SECTION 19

QUALITY IN RESEARCH AND DEVELOPMENT

Al C. Endres

INTRODUCTION

This section discusses managing for quality in research organizations and in development processes. The material will focus on concepts, infrastructure, methods, and tools for simultaneously improving customer satisfaction and reducing costs associated with both these areas. (Managing for quality within the software development process is discussed in Section 20, Software Development.) Frequently the *combined* term "R&D" is used to describe cross-departmental processes, which integrate new knowledge and technology emanating from the research function with the subsequent development of new (or improved) processes and products. However, in this section, it will be useful to distinguish between managing for quality in research organizations and managing for quality in development processes.

Juran's original spiral of progress in quality (see Juran and Gryna 1988, p. 2.5) focused on (for a manufacturing organization) the cross-functional flow involved in the "development" of a new product. In the context of the original spiral, requirements for the new product emanated from marketing research. Marketing conducted research to define customers' needs, as well as to obtain customers' feedback on how well the organization had met those needs. Based upon customers' feedback, and changing customer needs, a new turn of the spiral began.

Marketing research is not the only possible origin of new technology and product ideas. Post-it notes actually resulted from the "failure" of an experiment that was recognized by a researcher as an opportunity for a new product. Furthermore, Roussel et al. (1991) emphasize the criticality of using exploratory research, conducted *proactively* to support an organization's strategic focus. Nussbaum (1997) quotes Thomson's vice president of consumer electronics for multimedia products as stating that design processes are being used "to address overall strategic business issues." Strategic research is being increasingly focused on the delivery of concepts and technologies which will drive new or improved technologies, such as lasers and photonics. These technologies are then used to generate breakthroughs for the organization's next generation of products. These respective origins (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 an increasingly critical activity. In addition to focusing on information, technology, goods, and services which are fit for use, there has been an increasing need to decrease R&D cycle times and costs. The chief executive of Hitachi Corporation's portable computer division has said (Markoff 1996) that "Speed is God, and time is the devil." The importance of speed in the automotive industry's new product design and development processes has also been emphasized (Reitman and Simpson 1995). Ford, Honda, and Toyota have all targeted approximately 33 percent reductions in their cycle times from concept approval to production. Clearly, managing for quality in the R&D processes can simultaneously reduce cycle times and costs. At a Shell 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 dollars of cost reductions were realized over a 4-year period while new products were pushed out faster, and with lower costs. An early project, which addressed reducing 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.

The Missions of Research and Development. In order to manage the research function and development processes, it is critical to define and understand their respective missions. To help distinguish among various types of research and development activities, the Industrial Research Institute (1996) has 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 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 Total Quality Management (TQM) is to improve key processes which result in "products" which are "fit for use" by an organization's internal and external customers. In support of this perspective, Nussbaum (1997) has stated: "At the leading edge of design is the transformation of the industry to one that focuses on process as well as product." Similarly, Himmelfarb (1996a) has suggested 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) has 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 section, product will be used to denote the final or intermediary 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 which result from the application of the knowledge and technology. For example, a likely output of a research project is a report containing the conclusions stemming from the project. 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 experimental design. Correspondingly, likely intermediate outputs of the development process are physical models, prototypes, or minutes from design review meetings.

Processes of Research and Development. Examples of key research processes identified and improved at Eastman Chemical Company have been provided by Holmes and McClaskey (1994): business unit organization interaction, needs validation and revalidation, concept development, technology transfer, and project management. Figure 19.1, from Holmes and McClaskey (1994), is a macrolevel process map of Eastman Chemical Company's "Innovation" process. Steps 1 to 4 represent the macrolevel research activities which generate the "new or improved product and process concept" stemming from step 4. The last step is the macrolevel development process which 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) has 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."

The flowchart in Figure 19.2, from Boath (1993), represents the results of "reengineering" of an organization's new product development process.

The new process led to a 25 percent increase in efficiency in "resource utilization." At IBM Rochester, Rocca (1991) reported that after the organization redesigned its product development process from a *sequential* progression of activities to *overlapping* planning, design, and development activities, it essentially halved development times. Wheelwright and Clark (1992) compare the phased development processes of Kodak, General Electric, and Motorola and relate them to the organizations' development *strategies.* Himmelfarb (1992) has named this overlapping multifunctional process concept "fast parallel new product development," and provides examples of use and benefits at Deere, Eaton, AT&T, Hewlett-Packard, Motorola, and NCR. Himmelfarb (1992) and Iizuka (1987) both stress the importance of understanding the "as is" development process and specific responsibilities within the process. Iizuka states: "The most important factor in building quality into a process is to define the process clearly…[and to show] what each department should do at every stage of the process."

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

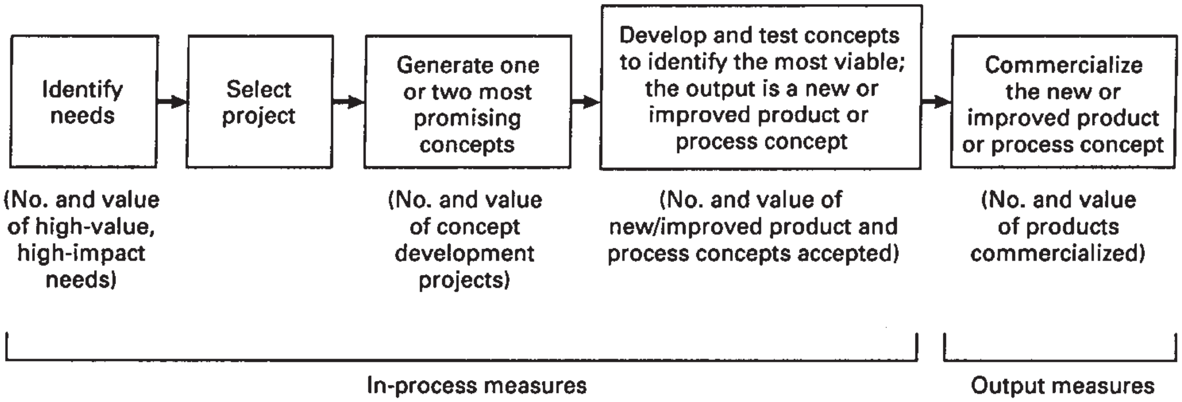


FIGURE 19.1 Eastman Chemical's innovation process (*Holmes and McClaskey 1994.*)

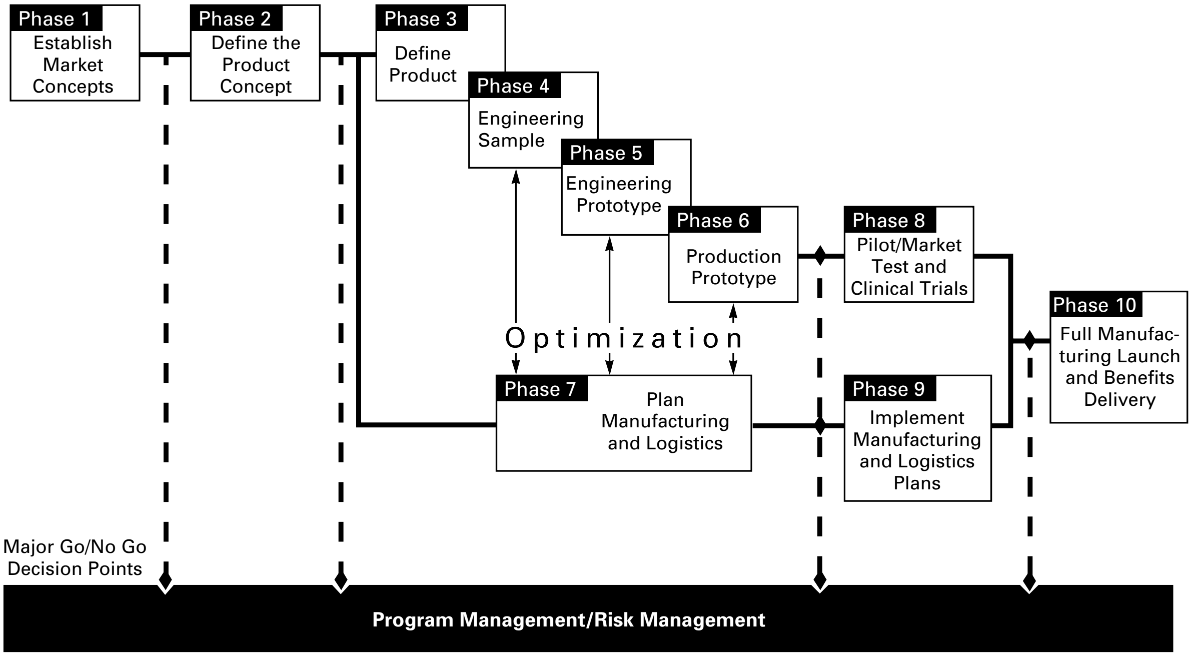


FIGURE 19.2 A new product development process. (*Boath 1993.*)

nine-step process depicted in Figure 19.3 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 19.1

Another example of new service product development process improvement was presented by Swanson (1995) of the Educational Testing Service organization. He discusses dividing the business process reengineering project into three phases: data collection and assessment, best practices investigation, and process design. In the data collection and assessment phase, the reengineering team used past projects and customer perception data to identify and prioritize improvement opportunities. During investigation of best practices, the team used the prioritized problem list as a basis for uncovering "a wealth of data on sound product development practices and grounded the redesign in the current state of the art." During the design phase, the best practices for the current problems were integrated within the new process, and an implementation plan was developed. The total reengineering project spanned a period of $6\frac{1}{2}$ months and was expected to reduce cycle times by 70 percent and development cost by 60 percent. Himmelfarb (1996b) provides additional examples of new product development in service industries.

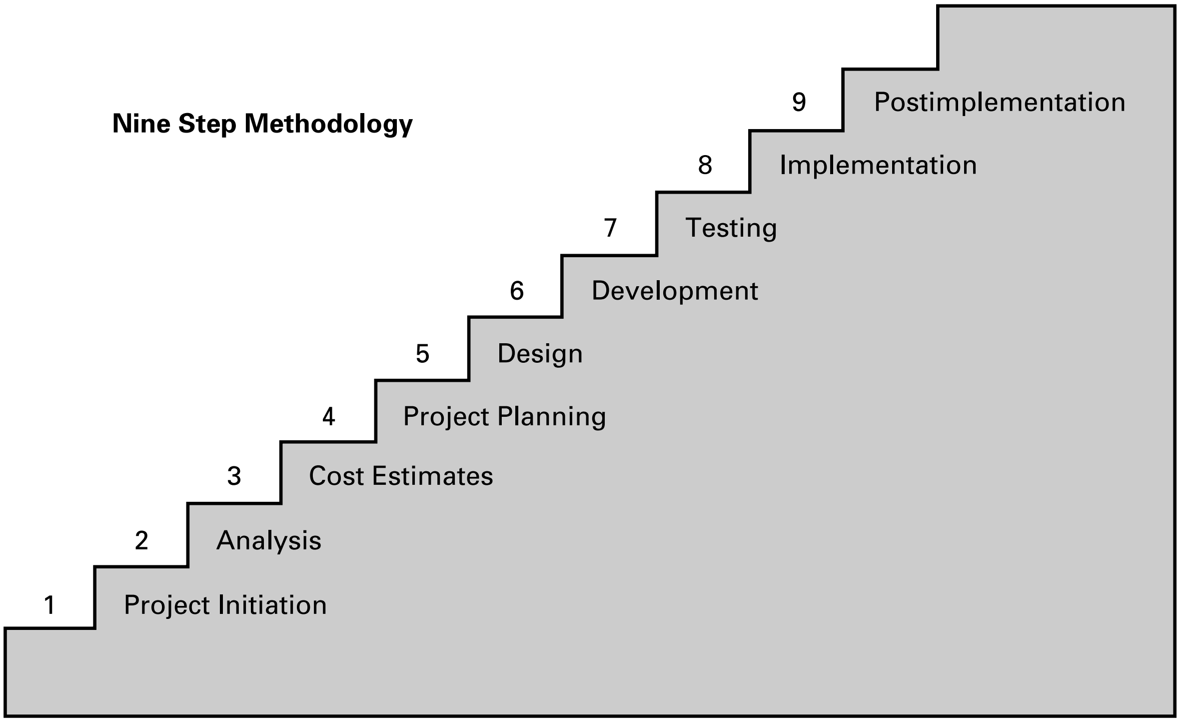


FIGURE 19.3 Merrill Lynch Insurance Group Services project planning and development process. (*Raven 1996.*)

DEFINING QUALITY FOR RESEARCH AND DEVELOPMENT

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). General Electric (Garfinkel 1990) 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) defined 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 hence 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," e.g., having to reissue a section of a progress report because of using a wrong formula or having to redo an experiment because an audit revealed that reference samples had been contaminated.

Combining these perspectives, research quality is defined as *the extent to which the features of the information and knowledge provided by the research function meet users' requirements.*

Defining Development Process Quality. The primary result of development is new or improved products and processes. The quality of a development process will be defined as *the extent to which the development process efficiently provides process and product features capable of repeatedly meeting their targeted design goals, e.g., for costs, safety, and performance.*

TABLE 19.1 Activities within Steps of Merrill Lynch Insurance Group Services Project Planning and Development Process

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, policy 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).

Resultant product and process features must be thought of from the perspective of “big Q” thinking. Port (1996) discusses the growing importance of environmentally friendly products and processes. Regulators are compelling designers to address such issues as the German ordinance requiring manufacturers to assure the disposibility of all packaging used in product transport, and, in the Netherlands, the rule that manufacturers must accept old or broken appliances for recycling.

Deficiencies (and hence 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 while 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 which caused this near catastrophe would have been precluded had those practices complied with the requirements of ISO 9000. (See Section 11 for discussion of the ISO 9000 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). Perry and Westwood (1991) measured the quality of Blount's development process by the extent to which technical targets are met, e.g., "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

Identifying and Addressing Barriers. To successfully plan for and utilize 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 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."

For development personnel, Gryna (1988) discusses the importance of placing product developers in a state of "self-control." (See Section 22, Operations, 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 19.2 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) have 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 and by

TABLE 19.2 A Self-Control Checklist for Designers

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 designers' 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?

> 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 (1992b): "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 Research and Development Quality. Several R&D organizations have developed structures which facilitate the attainment of their goals for improving customer satisfaction and reducing the costs of poor quality. 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) has 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 19.4, from Menger (1993), portrays the organization structure and process used to track and improve performance.

Figure 19.5, presented by Hildreth (1993), is a structure used to manage key business processes e.g., clinical research, development, product transfer in manufacturing, in R&D at Lederle-Praxis Biologicals. (See Section 6 for further discussion of managing key business process quality.) The Executive Quality Council is supported by a Business Process Quality Management (BPQM) Council and site-specific quality councils.

In addition to organization structure, other elements of infrastructure required to perpetuate R&D quality initiatives are training, councils, teams, facilitators, measurement, and rewards and recognition.

Training for Quality in Research and Development. Before managers or researchers can lead and 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

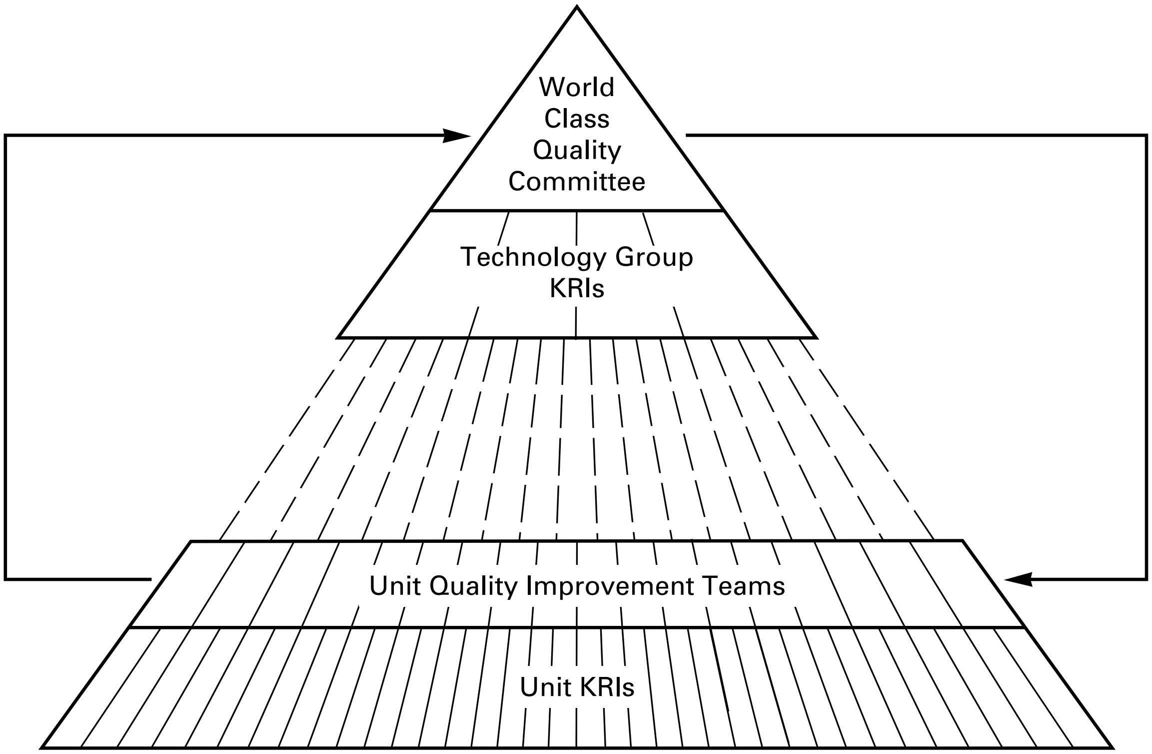


FIGURE 19.4 Corning's Technology Group quality organization and KRI improvement process. (*Menger 1993, p. 1-14.*)

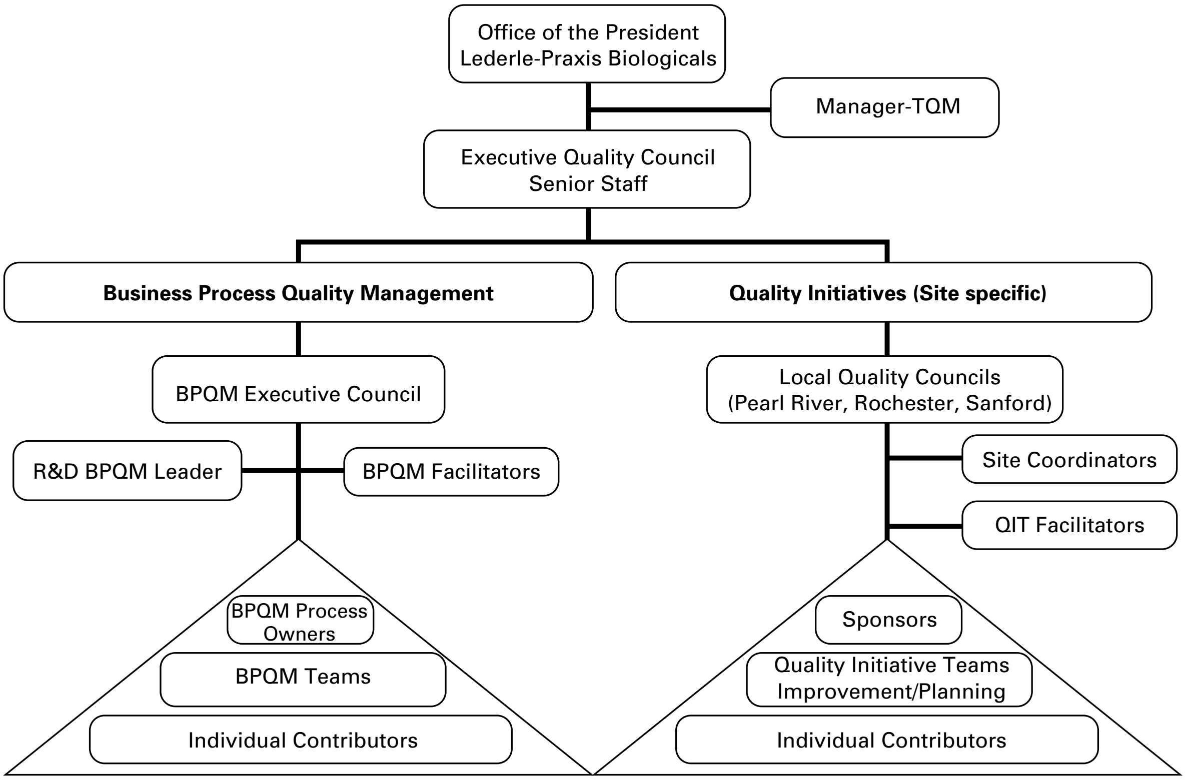


FIGURE 19.5 BPQM and site quality councils. (*Hildreth 1993, p. 2A-14.*)

based upon real problems that "Bell Labs engineers have had.…" Training designers in modern technology can yield significant paybacks. At Perkin-Elmer, DeFeo (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 Arnold Engineering Development Center, Arnold Air Force Base, concluded that teams whose 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.

Determining 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. The utility and types of measures for R&D process and product quality can be viewed from several perspectives. Gendason and Brown (1993) have 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 `down trend' meaningful; and one must be able to define a goal value for the metric." Endres (1997) has classified measures with respect to *timeliness, application,* and *completeness.*

Measures: Timeliness. Traditional measures for research quality have been lagging indicators, in that they report on what the research organization has already accomplished. 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 has discussed GE's use of patents granted per million dollars invested in research as a benchmarking performance measurement.

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, e.g., installation. Goldstein (1990) has suggested similar measures for design quality e.g., tracking the ratio of design corrective changes to the total number of drawings released for each new product.

Examples of *concurrent* indicators are the results of *peer reviews* and *design reviews.* Roberts (1990) discusses peer reviews used to verify progress by checking calculations, test data reduction, and research reports. Bodnarczuk (1991) provides insights into the nature of peer reviews in basic research at Fermi National Accelerator Laboratory.

Hiller (1986) at Electrolux AB in Stockholm, Sweden defines design review as "a documented review of a production project which is carried out at predetermined times and with participants who have backgrounds and experience different from those which the originator of the design could be expected to have." Hiller identifies, in the context of a phase-gated development process, four types of design reviews:

1. Preliminary (for specifications, drawings, early model)
2. Intermediate (for prototype test results)

3. Final (for prepilot lots and beta test results)
4. Production (for pilot lot products from production tools)

Gryna (1988) provides guidelines for structuring design reviews. Gryna provided Table 19.3 (adapted from Jacobs 1967) which summarizes design review team membership and responsibilities.

Kapur (1996) provides a similar design review responsibility matrix for a six-phase product design cycle. 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 outcomes of research and development processes. For example, Cole (1990) of Kodak presented Figure 19.6, which demonstrates the relationship between compliance scores during the product development projects and the length of the development cycle. There is an obvious correlation, which may be useful in identifying the major contributing factors (within the scoring system) to protracted development cycles.

A similar approach has been discussed by Rajasekera (1990) at Bell Laboratories. Rajasekera has provided a list of what he has identified as key quality driver issues in an industrial research laboratory:

1. Project mission
2. Top management support
3. Project schedule/plan
4. Client consultation
5. Personnel involved
6. Technical tasks
7. Client acceptance
8. Monitoring and feedback
9. Communication
10. Troubleshooting

and also provides an associated scoring mechanism to monitor project quality during each stage of the project.

An additional leading indicator for research effectiveness used by Holmes and McClaskey (1994) at Eastman Chemical is the estimated net present value of new/improved concepts accepted (by business units for products, and manufacturing departments for processes) for commercialization. Figure 19.7 from Endres (1997) demonstrates that the effect of implementing TQM in Eastman Chemical Research virtually doubled research's productivity.

Measures: Applications. In addition to viewing each R&D measure (or measurement process, e.g., peer review) with respect to timeliness, it is also helpful to examine each 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 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 (Section 2, How to Think about 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

TABLE 19.3 Design Review Team Membership and Responsibility

		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	Assures 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 voices opinion as to acceptability of design and may request further investigation on specific items			X

* P = Preliminary; I = Intermediate; F = Final.
Source: Gryna (1988), adapted from Jacobs (1967).

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.”

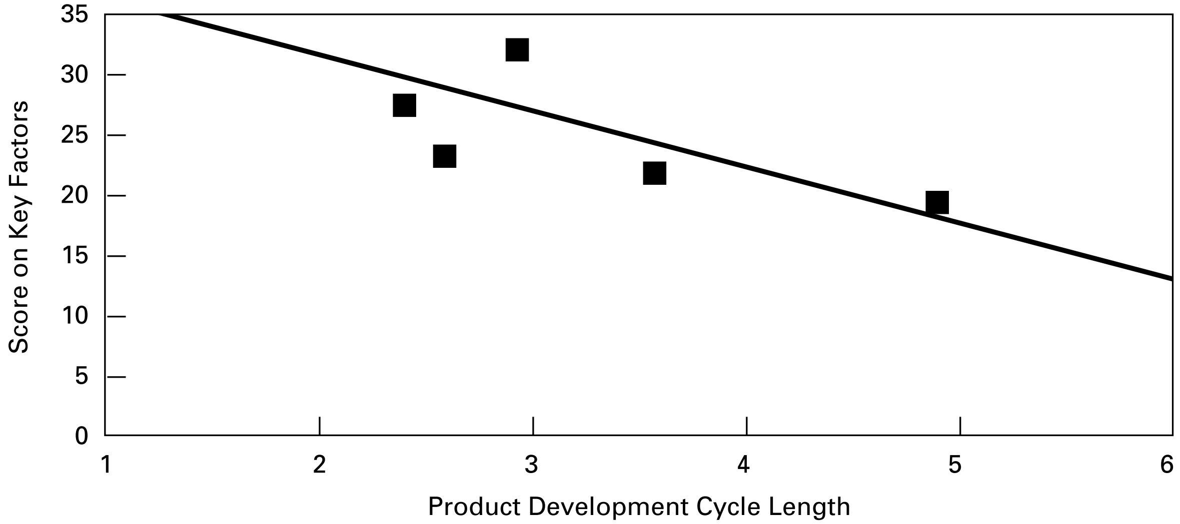


FIGURE 19.6 Correlation between development process compliance scores and cycle times at Kodak. (*Cole 1990.*)

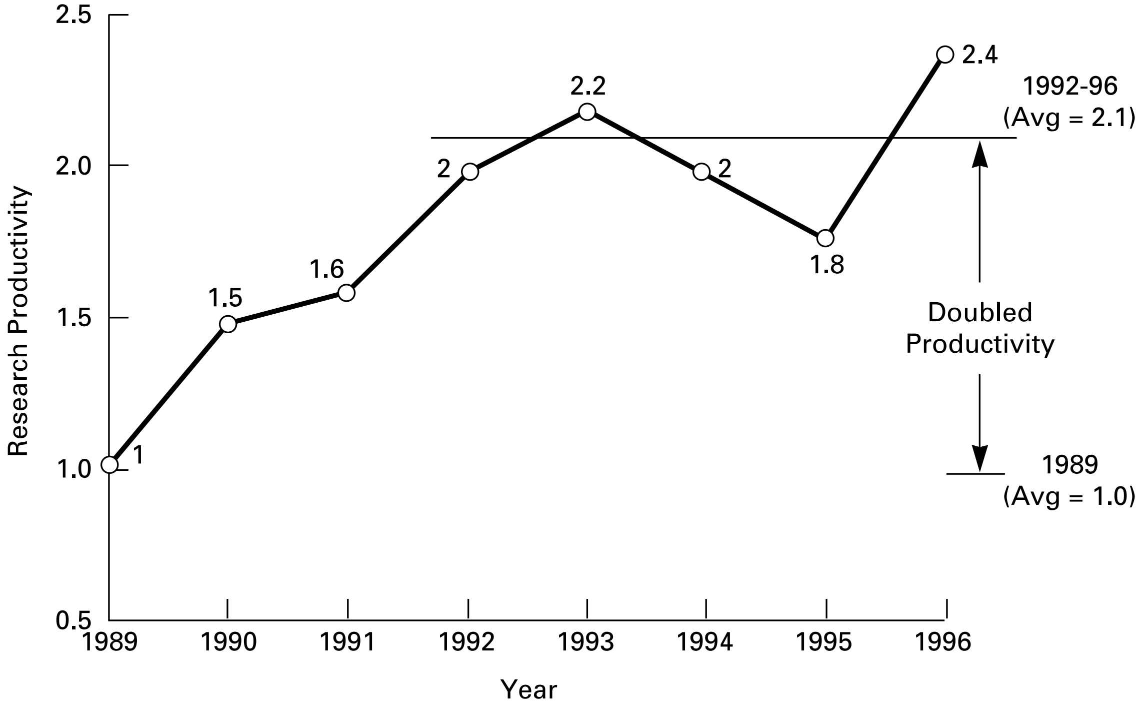


FIGURE 19.7 Eastman Chemical Research productivity as a ratio of 1989 NPV of improved concepts accepted and commercialized with major research input divided by total research expenditures. (*Endres 1997.*)

Figure 19.8 represents, at a macro level, the features of the process commonly used by the best-practice companies for R&D portfolio planning and review.

Among the organizations identified "for their exemplary R&D decision quality" practices were 3M, Merck, Hewlett-Packard, General Electric, Procter & Gamble, Microsoft, and Intel. 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:

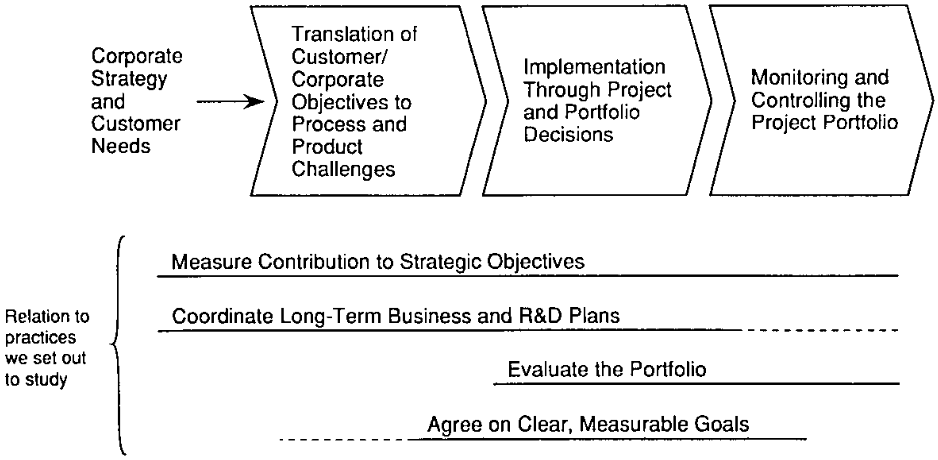


FIGURE 19.8 Common process for implementing best practices for R&D planning, implementation, and review. (*Lander et al. 1994, p. 3-14.*)

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 must also define and implement methods for improving their customers' satisfaction levels and their process's efficiencies. Ferm et al. (1993) also discuss the use of business unit surveys at AlliedSignal'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, the Laboratory management gave the same survey to Laboratory employees. The resulting data enabled comparison of 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.

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

1. Percentage of agreed-upon deliverables delivered
2. Percentage of technical results achieved
3. Results of customer satisfaction survey

Measures: 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) have identified the need for a comprehensive hierarchy of measures. Figure 19.9, from 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) defines the KRIs for the Technology Group. General areas for improvement and measurement used are

1. Cycle time
2. Productivity
3. Customer satisfaction
4. Employee satisfaction

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 provide 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. Juran

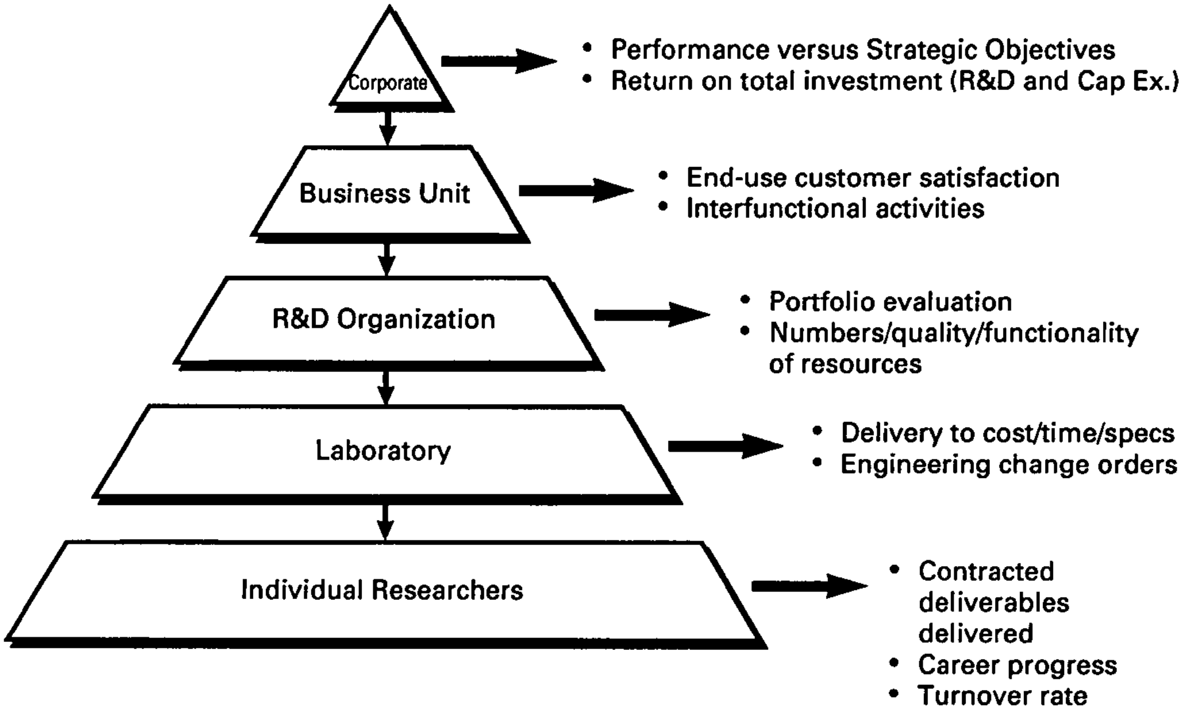


FIGURE 19.9 Boath's pyramid of R&D measures. (*Boath 1992, p. 2-4-4.*)

and Gryna (1993) have defined the benefits of determining the broad overall status of quality in organizations. This process has been defined as quality assessment. Quality assessment comprises:

1. Customer-based quality measurement
2. Quality culture review
3. Cost of poor quality determination
4. Quality system review

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 Eastman Research had determined that though 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 personnel that determined that although communications had improved:

1. Few process improvements had been implemented.
2. Most first-level managers and individual researchers saw nothing beneficial from the quality initiative.
3. 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 19.7.

Cost of poor quality has been discussed generally by Gryna (see Section 8, Quality and Costs). 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 the ISO 9000 standards. In Section 14, Total Quality Management, Godfrey provides insight into the use and benefits of the Baldrige National Quality Award. In Section 11, The ISO 9000 Family of International Standards, Marquardt 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) has 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) 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 VP 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.

McClaskey (1992) discusses how the Baldrige criteria were used at Eastman Chemical Company to accelerate the rate of performance in research, and provides guidelines effectively translating the criteria into action. One example is: "Give awards for both improvement as well as level [of quality]." Endres (1997) provides additional material from McClaskey's paper.

In Section 14, Total Quality Management, Godfrey provides additional insights into the way organizations use the Baldrige criteria.

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 too complex for beginning their quality journey. The pervasive preference for the ISO 9000 quality system standards over the Baldrige criteria can be attributed to the fact that their 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 has 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 19.4 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.

TABLE 19.4 ISO 9001 Elements for AT&T's TSBU R&D Units

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 indentification 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.

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 suggest 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."

OPERATIONAL QUALITY PLANNING FOR RESEARCH AND DEVELOPMENT

Quality Planning: Concepts and Tools for Design and Development. The focus of the following materials is to provide examples of methodology and tools which support the implementation of Juran's operational quality planning process within the design and development process.

Operational Quality Planning Tools. As discussed in Section 3, 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 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: QFD not only ensures customer satisfaction with a quality product or service, but reduces development time, start-up costs, and expensive after-the-fact design changes. It's also a useful political tool, since it guarantees that all affected parts of the organization are members of the QFD team.

Designing for Human Factors: Ergonomics and Errorproofing. 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 the limitations of operators and delivery personnel. They must also consider the possible types of errors that may be committed during operations and use. Ergonomics or "human engineering" is used to address the needs and limitations of operators, service providers, and the customers. 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.

In contrast with planning for ease of assembly, installation, and use, poka-yoke (pronounced POH-kah YOH-kay) is a methodology for preventing, or correcting errors as soon as possible. The term's English translation is "prevent inadvertent mistake." Poka-yoke was developed by Shigeo Shingo, a Japanese manufacturing engineer. The "MfgNet" Internet newsletter (the WEB site address is http://www.mfgnet.com/poka-yoke.html) provides an example from Varian Associates, a semiconductor equipment manufacturer. Varian had previously placed blame for machine assembly and field installation and service problems on its assemblers and service personnel respectively. Using poka-yoke concepts, designs for new high-current ion-implanter equipment have been targeted so that they can be assembled, installed, and serviced in "only one way—the right way.…" For example, in production, poka-yoke was used to ensure that correct alignment of a key assembly, "called a manipulator, which focuses an ion beam," is assured with the "use of holes tapped in the aluminum and graphite assembly." Similarly, "the design of an implanter's front door prevents it from being assembled in any way but the correct one." The *Mistake-Proofing Workshop Participant's Manual* (1995) provides a list of seven steps for developing poka-yoke devices. J. Grout provides multiple cases, examples (with illustrative photographs), and references for poka-yoke concepts. One example provided by Grout is the design of the 3.5-in computer "floppy disk." The disk's beveled corner design permits it to be inserted into a computer only by correctly orienting it. (The Web site address for accessing Grout's poka-yoke information is http://www.Cox.smu.edu/jgrout/pokayoke.html#read.) Kohoutek (1996b) also discusses "human-centered" design and presents approaches and references for predicting human error rates for given activities.

Designing for Reliability, Maintainability, and Availability

Designing for Reliability. A product feature that customers require for products is reliability. Juran and Gryna (1993) have defined reliability as 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. MIL-STD-721C (1981), Notice 1, *Definition of Terms for Reliability and Maintainability,* and MIL-STD-2074 (1978), *Failure Classification for Reliability Testing,* provide additional definitions and classification information. An excellent source for many terms used in quality management is ISO 8402 (1994), *Quality Management and Quality Assurance—Vocabulary.* International sources for obtaining ISO Standards are listed on the International Organization for Standardization's Web site: http://www.hike.te.chiba-u.ac.jp/Acadia/ISO/home.html. Rees (1992) also discusses the importance of identifying and defining the intended purpose of the application and test procedure *prior to* defining failures.

The following materials will describe approaches and tools for "designing in" reliability. (Section 48 provides information on reliability concepts and the use of statistical tools for *analyzing* reliability data emanating from design tests and field failure data.) MIL-STD-785B, Notice 2, *Reliability Program for Systems and Equipment,* provides both general reliability program requirements and required specific tasks. Major program elements discussed by Juran and Gryna (1993) are

1. Setting reliability goals
2. Reliability modeling
3. Apportioning the reliability goals
4. Stress analysis
5. Reliability prediction
6. Failure mode and effects analysis
7. Identification of critical parts
8. Design review
9. Supplier selection
10. Control of reliability in manufacturing
11. Reliability testing
12. Failure reporting and corrective action

Section 18 discusses market research for identifying quality and reliability goals. Standinger (1990) discusses using competitive benchmarking and Weibull distributions for establishing reliability goals for products during the infant mortality, random failure, and wear-out phases for a new product's life cycle. Table 19.5, from Juran and Gryna (1993), provides typical indicators for reliability performance for which specific numerical goals may be established.

As seen earlier, 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. Section 21 discusses the management of supplier performance. The effect of manufacturing processes on reliability must be addressed during process design selection and implementation. Section 22, Operations, provides guidance for controlling quality and reliability during manufacturing.

Juran and Gryna (1993) divide the process of reliability quantification into the three phases: apportionment, prediction, and analysis. Reliability apportionment is the process used to divide and allocate the design's overall reliability goal among its major subsystems and then to their components. Reliability prediction is the process of using reliability modeling and actual past performance data to predict reliability for expected operating conditions and duty cycles. Reliability analysis utilizes the results of reliability predictions to identify opportunities for improving either predicted or actual reliability performance.

Reliability Apportionment. The top two sections in Table 19.6, from Juran and Gryna (1993), provide an example of reliability apportionment. A missile system's reliability goal of 95 percent for 1.45 hours must be 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 apportioned to its three components. The allocation for the fusing circuitry is 0.998 or, in terms of mean time between failures, 725 hours.

TABLE 19.5 Typical Reliability Indicators

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
Repairs/100	Number of repairs per 100 operating hours

Source: Juran and Gryna (1993), p. 262.

TABLE 19.6 An Example of Reliability Apportionment And Prediction

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-shot	0.999	0.001	1/1000 operations
Warhead	One-shot	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
			71.51

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

*For a mission time of 1.45 h.

Source: Juran and Gryna (1993), adapted from G. N. Beaton (1959). “Putting the R&D Reliability Dollar to Work,” *Proceedings of the Fifth National Symposium on Reliability and Quality Control,* IEEE, New York, p. 65.

Kohoutek (1996a) 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 also discusses the use of reliability policies to support goal setting and improvement for both individual products and product families.

Reliability Modeling, Prediction, Analysis, and Improvement. In general, before a prediction of reliability can be made, a model of the system must be constructed, stress levels for the model’s components be determined, and, on the basis of the estimated stress levels, failure rates for the components be obtained and used to estimate the reliability of subsystems and systems. Turmel and Gartz (1997) provide a layout for an “item quality plan” which includes the part’s critical characteristics and specification limits. It 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.

Reliability Modeling. In order to construct a model for reliability prediction, the interrelationships among the system's subsystems and their components must be understood. Gryna (1988) suggests the following steps to developing reliability models and using them for reliability prediction:

1. *Define the product:* 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 19.10) which shows the subsystems and lower-level products, their interrelation, and the interfaces with other systems. For large 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, the conditions which 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 assure that important items are neither neglected nor considered more than once. For example, a switch used to connect two units must be classified as belonging to one unit or the other (or as a separate unit.)

2. *Develop a reliability block diagram:* The reliability block diagram (Figure 19.11) is similar to the functional block diagram, but it is modified to emphasize those aspects which influence reliability. The diagram shows, in sequence, those elements which must function for successful operation of each unit. Redundant paths and alternative modes should be clearly shown. Elements which 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 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. *List factors relevant to reliability:* These factors include part function, tolerances, part ratings, internal environments and stresses, and duty (on time) cycles. This detailed information makes

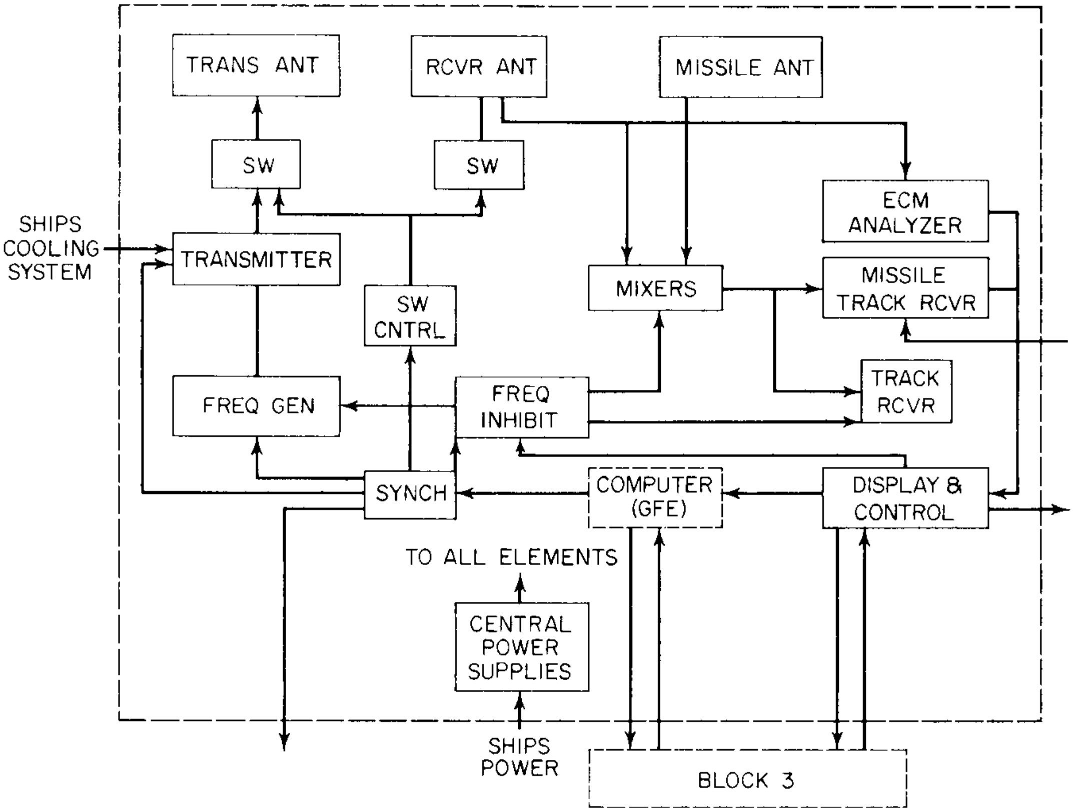


FIGURE 19.10 Functional block diagram. (*From Handbook of Reliability Engineering, NAVAIR 00-65-502, courtesy the Commander, Naval Air Systems Command.*)

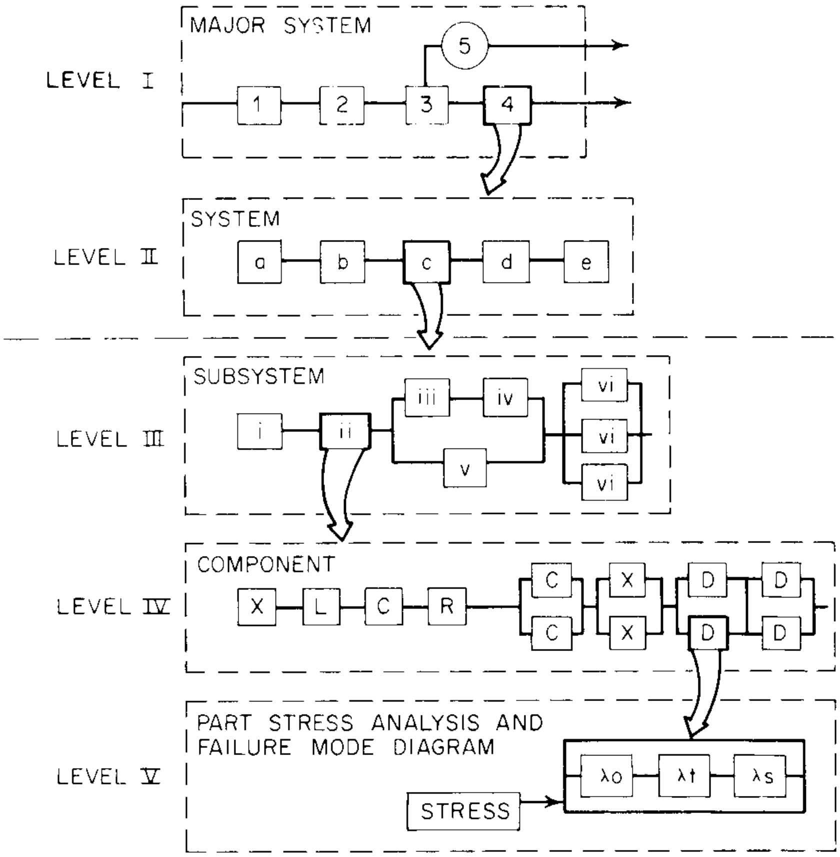


FIGURE 19.11 Reliability block diagram. (*From Handbook of Reliability Engineering, NAVAIR 00-65-502, courtesy the Commander, Naval Air Systems Command.*)

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. (A methodology used by designers to improve part and product ability to perform in various environments is called "robust design." Phadke (1989) and Taguchi (1995) provide approaches and examples.) Parts with dependent failure probabilities should be grouped together into modules so that the assumptions upon which the prediction is based are satisfied.

4. *Determine part 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, since there is no single reliability data bank comparable to handbooks such as those which 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 data banks such as MIL-HDBK-217F, which contains component failure rate data and curves for various components' operating environments and stress levels. The handbook also provides examples of reliability prediction procedures appropriate for various stages of the design's evolution.

5. *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.

6. *Determine block and subsystem failure rates:* The failure rate data obtained in step 4 or 5 are used to calculate failure rates for the higher-level systems and the total system. (Pertinent subsystem or assembly correction factors, such as those determined for the effects of preventive maintenance, should also be applied.)

7. *Determine the appropriate reliability unit of measure:* This is the choice of the reliability index or indicators as listed in Table 19.5

8. *Use the reliability model and predictions* to identify the design's "weak points" and the required actions and responsibilities for reliability improvement.

Reliability Prediction. The bottom portion of Table 19.6 provides an example of predicting, for known part counts, the failure rates for each component of the fusing circuitry. 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 per/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 hours requirement for the fusing circuitry. MIL-HDBK-217F (1991), Notice 2, Reliability Prediction of Electronic Equipment, provides formulas for estimating failure rates for classes of electronic parts and microcircuits in various operating environments. Additional sources of reliability data from Air Force databases, Navy databases, and Army databases are available in the Reliability Engineer's Toolkit (1993) available as ADA278215 from the National Technical Information Service in Springfield, VA. (The latter reference also provides sources forreliability prediction software programs.) The Government Industry Data Exchange Program (GIDEP) provides an on-line menu for accessing a data bank for reliability and maintainability data and information, and provides participants with alerts for known part problems. GIDEP may be contacted at: GIDEP Operations Center, Corona, CA 91718-8000 or on the World Wide Web at www.gidep.corona.navy.mil/data_inf/opscntr.htm.

Reliability Analysis

FAILURE MODE, EFFECT, AND CRITICALITY ANALYSIS; FAULT TREE ANALYSIS. In planning for reliability, the engineer's analysis of the expected effects of operating conditions on design reliability and safety are often enhanced by use of failure mode effect and criticality analysis (FMECA) and fault tree analysis (FTA). General introductions to failure mode effects analysis (FMEA), FMECA, and FTA are provided in Section 48. FMEA and FMECA are intended for use by product and process designers in identifying and addressing potential failure modes and their effects. Figure 19.12, from Gryna (1988), 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. MIL-STD-1629A, (1984) Notice 2, Procedures for Performing a Failure Mode, Effects, and Criticality Analysis, provides, with examples, additional details on developing severity classifications and criticality numbers.

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. Figure 19.13, from 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 symbol with a straight bottom is an "and gate," meaning the output occurs only if all input events below 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 below 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. In Section 48, Reliability Concepts and Data Analysis, Meeker et al. cite Hoyland and Rausand (1994) and Lewis

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

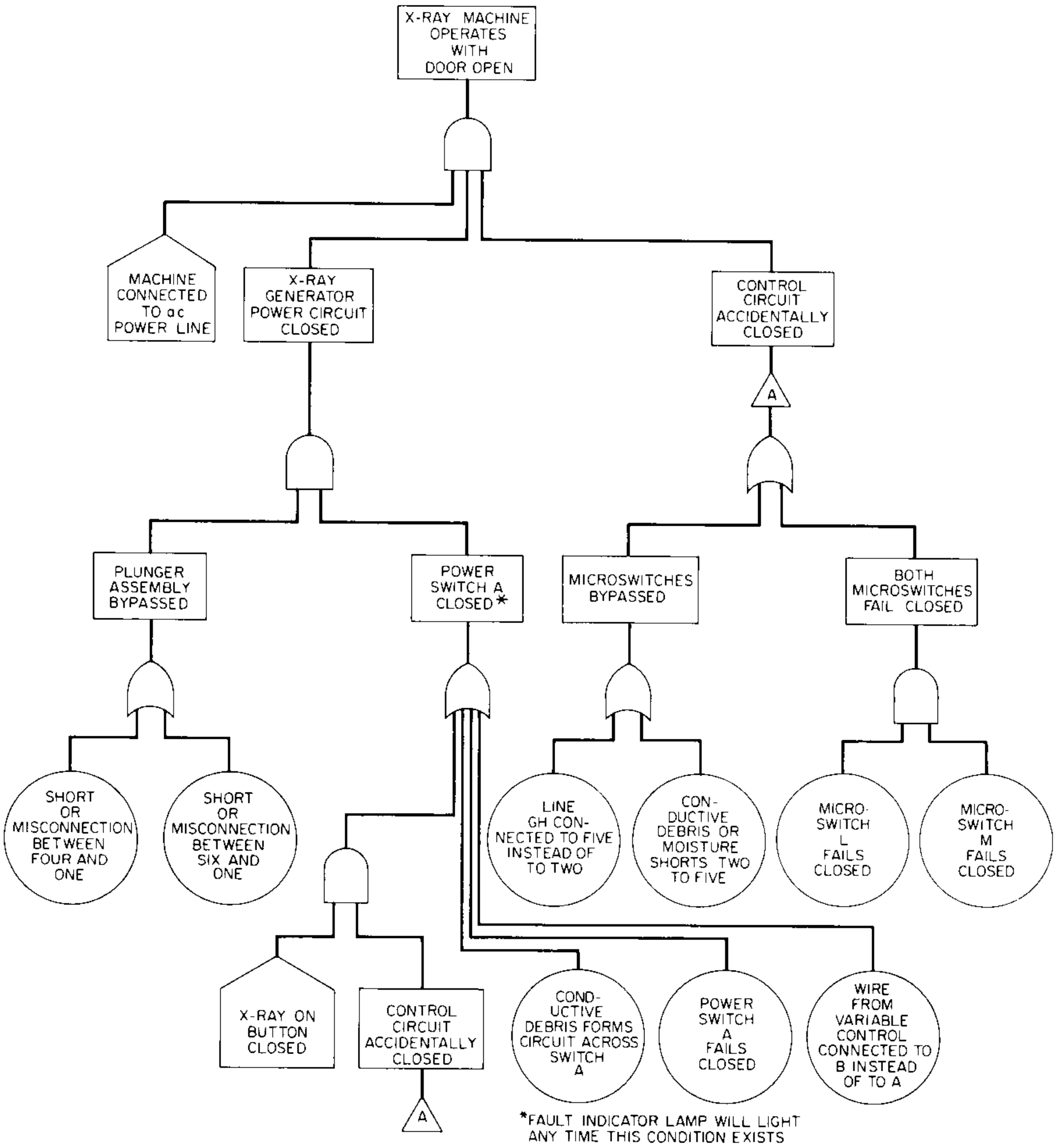
FIGURE 19.12 Failure mode, effect, and criticality analysis. (*Gryna 1988, from Hammer 1980.*)

(1996) as providing examples which include calculations for event probabilities. 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. In Section 48 Meeker et al. provide references for computer software for facilitating FMEA/FMECA and FTA analyses.

OTHER FAILURE ANALYSIS PREDICTION TECHNIQUES. Other analytical techniques have been developed to aid in analyzing possible causes of product failures. The Transactions on Reliability of the Institute of Electrical and Electronics Engineers is a good source of information on such techniques. Worst-case analysis, statistical tolerancing, and sneak-circuit analysis will be highlighted.

"Worst-case" analysis, often facilitated via computer software, is a detailed environmental analysis. The purpose is to identify the conditions under which maximum stresses will be placed on components/circuits, and to verify the ability of the product to meet its goals when subjected to extremes, or highly probable combinations of electrical and physical conditions.

Although worst-case analysis is useful for identifying which combinations of conditions will produce the most severe environments (or interferences for mechanical assemblies), it does not consider the probability that these combinations will actually occur. Under varying sets of assumptions, statistical tolerancing can be used to estimate the actual probabilities of the worst-case conditions. These estimates can then be used by designers to decide on trade-offs of tolerance versus cost. Statistical tolerancing decisions generally result in allowing larger component tolerances. Dudewicz (1988) discusses statistical tolerancing and provides guidelines and examples for comparison with worst-case tolerance analysis. See Section 45 under "Statistical Estimation, Tolerance Intervals. MIL-STD-785B, (1988), Notice 2, provides additional information.



*FAULT INDICATOR LAMP WILL LIGHT ANY TIME THIS CONDITION EXISTS

FIGURE 19.13 Fault-tree analysis of an interlock safety circuit. (*Gryna 1988.*)

In the analysis of electrical circuits, sneak-circuit analysis is similar to worst-case analysis and is a valuable supplement to it. Sneak-circuit analysis is usually performed by computer software to identify latent paths in a circuit which could cause the occurrence of unanticipated and unwanted functions which could prevent or degrade desired performance, *even with all components functioning properly.* Rome Laboratory's *Reliability Engineer's Toolkit* (1993) provides an example and identifies some available software.

Reliability Improvement. The general approach to quality improvement (see Section 5, The Quality Improvement Process) 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 indicate 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 redundancy
n = number of identical redundant elements

Figure 19.14 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.)

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. Juran and Gryna (1993) 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.

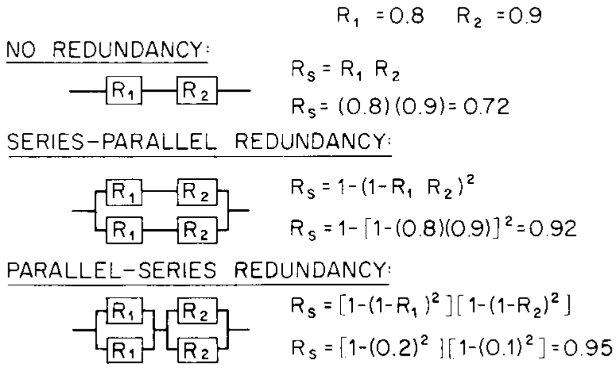


FIGURE 19.14 Series-parallel and parallel-series redundance. (*Gryna 1988.*)

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 which 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," 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." *Proceedings of the Annual Meeting on Reliability Physics,* sponsored by the Institute of Electrical and Electronic Engineers, Inc., is an excellent reference.

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. Designers must therefore also address 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.

A formal definition of maintainability is provided by MIL-STD-721C (1981):

> The measure of the ability of an item to be retained in or restored to specified condition when maintenance is performed by personnel having specified skill levels, using prescribed procedures and resources, at each prescribed level of maintenance and repair.

The definition emphasizes the distinction between maintainability, a *design* parameter, and maintenance, an *operational* activity.

Mean time to repair (MTTR) is an index used for quantifying maintainability, analogous to the term MTBF used as an index for reliability. Table 19.7, from MIL-STD-721C (1981), summarizes 11 possible indexes for maintainability.

MIL-HDBK-472 (1984), *Maintainability Prediction of Electronic Equipment,* may be used to estimate maintainability for various design alternatives. Kowalski (1996) provides an example of allocating a system's maintainability requirement among its subsystems. The allocation is analogous to the method by which reliability was apportioned (See above under Reliability Apportionment.). Kowalski also discusses the impact of *testability* on the ability to achieve maintainability goals. MIL-STD-2165A (1993), *Testability Program for Systems and Equipments,* defines testability as "a design characteristic which allows the status (operable, inoperable, or degraded) of an item to be determined and the isolation of faults within the item to be performed in a timely manner," and provides guidelines for testability planning and reviews. 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.

TABLE 19.7 Maintainability Figures of Merit

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).

Designing for Availability. Both design reliability and maintainability affect the probability of a product being available when required for use. 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" (A_i).

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

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

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

These formulas indicate that a 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. Gryna (1988) provides some specific trade-off decisions that should be considered by designers for increasing maintainability (decreasing diagnosis and repair times):

Modular versus nonmodular construction: Modular design requires added design effort but reduces the time required for diagnosis and remedy in the field. The fault need only be localized to the module level, after which the defective module is unplugged and replaced. This concept has been used by manufacturers of consumer products such as television sets.

Repair versus throwaway: For some products or modules, the cost of field repair exceeds the cost of making new units in the factory. In such cases, design for throwaway is an economic improvement in maintainability.

Built-in versus external test equipment: Built-in test capability reduces diagnostic time, but usually requires additional cost. 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.

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

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

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

For these conditions, O'Connor (1995) provides formulae 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.

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 those which emerge from the various applicable analyses: the 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 their 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, for each critical component, the nature of the critical features, and the plan for controlling and improving its performance. 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 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 which comprise configuration management:

Configuration identification: The process of defining and identifying every element of the product.

Configuration control: The process which manages a design change from the time of the original proposal for change through implementation of approved changes.

Configuration accounting: The process of recording the status of proposed changes and the implementation status of approved changes.

Configuration management is needed to help ensure:

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 assure that the resulting design can ultimately be manufactured, delivered, installed, and serviced to meet customers' requirements. To assure this, it is imperative to conduct actual tests on prototypes and pilot units prior to approval for full-scale manufacturing. Table 19.8 summarizes the various types and purposes of design evaluation tests.

In Section 48, Meeker et al. 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 Reliability Engineer's Toolkit* (1993) discusses the selection and use of reliability test plans from MIL-HDBK-781 (1987), *Reliability Test Methods, Plans and Environments for Engineering Development, Qualification and Production.*

Comparing Results of Field Failures with Accelerated Life Tests. In order to verify design reliability within feasible time frames, it is often necessary to "accelerate" failure modes by use of various environmental stress factors. 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. Gryna (1988) provides an example of using plots on probability paper to compare and relate test results to "field" failures. Figure 19.15 contains plots of the estimated cumulative failure percentages versus number of accelerated test days and actual field usage days for two air conditioner models. Since the two lines are essentially 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.

TABLE 19.8 Summary of Tests Used for Design Evaluation

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.

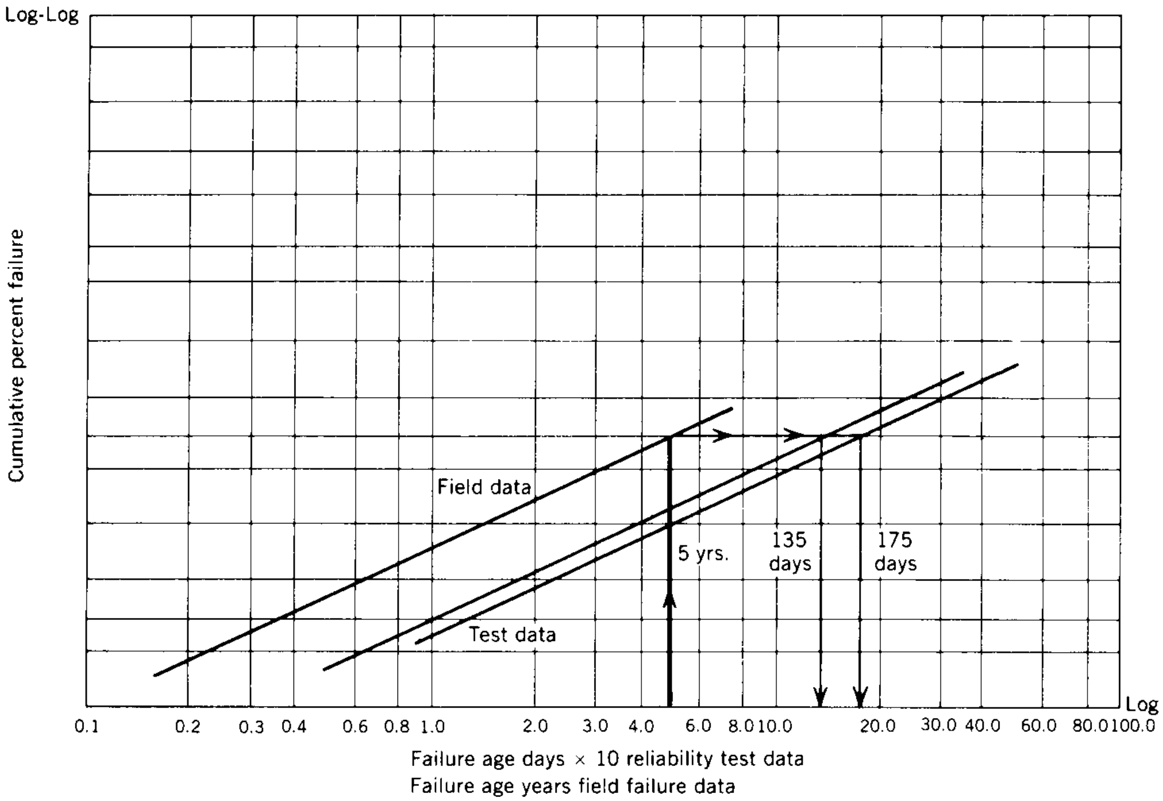


FIGURE 19.15 Weibull plot of accelerated test versus field failure data for two air conditioner models. (*Gryna 1988.*).

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, analyzing, and improving these design parameters. Many organizations call this process “failure reporting and corrective action systems” (FRACAS). Figure 19.16, reproduced from the *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.

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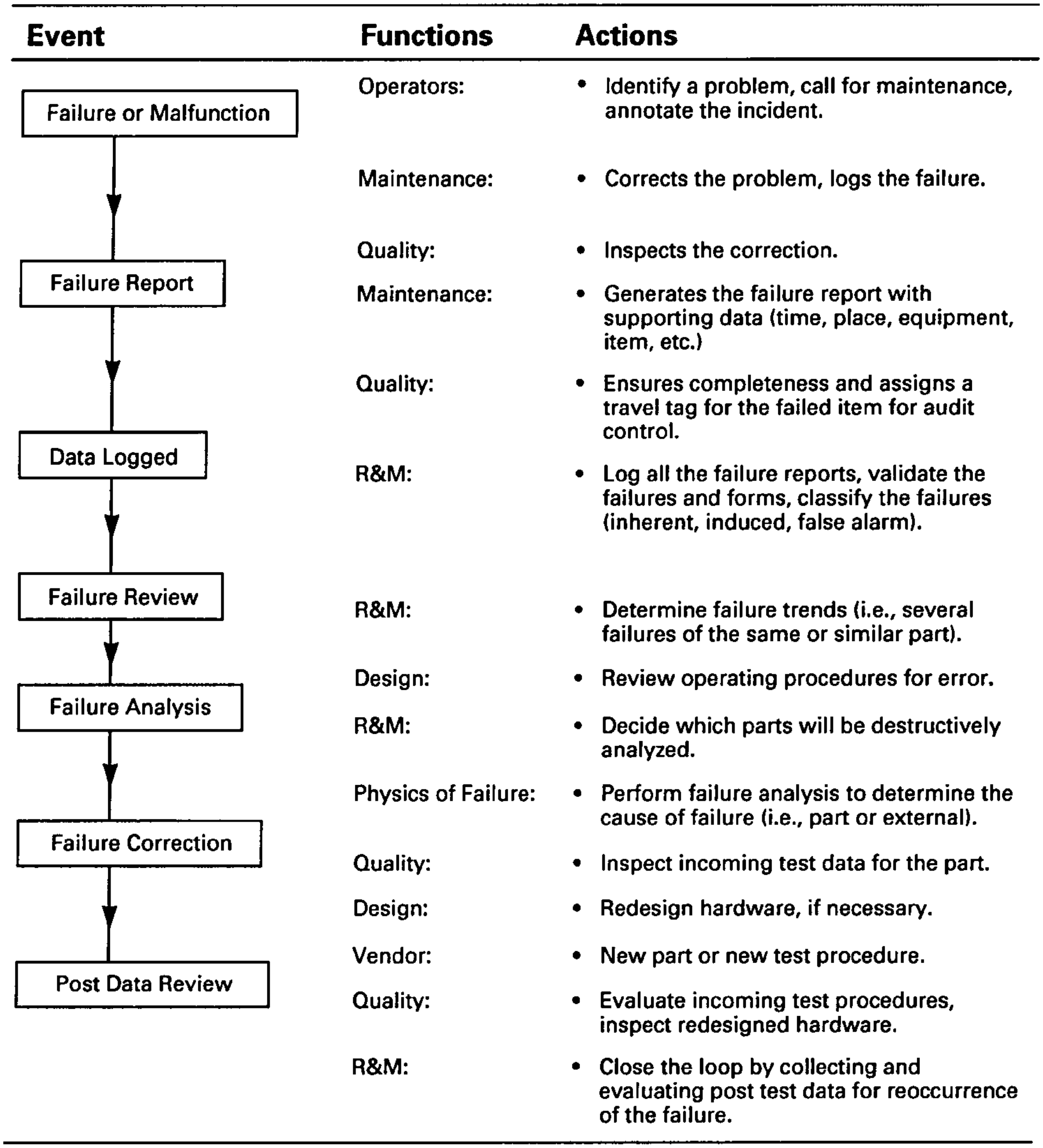

Event	Functions	Actions
Failure or Malfunction	Operators:	• Identify a problem, call for maintenance, annotate the incident.
	Maintenance:	• Corrects the problem, logs the failure.
	Quality:	• Inspects the correction.
Failure Report	Maintenance:	• Generates the failure report with supporting data (time, place, equipment, item, etc.)
	Quality:	• Ensures completeness and assigns a travel tag for the failed item for audit control.
Data Logged	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).
Failure Analysis	Design:	• Review operating procedures for error.
	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 necessary.
	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 19.16 FRACAS flow diagram. (*Reliability Engineer's Toolkit 1993.*)

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