REPORT OF SURVEY CONDUCTED AT

CALCE ELECTRONIC PRODUCTS AND SYSTEMS CENTER
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BEST MANUFACTURING PRACTICES CENTER OF EXCELLENCE
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Foreword

This report was produced by the Office of Naval Research's Best Manufacturing Practices (BMP) Program, a unique industry and government cooperative technology transfer effort that improves the competitiveness of America's industrial base both here and abroad. Our main goal at BMP is to increase the quality, reliability, and maintainability of goods produced by American firms. The primary objective toward this goal is simple: to identify best practices, document them, and then encourage industry and government to share information about them.

The BMP Program set out in 1985 to help businesses by identifying, researching, and promoting exceptional manufacturing practices, methods, and procedures in design, test, production, facilities, logistics, and management – all areas which are highlighted in the Department of Defense's 4245.7-M, *Transition from Development to Production* manual. By fostering the sharing of information across industry lines, BMP has become a resource in helping companies identify their weak areas and examine how other companies have improved similar situations. This sharing of ideas allows companies to learn from others' attempts and to avoid costly and time-consuming duplication.

BMP identifies and documents best practices by conducting in-depth, voluntary surveys such as this at CALCE Electronic Products and Systems Center in College Park, Maryland, conducted during the week of November 1, 2004. Teams of BMP experts work hand-in-hand on-site with the company to examine existing practices, uncover best practices, and identify areas for even better practices.

The final survey report, which details the findings, is distributed electronically and in hard copy to thousands of representatives from industry, government, and academia throughout the U.S. and Canada – *so the knowledge can be shared*. BMP also distributes this information through several interactive services which include CD-ROMs and a World Wide Web Home Page located on the Internet at http://www.bmpcoe.org. The actual exchange of detailed data is between companies at their discretion.

Established in 1986, the CALCE Electronic Products and Systems Center is recognized internationally as a founder, driving force, and leader in the development and implementation of physics-of-failure analysis and approaches to reliability and life-cycle prediction. Over the past 15 years, the CALCE Electronic Products and Systems Center has invested more than $50 Million in developing methodologies, models, and tools that address the design, manufacture, analysis, and management of electronic systems.

The BMP Program is committed to strengthening the U.S. industrial base. Survey findings in reports such as this on the CALCE Electronic Products and Systems Center expand BMP's contribution toward its goal of a stronger, more competitive, globally-minded, and environmentally-conscious American industrial program.

I encourage your participation and use of this unique resource.

Anne Marie T. SuPrise, Ph.D.
Director
Best Manufacturing Practices

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Report Summary

Background

The Computer-Aided Life-Cycle Engineering (CALCE) Electronic Products and Systems Center (EPSC) at the University of Maryland in College Park was established in 1986 by Dr. Michael Pecht, a Chaired Professor in the Mechanical Engineering Department. It is recognized internationally as a founder, driving force, and leader in the development and implementation of physics-of-failure analysis and approaches to reliability and life-cycle prediction. The CALCE EPSC includes various sponsored programs, groups, and alliances, and is comprised of renowned research and teaching faculty and research scientists and engineers. The CALCE EPSC is a world leader in accelerated testing and electronic parts selection and management, and provides a knowledge and resource base to support the development and sustainment of competitive electronic products and systems. Staffed by more than 100 faculty, staff, and students from nearly every engineering discipline, the CALCE EPSC became the first academic research facility in the world to be ISO 9001 certified in 1999. CALCE EPSC was formally started with a National Science Foundation Center Planning Grant, and over the past 15 years has invested more than $50 Million in developing methodologies, models, and tools that address the design, manufacture, analysis, and management of electronic systems.

The CALCE EPSC has grown into a Consortium of more than 50 members and is comprised of leading industrial, government, and academic organizations from all areas of the electronics industry. The Consortium promotes research in areas that have an across-the-board impact on industry, and provides a knowledge and resource base that includes design and manufacturing methods, simulation techniques, models, and guidelines to support the development of competitive electronic products and systems. CALCE performs core research projects that are developed in collaboration with Consortium members. These projects address the needs of the members as well as the Consortium as a whole. Consortium members participate in the direction of core research projects, have access to the CALCE web site, participate in technical exchanges with other members, and are represented on the CALCE Industrial Advisory Board.

With its state-of-the art equipment, technology, and expertise, the CALCE EPSC's Laboratory Services include, among others, Environmental/Accelerated Testing, Non-Destructive Evaluation, Failure Analysis, Electronic Characterization, and Thermal Assessment. Laboratory Services has assisted more than 100 companies in reliability and failure analysis, and provides virtual qualification, supply-chain creation and audits, and design benchmarking. Organizations using the Laboratory Services benefit by reducing capital costs and ensuring continued access to best practices in electronics. Consortium members and companies outside the Consortium often enter into private project and consulting agreements with CALCE for expert assistance and research in advanced electronic systems. This company-specific research is designed to help organizations identify the causes of failure or poor performance in electronic products, assess and mitigate the risks of producing and incorporating new technologies, perform lifetime and life-cycle assessments on electronic products, improve product quality and reliability, maximize cost avoidance during product sustainment, and reduce time-to-market and time-to-profit.

The CALCE EPSC faculty and research staff work as a team and understand the benefits of teaming in individual efforts. The CALCE Education Program is a multi-faceted approach to transfer ideas and knowledge to all levels of students through dedicated courses, textbooks, and multi-media courses (Internet-based courses). Several training modules have been developed to help educate engineers involved in the development and analysis of electronic hardware. These courses are taught at company sites, are designed for practicing engineers, and provide real-world examples.

The CALCE EPSC developed and is a leader in the Physics-of-Failure approach to electronics reliability. This approach includes Virtual Qualification, a simulation-based process that models a product's stress history when subjected to its anticipated life-cycle, and assesses if the anticipated reliability is achievable. This process is facilitated by custom software, such as CALCE Printed Wiring Assembly, which is developed and maintained by CALCE EPSC. CALCE researchers agree that the physics-of-failure approach holds the greatest promise for evaluating accelerated life tests under adverse environments. Among the CALCE EPSC's best practices were its Parts Selection and Management Process, a methodology for evaluating life-cycle risks of electronic parts before committing them to final design; Manufacturing Cost Modeling, a well designed process and integration of cost tools; and Root-Cause Analysis, which goes beyond defining root-cause and provides corrective actions to prevent the same types of failures in the future. With obsolescence being a large problem for the avionics, industrial controls, and military communities because of a product's extended life-cycle, the CALCE EPSC's Electronic Parts Obsolescence Forecasting tool exceeds current industry models; and its High Temperature Electronics Design for Reliability methodologies and software tools have been used successfully to design, develop, and enhance many high temperature electronic systems. The BMP survey team congratulates the CALCE Electronic Products and Systems Center and considers the practices in this report to be among the best in industry and government.

Point of Contact:

For further information on items in this report, please contact:

Ms. Ania Picard
Assistant to the Director
University of Maryland
CALCE Electronic Products and Systems Center
1103 Engineering Lab Building #89
College Park, Maryland 20742
Phone: (301) 405-5323
Fax: (301) 314-9268
E-Mail: appicard@calce.umd.edu
Website: www.calce.umd.edu

Section 2

Best Practices

Design

Assessment of Electronic Connector Reliability

CALCE Electronic Products and Systems Center has developed a systematic methodology for identifying potential failure mechanisms in separable electronic connectors using a physics-of-failure approach. The methodology can be used to predict the reliability of existing connectors, and assist in the design of more reliable connectors for existing applications.

Most manufacturers conduct standard benchmarking tests, which do not address specific failure mechanisms, nor do they usually test to failure. This lack of failure information makes it difficult to capture failures prior to the product being introduced to the field. There is little, if any, correlation of test data to the field application, which prevents an accurate prediction of field reliability.

CALCE Electronic Products and Systems Center (EPSC) has developed a systematic methodology for identifying potential failure mechanisms in separable electronic connectors using a physics-of-failure (PoF) approach. The process includes the following steps:

- Specify functions and requirements of specific applications
- Identify life-cycle environmental loads and stresses
- Characterize "critical" material and design properties including electrical, mechanical, and thermal properties
- Identify potential failure modes and mechanisms and stress-damage models based on application functions and requirements, environmental loads, and the materials of the connector
- Identify failure criteria based on failure mechanisms and specific applications
- Develop reliability test plans to address identified potential failure mechanisms
- Conduct failure analysis to verify failure mode, site, and mechanisms
- Perform lifetime assessment based on failure data, criteria, mechanisms, and life-cycle environment

The CALCE EPSC methodology allows for correlation of test data to field applications for predictions of reliability in the field. The methodology can also be used to assist in the design of more reliable connectors for existing applications.

Design for Harsh Environments: Low Temperature Operation

CALCE Electronic Products and Systems Center has developed assessment methodologies and performance characterization expertise for electronic components in low temperature application environments. This expertise assists systems designers and manufacturers in developing cost-effective systems that function in these environments.

Until recently, low temperature applications for electronic components were addressed using selective heating pads in printed circuit boards (PCBs) or extensive experimentation and testing to select the best materials and design parameters. This method was used primarily because of the lack of data on performance and reliability at low temperatures, and the lack of parts rated for low temperatures.

Using a physics-of-failure (PoF) approach, CALCE Electronic Products and Systems Center (EPSC) developed a methodology for characterization of device performance, materials behavior, and package failure modes at low temperatures. The methodology has been used on telecommunication infrastructure equipment application, where the parts were divided into major technology categories and information from the manufacturers was obtained. Examples of the property trends for package materials at -70°C include increases in Young's modulus, yield strength, and thermal conductivity of some materials, and decreases in specific heat, co-efficient of thermal expansion, and thermal conductivity of metal alloys. The categories of the devices were then analyzed and characterized, allowing for reduction in the need for selective heating pads. This could potentially result in cost savings of approximately 10% per PCB assembly where the pads could be eliminated.

The methodology has also been used in a Mars application where the wire span and loop height were optimized for Chip-on-Board technology, using analytical model. The results from the model were verified by experiments conducted at the Jet Propulsion Laboratory and Applied Physics Laboratory. This approach can potentially save more than $200K in test resources per year per mission.

High Temperature Electronics Design for Reliability

The CALCE Electronic Products and Systems Center has developed design for reliability methodologies and software tools that guide the environmental characterization, component testing, material selection, package architecture determination, and reliability assessment of electronic products and systems for high temperature electronic applications. The result enables the timely development of competitive, cost effective, high temperature electronic products and systems.

Electronics that can operate in extreme high temperature (T > 125 C) environments are important for two types of systems — distributed control systems and power management systems. Distributed control systems are used in applications such as aerospace engine combustion monitoring and vane actuation, flight surface control, automotive engine and transmission control, chemical process control, and deep well drilling and logging. The integration of sensors, control electronics, and actuators as one remotely placed package improves cost, performance, reliability, and maintainability. Power management systems generate high heat that raises the operating temperature of the device it is controlling, unless the system packaging dissipates the heat. Extreme temperature electronics are desirable because of their ability to permit distribution control and power management without requiring external cooling systems.

The reliability of electronic systems is usually assessed at the end of the design phase using standardized qualification testing of prototypes. The method used by CALCE Electronic Products and Systems Center (EPSC) is based on the physics-of-failure (PoF) approach to reliability assessment and enhancement. Models of fundamental failure mechanisms are modified to adapt to any changes that occur in the failure mechanism at elevated temperatures. They can be used to assess the reliability of specific electronic designs in unfamiliar envi-

Process Steps

Step	Process Step Description	Method Used
1	Characterize product environment	In-situ environmental condition monitoring practices
2	Simulate microclimates and operating stresses	Thermal and vibrational simulation using software
3	Assess device performance at high temperature	Uprating
4	Select packaging materials with high thermal conductivity	Utilize High Temperature Materials Database
5	Characterize material properties at high temperatures	Enhanced Materials Testing – DMA, TMA, Tytron
6	Identify and mitigate materials transformations	Enhanced Materials Testing – DSC, TMA
7	Identify and Mitigate Materials Compatibility Issues	PoF Failure Mechanism Model Development
8	Examine the Fundamental IC Failure Mechanisms at Temp.	PoF Failure Mechanism Model Development
9	Examine the Fundamental Packaging Failure Mechanisms	PoF Failure Mechanism Model Development
10	Model Identification/Modification/ Validation and Calibration	Environment Exposure and Accelerated Testing
11	Enhance Package Design for High Temperature Reliability	Computer Enabled Design for Reliability
12	Make Prototype of Design	Package Manufacturing
13	Test Prototype for Performance and Reliability in Use Environment	Electronic Testing, Environmental Exposure, and Accelerated Testing

Table 2-1. High Temperature Package Design Process

ronments. This method is a streamlined, systematic, 13-step process that uses material selection processes and simulation techniques that flow in a logical transition (Table 2-1).

CALCE EPSC's knowledge and resources provide a fundamental scientific method for the rapid development of competitive, cost effective, high temperature electronic products and systems. The methodology has been used successfully to design, develop, and enhance many high temperature electronic systems.

Manufacturing Cost Modeling

The CALCE Electronic Products and Systems Center provides manufacturing cost modeling tools and methodologies targeted to the electronic fabrication and assembly industries. The Center uses four general approaches to cost modeling, and has created several modeling applications and tools to facilitate the process.

During the mid-1990s, engineers designing electronic systems were not concerned about the impact of their designs on manufacturing costs. Consequently, no means existed to determine if the design was cost effective. In today's competitive environment, all cost impacts associated with the assemblies must be understood to properly assess the assemblies' market value. This is as true in low-volume avionics applications as it is in the retail electronics field. Engineers are now expected to participate in determining the economic tradeoff for their design decisions. The CALCE Electronic Products and Systems Center (EPSC) develops application-specific models that facilitate the tradeoff analyses required within the electronic substrate manufacturing and electronic assembly business areas.

CALCE EPSC's approach is unique because of its ability to make application-specific and application-independent models targeting the electronic substrate and electronic assembly manufacturing. This results in modeling techniques that target conditions of interest to determine if a new technology, material, or process will be cost competitive with existing ones. CALCE EPSC also addresses the "performance" requirements that determine the cost effectiveness of that process. Typically, the measured performance equates to the process throughput or yield. These techniques have been useful for evaluating processes from the component level to the multi-board assembly level.

The approaches most often used by CALCE EPSC in modeling the range of electronic systems are:

- Cost of Ownership: Basis for costing semiconductor fabrication that is driven by capital machinery intensive processes.
- Process-Flow Based Cost Modeling (Technical Cost Modeling): Determines total cost based on labor, material, capital, and tooling factors in continuous processes. The CALCE analysis also includes concurrent generation of material use and waste inventories for Life-Cycle Assessment.
- Test/Rework Economics: Determines the optimum number and placement of test points in a process to assure desired throughput.
- Top-down and Bottoms-up: Analysis that yields the total product cost at both a high level of abstraction and at a detailed process step level.

CALCE EPSC has developed several specific noteworthy modeling tools that enhance the costing models:

- Test/Rework Models highlight the costs associated with various test and rework scenarios inserted along the process flow. These costs facilitate the test/rework optimization models that determine where or where not to test and the amount of fault coverage to buy.
- Yielded Cost Metrics provide a rigorous cumulative process cost and means to show the actual effective costs associated with any given step in the process. Using the associated omission methodology provides a rigorous cost impact for any given step in the process.
- Ghost Software Tool facilitates the assessment of the design hardware/software co-design tradeoffs. The tool predicts performance, size, yield, and cost for the specified hardware and software combinations needed for a specific design.
- Salvage Software Tool provides an application-specific assessment of what components on an assembly are reusable within secondary assemblies and what should be scrapped. This tool provides useful insight into potential life-cycle cost savings strategies.
- Embedded Passives/IPD Tradeoff Analysis Tool (Figure 2-1) provides a means to compare the benefits of embedding certain passive components (resistors and capacitors) in the printed circuit board in lieu of

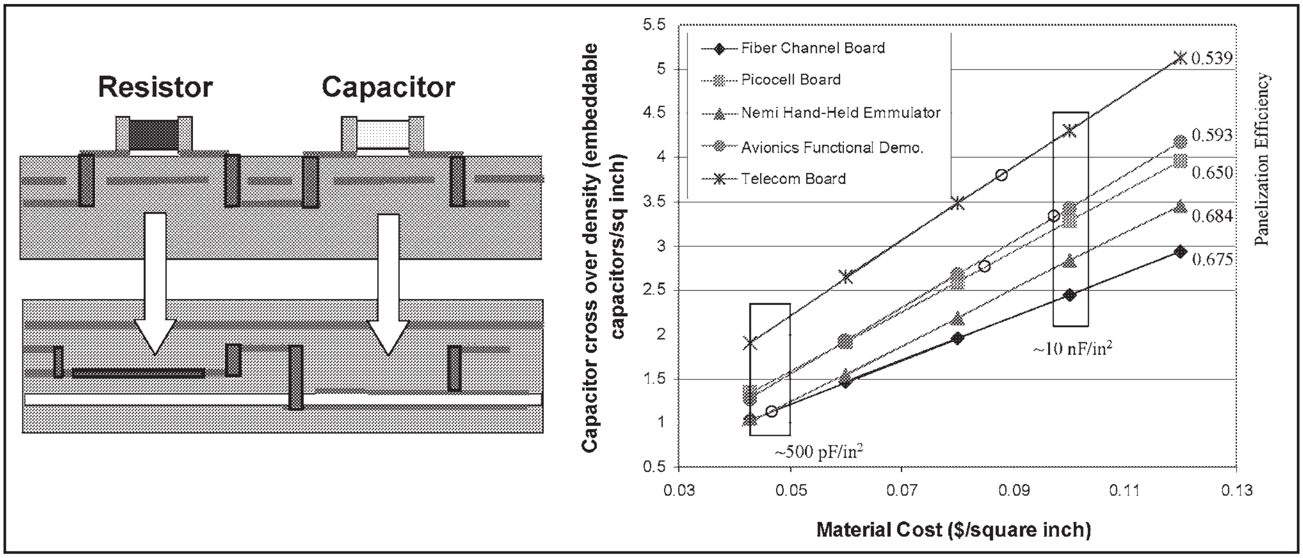


Figure 2-1. Embedded Passives/IPD Tradeoff Analysis Tool

mounting them on the surface. This tool highlights key cost differences that would occur with component embedding, thus providing metrics that are useful for determining if embedding is justified. When used to evaluate the main board layout for a cell phone, one example showed that the assessment tool highlighted a $2.50 per phone cost savings.

CALCE EPSC's Manufacturing Cost Modeling for electronic systems represents a rigorous approach to process-specific and process-independent modeling, addressing a range of requirements from component fabrication to multi-board assembly. The models enable the assessment of specific cost factors essential for process improvements. CALCE EPSC is capable of using the tools to provide the associated assessment, or of making the tool available to customers so they have the methodology to perform their own assessment.

Parts Selection and Management

The CALCE Electronic Products and Systems Center's Parts Selection and Management methodology helps companies of all sizes implement effective part selection and management procedures. By employing the methodology effectively, an organization need not conduct expensive on-site audits, and can avoid warranty and/or product recall problems that commonly result from selection of sub-par parts.

The CALCE Electronic Products and Systems Center (EPSC) has developed a methodology for selecting and managing electronic parts that provides users a means of evaluating the life-cycle risk posed by candidate parts before selecting them for use in their systems. The methodology also enables the capture of lessons learned during use of the selected parts in the application (product) to provide feedback for use in future decisions.

The rapid pace of technology in the area of electronics and the transition from military grade parts to commercial ones have created a new supply chain dynamic that has tremendous impact, not only on the commercial world, but on the Military/Aerospace community and other makers and users of electronic systems requiring high reliability. In the past, the Department of Defense represented a significant part of the electronics market, and was influential in directing developments and standards used to guide their manufacturing processes (MIL SPECs and STDs). During the 1980s and 1990s, the commercial electronics industry began to boom, driven by industry and consumer demand for computers, communication equipment, and consumer electronics. Electronic component packaging trends are now heavily driven by market application requirements and device technology. Considerations include speed, miniaturization, increased functionality, improved cost and performance, portability, lighter weight, and other factors. At the same time, the supply chain has transformed into a "supply web" as vertically integrated companies that "did it all" (made the chips, and packaged, tested, and integrated them into products) have given way to a diverse array of companies that specialize in specific steps in the overall design, build, and test process. Although Military standards have shifted to improved and more flexible commercial standards, the latter often do not go far enough to control processes and ensure product quality and reliability. The complexity of today's electronic products and systems and the supply chain that feeds them demand a sound and comprehensive method for selecting and managing parts. CALCE EPSC's Parts Selection and Management methodology (Figure 2-2) helps maximize profits, minimize time-to-profit, provide product differentiation, make effective use of the global supply chain, and enable the assessment, mitigation, and management of life-cycle risks associated with the selection and use of electronic parts. The process consists of the following steps:

1. A product's Requirements and Constraints are defined by customer demands and the builder's core competencies, culture, and goals, which enable designers to choose parts that conform to a set of engineering criteria. A product specification can be created and used as a basis for part selection.
2. Technology Sensing determines when a technology is (or will be) available and mature enough for use, and when it will become obsolete. Potentially disruptive technologies are also considered (e.g., the transition to lead-free solders and component lead finishes).
3. A Candidate Part must conform to functional, electrical, mechanical, and environmental requirements and be available at reasonable cost (this is a part pre-selection step).
4. During Manufacturer Assessment, a part maker's ability to produce parts with consistent quality and provide customer support are evaluated.
5. Part Assessment determines the specific quality and reliability of the part and the adequacy of the manufacturer's recommended assembly guidelines.
6. Distributor Assessment is conducted to evaluate the distributor's ability to provide parts without compromising their quality and reliability, and without becoming a bottleneck in the supply chain.
7. If and when the candidate part meets the above criteria, it moves to the Application-Dependent Assessment Phase (the methodology also provides some criteria for the allowable use of a rejected part when no acceptable alternative can be found). Application-Dependent Assessment begins with a determination of the local environment — the environment in the vicinity of the part as it is exposed to assembly, storage, handling, and use environments over its life-cycle.
8. Performance Assessment evaluates the part's ability to meet product functionality and electrical performance requirements. In most cases, the part manufacturer's ratings (data sheets) are used to determine limiting values for minimum and maximum stresses to which the part can be subjected.

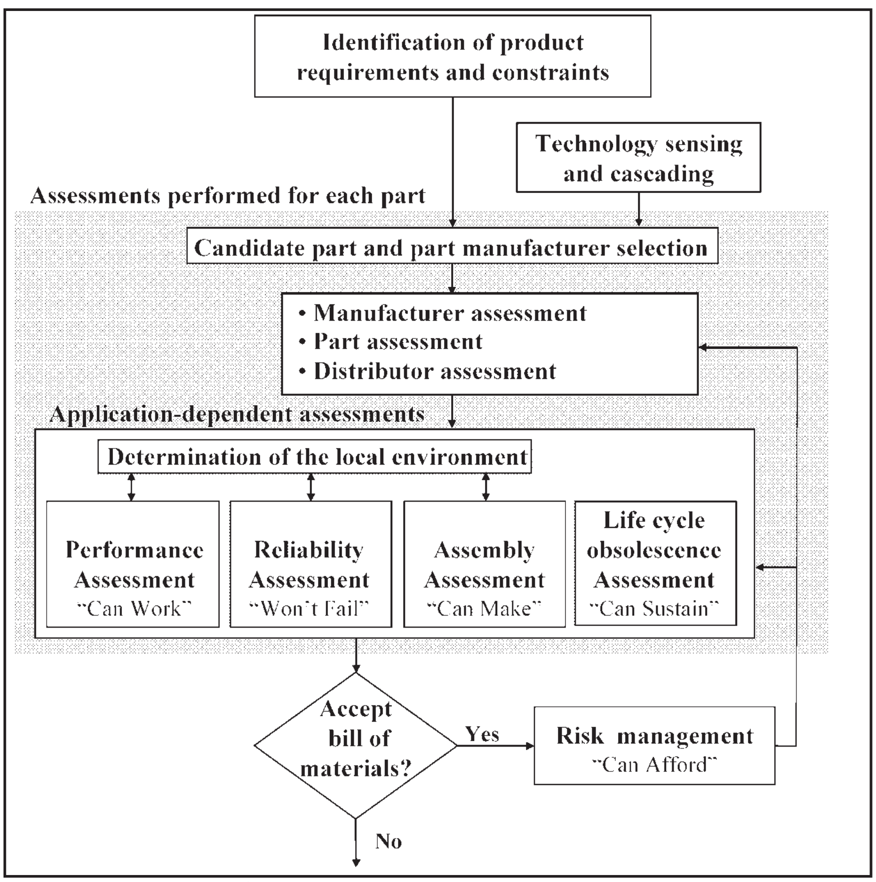


Figure 2-2. Parts Selection and Management Process

9. Reliability Assessment provides data supporting the part's ability to perform according to specification in the life-cycle environment for a specified period of time. Manufacturer- provided integrity (qualification and reliability monitoring) test data can help substantiate the assessment. Reliability Assessment is conducted through the use of integrity test data, virtual qualification (VQ) (physics-of-failure [PoF] simulation methodology) results, or if necessary, accelerated testing.
10. Assembly Assessment determines if the part can be assembled into the product, if it can be interconnected into its assembly and tested, and if necessary, reworked during and after assembly.
11. Life-cycle Obsolescence Assessment is conducted to determine the availability mismatch between the part and the product in which it will be used. The objective is to prevent the selection of parts that are or will soon be obsolete, or will be difficult to manage once they become obsolete. If no other part is available, an obsolescence mitigation strategy (e.g., lifetime buy) may be employed.

Once a part is selected, resources must be applied to risk management of the life-cycle factors including supply chain management, obsolescence management, manufacturing and assembly feedback, warranty management, and field failure and root-cause analysis.

Virtual Qualification (Simulation Assisted Reliability Assessment)

The CALCE Electronic Products and Systems Center has developed a simulation-assisted reliability assessment process for electronic hardware. This process includes the use of unique software (e.g., CALCE Printed Wiring Assembly) developed by the CALCE Electronic Products and Systems Center, and is used for reliability assessment of electronic hardware. One function of the Virtual Qualification process is to establish correlations between qualification tests and anticipated field conditions.

Reliability prediction modeling has been underway for decades. The traditional method of predicting reliability was to follow the Military Handbook for Reliability Prediction of Electronic Equipment (MIL-Hdbk-217) that used prediction methods that lead to reliability being directly correlated to temperature. Failure rates were a function of device quantity, characteristics, and temperature, not the underlying physical mechanisms that produced the failures. With constant changes that microcircuits were undergoing, the virtual elimination of ceramic, and the growing quality aspects of plastic parts, the world was being driven away from MIL-Hdbk-217 as a reliability prediction method. This has given rise to the CALCE Electronic Products and Systems Center's (EPSC's) physics-of-failure (PoF) approach to reliability assessment, which includes Virtual Qualification (VQ) and physical verification.

Because of the time involved in building a prototype, VQ offers the ability to assess a design prior to physical construction. VQ is a simulation-based process that models the product design and its anticipated life-cycle lead history to assess if the anticipated reliability is achievable. This approach has been successfully applied on avionics, automotive, and military electronic hardware, and has been shown to reduce the life-cycle cost and reliability risks of a product. VQ relies on the ability of the practitioner to adequately model the product and its anticipated life-cycle loads, and evaluate potential failure sites based on the anticipated life-cycle loads. Failure models derived and documented from test and physical analysis are used to conduct the failure assessment.

Figure 2-3 depicts the four main tasks into which the VQ process is divided. First, the anticipated design is captured. This provides relevant detail of the product configuration and layout, including physical dimensions and material properties, to create computer models for the life assessment. Second, the life-cycle loading characteristics are identified and modeled to represent the anticipated environmental loads that the design will experience through its life-cycle. Third, the load transformation relates the response of the system to the environmental and operational loads. Last, a failure risk assessment pulls all of these aspects together by evaluating failure models with data from design capture, life-cycle loads, and load transformation. The output of VQ is an assessment of the product's life expectancy and a ranking of the potential failure sites under life-cycle load combinations. The VQ process can be closely tied to physical testing.

CALCE EPSC's approach to VQ and CALCE-developed software have been applied to a variety of electronic hardware. In one application, three circuit card assemblies from an airborne radio system

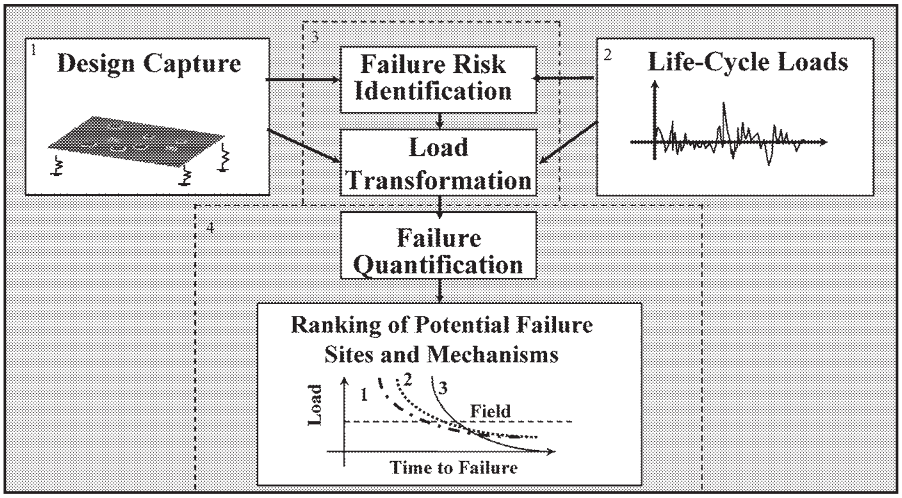


Figure 2-3. Virtual Qualification Process

were examined and found to be unable to meet desired life-cycle requirements. The total time to construct and perform the initial simulation on the three circuit cards was approximately six weeks. An application on an automotive module produced results that improved thermal and structural performance that translated into increased product life. Comparisons between the VQ method and the traditional design-build-test-fix method showed a 16% reduction in development time and an 83% reduction in test issues.

Test

Electronic Parts Uprating

The CALCE Electronic Products and Systems Center's Electronic Parts Uprating methodology is an effective tool for solving the problem of using electronic parts beyond their specified ranges. The International Electro-technical Commission and the Electronics Industry Association accept the CALCE Electronic Products and Systems Center's methods as best practices.

Uprating is defined as a process to assess the ability of a part to function and perform outside the manufacturer's recommended operating range within an application in which the part is used. Thermal uprating is a process to assess the ability of a part to function and perform outside the manufacturer's recommended operating temperature range within an application in which the part is used.

Most semiconductors are not rated for use beyond the traditionally understood commercial and industrial environments of -40° to 85°C. Semiconductors with specifications outside this range are in low demand and are difficult to buy. However, there are certain industries (e.g., oil exploration, military) that require parts to operate under extreme temperatures. The CALCE Electronic Products and Systems Center (EPSC) has developed a Parts Uprating methodology for use with electronic parts that must perform beyond the normal operating range.

CALCE EPSC uses three methods for parts uprating:

- Parameter Conformance is a process of thermal uprating in which the part is tested to assess if its functionality and electrical parameters meet the manufacturer's recommended operating conditions over the target temperature range of operation.
- Parameter re-characterization is a thermal uprating process in which the part functionality is assessed and the electrical parameters are characterized over the target temperature range, leading to a possible re-specification of one or more of the manufacturer-specified parameter limits.
- Stress balancing is a process of thermal uprating in which at least one of the part's electrical parameters is kept below its maximum allowable operation at a higher ambient temperature than that specified by the manufacturer. A tradeoff can be made between increased ambient temperature and a change in electrical parameters.

Assembly level testing, which confirms proper part interaction at the assembly level, finalizes the process of thermal uprating. Uprating has afforded companies the ability to successfully integrate the best part for their system without further development of parts for extended temperature range. CALCE EPSC used thermal uprating for a major electronic parts user to determine an extended range for a component, which resulted in a $2 Million per year component cost avoidance. In some cases, uprating also provides the opportunity for use of cutting-edge technology in designs.

Physics-of-Failure Strategies for Accelerated Stress Testing: Product Qualification

The CALCE Electronic Products and Systems Center has established systematic procedures to combine Physics-of-Failure modeling with accelerated stress testing to qualify new designs and processes for a given life-cycle. Proper Physics-of-Failure-based use of accelerated stress tests within cost and time budgets can achieve quality and stress margins that are far better than those achieved using traditional design-build-test-fix approaches.

Accelerated qualification is a key method for risk assessment in the electronics industry. However, qualification of devices, packages, and systems has consisted of decades-old military and commercial standards. Qualification is typically conducted late in product development, often after the design is frozen, putting a burden on product time to market. Furthermore, the old "one size fits all" standard tests do not address the actual failure mechanisms occurring in the application environment. As new reliability assessment and qualification techniques are being introduced, questioned, evaluated, and reinvented for today's marketplace, it is necessary to have a thorough understanding of the potential failure mechanisms, not only to prevent them under life-cycle stresses, but also to precipitate them effectively during accelerated testing.

The CALCE Electronic Products and Systems Center (EPSC) has demonstrated a thorough understanding of the failure mechanisms with its Physics-of-Failure (PoF)-based reliability prediction methodologies. CALCE EPSC determined the need for a method to relate the results of accelerated wearout tests to in-service reliability. CALCE EPSC researchers realize that successful answers to these issues can and will result in dramatic breakthroughs in reducing product development cycle time and increasing confidence in the product's life-cycle. Researchers realize that development budgets are shrinking and there is a push to enhance test time compression. This has served to develop the most cost effective and scientific way to conduct accelerated wearout testing for electronic packages. CALCE EPSC researchers agree that PoF principles hold the greatest promise for evaluating accelerated life tests under adverse environments.

CALCE EPSC's PoF approach to accelerated wearout testing follows a five-step process, starting with INPUTS of the product configuration (program objectives, product architecture, material properties) and life-cycle loads (operational use environment). In Step 1, PoF-based virtual qualification is used to identify the potential failure sites, damage mechanisms, and failure modes under the life-cycle loads. Computer models identify the intrinsic design limits of the product and rank the potential failures. Step 2 involves the design of an accelerated test plan to target the design weaknesses. Step 3 involves characterization of test loads specimens so the PoF model can be verified and calibrated, as well as development of an accelerated stress profile which does not violate any overstress limits. Step 4 involves accelerated life test on selected sample lots. Failure mechanisms are verified using failure analysis to ensure validity. Step 5 repeats the virtual qualification (VQ) assessment, but in an accelerated environment in order to identify the acceleration factors for the selected accelerated test program. The OUTPUT of this five-step process is a PoF assessment of durability of the product in the life-cycle environment, calibrated with accelerated test data.

CALCE EPSC has successfully demonstrated a systematic process for integrating PoF strategies for accelerated stress testing. The application of enhanced stresses ruggedizes the design and manufacturing process of electronics packages through systematic step-stress testing, and increases the stress margins by corrective action (reliability enhancement testing) and by conducting compressed/accelerated life tests in the laboratory to verify in-service reliability (qualification testing). When done early in the development phase, such PoF modeling and tailored accelerated testing can enhance process and design maturity, and enable early introduction of mature products with robust design margins.

Root-Cause Analysis

The CALCE Electronic Products and Systems Center provides the resources and demonstrates a capability that exceeds the ability of industry to perform Root-Cause Analysis for failed electronic components and assemblies. The CALCE Electronic Products and Systems Center follows an approach *that combines a holistic view on how failures occur, systematic processes for performing the analyses, and the appropriate resources in equipment and engineering personnel to accomplish it.*

American manufacturers spend more than $22 Billion in warranty costs resulting from product failures. A significant number of these failures are attributable to loss of either electrical or electronic functionality. Electronic reliability is the critical factor affecting decisions on the introduction of certain new technologies. The biggest challenge facing industry is completing sufficient analysis to identify the root-cause of failure, rather than troubleshooting a quick fix. Quite often companies do not have the equipment resources or time to determine the actual cause of a problem. The CALCE Electronic Products and Systems Center (EPSC) provides industry with a unique resource for conducting thorough Root-Cause Analysis for electronic components and assemblies. In addition, its ISO 9001 certification provides assurance that testing is conducted using well-documented procedures.

The CALCE EPSC's Root-Cause Analysis methodology is based on a physics-of-failure (PoF) approach, which is founded on the fact that failures are governed by fundamental mechanical, chemical, electrical, thermal, and radiation processes. These processes initiate when the applied stress exceeds the material strength. Understanding how to influence this interaction provides clues to the direction the Root-Cause Analysis process must follow. This fundamental approach is coupled with a systematic process that follows logical stages beyond accepted industry practice. This process involves gathering evidence for analysis, hypothesizing root causes, and sample testing to assess each hypothesized root cause. Results and key data obtained at each stage are documented and stored to ensure data completeness and integrity. The actual testing stages are scheduled so that non-destructive evaluation is performed prior to moving onto tests that would require destruction of the samples, thereby allowing the gathering of unique data from each testing technique. All tests are conducted using documented procedures to assure reproducibility and avoid inadvertent damage to the samples. Once the root cause is identified, corrective actions are developed to prevent the recurrence of the problem. A documented failure analysis knowledge base is maintained as a key reference tool to quickly review research that might hold clues to the current analysis, thus avoiding duplicate testing. The CALCE EPSC is equipped with the instrumentation and staff essential to the conduct of rigorous analysis — resources that exceed the reach of most companies. CALCE EPSC is also able to take advantage of its proximity to major testing facilities (both Government and private) to share highly specialized resources not readily available.

CALCE EPSC provides industry three unique capabilities that mark its Root-Cause Analysis methodology as an industry leader: a holistic approach based on PoF (probable causes are linked to sound scientific principles); a systematic and documented process for directing the actual investigation; and well-equipped facilities and a highly skilled staff. Combined, these capabilities assure higher likelihood that the actual root-cause of a problem is isolated and resolved.

Section 3

Information

Design

Design Refresh Planning

The CALCE Electronic Products and Systems Center has developed a robust analysis tool to provide a stochastic solution for Design Refresh Planning activities that can result in significant cost avoidance for sustainment-dominated systems. The CALCE Mitigation of Obsolescence Cost Analysis provides a more reliable planning predictor than common industry alternatives.

The increased semiconductor market dominance of consumer electronics has forced large-scale incorporation of commercial-off-the-shelf (COTS) assemblies into systems designed for extended lifecycles. However, COTS assemblies typically do not have the procurement life-cycle of the overall system in which they are used. Diminishing Manufacturing Sources and Materials Shortages (DMSMS) is the term used by the Military to describe the condition that results from parts becoming obsolete before the system they are in. In fact, the problem is most acute in avionics and complex military systems with long development and support life-cycles. The typical strategic approach has been to mitigate this obsolescence through reactive measures (e.g., life-time buy, last-time buy, part replacements, aftermarket sources, uprating, salvage). The CALCE Electronic Products and Systems Center (EPSC) is a leader in developing proactive strategies to mitigate the obsolescence. The methodology, known as Mitigation of Obsolescence Cost Analysis (MOCA), has shown to be an industry leading proactive approach to managing the obsolescence impact. In contrast, most existing methodologies used to mitigate DMSMS rely on databases that are effective only in determining the current availability of parts, and possibly the identification of alternative parts.

The CALCE EPSC's MOCA is a unique methodology that uses a detailed cost analysis model based on future production projections, maintenance requirements, and parts obsolescence forecasts. It provides the basis for determining the optimum Design Refresh Plan for specific components. Design Refresh is a system design strategy that sets a target point along the procurement timeline for revising the design to eliminate obsolete parts. MOCA determines the number of refresh activities (redesign) that will optimize the system sustainment costs, and identifies the dates for these activities. It uses inputs from the bills of material, part obsolescence forecasters, future production projections (including spares), and obsolescence mitigation choices. This methodology results in a robust analysis, since it is a stochastic tool that is supported by data represented by probability distributions. This is key to assuring that the results are within reasonable ranges, even though the problem being addressed is highly subjective.

The most mature MOCA methodology is known as the Technology Sustainment MOCA. This form of the tool provides planning data that supports refreshing the design at its current configuration. It provides a series of unique benefits:

- The analysis can be performed earlier in the development cycle allowing for more effective refresh budget planning. This extends the reaction time allowing for more planning time.
- Guidelines for addressing the refresh requirements are more accurate.
- Operational availability is improved as the design refreshes mitigate the obsolete parts before they become critical to system operation.
- "System-blind" results can be factored across systems. Because the methodology looks at components, it can be used to address planning for all systems using the same mix of components.
- Execution of the performance improvement roadmap is improved.

CALCE EPSC is developing an enhanced MOCA version known as the Technology Insertion MOCA. This version adds decision networks to the current sustainment methodology. The intended benefit is to consider other design factors besides obsolescence, making it possible to characterize key elements, such as performance and reliability, that influence design. Not only would it be possible to determine optimum refresh design dates, but also how the design might be improved. Although this methodology shows excellent promise, it is still not developed to the point of being a stable tool.

Test

Characterization of Degradation Behavior of Electronic Materials

The CALCE Electronic Products and Systems Center's research on the Characterization of Degradation Behavior of Electronic Materials has led to a better understanding of material characterizations that affect the degradation of materials, not just part functionality.

Characterization of new materials used in the manufacture of electronic parts/assemblies is usually performed by the material supplier. A shortcoming of this process is that the material supplier characterization effort is usually directed at measuring properties that influence part functionality, rather than properties that influence degradation of the component part. Degradation of electronic components can occur from outside environmental stimuli (e.g., temperature, vibration, or humidity). This data, gathered from the understanding of environmental stimuli effects, is a critical foundation to accurate reliability assessment and comprehensive root-cause analysis.

The CALCE Electronic Products and Systems Center (EPSC) recognized the need for identifying and analyzing all external stimuli that affect the total life-cycle and performance of any given electronic component. Thus, CALCE EPSC developed a comprehensive approach to material characterization, especially with those properties that influence degradation mechanisms. Much care is used to address uncertainty in measurements by using only National Institute of Standards and Technology calibration traceable equipment, and fully trained and certified personnel to perform the tests and analysis. A stringent peer review process is used during material characterization when required, such as when discrepancies in testing are noted and in performing the root-cause analysis to determine the cause or causes of aberrations in testing. During the peer review process, laboratory personnel are required to present multiple values obtained from literature on the same or similar materials and make comparisons to their material characterization results. When applicable, different techniques and/or equipment that can measure the same material properties are used for comparisons. Extensive discrepancies are then subjected to root-cause analysis in order to understand the effects of the data discrepancies.

Since 2001, CALCE EPSC has proven the value of material Characterization of Degradation Behavior in several studies with industry partners. Through these analyses, industry has been able to develop requirements for proper and validated material characterization data, with an appropriate focus on the characterization of material behaviors that influence product degradation and eventual failure.

Integrated Prognostics and Health Monitoring for Electronic Products and Systems

Health monitoring is emerging as a promising methodology for assessing and maintaining the reliability of a product. The CALCE Electronic Products and Systems Center has developed prognostic and health monitoring methodologies for next generation electronic equipment. These methodologies can be used to provide advance warning of failure, prevent catastrophic failure, assess reliability, reduce unscheduled maintenance, identify faults efficiently, and improve qualification methods and both the design and manufacture of future electronic products.

The CALCE Electronic Products and Systems Center's (EPSC's) motivation for developing Integrated Prognostics and Health Monitoring for Electronic Products and Systems was the lack of a dependable tool to assess the life-cycle reliability of an electronic product. A tool was needed that would go beyond the current reliability assessment methodologies and the insufficient knowledge of the product's actual environment. Although health monitoring methodologies have been routinely employed in mechanical systems, civil structures, and aircrafts, their application to electronics is extremely challenging due to the small scale of electronic structures and inadequate correlation between degradation and loss of performance.

Health monitoring is a method of assessing the degradation of a product (reliability) in its life-cycle environment by continuous or periodic monitoring and interpretation of the parameters indicative of its health. Product health monitoring can be implemented through the use of various techniques to sense and interpret the parameters indicative of performance degradation (deviation of operating parameters), physical or electrical degradation (material cracking, corrosion, delamination, increase in electrical resistance or threshold voltage), and changes in a life-cycle environment (usage duration and frequency, ambient temperature and humidity, vibration, and shock.). CALCE EPSC strategies include use of:

- Sensor technologies with physics-of-failure (PoF) analysis to assess real time life consumption;
- Diagnostic built-in-test software-firmware systems to identify and locate faults;
- In-situ semiconductor prognostic monitors to predict remaining life; and
- Software modules to support environment and usage data collection that enables health management.

CALCE EPSC's methodologies have been successfully demonstrated for an electronic board operated in an automotive underhood environment. CALCE has already conducted a remaining life assessment of the space shuttle remote manipulator system electronics for NASA, and is currently conducting health and life assessment for NASA's space shuttle rocket booster electronics hardware. On-going research focuses on the development of an integrated hardware-software that can enable real time health and usage monitoring of electronic products in the application environment. Software takes environmental and operational sensor data as input, and processes it using data reduction and cycle counting algorithms to predict the remaining life of the product using appropriate stress-damage model.

CALCE's vision for the future is to develop microprogrammable modules that will enable health monitoring and prognostics of electronics. The hardware will incorporate local sensors, microprocessor, memory, power supply, and networking capabilities. Embedded software takes environmental and operational sensor data as input, and processes it using data reduction and cycle counting algorithms to predict the remaining life of the electronic system. Adoption of this technology in air, land, and naval applications would enable real time life decisions to reconfigure the operational force structure, order spare parts, and schedule maintenance to maximize the combat utility.

Thermal Design and Analysis of Electronic Products and Systems

The CALCE Electronic Products and Systems Center has contributed to more timely and cost-efficient industry thermal design processes for electronic equipment through innovative thermal management solutions, improved thermal analysis and characterization methodologies, and professional development courses.

Increases in integrated circuit (IC) heat flux and power dissipation, combined with more stringent performance and reliability constraints in the future, pose challenges that will make thermal management a key enabling technology in the development of electronic systems. Many integrated circuit packaging failure mechanisms have been found to depend on spatial temperature gradients, temperature cycle magnitude, and rate of temperature change rather than absolute temperature, while die circuit electrical performance can be highly temperature dependent. Thus, electronics temperatures must be controlled through appropriate thermal management strategies to meet both performance and reliability requirements. Rising heat loads combined with ever-reducing product development times require increasing levels of engineering expertise, improved experimental facilities, and computing resources. Many companies are feeling the need to out-source their thermal design process and research.

Over the past 15 years, the CALCE Electronic Products and Systems Center (EPSC) has advanced the thermal management and reliability of electronic equipment by developing innovative thermal design solutions, efficient thermal design methodologies combining experimentation and numerical analysis, and by studying the dependency of electronics failure mechanisms on temperature. Electronics cooling strategies developed and optimized at the Center include passive and forced air cooling solutions, and single and two-phase liquid cooling solutions. Because of cost and reliability constraints, air-cooling will remain an important thermal management approach for many electronic products in the foreseeable future. CALCE has addressed key thermal management areas to extend the limits of air-cooling. Advances in heat sink cooling performance have been achieved by addressing the following areas, to optimize the complete heat transfer chain from the heat dissipating components acting as thermal source, to the environment external to the system enclosure: minimization of thermal contact resistance between component and heat sink, integration of heat spreading technologies (e.g., heat pipes and high thermal conductivity materials), hybrid cooling solutions such as phase change materials, and minimization of heat sink surface fouling. Liquid cooling-based solutions have been developed (both single- and two-phase) for applications where air-cooling alone is not sufficient enough to meet thermal design specifications. Liquid cooling solutions include advanced liquid cooled modules for cooling of high heat flux electronics, and high performance cold plates with porous and other micro-structures.

An efficient thermal design strategy requires a balanced combination of experimental and numerical efforts, applied to the development of high-performance cooling technologies. Over the last decade, thermal design practices within the electronics industry have progressed from basic analytical and semi-empirical calculations, applicable to systems in tandem with extensive physical prototype characterization, to a high reliance on virtual prototyping using numerical predictive techniques, such as computational fluid dynamics- (CFD) base methods. Using experimental benchmarks, CALCE has assessed the predictive capability of CFD software dedicated to the thermal analysis of electronics, and highlighted the need for experimental verification due to inherent limitations in the codes used. CALCE has demonstrated the capability of alternative low-Reynolds number eddy viscosity turbulence modeling strategies, available in general-purpose CFD codes, to improve predictive accuracy for electronic component heat transfer. Apart from the prediction of operational temperature in application environments, the value of CFD in optimizing electronic component assembly processes (e.g., corrective re-flow soldering), and optimizing the thermal loads imposed in accelerated reliability tests (e.g., air temperature and power cycling), has also been demonstrated.

Logistics

Electronic Part Obsolescence Forecasting

Electronic Part Obsolescence Forecasting plays a crucial role in managing system obsolescence and life-cycle costs. Current tools are prescriptive and have significant limits when it comes to predicting future part obsolescence. The CALCE Electronic Products and Systems Center has developed a methodology that is more accurate at predicting part obsolescence. This is a huge step toward enabling proactive life-cycle planning.

The advent of acquisition reform has caused a shift from traditional Mil-Spec parts to commercial-off-the-shelf (COTS) parts. The Government, with longer life-cycle systems, is about 1% of COTS micro-electronic business. However, the majority of COTS micro-electronic business is driven by industry, which has shorter life-cycle systems. The shift has raised the need for solutions that help mitigate the inherent risk of sustaining and supporting COTS in legacy systems. CALCE Electronic Products and Systems Center (EPSC) has developed algorithms to forecast electronic part obsolescence for use in proactive obsolescence management.

The electronics industry has a continuous pattern of growth and change. The tremendous growth of the industry causes electronic parts to have shorter life-cycles than the assemblies they are used within — one reason why a longer life-cycle system becomes obsolete. Part obsolescence occurs when there is a slow demand for the part or a shortage of materials to make the part. There are significant cost impacts associated with electronic part obsolescence in a system's life-cycle, including procurement of new parts, storing of parts, upgrading the system, and mitigating risks in the system.

The objective of Part Obsolescence Forecasting is to track and archive obsolete parts and predict when existing parts will become obsolete. Current forecasting tools excel at articulating the current state of a part's availability and identifying alternative options. However, limitations exist in the capability to forecast future obsolescence dates and provide quantitative confidence limits when predicting future obsolescence. Most forecasting is based on the development of models for the part's life-cycle. These models compute risk of obsolescence using methods based on ordinal scales where risk is a probability and the scales are not based on probability data.

In the basic CALCE EPSC method, sales data for an electronic part is curve fit. The attributes of the curve fits are plotted, and trend equations are created that can be used for predicting the life-cycle curve of future versions of the part type. In order to determine "windows of obsolescence" in the forecasted part life-cycle curves, the CALCE EPSC has developed a methodology based on data mining historical last order dates for selected part families. Using the data supplied by part database suppliers, the CALCE EPSC has demonstrated the development of data mining based algorithms for electronic part vendor-specific windows of obsolescence that can be used in conjunction with the life-cycle curve forecasting approach. Together they substantially increase the predictive capabilities of obsolescence forecasting approaches. This methodology enables more accurate obsolescence forecasts and can be generated for user-specified confidence levels.

Appendix A

Table of Acronyms

ACRONYM	DEFINITION
CALCE	Computer-Aided Life-Cycle Engineering
CFD	Computational Fluid Dynamics
COTS	Commercial-Off-The-Shelf
DMSMS	Diminishing Manufacturing Sources and Materials Shortages
EPSC	Electronic Products and Systems Center
IC	Integrated Circuit
MOCA	Mitigation of Obsolescence Cost Analysis
PCB	Printed Circuit Board
PoF	Physics-of-Failure
VQ	Virtual Qualification

Appendix B

BMP Survey Team

Team Member	Activity	Function
Larry Halbig 317-891-9901	**BMP Field Office-Indianapolis** Indianapolis, IN	**Team Chairman**
Caryl Bremer 301-405-9990	**BMP Center of Excellence** College Park, MD	**Technical Writer**
	Team A	
Don Hill 317-849-3202	**BMP Field Office – Indianapolis** Indianapolis, IN	**Team Leader**
Brock Christoval 951-273-5589	**Naval Surface Warfare Center – Corona** Corona, CA	
Charlie Minter 301-405-9990	**BMP Center of Excellence** College Park, MD	
Ron Williams 301-405-9990	**BMP Center of Excellence** College Park, MD	
	Team B	
Ron Cox 812-854-5330	**Naval Surface Warfare Center – Crane** Crane, IN	**Team Leader**
Peter Bissegger 951-273-5766	**Naval Surface Warfare Center – Corona** Corona, CA	
Andrew Kostic 301-512-8291	**BMP Center of Excellence** College Park, MD	
George Neidardt 301-405-9990	**BMP Center of Excellence** College Park, MD	

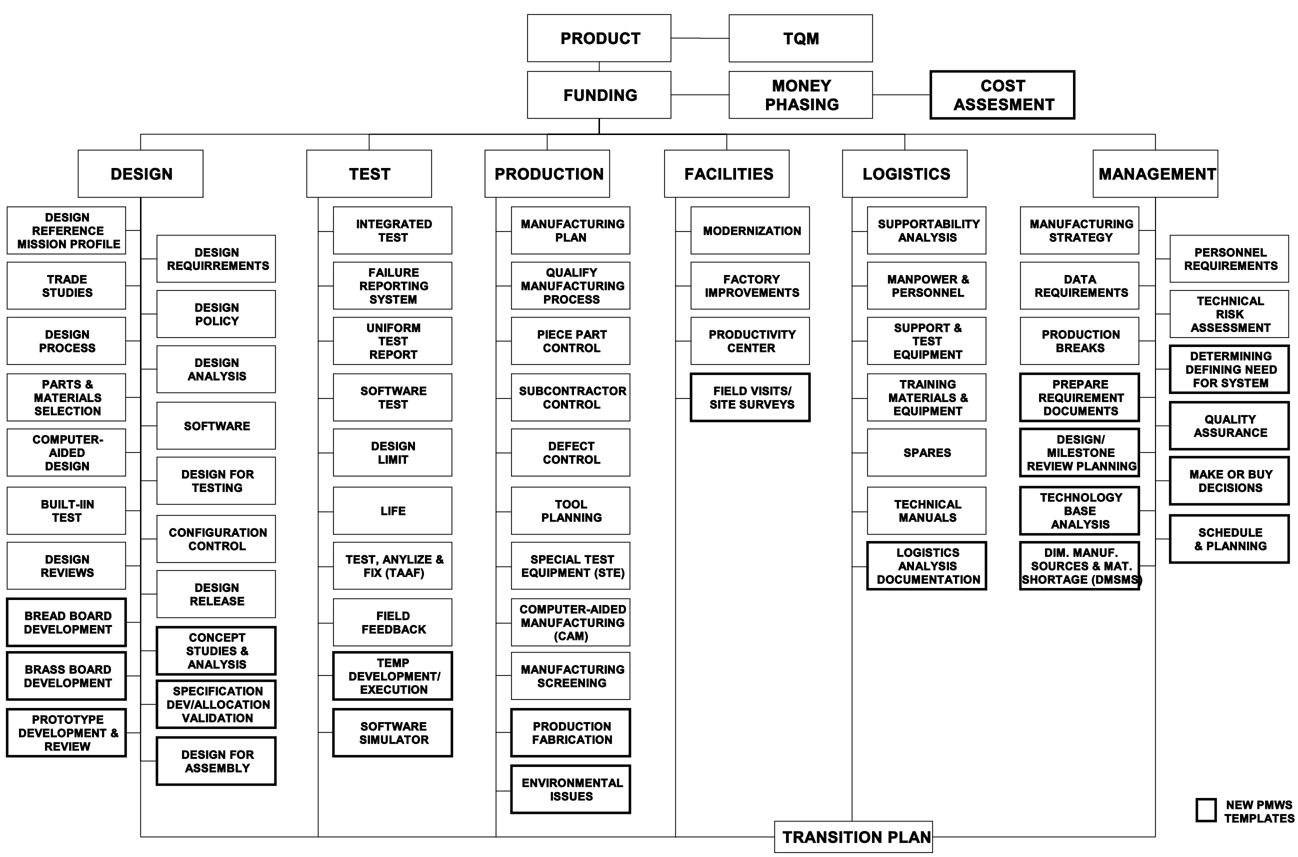
Appendix C

Critical Path Templates and BMP Templates

This survey was structured around and concentrated on the functional areas of design, test, production, facilities, logistics, and management as presented in the Department of Defense 4245.7-M, Transition from Development to Production document. This publication defines the proper tools-or templates-that constitute the critical path for a successful material acquisition program. It describes techniques for improving the acquisition process by addressing it as an industrial process that focuses on the product's design, test, and production phases which are interrelated and interdependent disciplines.

The BMP program has continued to build on this knowledge base by developing 17 new templates that complement the existing DOD 4245.7-M templates. These BMP templates address new or emerging technologies and processes.

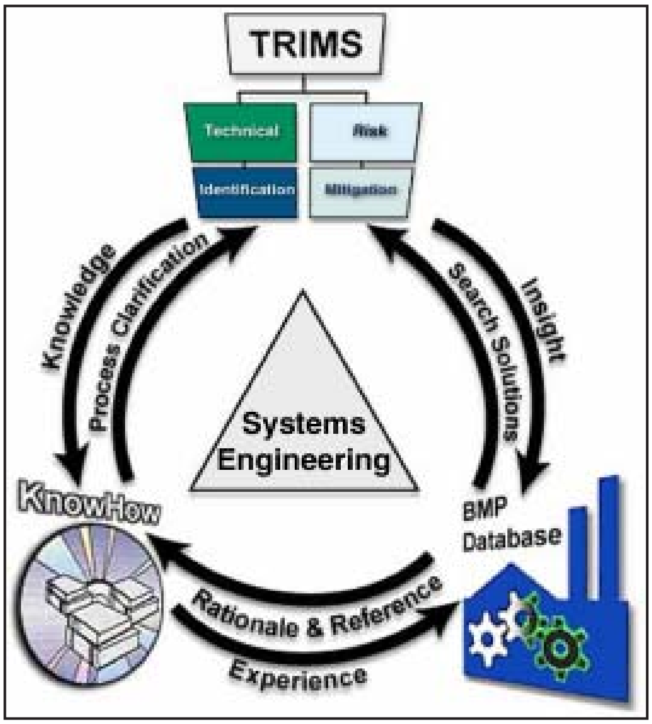
"CRITICAL PATH TEMPLATES FOR TRANSITION FROM DEVELOPMENT TO PRODUCTION"



Appendix D

The Program Manager's WorkStation

The Program Manager's WorkStation **(PMWS)** is an electronic suite of tools designed to provide timely acquisition and engineering information to the user. The main components of PMWS are KnowHow; the Technical Risk Identification and Mitigation System (TRIMS); and the BMP Database. These tools complement one another and provide users with the knowledge, insight, and experience to make informed decisions through all phases of product development, production, and beyond.



KnowHow provides knowledge as an electronic library of technical reference handbooks, guidelines, and acquisition publications which covers a variety of engineering topics including the DOD 5000 series. The electronic collection consists of expert systems and simple digital books. In expert systems, KnowHow prompts the user to answer a series of questions to determine where the user is within a program's development. Recommendations are provided based on the book being used. In simple digital books, KnowHow leads the user through the process via an electronic table of contents to determine which books in the library will be the most helpful. The program also features a fuzzy logic text search capability so users can locate specific information by typing in keywords. KnowHow can reduce document search times by up to 95%.

TRIMS provides insight as a knowledge based tool that manages technical risk rather than cost and schedule. Cost and schedule overruns are downstream indicators of technical problems. Programs generally have had process problems long before the technical problem is identified. To avoid this progression, TRIMS operates as a process-oriented tool based on a solid Systems Engineering approach. Process analysis and monitoring provide the earliest possible indication of potential problems. Early identification provides the time necessary to apply corrective actions, thereby preventing problems and mitigating their impact. TRIMS is extremely user-friendly and tailorable. This tool identifies areas of risk; tracks program goals and responsibilities; and can generate a variety of reports to meet the user's needs.

The **BMP Database** provides experience as a unique, one-of-a-kind resource. This database contains more than 2,500 best practices that have been verified and documented by an independent team of experts during BMP surveys. BMP publishes its findings in survey reports and provides the user with basic background, process descriptions, metrics and lessons learned, and a Point of Contact for further information. The BMP Database features a searching capability so users can locate specific topics by typing in keywords. Users can either view the results on screen or print them as individual abstracts, a single report, or a series of reports. The database can also be downloaded, run on-line, or purchased on CD-ROM from the BMP Center of Excellence. The BMP Database continues to grow as new surveys are completed. Additionally, the database is reviewed every other year by a BMP core team of experts to ensure the information remains current.

For additional information on PMWS, please contact the Help Desk at (301) 403-8179, or visit the BMP web site at http://www.bmpcoe.org.

Appendix E

Best Manufacturing Practices Satellite Centers

There are currently ten Best Manufacturing Practices (BMP) satellite centers that provide representation for and awareness of the BMP Program to regional industry, government and academic institutions. The centers also promote the use of BMP with regional Manufacturing Technology Centers. Regional manufacturers can take advantage of the BMP satellite centers to help resolve problems, as the centers host informative, one-day regional workshops that focus on specific technical issues.

Center representatives also conduct BMP lectures at regional colleges and universities; maintain lists of experts who are potential survey team members; provide team member training; and train regional personnel in the use of BMP resources.

The ten BMP satellite centers include:

California

Izlay (Izzy) Mercankaya
BMP Satellite Center Manager
Naval Surface Warfare Center, Corona Division
Code QA-21, P.O. Box 5000
Corona, CA 92878-5000
(951) 273-5440
FAX: (951) 273-5315
izlay.mercankaya@navy.mil

District of Columbia

Brad Botwin
BMP Satellite Center Manager
U.S. Department of Commerce
Bureau of Industry & Security
14th Street & Constitution Avenue, NW
H3876
Washington, DC 20230
(202) 482-4060
FAX: (202) 482-5650
bbotwin@bis.doc.gov

Illinois

Robert Lindstrom
BMP Satellite Center Manager
Rock Valley College
3301 North Mulford Road
Rockford, IL 61114-5699
(815) 921-2073
FAX: (815) 654-4343
r.lindstrom@rvc.cc.il.us

Iowa

Bruce Coney
BMP Satellite Center Manager
Iowa Procurement Outreach Center
2273 Howe Hall, Suite 2617
Ames, IA 50011
(515) 294-4461
FAX: (515) 294-4483
bruce.coney@ciras.iastate.edu

Louisiana

Alley Butler
BMP Satellite Center Manager
Maritime Environmental Resources & Information Center
Gulf Coast Region Maritime Technology Center
University of New Orleans
UAMTCE, Room 163-Station 122
5100 River Road
New Orleans, LA 70094-2706
(504) 458-6339
FAX: (504) 437-3880
alley.butler@gcrmtc.org

Ohio

Larry Brown
BMP Satellite Center Manager
Edison Welding Instiitute
1250 Arthur E. Adams Drive
Columbus, Ohio 43221-3585
(614) 688-5080
FAX: (614) 688-5001
larry_brown@ewi.org

Pennsylvania

John W. Lloyd
BMP Satellite Center Manager
MANTEC, Inc.
P.O. Box 5046
York, PA 17405
(717) 843-5054
FAX: (717) 843-0087
lloydjw@mantec.org

South Carolina

Henry E. Watson
BMP Satellite Center Manager
South Carolina Research Authority - Applied Research and Development Institute
100 Fluor Daniel
Clemson, SC 29634
(864) 656-6566
FAX: (843) 767-3367
watson@scra.org

Tennessee

Mike Monnett
BMP Satellite Center Manager
Y-12 National Security Complex
BWXT Y-12, L.L.C.
P.O. Box 2009
Oak Ridge, TN 37831-8091
(865) 241-5631
FAX: (865) 574-2000
monnettmg@y12.doe.gov

Virginia

William Motley
BMP Satellite Center Manager
DAU Program Director, Manufacturing Manager
Defense Acquisition University
9820 Belvior Road, Suite G3
Ft. Belvior, VA 22060-5565
(703) 805-3763
FAX: (703) 805-3721
bill.motley@dau.mil

Appendix F

Navy Manufacturing Technology Centers of Excellence

The Navy Manufacturing Technology Program has established Centers of Excellence (COEs) to provide focal points for the development and technology transfer of new manufacturing processes and equipment in a cooperative environment with industry, academia, and the Navy industrial facilities and laboratories. These consortium-structured COEs serve as corporate residences of expertise in particular technological areas. The following list provides a description and point of contact for each COE.

Best Manufacturing Practices Center of Excellence

The Best Manufacturing Practices Center of Excellence (BMPCOE) provides a national resource to identify and share best manufacturing and business practices being used throughout government, industry, and academia. The BMPCOE was established by the Office of Naval Research's BMP Program, the Department of Commerce, and the University of Maryland at College Park. By improving the use of existing technology, promoting the introduction of improved technologies, and providing non-competitive means to address common problems, the BMPCOE has become a significant factor to counter foreign competition.

Point of Contact:
Dr. Anne Marie T. SuPrise
Best Manufacturing Practices Center of Excellence
4321 Hartwick Road
Suite 400
College Park, MD 20740
Phone: (301) 405-9990
FAX: (301) 403-8180
E-mail: annemari@bmpcoe.org

Institute for Manufacturing and Sustainment Technologies

The Institute for Manufacturing and Sustainment Technologies (iMAST) is located at the Pennsylvania State University's Applied Research Laboratory. iMAST's primary objective is to address challenges relative to Navy and Marine Corps weapon system platforms in the areas of mechanical drive transmission technologies, materials processing technologies, laser processing technologies, advanced composites technologies, and repair technologies.

Point of Contact:
Mr. Robert Cook
Institute for Manufacturing and Sustainment Technologies
ARL Penn State
P.O. Box 30
State College, PA 16804-0030
Phone: (814) 863-3880
FAX: (814) 863-1183
E-mail: rbc5@psu.edu

Composites Manufacturing Technology Center (Operated by South Carolina Research Authority)

The Composites Manufacturing Technology Center (CMTC) is a Center of Excellence for the Navy's Composites Manufacturing Technology Program. The South Carolina Research Authority (SCRA) operates the CMTC and The Composites Consortium (TCC) serves as the technology resource. The TCC has strong, in-depth knowledge and experience in composites manufacturing technology. The SCRA/CMTC provides a national resource for the development and dissemination of composites manufacturing technology to defense contractors and subcontractors.

Point of Contact:
Mr. Henry Watson
Applied Research and Development Institute
Composites Manufacturing Technology Center
934-D Old Clemson Highway
Eagles Landing Professional Park
Seneca, SC 29672
Phone: (864) 656-6566
FAX: (864) 653-7434
E-mail: watson@scra.org

Electronics Manufacturing Productivity Facility (Operated by American Competitiveness Institute)

The Electronics Manufacturing Productivity Facility (EMPF) identifies, develops, and transfers innovative electronics manufacturing processes to domestic firms in support of the manufacture of affordable military systems. The EMPF operates as a consortium comprised of government, industry, and academic participants led by the American Competitiveness Institute under a Cooperative Agreement with the Navy.

Point of Contact:
Mr. Michael Frederickson
Electronics Manufacturing Productivity Facility
One International Plaza, Suite 600
Philadelphia, PA 19113
Phone: (610) 362-1200, ext. 215
FAX: (610) 362-1288
E-mail: mfrederickson@aciusa.org

Electro-Optics Center (Operated by The Pennsylvania State University's Applied Research Laboratory)

The Electro-Optics Center (EOC) is a national consortium of electro-optics industrial companies, universities, and government research centers that share their electro-optics expertise and capabilities through project teams focused on Navy requirements. Through its capability for national electronic communication and rapid reaction and response, the EOC can address issues of immediate concern to the Navy Systems Commands. The EOC is managed by the Pennsylvania State University's Applied Research Laboratory.

Point of Contact:
Dr. Karl Harris
Electro-Optics Center
West Hills Industrial Park
77 Glade Drive
Kittanning, PA 16201
Phone: (724) 545-9700
FAX: (724) 545-9797
E-mail: kharris@psu.edu

Navy Joining Center (Operated by Edison Welding Institute)

The Navy Joining Center (NJC) provides a national resource for the development of materials joining expertise and the deployment of emerging manufacturing technologies to Navy contractors, subcontractors, and other activities. The NJC works with the Navy to determine and evaluate joining technology requirements and conduct technology development and deployment projects to address these issues. The NJC is operated by the Edison Welding Institute.

Point of Contact:
Mr. Harvey R. Castner
EWI/Navy Joining Center
1250 Arthur E. Adams Drive
Columbus, OH 43221-3585
Phone: (614) 688-5063
FAX: (614) 688-5001
E-mail: harvey_castner@ewi.org

National Center for Excellence in Metalworking Technology (Operated by Concurrent Technologies Corporation)

The National Center for Excellence in Metalworking Technology (NCEMT) provides a national center for the development, dissemination, and implementation of advanced technologies for metalworking products and processes. Operated by the Concurrent Technologies Corporation, the NCEMT helps the Navy and defense contractors improve manufacturing productivity and part reliability through development, deployment, training, and education for advanced metalworking technologies.

Point of Contact:
Dr. Daniel Winterscheidt
National Center for Excellence in Metalworking Technology
c/o Concurrent Technologies Corporation
100 CTC Drive
Johnstown, PA 15904-1935
Phone: (814) 269-6840
FAX: (814) 269-2501
E-mail: winter@ctcgsc.com

Energetics Manufacturing Technology Center

The Energetics Manufacturing Technology Center (EMTC) addresses unique manufacturing processes and problems of the energetics industrial base to ensure the availability of affordable, quality, and safe energetics. The EMTC's focus is on technologies to reduce manufacturing costs, improve product quality and reliability, and develop environmentally benign manufacturing processes. The EMTC is located at the Indian Head Division of the Naval Surface Warfare Center.

Point of Contact:
Mr. John Brough
Naval Surface Warfare Center
Indian Head Division
101 Strauss Avenue
Building D326, Room 227
Indian Head, MD 20640-5035
Phone: (301) 744-4417
DSN: 354-4417
FAX: (301) 744-4187
E-mail: broughja@ih.navy.mil

Center for Naval Shipbuilding Technology

The Center for Naval Shipbuilding Technology (CNST) supports the Navy's ongoing effort to identify, develop and deploy in U.S. shipyards, advanced manufacturing technologies that will reduce the cost and time to build and repair Navy ships. CNST provides a focal point for developing and transferring new manufacturing processes and technologies; benefits that will accrue not only to the Navy, but to industry as well. CNST is operated and managed by ATI in Charleston, South Carolina.

Point of Contact:
Mr. Ron Glover
Center for Naval Shipbuilding Technology
5300 International Blvd.
Charleston, SC 29418
Phone: (843)760-4606
FAX: (843)760-4098
E-mail: glover@aticorp.org

Gulf Coast Region Maritime Technology Center (Operated by University of New Orleans, College of Engineering)

The Gulf Coast Region Maritime Technology Center (GCRMTC) fosters competition in shipbuilding technology through cooperation with the U.S. Navy, representatives of the maritime industries, and various academic and private research centers throughout the country. Located at the University of New Orleans, the GCRMTC focuses on improving design and production technologies for shipbuilding, reducing material costs, reducing total ownership costs, providing education and training, and improving environmental engineering and management.

Point of Contact:
Mr. Frank Bordelon, New Orleans Site Director
Gulf Coast Region Maritime Technology Center
Research and Technology Park
CERM Building, Room 409
University of New Orleans
New Orleans, LA 70148-2200
Phone: (504) 280-5609
FAX: (504) 280-3898
E-mail: fbordelo@uno.edu

Appendix G

Completed Surveys

As of this publication, 142 surveys have been conducted and published by BMP at the companies listed below. Copies of older survey reports may be obtained through DTIC or by accessing the BMP web site. Requests for copies of recent survey reports or inquiries regarding BMP may be directed to:

Best Manufacturing Practices Program
4321 Hartwick Rd., Suite 400
College Park, MD 20740
Attn: Anne Marie T. SuPrise, Ph.D., Director
Telephone: 1-800-789-4267
FAX: (301) 403-8180
annemari@bmpcoe.org

1985 Litton Guidance & Control Systems Division - Woodland Hills, CA

1986
Honeywell, Incorporated Undersea Systems Division - Hopkins, MN (now Alliant TechSystems, Inc.)
Texas Instruments Defense Systems & Electronics Group - Lewisville, TX
General Dynamics Pomona Division - Pomona, CA
Harris Corporation Government Support Systems Division - Syosset, NY
IBM Corporation Federal Systems Division - Owego, NY
Control Data Corporation Government Systems Division - Minneapolis, MN

1987
Hughes Aircraft Company Radar Systems Group - Los Angeles, CA
ITT Avionics Division - Clifton, NJ
Rockwell International Corporation Collins Defense Communications - Cedar Rapids, IA
UNISYS Computer Systems Division - St. Paul, MN

1988
Motorola Government Electronics Group - Scottsdale, AZ
General Dynamics Fort Worth Division - Fort Worth, TX
Texas Instruments Defense Systems & Electronics Group - Dallas, TX
Hughes Aircraft Company Missile Systems Group - Tucson, AZ
Bell Helicopter Textron, Inc. - Fort Worth, TX
Litton Data Systems Division - Van Nuys, CA
GTE C^3 Systems Sector - Needham Heights, MA

1989
McDonnell-Douglas Corporation McDonnell Aircraft Company - St. Louis, MO
Northrop Corporation Aircraft Division - Hawthorne, CA
Litton Applied Technology Division - San Jose, CA
Litton Amecom Division - College Park, MD (now Northrop Grumman Electronic Systems Division)
Standard Industries - LaMirada, CA (now SI Manufacturing)
Engineered Circuit Research, Incorporated - Milpitas, CA
Teledyne Industries Incorporated Electronics Division - Newbury Park, CA
Lockheed Aeronautical Systems Company - Marietta, GA
Lockheed Missile Systems Division - Sunnyvale, CA (now Lockheed Martin Missiles and Space)
Westinghouse Electronic Systems Group - Baltimore, MD (now Northrop Grumman Corporation)
General Electric Naval & Drive Turbine Systems - Fitchburg, MA
Rockwell Autonetics Electronics Systems - Anaheim, CA (now Boeing North American A&MSD)
TRICOR Systems, Incorporated - Elgin, IL

1990
Hughes Aircraft Company Ground Systems Group - Fullerton, CA
TRW Military Electronics and Avionics Division - San Diego, CA
MechTronics of Arizona, Inc. - Phoenix, AZ
Boeing Aerospace & Electronics - Corinth, TX
Technology Matrix Consortium - Traverse City, MI
Textron Lycoming - Stratford, CT

1991	Resurvey of Litton Guidance & Control Systems Division - Woodland Hills, CA Norden Systems, Inc. - Norwalk, CT (now Northrop Grumman Norden Systems) Naval Avionics Center - Indianapolis, IN United Electric Controls - Watertown, MA Kurt Manufacturing Co. - Minneapolis, MN MagneTek Defense Systems - Anaheim, CA (now Power Paragon, Inc.) Raytheon Missile Systems Division - Andover, MA AT&T Federal Systems Advanced Technologies and AT&T Bell Laboratories - Greensboro, NC and Whippany, NJ Resurvey of Texas Instruments Defense Systems & Electronics Group - Lewisville, TX
1992	Tandem Computers - Cupertino, CA Charleston Naval Shipyard - Charleston, SC Conax Florida Corporation - St. Petersburg, FL Texas Instruments Semiconductor Group Military Products - Midland, TX Hewlett-Packard Palo Alto Fabrication Center - Palo Alto, CA Watervliet U.S. Army Arsenal - Watervliet, NY Digital Equipment Company Enclosures Business - Westfield, MA and Maynard, MA Computing Devices International - Minneapolis, MN (now General Dynamics Information Systems) (Resurvey of Control Data Corporation Government Systems Division) Naval Aviation Depot Naval Air Station - Pensacola, FL
1993	NASA Marshall Space Flight Center - Huntsville, AL Naval Aviation Depot Naval Air Station - Jacksonville, FL Department of Energy Oak Ridge Facilities (Operated by Martin Marietta Energy Systems, Inc.) - Oak Ridge, TN McDonnell Douglas Aerospace - Huntington Beach, CA (now Boeing Space Systems) Crane Division Naval Surface Warfare Center - Crane, IN and Louisville, KY Philadelphia Naval Shipyard - Philadelphia, PA R. J. Reynolds Tobacco Company - Winston-Salem, NC Crystal Gateway Marriott Hotel - Arlington, VA Hamilton Standard Electronic Manufacturing Facility - Farmington, CT (now Hamilton Sundstrand) Alpha Industries, Inc. - Methuen, MA
1994	Harris Semiconductor - Palm Bay, FL (now Intersil Corporation) United Defense, L.P. Ground Systems Division - San Jose, CA Naval Undersea Warfare Center Division Keyport - Keyport, WA Mason & Hanger - Silas Mason Co., Inc. - Middletown, IA (now American Ordnance LLC) Kaiser Electronics - San Jose, CA U.S. Army Combat Systems Test Activity - Aberdeen, MD (now Aberdeen Test Center) Stafford County Public Schools - Stafford County, VA
1995	Sandia National Laboratories - Albuquerque, NM Rockwell Collins Avionics & Communications Division - Cedar Rapids, IA (now Rockwell Collins, Inc.) (Resurvey of Rockwell International Corporation Collins Defense Communications) Lockheed Martin Electronics & Missiles - Orlando, FL McDonnell Douglas Aerospace (St. Louis) - St. Louis, MO (now Boeing Aircraft and Missiles) (Resurvey of McDonnell-Douglas Corporation McDonnell Aircraft Company) Dayton Parts, Inc. - Harrisburg, PA Wainwright Industries - St. Peters, MO Lockheed Martin Tactical Aircraft Systems - Fort Worth, TX (now Lockheed Martin Aeronautics Company) (Resurvey of General Dynamics Fort Worth Division) Lockheed Martin Government Electronic Systems - Moorestown, NJ Sacramento Manufacturing and Services Division - Sacramento, CA JLG Industries, Inc. - McConnellsburg, PA
1996	City of Chattanooga - Chattanooga, TN Mason & Hanger Corporation - Pantex Plant - Amarillo, TX Nascote Industries, Inc. - Nashville, IL Weirton Steel Corporation - Weirton, WV NASA Kennedy Space Center - Cape Canaveral, FL Resurvey of Department of Energy, Oak Ridge Operations - Oak Ridge, TN

1997	Headquarters, U.S. Army Industrial Operations Command - Rock Island, IL (now Operational Support Command) SAE International and Performance Review Institute - Warrendale, PA Polaroid Corporation - Waltham, MA Cincinnati Milacron, Inc. - Cincinnati, OH Lawrence Livermore National Laboratory - Livermore, CA Sharretts Plating Company, Inc. - Emigsville, PA Thermacore, Inc. - Lancaster, PA Rock Island Arsenal - Rock Island, IL Northrop Grumman Corporation - El Segundo, CA (Resurvey of Northrop Corporation Aircraft Division) Letterkenny Army Depot - Chambersburg, PA Elizabethtown College - Elizabethtown, PA Tooele Army Depot - Tooele, UT
1998	United Electric Controls - Watertown, MA Strite Industries Limited - Cambridge, Ontario, Canada Northrop Grumman Corporation - El Segundo, CA Corpus Christi Army Depot - Corpus Christi, TX Anniston Army Depot - Anniston, AL Naval Air Warfare Center, Lakehurst - Lakehurst, NJ Sierra Army Depot - Herlong, CA ITT Industries Aerospace/Communications Division - Fort Wayne, IN Raytheon Missile Systems Company - Tucson, AZ Naval Aviation Depot North Island - San Diego, CA U.S.S. Carl Vinson (CVN-70) - Commander Naval Air Force, U.S. Pacific Fleet Tobyhanna Army Depot - Tobyhanna, PA
1999	Wilton Armetale - Mount Joy, PA Applied Research Laboratory, Pennsylvania State University - State College, PA Electric Boat Corporation, Quonset Point Facility - North Kingstown, RI Resurvey of NASA Marshall Space Flight Center - Huntsville, AL Orenda Turbines, Division of Magellan Aerospace Corporation - Mississauga, Ontario, Canada
2000	Northrop Grumman, Defensive Systems Division - Rolling Meadows, IL Crane Army Ammunition Activity - Crane, IN Naval Sea Logistics Center, Detachment Protsmouth - Portsmouth, NH Stryker Howmedica Osteonics - Allendale, NJ
2001	The Tri-Cities Tennessee/Virginia Region - Johnson City, TN General Dynamics Armament Systems - Burlington, VT (now General Dynamics Armament and Technical Products) Lockheed Martin Naval Electronics & Surveillance Systems-Surface Systems - Moorestown, NJ Frontier Electronic Systems - Stillwater, OK
2002	U.S. Coast Guard, Maintenance and Logistics Command-Atlantic - Norfolk, VA U.S. Coast Guard, Maintenance and Logistics Command-Pacific - Alameda, CA Directorate for Missiles and Surface Launchers (PEO TSC-M/L) - Arlington, VA General Tool Company - Cincinnati, OH
2003	University of New Orleans, College of Engineering - New Orleans, LA Bender Shipbuilding and Repair Company, Inc. - Mobile, AL In Tolerance - Cedar Rapids, IA ABC Virtual Communications, Inc. - West Des Moines, IA Resurvey of Electric Boat Corporation, Quonset Point Facility - North Kingstown, RI United Defense, L.P. Ground Systems Division - Aiken, SC Auto-Valve, Inc. - Dayton, OH
2004	United Defense, L.P. Armament Systems Division - Aberdeen, SD TOMAK Precision - Lebanon, OH RB Tool & Manufacturing Company - Cincinnati, OH Forest City Gear - Roscoe, IL CALCE Electronic Products and Systems Center - College Park, MD