Eastman Research Center determined that although many elements of TQM had been installed (e.g., "Many processes had been studied and flow charted; some processes were being routinely measured and reviewed"), research output, as measured by the NPV of new/improved concepts accepted, had not improved. The authors conducted interviews with Research Center personnel that determined that although communications had improved:

- Few process improvements had been implemented.
- Most first-level managers and individual researchers saw nothing beneficial from the quality initiative.
- Employees were confused as to what Research management wanted them to deliver ("What is Research's main output?").

As a result of the interviews, Eastman Chemical refocused its effort on improving the key processes that directly affected its primary deliverable category: new/improved concepts accepted for commercialization. The ultimate effect of shifting initiative focus from team activities and tools to mission and output is reflected in Figure 28.8.

The cost of poor quality is discussed generally by J. De Feo in Chapter 2 (Quality's Impact on Society and the National Culture). At Corning, Kozlowski (1993) discusses using quality cost data to identify high cost-of-poor-quality areas. For example, one primary contributor to internal failure costs was the "rework" associated with having to redo experiments. An improvement team assigned to reduce associated costs determined that an internal training program on experimental design was necessary to improve efficiency and that it was necessary to improve communications with support groups through formally defining and sharing experimental objectives.

Quality System Assessments for R&D. Quality Systems assessments may be conducted using the Baldrige criteria or ISO 9000 standards. Chapter 17, Using National Awards for Excellence to Drive and Monitor Performance, provides insight into the use and benefits of the Baldrige National Quality Award. Chapter 16, Using International Standards to Ensure Organization Compliance, provides similar perspectives of the use of ISO 9000 family of international standards for reviewing quality systems.

Baldrige Assessments for R&D Organizations. Within research organizations, Kozlowski (1993) discussed using the Baldrige criteria to provide "outside focus to the quality process . . . this outside focus, specifically the emphasis on the customer, is the single biggest difference between where we started in 1985, and where we are today." Van der Hoeven (1993; unpublished paper "Managing for Quality in IBM Research.") has discussed the process used at IBM's Thomas J. Watson Research Center to organize a Baldrige assessment and the importance of translating the Baldrige criteria into relevant interpretations for a research organization. Each Baldrige category was allocated to a senior research executive. For example, strategic planning and data collection and analysis were assigned to the vice-president of technical plans and controls; the director of quality coordinated work on training and writing the category assessments. Van der Hoeven reported that "it required a significant effort to interpret and formulate appropriate responses . . . this careful tailoring of responses to the Baldrige questions, in terms of existing division processes and management systems . . . is unique. And the assessment raises gaps in processes and practices to the surface." For example, the assessment revealed the need to improve processes for strategic planning, customer satisfaction, and capturing quality data in the divisionwide database.

The Armament Research, Development and Engineering Center (ARDEC) was one of the first organizations to successfully apply BNQA criteria under the nonprofit category. An R&D center selected as the benchmark for the U.S. Army in technology transfer, ARDEC transitioned approximately 75 percent of its technology research projects into customer-funded development. ARDEC also received awards and recognition for customer satisfaction and perceived value. Internally, job satisfaction increased from approximately 87 percent positive in FY2004 to 92 percent positive in FY2007, exceeding government productivity and quality benchmarks. Finally, diversity of scientists and engineers increased in six of eight target groups from FY2005 to FY2007 (NIST 2008).

More recently, Prajogo and Hong (2008) studied the relationship between TQM practices and R&D performance using the Baldrige criteria applied to 130 R&D divisions of Korean manufacturing firms. Their findings demonstrate that TQM, as measured via the Baldrige criteria, provides a generic set of principles that can be applied successfully to R&D environments.

ISO 9000 Assessments for R&D Organizations. Although the Baldrige criteria provide organizations with a comprehensive review mechanism for improving quality systems, some organizations perceive the criteria as being simultaneously too general and too complex for beginning their quality journey. The ongoing preference for the ISO 9000 quality system standards over the Baldrige criteria can be attributed to the fact that the ISO 9000 scope is more limited, being focused on quality control and corrective action systems. Also, the ISO standards are frequently required by suppliers' customers. These drivers for the use of standards have led to the need to tailor and implement ISO standards for research and design organizations.

Fried (1993) discusses the process AT&T's Transmission Systems Business Unit (TSBU) used to pursue ISO 9001 registration. One consequence was the need for each of the TSBU design sites to support the decision by attaining ISO 9001 registration. Each TSBU design laboratory appointed an ISO coordinator; ISO managers were appointed in each of their two major geographical locations. A key initial decision was to review ISO 9001 and to identify those sections which were applicable to the design organizations. Each of the elements that were judged applicable were further categorized as "global" (where compliance could be most effectively addressed by a solution common to multiple organizations) or "local" (where compliance would require a site-by-site approach). Table 28.5 summarizes the results of the review process.

After holding ISO 9001 overview meetings with the design managers and engineers, the site coordinators and area managers coordinated self-assessments and subsequent improvement action planning. Communicating the needed changes to design procedures, coordinating planning with the manufacturing organizations, and coaching on audit participation were identified as being crucial activities in TSBU's successful registration process.

Endres (1997) includes materials from a presentation by Gibbard and Davis (1993) on pursuit of ISO 9001 registration by Duracell's Worldwide Technology Center (DWTC). An initial barrier identified was the belief of the technical managers and staff that formal procedures were unnecessary and would "stifle creativity." The authors suggested that the way to address this resistance is for upper management to drive registration via a "top-down effort," including required periodic progress reviews in which upper management participates. DWTC reported that two primary benefits of ISO registration were that it "forced us to identify precisely who our customers were for all projects carried out in our center . . ." and that ISO established "the foundation of a quality management system on which a program for quality improvement could be built."

Thelen (1997) provides a case study in which SITA (the Société Internationale de Télécommunications Aéronautiques) took a synthetic approach by combining elements of ISO 9000 with TQM and BPI (Business Process Improvement). SITA found that ISO 9000 represented a natural milestone within their path of continuous improvement and complemented the business process improvements by providing competitive advantage (conversely, increased efficiency facilitates business expansion). Thelen also reported that ISO 9000 applied more easily to R&D if each project was viewed as a service having a formal customer.

ISO 9001 Element	Applicable?	Global/Local
Management responsibility	Yes	Both
Quality system	Yes	Both
Contract review	No	
Design control	Yes	Local
Document control	Yes	Local
Purchasing	Yes	Local
Purchaser supplied product	No	
Product identification and traceability	No	
Process control	No	
Inspection and testing	No	
Inspection measuring and test equipment	Yes	Global
Inspection and test status	No	
Control of nonconforming product	No	
Corrective action	Yes	Local
Handling, storage, packaging, and delivery	Yes	Local
Quality records	Yes	Local
Internal quality audits	Yes	Global
Training	Yes	Local
Servicing	No	
Statistical techniques	No	

[*Source:* Fried (1993), p. 2B-25.]

Table 28.5 ISO 9001 Elements for AT&T's TSBU R&D Units

Operational Quality Planning for Research and Development

Next we consider the planning phase of R&D, with an emphasis on design.

Quality Planning: Concepts and Tools for Design and Development

The focus of the following materials is to provide examples of methodology and tools that support the implementation of Juran's operational quality planning process within the design and development process.

Operational Quality Planning Tools

As discussed in Chapter 4, Juran's quality planning process is used to identify customers and their needs, develop product design features responding to those needs and process design features required to yield the product design features, and develop process control required to ensure that the processes repeatedly and economically yield the desired product features. Quality Function Deployment (QFD) is a valuable tool for collecting and organizing the required information needed to complete the operational quality planning process.

Zeidler (1993) provides examples of using customer focus groups, surveys, and QFD at Florida Power and Light to identify customers' needs and to determine design features for a new voice-response unit. Zeidler concluded that QFD not only ensures customer satisfaction with a quality product or service but also reduces development time, startup costs, and expensive after-the-fact design changes. QFD also a useful political tool because it guarantees that all affected parts of the organization are members of the QFD team.

Delano et al. (2000) provide an R&D case study from the aircraft industry in which they compared the techniques of QFD and Decision Analysis (DA). The authors conclude that the two methods have many similarities and suggest that QFD be supplemented with DA to improve multiobjective decisions in terms of generating alternatives and supporting data analysis.

In a multiyear study, Miguel and Carnevalli (2008) examined the application of QFD in product development across 500 Brazilian companies. From their assessment, the authors identified best practices in QFD application; these practices included practical recommendations regarding upper management support, the need for training, team formation, frequency and length of meetings, benefit of a pilot project, and the utility of a conceptual model to identify future deployments needed for manufacture. Herrmann et al. (2006) also focus on the need for a conceptual framework suitable for empirical research. They evaluate QFD with regard to three dimensions of performance: product quality improvement, R&D cost reduction, and faster R&D cycle time. After building and testing a model, it is concluded that while valuable, the rigor of QFD is not a key success factor. Instead, outcomes of QFD are more strongly dependent on the motivation of QFD team members, and technical support for the team. This echoes Zeidler (1993) and Miguel and Carnevalli (2008) in that QFD is a useful tool but is unlikely to be successful without clear commitment and support from the business.

Finally, Kang et al. (2007) specifically address the difficulties in the interface between R&D and marketing domains by proposing an integrated new product design process. The process applies the QFD House of Quality to identify design features and subsequently compares the results of conjoint analysis (traditionally used by marketing to better understand preferences and how people value different features) with Taguchi methods (used in research to create a more robust design). The parallel use of the latter methods with QFD at the front end reportedly helps resolve the trade-offs that otherwise can result in an inferior final design.

Designing for Human Factors: Ergonomics and Error-proofing

As a design feature, the design's ability to be built/delivered and used by customers must be considered from two perspectives: that of operations (manufacturing and service) and that of the customer. From the perspective of manufacturing or service operations, designers must consider, among other factors, the limitations of people (e.g., operators and delivery personnel). Designers also must consider the possible types of errors that may be committed during operations and use and anticipate these as a part of design. Ergonomics or "human engineering" is used to address the needs and limitations of operators, service providers, and customers.

From the operations side, Thaler (1996) presents the results of an ergonomics improvement project for facilitating the assembly of aircraft doors. Originally, operators "had to hold the doors in place with one hand while trimming or drilling with the other and carrying them for several feet." This job design resulted in a high incidence of worker back injuries. The job redesign included designing a universal clamp to hold the aircraft doors in any position and providing the operators with adjustable work chairs and transportation carts. These and other improvements resulted in a 75 percent reduction in OSHA-lost workday incidents and dramatically decreased workers' compensation costs. Gross (1997) provides additional insights and guidance for improving manufacturability and customer usability by integrating ergonomics with the design process. Laboratory environments also can be enhanced, for example, rubber floor mats, and lab bench configurations based on Lean cell concepts to minimize movement (e.g., reticulated bench space as opposed to traditional linear bench space that requires frequent shifting in position left and right).

Nagamachi (2008) explores an approach to ergonomics that uses multivariate statistical analysis to accommodate the hierarchy of customer values and bridge customer input to create design specifications. This is specifically intended to enhance the market pull approach described earlier (called "market-in" by Nagamachi) rather than the technology push method (called "product-out" by Nagamachi). Termed "Kansei engineering," from the Japanese word implying psychological feelings and needs, the method takes qualitative, ambiguous data and translates it into new product designs. For example, Kansei engineering that was applied to refrigerators eliminates the frequent need to bend over by placing the freezer at the bottom of the unit. Efforts to redesign roads, signage. and cars to accommodate aging drivers are prompted by similar ergonomic and also safety concerns ("Highway, Car Changes Designed to Help Older Drivers," 2009).

In contrast with planning for ease of assembly, installation, and use, *poka-yoke* is a methodology for preventing, or correcting errors as soon as possible. The term's English translation is roughly "prevent inadvertent mistake." *Poka-yoke* was developed by Shigeo Shingo, a Japanese manufacturing engineer. Although common usage interchanges the associated terms "mistake-proofing" and "error-proofing," a technical difference is that mistake proofing applies more to the assembly line, whereas error proofing applies more to product design. For example, mistake proofing in an assembly process might incorporate a glue applicator that indicates when insufficient glue has been dispensed. Error proofing would be a design that permits parts to be snapped together, thereby eliminating the need for glue and monitoring of the amount applied. Although human error often receives blame, the root cause of errors usually can be traced back to the failure of designers to adequately account for the possibility of errors or omissions. Kohoutek (1996a) discusses "human-centered" design and presents approaches and references for predicting human error rates for given activities. An example of error proofing in the redesign of a manufacturing process can be found in Bottome and Chua (2005). Through a series Six Sigma projects, Genentech substantially reduced errors during drug production by changing from black to more visible blue ink (to make omissions more apparent), clarifying documentation rules for batch record creation, and reducing the complexity of production instructions (tickets). Through the combined efforts of error-proofing, errors per 100 tickets were reduced from approximately 10 to 3.5.

Designing for Reliability

A product feature that customers require in products is reliability. Gryna et al. (2007) defined reliability as the "ability of a product to perform a required function under stated conditions for a stated period of time" or, more simply, the "chance that a product will work for the required time." Introducing the concept of operating environment, Ireson (1996) states that reliability is the "the ability or capability of the product to perform the specified function in the designated environment for a minimum length of time or minimum number of cycles or events," which also references specific operating conditions/environments. It is important to note that a precise and agreed-upon definition of a "failure" is needed by customers, designers, and reliability engineers. Rees (1992) also discusses the importance of identifying and defining the intended purpose of the application and test procedure prior to defining failures. Requiring designers to precisely establish parameters for both successful product performance and environmental conditions obliges designers to develop a deeper understanding of the product, its use, and design.

The following materials will describe approaches and tools for "designing in" reliability. A reliability program consists of the specific tasks needed to achieve high reliability; Gryna et al. (2007) identified the following major tasks:

- Setting overall reliability goals
- Apportionment of the reliability goals
- Stress analysis
- Identification of critical parts
- Failure mode and effect analysis
- Reliability prediction
- Design review
- Selection of suppliers
- Control of reliability during manufacturing
- Reliability testing
- Failure reporting and corrective action system

Table 28.6 (Gryna et al. 2007) provides typical reliability metrics for which specific numerical goals may be established.

As described earlier in this chapter, design reviews can be used as concurrent indicators for a design's reliability. Therefore, one of the key requirements for design review meetings is to ensure that reliability goals have been established and that intrinsic and actual reliability are being measured and improved during the design's evolution, manufacture, and use. Reliability of procured materials must be considered during supplier selection and control (see Chapter 30, Supply Chain: Better, Faster, Friendlier Suppliers, for additional discussion). The effect of manufacturing processes on reliability must be addressed during process design selection and implementation. Refer to Chapter 13, Root Cause Analysis to Maintain Performance, and Chapter 20, Product-Based Organizations: Delivering Quality While Being Lean and Green, and Gryna et al. (2007) for guidance in controlling quality and reliability during manufacturing.

Gryna et al. (2007) divide the process of reliability quantification into the three phases: apportionment (or budgeting), prediction, and analysis. Reliability apportionment is division and allocation of the design's overall reliability objectives among its major subsystems and then to their components. Reliability prediction is the process of using reliability modeling, probability theory and actual past performance data to predict reliability for expected operating conditions and duty cycles. Reliability analysis uses the results of reliability predictions to identify strong and weak parts of the design, trade-offs, and opportunities for improving either predicted or actual reliability performance. These three phases will be discussed in turn.

Reliability Apportionment: The top two sections in Table 28.7 (Gryna et al. 2007) provide an example of reliability apportionment. A missile system's reliability goal of 95 percent for 1.45 hours is apportioned among its subsystems and their components. The top section of the table demonstrates the first level apportionment of the 95 percent goal to the missile's six subsystems. The middle section of the table exemplifies the apportionment of the goal of one of those subsystems; the reliability goal of 0.995 for the missile's explosive subsystem is

Figure of Merit	Meaning
Mean time between failures (MTBF)	Mean time between successive failures of a repairable product
Failure Rate	Number of failures per unit time
Mean time to failure (MTTF)	Mean time to failure of a nonrepairable product or mean time to first failure of a repairable product
Mean life	Mean value of life ("life" may be related to major overhaul, wear-out time, etc.)
Mean time to first failure MTFF)	Mean time to first failure of a repairable product
Mean time between maintenance (MTBM)	Mean time between a specified type of maintenance action
Longevity	Wear-out time for a product
Availability	Operating time expressed as a percentage of operating and repair time
System effectiveness	Extent to which a product achieves the requirements of the user
Probability of success	Same as reliability (but often used for "one-shot" or non-time-oriented products)
b_{10} life	Life during which 10% of the population would have failed
b_{50} life	Median life, or life during which 50% of the population would have failed
Repair/100	Number of repair per 100 operating hours

[*Source*: Gryna et al. (2007), p. 326.]

Table 28.6 Summary of Tests Used for Design Evaluation

apportioned to its three components. For example, the allocation for the fusing circuitry is 0.998 or, in terms of the reliability objective of mean time between failures, 725 hours.

Kohoutek (1996b) suggests that, in order to allow for design margins, only 90 percent of the system failure rate be apportioned to its subsystems and their components. He discusses five other methods for reliability apportionment. Kapur (1996) provides several examples of using alternative apportionment methods. Kohoutek (1996b) also discusses the use of reliability policies to support goal setting and improvement for both individual products and product families.

Reliability Prediction and Modeling: In general, a model of the system must be constructed before a prediction of reliability can be made. This may start as a paper model (i.e., using only mathematical calculations) but eventually ends with an actual reliability measurement derived from customer use of the product. As a part of this, stress levels for the model's components are determined, and, on the basis of the estimated stress levels, failure rates for the components are obtained and used to estimate the reliability of subsystems and systems. Turmel and Gartz (1997) provide a layout for an "item quality plan" that includes the part's critical characteristics and specification limits. The plan also includes the manufacturing process to be used and test and inspection procedures, with requirements for process stability and capability measures for these processes and procedures.

System Breakdown

Subsystem	Type of Operation	Reliability	Unreliability Per Hour	Failure Rate Objective*	Reliability
Air Frame	Continuous	0.997	0.003	0.0021	483
Rocket motor	One-shot	0.995	0.005		1/200 operations
Transmitter	Continuous	0.982	0.018	0.0126	80.5 h
Receiver	Continuous	0.988	0.012	0.0084	121 h
Control system	Continuous	0.993	0.007	0.0049	207 h
Explosive system	One-shot	0.995	0.005		1/200 operations
System		0.95	0.05		

Explosive Subsystem Breakdown

Unit	Operating Mode	Reliability	Unreliability	Reliability Objective
Fusing circuitry	Continuous	0.998	0.002	725 h
Safety and arming mechanism	One-short	0.999	0.001	1/1000 operations
Warhead	One-short	0.998	0.022	2/1000
Explosive subsystem		0.995	0.005	

Unit Breakdown

Fusing Circuitry Component Part Classification	Number Used, n	Failure Rate Per Part, λ, % 1000 h	Total Part Failure Rate, $n\lambda$, % 1000 h
Transistors	93	0.30	27.90
Diodes	87	0.15	13.05
Film resistors	112	0.04	4.48
Wirewound resistors	29	0.20	5.80
Paper capacitors	63	0.04	2.52
Tantalum capacitors	17	0.50	8.50
Transformers	13	0.20	2.60
Inductors	11	0.14	1.54
Solder joints and wires	512	0.01	5.12

$$\text{MTBF} = \frac{1}{\text{failure rate}} = \frac{1}{\sum n\lambda} = \frac{1}{0.0007151} = 1398 \text{ h}$$

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*For a mission time of 1.45 h.

(*Source:* Gryna et al. 2007, p. 327, adapted by F. M. Gryna, Jr. from Beaton 1959, p. 65.)

Table 28.7 Establishment of Reliability Objectives

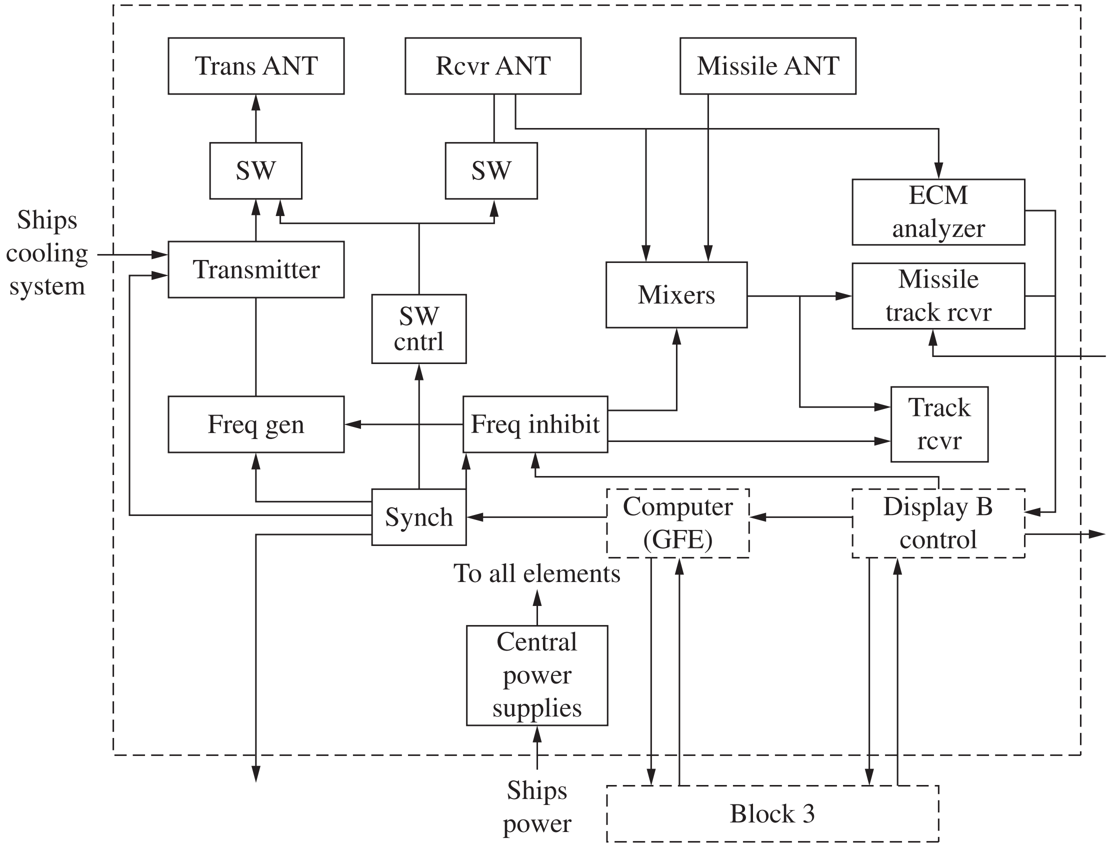


FIGURE 28.11 Functional block diagram. (*Gryna 1988, p. 19.10.*)

In order to construct a model for reliability prediction, interrelationships among the system's subsystems and their components must be understood. Gryna (2001) suggests the following steps to developing reliability models and using them for reliability prediction:

1. *Define the product and its functional operation*. The system, subsystems, and units must be precisely defined in terms of their functional configurations and boundaries. This precise definition is aided by preparation of a functional block diagram (Figure 28.11), which shows the subsystems and lower-level products, their interrelation, and the interfaces with other systems. For large or complex systems it may be necessary to prepare functional block diagrams for several levels of the product hierarchy.

Given a functional block diagram and a well-defined statement of the functional requirements of the product, conditions that constitute failure or unsatisfactory performance can be defined. The functional block diagram also makes it easier to define the boundaries of each unit and to ensure that important items are neither neglected nor considered more than once. For example, a switch that is used to connect two units must be classified as belonging to one unit or the other, or as a separate unit.

2. *Prepare a reliability block diagram*. The reliability block diagram (Figure 28.12) is similar to the functional block diagram, but it is modified to emphasize those aspects that influence reliability. The diagram shows, in sequence, elements that must function for successful operation of each unit. Redundant paths and alternative modes should be clearly shown. Elements that are not essential to successful operation need not be included (e.g., decorative escutcheons). Also, because of the many thousands of individual parts that constitute a complex product, it is necessary to exclude from the calculation those classes of parts that

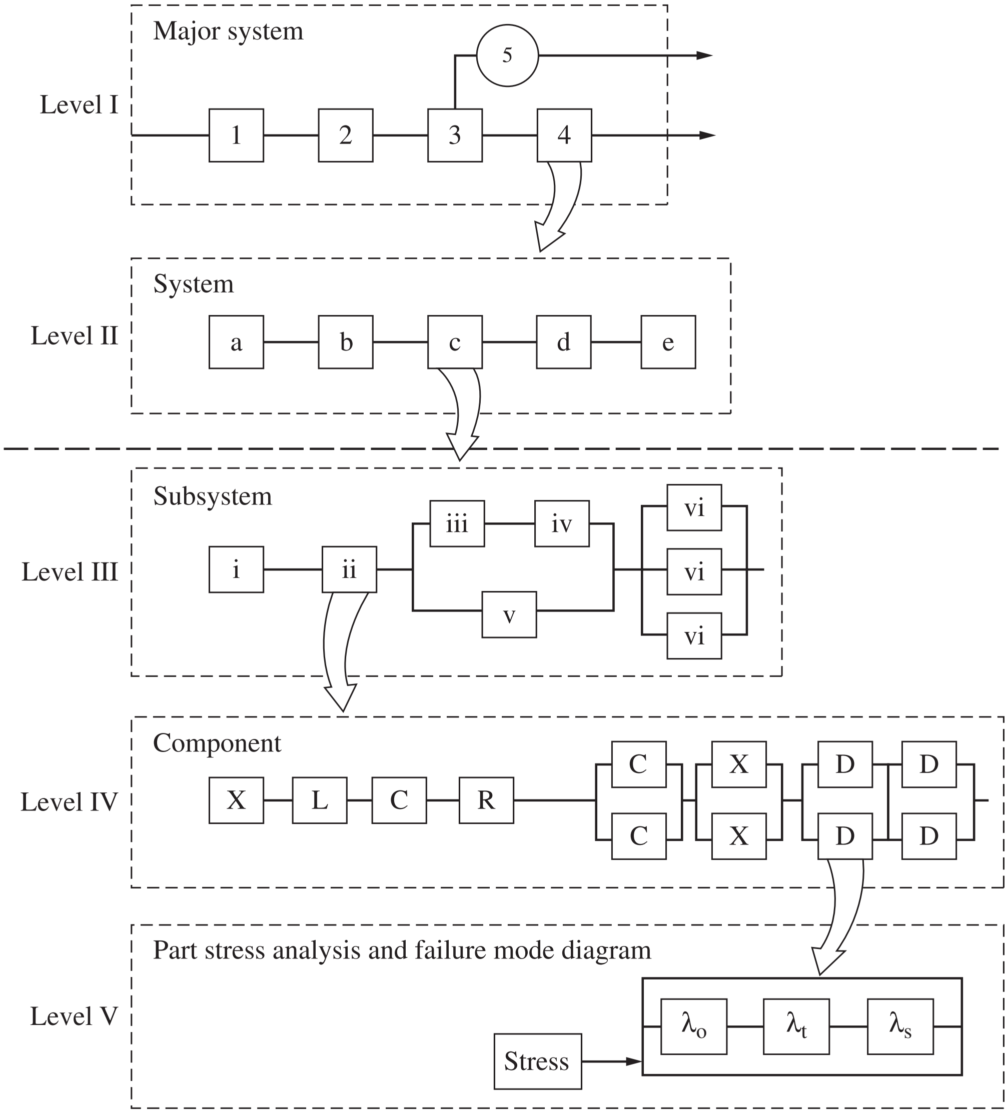


FIGURE 28.12 Reliability block diagram. (*Gryna 1988, p. 19.11.*)

are used in mild applications. The contribution of such parts to product unreliability is relatively small. Examples of items that can generally be disregarded are terminal strips, knobs, chassis, and panels.

3. *Develop the probability model for predicting reliability.* This may be a very simple model (e.g., an exponential model that assumes a constant failure rate and is based on the addition of component failure rates), somewhat more complicated (e.g., application of the Weibull distribution based on prediction of reliability as a function of time) or very complex (e.g., using more esoteric distributions and accommodation of redundancies or special conditions).

4. *Collect information relevant to parts reliability.* Factors include part function, tolerances, part ratings, internal and external environments, stresses, and operating time (duty cycles). Parts with dependent failure probabilities should be grouped together into modules so that the assumptions upon which the prediction is based are satisfied. This detailed information makes it possible to perform a stress analysis, which will not only provide information on the appropriate adjustments to standard input data but also serve to uncover weak or questionable areas

in the design. Operating parameters often are closely associated with reported failure rate information, in recognition that conditions may strongly influence failure rates. (It is worth noting here the methodology of "robust design" that is intended to assist designers to improve part and product ability to perform in various environments. Phadke (1989), Taguchi et al. (2005), and, more recently, Park and Antony (2008) provide approaches and examples.)

5. *Select parts reliability data*. The required part data consist of information on catastrophic failures and on tolerance variations with respect to time under known operating and environmental conditions. Acquiring these data is a major problem for the designer, because there is no single reliability data bank comparable to handbooks such as those that are available for physical properties of materials. Instead, the designer (or supporting technical staff) must either build up a data bank or use reliability data from a variety of sources:

- Field performance studies conducted under controlled conditions
- Specification life tests
- Data from parts manufacturers or industry associations
- Customers' part-qualification and inspection tests
- Government agency and related data banks such as the Reliability Information Analysis Center (RIAC), and RDF 2000 (formerly CNET RDF 93). These sources provide component failure rate data and curves for various components' operating environments and stress levels, and examples of reliability prediction procedures appropriate for various stages of a design's evolution.

6. *Combine all of the above to obtain the numerical reliability prediction.*

- *Make estimates*. In the absence of basic reliability data, it may be feasible to make reasonably accurate estimates based upon past experience with similar part types. Lacking such experience, it becomes necessary to obtain the data via part evaluation testing.
- *Determine block and subsystem failure rates*. The failure rate data obtained in step 4 or via estimation are used to calculate failure rates for the higher-level systems and the total system. Pertinent subsystem or assembly correction factors, before such as those determined for the effects of preventive maintenance, should also be applied.
- *Determine the appropriate reliability unit of measure*. This is the choice of the reliability index or indicators as listed in Table 28.6.

The bottom portion of Table 28.7 provides an example of predicting the failure rates for each component of the fusing circuitry for known part counts. The prediction is based upon the assumptions of the statistical independence of the failure times of the components, conformance to an exponential failure distribution, and equal hours of operation. The estimated unit failure rate is of 0.7151/1000 hours of operation or 0.0007151 failures per hour. The reciprocal of the latter failure rate yields an estimated mean time between unit failures of 1398 hours, which exceeds the 725-hour requirement for the fusing circuitry.

Reliability analysis: After completing the steps of reliability prediction, use the reliability model and predictions to identify the design's "weak points" and the required actions and responsibilities for reliability improvement. Three primary methods for evaluation are Failure Mode, Effect, and Criticality Analysis (FMECA), Fault Tree Analysis (FTA), and Testing. The first two are discussed as follows; design testing is deferred until later in the chapter.

- *Failure Mode, Effect, and Critically Analysis*. This method enhances planning for reliability by facilitating the engineer's analysis of the expected effects of operating

1 = Very low (<1 in 1000)
2 = Low (3 in 1000)
3 = Medium (5 in 1000)
4 = High (7 in 1000)
5 = Very high (>9 in 1000)

T = Type of failure
P = Probability of occurrence
S = Seriousness of failure to system
H = Hydraulic failure
M = Mechanical failure
W = Wear failure
C = Customer abuse

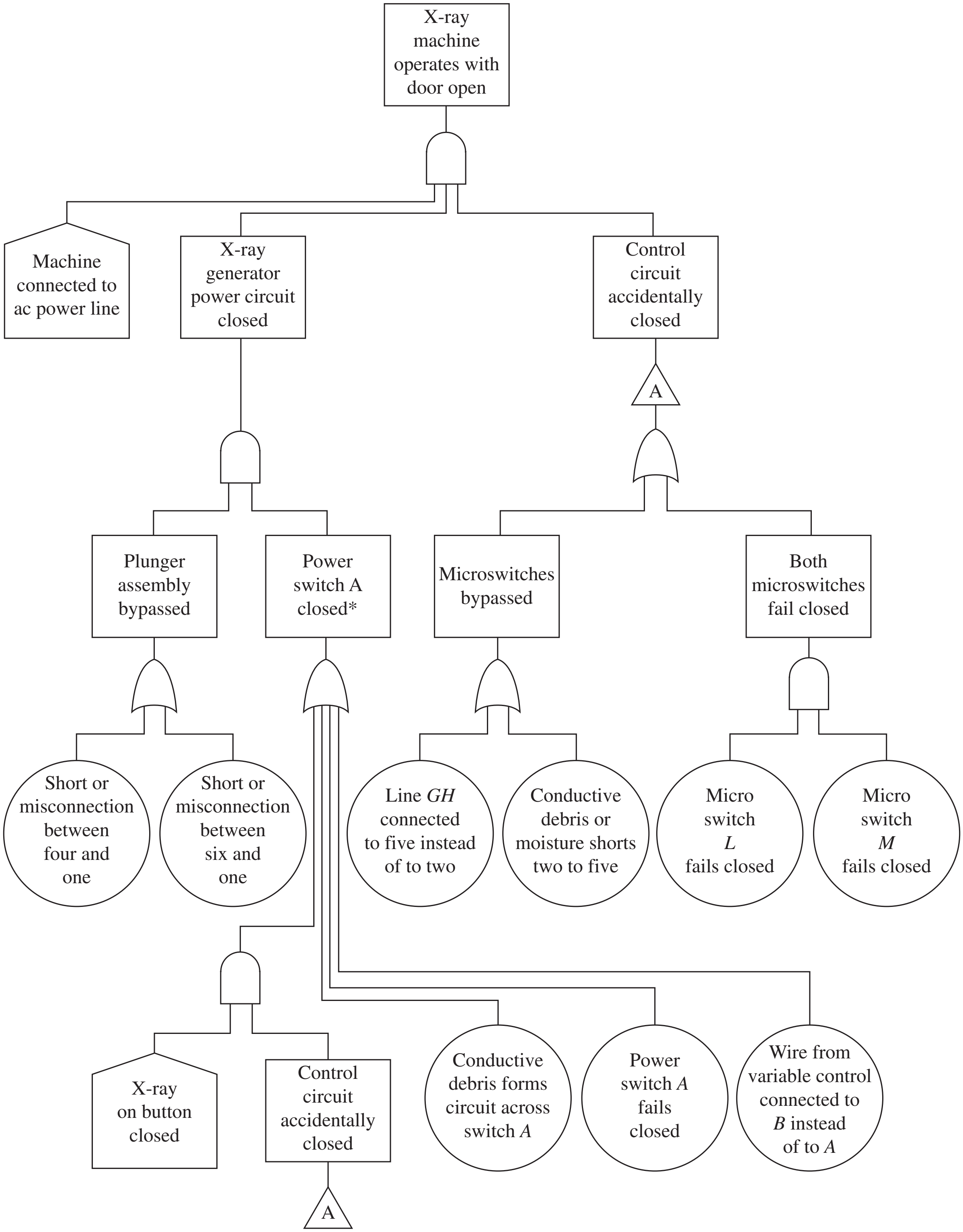
Product	HRC-1
Date	Jan. 14, 1987
By	S.M.

Component part number	Possible failure	Cause of failure	T	P	S	Effect of failure on product	Alternatives
Worn bearing 4224	Bearing worn	Not aligned with bottom housing	M	1	4	Spray head wobble or slowing down	Improve inspection
Zytel 101		Excessive spray head wobble	M	1	3	DITTO	Improve worm bearing
Bearing stem 4225	Excessive wear	Poor bearing/ material combination	M	5	4	Spray head wobbles and loses power	Change stem material
Brass		Dirty water in bearing area	M	5	4	DITTO	Improve worm seal area
		Excessive spray head wobble	M	2	3	DITTO	Improve operating instructions
Thrust washer 4226	Excessive wear	High water pressure	M	2	5	Spray head will stall out	Inform customer in instructions
Fulton 404		Dirty water in washers	M	5	5	DITTO	Improve worm seal design
Worm 4527	Excessive wear in bearing area	Poor bearing/ material combination	M	5	4	Spray head wobbles and loses power	Change bearing stem material
Brass		Dirty water in bearing area	M	5	4	DITTO	Improve worm seal design
		Excessive spray head wobble	M	2	3	DITTO	Improve operating instructions

FIGURE 28.13 Failure mode, effect, and criticality analysis. (*Gryna et al. 2007, p. 331.*)

conditions on design reliability and safety. General introductions to failure mode effect analysis (FMEA) and FMECA are provided in Gryna at al. (2007). FMEA and FMECA are intended for use by product and process designers in identifying and addressing potential failure modes and their effects. Figure 28.13 (Gryna et al. 2007) is an example of a FMECA for a traveling lawn sprinkler, which includes, for each part number, its failure mode, result of the failure mode, cause of failure mode, estimated probability of failure mode, severity of the failure mode, and alternative countermeasures for preventing the failure.

- *Fault Tree Analysis*. Whereas FMECA examines all possible failure modes from the component level upward, FTA focuses on particular known undesirable effects of a failure (e.g., fire and shock, and proceeds to identify all possible failure paths resulting in the specified undesirable outcome). In addition to hazard analysis, FTA is a tool often used in designing for safety. Figure 28.14 (Gryna et al. 2007) and Hammer (1980) is a fault tree for a safety circuit. The failure outcome of concern is that X-rays will be emitted from a machine whose door has been left open. The spadelike



* Fault indicator lamp will light anytime this condition exists.

FIGURE 28.14 Fault-tree analysis of an interlock safety circuit. (*Gryna et al. 2007, p. 339.*)

symbol with a straight bottom is an "and gate," meaning that the output occurs only if all input events before it happen. The spade symbol with the curved bottom is an "or gate," meaning the output occurs if any one or more of the input events before it happen. The probabilities of specific occurrences can be estimated by providing estimates of the probabilities of occurrence of each event in the fault tree. Lazor (1996) also provides examples and comparisons of FMECA and FTA analyses, with an interesting discussion on the relationship between fault trees and reliability block diagrams.

Reliability Improvement

The general approach to quality improvement is widely applicable to reliability improvement as far as the economic analysis and the managerial tools are concerned. The differences are in the technological tools used for diagnosis and remedy. Projects can be identified through reliability prediction; design review; failure mode, effect, and criticality analysis, and other reliability evaluation techniques.

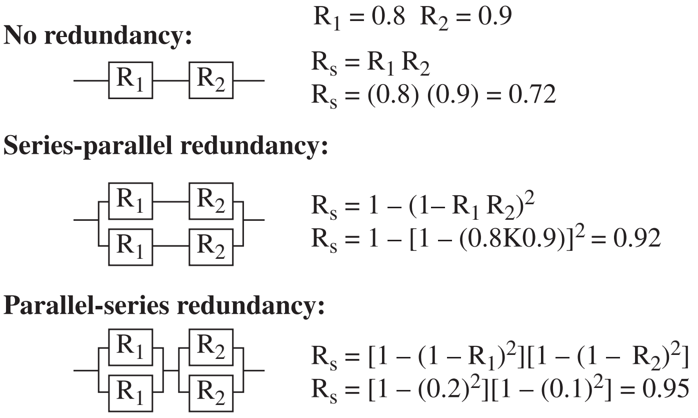
Action to improve reliability during the design phase is best taken by the designer. The reliability engineer can help by defining areas needing improvement and by assisting in the development of alternatives. The following actions provide some approaches to improving a design:

1. Review the users' needs to see if the function of the unreliable parts is really necessary to the user. If not, eliminate those parts from the design. Alternatively, look to see if the reliability index (figure of merit) correctly reflects the real needs of the user. For example, availability is sometimes more meaningful than reliability. If so, a good maintenance program might improve availability and, hence ease the reliability problem.
2. Consider trade-offs of reliability for other parameters (e.g., functional performance or weight). Here again, it may be found that the customer's real needs may be better served by such a trade-off.
3. Use redundancy to provide more than one means for accomplishing a given task in such a way that all the means must fail before the system fails.
    - There are several types of redundancy, a common form being parallel redundancy. A familiar example is the multiengine aircraft, which is so designed that even if one engine fails, the aircraft will still be able to continue on to a safe landing.
    - Under conditions of independent failures, the overall reliability for parallel redundancy is expressed by the formula:

    $$P_s = 1 - (1 - P_i)^n$$

    where P_s = reliability of the system
    P_i = reliability of the individual elements in the redundaney
    n = number of identical redundant elements

    - Figure 28.15 shows some simple examples of series-parallel and parallel-series redundancies and calculates the system reliability versus that prevailing for the case of no redundancy.
4. Review the selection of any parts that are relatively new and unproven. Use standard parts whose reliability has been proven by actual field use. (However, be sure that the conditions of previous use are applicable to the new product.)



$R_1 = 0.8 \quad R_2 = 0.9$

$R_s = R_1 R_2$

$R_s = (0.8)\,(0.9) = 0.72$

$R_s = 1 - (1 - R_1 R_2)^2$

$R_s = 1 - [1 - (0.8K0.9)]^2 = 0.92$

$R_s = [1 - (1 - R_1)^2][1 - (1 - R_2)^2]$

$R_s = [1 - (0.2)^2][1 - (0.1)^2] = 0.95$

Figure 28.15 Series-parallel and parallel-series redundancy. (*Juran Institute. ©1994. Used with permission.*)

5. Use derating to assure that the stresses applied to the parts are lower than the stresses the parts can normally withstand. Derating is one method that design engineers use to improve component reliability or provide additional reliability margins. Gryna et al. (2007) define derating as the assignment of a product (component) to operate at stress levels below its normal rating, e.g., a capacitor rated at 300 V is used in a 200-V application. Kohoutek also provides examples of derating graphs, to be used by design engineers for specific types of integrated circuits. Before using the graphs for a specific application, the design engineer first determines the expected operating temperatures, voltages, stresses, etc. of the component under study, then uses the graphs to select the appropriate derating factor.
6. Use "robust" design methods that enable a product to handle unexpected environments.
7. Control the operating environment to provide conditions that yield lower failure rates. Common examples are (a) potting electronic components to protect them against climate and shock and (b) use of cooling systems to keep down ambient temperatures.
8. Specify replacement schedules to remove and replace low-reliability parts before they reach the wear-out stage. In many cases, the replacement is made but is contingent on the results of checkouts or tests that determine whether degradation has reached a prescribed limit.
9. Prescribe screening tests to detect infant-mortality failures and to eliminate substandard components. The tests take various forms—bench tests, "burn in," and accelerated life tests. Jensen and Petersen (1982) provide a guide to the design of burn-in test procedures. Chien and Kuo (1995) offer further useful insight into maximizing burn-in effectiveness.
10. Conduct research and development to attain an improvement in the basic reliability of those components which contribute most of the unreliability. While such improvements avoid the need for subsequent trade-offs, they may require advancing the state of the art and hence an investment of unpredictable size. Research in failure mechanisms has created a body of knowledge called the "physics of failure" or

"reliability physics." The IEE International Reliability Physics Symposium (IRPS) conference proceedings remains an excellent reference on this topic.

Although none of the foregoing actions provides a perfect solution, the range of choice is broad. In some instances the designer can arrive at a solution single-handedly. More usually it means collaboration with other company specialists. In still other cases the customer and/or the company management must concur because of the broader considerations involved.

Designing for Maintainability

Although the design and development process may yield a product that is safe and reliable, it may still be unsatisfactory. Users want products to be available on demand. Therefore, designers must also address the issue of the ease of preventive maintenance and repair. "Maintainability" is the accepted term used to address and quantify the extent of need for preventive maintenance and the ease of repair. Dhillon (1999) provides a definition of maintainability as follows:

> the measures taken during the development, design and installation of a manufactured product that reduce required maintenance, manhours, tools, logistic cost, skill levels, and facilities, and ensure that the product meets the requirements for its intended use (p. 1).

Note that maintainability is a design parameter, whereas maintenance is an operational activity.

Mean time to repair (MTTR) is an index used for quantifying maintainability, analogous to the term MTBF, which is used as an index for reliability. MTTR is the mean time needed to perform repair work, assuming that there is no delay in obtaining spare parts and that a technician is available. Similar to reliability, there are numerous possible measures of maintainability; Table 28.8 (MIL-STD-721C 1981), summarizes possible indexes for maintainability.

For example, Kowalski (1996) discusses allocating a system's maintainability requirement among its subsystems. The allocation is analogous to the method by which reliability was apportioned (See paragraph, "Reliability Apportionment."). Kowalski also discusses the impact of testability on the ability to achieve maintainability goals. Turmel and Gartz (1997) of Eastman Kodak provide, for a specific test method, a test capability index (TCI) index for measuring the proportion of the specification range taken by the intrinsic variation of a test/measurement method. The reported guideline was to target test variation at less than 25 percent of the total tolerance range.

Designing for Availability

Both design reliability and maintainability affect the probability of a product being available when required for use (i.e., it performs satisfactorily when called upon). Availability is calculated as the ratio of operating time to operating time plus downtime. However, downtime can be viewed in two ways:

1. *Total downtime*. This includes the active repair time (diagnosis and repair), preventive maintenance time, and logistics time (time spent waiting for personnel, spare parts, etc.). When total downtime is used, the resulting ratio is called operational availability (A_o).
2. *Active repair time*. When active repair time is used, the resulting ratio is called "intrinsic availability."

Figure of Merit	Meaning
Mean time to repair (MTTR)	Mean time to correct a failure
Mean time to service	Mean time to perform an act to keep a product in operating condition
Mean preventive maintenance time	Mean time for scheduled preventive maintenance
Repair hours per 100 operating hours	Number of hours required for repairs per 100 product operating hours
Rate of preventive maintenance actions	Number of preventive maintenance actions required per period of operative or calendar hours
Downtime probability	Probability that a failed product is restored to operative condition in a specified downtime
Maintainability index	Score for a product design based on evaluation of defined maintainability features
Rate of maintenance cost	Cost of preventive and corrective maintenance per unit of operating or calendar time

[*Source:* MIL-STD-721C (1981).] Note: this standard was canceled without replacement (12/5/1995) but remains a useful reference.

Table 28.8 Maintainability Figures of Merit

Under certain conditions, "steady state" availability can be calculated as follows:

$$A_o = \frac{\text{MTBF}}{\text{MTBF} + \text{MDT}} \qquad \text{and} \qquad A_i = \frac{\text{MTBF}}{\text{MTBF} + \text{MTTR}}$$

where MTBF = mean time between failures
MDT = mean total downtime
MTTR = mean active time to repair

These formulas indicate that specified product availability may be improved (increased) by increasing product reliability (MTBF) or by decreasing time to diagnose and repair failures (MDT or MTTR). Achieving any combination of these improved results requires an analysis of the trade-offs between the benefits of increasing reliability or maintainability.

Formulas for steady-state availability have the advantage of simplicity. However, they are based upon the following assumptions:

- The product is operating in the constant-failure-rate portion of its overall life where time between failures is exponentially distributed.
- Downtime and repair times are also exponentially distributed.
- Attempts to locate system failures do not change failure rates.
- No reliability growth occurs. (Such growth might be due to design improvements or removal of suspect parts.)
- Preventive maintenance is scheduled outside the time frame included in the availability calculation.

For these conditions, O'Connor (2002) provides formulas and examples for various reliability block diagrams (e.g., series, parallel, and parallel-standby configurations). Malec (1996) provides general formulas and examples for calculating instantaneous availability and mission interval availability—the probability that a product will be available throughout the length of its mission.

Some trade-off decisions that should be considered to improve maintainability through design are described in Gryna et al. (2007), including:

- *Reliability versus maintainability*. For any particular availability requirement, a designer may have a choice of improving either reliability or maintainability.
- *Modular versus nonmodular construction*. Although modular design takes greater design effort, it can reduce the time needed for diagnosis and repair in the field. In many cases, once a fault is located, the offending module can simply be removed and replaced. Repair to the module, if needed, can then take place at another time and place without delaying equipment use by the customer.
- *Repairs versus throwaway*. In many circumstances it may be more economical to discard a faulty part than to attempt repair. In such situations, the design may ease the process of discard and replacement.
- *Built-in versus external test equipment*. Having internal diagnostic capability reduces downtime, but adds to overall cost of the product. However, the additional costs can also reduce overall repair costs by providing users with simple repair instructions for various failure modes diagnosed by the diagnostic equipment or software. For example, office copiers provide messages on where and how to remove paper jams. Increasingly, elements for diagnostics may reside in a piece of equipment, but monitoring and diagnosis can take place remotely via the Internet.
- *Person versus machine*. Designers should consider trade-offs between a highly tuned product that may require special instrumentation and repair facilities and a product that may have reduced performance but easier maintenance and greater uptime.

Kowalski (1996) provides additional examples of criteria for maintainability design.

Identifying and Controlling Critical Components

The design engineer will identify certain components as critically affecting reliability, availability, and maintainability (RAM) or for attaining cost objectives. These critical components are ones that emerge from the various applicable analyses: reliability block diagrams, stress analysis, FMEA/FMECA, FTA, and RAM studies. These components may be deemed critical because of their estimated effects on design RAM and cost, insufficient knowledge of their actual performance, or the uncertainty of their suppliers' performance. One approach to ensuring performance and resolving uncertainties is to develop and manage a list of critical components. The critical components list (CCL) should be prepared early in the design effort. It is common practice to formalize these lists, showing the nature of the critical features and planning for controlling and improving performance for each critical component. The CCL becomes the basic planning document for (1) test programs to qualify parts, (2) design guidance in application studies and techniques, and (3) design guidance for application of redundant parts, circuits, or subsystems.

Configuration Management

Configuration management is the process used to define, identify, and control the composition and the cost of a product. A configuration established at a specific point in time is called a "baseline." Baseline documents include drawings, specifications, test procedures, standards, and inspection or test reports. Configuration management begins during the design of the product and continues throughout the remainder of the product's commercial life. As applied to the product's design phase, configuration management is analogous, at the level of total product, to the process described in the last paragraph for the identification and control of critical components. Gryna (1988) states that "configuration refers to the physical and functional characteristics of a product, including both hardware and software" and defines three principal activities that comprise configuration management:

1. *Identification*. Process of defining and identifying every element of the product.
2. *Control*. Process that manages a design change from the time of the original proposal for change through implementation of approved changes.
3. *Accounting*. Process of recording the status of proposed changes and the implementation status of approved changes.

Configuration management is needed to help ensure that:

1. All participants in the quality spiral know the current status of the product in service and the proposed status of the product in design or design change.
2. Prototypes, operations, and field service inventories reflect design changes
3. Design and product testing are conducted on the latest configurations.

Design Testing

Once the foregoing tools and analyses of design quality have been invoked, it is necessary to ensure that the resulting design can ultimately be manufactured, delivered, installed, and serviced to meet customers' requirements. To achieve this, it is imperative to conduct actual tests on prototypes and pilot units prior to approval for full-scale manufacturing. Table 28.9 summarizes the various types and purposes of design evaluation tests.

In Chapter 48 of *Juran's Quality Handbook* (Juran and Godfrey 1999), Meeker et al. (1999) discuss the purpose and design of environmental stress tests, accelerated life tests, reliability growth tests, and reliability demonstration testing and analysis of the data from these tests. Graves and Menten (1996) and Schinner (1996) provide similar discussions on designing experiments for reliability measurement and improvement, and accelerated life testing respectively. The Rome Laboratory Reliability Engineer's Toolkit (1993) and, more recently, related publications in the series, provide useful tools and discussion including the selection and use of reliability test plans from MIL-HDBK-781 (1987).

Comparing Results of Field Failures with Accelerated Life Tests

In order to verify design reliability within feasible time frames, it often is necessary to "accelerate" failure modes by using various environmental stress factors. This applies not only to equipment but to other products of R&D such as in accelerated aging of pharmaceuticals and food products to determine shelf life. A key issue to address when introducing stress factors is to ensure that the failure modes that they produce are equal to those observed in actual use; this is not necessarily given due to the artificial testing conditions (e.g., chemical kinetics may be sensitive to specific conditions). Gryna (1988) provides an example of using probability plots to compare and relate test results to "field" failures. Figure 28.16 contains

Type of TEST	Purpose
Performance	Determine ability of product to meet basic performance requirements
Environmental	Evaluate ability of product to withstand defined environmental levels; determine internal environments generated by product operation; verify environmental levels specified
Stress	Determine levels of stress that a product can withstand in order to determine the safety margin inherent in the design; determine modes of failure that are not associated with time
Reliability	Determine product reliability and compare to requirements; monitor for trends
Maintainability	Determine time required to make repairs and compare to requirements
Life	Determine wear-out time for a product, and failure modes associated with time or operating cycles
Pilot Run	Determine if fabrication and assembly processes are capable of meeting design requirements; determine if reliability will be degraded.

[*Source:* Gryna et al. (2007), p. 334.]

Table 28.9 Summary of Tests Used for Design Evaluation

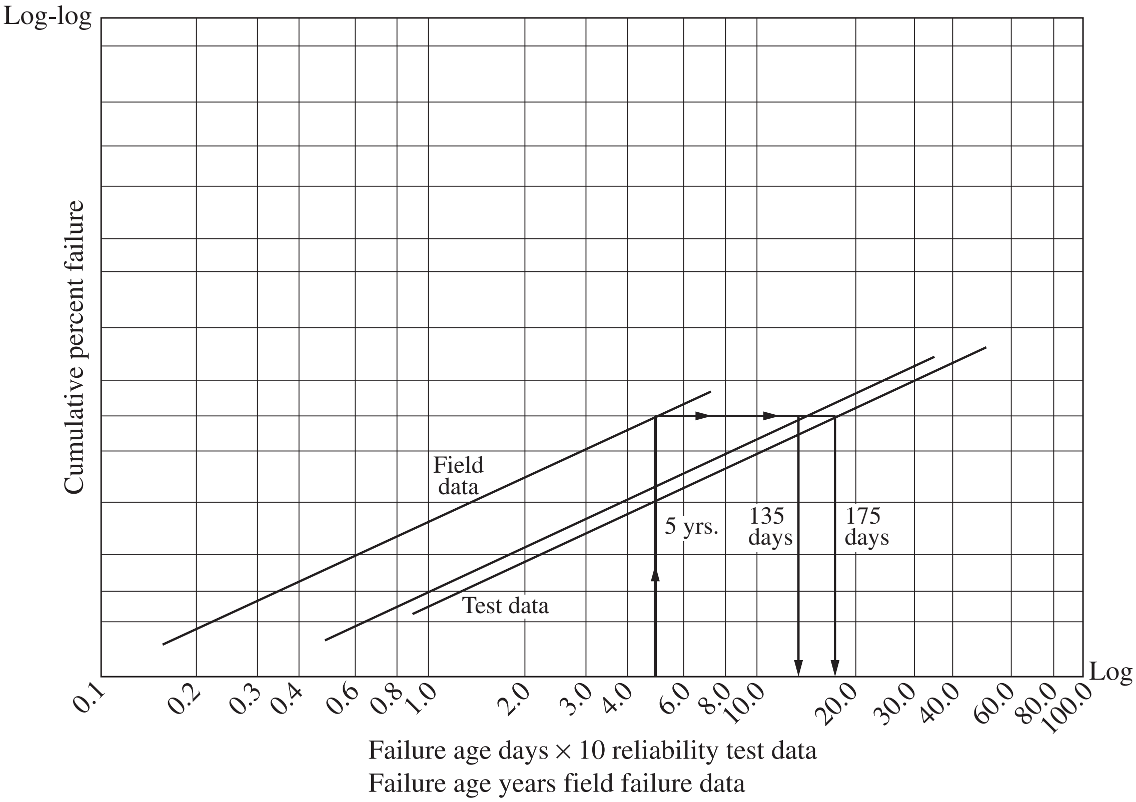


Figure 28.16 Weibull plot of accelerated test versus field failure data for two air-conditioner models. (*Juran Institute. ©1994. Used with permission.*)

plots of the estimated cumulative failure percentages versus number of accelerated test days and actual field usage days for two models of air conditioners. Because the two lines essentially are parallel, it appears that the basic failure modes produced by the accelerated and field usage environments are equivalent. The test data are plotted in tens of days. The 5-year warranty period is represented by a heavy vertical line. Following the vertical line from where it intersects the field data line, and proceeding horizontally to the lines for the accelerated test data, the accelerated test time required to predict the percentage of field failures occurring during the 5-year warranty period is estimated at 135 days for one air conditioner model and 175 days for the other model.

Failure Reporting and Corrective Action Systems

In order to drive improvements in RAM and safety of designs, an organization must define and develop a formal process for reporting, classifying, analyzing, and improving these design parameters. Many organizations call this process "failure reporting and corrective action systems" (FRACAS). Figure 28.17, reproduced from the Rome Laboratory Reliability Engineer's Toolkit (1993), is a high-level flow diagram for a generic FRACAS process. In addition to the process steps, process-step responsibilities are identified by function. The same publication also provides a checklist for identifying gaps in existing FRACAS processes. Ireson (1996) provides additional guidance on reliability information collection and analysis, with discussion on data requirements at the various phases of design, development, production, and usage. Adams (1996) focuses on details of identifying the root causes of failures and driving corrective action with an example of a "business plan" for justifying investment in the equipment and personnel required to support a failure analysis process.

Prognosis

The concepts, tools, and processes discussed here have guided R&D managers, scientists, and engineers in creating successful products and commercial development in the past and will serve them well into the future. Nonetheless, R&D will need to adapt to changes that may create pressure to deviate from accepted quality principles or force new ways of ensuring performance. Some considerations are discussed as follows.

- *Greater entrepreneurial spirit*. The recent global economic downturn has forced consolidation and released many R&D staff to pursue their own interests. If history is any indication, this, in combination with the technological innovations previously cited, will drive the creation of start-up organizations. In turn, this will fuel "intrapreneurialism" as the older organizations act in response.
- *More cross-disciplinary interaction*. The continuing ease of communication has allowed formation of loose, informal groups and affiliations consisting of people with common interests (e.g., networking organizations such as Facebook, MySpace, Twitter, and LinkedIn; whereas the longevity of any particular organization is questionable, the general trend will prevail). Physical boundaries are less meaningful constraints to cooperation and collaboration, thereby promoting synergies and innovations previously not possible.
- *Increased tension between R&D and marketing*. The most disruptive and game-changing technological innovations are those that do not necessarily come from market pull; instead, they are serendipitous inventions that at first have no apparent market. These gems may be buried among many other innovations that are solutions seeking a problem. The net result will be greater technology push, with need for

Event	Functions	Actions
Failure or malfunction	Operations	• Indentify a problem, call for maintenance, annotate the incident.
	Maintenance	• Corrects the problem, logs the failure.
	Quality	• Inspects the correction.
Failure report	Maintenance	• Generates the failure report with supporting data (time, place, equipment, item, etc.)
Data logged	Quality	• Ensure completeness and assigns a travel tag for the failed item for audit control.
	R&M	• Log all the failure reports, validate the failures and forms, classify the failures (inherent, induced, false alarm).
Failure review	R&M	• Determine failure trends (i.e., several failures of the same or similar part).
	Design	• Review operating procedures for error.
Failure analysis	R&M	• Decide which parts will be destructively analyzed.
	Physics of failure	• Perform failure analysis to determine the cause of failure (i.e., part or external).
Failure correction	Quality	• Inspect incoming test data for the part.
	Design	• Redesign hardware, if necessarry.
	Vendor	• New part or new test procedure.
Post data review	Quality	• Evaluate incoming test procedures, inspect redesigned hardware.
	R&M	• Close the loop by collecting and evaluating post test data for reoccurrence of the failure.

FIGURE 28.17 FRACAS flow diagram. (*Juran Institute. ©1994. Used with permission.*)

marketing to expand efforts to better understand unmet market needs. This can be a difficult step because existing customers may not be interested in the new technology ("marketing says our customers aren't interested, so kill the project"), and it requires "listening" to customers that do not yet exist, do not know of the technology, and cannot articulate how their needs could be met through the innovation.

- *Resynthesis of quality tools.* Readers may note the prevalence of research on quality topics directed toward the development of new and modified tools (e.g., the integration of QFD, benchmarking, and decision analysis cited earlier). Online accessibility to research papers, cross-disciplinary interaction, and the prevalence of software that helps users through technically challenging techniques (e.g., statistics) will encourage new applications. R&D managers should remain diligent in scanning the literature outside their immediate area to find methods that could improve quality at reduced cost and provide competitive advantage.

- *Dispersed organizational structure*. In the past, R&D relied heavily on centralized physical laboratories in which people were in close proximity. As technological innovations facilitate knowledge transfer and lower barriers to entry (witness the availability of DNA testing kits sold for children's amusement; such technology required expensive equipment only a few years ago), it will become increasingly viable to structure a geographically- and time-dispersed R&D organization. This may strain quality, however, and it will be essential to vigilantly coordinate activities and handoffs.
- *Business process innovation in R&D*. Although widespread, quality improvement initiatives such as Six Sigma have not penetrated R&D as much as in other business processes. This is due to a combination of cultural resistance and lack of fit. As shown in Figure 28.1, product innovation and process innovation tend to occur at different phases of development. Although perhaps in modified form, continuous process improvement and innovation methodologies will tend to blur the distinction between phases, so that the early R&D creative process will receive greater focus.
- *Shift in basic, long-term research from companies to universities*. Retrenchment in the face of difficult economic conditions tends to favor short-term R&D projects perceived as having a safer risk to reward profile and more immediate financial returns. Accordingly, basic long-term research and risk will be shifted away from businesses and into not-for-profit organizations such as government laboratories and universities. This is happening at present (Clark and Rhoads 2009), and, in turn, may lead to greater sharing of intellectual property and profits.
- *Greater sharing of intellectual property*. In some industries such as biotechnology and electronics, R&D efforts are stymied by a thicket of patents. Organizations increasingly will need to consider the downside of rigidly protecting intellectual property and trying to navigate through competing positions and consider instead the upside of cross-licensing to clear the path for their R&D staff to truly innovate and meet customer needs unhindered by intellectual property concerns.
- *Improved metrics that better reflect true R&D quality*. Organizations gradually are becoming more aware that quota types of metrics do a poor job in estimating the value created by R&D, and are, at best, proximal measures. In spite of perceived intrusiveness by R&D staff, expect managers to cautiously shift towards new and more meaningful metrics with mixed but steady success.

As stated earlier, few organizations are able to attain true, enterprisewide quality leadership. This is due, in large part, to practical trade-offs, resource constraints, and the shifting context of business, both micro- and macroeconomic. Recalling that "chance favors the prepared mind," it is incumbent upon R&D bench scientists, laboratory engineers, development staff, and management to lay a firm foundation of quality principles and tools, providing the flexibility to respond with unified action to unforeseen events, challenges, and opportunities.

Where to Find It

Following is a list of various online resources that may be useful to R&D professionals. The list is intended to provide a sampling of sites and is not intended to be comprehensive. Links to additional resources may be found on most websites, so the list may be viewed as a starting point for research.

Professional Societies, Institutes, and Communities

American Society for Quality (ASQ): <http://www.asq.org/> (includes a Reliability Division: <http://www.asq.org/divisions-forums/reliability/index.html>). *A professional society devoted entirely to quality. Catering to numerous sectors (education, government, healthcare, manufacturing, service), ASQ is a source for publications, conferences, standards, and certification.*

Industrial Research Institute (IRI): <http://www.iriinc.org/> *A source of publications, conferences and workshops, and networking opportunities related to research within the industrial sector.*

Institute of Electrical and Electronics Engineers (IEEE): <http://www.ieee.org/portal/site> *A large, long-standing professional association dedicated to the advancement of innovation and technology. IEEE is a source of publications (including books and journals), conferences, professional development opportunities, and standards.*

PharmWeb: <http://www.pharmweb.net/> *Portal and online community of pharmacy, pharmaceutical and healthcare-related professionals. Contains a large number of links to additional resources worldwide.*

Society of Reliability Engineers (SRE): <http://www.sre.org/> *A U.S. professional society of engineers interested in reliability Contains military handbooks and standards relating to reliability.*

Technical Standards Organizations

ASTM International: <http://www.astm.org/> *A voluntary standards development organization and source for technical standards for materials, products, systems, and services.*

European Committee for Standardization (CEN): <http://www.cen.eu/> *A European business facilitator that seeks to removing trade barriers for European industry and consumers; provides a platform for the development of European Standards and other technical specifications.*

National Institute of Standards and Technology (NIST): <http://www.nist.gov/index.html> *A nonregulatory federal agency within the U.S. Department of Commerce that promotes U.S. innovation and industrial competitiveness by advancing measurement science, standards, and technology. NIST administers four cooperative programs:*

- *NIST Laboratories*, conducting research to advance the U.S. technology infrastructure needed by industry to continually improve products and services.
- *Baldrige National Quality Program*, which promotes performance excellence among U.S. organizations, conducts outreach programs and manages the annual Malcolm Baldrige National Quality Award to recognize performance excellence and quality achievement.
- *Hollings Manufacturing Extension Partnership*, a nationwide network of local centers that offers technical and business assistance to small manufacturers.
- *Technology Innovation Program*, which provides cost-shared awards to industry, universities, and consortia for research on potentially revolutionary technologies.

Reliability Resources

- **Reliability Information Analysis Center (RIAC):** <http://www.theriac.org/> *A Center of Excellence and technical focal point for information, data, analysis, training, and technical assistance in the engineering fields of reliability, maintainability, quality, supportability, and interoperability (RMQSI). Serves primarily, but not exclusively, the U.S. Department of Defense.*

- **Weibull.com:** <http://www.weibull.com/> *A website devoted entirely to the topic of reliability engineering and reliability theory.*
- **U.S. Government Defense R&D:** *Organizations involved in R&D related to* national security.

  Air Force Research Laboratory: <http://www.wpafb.af.mil/AFRL/>

  Army Research Laboratory: <http://www.arl.army.mil/>

  Defense Advanced Research Projects Agency: <http://www.darpa.mil/>

  Naval Research Laboratory: <http://www.nrl.navy.mil/>

  Office of Naval Research: <http://www.onr.navy.mil/>

- **U.S. Government Foundations and Related Organizations:** *Federally supported organizations conducting and facilitating research in the national interest; refer to individual websites for details.*

  Federal Laboratory Consortium (FLC): <http://www.federallabs.org/>

  National Academies: <http://www.nationalacademies.org/>

  National Institutes of Health: <http://www.nih.gov/science/index.html> *(see also NIH Office of Technology Transfer (OTT):* <http://ott.od.nih.gov/index.aspx>

  National Center for Supercomputing Applications: <http://www.ncsa.illinois.edu/>

  National Science Foundation: <http://www.nsf.gov>. *(For a list of federally funded R&D centers, see* <http://www.nsf.gov/statistics/ffrdc/>)

  North American Space Administration (NASA): <http://www.nasa.gov/>

- **U.S. National Laboratories and Technology Centers:** *Department of Energy research centers supporting a broad range of scientific and engineering research. Visit specific sites for current research programs.*

  Ames Laboratory: <http://www.ameslab.gov/>

  Argonne National Laboratory: <http://www.anl.gov/>

  Brookhaven National Laboratory: <http://www.bnl.gov/world/>

  Fermi National Accelerator Laboratory: <http://www.fnal.gov/>

  Idaho National Laboratory: <http://www.inl.gov/>

  Lawrence Berkeley National Laboratory: <http://www.lbl.gov/>

  Lawrence Livermore National Laboratory: <https://www.llnl.gov/>

  Los Alamos National Laboratory: <http://www.lanl.gov/>

  National Renewable Energy Laboratory: <http://www.nrel.gov/>

  New Brunswick Laboratory: <http://www.nbl.doe.gov/>

  Oak Ridge National Laboratory: <http://www.ornl.gov/>

  Pacific Northwest National Laboratory: <http://www.pnl.gov/>

  Princeton Plasma Physics Laboratory: <http://www.pppl.gov/>

  Radiological & Environmental Sciences Laboratory: <http://www.inl.gov/resl>

  Sandia National Laboratories: <http://www.sandia.gov/>

  Savannah River National Laboratory: <http://srnl.doe.gov/>

SLAC National Accelerator Laboratory: <http://www.slac.stanford.edu/>

Thomas Jefferson National Accelerator Facility: <http://www.jlab.org/>

- **European R&D Organizations:** *These organizations provide information and support for research, development and innovation activities within the European Community.*

EUREKA: <http://www.eureka.be/home.do>

European Association of Research and Technology Organisations: <www.earto.org>

European Research Area (European Commission: CORDIS): <http://cordis.europa.eu/era/home_en.html>

Joint Research Centre: <http://ec.europa.eu/dgs/jrc/>

Commercial and Corporate Research Facilities: *A sampling of well-known research organizations. Specific internet addresses change frequently; refer to individual websites to locate R&D information.*

Bell Labs: <http://www.bell-labs.com>

Hewlett-Packard Labs: <http://www.hpl.hp.com>

IBM Research: <http://www.research.ibm.com/>

Intel Research: <http://www.intel.com/research>

Microsoft Research: <http://research.microsoft.com>

Mitsubishi Electric Research Labs: <http://www.merl.com>

SRI International: <http://www.sri.com>

Palo Alto Research Center Inc.: <http://www.parc.com>

- **University Research Labs:** *A sampling of academic institutions known for research and technology development. Specific web addresses are subject to change, but research program information typically can be found via the home page.*

California Institute of Technology: <http://www.caltech.edu/>

Massachusetts Institute of Technology: <http://web.mit.edu/>

Princeton University: <http://www.princeton.edu/main/research/>

Stanford University: <http://www.stanford.edu/research/>

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