THE APPLICATION OF QUALITY FUNCTION DEPLOYMENT
TO THE DESIGN AND MANUFACTURE OF ENGINE MAIN
BEARINGS

by

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(ABSTRACT)

Quality Function Deployment is an extremely useful tool which can be applied within the Systems Engineering Process, to optimize product design and the design process. The use of cross functional teams to analyze customer needs, translate them into design attributes, and subsequently deploy them through every facet of product design, development, and production, can significantly enhance the effectiveness and efficiency of the entire process. Unfortunately the few examples of Quality Function Deployment application, in the academic literature, are generally simplistic and lack any significant depth.

The objective of this report is to investigate the application of Quality Function Deployment to a relatively complex product design requirement in an actual manufacturing environment. Specifically, the design and production of engine main bearings at the Federal Mogul plant in Blacksburg, Virginia, are considered.

The report examines the use of Quality Function Deployment, as a general design tool; the functional requirements and design constraints of engine main bearings; and the application of one variation of Quality Function Deployment to the evaluation of proposed changes to a bearing’s design configuration and the bearing production process.

The report concludes with recommendations concerning the implementation of Quality Function Deployment at Federal Mogul, the conduct of Quality Function Deployment instruction at Virginia Tech and a possible avenue for future research.
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GLOSSARY

BABBITT - a lead or tin based bearing lining material in which the lead or tin constitutes 80% to 90% of the lining alloy.

BEARING WALL THICKNESS - The thickness of the bearing shell, including the backing material and the lining material.

CONCURRENT ENGINEERING - Conducting interdepartmental design and development activities concurrently, rather than sequentially, using cross functional teams. The early integration of input from design engineers, process and production personnel, principal component suppliers and other key company members results in: better communication, early identification and resolution of conflicts or problems, shorter product development time frames and fewer design changes.

CONFORMABILITY - The ability of the bearing lining material to deform slightly to accommodate minor variations in the shaft surface, without degrading the bearing function.

CRANKSHAFT - The main shaft of the engine, which transmits power to the driveline.

EMBEDABILITY - The ability of the bearing lining material to absorb small amounts of dirt or metal particulate matter, thereby reducing shaft wear.

FATIGUE STRENGTH - The ability of the bearing to withstand engine operating loads.

HOSHIN PLANNING - Also called Hoshin Kanri, Policy Deployment and Management by Planning. This is the Japanese replacement for Management by Objectives (MBO). It
involves the participative setting of two to three major goals, communication of these goals to every member of the company and the alignment of subordinate level plans and objectives to the primary company goals.

**JOURNAL** - The portion of the shaft in contact with the bearing surface.

**MAIN BEARING** - A bearing that is used to support the crankshaft of an engine.

**OIL CLEARANCE** - The difference in diameter between the journal and the bearing inside face.

**WEAR** - The gradual loss of surface material caused by the friction generated during engine operation.
CHAPTER 1

INTRODUCTION

The modern marketplace is an increasingly competitive environment. In addition, many products and services have become very complex, generating expensive design and production costs. It has, therefore, become extremely important to correctly identify consumer needs and desires; to quickly design, develop, produce and maintain products and services to meet these needs; and to get it right the first time. Quality Function Deployment (QFD) is one method that can be used to gain a competitive advantage by: improving product design and production effectiveness; improving the efficiency of product development; and increasing overall customer satisfaction.

1.1 OBJECTIVE

The objective of this report is to illustrate the application of QFD to an industrial manufacturing process. Specifically, the report will examine the application of several facets of QFD in the design and manufacture of engine main bearings, at the Federal Mogul plant in Blacksburg, Virginia.

QFD is an extremely useful tool that can be applied to every phase of the product or service design, development and production process. Although widely used in Japan, and increasingly popular in the United States, there are very few comprehensive examples of its application, in the academic literature. This may be due, in part, to the
secretive nature of companies that have used QFD successfully (and wish to retain a competitive advantage). It may also be due to the perception that QFD is a highly complicated process, requiring a great deal of time and effort to apply, to any significant depth. Whatever the reason, the available examples that do give more than a passing reference to the in depth application of QFD, tend to use extremely simplistic and superficial examples, to demonstrate general principles and concepts. This report will, therefore, illustrate the application of QFD to several aspects of the design and production of a relatively complex manufactured product.

Hopefully the areas of QFD examined in this report will also serve as the foundation for expanded application of the QFD process within the Federal Mogul manufacturing facility.

1.2 ORGANIZATION OF THIS REPORT

This report is organized into eight chapters. Introductory material and objectives are detailed in this chapter. A brief overview of the Systems Engineering Process, and the role of QFD within that process, are described in Chapter 2.

Chapter 3 provides background information on the QFD process, providing a brief historical summary and an introduction to the main variants of QFD. A step by step guide to the application of QFD is also presented.

Chapter 4 discusses the principal types of bearings and then examines the functions and operating characteristics of engine main bearings. An overview of design
considerations and production processes is also provided. Essentially this chapter provides the context and frame of reference for the remainder of the report.

The Voice of The Customer and the development of the primary QFD matrix (also known as the House of Quality) is addressed in Chapter five. Technical characteristics deployment is covered in Chapter six. Chapters five and six represent the product design and development aspects of QFD.

Chapter 7 details the use of QFD in evaluating the impact of design and production process changes. The Voice of the Customer is cascaded through to the production planning and decision making process. This is the process deployment facet of QFD.

Finally, Chapter 8 presents a summary of the project conclusions and recommendations. The recommendations include suggestions for additional research and further study.
CHAPTER 2

SYSTEMS ENGINEERING

Systems Engineering originated during the 1940’s, largely due to the urgency imposed by the Second World War. Complex, highly sophisticated equipment, and the requisite support and maintenance equipment to keep it operational, had to be designed, manufactured and fielded in minimum time. In addition, personnel had to be trained to operate and support the equipment. The conduct of training, acquisition and deployment of spares, support supplies and maintenance tools and equipment and numerous other considerations had to be coordinated to ensure that the primary equipment would meet its performance and availability requirements. In order to deal with the numerous resulting interactions and interdependencies, within a constricted time frame, the equipment and all of its related aspects had to be designed and produced as an equipment system. Further, all phases of the system life cycle, from conception to disposal, had to be considered in an unprecedented, highly integrated manner.

From this beginning, Systems Engineering has continued to evolve. Current relevant definitions include:

1. **System**: A system is a composite of people, products and processes that provide a capability to satisfy stated needs. A complete system includes the facilities, equipment (hardware and software), material, services, data, skilled personnel, and
techniques required to achieve, provide and sustain system

effectiveness [1]. This is illustrated at Figure 2.1.

![Diagram of System Elements](image)

**Figure 2.1** The Elements of a System [2]

2. **Systems Engineering:** The application of scientific and engineering
efforts to:

   a. Transform an operational need into a description of system

   performance parameters and a preferred system configuration
through the iterative process of functional analysis, synthesis, optimization, design, test and evaluation.

b. Integrate related technical parameters and assure compatibility of all physical, functional and program interfaces in a manner that optimizes the total system design and definition.

c. Integrate functional design, reliability, maintainability, human factors, system support, safety, security, producibility, and other related specialties into the total engineering effort [3].

2.1 THE SYSTEMS ENGINEERING PROCESS

Systems Engineering is a process employed in the evolution of systems from the point when a need is identified through production and/or construction and ultimate deployment of that system for consumer use [4]. It addresses not only the primary equipment, but also the system elements necessary to produce the equipment and to support and maintain it after deployment. In short, the process integrates the functional design, producibility and supportability of the equipment and its associated logistical elements, throughout the entire life cycle of the system, as shown at Figure 2.2 [5].

As a conceptual process, Systems Engineering utilizes many interrelated engineering and management, tools and techniques such as:

1. Concurrent Engineering (CE)

2. Total Quality Management (TQM)
3. Total Productive Maintenance (TPM)
4. Integrated Logistic Support (ILS)
5. Company Wide Quality Control (CWQC)
6. Total Quality Control (TQC)

Figure 2.2 The System Life Cycle [5]

Although the detailed process must be tailored to meet the specific requirements of a particular project, a general outline of the Systems Engineering Process activities, at each particular stage in the system life cycle, is illustrated at Figure 2.3. Starting from an identified need, the process refines the need definition. Conceptual design follows, to identify an approach to meet the need. Preliminary design starts with a functional analysis of the system and then uses an iterative approach to allocate design criteria and to ultimately generate the detailed design specification. Detailed design follows, including prototyping and testing. Production and utilization of the product by the
consumer also incorporate support activities, system assessment and modifications for corrective action. Finally, the system is phased out and disposed of.
Figure 2.3 The Systems Engineering Process[6]
By considering a new product or service requirement from a systems perspective, in the context of the entire system life cycle, systems engineering attempts to optimize the design at the earliest possible time. In this way, the requirement for “downstream” design changes can be reduced and total system life cycle cost will be minimized. As shown at Figure 2.4, the potential for life cycle cost savings is significantly reduced as the design process progresses.

Figure 2.4 Life Cycle Relative Costs [7]
The life cycle cost relationships illustrated at Figure 2.4 are largely attributed to two significant facts:

1. As decisions are made, flexibility is reduced.
2. The cost of design changes increases dramatically as the project progresses, as shown in Figure 2.5.

Figure 2.5 Relative Design Change Costs [8]

The extent to which the Systems Engineering Process can be used to “get it right the first time,” in the design of products and services, can greatly reduce the overall system life cycle costs, in addition to providing better solutions to meet customer needs.
2.2 THE REPORT DOMAIN

In terms of the Systems Engineering Process, QFD is an extremely useful tool that can be applied to numerous aspects (and throughout the life cycle) of the product design, development and production process. As illustrated at Figure 2.6, QFD is one of the most versatile tools, from a Concurrent Engineering perspective. This is one of the unique features of QFD: the initial process which captures the Voice of the Customer (VOC) can be expanded, through several iterations, and applied to subsequent product development phases. In this way, the VOC is integrated into the decision making process at each stage.

This report will focus on the application of QFD to the Systems Engineering Process, with particular emphasis on the definition of customer need and the subsequent design of the product itself, and its production process. As previously discussed, these stages offer the greatest opportunity to influence the total system life cycle cost. QFD can be used to do this by reducing product development time frames, increasing the efficiency and effectiveness of design activities and reducing the requirement for costly downstream design changes.

Insights gained by the QFD process can also be applied to the design, development and deployment of the primary equipment’s systemic envelope i.e. the equipment and facilities required for production, personnel training, tools and test equipment, spares and so forth. While these factors are beyond the scope of this report, they remain an integral part of the overall Systems Engineering Process.
Figure 2.6 Concurrent Engineering Development Tools (adapted from Syan)[9]
CHAPTER 3

QUALITY FUNCTION DEPLOYMENT

Quality Function Deployment is an approximate translation of Hin Shitsu Ki No Ten Kai, in Japanese. Hin and Shitsu can be interpreted as ‘quality’, ‘features’, ‘attributes’, or ‘qualities’; Ki and No could represent the terms ‘function’ or ‘mechanization’; and the terms ‘deployment’, ‘diffusion’ or ‘evolution’ could be inferred from the terms Ten and Kai [10].

As can be seen from the preceding translation, QFD is not a straightforward ‘quality’ based concept. In fact, “QFD is not a quality tool, although it can certainly improve quality in the broadest sense of the word. Rather, QFD is a structured method for planning. QFD allows product planners to begin the planning process with a structured list of customer needs and to evaluate each proposed product feature and function according to the impact it has in meeting the customer’s needs.” [11]

For the purposes of this report QFD is defined as:

a process used for converting the consumers demands into ‘quality characteristics’ and developing a design quality for the finished product by systematically deploying the relationships between the demands and the characteristics, starting with the quality of each functional component and extending the deployment to the quality of each part and process. The overall quality of the product will be formed through this network of relationships. [12]
It should be noted that QFD can also be used in the design and development of services. As this report focuses on a manufactured product, however, all subsequent discussion will be phrased in that context.

3.1 QFD BACKGROUND

QFD is a concept that was developed by Dr. Yoji Akao, in Japan, in 1966. It was introduced into the Kobe shipyards of Mitsubishi Heavy Industries Ltd. in 1972 and is generally regarded as the first large scale successful application of QFD. After this widely publicized successful introduction, QFD has grown in popularity in Japan: a 1986 survey indicated that 54% of the Japanese Union of Scientists and Engineer member companies were using QFD [13]. Yoji Akao also introduced the QFD concept to the United States, in 1983. Since that time, it has been adopted by many large prominent firms including: Digital Equipment Corporation, Ford, General Motors, Procter & Gamble, Polaroid, Hughes Aircraft, Hewlett Packard and Rockwell International [14].

QFD was developed as a design tool which could be used to convert consumer demands and needs into "quality characteristics." The interrelationships between the demands and the characteristics could then be "deployed" through the products functional components, parts and processes; into the design and manufacture of the final product.

Another cornerstone of the QFD process is the interdisciplinary team approach used in its implementation. Ideally, every department in the company, and its major
suppliers, should be represented on the QFD team. The product design can then be discussed in terms of technical specifications, producibility, marketability, cost, etc., at the earliest possible stage. This process ensures that potential interdepartmental design priority conflicts can be identified and resolved, before the design is finalized. In addition, the enhanced communication between team members, and the general awareness of the customer's needs and priorities, increases the overall effectiveness of product design, development, production, sales and support.

3.2 QFD METHODOLOGIES

There are currently three, somewhat different, approaches to the application of QFD. The first is a 'condensed' version of Dr. Akao's concepts (referred to as the Makabe approach) that has been popularized in the United States by Don Clausing and John Hauser [15]. The second is an 'enhanced' version of Dr. Akao's original concept that has been expanded to include technology deployment, reliability deployment and cost deployment, into the overall process.

In the third approach, Dr. Akao's approach has been further modified by Bob King, an American associate of Dr. Akao, who has taken the rather complex structure of Akao's QFD model and transformed it into a matrix of matrices, with a 'cookbook' style of implementation. This will be explained below, following the overview of the two basic approaches.
3.2.1 The Makabe/Clausing Approach

The Makabe/Clausing approach uses the Voice of the Customer in an initial matrix (The House of Quality) to develop the system or product design requirements. The Voice of the Customer is then deployed through successive matrixes to carry the customer requirements through into part characteristics, manufacturing requirements and production operations. This sequence is depicted at Figure 3.1. The four matrix operations are described briefly below.

![Diagram of the Makabe/Clausing Approach](image)

**Figure 3.1 The Makabe/Clausing Approach to QFD [16]**

3.2.1.1 The Product Planning Matrix

The product planning matrix translates the Voice of the Customer into design requirements for the complete product. The process by which this is done will be described later, in more detail. In short, however, the matrix is a conceptual map that provides a means for personnel from all departments to communicate and interact in the
product planning. The ‘big picture’ is developed with input from all concerned functional areas, and the needs of the customer are prioritized and weighted. The engineering implications of the customers requirements are also determined and potential conflicts and interactions are identified and evaluated. A competitive analysis is also conducted to determine potential sales points and areas in which to concentrate to improve competitive advantage.

3.2.1.2 Part Deployment Matrix

Key design requirements are determined from the first matrix using a weighting system. These attributes are then correlated with each of the component parts of the product under consideration using a second matrix: the part deployment matrix. In this way, the contribution and criticality of each part, to each of the key design requirements can be identified. Further, interactions between the product’s component parts, in meeting the overall product design requirements, can be identified and discussed by the project design team. These relationships and information are used in subsequent decisions with respect to the design and manufacture of each part.

3.2.1.3 Process Planning Matrix

The product components and critical component characteristics identified in the second matrix are deployed to the third matrix: the process planning matrix. This matrix identifies the relationships between the required parts characteristics and the
manufacturing processes which can be used to achieve them. This stage of the process constitutes a transition from product design to manufacturing design i.e. how to produce the design requirements to satisfy the needs of the customer. Again, the importance of multi-level and multi-functional personnel involvement in the QFD process is self evident.

3.2.1.4 The Production Planning Matrix

This final matrix translates the process requirements of the third matrix into detailed ‘shop floor’ information. This information includes items such as: which machines will be used to carry out specific processes on specific parts, which processes will be inspected and how, critical control points, reporting procedures and so on. In essence, the customer’s needs have been deployed through design requirements, to parts characteristics, processing decisions and ultimately down to the individual machine operators instructions. A detailed representation of this process is shown at Figure 3.2.
Figure 3.2 Detailed Makabe/Clausing Approach [17]
3.2.2 The Akao Approach

As previously stated, Dr. Akao developed the original QFD concept and has subsequently modified his approach. He believes that the design process must include not only quality function deployment but technology, reliability and cost deployment considerations as well [18]. These ideas are represented graphically at Figure 3.3. Dr. Akoa suggests that the four ‘deployments’ should be completed in sequential order, that is completion of the Quality Deployment portion of the chart should precede any work on the Technology Deployment. Each of the four ‘deployments’ are briefly described below.

3.2.2.1 Quality Deployment

Dr. Akao’s quality deployment stage consists of four charts:

1. Chart 1-I called ‘quality chart’ by Dr. Akao. This chart relates customer needs to quality characteristics. In essence it is identical to the ‘House of Quality’ described in the Makabe/Clausing approach.

2. Chart 2-I relates desired product functions to the quality characteristics. This chart is developed by translating the voice of the customer into desired product functions and correlating them with the quality characteristics identified in Chart 1-I.
3. Chart 3-1 relates product sub-assemblies and parts to the quality characteristics from Chart 1-1. This chart is therefore very similar to the Parts Deployment phase of the Makabe/Clausing approach.

4. Chart 2'-1 relates product functions to customer needs. This ensures that all needs have been translated into representative functions and gives an indication of the interdependencies. Note that there may be an iterative process between Charts 1-1, 2-1 and 2'-1.

The overall purpose of the four Quality Deployment charts is to identify product design requirements (quality characteristics) based on the Voice of the Customer and to then evaluate them in terms of product parts/assemblies and desired product performance functions.

3.2.2.2 Technology Deployment

Technology deployment uses the matrices as indicated in Figure 3.3, to identify relationships between product mechanisms and functions and any new technologies. Mechanism costs and function costs are also determined as proportions of the overall product cost. Finally, the degree of difficulty in achieving the application of a new technology to a specific function or mechanism is also estimated. Based on this information, the targets for the application of new technology are selected.
3.2.2.3 Cost Deployment

This deployment begins by identifying/estimating the product's market price, market share, sales volume and targeted manufacturing costs. A series of matrices are then used to estimate the costs of each function, mechanism, part or assembly and quality characteristic of the desired product. This information is then used to compare the company's own products and those of its competitors, to the plans for the new product.

3.2.2.4 Reliability Deployment

Fault Tree Analysis (FTA) and Failure Modes and Effects Analysis (FMEA) are used to determine the products potential failure modes and reliability weaknesses. This information is then evaluated using matrices that compare product failure modes to customer needs, product functions and product mechanisms. The cost and likelihood of each failure mode is then evaluated. This information is used to identify quality control points and checks on the product and the production processes.
Figure 3.3a The Akao Approach [19]
3.2.3 The King Approach

It is readily apparent that the process outlined above is quite complicated. The diagram of the process at Figure 3.3 is difficult to decipher and involves many complex interrelationships, which may not be immediately evident to the inexperienced QFD practitioner. In addition, many of the specific charts in the four ‘deployments may not be applicable to the needs of every user. Dr. Akao’s process offers little explanation of how to bypass unrequired charts or how to modify the process when a completely new design is not required. Nevertheless, the process is clearly intended to be flexible and users are encouraged to “copy the spirit, not the form” [19]. For this reason, Mr. Bob King has taken Dr. Akao’s QFD process and converted it into a much simpler group of matrices [20]. Further, he has simplified the process into a ‘cookbook’ format which prescribes a series of matrices for use, depending on the objective of the user. It should be noted that Dr. Akao has strongly endorsed Mr. King’s book as a much simpler, yet extremely effective explanation of his QFD approach [21].

The matrix of matrices is shown at Figure 3.4. It consists of seven groups (A to G) of related matrices, focusing on different aspects of the product design, development and production process. Although Mr. King does offer suggested matrix sequences for different applications, the user can select the individual matrixes needed to satisfy their particular requirement. Unfortunately, a detailed discussion of each matrix is beyond the scope of this project and report. Several matrices will, however, be developed to address specific issues related to the manufacture of bearings at Federal Mogul. The reader is,
therefore, referred to Mr. King’s book: “Better Designs in Half the Time” for a comprehensive explanation of the method of use and application of each matrix.

**Figure 3.4 Matrix of Matrices [22]**

It should be noted that the seven groups of matrices can be applied to a wide range of activities spanning the entire product development process, from initial concept
design to final production. This is illustrated at Figure 3.5. The overlap of each series provides several QFD matrices which can be applied to any particular design requirement and individual results can be compared as a form of validation.

Figure 3.5 Matrix Groups Applicable to Product Design Steps [23]
3.3 APPLICATION OF QFD

There is no single ‘correct’ way to employ QFD. Indeed, the user should tailor the application of QFD to meet the specific requirements of the situation at hand and to conform to the general culture of their company or organization. Nevertheless, there are some central guidelines, particularly with respect to the first matrix, the ‘House of Quality,’ which are common to all three QFD approaches. As this first chart is the key to all subsequent matrices, it is imperative that it be completed effectively.

The exact structure of the House of Quality can vary. A representative example is shown at Figure 3.6. This matrix will be completed using the development of a new textbook, as an example to illustrate the process. The process is completed in six steps\(^1\) as outlined below [25].

3.3.1 Step 1: Identify Customer Requirements

The voice of the customer is the primary input to the QFD process. The most critical and difficult step of the process is to capture the essence of the customer’s comments. A variety of techniques can be used to capture the customer’s voice including: direct customer interviews, questionnaires, review of customer complaints, interviews with sales staff and service representatives and many other avenues.

---

1 The number of steps required to complete the House of Quality varies, depending on the reference consulted. Invariably, however, procedures involving additional steps have merely broken down the six step process into smaller segments, creating additional steps. There is, however, some variation in the recommended order to perform these steps. This is due to the inherent flexibility and adaptability of QFD.
Customer requirements normally expand into secondary and tertiary requirements. For a textbook, the primary attribute “meets instructional needs” might encompass secondary attributes of “good topical coverage,” “appropriate level for the course,” and “good exercises.” “Good exercises” might be further subdivided into “sufficient quantity” and “range of difficulty.” These desired product attributes are used as inputs to the QFD process as shown at Figure 3.7.
3.3.2 Step 2: Identify Technical Requirements

This stage is sometimes called the “Voice of the Engineer”. Essentially technical requirements are the “hows” by which the company will respond to the “whats” --
customer requirements. These technical requirements are design characteristics that can be measured and compared to objective targets. The author and publisher of a textbook have a variety of technical characteristics to consider, including the amount of research literature to cite, the amount of popular literature to reference, the number of numerical exercises, the number of open ended exercises, the design and purpose of software ancillaries, the use of figures and tables, color, correctness of grammar, and size of the book.

The roof of the House of Quality shows the interrelationships between any pair of technical requirements. These relationships indicate answers to questions such as “How does one change of product characteristics affect others?” This matrix process encourages one to view features collectively rather than individually\(^2\). The addition of this information to the House of Quality is shown at Figure 3.8.

**3.3.3 Step 3: Customer Requirements And Technical Requirements Relationships**

In the main body of the matrix, the relationships between the customer requirements and technical requirements are evaluated and the degree or strength of the relationship is indicated symbolically. The purpose of the relationship matrix is to show whether the final technical requirements adequately address customer requirements. This assessment is usually based on expert experience, customer responses or controlled experiments.

\(^2\) Not all Houses of Quality are completed using the “roof.” Akao and King recommend using a separate matrix for this purpose.
Figure 3.8 Technical Requirements [27]

The lack of a strong relationship between a customer requirement and any technical requirement shows that the customer needs are either not addressed or that the final product will have difficulty in meeting them. Similarly, if a technical requirement
does not affect any customer requirement, it may be redundant or the designers may have missed some important customer need. This information is added to the House of Quality as shown at Figure 3.9.

![Figure 3.9 Relationships Matrix [28]](image)
3.3.4 Step 4: Competitive Evaluation

This step identifies importance ratings for each customer requirement and evaluates existing products for each of them. Customer importance ratings represent the areas of greatest interest and highest expectations as expressed by the customer. Competitive evaluation highlights the absolute strengths and weaknesses in competing products, based on customer perceptions. By using this step, designers can discover opportunities for improvement and competitive advantage.

In designing a textbook, the author and publisher may find that two major competing textbooks, A and B, are weak in applications, whereas customer surveys of instructors reveal applications to be a highly desirable attribute. By focusing on this attribute and using it as a key selling point, the author and publisher gain a competitive advantage as illustrated in Figure 3.10.

3.5 Step 5: Technical Evaluation

This step compares the performance of competitor products, to the company’s own product, for each technical requirement. This information can be often be obtained through product technical information, but may also require some testing of competitor products. On the basis of customer importance ratings and existing product strengths and weaknesses, targets for each technical requirement are set, as shown in Figure 3.11.
Figure 3.10 Competitive Evaluation [29]
Figure 3.11 Completed House of Quality [30]
3.3.6 Step 6: Select Technical Requirements for Deployment

The technical requirements that have a strong relationship to customer needs, have poor competitive performance, or are strong selling points are identified during this step. These characteristics have the highest priority and need to be “deployed” throughout the remainder of the QFD process. Those characteristics not identified as critical do not need such rigorous attention. This step is also demonstrated in Figure 3.11.

3.4 QFD LIMITATIONS

There are several limitations to the QFD process that should be considered by the prospective user. First, QFD is not a “stand alone” tool, it is a cross-functional tool, usually considered to be a part of Total Quality Management, as illustrated in Figure 3.12. In order to work most effectively, a company should have a culture based on participation and cooperation. It is extremely difficult to transplant a tool that relies on interdisciplinary participation and cooperation, if this is counter to the normal ‘way of doing business’ in the company. The introduction is very likely to be viewed suspiciously, and approached superficially, and is therefore almost certain to fail.

A second limitation is that QFD is often mistakenly employed as a rigid process. It does not work well if the user attempts to copy a pattern, rather than the principles of the process. An example of this occurred in 1975, when Kayaba, a Japanese shock
absorber manufacture decided to implement QFD. They went to Toyota, a recognized highly successful user of QFD, and copied their sample charts. The results were dismal.

Figure 3.12 QFD: An Element of TQM [31]

Following this failure they decided to customize their QFD system to meet their needs and in 1980 they won the Deming prize for their Total Quality Control, with special recognition for their QFD [32].

Third, QFD does not work unless the process is sharply focused on the most important technical characteristics, from the outset. If the House of Quality matrix
becomes too big, the important information becomes buried in detail and the process becomes cumbersome. Similarly, subsequent deployments to later matrices become labour intensive and unwieldy if the information from the first House of Quality is not reduced to “the critical few.”

Finally, QFD takes a long time. Two to three years is a suggested time frame to allow a company to gain experience with QFD before changing the company’s design system [33].
CHAPTER 4

ENGINE BEARINGS

4.1 GENERAL

Before addressing the application of QFD to engine bearing design and production, a brief overview of bearing types, functions and manufacturing is appropriate. The information in this chapter is intended to provide a background to bearing operation, and as a frame of reference in which to relate the discussion of subsequent chapters. For those readers who are completely familiar with the design of engine main bearings, this chapter may be by-passed.

4.1.1 Types of Bearings

There are essentially two types of bearings:

1. *Bearings with rolling contact*: these are the bearings with which most people are familiar. Rolling contact bearings are designed to support and locate rotating shafts or parts in machines, to transfer loads between the rotating and stationary members, and to permit free rotation with a minimum of friction. They are composed of rolling elements interposed between an inner and outer ring. Separators, sometimes called cages or retainers, are used to space the rolling elements from each other. The rolling elements are usually of the ball, roller or taper roller type. A typical bearing of this type is shown at Figure 4.1.
2. *Sleeve bearings*: These bearings do not rotate but are held in place, around a rotating shaft, resulting in sliding contact. They can be non-*lubricated*, using material such as a nylon or teflon or *lubricated* using some type of grease, oil or graphite. The sleeve bearings of interest to this project are called *full film* bearings, because at operating speeds, the shaft inside the bearing is intended to be supported on a film of oil between the shaft and the bearing wall. This type of operation is illustrated at Figure 4.2.

### 4.1.2 Federal Mogul Bearings

Federal Mogul manufactures three different kinds of engine bearings: cam shaft bearings, connecting rod bearings and main bearings. The relative shape and location of these bearings, in a typical engine, is illustrated in Figure 4.3.
Figure 4.2  Full Film Bearing Operation [35]

Figure 4.3  Federal Mogul Engine Bearings [36]
This project is concerned with engine main bearings, which are located in the engine block, in order to support the crankshaft and allow it to rotate and transmit power to the drive-train. A typical application is shown in Figure 4.4.

Figure 4.4 Crankshaft and Main Bearings [37]
4.2 ENGINE MAIN BEARING FUNCTIONS

The engine main bearings serve three primary functions during engine operation:

1. The first function is to reduce friction between the crankshaft and its mounts within the engine block. This is accomplished by placing the bearing between the shaft and the engine block and then establishing and maintaining an oil film between the rotating shaft and the bearing surface.

2. The second function is to support the weight of the shaft and the loads generated during operation. The bearing materials must have sufficient load bearing capabilities to withstand the wide range of load conditions that can occur during the operating cycle of an engine.

3. The third function is to provide a wear surface between the shaft and the engine block. Even with lubrication, there is some wear inherent in normal operation. The bearing provides a replaceable lining that is significantly cheaper and easier to replace than either the shaft it supports or the casing in which it is mounted.

4.3 ENGINE BEARING DESIGN

The bearing functions described above are reflected in technical characteristics that must be designed into the engine bearings. Three key design considerations are discussed in the following sections.
4.3.1 Bearing Lubrication Factors

Oil Characteristics

Oil molecules exhibit two important characteristics, with respect to engine lubrication:

1. Oil molecules stick to metal surfaces more readily than to each other.
2. Oil molecules readily slide over each other.

The result of these two factors combined is that a shaft rotating in a sleeve, supported by an oil film, will retain a layer of lubricant between the two metallic surfaces and the friction resulting from rotation will be much less than that of the metallic surfaces rotating in direct contact.

Modes of Operation

A shaft in a fluid film bearing, starting from rest and accelerating to operating speeds, will pass through three phases of lubrication. These are: boundary lubrication, mixed-film lubrication and full film lubrication. These three modes of operation are illustrated at Figure 4.5 and briefly discussed below. Variables represented in the figure are:

\[ Z = \text{oil viscosity measured in centipoise} \]
\[ N = \text{shaft revolutions per minute (RPM)} \]
\[ P = \text{mean pressure on the bearing (psi)} \]
It is readily apparent that for a fixed viscosity lubricant, the phase of lubrication is largely dependent on engine RPM and load.

![Diagram of bearing modes of operation](image)

**Figure 4.5 Bearing Modes of Operation [38]**

1. **Boundary Lubrication.** Boundary lubrication takes place when the sliding surfaces are rubbing together, with only an extremely thin film of lubricant present. This state exists on start up, when the shaft is resting on the bearing surface, as shown in Figure 4.6. The coefficient of friction in this mode is high, as shown in Figure 4.5 and the direct contact results in
some wear on the bearing surface. The bearing would not last long under these conditions, due to the build up of heat and bearing frictional wear.

2. *Mixed Film Lubrication.* This is a transition phase. As the shaft rotational speed increases it begins to climb the bearing wall. At the same time oil is drawn between the shaft and the bearing and a hydrodynamic wedge begins to form, as shown in Figure 4.7.

3. *Full Film Lubrication.* In this phase of operation the hydrodynamic pressure increases and the oil wedge lifts the rotating shaft completely clear of the bearing surface. After reaching operating speed the shaft will continue to rotate on a continuous film of oil, as shown in Figure 4.8.

![Figure 4.6 Bearing on Startup: Boundary Lubrication [39]](image)
Figure 4.7 Mixed Film Bearing Rotation [40]

Figure 4.8 Full Film Bearing Rotation [41]
Engine Lubrication System

Oil is transferred to the bearing through a series of channels or ‘galleries’ cut into the engine block, which allow oil to pass into the bearings. This is illustrated at Figure 4.9. The passageways allow oil to be continuously cycled from the oil reservoir, at the bottom of the crankcase, through the engine bearings, before returning to the sump. In order to receive this oil, the bearings have a hole which aligns with the oil gallery in the engine block. In addition, the bearing is usually grooved to allow the oil to flow from the hole across the entire bearing surface. These features are shown at Figure 4.10.

Figure 4.9 Engine Bearing Lubrication System [42]
Figure 4.10 Oil Holes and Grooves [43]

Minimum Bearing Clearance

Figure 4.11 illustrates basic bearing dimensional characteristics:

\[ W = \text{applied load} \]
\[ N = \text{rotation} \]
\[ e = \text{eccentricity of shaft centre to bearing centre} \]
\[ \theta = \text{angle between applied load and point of max pressure} \]
\[ d = \text{shaft diameter} \]
\[ c_d = \text{bearing clearance} \]
\[ d + c_d = \text{bearing diameter} \]
\[ h_o = \text{minimum film thickness} \]

The point of minimum film thickness, \( h_o \), is also the point of maximum pressure. For a given oil viscosity and shaft rotation speed, the sustainable pressure at this point is largely determined by the film thickness, that is, the minimum clearance between the shaft and the bearing surface. A high quality finish on the bearing surface permits \( h_o \) to
be minimized. This increases the load capacity of the bearing and reduces bearing and shaft wear. In automotive engines typical values are $h_o = 0.0001$ to $0.0002$ in. [44].

![Diagram of Bearing Dimensions](image)

**Figure 4.11 Bearing Dimensional Characteristics [45]**

### 4.3.2 Bearing Load Factors

The bearing surface is typically a layer or layers of relatively softer material on a steel backing, as shown in Figure 4.12. This bearing material is called the bearing lining. Several factors must be considered in selecting lining materials to meet load requirements. Some of the most significant are discussed below.
Operating Pressure

The bearing surface material must be able to carry the weight of the shaft at rest and the additional pressure load created during rotation, without significant deformation. Typical peak operating pressures, under conditions of full film lubrication, for internal combustion engines are: diesel engine main bearings -- 800 to 1500 psi; and for gasoline engines -- 500 to 1000 psi [47].

Clearly, one of the criteria which will determine the selection of babbitt composition will be the anticipated operating pressures of the engine for which the bearing is being designed. Maximum recommended design pressures for various babbitt alloys are shown in Table 4.1 below.

Bearing Material Hardness

One of the functions of the bearing is to act as a wear surface, so that any contact between the shaft and the bearing will result in wear on the inexpensive bearing and not on the much more costly crankshaft. For all applications it is recommended that the
hardness of the bearing surface be at least 100 BHN points less (on the Brinell Hardness Scale) than the hardness of the crankshaft [48]. Babbitt material selection will therefore depend, in part, on the hardness of the shaft being supported.

Table 4.1 Bearing Lining Material Load Capabilities [49]

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Composition</th>
<th>Maximum Pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lead Base Babbitt</td>
<td>75 - 85% lead</td>
<td>600 to 800 psi</td>
</tr>
<tr>
<td></td>
<td>4 - 10% tin</td>
<td></td>
</tr>
<tr>
<td></td>
<td>9 - 15% antimony</td>
<td></td>
</tr>
<tr>
<td>Tin Base Babbitt</td>
<td>86 - 90% tin</td>
<td>800 to 1000 psi</td>
</tr>
<tr>
<td></td>
<td>4 - 9% antimony</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4 - 6% copper</td>
<td></td>
</tr>
<tr>
<td></td>
<td>.4 - .6% lead</td>
<td></td>
</tr>
<tr>
<td>Cadmium Base</td>
<td>97% cadmium</td>
<td>1200 to 1500 psi</td>
</tr>
<tr>
<td></td>
<td>1 - 1.5% nickel</td>
<td></td>
</tr>
<tr>
<td></td>
<td>.5 - 1% silver</td>
<td></td>
</tr>
<tr>
<td></td>
<td>.4 - .8% copper</td>
<td></td>
</tr>
<tr>
<td>Copper-Lead Base</td>
<td>55% copper</td>
<td>2000 to 3000 psi</td>
</tr>
<tr>
<td></td>
<td>45% lead</td>
<td></td>
</tr>
<tr>
<td>Copper-Lead Alloy</td>
<td>72% copper</td>
<td>3000 to 4000 psi</td>
</tr>
<tr>
<td>Base</td>
<td>25% lead</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3% tin</td>
<td></td>
</tr>
<tr>
<td>Silver (with lead</td>
<td>99% silver</td>
<td>5000 + psi</td>
</tr>
<tr>
<td>coating)</td>
<td>1% lead</td>
<td></td>
</tr>
</tbody>
</table>
**Bearing Thickness**

To facilitate load handling and heat dissipation, general guidelines for thickness of the bearing lining and bearing steel backing are [50]:

\[
Lining \; Thickness
\]
\[
b = \frac{1}{32} \times \text{shaft diameter} + \frac{1}{8} \; \text{in.}
\]

\[
Steel \; Backing
\]
\[
s = 0.18 \times \text{shaft diameter}
\]

**Surface Finish**

In hydrodynamic or full film bearing operation, peak surface variations should be less than the expected minimum film thickness, \( h_o \); otherwise peaks on the journal surface will contact peaks on the bearing surface, resulting in high friction and temperature increase. For bearings with high eccentricity ratios and harder surface materials, this is even more important. Typical root mean square (rms) values for shaft and bearing surface variations are illustrated at Figure 4.13.

**4.3.3 External Factors**

In addition to the constraints imposed on bearing design by the nature of the bearing materials and physics of oil film hydrodynamics, there are numerous other
application specific factors which the bearing design must take into account. These include\cite{52}:

1. The physical space available in the engine.
2. Engine operating temperatures e.g. air or water cooled.
3. The load cycle of the engine.
4. Number and size of bearings specified for the application.

\textbf{Figure 4.13 Bearing and Shaft Surface Finish Ranges [51]}
4.4 ENGINE BEARING MANUFACTURE

Main bearings are generally produced using a strip process. In the process the bearing lining material is applied to a continuous steel strip. The resulting bi-metallic strip is then cut into blanks of appropriate length and then formed into the required shape, through a series of pressing and machining operations. This process is illustrated at Figure 4.14.

![Figure 4.14 Bearing Manufacture Process [53]](image)

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3 At Federal Mogul, the exact nature of this process is proprietary information.
CHAPTER 5

THE HOUSE OF QUALITY

5.1 THE VOICE OF THE CUSTOMER

As described in Chapter Three, the first step in applying QFD (after selecting a problem or product to investigate) is to gather information from the customer. The methods used to capture the "Voice of the Customer" and the raw data acquired will be discussed in this section.

5.1.1 Data Collection

Information was collected in the following manner:

1. A survey was prepared and forwarded to two of Federal Mogul's largest customers. A copy of the survey is attached as Appendix A. It should be noted that the questionnaire is a hybrid, in that it addresses both quality characteristics and technical characteristics. This was done in an attempt to take advantage of the fact that the questionnaires were completed by the customers' engineering staffs, who have considerable insight into the technical requirements of bearing design.
2. An extensive on-site interview, with a third Federal Mogul customer, was conducted. This facilitated two way communication and allowed for the clarification of specific details and the pursuit of follow up questions.

3. The results of a previous Federal Mogul customer survey were incorporated into the QFD process, where applicable. A copy of this survey is attached as Appendix B.

4. Discussions were held with Federal Mogul employees, and a copy of the questionnaire was also completed, to incorporate the manufacturer’s perceptions of customer needs.

5.1.2 Project Participants

The companies or divisions that supplied information and/or other assistance in this project were:

1. **Company/Division Name:** The Technology Resource Centre
   GM Powertrain
   General Motors

   **Bearing Use:** Gasoline and diesel engine construction

   **Bearing Consumption:** 140 million bearings per year

---

4 In order to obtain objective and candid information, individual project participants were guaranteed confidentiality. In addition, specific comments, with respect to Federal Mogul and its competitors, were solicited with the assurance that they would not be attributed to individual participants or parent companies. This was done to prevent possible legal liability or personal embarrassment.
2.  
   **Company/Division Name:** Romeo Engine Plant  
       Ford Motor Company  
   **Bearing Use:** Gasoline engine construction  
   **Bearing Consumption:** 4 million bearings per year

3.  
   **Company/Division Name:** Carter Machinery  
       Caterpillar  
   **Bearing Use:** Diesel engine rebuild  
   **Bearing Consumption:** 4000 bearings per year

4.  
   **Company/Division Name:** Blacksburg Division  
       Federal Mogul  
   **Bearing Use:** Bearing manufacturer

### 5.1.3 Data Summary

The mean values for each attribute’s importance, and the performance assessment of Federal Mogul and three of its competitors, are attached at Appendix C.
5.2 QUALITY CHARACTERISTICS

Survey and interview responses were remarkably consistent in identifying desirable bearing quality characteristics\(^5\). The primary needs of the customer were:

1. Bearings must be of **High Quality**.
2. Bearings must be easy to use: **Ease of Use**.
3. Wide selection of bearings: **Product Range**.
4. Order responsiveness: **Product Availability**.
5. Customer should receive **Good Service**.

These primary requirements were then broken down into secondary and third level quality characteristics as shown in Table 5.1.

It should be noted that several of these quality characteristics relate to customer service and support, and not specifically to **bearing design**. They are included here for completeness and because there are some interrelationships with design criteria (such as product range and dimensional design). In order to streamline the process, however, customer needs not specifically related to the design of the actual bearing are not carried through into the House of Quality or subsequent matrices.

\(^5\) It is significant that none of the survey respondents rated cost, price or value as a particularly high priority. This is probably due to the fact that bearings are very competitively priced and/or a belief on the respondents part that concern for quality over price is presently 'politically correct.'
<table>
<thead>
<tr>
<th>PRIMARY</th>
<th>SECONDARY</th>
<th>TERTIARY</th>
</tr>
</thead>
<tbody>
<tr>
<td>High Quality</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Appearance</td>
<td>smooth bearing surface</td>
<td>load capacity</td>
</tr>
<tr>
<td>Meet Performance</td>
<td>operating temperature</td>
<td>duty cycle</td>
</tr>
<tr>
<td>Specifications</td>
<td>low operating noise</td>
<td></td>
</tr>
<tr>
<td>Dimensional Precision</td>
<td>dimensional consistency</td>
<td>dimensional accuracy</td>
</tr>
<tr>
<td></td>
<td>good oil film</td>
<td>good heat dissipation</td>
</tr>
<tr>
<td></td>
<td>good lubrication</td>
<td>tolerates minor dirt</td>
</tr>
<tr>
<td></td>
<td></td>
<td>accommodates shaft imperfections</td>
</tr>
<tr>
<td></td>
<td></td>
<td>score resistant</td>
</tr>
<tr>
<td>Long Lasting</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Easy to Identify</td>
<td>Packaging clearly marked</td>
<td>Bearings individually marked</td>
</tr>
<tr>
<td>Safe to Handle</td>
<td>Burr free</td>
<td></td>
</tr>
<tr>
<td>Easy to Install</td>
<td>Quick location</td>
<td>Precise location</td>
</tr>
<tr>
<td>Product Range</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Size Selection</td>
<td>Shaft size</td>
<td>Housing bore</td>
</tr>
<tr>
<td></td>
<td>Oil Clearance</td>
<td>Max wall thickness</td>
</tr>
<tr>
<td></td>
<td>Overall length</td>
<td>Load range</td>
</tr>
<tr>
<td></td>
<td>Application Selection</td>
<td>Dimensional precision</td>
</tr>
<tr>
<td>Product Availability</td>
<td>Orders Filled Quickly</td>
<td></td>
</tr>
<tr>
<td>Good Service</td>
<td>Technical Support</td>
<td>Good technical knowledge</td>
</tr>
<tr>
<td></td>
<td>Good customer knowledge</td>
<td>Timely response</td>
</tr>
<tr>
<td></td>
<td>Courteous service</td>
<td>Accurate service</td>
</tr>
<tr>
<td></td>
<td>Timely service</td>
<td></td>
</tr>
</tbody>
</table>
5.3 TECHNICAL ATTRIBUTES

Technical attributes are listed in Table 5.2. The bearing primary characteristics were identified as: proportional characteristics, dimensional characteristics, feature characteristics and material characteristics. It should be noted that several of the technical attributes are subordinate to more than one primary characteristic. This is due to the fact that not all bearings have the same features and, for example, if it is decided to add an annular groove, then this feature characteristic has a dimensional attribute that must be considered. Briefly, the primary characteristics are:

1. *Proportional characteristics*: These are characteristics that represent the various dimensional interrelationships that affect the physics of bearing operation. The length over diameter ratio, for example, determines the rate of oil loss out of the side of the bearing and therefore affects oil wedge development and operating pressure.

2. *Dimensional characteristics*: These are characteristics with respect to the location of various bearing features and the precision or tolerances of specific dimensions.

3. *Feature characteristics*: These are characteristics that reflect optional design features which may or may not be part of a specific bearing design.

4. *Material characteristics*: These are characteristics related to the composition and physical properties of the materials used to manufacture the bearing.
<table>
<thead>
<tr>
<th>PRIMARY</th>
<th>SECONDARY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proportional Characteristics</td>
<td>length over diameter ratio</td>
</tr>
<tr>
<td></td>
<td>bearing eccentricity</td>
</tr>
<tr>
<td></td>
<td>bearing eccentricity ratio</td>
</tr>
<tr>
<td>Dimensional Characteristics</td>
<td>wall thickness</td>
</tr>
<tr>
<td></td>
<td>wall thickness tolerance</td>
</tr>
<tr>
<td></td>
<td>lining thickness</td>
</tr>
<tr>
<td></td>
<td>lining surface variation</td>
</tr>
<tr>
<td></td>
<td>back surface variation</td>
</tr>
<tr>
<td></td>
<td>oil hole distance from $ho$</td>
</tr>
<tr>
<td></td>
<td>oil hole diameter</td>
</tr>
<tr>
<td></td>
<td>locating lug position</td>
</tr>
<tr>
<td></td>
<td>locating lug tolerances</td>
</tr>
<tr>
<td></td>
<td>annular groove depth</td>
</tr>
<tr>
<td></td>
<td>annular groove width</td>
</tr>
<tr>
<td></td>
<td>oil clearance</td>
</tr>
<tr>
<td></td>
<td>crush relief</td>
</tr>
<tr>
<td></td>
<td>bearing height</td>
</tr>
<tr>
<td></td>
<td>spreader groove depth</td>
</tr>
<tr>
<td></td>
<td>spreader groove width</td>
</tr>
<tr>
<td></td>
<td>free spread diameter</td>
</tr>
<tr>
<td>Feature Characteristics</td>
<td>locating lug position</td>
</tr>
<tr>
<td></td>
<td>locating lug tolerances</td>
</tr>
<tr>
<td></td>
<td>annular groove width</td>
</tr>
<tr>
<td></td>
<td>annular groove depth</td>
</tr>
<tr>
<td></td>
<td>spreader groove depth</td>
</tr>
<tr>
<td></td>
<td>spreader groove width</td>
</tr>
<tr>
<td>Material Characteristics</td>
<td>lining hardness</td>
</tr>
<tr>
<td></td>
<td>lining composition</td>
</tr>
<tr>
<td></td>
<td>backing composition</td>
</tr>
</tbody>
</table>
The technical attributes shown in Table 5.2 (that are not self evident or explained in Chapter 4) are discussed briefly below:

1. **Length to diameter ratio.** The length of the bearing is actually the width of the bearing surface, as shown in Figure 5.1. This ratio is one of the factors which determine the bearing side oil loss, bearing peak pressure and bearing load capacity and the heat transfer capability of the bearing.

![Figure 5.1 Length to Diameter Ratio [54]](image)

2. **Bearing eccentricity** is different from the eccentricity ratio. The eccentricity ratio refers to the relationship between the diametric centre of the bearing and the shaft centre of rotation. The bearing eccentricity is the difference

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6 Additional information concerning bearing design technical attributes can be obtained from any comprehensive Mechanical Engineering Handbook, such as: T. Baumeister, *Standard Handbook for Mechanical Engineers*, (McGraw Hill, New York, 1967).
in wall thickness from the centre of the bearing to its outside edge. This dimension is usually manufactured as a taper, as shown in Figure 5.2.

There are two reasons for this taper:

a. The slight eccentricity helps to build the oil film wedge effect, allowing oil to be swept into narrowing oil clearance and creating the point of minimum film thickness and maximum pressure, $h_0$.

b. The tapering effect after $h_0$ allows the oil to flow away quickly, increasing the cooling effect of the oil.

Figure 5.2 Bearing Eccentricity [55]
3. *Oil hole size and position.* The oil hole allows oil to flow from the engine block galleries into the bearing. Although it does not require extremely precise dimensions, it must allow for minor variations in the position of the oil gallery. In addition, it must be positioned before the point of minimum oil clearance. The closer it is to $h_o$, the higher the pressure the oil must overcome to enter the bearing.

4. *Locating lug.* The locating lug is used to position the bearing in the engine block, as shown in Figure 5.3. Clearly, the greater the dimensional tolerance in the lug the greater the chance of misalignment and/or failure of the lug to fit properly into the engine block recess.

![Diagram of bearing locating lug](image)

**Figure 5.3 Bearing Locating Lug [56]**
5. *Annular Groove.* The annular groove allows oil to flow quickly over the entire bearing and shaft circumference. Although precise dimensional tolerance is not required, the size of the groove does impact on the heat and load capacity of the bearing capacity. Location of this groove is shown in Figure 5.4.

6. *Spreader Groove.* The spreader groove, also shown in Figure 5.4, allows oil to flow laterally across the entire shaft surface, especially in bearings with high length to diameter ratios.

![Figure 5.4 Annular and Spreader Grooves](image)

7. *Bearing Height.* The bearing is manufactured to fit slightly ‘proud’ of the recess into which it fits, as shown in Figure 5.5. Therefore, as the engine is assembled the bearings are compressed into their housings. This is called a bearing crush fit. In this way, the bearings are held tightly in place and the
resulting frictional force between the bearing back and its housing prevents rotation of the bearing during operation.

Figure 5.5 Bearing Height [58]

8. *Crush Relief.* In order to prevent the bearing surface from intruding into the oil clearance space, due to the bearing crush fit, the outside ends of the bearings are reduced in thickness, as shown in Figure 5.6. This reduction is called crush relief. Dimensioning must permit adequate relief, without adversely affecting the strength of the bearing edge.

9. *Free Spread Diameter.* In order to facilitate assembly, the bearings are made with a slightly larger diameter than the housing into which they are placed, as shown in Figure 5.7. In this way the bearing can be ‘snapped’ into place, where it will be held by its own spring tension. This facilitates assembly by retaining the bearings in their housings and in the end caps, while being handled
and positioned. Clearly this dimension must be taken into consideration when
determining the design dimensions of many of the bearings other attributes.

Figure 5.6 Crush Relief [59]

Figure 5.6 Free Spread Diameter [60]
10. *Lining Thickness, Composition and Hardness.* These factors allow the bearing to compensate for minor irregularities in the shaft’s surface and to absorb and entrap small particulate matter. These two attributes are called conformability and embedability, respectively. They contribute to reductions in frictional wear and improve bearing and shaft life. They are illustrated at Figures 5.7 and 5.8

![Figure 5.7 Bearing Conformability [61]](image1)

![Figure 5.8 Bearing Embedability [62]](image2)
5.4 THE HOUSE OF QUALITY

The quality characteristics at Table 5.1 and technical attributes at Table 5.2 were correlated in the matrix shown at Figure 5.9. This matrix is similar to the A-1 Chart, used by King [63]. This is the starting point of the House of Quality, regardless of which QFD methodology is used. Customer importance ratings and competitive assessments were added on the basis of survey and interview data. Importance ratings are based on a scale of 1 to 5, with 1 being unimportant and 5 being very important. Similarly, the competitive assessment scale ranges from 1 (poor) to 5 (very good). Current and planned technical characteristic target figures are not included, as the specific values will vary between bearing applications.

The principle objective of the A-1 Chart matrix is to identify correlations between design quality characteristics (customer wants) and the design technical attributes (the engineering hows). Secondary functions of the table are:

1. To identify the relative importance of each quality characteristic and the relative position of one’s own product, in comparison to the competition, with respect to each characteristic.

2. To identify the relative importance of the design technical attributes and from this, to select the three to six key attributes for deployment to subsequent matrices.
3. To ensure that each quality characteristic (customer demand/need) is represented by one or more technical attributes, and vice versa. This is immediately evident if there are any blank rows or columns in the table.

Although the matrix is largely self evident, the following additional points of clarification are offered:

1. **Column B.** This column reflects the planned customer satisfaction target in light of the Company’s present rating and those of its three principle competitors.

2. **Ratio of Improvement.** The ratio of planned rating (B) over present rating (A).

3. **Absolute Weight.** This is the ratio of improvement multiplied by the customers weighting of the characteristic’s importance.

4. **Demanded Weight.** The absolute weight of each characteristic (D) divided by the total absolute weight of all characteristics (Σ D) i.e. each characteristic’s absolute weight expressed as a percentage.

5. **Technical Characteristic Totals.** These figures (Row T) are the sum of the products of each technical characteristic’s correlation relationship value and the customer’s importance rating. They are expressed as a percentage in Row P.
The matrix at Figure 5.9 provides an excellent opportunity for all members of the design team to discuss the various interrelationships between customer needs and design technical characteristics. It also indicates that the top six customer needs are:

1. The smoothness or uniformity of the bearings wear surface.
2. Bearing dimensional precision.
3. The ability of the bearing to produce a good oil film during hydrodynamic operation.
4. The bearings heat dissipation capability.
5. The ability to locate the bearing in its housing quickly.
6. The ability to locate the bearing in its housing precisely.

Similarly the five most important technical characteristics are:

1. The oil clearance dimension.
2. The bearing lining composition.
3. The design tolerance of the bearing wall thickness.
4. The extent of surface variations on the bearing lining.
5. The bearing eccentricity.
Table: Chart A-1

<table>
<thead>
<tr>
<th>QUALITY CHARACTERISTICS</th>
<th>TECHNICAL CHARACTERISTICS</th>
<th>TECH CHARACTERS</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
</tr>
</thead>
<tbody>
<tr>
<td>smooth surface</td>
<td></td>
<td></td>
<td>4</td>
<td>4</td>
<td>4</td>
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<td>2</td>
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<td>high load capacity</td>
<td></td>
<td></td>
<td>4</td>
<td>4</td>
<td>4</td>
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<td>4</td>
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<td>high temp tolerance</td>
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<td>3</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>demanding duty cycle</td>
<td></td>
<td></td>
<td>3</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>low operating noise</td>
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<td>4</td>
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<tr>
<td>dimensional precision</td>
<td></td>
<td></td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>good oil film (wedge)</td>
<td></td>
<td></td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>5</td>
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<tr>
<td>good heat dissipation</td>
<td></td>
<td></td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>good lubrication</td>
<td></td>
<td></td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>tolerates minor dirt</td>
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<td></td>
<td>4</td>
<td>4</td>
<td>4</td>
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<td>4</td>
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<tr>
<td>acc. shaft imperfect.</td>
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<td>4</td>
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<td>4</td>
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<tr>
<td>score resistant</td>
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<td></td>
<td>4</td>
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<td>4</td>
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<td>4</td>
</tr>
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<td>burr free</td>
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<td>quick location</td>
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<tr>
<td>precise location</td>
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<td></td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
</tbody>
</table>

Total: 69 162 60 30 192 43 184 117 21 21 37 5 47 47 21 20 5 2 18 18 74 127 215 94 1929

Current value

Planned value

Units

Correlations
- 9 strong correl.
- 3 moderate correl.
- 1 some correl.
- -1 some neg. correl.
- -3 moderate neg. correl.
- -9 strong neg. correl.

Symbols
* - unitless ratio
# - non quantity

Figure 5.10 The House of Quality
CHAPTER 6

TECHNICAL CHARACTERISTIC DEPLOYMENT

In the next QFD phase, the technical characteristics (attributes) identified in the House of Quality are deployed. This involves correlating them against several factors to collect additional useful design information. This is illustrated in the following sections.

6.1 FUNCTION DEPLOYMENT

Function deployment is carried out to ensure that each of the products operating functions is adequately represented by the technical design characteristics identified in Chart A-1. It also quickly identifies correlations between the technical characteristics and the specific product functions on which they will have the greatest impact during design or redesign of the product.

The function deployment for the engine main bearing is shown at Figure 6.1. This chart (A-2) indicates that the seven primary functions performed by the bearing are:

1. To reduce friction during boundary lubrication i.e. at startup or low rpm.
2. To reduce friction during full film i.e. hydrodynamic operation.
3. To support the weight of the crankshaft and associated pressures at rest.
4. To support the additional engine loads and pressures during operation.
5. To assist in cooling of the bearing/shaft interface by direct heat conductance to the engine housing.

6. To assist crankshaft and bearing assembly cooling, through oil flow.

7. To act as a wear surface and thereby minimize wear on the crankshaft.

A review of the correlation matrix indicates two technical characteristics with no corresponding functional correlation. These are “locating lug tolerances” and “free spread diameter.” These attributes are directly related to the assembly of the bearing in the engine and although they have some minor impact on the operational functions, they are not significant. This does not mean that they are unimportant, merely that the designers must consider aspects in the bearing’s design, other than its purely functional performance.

Other relationships in the matrix stand out immediately. For example, even though there is only one correlation between the technical attribute ‘back surface variation” and the functional characteristics (in this case Heat Transfer) the high negative rating clearly indicates that this is an area of concern. Similarly there are a large number of strong correlations for “lining surface variation”, “lining composition”, “oil clearance” and “bearing eccentricity”, indicating that these will probably be key design characteristics.
### TECHNICAL CHARACTERISTICS

#### Chart A-2

| FUNCTIONS | Length / diameter ratio | Bearing eccentricity ratio | Bearing eccentricity ratio | Wall thickness | Wall thickness tolerance | Lining thickness | Lining surface variation | Back surface variation | Oil hole distance from housing | Oil hole diameter | Locating lug tolerances | Annular groove depth | Annular groove clearances | Crankshaft relief | Bearing height | Spreader groove depth | Spreader groove width | Free spread diameter | Lining hardness | Lining composition | Backing composition |
|-----------|-------------------------|---------------------------|---------------------------|----------------|-------------------------|-----------------|--------------------------|------------------------|--------------------------|-----------------|------------------------|-------------------|------------------------|------------------|----------------|----------------------|------------------|------------------|-----------------|-------------------|
| Reduce Friction - Boundary | ■ | ○ | □ | ■ | ■ | □ | ○ | ● | ● | ○ | ● | ○ | ● | ○ | ● | ○ | ■ | ○ |
| Reduce Friction - Full Film | ● | ○ | ● | ■ | ■ | □ | ○ | ● | ● | ■ | ● | ○ | ● | ○ | ● | ○ | ■ | ○ |
| Support Load - Static | ● | ○ | □ | ○ | □ | ○ | □ | □ | □ | □ | □ | □ | □ | □ | □ | □ | □ | □ |
| Support Load - Hydrodynamic | ● | ○ | ○ | □ | ○ | □ | ○ | □ | □ | □ | □ | □ | □ | □ | □ | □ | □ | □ |
| Cooling - Heat Transfer | ● | ○ | ○ | ■ | ■ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| Cooling - Oil Flow | □ | ○ | ■ | ■ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| Act as Wear Surface | ● | □ | ○ | ○ | ○ | ○ | □ | □ | □ | □ | □ | □ | □ | □ | □ | □ | □ | □ | □ |

**Correlations**

- • : 9 strong correl.
- ○ : 3 moderate correl.
- □ : 1 some correl.
- □ : -1 some neg. correl.
- ■ : -3 moderate neg. correl.
- ▲ : -9 strong neg. correl.

**Figure 6.1 Function Deployment**
6.2 TECHNICAL CHARACTERISTICS INTERACTION

Chart A-3 of King’s QFD process is essentially the completion of the ‘roof’ of the House of Quality, seen in many other publications [64]. It is included in this QFD process as a separate matrix to ensure that the possible interactions of the design technical characteristics are not treated as a secondary issue. Clearly, as King suggests “one of the major problems with design is not what is not known; it is interactions that are forgotten.”[65]

The technical characteristic interaction matrix for the engine main bearing is shown at Figure 6.2. From this matrix it is evident that there are a large number of negative interactions. In other words, changes in one characteristic may have an adverse affect on one or more other characteristics. The impact of this chart on the bearing design process is that the designers must be cognizant of the interrelationships and be prepared to do a trade-off analysis, to resolve each conflicting interaction in a systemically optimal manner.
### TECHNICAL CHARACTERISTICS

![Chart A-3](chart.png)

**Figure 6.2 Technical Characteristic Interaction**
6.3 PARTS DEPLOYMENT

Parts deployment is carried out to identify which product components or system elements to focus on. Clearly, not all parts of the product will affect or be affected equally by changes in portions of the product's range of technical characteristics. It is therefore important to identify how each of the product's parts interrelate to the key design technical characteristics which were identified in Chart A-1. In this way, critical parts to address during the design phase and to be controlled during the manufacturing process can be identified.

Although the engine main bearing is a single component, it has a number of individual faces, recesses and surfaces that serve specific purposes and require individual design consideration and manufacturing processes. These are identified in Figure 6.3, (Chart A-4) as the bearing's parts7. From the chart it is evident that the bearing lining (the surface that supports the crankshaft) is strongly interrelated to four of the five key design technical characteristics. Similarly, the extent of each part’s technical characteristic correlation, and their relative strengths, can be read directly from the chart. As always in the QFD process, a secondary benefit of completing this deployment is the interaction and communication which takes place between the design team, in discussing the individual parts.

---

7 This demonstrates the inherent flexibility of QFD in that the process can be adapted to the user's unique requirements.
### TECHNICAL CHARACTERISTICS

<table>
<thead>
<tr>
<th>PARTS</th>
<th>Bearing eccentricity</th>
<th>Lining surface variation</th>
<th>Back surface variation</th>
<th>Oil clearance</th>
<th>Lining composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bearing Lining</td>
<td>◯</td>
<td>◯</td>
<td>◯</td>
<td>◯</td>
<td>◯</td>
</tr>
<tr>
<td>Bearing Backing</td>
<td>◯</td>
<td>◯</td>
<td>◯</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>Locating Lug</td>
<td>◯</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Oil Hole</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Annular Groove</td>
<td>○</td>
<td></td>
<td>●</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Spreader Groove</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Crush Relief</td>
<td></td>
<td></td>
<td>○</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>Inner Chamfer</td>
<td></td>
<td></td>
<td></td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Outside Chamfer</td>
<td></td>
<td></td>
<td></td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Groove Chamfer</td>
<td></td>
<td></td>
<td></td>
<td>○</td>
<td>○</td>
</tr>
</tbody>
</table>

**Correlation**

- ◯ : 1 some correl.
- ● : 3 moderate correl.
- ○ : 9 strong correl.

**Figure 6.3 Parts Deployment**
CHAPTER 7

NEW CONCEPT DEPLOYMENT

The next series of QFD charts are primarily used to evaluate the impact of new
design or production concepts, on the quality and technical characteristics of the product.
This process is most useful when considering modifications to an existing product, as in
the case of the Federal Mogul engine bearing. Stuart Pugh, noted originator of the “Pugh
Method”, suggests that new concept development should take place before the use of
QFD, and the completion of the first House of Quality [66]. Unless the product is
completely new or being entirely redesigned, however, the application of new concepts to
enhance some aspects of a product must take into account the customers pre-existing
expectations and needs. In the King approach, these are assessed using the A series of
matrices.

Two new concepts were considered for the purposes of this project. The first, a
design change, concerns the locating lug which protrudes from the outside edge of the
bearing. This lug fits into recesses which are machined into the engine block. The
relationship of the lug to the recess ensures that the bearing cannot be put into the block
backwards, causing misalignment of the bearing oil hole and the engine oil gallery.
Although this is a relatively simple function, the locating lug involves several
manufacturing processes, which increase the production cost of the bearing significantly.
In addition, the lug adds to the tolerance specifications of the product. A possible alternative to the locating lug is to produce the bearings symmetrically, with a second oil hole, so that regardless of orientation in the engine block the oil passage will remain unobstructed. This design would be compatible with existing engine blocks in that the empty lug recess would not affect engine operation. In addition, as engine manufacturers 'got used to the idea' of a lug free bearing, the recess could be eliminated from the engine design, saving additional machining costs.

The second new concept, a production process change, concerns the manner in which the bearing surfaces are machined. At present, Federal Mogul predominantly produces its bearings by broaching. This is a linear cutting method that involves passing a cutting edge across the width of the bearing, removing the required amount of metal to achieve the desired wall thickness. While this method is relatively simple and inexpensive, it is limited by the degree of precision that can be achieved. Federal Mogul has recently undertaken the development of a group of bearings requiring very fine tolerances. In order to meet these specifications a rotary machining process is being implemented. In addition to the improvement in the bearing surface dimensional tolerances, the turning process produces a 'nicer looking', and therefore more appealing finish.
7.1 NEW CONCEPTS AND CUSTOMER DEMANDS

The first matrix in this series starts, not surprisingly, with the Voice of the Customer. The customer’s needs, in the form of quality characteristics, are evaluated in terms of the possible effect of implementing the two proposed new concepts. The objective is to identify new concepts that will significantly enhance the satisfaction of consumer demands, with a minimum of negative impacts in other areas. For this reason the ‘pluses’ and ‘minuses’ are totaled separately and not added together. This ensures that the ‘minuses’ are not canceled out and remain visible. This process is shown in Chart E-1, at Figure 7.1.

From Figure 7.1, it is believed that the introduction of the rotary machining process will significantly improve seven of the fifteen customer demanded quality characteristics. It is also possible that two characteristics will be adversely affected. The introduction of extremely precise tolerances in bearing dimensions may result in bearings that are somewhat less ‘forgiving’ in terms of minor oil contamination and or slight shaft misalignment.

The case for the locating lug design change is less convincing. Here there are three positive aspects and two negatives. Further, the two negative implications were emphatically stressed during several interview conversations and in response to one of the two questionnaires. In addition to correct bearing orientation, the locating lug positions the bearing laterally in the bearing housing and is used as a reference point during assembly, to greatly speed up the bearing insertion process.
<table>
<thead>
<tr>
<th>QUALITY CHARACTERISTICS</th>
<th>PRESENT CONCEPT</th>
<th>NEW CONCEPTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Present Concept:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Broaching of bearing</td>
<td>Bore/ream/mill</td>
<td>Eliminate lug: use</td>
</tr>
<tr>
<td>surface.</td>
<td>bearings i.e.</td>
<td>alternative method or</td>
</tr>
<tr>
<td></td>
<td>rotary</td>
<td>make bearings</td>
</tr>
<tr>
<td></td>
<td>machining</td>
<td>symmetrical to eliminate</td>
</tr>
<tr>
<td>2. Bearing positioned</td>
<td></td>
<td>requirement</td>
</tr>
<tr>
<td>using locating lug.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>smooth surface</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>high load capacity</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>high temp. tolerance</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>demanding duty cycle</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>low operating noise</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>dimensional precision</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>good oil film (wedge)</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>good heat dissipation</td>
<td>+</td>
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<tr>
<td>good lubrication</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>tolerates minor dirt</td>
<td>-</td>
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<tr>
<td>acc. shaft imperfect.</td>
<td>-</td>
<td></td>
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<tr>
<td>score resistant</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>burr free</td>
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<tr>
<td>quick location</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>precise location</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

| Anticipated Result     | +s  | 3+ | 2- |
|                        | -s  | 2- | 2- |

Figure 7.1 New Concept - Customer Demands Deployment
Chart E-1 also provides additional correlation information such as which customer demands will be enhanced by the greatest number of new concepts or which new concepts will have conflicting impacts on the same quality characteristic. Again, trade-off analysis and/or simple discussion amongst the design team can be initiated on the basis of this chart.

7.2 NEW CONCEPTS AND PRODUCT FUNCTIONS

This matrix, Chart E-2, assesses the effect of proposed new concepts on the basic functions of the product. The functions used for this evaluation are those developed during the completion of the A series of charts. As shown in Figure 7.2, the new cutting process appears to impact five of the bearing’s seven functions in a positive manner. It is assessed that there are no corresponding ‘down sides’ of this change, to any of the bearing functions.

Notably, the proposed design change i.e. the removal of the locating lug, has no significant impact to any of the bearing’s principal functions. This is due to the fact that bearing installation and positioning is the ‘function’ of the assembly worker or mechanic, and not of the bearing itself. This relationship was, however, clearly evident in the previous E-1 Chart. This is another example of the way in which the use of the QFD multiple matrices can be used to minimize the potential to overlook a design consideration, that might be missed in a more ‘traditional’ design sequence.
<table>
<thead>
<tr>
<th>FUNCTIONS</th>
<th>PRESENT CONCEPT</th>
<th>NEW CONCEPTS</th>
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</thead>
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<td>Present Concept:</td>
<td>Bore/ream/mill bearings i.e. rotary machining</td>
</tr>
<tr>
<td></td>
<td>1. Broaching of bearing surface.</td>
<td>Eliminate lug: use alternative method or</td>
</tr>
<tr>
<td></td>
<td>2. Bearing positioned using locating lug.</td>
<td>make bearings symmetrical to eliminate</td>
</tr>
<tr>
<td></td>
<td></td>
<td>requirement</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Anticipated Result</td>
</tr>
<tr>
<td>Reduce Friction - Boundary</td>
<td></td>
<td>+</td>
</tr>
<tr>
<td>Reduce Friction - Full Film</td>
<td></td>
<td>+</td>
</tr>
<tr>
<td>Support Load - Static</td>
<td></td>
<td>+</td>
</tr>
<tr>
<td>Support Load - Hydrodynamic</td>
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<td>Cooling - Oil Flow</td>
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</tr>
<tr>
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<td>0 -</td>
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<tr>
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<td></td>
<td>0 -</td>
</tr>
</tbody>
</table>

**Figure 7.2 New Concept - Functions Deployment**
7.3 NEW CONCEPTS AND TECHNICAL CHARACTERISTICS

The new concept series of charts next compares 'The Voice of The Engineer', in the form of the technical characteristics developed in the original House of Quality, to the proposed new concepts. This is illustrated in Chart E-3 at Figure 7.3. Here the design team is looking for the positive and negative impact of the proposed new concept on each technical attribute and the combined net effect. Again, the interactions between two or more proposed new concepts on the same design technical characteristic should also be considered, if more than one 'new idea' may be implemented.

As shown in Figure 7.3, there is a very strong positive impact between the proposed new production process and a large number of the technical characteristics. This is consistent with the correlation obtained in considering the bearing functions and the original customer demands. This fact would suggest that the translation of the customer’s needs into technical characteristics and the subsequent deployment of The Voice of The Customer through the series of matrices has been successful.

The results obtained for the proposed design change, again suggest that there could be more problems than benefits, to the change. The negative correlations are explained briefly below:

1. **Length/Diameter Ratio.** The length over diameter ratio affects the amount of oil lost out of the sides of the bearing surface, under operating pressure. This can affect the flow of oil through the bearing and result in a reduced
<table>
<thead>
<tr>
<th>Technical Characteristic</th>
<th>Present Concept</th>
<th>New Concepts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Present Concept: 1. Broaching of bearing surface. 2. Bearing positioned using locating lug.</td>
<td>Bore/ream/mill bearings i.e. rotary machining</td>
<td>Eliminate lug: use alternative method or make bearings symmetrical to eliminate requirement</td>
</tr>
<tr>
<td>Length / diameter ratio</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>Bearing eccentricity</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>Bearing eccentricity ratio</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>Wall thickness</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>Wall thickness tolerance</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>Lining thickness</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>Lining surface variation</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>Back surface variation</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>Oil hole distance from ho</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>Oil hole diameter</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>Locating lug tolerances</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>Annular groove depth</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>Annular groove width</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>Oil clearance</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>Crush relief</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>Bearing height</td>
<td>+</td>
<td>-</td>
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<tr>
<td>Spreader groove depth</td>
<td>+</td>
<td>-</td>
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<tr>
<td>Spreader groove width</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>Free spread diameter</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>Lining hardness</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>Lining composition</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>Backing composition</td>
<td>+</td>
<td>-</td>
</tr>
</tbody>
</table>

Figure 7.3 New Concept - Technical Characteristics Deployment
oil film (the supporting oil wedge) load capacity. By drilling a second hole in the bearing, it is possible that the resulting oil seepage will have the effect of a ‘virtual length over diameter reduction.’ An adjustment in this proportion might therefore be necessary to compensate for the change.

2. *Wall Thickness.* The addition of a second hole may require adjustments to the entire bearing wall thickness, to increase bearing rigidity and structural strength.

3. *Oil Hole Diameter.* This attribute indicates a negative correlation because the removal of the locating lug would necessitate the drilling of a second oil hole diameter, to achieve bearing symmetry.

### 7.4 NEW CONCEPT SUMMARY

This is the final matrix in the E-series. It summarizes the data obtained from the three preceding charts and provides a good overview of the net impact of each proposed idea in terms of the customer’s expressed needs, the products actual functions and the technical characteristics needed to accommodate the customer and achieve the desired functions.

Figure 7.4 summarizes this process for the Federal Mogul engine main bearing. As indicated in the chart, the rotary machining process is an extremely positive measure, strongly supported from all three perspectives. The lug elimination proposal, on the other hand, is not supported by the evaluation. If the concept is to be pursued, the design
team might consider developing a simpler locating system. Another possibility may be to simplify the lug design by reducing its tolerance requirements and/or reducing the number and complexity of its manufacturing processes.
<table>
<thead>
<tr>
<th>Quality Characteristics</th>
<th>Present Concept</th>
<th>New Concepts</th>
<th>Anticipated Result</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1. Broaching of bearing surface. 2. Bearing positioned using locating lug</td>
<td>Bore/ream/mill bearings i.e. rotary machining</td>
<td>Eliminate lug: use alternative method or make bearings symmetrical to eliminate requirement</td>
</tr>
<tr>
<td></td>
<td>7 + 2 -</td>
<td>3 + -</td>
<td>2</td>
</tr>
<tr>
<td>Functions</td>
<td>5 + 0 -</td>
<td>0 + 0 -</td>
<td></td>
</tr>
<tr>
<td>Technical Attributes</td>
<td>11 + 0 -</td>
<td>1 + 3 -</td>
<td></td>
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<tr>
<td></td>
<td>+’s 23 +</td>
<td>-’s 2 -</td>
<td></td>
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<tr>
<td></td>
<td>-’s 2 -</td>
<td>+’s 4 +</td>
<td></td>
</tr>
</tbody>
</table>

**Figure 7.4 New Concept Summary**
CHAPTER 8

CONCLUSIONS AND RECOMMENDATIONS

This chapter summarizes the principal conclusions of the report. Conclusions are presented in two groups: those directly relevant to the project topic and those concerning related matters, that are indirectly associated with the report. Similarly, recommendations reflect suggested courses of action, based on the report results, and additional topics for possible future investigation. Finally, the report’s significance and contribution is also summarized.

8.1 CONCLUSIONS

8.1.1 Direct Conclusions

The application of multiple QFD matrices to the bearing design and production process at Federal Mogul proved to be extremely effective. The consistency of results at all levels suggests that the Voice of the Customer was ‘deployed’ through successive matrices. In addition, the usefulness of multiple matrices in ensuring that key design factors and interrelationships are not overlooked, was repeatedly observed.
With respect to the design and manufacture of engine bearings, the following conclusions have been demonstrated:

1. The customer's most important bearing quality characteristics are:
   a. wear surface smoothness and uniformity;
   b. dimensional precision;
   c. hydrodynamic oil film formation;
   d. heat dissipation capability;
   e. ease of location during assembly; and
   f. precision of location during assembly.

2. The most important bearing technical attributes are:
   a. oil clearance dimensional precision;
   b. bearing lining composition;
   c. bearing wall thickness tolerance;
   d. bearing lining surface variation; and
   e. bearing eccentricity.

3. Federal Mogul has a very favourable competitive position, meeting or exceeding competitor performance with respect to every quality characteristic (customer needs). The new targets which have been established will further enhance this advantage.
4. Federal Mogul’s new manufacturing process concept (rotary machining vice broaching) has been validated by the QFD process as an extremely effective decision.

5. The design proposal (remove the locating lug) was demonstrated to require considerable additional examination and investigation.

### 8.1.2 Related Conclusions

In addition to the direct results of the topic under investigation, it has also been concluded that:

1. QFD’s primary function is to deploy customer needs and demands through the entire product development process. It is, essentially, a design tool and not a quality tool. *Quality* is achieved by ensuring that the customer receives the *qualities* that are desired.

2. QFD is an effective tool that has been demonstrated to be adaptable to Federal Mogul’s needs.

3. The QFD process validated many of the “common sense” beliefs held at Federal Mogul with respect to bearing design and customer needs and priorities.

4. The King QFD approach provides an extremely simple, flexible, versatile and comprehensive system for conducting QFD.
5. The use of spreadsheets in completing QFD matrices puts QFD within the grasp of anyone with a PC, at a fraction of the cost of specialized software.

8.2 RECOMMENDATIONS

8.2.1 Direct Recommendations

Recommendations based on the project results are as follows:

1. Federal Mogul’s planned move away from linear broaching, to a rotary machining system capable of achieving better tolerance control, should be implemented.

2. Additional study should be directed to the matter of the locating lug, to determine if the design can be modified to reduce the requirement for machining complexity and precision. Customers definitely do not want the feature eliminated.

3. Federal Mogul should consider the use of this project:
   a. as a template for developing their own QFD system; and
   b. as a training vehicle to explain and demonstrate the application of QFD.
8.2.2 Related Recommendations

The following additional proposals are made:

1. In future, when QFD is being taught, it should be stressed that there is no "the way to do QFD". Rather, it is a way of thinking and planning that emphasizes:
   a. flexibility;
   b. adaptability to the specific application circumstances; and
   c. integration into a broader TQM system and environment.

2. The development of spreadsheet based software templates for each matrix in the King approach would be a valuable project or projects, for future study.

8.3 SUMMARY

It is believed that the objectives of this project were achieved, and that the following contributions have been made:

1. The project demonstrated the use of QFD in a real world industrial setting, based on a relatively complex and technically demanding product.

2. The application of numerous matrices beyond "The House of Quality" was illustrated.

3. The matrices prepared for this project can be easily adapted for future use, as a teaching aid, to explain the QFD process.
4. Federal Mogul has been given “food for thought” with respect to the potential application of QFD and a template on which they can build, should they decide to do so.
REFERENCES


BIBLIOGRAPHY

References Cited


**Further References**


APPENDIX A

VOICE OF THE CUSTOMER SURVEY

The following survey was used to gather customer input into this project. It also served as the starting point for on site and telephone interviews, which were also conducted. An accompanying letter introduced the project, and survey, in greater detail and provided additional background information. The survey attached to the letter was as follows:

BACKGROUND

Your cooperation and assistance in completing the following questionnaire is greatly appreciated. Information obtained will be used solely to complete a project, at Virginia Tech, into the use of Quality Function Deployment (QFD) in bearing manufacture and by Federal-Mogul, to improve customer service. Answers are absolutely confidential and non-attributable. All data will be aggregated, to examine trends and identify key issues. Answers from participating companies will not be individually identified and other bearing manufacturers will be referred to only as Company A, B, etc. If there are any questions that you do not wish to answer, do not know the answer to, or have no opinion on, leave them blank.

PART I

Company Identification and Usage Information

Name of Your Company: ____________________________________________

Your name: ___________________________ Phone: _________________

Position: _______________________________________________________

Company’s primary use of bearings (gasoline engine manufacture, heavy industrial diesel engine rebuild, etc.): _______________________________________

Average annual bearing consumption: ____________________________
Types of Federal-Mogul bearings currently used:

Other suppliers of bearings for similar applications:

Competitor A:
Name: __________________ Type(s) of Bearing: ____________

Competitor B:
Name: __________________ Type(s) of Bearing: ____________

Competitor C:
Name: __________________ Type(s) of Bearing: ____________

PART II

Attribute Importance and Federal Mogul Performance Rating

Please rate the following attributes in terms of importance to your primary application and assess your level of satisfaction with Federal Mogul’s products and those of its competitors.

Attribute Importance

The rating scale for attribute importance is:

1--not important, 2--somewhat important, 3--important, 4--very important, 5--extremely important

Performance Ratings

Place an ‘X’ on the scale to indicate your assessment of Federal Mogul’s product performance in each attribute. Indicate your assessment of competitive products by placing an A, B and/or C, on the same line, to reflect your opinion of products produced by competitors identified in Part I. Note: Precise detailed answers are not required, your company’s perceptions and opinions are more important. Any comments which may clarify your answers would be greatly appreciated. The rating scale is indicated below.

Note: partial scores (e.g. 3.5) are acceptable.

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<tr>
<td></td>
<td>poor</td>
<td>acceptable</td>
<td>good</td>
<td>very good</td>
<td>excellent</td>
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</tbody>
</table>
Example

1. Attribute A: **Price**  (Illustrative only)

   Attribute Importance: 4

   Performance Rating Assessment:

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<th>4</th>
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<tbody>
<tr>
<td>poor</td>
<td>acceptable</td>
<td>good</td>
<td>very good</td>
<td>excellent</td>
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</tbody>
</table>

   This example indicates that price is very important to your company and that Federal Mogul’s performance is slightly better than its competitors (that you are familiar with). Competitor rating would be Company B, then C, then A in terms of satisfying your company’s requirements for this attribute.

   **Attribute Assessment**

Cost Attributes

1. Attribute A: **Price**  (Straight dollar for dollar price comparison of similar products)

   Attribute Importance: __________

   Performance Rating Assessment:

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<tr>
<td>poor</td>
<td>acceptable</td>
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<td>very good</td>
<td>excellent</td>
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</tbody>
</table>

   Comments: _______________________________________
   _______________________________________
   _______________________________________
2. Attribute B: **Value** (Quality/Performance in relation to Price: the ‘best buy’ all round)

Attribute Importance: 

Performance Rating Assessment:

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<td>poor</td>
<td>acceptable</td>
<td>good</td>
<td>very good</td>
<td>excellent</td>
</tr>
</tbody>
</table>

Comments: ______________________________

______________________________

Performance Attributes

Note: **Accurate assessment of these attributes may require examination and evaluation of historical bearing failure data. Please indicate in comments section if assessment is based on ‘gut feel’ or actual data.**

3. Attribute C: **Durability** (Overall expected useful life of the bearing)

Attribute Importance: 

Performance Rating Assessment:

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<td>poor</td>
<td>acceptable</td>
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<td>very good</td>
<td>excellent</td>
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Comments: ______________________________

______________________________

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______________________________
4. Attribute D: **Fatigue Strength** (Ability of bearing to handle load. Please comment on relative importance of peak or surge capacity and/or continuous loading)

Attribute Importance: 

Performance Rating Assessment:

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<td>good</td>
<td>very good</td>
<td>excellent</td>
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Comments: 

5. Attribute E: **Heat Dissipation** (How efficient the bearing is at transferring heat)

Attribute Importance: 

Performance Rating Assessment:

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<td>good</td>
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Comments: 

6. Attribute F: **Noise Reduction** (Noise level in operation i.e. how significant is it that the bearing 'run' quietly in comparison to other engine noise levels)

Attribute Importance: 

Performance Rating Assessment:

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<td>good</td>
<td>very good</td>
<td>excellent</td>
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Comments: 
7. Attribute G: **Oil Transfer Efficiency** (How well the oil flows through and is distributed by the bearing)

Attribute Importance: 

Performance Rating Assessment:

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<td>poor</td>
<td>acceptable</td>
<td>good</td>
<td>very good</td>
<td>excellent</td>
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Comments: 

8. Attribute H: **Oil Film Quality** (The wedge of oil that supports the bearing load during operation. Comment on consistency across width of bearing, speed of wedge formation and thickness, if relevant)

Attribute Importance: 

Performance Rating Assessment:

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<th>1</th>
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<td>poor</td>
<td>acceptable</td>
<td>good</td>
<td>very good</td>
<td>excellent</td>
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Comments: 

9. Attribute I: **Conformability** (Ability of lining material to adjust to minor variations on shaft and slight misalignments)

Attribute Importance: 

Performance Rating Assessment:

<table>
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<th>2</th>
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<td>acceptable</td>
<td>good</td>
<td>very good</td>
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</tbody>
</table>

Comments: 

113
10. Attribute J: **Embedability** (Ability of bearing material to absorb normal wear and operation particles)

Attribute Importance: 

Performance Rating Assessment:

<table>
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<td>poor</td>
<td>acceptable</td>
<td>good</td>
<td>very good</td>
<td>excellent</td>
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</table>

Comments: 


11. Attribute K: **Corrosion Resistance** (Ability of bearing materials to resist corrosion. Comment if primary concern is during storage or after application installation)

Attribute Importance: 

Performance Rating Assessment:

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<thead>
<tr>
<th>1</th>
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<td>poor</td>
<td>acceptable</td>
<td>good</td>
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<td>excellent</td>
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</tbody>
</table>

Comments: 


**Appearance Attributes**

12. Attribute L: **Finish -- Non-Bearing Surfaces** (i.e. importance of finish quality on the flanges, sides, backs of bearings. Comment on preference for flash coating, buffing.)

Attribute Importance: 

Performance Rating Assessment:

<table>
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<td>poor</td>
<td>acceptable</td>
<td>good</td>
<td>very good</td>
<td>excellent</td>
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</tbody>
</table>
13. Attribute M: Finish – Bearing Surfaces (i.e. perceived smoothness of bearing surface. Comment on preference for rotary machining Vs broaching, in terms of finish)

Attribute Importance: _______

Performance Rating Assessment:

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Comments: ________________________________________________________________
______________________________________________________________
______________________________________________________________

Ease of Use Attributes

14. Attribute N: Locating Lug (Comments requested: is locating lug essential to your application, since bearing crush is what actually prevents bearing rotation? If bearings were reversible (symmetric) i.e. correctly orientated oil holes regardless of position in bearing housing, could lug be eliminated?)

Attribute Importance: _______

Performance Rating Assessment:

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Comments: ________________________________________________________________
______________________________________________________________
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15. **Attribute O: Identification** (Alpha-numeric codes stamped on individual bearings)

Attribute Importance: _______

Performance Rating Assessment:

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Comments: ____________________________________________
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**Packaging Attributes**

16. **Attribute P: Protection** (Package protection against rough handling/environmental conditions during transport and/or storage)

Attribute Importance: _______

Performance Rating Assessment:

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Comments: ____________________________________________
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17. **Attribute Q: Identification** (Labeling of packaging materials)

Attribute Importance: _______

Performance Rating Assessment:

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</table>

Comments: ____________________________________________
____________________________________________________

116
Dimensional Conformity Attributes

Note: Importance of dimensional conformity refers to relative importance of precision in meeting design specifications i.e. criticality of tolerances for each dimension. If all attributes are extremely important, then please indicate the following eleven (18 to 28) attributes in order of importance to your application.

18. Attribute R: Bearing Height

Attribute Importance: _______

Performance Rating Assessment:

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<td>excellent</td>
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Comments: ____________________________________________________________

19. Attribute S: Bearing Spread

Attribute Importance: _______

Performance Rating Assessment:

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<td>excellent</td>
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Comments: ____________________________________________________________
20. Attribute T: **Locating Lip Location**

Attribute Importance: ________

Performance Rating Assessment:

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<td>good</td>
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<td></td>
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<tr>
<td>very good</td>
<td></td>
<td></td>
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Comments: ____________________________________________

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_____________________________________________________

21. Attribute U: **Locating Lip Height**

Attribute Importance: ________

Performance Rating Assessment:

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Comments: ____________________________________________

_____________________________________________________

_____________________________________________________

22. Attribute V: **Locating Lip Width**

Attribute Importance: ________

Performance Rating Assessment:

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<tr>
<td>acceptable</td>
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Comments: ____________________________________________

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_____________________________________________________

118
23. Attribute W: **Bearing Wall Thickness**

Attribute Importance: ________

Performance Rating Assessment:

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<td>very good</td>
<td>excellent</td>
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Comments: __________________________________________

________________________________________________________________________

24. Attribute X: **Bearing Lining Thickness**

Attribute Importance: ________

Performance Rating Assessment:

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<thead>
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<td>excellent</td>
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Comments: __________________________________________

________________________________________________________________________

25. Attribute Y: **Crush Relief**

Attribute Importance: ________

Performance Rating Assessment:

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<td>very good</td>
<td>excellent</td>
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Comments: __________________________________________

________________________________________________________________________
26. Attribute Z: **Oil Hole** (Precision of location and hole size)

Attribute Importance: 

Performance Rating Assessment:

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<th>4</th>
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<td>very good</td>
<td>excellent</td>
</tr>
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Comments: ____________________________________________

27. Attribute AA: **Edge Chamfer** (Both inside and outside: comment if one is more important than the other to your application)

Attribute Importance: 

Performance Rating Assessment:

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<th>4</th>
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<td>very good</td>
<td>excellent</td>
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Comments: ____________________________________________

28. Attribute AB: **Bearing Eccentricity**

Attribute Importance: 

Performance Rating Assessment:

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<td>good</td>
<td>very good</td>
<td>excellent</td>
</tr>
</tbody>
</table>

Comments: ____________________________________________
Service Attributes

29. Attribute AC: **Product Range** (Availability of wide range of bearing types, construction materials and dimensions. Comment on suitability of range of products currently offered by Federal Mogul.)

Attribute importance: ______

Performance Rating Assessment:

1 2 3 4 5
poor acceptable good very good excellent

Comments: ___________________________________________________________
______________________________________________________________
______________________________________________________________

30. Attribute AD: **Product Availability** (Product is in stock or deliverable on very short notice. Comment on Federal Mogul’s performance in this area.)

Attribute importance: ______

Performance Rating Assessment:

1 2 3 4 5
poor acceptable good very good excellent

Comments: ___________________________________________________________
______________________________________________________________
______________________________________________________________
______________________________________________________________
31. Attribute AE: **Order Responsiveness** (Time taken between order placement and delivery of product. Comment on Federal Mogul’s performance in this area)

Attribute Importance: ________

Performance Rating Assessment:

<table>
<thead>
<tr>
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<th>2</th>
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<th>4</th>
<th>5</th>
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<td>good</td>
<td>very good</td>
<td>excellent</td>
</tr>
</tbody>
</table>

Comments: ________________________________________________________________

__________________________________________________________________________

__________________________________________________________________________

32. Attribute AF: **Technical Support** (Assistance in answering questions with respect to bearing applications and/or technical problems related to application difficulties.)

Attribute Importance: ________

Performance Rating Assessment:

<table>
<thead>
<tr>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
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<tbody>
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<td>good</td>
<td>very good</td>
<td>excellent</td>
</tr>
</tbody>
</table>

Comments: ________________________________________________________________

__________________________________________________________________________

__________________________________________________________________________

__________________________________________________________________________
33. Attribute AG: **Technical Assistance** (Assistance with application design or producing application specific products to meet your unique requirements i.e. design assistance/collaboration)

Attribute Importance: ________

Performance Rating Assessment:

<table>
<thead>
<tr>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
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<tbody>
<tr>
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<td>good</td>
<td>very good</td>
<td>excellent</td>
</tr>
</tbody>
</table>

Comments: ____________________________________________________________

__________________________________________________________

34. Attribute AH: **Customer Service** (General responsiveness and helpfulness when dealing with firm in terms of billing, complaints, administration, etc.)

Attribute Importance: ________

Performance Rating Assessment:

<table>
<thead>
<tr>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>poor</td>
<td>acceptable</td>
<td>good</td>
<td>very good</td>
<td>excellent</td>
</tr>
</tbody>
</table>

Comments: ____________________________________________________________

__________________________________________________________

35. Any additional comments or suggestions with respect to any aspect of this survey? Any areas that should have been evaluated that were not?

__________________________________________________________

__________________________________________________________

__________________________________________________________

__________________________________________________________

__________________________________________________________

__________________________________________________________

__________________________________________________________

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APPENDIX B

FEDERAL MOGUL CUSTOMER SURVEY

The following questionnaire was conducted by Federal Mogul, to solicit feedback from their primary customers. The survey was completed on 15 March 1996, by eleven customers including: Detroit Diesel, GM Powertrain, Ford, Chrysler, Caterpillar and several smaller firms. Customers were asked to indicate the importance of a particular survey attribute (on a scale of 1 to 10; with 1 being the least important and 10 being the most important) and to rate Federal Mogul’s performance with respect to the same attribute (again using a scale of 1 to 10). The importance and rating scores shown in the following table are the averages of the 11 responses.
<table>
<thead>
<tr>
<th>Engineering</th>
<th>Importance</th>
<th>Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>How do you perceive our R&amp;D capabilities?</td>
<td>9.3</td>
<td>7.5</td>
</tr>
<tr>
<td>Are testing and evaluation methods adequate?</td>
<td>8.8</td>
<td>7.4</td>
</tr>
<tr>
<td>Are our theoretical analysis tools current and acceptable?</td>
<td>9.2</td>
<td>8.0</td>
</tr>
<tr>
<td>Does our material availability cover your needs?</td>
<td>9.5</td>
<td>8.3</td>
</tr>
<tr>
<td>Is it easy to explain to us what you want?</td>
<td>8.4</td>
<td>9.1</td>
</tr>
<tr>
<td>Is our output easily understood?</td>
<td>8.4</td>
<td>8.8</td>
</tr>
<tr>
<td>Do you have confidence in our technical advice?</td>
<td>9.5</td>
<td>8.3</td>
</tr>
<tr>
<td>Is our participation in new program launches sufficient?</td>
<td>8.9</td>
<td>8.6</td>
</tr>
<tr>
<td>Do we adequately solve problems when they occur?</td>
<td>9.5</td>
<td>8.1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Responsiveness</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Are key personnel readily accessible?</td>
<td>8.9</td>
<td>8.8</td>
</tr>
<tr>
<td>Are we responsive to your requests for design services?</td>
<td>8.7</td>
<td>3.5</td>
</tr>
<tr>
<td>Do we meet your expectations for prototype requests?</td>
<td>9.1</td>
<td>8.6</td>
</tr>
<tr>
<td>Are we responsive to design changes?</td>
<td>8.9</td>
<td>8.8</td>
</tr>
<tr>
<td>Is the timeliness of our delivery for product/services adequate?</td>
<td>8.8</td>
<td>7.7</td>
</tr>
<tr>
<td>Is our participation in cost reduction activity satisfactory?</td>
<td>8.2</td>
<td>6.9</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Other</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>What is your overall opinion of our technical services?</td>
<td>9.5</td>
<td>8.1</td>
</tr>
<tr>
<td>What is your opinion of Federal-Mogul vs. competition?</td>
<td>8.6</td>
<td>7.9</td>
</tr>
<tr>
<td>Are our price levels competitive?</td>
<td>8.3</td>
<td>7.3</td>
</tr>
<tr>
<td>Do we anticipate future product requirements adequately?</td>
<td>8.6</td>
<td>8.0</td>
</tr>
<tr>
<td>Is it easy to do busy with Federal-Mogul?</td>
<td>8.6</td>
<td>8.9</td>
</tr>
</tbody>
</table>
APPENDIX C

QFD: VOICE OF THE CUSTOMER SURVEY RESULTS

The following table summarizes the results of the customer survey carried out to gather data for this project. Details of the survey content, and conduct, are included in Appendix A. Customers were asked to rate the importance of the design attributes on a scale of 1 to 5 (with 1 being not important and 5 being extremely important). Similarly, customers were asked to rate the performance of Federal Mogul and three of its major competitors\(^8\)\(^9\) in their performance, with respect to each design attribute (again rated on a scale of 1 to 5; with 1 being poor and 5 being excellent).

The table presents the average scores for attribute importance and performance ratings. It should be noted that averages were calculated by adding the scores reported by each customer and then dividing by the number of customers responding, with respect to the attribute.\(^10\) Survey data was then integrated with interview results, and additional information provided by Federal Mogul, to produce the quality characteristics and importance ratings used in the project.

---

\(^8\) Only one customer actually rated competitor performance. Nevertheless, the volume of bearing use and familiarity with producers were sufficient to use the comparisons, for the purposes of this report.

\(^9\) Competitors are identified only as company A, B, and C to avoid embarrassment to, and possible legal problems for, the survey participants. In addition, survey participants were guaranteed non-attribution of their responses, to encourage candidness. The competitors (A, B & C) are real firms, however, and are major producers of engine bearings.

\(^10\) Not all customers responded to all questions, due to a lack of accurate information. Similarly, blank ratings in the table indicate insufficient confusion among the participants, with respect to the meaning of an attribute, to the extent that the averaging process was considered invalid.
## Survey Data Summary

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<th>C</th>
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